

**MODELLING UNCERTAINTY OF COST AND TIME IN INFRASTRUCTURE
PROJECTS**

by

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ABSTRACT

The construction of infrastructure projects is characterised by cost overruns and time delays. Scholars view that the estimation approach and inappropriate tools and techniques used to forecast possible uncertainty in the construction processes are a primary cause of cost overruns and time delays on construction projects. Uncertainties encountered in the construction process are underestimated and these impact on the final cost and time of construction projects through a combination of individual construction activities. The study, therefore, examines the initial and final cost of construction activities, towards developing a hybrid tool that captures and models' different sources of uncertainty in infrastructure projects and their effect on cost and time underestimation.

The study adopted a sequential exploratory mixed method research approach that went beyond the basic mixed method approaches, employing a combination of sequential and concurrent aspects of mixed methods. Data was gathered through a series of expert panel estimation sessions, technical brainstorming of experienced professionals (with 30 years' experience and more) in the construction of infrastructure projects, and a structured self-administered questionnaire survey distributed to project managers of South African highway projects. The developed hybrid tool models the main structures from the activity level to the entire highway project. Consequently, three identified uncertainties in the construction process of infrastructures, namely variability in the construction process, correlations between the costs, times and cost-time of construction activities and disruptive events, are modelled jointly at the construction activity level.

Data obtained from both qualitative and quantitative approaches were analysed using various techniques. The probability distribution function of cost and time were modelled using the lognormal and triangular probability distributions; while Monte Carlo Simulation (MCS), Copula analysis technique, the Markov processes, and Adaptive Neuro-Fuzzy Inference System (ANFIS) analytical technique were used in modelling the variability of the cost and time activity, correlation between costs, time and cost-time activities, and to model the occurrence of disruptive events, so that the impact size of disruptive events on the cost and time of activities respectively, can be intelligently assessed. The developed uncertainty model was validated against the final cost and time of a project case study, as well as against historical data of construction cost overruns and time delays in infrastructure projects.

The study found that the different uncertainties had a distinct influence on construction cost and time of different project structures. Furthermore, the comparison of the deterministic estimates with the uncertainty estimates shows that the accumulated impact of the three uncertainty sources significantly increases the construction cost and time of infrastructure projects. Based on these findings, the research concludes that the disruptive event is the main cause of cost overruns and time delays in infrastructure projects. In the scale of activity, the correlation between the costs of different activities in the same structure causes the largest increase in the cost of activity, while

the correlation between the times of repeated activity in the same structure causes the largest increase in time of the activity. Furthermore, the study concludes that the improvement in the accuracy of cost and time estimation of infrastructure projects depends on a combination of probability analysis and intelligent machine learning. The contributions of the study to construction management knowledge include a clear definition of uncertainty and the sources of uncertainties in the construction of infrastructure projects; an in-depth understanding of the construction process of linear infrastructure projects; and an improvement in the quality of data used (combination of experts' estimation and historical data) for research in the area of project performance. The developed uncertainty model based on three sources of uncertainty at the activity level provides infrastructure project planners with a hybrid dynamic tool to accurately model and predict the construction cost and time of infrastructure projects at any stage of the project. Also, the uncertainty model has three other purposes: it is the preparatory point for allocation of budget, it facilitates the update of the impact of uncertainties and evaluates the effectiveness of countermeasures to mitigate against the threat of uncertainties.

DECLARATION STATEMENT

I declare that the contents of this thesis signify my own work, except for the specific and acknowledged references to the published work of others made in the text. I declare that it contains neither material previously published, nor material submitted in parts or whole for the award of any other degree or qualification.

Signed:

Signed by candidate

Moghayedi A.

MGHALI001

DEDICATION

This thesis is dedicated to my parents who have always loved me unconditionally.
This thesis is also dedicated to my wife, for her love, endless support and encouragement

تقدیم بابوسہ بردستان پدرم
به او که نمی دانم از بزرگی اش بگویم یا مردانگی سخاوتش.
پدرم اسطوره تمام زندگیم.

تقدیم به مادر عزیزتر از جانم
مادم، هستی من ز، هستی تو ست تا، هستم و، هستی دارم دست دوست.
گلزار جاودانی مادرم.

تقدیم به همسر مهربانم
که خوشبختی و آرامشم را دیدیون صفای باطنش، هستم

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CHAPTER ONE: GENERAL INTRODUCTION

1.1 INTRODUCTION

This research examines the influence of uncertainty in the construction process of infrastructure projects and whether there are key uncertainties that impact on estimated cost and completion time of infrastructure projects. The study further develops appropriate techniques to estimate accurate cost and time of infrastructure projects by modelling the uncertainty of cost and time. This chapter provides an outline of the relevance and rationale of this research study. It also presents an overview of the background of the research study, describes the problem statement, and states the research questions. The chapter further defines the scope and the objectives, gives an overview of the research methodology and outlines the structure of this thesis.

1.2 BACKGROUND TO THE RESEARCH

The construction of infrastructure projects has been characterised by costs exceeding budgetary limits and completion times extending further than what was set out initially (Flyvbjerg, 2014, Flyvbjerg et al., 2003, Adam et al., 2015). Providing accurate estimating cost and duration of infrastructure projects is a difficult task because infrastructure projects are subject to risks and uncertainties, especially in the planning phase of the project, when very limited data and information about the project is available (Ökmen and Öztaş, 2010, Commission, 2013). As an infrastructure project progresses, additional data and information become available to allow costs and times of the project to be predicted with a greater degree of accuracy (Commission, 2013). Cost and time estimation is the procedure of calculating the costs and duration of construction activities required to complete all the construction activities within the scope of the project. Accurate estimation of project cost and time is crucial to ensure the successful completion of a construction project (Kerzner and Kerzner, 2017). Estimating construction costs and times at the early stage of project development represents a prediction provided by the estimator based on available information and data. Cost and time estimating are defined as that area of construction practice where estimators' experience and judgment are utilised in the application of scientific principles and techniques to the problem of predicting and controlling costs and times of projects (Brook, 2016).

One of the leading pieces of research in the field of cost overruns and time delays in infrastructure projects was done by Flyvbjerg et al. (2002). They conducted a statistical study of the construction costs of 258 infrastructure projects worldwide, and their research found cost underestimation (final construction cost is larger than initially estimated cost) was far more common than cost overestimation. More specifically, on average, a project cost was underestimated by 27.6%. The probability of cost underestimation was 86%, while the probability of overestimation was 14%. The cost underestimation was substantially larger (maximum of +280%) than the cost overestimation (maximum -80%).

According to Flyvbjerg et al. (2002), infrastructure construction projects are frequently characterised by cost overruns and time delays. Two examples provided are the Central Artery/Tunnel Project and the transalpine tunnels in Switzerland. The (CA/T) in Boston was estimated to cost six billion US dollars and to be completed in 2001, but on completion, it cost nearly fifteen billion US dollars and was completed in 2007, six years after the initial forecast (Ehrbar, 2013). The transalpine tunnels, namely the Lotschberg and Gotthard base tunnels, connected Italy to central Europe. The Lotschberg base tunnel cost 4,365 million Swiss francs instead of the estimated 3,214 million and was completed according to schedule. The initial estimated cost of the Gotthard base tunnel was 7,716 million Swiss Francs, and the current additional cost amounts to 2,833 million Swiss francs. Initially, the Gotthard base tunnel was planned to be completed by 2012; however, it was completed by 2017 (Ehrbar, 2013, Amberg, 2014, Fabbri, 2017).

Estimating construction costs and times of projects is an example of a knowledge-intensive engineering task (Anderson et al., 2007) that is dependent on the expertise of the human professional. Shane et al. (2015) observed that the main problem is that the estimators' expertise is often not documented or authenticated. Hence, this expertise is prone to subjectivity. There are different techniques that attempt to predict accurate cost and duration of construction projects. According to Anderson et al. (2007), cost and time estimation processes usually contain the following main steps: determining the basis of the estimate, preparing a base estimate, determining risk and setting contingency, reviewing the entire estimate, and lastly, communicating the estimate.

Accuracy and comprehensiveness in estimating cost and time are sensitive issues and can be easily influenced by various parameters; with the aim of retaining a fair degree of accuracy during the estimating process, each parameter must be properly addressed (Shane et al., 2009). Ökmen and Öztaş (2010) emphasised that many parameters that influence project costs are undefined during the early stages of project development. Also, estimating construction cost and time to an acceptable level of accuracy is impossible to achieve manually.

On the other hand, inaccurate cost estimation leads to the incorrect evaluation of projects and misallocation of scarce resources, and the result is cost escalation and delay in total cost and duration of the project (Flyvbjerg, 2007). These two issues, namely, the impossibility of conducting cost and time estimation manually and the uncertainty of cost and time escalation parameters, illustrate the need to establish estimation methods that appropriately capture the uncertainties in the construction process of infrastructure projects, which have an impact on the final cost and duration of the projects.

Uncertainty means an unknown phenomenon. Typically, in the estimation of construction projects, several variables are not known since construction projects are populated by uncertainties. Compared to risk, the concept of uncertainty has a neutral connotation: uncertainty can have a positive or negative impact on the project objectives (Kurowicka and Cooke, 2006). It is an opportunity if it has a positive impact; a threat if it has a negative impact on the project objectives (Hirano and Wright, 2017).

The causes of infrastructure projects cost overruns and time delays have been considered by many industry and academic analysts. These causes have been attributed to poor planning and/or implementation of projects, inadequate budget of projects, incompatible organisation of projects, lack of communication between project enterprises (Ahiaga-Dagbui et al., 2015), politics and inflation (Larsen et al., 2015), material price fluctuation, variation/additional works/reworks, and cost estimation method (Odediran and Windapo, 2016). Furthermore, sources of cost overruns and time delays can be classified into several major categories such as unreasonable estimation and adjustment of project costs and times, delays during construction, changes in scope, and no practical use of the earned value management system (Cantarelli et al., 2013).

The risk and uncertainty factors causing infrastructure projects' cost and time underestimation have been identified in the literature (Anderson et al., 2007, Flyvbjerg, 2007, Flyvbjerg et al., 2002, Chai et al., 2009, Cantarelli et al., 2013, Memon et al., 2011, Sovacool et al., 2014a, Adam et al., 2017b, Moret and Einstein, 2016). Flyvbjerg (2007) and Cantarelli et al. (2013) identified technical, economic, psychological, and political risk factors as the frequent causes of cost and time underestimation in infrastructure projects. Anderson et al. (2007) identified 18 risk factors that lead to cost and time escalation in infrastructure projects, which were subdivided into factors stemming from internal and external sources.

To address the factors causing cost and time underestimation, Flyvbjerg (2007) suggested that cost underestimation should be limited with a policy change, improved forecasting techniques such as reference class forecasting, and debiasing techniques. In contrast, Cantarelli et al. (2013) proposed the following: delivery and procurement, management, document quality, scope and schedule, integrity, off-prism, and estimate quality strategies. Ahiaga-Dagbui et al. (2015) suggested the use of improved estimation tools, such as debiasing techniques, and a change in policy to counteract the identified causes.

Moret (2011), Brook (2016), Kim et al. (2004) studied most available estimation techniques such as: three-point estimating technique, analogous estimating technique, expert judgment estimating technique, parametric model estimating technique, published data estimating technique, reserve analysis technique, vendor bid analysis technique, and bottom-up analysis technique, and they found that the available estimation techniques do not capture the uncertainty in the construction process of projects. These conventional cost and time estimating techniques provide the finest scenario estimate, which is rarely the case in practice.

The American Association of State Highway and Transportation Officials (AASHTO) pointed out the conventional estimating approaches are preparing times and cost of construction projects with small variability. The cost and time estimate of infrastructure projects are generally prepared quickly with minimum effort because risks and uncertainties involved in the project are not quantified and this makes it extremely difficult to control as projects develop (AASHTO, 2013).

In light of this, the construction process of infrastructure projects is often beset by cost and time overruns. The actual cost and duration of an infrastructure project are influenced by many variables and uncertainties, and that can affect the predicted cost and time significantly. However; scholars

(Moret, 2011, Mok et al., 2015, Ang and De Leon, 2005, El Khalek et al., 2016, Flyvbjerg, 2014) are of the view that the tools and techniques developed to counteract these variables and uncertainties lack an in-depth understanding of the construction process of infrastructure projects and their uncertainties, and modelling risks only without capturing the cumulative impact of different sources of uncertainty was a limitation. Moreover, Moret and Einstein (2016) identified two limitations on solutions proposed by Flyvbjerg (2007), Cantarelli et al. (2013), Anderson et al. (2007): the lack of an in-depth understanding of the construction process and its uncertainties, and the limitation of modelling risks only without capturing the cumulative impact of different sources of uncertainty. To overcome these limitations, they proposed the use of a construction model and an uncertainty model. In addition, limited research has been done holistically and in South Africa to evaluate the construction process and model the risks and uncertainties within the process, and their impact on estimated infrastructure project cost and time. Therefore, this research seeks to fill this knowledge gap.

1.3 STATEMENT OF THE PROBLEM

The construction process of infrastructure projects is frequently beset by cost overruns and time delays due to the estimation approach and inappropriate tools and techniques used to forecast possible risk and uncertainty in the construction processes (Moret and Einstein, 2016). Also, some of the solutions provided have been found to lack an in-depth understanding of the construction process and its uncertainties. There is also limited research done holistically and in South Africa to evaluate the construction process and model the uncertainties within the process and their impact on the estimated cost and duration of construction of infrastructure projects. Therefore, this research examines risks and uncertainties occurring at the single activities level of the construction processes of building infrastructure projects, and whether there are key uncertainties in the process that impact on the cost and duration of infrastructure projects. The study seeks to propose an estimation method consisting of two components: the construction model and the uncertainty model that captures cost and time uncertainty in infrastructure projects.

1.4 RESEARCH QUESTIONS

The main research question, which has been determined and will be answered through the development of the research is:

What are the key sources of uncertainty in the construction process of infrastructure projects and what are the levels of impact of these uncertainties individually and cumulatively on the cost and duration of infrastructure projects?

To address the main research questions, answers were sought to the following specific sub-questions:

Research question 1: What are the common processes used in the construction of infrastructure projects?

Research question 2: What is the association between the characteristics of infrastructure projects and cost and duration of infrastructure projects?

Research question 3: What are the key sources of uncertainty in the construction process of infrastructure projects that impact on cost and duration of infrastructure projects?

Research question 4: What is the association between the impacts of different sources of uncertainty and cost and duration of infrastructure projects?

Research question 5: How can an uncertainty model be developed which will improve the accuracy of the estimation of cost and duration of infrastructure projects?

Research question 6: What is the difference in the construction cost and duration of infrastructure projects before and after applying the uncertainty?

1.5 AIM OF THE RESEARCH

This research examines the impacts of various sources of uncertainty in the construction process of infrastructure projects and whether the incorporation of the construction and uncertainty models improve the accuracy of the estimation of cost and duration of the projects.

1.6 OBJECTIVES OF THE RESEARCH

The research objectives are to:

Research objective 1: Investigate the construction process of infrastructure projects and develop a representative construction model.

Research objective 2: Determine the association between the characteristics of infrastructure projects and cost and duration of infrastructure projects.

Research objective 3: Identify the key sources of uncertainty in the construction process of projects that impact on cost and duration of infrastructure projects.

Research objective 4: Determine the association between the impacts of different sources of uncertainty and the cost and duration of infrastructure projects.

Research objective 5: Develop an uncertainty model, which will be used to forecast the impact size of different sources of uncertainty and model their cumulative impacts to improve the accuracy of construction cost and duration of infrastructure projects.

Research Objective 6: Apply the uncertainty model in the construction of infrastructure projects, validate and measure the effect of applying the model on the estimation of cost and duration of highway infrastructure projects.

1.7 SIGNIFICANCE OF THE STUDY

Infrastructure projects fuel economic growth by reducing the cost of production and transport of goods and services, increasing the productivity of input factors, creating indirect positive

externalities, and smoothing the business cycle (Ansar et al., 2016). However, nine out of ten infrastructure projects overrun their budgets and duration (Flyvbjerg et al., 2002).

Infrastructure projects are well-known for being poorly managed and unacceptably over budget and duration, rather than for stimulating economic growth and social integration of communication. The most important cause of this global phenomenon in infrastructure projects is that the actual cost and time of an infrastructure project are influenced by many uncertain and unforeseen events.

Therefore, infrastructure planners need a valid tool that provides accurate construction cost and duration of infrastructure projects. Such a predictive tool requires identifying the uncertainties in the construction process and modelling their impacts on construction cost and time of infrastructure projects, which is not currently popular among infrastructure planners, particularly in Africa.

The developed uncertainty model of cost and duration is such an advanced tool that it adds two novel contributions to the existing body of infrastructure management knowledge. First, it deepens the understanding of the construction process of infrastructure projects. The representation of the construction process of an infrastructure project with activity networks, deepens the understanding of the construction process and provides insight when identifying the sources of uncertainty. Second, it contributes to the understanding of the sources of uncertainty by quantitatively modelling and capturing their cumulative impact.

In a novel approach, uncertainty is analysed at the activity level, from the perspective of its sources, and considering both positive and negative outcomes. Three sources of uncertainty have been identified: 1) the variability of the activity cost and time; 2) the correlations between the costs/times of the construction activities, and 3) the uncertainty events. For the first time, all three sources of uncertainty are modelled jointly at the activity level: the cost and the time of activity are variable; the cost/time of the activity is correlated with the costs/times of other activities; and, during the activity, one or more uncertainty event/s can occur. Analysing and modelling the sources of uncertainty shows the impact of a single source of uncertainty and, most importantly, captures the cumulative impact of different sources of uncertainty on project cost and time.

The extended form of the tailormade simulation in a MATLAB environment integrates the construction and uncertainty models to simulate the uncertainty in the construction of a highway project. Implemented in the simulation are: 1) the probability distributions, which model the variability of the activity cost and time; 2) the copula, which represents the cost and time correlations; 3) the group of experts brainstorming (rapid idea generation) analysis, which justifies the identified uncertainty events from previous scholars by the technique of bibliometrics; 4) the Markov process, which models the occurrence of uncertainty events; 5) ANFIS, which models the impact size of uncertainty events; and 6) the Monte Carlo method to generate the sets of cost and time based on the specific conditions and assumptions.

Finally, the practical application of the construction and uncertainty models to the construction of a highway project shows the feasibility of the models and their effectiveness in capturing the uncertainty in the construction process and provides invaluable insight into the magnitude and the impact of the sources of uncertainty on the construction cost and duration of infrastructure projects.

1.8 OVERVIEW OF THE RESEARCH METHODOLOGY

This study is grounded in the field of construction economics, infrastructure construction cost and time estimation, and infrastructure project management, which fall into the infrastructure management paradigm.

To achieve the research objectives, the study adopted a sequential exploratory mixed method research approach, involving the collection, analysis, and interpretation of both qualitative and quantitative data (Creswell and Creswell, 2017). The data collection process in this study utilised the sequential exploratory method, where the qualitative data is collected first, followed by the collection and analysis of quantitative data. The rationale for the use of this method is to develop an instrument to assist in the identification and classification of variables for further analysis (Creswell and Creswell, 2017).

The research was initiated by an extant review of existing literature relating to the research concepts, particularly quantitative studies of cost overrun and time delay in infrastructure projects, causes of cost and time underestimation and mitigation strategies, the definition of uncertainty, and sources of uncertainties in the construction of infrastructure projects. The in-depth review of the literature revealed the existing limitations in available solutions, which helped to establish a theoretical background of the study and developed the research conceptual framework.

Once the research framework had been developed, a series of estimation sessions and technical interviews were held with five experts with more than 30 years of experience in the construction of linear infrastructure projects. The aim was to determine the unit prices and the amount of uncertainty in production rates in the construction of three structures of highway projects. Other required data, such as probability and severity of disruptive events, were collected from experts through a structured self-administered questionnaire based on their last three projects.

To pursue the research objectives, the collected data were analysed using the following steps:

- The construction process of the main types of structures of linear infrastructure projects is analysed at the level of single activities and represented in networks. The activity networks of the main types of structures are interconnected in a construction network that models the construction of a linear infrastructure project. The construction model of the project contains the activity networks, and their interconnection in the construction network is presented.
- Sources of uncertainty in the construction process of infrastructure projects are identified, and quantitative models of the sources of uncertainty are developed. The correlation is modelled with the copulas. The occurrence of disruptive events is modelled with Markov processes and the cost and time impacts are modelled with an Adaptive Neuro-Fuzzy Inference

System (ANFIS). These three sources of uncertainty and their quantitative models form the uncertainty model.

- The construction model and the uncertainty model are integrated into the application to the construction of a section of the highway project in South Africa. The construction of all the structures of three main structures of the highway (earthworks, bridge, and pavement) are modelled with activity networks, and the sources of uncertainty are modelled with probability distributions, Markov processes and ANFIS. The impacts of the different sources of uncertainty are compared, and the cumulative impact of the sources of uncertainty is analysed using sensitivity analysis technique.

The study research overview is illustrated in Figure 1.1, and further discussion on the research approach and methodology is provided in Chapter Four.

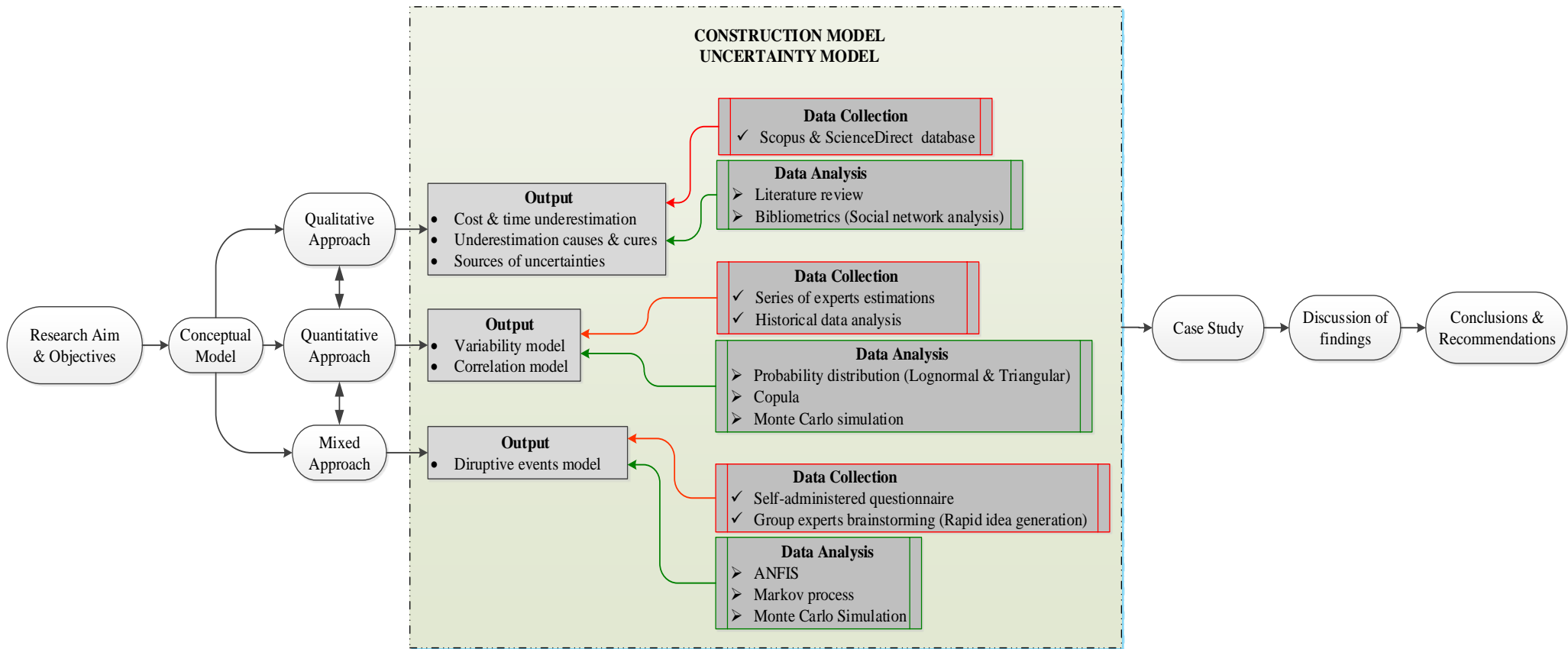


Figure 1.1: Research overview

1.9 SCOPE AND LIMITATIONS OF THE STUDY

The scope of this thesis is delimited to developing a tool that accurately estimates the cost and time of infrastructure projects by modelling construction and uncertainty. Due to the vast nature of infrastructure projects, it is essential to set boundaries to the extent of this research. Therefore, this thesis is focused on modelling uncertainty in linear infrastructure projects, particularly the construction of a highway project as a case study.

The study employs the combination of expert opinions and estimations, and historical data to ensure the quality of the input data. Estimations are sought from the panel of experts with long experience in their fields, while the historical data stem from records of comparable construction of infrastructure projects. However, some of the data, such as the probability of occurrence and severity of disruptive events, are not available from historical sources. Therefore, this data is obtained from the professional highway project managers with a minimum of 20 years of experience. This sets two limitations to the study: first, the number of qualified highway experts is very limited, and second, because there is no database of highway experts available in South Africa, the study centres on the project managers of highway projects under construction in 2017 in South Africa.

The developed estimation tool in this thesis has the benefit of capturing positive and negative effects and their combination of uncertainties in cost and time estimation of infrastructure projects. However, due to no availability of uncertainty historical data and the difficulty of measuring the positive impact of disruptive events on the project by experts, only the negative impacts of the disruptive events are modelled.

1.10 THESIS STRUCTURE

This thesis is organised into eight chapters as described below:

Chapter One: General Introduction

Chapter One provides the introductory material and the presentation of the research topic. This chapter presents a broad background to the research, problem statement, research aims and objectives, research question and justification for the study. The chapter also provides an overview of the research methodology, scope, and limitations of the study.

Chapter Two: Literature Review

Chapter Two provides a theoretical background of the study. The chapter presents extant reviews of the literature relating to cost and time underestimation in the construction of infrastructure projects, causes and cures of cost and time underestimation in the construction of the infrastructure projects, and mitigation strategies to address risk and uncertainty in the construction of infrastructure projects.

Chapter Three: Theoretical and Conceptual Framework

Chapter Three provides the theoretical and conceptual perspectives of the study. The chapter presents a comprehensive theoretical review of cost and time estimation modelling for emphasising a knowledge gap on modelling of cost and time in the construction of infrastructure projects and forming the research hypotheses. The chapter also develops the conceptual framework based on the established research hypotheses.

Chapters Four: Research Design and Methodology

Chapter Four provides the methodology and approach to the study. The chapter presents the underpinning philosophical and adopted paradigm and research strategy. The chapter also describes the methods of data collections and data analysis techniques employed in the study.

Chapter Five: Presentation of Data

Chapter Five presents the input data for modelling and analysing the case study. The chapter describes the selected case study and developed construction model of the highway infrastructure project. It provides a summary of the gathered input data including the deterministic estimation, variability estimation, correlation between the activities cost and times, and disruptive events.

Chapter Six: Application of the Uncertainty Model to an Infrastructure Project

Chapter Six presents the application and the results of the developed uncertainty model to a case study infrastructure project. The chapter describes the modelling of three sources of uncertainty (variability, correlation, and disruptive events) on the cost and time of highway projects. Furthermore, it clarifies the impacts of each source of uncertainty and cumulative impacts of three sources on different highway structures and finally tests the research hypotheses.

Chapter Seven: Validation of the Uncertainty Model and Discussion of Findings

Chapter Seven provides the validation of the developed uncertainty model and discussion of findings. The chapter presents the four-orders of validation for the uncertainty model and its results. It discusses and authenticates the findings of the study by relating them to the existing literature and body of knowledge in construction infrastructure projects estimation and infrastructure construction management.

Chapter Eight: Summary, Conclusions, and Recommendations

Chapter Eight presents the overall summary of the research findings based on the research objectives. The chapter outlines the study conclusions and significant contribution to the knowledge. Moreover, it presents the recommendations and outlines suggestions for future research.

1.11 SUMMARY OF THE CHAPTER

This chapter illustrated the entire research study. The background of the study provided an insightful explanation of the effect of uncertainty in construction cost and time of infrastructure

projects and explained the construction cost and duration underestimation of infrastructure projects associated with uncertainty in the construction process. The problem statement of the study described the lack of appropriate tools and techniques to forecast possible risk and uncertainty in the construction processes as the main problems in the frequent cost overruns and time delays in construction of infrastructure projects. Based on this problem, the research aim, research objectives, and research question were established. The subsequent chapter elaborates extant reviews of the literature related to the research aim and objectives.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

Cost overruns and time delays are common in the construction of infrastructure projects due to the high level of uncertainties in the construction processes of these projects (Flyvbjerg, 2007). However, these uncertainties in the infrastructure projects are underestimated at the pre-construction phase. This chapter presents an overview of the extant literature and practical manuals on modelling uncertainty in infrastructure projects. It presents several examples and a statistical study that outlines the problems in the cost and time estimation of infrastructure projects. Thereafter, the chapter examines the causes of cost overruns and time delays in infrastructure projects and strategies to mitigate their occurrence. It examines and classifies the uncertainty sources and events in infrastructure projects and finally, it presents an overview of available uncertainty modelling tools used in the estimation of cost and time of infrastructure projects.

2.2 CONSTRUCTION OF INFRASTRUCTURE PROJECTS

The Construction Industry Institute (CII) developed the Project Definition Rating Index (PDRI) to classify construction projects according to the scheme of projects. PDRI categorised construction projects as building projects, industrial projects, and infrastructure projects. PDRI delineated the infrastructure project as one often designed by civil engineers, and they primarily perform a function that is integral to the effective operation of a system. Infrastructural projects provide capacities such as transportation, transmission, distribution, collection, and the interaction of goods, services, or people. In terms of scale, these projects generally span a broad geographical region and affect multiple jurisdictions and stakeholder groups (Safa et al., 2015).

There is no standard classification of infrastructure projects across engineering and built environment studies. For instance, Fulmer (2009) classified infrastructure projects based on their sector, namely electrical power, oil and gas, potable and wastewater, transportation and communication. The American Society of Civil Engineers publish an Infrastructure Report Card, grading infrastructure projects into 16 categories, namely, aviation, bridges, dams, drinking water, energy, hazardous waste, inland waterways, levees, parks and recreation, ports, rail, roads, schools, solid waste, transit and wastewater (Herrmann, 2013).

Ammar and Elbeltagi (2001) classified the construction of infrastructure projects into repetitive and not-repetitive infrastructure projects. Construction infrastructure projects that contain many identical units, wherein activities repeat from one unit to another, are characterised as repetitive infrastructure projects. These projects are classified according to the nature of the repetition: horizontal repetition due to the geometrical layout, such as rail lines, pipelines and highways, which are called linear projects; vertical repetition due to vertical repetition of skeleton considerations, such as silos and towers; both horizontal and vertical repetition, applicable to projects that integrate the above two kinds, such as highway interchanges (Agrama, 2011).

Hajdasz (2014) stated that linearity of projects is due to the uniform repetition of a set of activities through the project (bridge); or due to the geometrical layout of the project (highway and pipelines). The construction of linear infrastructure projects consists of limited major structures and each structure contains several construction activities which are repeated. For instance, highway projects consist of three main structures, namely: earthwork, bridge, and pavement. Furthermore, the construction process of highway projects depends on the different parameters, such as highway construction methods, geology, location and terrain (Zayed et al., 2008). The construction process of a highway consists of sequential, parallel and repeated activities; therefore, construction of a highway is categorised as a linear infrastructure project (Hassanein and Moselhi, 2004)

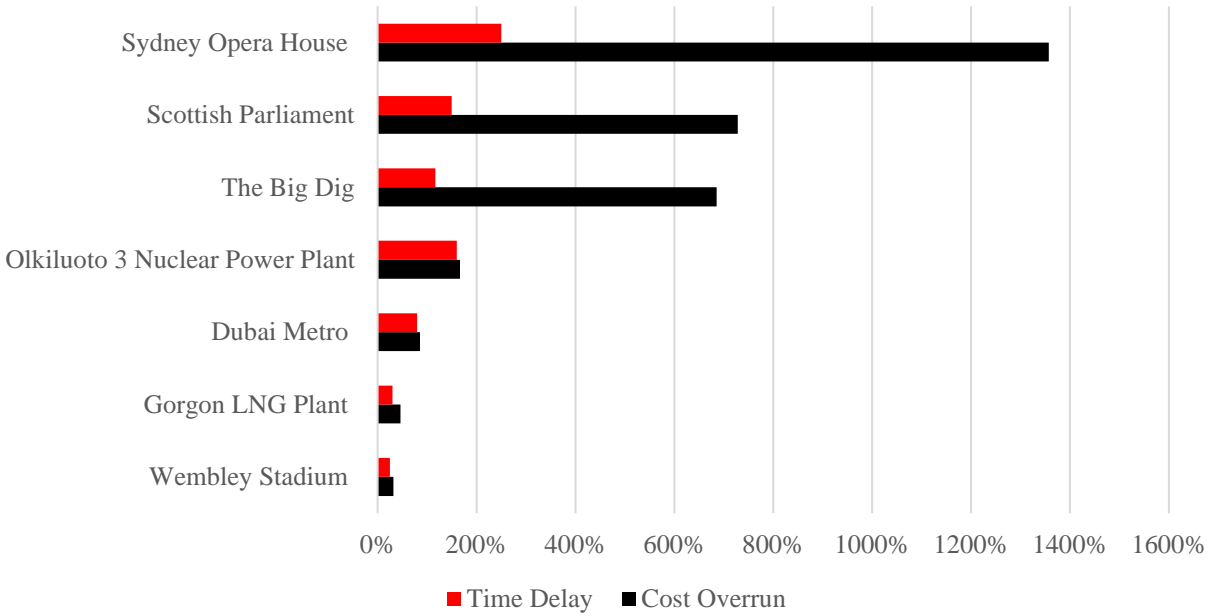
According to Flyvbjerg (2007), the cost and time underestimation in the construction of infrastructure projects, particularly in linear projects such as highway projects, is large than in other construction projects, due to unique features of these projects, which include a high level of uncertainty and correlation between major construction activities and projects, long duration of construction, dynamic process, repetitive linear process, and a mobile construction site.

Since the main focus of this research is on a linear infrastructure project, to deepen the understanding of the construction process of linear infrastructure projects, the comprehensive model of construction of a highway project, as the most common linear infrastructure project, is discussed.

2.3 COST AND TIME UNDERESTIMATION IN THE CONSTRUCTION OF INFRASTRUCTURE PROJECTS

The cost and time underestimation in the construction of infrastructure projects is a global phenomenon (Flyvbjerg, 2014). Flyvbjerg et al. (2003) observed in their extensive study that cost and time underestimation are the main challenges in infrastructure projects for over a 70-year period and have not declined over the period. They also discovered that 9 out of 10 infrastructure projects have cost and/or time overruns. Ahiaga-Dagbui et al. (2015) found that, in spite of the vast attention given to infrastructure projects' cost overruns and time delays in the literature, not much improvement has been made in accuracy and reliability of estimation of cost and time of infrastructure projects over the years.

The Wembley Stadium in the UK is one of the seven most disreputable examples of cost overrun and time delays in infrastructure projects, the others are Gorgon LNG Plant, Dubai Metro, Olkiluoto 3 Nuclear Power Plant, the Big Dig tunnel, Scottish Parliament and Sydney Opera House. These seven infrastructure projects encountered cost overruns of 32% to 1357% of their initial estimated budget and delays of 25% to 250% of their initial estimated duration, as illustrated in Figure 2.1.



Source: Flyvbjerg, (2014)

Figure 2.1: Cost overruns and time delays in the most disreputable infrastructure projects

The Wembley Stadium cost 1 billion pounds instead of the estimated 757 million pounds at completion with a year delay (five years instead of the scheduled four years). The Gorgon LNG Plant located in Western Australia, which started operations in 2017, cost USD 54 billion, about USD 17 billion more than its budget and was completed with an 18-month delay, the Dubai Metro was estimated to cost USD 4.2 billion and to be completed in 2009, but was completed in 2014 at the total cost of USD 7.8 billion (Siemiatycki, 2015, Love et al., 2016). The Central Artery/Tunnel Project in Boston estimated to cost USD 6 billion and to be completed in 2001, cost nearly USD 15 billion on completion in 2007, six years after the initial forecast. Olkiluoto 3 Nuclear Power Plant in Finland, planned for construction in five years at 3 billion euro, was completed with an eight-year delay and 5-billion-euro cost overrun. The Big Dig tunnel of Boston was estimated to cost USD 2.8 billion and to be completed by 2001; the project cost almost ten times its initial cost at USD 22 billion and was completed in 2007 (Mulla and Waghmare, 2015).

The Scottish Parliament was estimated to be constructed at 50 billion pounds in three years; however, the project completed at 414 billion pounds with a three-year delay. The Sydney Opera House construction was originally scheduled for four years, with a budget of AUS \$7 million. It cost AUS \$102 million and took 14 years to be completed (Siemiatycki, 2015).

As illustrated in Figure 2.1, the magnitude of cost overrun is greater than the magnitude of time delay in all seven most disreputable infrastructure projects.

2.4 STATISTICAL STUDIES OF COST AND TIME UNDERESTIMATION IN THE CONSTRUCTION OF INFRASTRUCTURE PROJECTS

This section presents the results of previous studies into the cost overrun and time delay issues in the construction of infrastructure projects, with outlines of the trends in the magnitude and type of infrastructure projects.

2.4.1 Overview of cost underestimation

One of the leading pieces of statistical study in the field of cost underestimation in infrastructure projects were done by Flyvbjerg et al. (2002). They conducted a statistical study of the construction costs of 258 infrastructure projects to identify the ratio of cost underestimation to cost overestimation in the construction of infrastructure projects, which were constructed between 1927 and 1998 in 20 different countries on five continents. Furthermore, Flyvbjerg et al. (2002) classified the transportation infrastructure project according to the analysis of cost escalation of three types of projects road (highways and freeways), rail (high-speed railway, urban railway, and conventional railway) and fixed link (bridges and tunnels). Their study revealed that the cost escalation distributions of each type of project varied in mean and standard deviation.

The rail infrastructure projects had the largest mean cost escalation, and the fixed link infrastructure projects had the largest standard deviation cost escalation among the three types of infrastructure projects. These findings suggest that the type of infrastructure project had an impact on the cost escalation. Therefore, the cost escalation of distribution (Lognormal) of the road projects is considered as the cost escalation of infrastructure projects in this study.

The study by Flyvbjerg et al. (2002) on cost underestimation and overestimation revealed that on average, a project cost was underestimated by 27.6% (instead of 0%, in the case for a normal distribution). The probability of cost underestimation was 86%, while the probability of overestimation was 14% and the maximum cost underestimation was +280% while the maximum cost overestimation was -80%, which evidenced that the cost underestimation was significantly greater than the cost overestimation. The study also revealed that a cost underestimation error was not as common as a cost overestimation error and the magnitude of cost underestimation errors was significantly higher than the magnitude of cost overestimation errors.

Similarly, to the findings of the Flyvbjerg et al. (2002) the study of infrastructure projects cost by Žujo et al. (2010) revealed that 63% of World Bank infrastructure projects encountered cost underestimation, with an average of 40% of initial estimated costs. Abdullah et al. (2010) found that 90% of the People's Trust Council infrastructure projects suffered from the significant effect of cost underestimation since 1984. Also, Sovacool et al. (2014a), in their analysis of 401 electricity infrastructure projects in 57 countries, observed that three out of four projects were faced with cost underestimation with an average of 80%. Alex et al. (2009) found a 60% cost underestimation in 800 water and sewer infrastructure projects.

From the research of Flyvbjerg et al. (2002), the following remarks (pertinent to the current research) are observed:

- Infrastructure project costs are consistently underestimated.
- The infrastructure project costs are dependent on the construction model (type) of projects.
- The cost escalation of infrastructure projects is skewed to the right (lognormal with positive skewed).

2.4.2 Overview of time underestimation

The studies of time underestimation undertaken by Singh (2010) in India, Love et al. (2012) in Australia, Ahsan and Gunawan (2010) of Asian Development Bank funded projects, Assaf and Al-Hejji (2006), Ngacho and Das (2014) in Kenya and Kaliba et al. (2009) in Zambia proved that like cost underestimation, time underestimation are common in the construction of infrastructure projects. Singh (2010) found that 25% of 1035 studied infrastructure projects faced average time underestimation by 117.5% of their initial estimated duration. Love et al. (2012) stated that the cost and time underestimation in infrastructure projects could average 70% and 183%, respectively, over the initial stipulated estimate.

The study of Ahsan and Gunawan (2010) revealed that the time underestimation of infrastructure projects funded by Asian Development Bank in China, India, Thailand, and Bangladesh was by 13.63%, 55.69%, 32.71% and 34.41%, respectively. Similarly, Assaf and Al-Hejji (2006) found that most contractors and consultants of infrastructure projects indicated that average time underestimation ranges between 10% and 30% of the original project period, and about 25% of the infrastructure consultants indicated 30% to 50% time variation. In Africa, Ngacho and Das (2014) reported the time underestimation in the construction of Kenyan infrastructure by 87%. Similarly, Kaliba et al. (2009) calculated the average time variation of 86.7% for infrastructure projects of Zambia. Following the above observations, the next sections present a review of the causes of cost escalations and time delays in infrastructure projects and the available mitigation strategies to counteract them.

2.5 CAUSES OF COST AND TIME UNDERESTIMATION IN THE CONSTRUCTION OF INFRASTRUCTURE PROJECTS AND MITIGATION STRATEGIES

The causes of infrastructure projects' cost escalation and time delays have been considered by many industries and previous research (Renuka et al., 2014, Cantarelli et al., 2013, Anderson et al., 2009, Flyvbjerg, 2007). This section presents an extant review of the causes of cost and time underestimation in infrastructure projects and mitigating measures provided by Flyvbjerg (2007) and Anderson et al. (2009). The established causes and proposed mitigations for the cost and time underestimation in infrastructure projects by Flyvbjerg (2007) and Anderson et al. (2009) are summarised in Table 2.1.

Table 2.1: Causes and mitigation measures

Causes	Mitigation measures
Flyvbjerg	
Technical <ul style="list-style-type: none"> ▪ Imperfect forecasting techniques ▪ Insufficient data ▪ Inexperienced forecasters ▪ Inherent difficulty in forecasting the future ▪ Honest mistakes Economic-Political <ul style="list-style-type: none"> ▪ Economic self-interest ▪ Economic public-interest Psychological <ul style="list-style-type: none"> ➤ Optimism bias 	<ul style="list-style-type: none"> ➤ Improved estimation tools ➤ Improved quality of data ➤ Employing experienced forecasters <ul style="list-style-type: none"> ○ Reference class forecasting ➤ Policy change <ul style="list-style-type: none"> ○ Transparency ○ Performance specifications ○ Regulatory regime ○ Risk capital ➤ Debiasing technique <ul style="list-style-type: none"> ○ Outside view
Anderson	
Technical <ul style="list-style-type: none"> ▪ Project schedule changes ▪ Engineering and construction complexities ▪ Poor estimations ▪ Inconsistent application of contingencies ▪ Faulty execution ▪ Unforeseen events ▪ Unforeseen conditions Economic <ul style="list-style-type: none"> ▪ Effects of inflation ▪ Market conditions ▪ Delivery and procurement approach Economic-Political <ul style="list-style-type: none"> ▪ Bias ▪ Local concerns and requirements ▪ Scope change ▪ Scope creep Legal <ul style="list-style-type: none"> ▪ Ambiguous contract provisions ▪ Contract document conflicts 	<ul style="list-style-type: none"> ➤ Management strategy ➤ Scope and schedule strategy ➤ Off-prism strategy ➤ Risk strategy <ul style="list-style-type: none"> ✓ Identification ✓ Analysis ✓ Mitigation & Planning ✓ Allocation ✓ Monitoring & Controlling ➤ Delivery and procurement strategy ➤ Document quality strategy ➤ Estimate the quality strategy ➤ Integrity strategy

Source: Flyvbjerg (2007) and Anderson et al. (2009)

2.5.1 Causes of cost and time underestimation on infrastructure projects

Based on the previous research, Flyvbjerg (2007) identified causes of cost and time underestimation in infrastructure projects and classified them into technical, economic-political and psychological. Unlike the three causes of cost and time underestimation proposed by Flyvbjerg (2007), Anderson et al. (2009) identified 15 factors, classified into technical, economic, economic-political and legal, which cause cost escalation and time delays on infrastructure construction projects. (See Table 2.1).

The main difference in the identification of causes for cost escalation and time delays by Flyvbjerg (2007) and Anderson et al. (2009) are observed as the classification of causes. While Flyvbjerg (2007) determined technical, economic-political and psychological causes, Anderson et al. (2009) classification consisted of economic, economic-political, legal and technical factors and none considered the psychological aspect of optimism bias.

Technical causes represented technical difficulties and errors in the process of project estimation. These difficulties and errors were caused by various factors, such as imperfect forecasting techniques, insufficient data, inexperienced forecasters, inherent difficulty in forecasting the future, honest mistakes, and other technical difficulties and errors. Due to the positive skew of cost escalation of infrastructure projects and the cost and time underestimation occurring in construction of infrastructure projects over time, the technical difficulties and errors are not the only cause of the frequent cost and time underestimation in infrastructure projects (Flyvbjerg, 2007). Anderson et al. (2009) associated the following seven factors with the technical cause of cost and time underestimation: project schedule changes due to project extensions, and budget constraints which cause additional costs depending on the two primary components of inflation and the time of the expenditure; engineering and construction complexities, which affect the internal coordination errors between project components and constructability problems; poor estimations including general errors, omissions, inadequacies and poor performance in planning and estimation procedures and techniques, inconsistent application of contingencies, including misuse and failure to define what costs and times contingencies cover; faulty execution; unforeseen events; and unforeseen conditions.

The economic self-interest and economic public-interest are two sorts of economic-political reasons for cost underestimation in infrastructure projects (Flyvbjerg, 2007). An example of economic self-interest is when of planners increase the chances of a project obtaining funding with the help of a favourable cost forecast. An example of economic public interest is the cost underestimations by planners and project promoters to encourage the minimisation of costs and saving of public finance (Flyvbjerg, 2007). Local concerns and requirements (perceived negative impacts of construction on the local societal and natural environment), scope changes, scope creep and bias: (deliberate underestimation of project costs to ensure that a project remains in the construction programme) are the four economic-political factors determined by Anderson et al. (2009).

Flyvbjerg et al. (2002) defined psychological reasons as optimism bias which is the tendency of planners and project promoters to be excessively optimistic by focusing on success scenarios and overlooking the chance of mistakes and failure. The optimism bias is very common among decision-makers in infrastructure projects (Cantarelli et al., 2013).

Anderson et al. (2009) recognised the effects of inflation (when the project estimates are not communicated in the year of construction costs), market conditions and delivery and procurement approach as the three factors of economics that cause cost and time underestimations. Two main factors of cost and time underestimation due to legal causes identified by Anderson et al. (2009) are ambiguous contract provisions and contract document conflicts.

2.5.2 Mitigation measures

In order to counteract the discussed causes of cost underestimation, Flyvbjerg et al. (2002) and Flyvbjerg (2007) recommended that cost escalation errors due to technical difficulties are eliminated or reduced by applying better forecasting techniques, improved quality of data, and

employing experienced forecasters. However, Flyvbjerg et al. (2002) do not reflect the following important factors in the study of cost underestimation of infrastructure projects due to the technical causes: infrastructure project scope and new technology. Scope creep causes increases in the construction cost, as well as in the construction cost variance. New technologies often add to the technical complexity of projects, which is the main driver of cost escalation (Flyvbjerg, 2007).

Flyvbjerg (2007) suggested that cost underestimation due to both types of economic-political they identified are limited with measures of accountability and proposed applying simple reality checks and debiasing techniques to eliminate cost underestimation due to psychological factors.

2.5.2.1 Reference Class Forecasting (RCF)

Flyvbjerg (2007) developed reference class forecasting techniques to counteract cost underestimation and time delay due to technical and psychological causes in infrastructure projects by estimating the performance of project cost and time from an outside view (statistical analyses of past projects) rather than the inside view (project specifics).

RCF improves the accuracy of project cost and time estimations by reducing the optimism bias (Batselier and Vanhoucke, 2017) through applying the techniques systematically to infrastructure projects by identifying the reference class of past similar infrastructure projects, creating the probability distribution of the project cost and time performance measure based on empirical data from the reference class projects, and estimating the most likely outcome by comparing the project considered to the reference class distribution

Flyvbjerg et al. (2004) calculated the probability of cost escalations due to the optimism bias in three categories of infrastructure projects namely: rails, roads, and fixed links by applying RCF, as shown in Table 2.2.

Table 2.2: Applicable cost escalation due to optimism bias

Infrastructure category	Cost escalation	
	50 th percentile	80 th percentile
Roads	15%	32%
Rails	40%	57%
Fixed links	23%	55%

Source: Flyvbjerg et al. (2004)

Table 2.2 shows that the rail projects had the largest cost escalation due to optimum bias at both 50th and 80th percentile, fixed link also lay above 55% cost escalation at 80th percentile. Based on the evaluated cost escalation due to optimism bias, Flyvbjerg et al. (2004) suggested raising the constant budget of these infrastructure projects to produce more realistic forecasts for the individual projects’ capital expenditure as presented in Table 2.3.

Table 2.3: Applicable capital expenditure increases

Infrastructure category	Cost escalation	
	50 th percentile	90 th percentile
Roads	15%	45%
Rails	40%	68%
Fixed links	23%	63%

Source: Flyvbjerg et al. (2004)

RCF as an estimation technique contains two limitations: it is difficult to find comparable projects and it may be impossible to predict extreme outcomes. In addition to the RCF limitations, the use of RCF has a major disadvantage, in that it may lead to too large construction cost estimates, with diverging consequences (Batselier and Vanhoucke, 2017).

Although Flyvbjerg (2006) has emphasised the capability of RCF and the outside view estimation technique to reduce or eliminate the optimism bias in the estimation of cost and time of infrastructure projects, Flyvbjerg (2006) also acknowledged the usefulness of other estimation techniques based on the inside view, such as Monte Carlo simulations and the Estimate Validation Process (EVP).

2.5.2.2 *Change in Policy*

Flyvbjerg et al. (2003) recommended a policy change based on accountability to counteract the cost underestimation due to economic-political causes, which could be executed through four mechanisms: transparency (public discussion of projects involving stakeholders and civil society), performance specifications (shift the perspective from a technical solution-driven approach to a goal-driven approach), specifying the regulatory regime (compound of economic rules), and risk capital (participation of private investors in the construction of an infrastructure project without a sovereign guarantee).

Anderson et al. (2009) proposed the following eight strategies as solutions to the identified 15 factors causing cost escalation and time delays on infrastructure projects: management strategy (manage the cost and time estimation process during the entire infrastructure project development), scope and schedule strategy (create processes to control changes in project scope and project scheduling), off-prism strategy (proactive engagement of external stakeholders and assessment of macro-environmental conditions possibly influencing project costs and times), risk strategy (identification, analysis, mitigation and planning, allocation, monitoring, and controlling), delivery and procurement strategy, document quality strategy (improve accuracy and consistency of estimate), estimate quality strategy (improved accuracy and consistency of estimate through uniform approaches and qualified personnel) integrity strategy (minimise the influence of outside pressures that can cause biases).

A focus on the tools of the first two phases of the risk strategy, identification and analysis, is needed since the uncertainty model proposed by the researcher allows one to identify and analyse

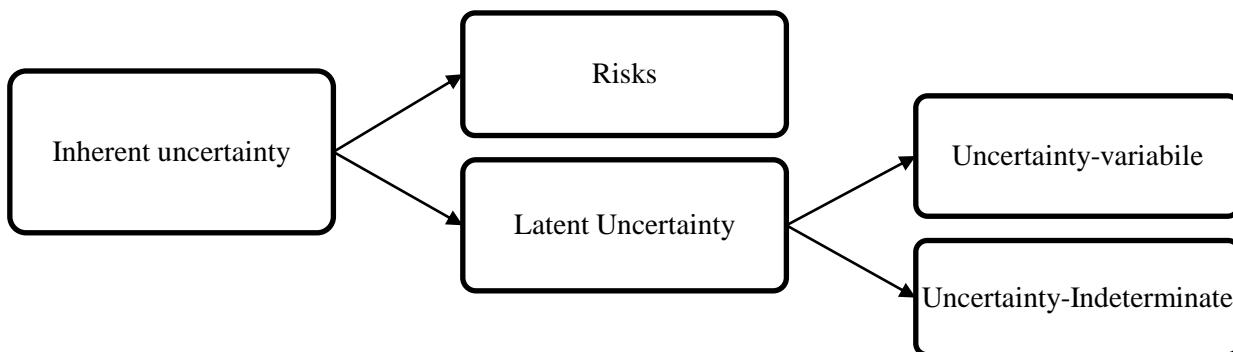
uncertainties. Thus, there is an interest in giving a complete overview of the analysis techniques used by Anderson et al. (2009) before introducing the new tool.

The main focus of the research is on the debiasing technique (outside view) and risk strategy, from among other proposed mitigations by Flyvbjerg (2007) and Anderson et al. (2009) to counteract cost escalation and time delays in infrastructure projects. Risk strategy includes five phases: identification; analysis; planning and mitigating; allocation; and controlling, and monitoring. The focus on the risk strategy is needed to prepare the basis of the uncertainty model. Before discussing risk strategy in detail, it is necessary to define the concept of risk.

2.6 UNCERTAINTY VERSUS RISK

In common use, words such as doubt, uncertainty, risk and ambiguity are often used interchangeably, but to develop a detailed understanding of uncertainty, clear definitions and the difference between uncertainty and risk are discussed in this section.

Winch (2012) defined uncertainty as the lack of all the information required to make a decision at a given time. When enough data are available to assign meaningful probabilities to the information required, then it is called risk, rather than uncertainty. Therefore, the main difference between uncertainty and risk is the level of availability of information and the methods used to measure the potential outcomes (Knight, 2012). Many scholars (Loch et al., 2006; Chapman and Wad, 2003) defined uncertainty as being the basis of risk. Cleden (2009) classified inherent uncertainty as the basis of both risks and latent uncertainty, and the latter as the basis of the uncertainty-variable and uncertainty-indeterminate, as illustrated in Figure 2.2.



Source: Winch (2012)

Figure 2.2: Classification of uncertainty in a project

It follows that two kinds of uncertainty exist: the uncertainty before any attempt at analysing the risks, which is called inherent uncertainty, and the uncertainty that remains once all the risks have been identified, which is called latent uncertainty (Cleden, 2009).

Hence, where enough data are available to assign meaningful probabilities to the information required, some inherent uncertainty transforms to risk (Winch, 2012). Risk is the condition where information is still missing, but a probability distribution is able to be assigned to the occurrence

of the event. This can only be done if a reliable and appropriate data set is available (Chapman Ward, 2003).

According to Cleden (2009), this process of risk analysis transforms some, but not all, of the inherent uncertainty into risks. Uncertainty and risk management must, therefore, be considered complementary approaches. Strategies which reduce inherent uncertainty will reduce the workload in capturing, analysing and mitigating risks. While risk management remains an important tool, the strategies for managing uncertainty, that is, dealing with the areas in which risk management is not functional, are vital. Furthermore, Cleden (2009) grouped latent uncertainty into two main classes, namely, uncertainty-variable and uncertainty-indeterminate.

Cleden (2009) defined uncertainty-variable as a type of uncertainty where the outcome is unknown but limited to a knowable set of possible outcomes. While Cleden (2009) described uncertainty-indeterminate as a type of uncertainty where the outcome is unknown, and the set of possibilities is also unknown. According to Winch (2012) the main difference between uncertainty and risk is in the process of predicting and assessing the outcome. The potential outcomes of the risk can be quantified by the classical mathematics models, such as risk matrix. However, the impacts of uncertainty cannot be quantified by the classical mathematics models due to unknown outcome, no background and the need to use nondeterministic probability distributions, such as Monte Carlo simulation (Winch, 2012).

2.7 RISK IN THE CONSTRUCTION OF INFRASTRUCTURE PROJECTS

The concept of risk is the fundamental of any risk strategy tool, however, there is no agreement on the definition of risk in the academic and professional communities. Although the concept of risk is not clearly defined, the word “risk” is used profusely in the next sections, since “risk” is the word mainly used in the literature reported here.

2.7.1 Risk definition

Risk is identified in the literature with either an event with some consequences on the project objectives (WSDOT, 2018, AASHTO, 2013, PMI, 2013, ICE, 2014) or the combination of the probability and the consequences of such an event (Anderson et al., 2007, Caltrans, 2012, ISSMGE, 2004, Haines, 2015, Harris, 2017).

Therefore, the risk has been described in the literature in different ways. For instance, PMI (2013) defined risk as an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives, likewise, the California Department of Transportation (Caltrans, 2012) outlines a risk as a combination of the probability of an uncertain event and its consequences, also the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE, 2004) characterises the initial risk associated with an identified hazard as the product of the likelihood of the occurrence of a hazard, and severity of the hazard, in terms of safety, time, and cost.

Haines (2015) describes risk as the product of the probability of unsatisfactory performance, while Harris (2017) states that risk is the measure of the probability and severity of an adverse effect.

Anderson et al. (2007) define risk as a combination of the probability of an adverse event and its consequences, similarly the American Association of State Highway and Transportation Officials (AASHTO, 2013) defines it as a potentially adverse circumstance, expressed mainly in terms of causing undesired cost growth or time delays. The Institution of Civil Engineers of Great Britain (ICE, 2014) state that risk is a threat (or opportunity) which could affect adversely (or favourably) achievement of the objectives of an investment.

Another major discrepancy in the definition of risk concerns the character of risk: some definitions describe risk as a neutral event where the event has positive or negative consequences (PMI, 2013, WSDOT, 2018, ICE, 2014), some describe it as an adverse event (Harris, 2017, Anderson et al., 2007, AASHTO, 2013), others do not specify the positive or negative implication of risk (Haimes, 2015, ISSMGE, 2004, Caltrans, 2012). Furthermore, it should be noted that the word “risk” has an inherent negative reference implying the presence of a threat.

Despite the lack of a unifying definition, identified causes (risks) and proposed mitigation to risk by Anderson et al. (2009) are presented and discussed in detail in the next sections. The divergences in the concept of risk prove that there is no agreement on the definition of risk in the construction industry.

2.7.2 Risk strategy

Anderson et al. (2009) proposed a risk strategy as one of the approaches to counteract the causes of cost underestimation and time delays in infrastructure projects. The risk strategy contains a comprehensive consideration of risks by identifying the risks, quantifying their impacts, and mitigating their impacts during the infrastructure project. More specifically, the risk strategy consists of five phases: risk identification, risk analysis, risk planning and mitigating, risk allocation and risk controlling, and monitoring, which are repeated iteratively throughout the project execution (Rausand, 2013).

Among the five phases of risk strategy, the first two phases, risk identification and risk analysis, are discussed in more detail and available techniques on risk identification and analysis are presented. The focus on the risk identification and risk analysis phases is pertinent, as the developed uncertainty model in the current thesis is an advanced tool to identify and analyse the uncertainties in the construction of infrastructure projects.

Risk strategy is an iterative process, since the different phases of risk strategy need to be repeated during the execution of the project to document and pursue new situations and changed risks. Through the execution of a project, new risks that have occurred are identified, and their impact and possible mitigation measures are considered as such risks are identified. Other risks disappear in more advanced stages of the project and/or are averted with mitigation measures, leaving new resources available to counteract the remaining risks (Cleden, 2017).

The other most important feature of a risk strategy is its scalability (Carr and Tah, 2001) which is the capability of the risk strategy to be applied successfully to large and complex infrastructure projects as well as to small and relatively simple ones.

In small projects, risks are identified with the help of risk lists and analysed with qualitative risk analysis, and mitigation and monitoring consist of a few measures for the most important risks. For infrastructure projects, risk identification requires brainstorming with construction experts; risk analysis may include quantitative risk analysis based on the Monte Carlo simulation; risk mitigation involves a series of measures; risk allocation is covered with insurance contracts; and risk monitoring and control may consist of possible alarm systems for incumbent risks (Sadeghi et al., 2010).

The objectives and goals of the five phases of risk strategy, including the most comprehensive approach to counteract risks causing cost underestimation and time delays in infrastructure projects, is presented to provide the background to the proposed uncertainty model in this thesis.

2.7.2.1 Risk identification

The first phase of the risk strategy is risk identification, which determines the risks that may affect the construction project and verifies the risks' characteristics. Risk identification includes the examination of the construction project scope, the construction design, the work breakdown structure, cost estimates, construction schedules, and others, to provide a list of risks that is used in following the risk strategy phases (Anderson et al., 2009, Tran and Molenaar, 2015).

Several tools, such as the Crawford slip method; strengths, weaknesses, opportunities, threats (SWOT) analysis; red flag; risk checklist; assumption analysis; expert interviews; risk workshop, risk register; and risk breakdown structure are available to identify potential risks in infrastructure projects.

To provide a better overview of the tools used in the identification phase and the analysis phase of the risk strategy, the discussed tools are summarised in Table 2.4.

Table 2.4: Risk identification and risk analysis tools

Identification tools	Analysis tools	Identification and analysis tools
<ul style="list-style-type: none"> • Red flag items • Risk checklist • Assumption analysis • Crawford slip method • SWOT analysis • Risk register 	<ul style="list-style-type: none"> • Percentage contingency • Monte Carlo analysis • Three-point analysis • Risk priority analysis • Impact matrix • Risk comparison matrix • Risk map • Risk management information system • Self-modelling worksheet 	<ul style="list-style-type: none"> • Expert interview • Risk workshop • Risk breakdown structure

The Crawford slip method is a rapid brainstorming technique which obtains the participants' opinions independently. According to Pritchard (2014), the Crawford slip method generates a large number of risks and it should be used at the beginning of the risk identification step. Similar to the Crawford slip method, the SWOT analysis is used early in the risk identification process, and it

can be the starting point for the brainstorming as well as an additional tool to provide a comprehensive map for identifying risks (Berg, 2010).

Red flag refers to the high-risk items in terms of cost and schedule impacts at the definition and design phases of project development and updated at succeeding project phases. Raftery (2003) stated the ability to set the contingencies and control on cost and time escalation, and facilitating the communication between project team members as two main advantages of the red flag. The red flag does not involve any formal qualitative or quantitative risk analysis of the items but reminds the project team of these high-risk items' existence (Raftery, 2003).

A risk checklist is a list of risks that have occurred or have been identified in past projects. According to Caltrans (2012), risk checklists practise two goals: it transfers knowledge in risk identification from previous projects and past team members to the new project and team; and it ensures that common risks are not overlooked. The risk checklist should be used after some form of risk brainstorming for two reasons: it might not contain crucial risks specific to the project, and it might prevent thinking out of the box (Caltrans, 2012).

Assumption analysis: records assumptions as potential risks, which impact on the cost and time of projects. Assumption analysis has the advantage of bringing the attention of designers and estimators to the assumptions and of being an alternative way to brainstorm risks (Pritchard, 2014).

Expert interviews are used to identify risks that are not initially apparent and can indicate the probability of occurrence and the impact of risks both qualitatively and quantitatively. WSDOT (2018) affirmed that it is practical to conduct expert interviews in risk identification and risk analysis and generally when additional input is needed.

A risk workshop is a series of formal meetings between project team members, experts, facilitators and stakeholders, which are convened to identify and analyse risks (WSDOT, 2018). WSDOT (2018) mentioned the description of project risks, the quantification of the probability of occurrence and impact, ranges of project cost and time to calculate contingencies, preliminary risk registers, and/or a risk management plan as the outputs of the risk workshop and that it is beneficial in the risk identification phase as well as in the other four steps of the risk strategy (WSDOT, 2018).

A risk register is a document that describes comprehensively all identified risks including risk triggers, the probability of occurrence and severity, overall risk rating, responses, resources allocated, and current status (Pritchard, 2014). Burtonshaw-Gunn (2017) declared that the risk register is not only a risk identification tool but also a tool to analyse, mitigate and monitor risks and it is scalable by varying the level of detail from minimal for small, simple projects to comprehensive for complex infrastructure projects. Risk breakdown structure is a tool that visually illustrates the interrelations between different risks belonging to different aspects of a project. It is particularly appropriate for complex infrastructure projects (PMI, 2013).

As discussed above, expert interviews, risk workshops, and risk registers are also used in the risk analysis phase of the risk strategy.

2.7.2.2 *Risk analysis*

The second phase of risk strategy is risk analysis, the process of evaluating the project risks documented in the risk identification phase of the risk management strategy. Its objective is to systematically consider risks, their probability of occurrence and the consequences of their occurrence. Risk analysis tools are scalable in that they can be used to prioritise red flag items of a relatively simple project as well as estimate probabilistically the cost of complex projects (Tran and Molenaar, 2015). There are two types of risk analysis, qualitative and quantitative, which ideally are combined into a comprehensive risk analysis. Qualitative tools are used to prioritise risks and to decide mitigation strategies and risk allocation, while quantitative tools are used to calculate the risk exposure of a project (Rausand, 2013).

Several risk analysis tools are available to analyse qualitatively and/or quantitatively the risk of a project. Some tools, such as expert interviews, risk workshops, and risk registers, are used in both the risk identification and the risk analysis phases, while others, namely, percentage contingency, fault tree analysis, the Monte Carlo analysis, three-point estimate, risk priority ranking, impact matrix, risk comparison table, risk map, risk management information system and self-modelling worksheets are specific to the risk analysis phase of the risk strategy (Molenaar, 2010).

Percentage contingency is a percentage of the cost and time estimate to account for unforeseen, unidentified costs and delays. According to WSDOT (2018), contingency is set to cover known but not quantified, costs and delays and unknown costs and delays.

Monte Carlo analysis is a simulation tool that generates probability distributions for total cost and total time by simulating a project repetitively. Zio (2013) mentioned the three following advantages of a Monte Carlo analysis: it visualises the project uncertainties, it gives insight into which risks have the most significant impact, and it can be used to generate range estimates and to calculate contingencies. According to Sadeghi et al. (2010), a Monte Carlo analysis requires a trained professional to perform it, and all risks must be described quantitatively with probability distributions, which must be defined in terms of probability distribution type and distribution parameters. Three-point estimate is a type of Monte Carlo simulation where each risk is evaluated in terms of a three-point estimate. It is assumed that the mean is larger than the most likely estimate (the distribution is skewed to the right). Three-point estimates are widely used to quantitatively estimate risks in infrastructure projects (Caltrans, 2012).

Risk priority ranking allows one to rank risks based on qualitative or quantitative risk analysis or experts' judgement. The choice of qualitative or quantitative analysis depends on the project complexity: while a qualitative approach is sufficient to allocate scarce resources, a Monte Carlo analysis is required to rank risks to determine the contingency (Haines, 2015).

Impact matrix combines the qualitative evaluation of the probability of occurrence and the severity of risk. Depending on the combination of probability and severity, the impact of risk classifies (colour coded) into five levels namely: minimal, low, moderate, high and extreme. The two main

goals of an impact matrix are to prioritise the risks to efficiently allocate resources and identify an initial analysis of the risks that require further qualitative/quantitative analysis (ISO, 2018).

Another risk analysis tool is the risk map, which is a probability/severity diagram on which the impact of risks on project objectives is positioned. It is a powerful communication tool that visualises the impact size of risk relative to other risks. It is also used to track changes over time (Harris, 2017).

The self-modelling worksheet is a spreadsheet to analyse risks quantitatively. It works as a Monte Carlo simulation and three-point estimates to calculate the impact of risks on a project. According to WSDOT (2018), the self-modelling worksheet is less complex than other risk analysis software and it is suitable for use for non-complex infrastructure projects (WSDOT, 2018).

From among the available risk identification and risk analysis tools, the study largely utilises the expert interview, three-point analysis and impact matrix to identify and analyse the existing risk (disruptive events) in the process of construction of an infrastructure project.

2.7.2.3 Risk planning and mitigation

The third phase of the risk strategy is risk planning and mitigation. It explores response strategies for the risks that have been identified, analysed (qualitatively or quantitatively) and prioritised in the risk identification and risk analysis phases. Risk planning and mitigation identifies the best risk response plan for each risk, and designs action to implement the selected risk response plan (Caltrans, 2012). Risk planning is the process of developing, implementing and monitoring the risk response strategies. It involves the detailed formulation of a plan of action, in the form of a risk register for simple projects, and a formal risk management plan for an infrastructure project.

There are five main risk response plans: avoidance (the project plan is changed to eliminate risk); acceptance (involves planning the risk into the project); monitoring and preparation (involves two steps: creating monitoring plans and developing action plans for immediate action upon occurrence of the risk); mitigation: (the probability of occurrence or the severity of risk are reduced to an acceptable threshold) and transference (transfers the risk onto another party using some form of trade-off).

2.7.2.4 Risk allocation

The fourth phase of the risk strategy is risk allocation. It is the process of identifying and assigning the responsibility to a party (Tran and Molenaar, 2015). Risk allocation follows four principles: allocate a risk to the party that is able to manage it in the best way; allocate a risk in alignment with project goals; share a risk, when appropriate, to achieve project goals, and allocate a risk to promote alignment with customer-oriented performance goals.

2.7.2.5 Risk monitoring and controlling

The fifth phase of the risk strategy is risk monitoring and controlling. It pursues the following four objectives: systematically track the identified risks; identify new risks; effectively manage the

contingency reserve; and capture the lessons learned for managing risk in future (Burtonshaw-Gunn, 2017).

Risk monitoring and controlling continue throughout the whole execution of the project: in periodic risk identification reviews, in the analysis phase, in the mitigation and the allocation phases (Molenaar, 2010). Risk monitoring and controlling have three main tasks: develop comprehensive reporting procedures; monitor risk and contingency reserves; and provide feedback for future risk management.

The next section discusses estimating tools used for infrastructure projects that engaged a risk strategy.

2.8 UNCERTAINTY IN THE CONSTRUCTION OF INFRASTRUCTURE PROJECTS

Hirano and Wright (2017) defined uncertainty as an unknown phenomenon. Apart from uncertainty due to lack of knowledge, there is an uncertainty due to randomness (El Khalek et al., 2016). In the estimation of construction of infrastructure projects, several variables are not known, since construction projects are populated by uncertainties (Zhu and Mostafavi, 2016). It is an opportunity if it has a positive impact, a threat if it has a negative impact, on the project objectives (Kurowicka and Cooke, 2006). The main difference between uncertainty and risk is stated as being whether it is possible to measure and quantify the potential of outcomes of future events through the theoretical models mathematically (Knight, 2012).

According to the AASHTO (2013), uncertainties in construction of infrastructure projects impact the cost and time of the project through a combination of the following factors: the cost and time of the activity vary from repetition to repetition, which causes the cost and time of the project to change; the costs and times of construction activities are correlated, which causes the standard deviation of the total cost and time to increase; and during the construction of infrastructure, some unforeseen incidents occur, which influence the construction cost and time of the projects.

Moret and Einstein (2016) considered the three following sources of uncertainties in infrastructure projects: variability; correlations between construction costs; and disruptive events. However, to adequately model the uncertainty of construction cost and duration in the construction process of infrastructure projects, Moret and Einstein (2016) proposed that uncertainties expand further to the variability in the construction cost and time of infrastructure construction projects, the correlations between construction costs, times and cost/time activities, and disruptive events.

2.8.1 Variability in the construction process

The variability is the change in a variable (cost and time) under normal conditions (Moret and Einstein, 2016). Several scholars view variability as one of the main causes of uncertainty in construction projects (Thomas et al., 2002, Ward and Chapman, 2003, Arashpour, 2015). The variability in construction process causes changes in estimated cost and time of activities and generates the range of costs and times unless the deterministic estimation corresponds to one value (Touran, 2003).

The variability in infrastructure projects is quantified by defining probability distributions and the distribution parameters (Moret and Einstein, 2011a, Touran and Lopez, 2006).

2.8.2 Correlation between construction activities' cost and time

Construction activities are influenced by different internal and external factors, such as technical, financial, political, environmental, social and economic (Odediran and Windapo, 2018). When numerous activities are influenced by the same factor at the same time, their costs and times are correlated. If many activities in the project are correlated, the uncertainty of the cost and time of the project will increase (Bakhshi and Touran, 2012).

Bakhshi and Touran (2012) identified three types of correlation between the construction activities costs and times namely: correlation between the costs of activities, correlation between the times of activities and correlation between a construction cost and duration. Moret and Einstein (2011b) identified four types of correlations between the costs of activities in the construction of the rail line, but only modeled the correlation between the cost of a repeated activity and the costs of different activities. Because of the difficulty of measuring and modelling the correlation in construction projects, Moret and Einstein (2011b) did not attempt to model the correlation between cost and time of construction activities.

2.8.3 Disruptive events

A disruptive event, also known as the unforeseen event, is an event with a large impact on the construction activities and process, and it occurs with some probability of occurrence, and it can severely disrupt the construction process if it occurs. (Goodwin and Wright, 2010). In other words, it is an event with an unknown outcome and no background information (El Khalek et al., 2016).

Disruptive Events is one of the major sources of uncertainty which are considered to measure the impacts of unforeseen events in the infrastructure projects. The nature of these events is uncertain (Inherent); however, employing the adequate knowledge gathered from the questionnaire, the probabilities can be used to predict their impacts (Moret and Einstein, 2016). In another word, by using the information collected from the questionnaire, the disruptive events are transformed to risk.

According to Flyvbjerg (2007), the occurrence of disruptive events in the construction of infrastructure projects, particularly in transportation infrastructure projects, is higher than other construction projects, due to unique features of these infrastructure projects, which include complexity between major construction activities, long duration of construction, dynamic process, repetitive linear project, and mobile construction site. Due to the peculiar nature of uncertainty, there is a need to identify and classify the disruptive events and their factors.

Previous research by Aziz and Abdel-Hakam (2016) classified 293 disruptive events as delay causes of road construction projects in Egypt under 15 major groups, and Odediran and Windapo (2018) identified 81 risks in African construction markets under five major factors, namely: political, social, economic/financial, procurement, and design and construction. Similarly, Assaf

and Al-Hejji (2006) evaluated 73 uncertain events that caused a delay in different types of large construction projects in Saudi Arabia under the following factors: project, owner, contractor, design, materials, equipment, labours and external. Adam et al. (2017b) studied the risk events causes of cost overruns and time delays in large public construction projects on literature, ranging from 1985-2014 and grouped them into eight groups: communication, financial, management, material, organizational, project, psychological and weather.

Through a systematic review of the literature in the area of uncertainty and risk in construction projects using the bibliometrics technique, 317 disruptive events were classified into seven main factors, namely: economic, environmental, financial, legal, political, social and technical as shown in the disruptive events cluster map in Figure 2.3. These events were ranked according to their occurrence in 17 studies applicable to this research, and the top 20 disruptive events mentioned in the literature are listed in Table 2.5.

Table 2.5: Disruptive events most frequently mentioned in the literature review (top 20)

Event	Factor	Reference*																	Total of citation
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Weather	Environment	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	16
Availability of materials	Technical	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	15
Inaccurate management or supervision	Technical			✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	14
Availability of skilled labour	Technical	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	14
Health and safety	Technical	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓		✓	✓	✓	✓	13
Materials delivery	Technical				✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	12
Construction methods	Technical	✓			✓	✓	✓	✓		✓	✓	✓		✓	✓	✓		✓	12
Availability of equipment	Technical			✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	✓	12
Cash flow difficulties (Contractor finance)	Financial	✓	✓	✓	✓		✓	✓	✓		✓	✓		✓	✓			✓	12
Design, drawings, specifications and samples	Technical			✓	✓	✓	✓	✓		✓	✓		✓		✓	✓	✓	✓	11
Incompetent contractor/subcontractor	Technical				✓	✓	✓	✓		✓	✓		✓		✓	✓	✓	✓	10
Low productivity level work	Technical				✓	✓	✓	✓		✓	✓		✓		✓	✓	✓	✓	10
Payment delay	Financial	✓	✓			✓		✓	✓	✓		✓	✓		✓			✓	10
Planning and scheduling of project by contractor	Technical			✓		✓	✓	✓		✓	✓		✓		✓	✓	✓	✓	10
Difficulty of schedule	Technical					✓	✓	✓		✓	✓		✓		✓	✓	✓	✓	9
Lack of capital by owner	Financial	✓	✓			✓		✓	✓		✓	✓		✓				✓	9
Change order (Change in the scope of the project)	Technical			✓		✓	✓			✓	✓		✓		✓	✓	✓	✓	9
Legal/industrial disputes between various parties in the construction project	Legal	✓				✓		✓	✓		✓		✓		✓		✓	✓	8
Communication/ coordination between construction parties	Technical					✓	✓			✓	✓		✓		✓	✓	✓	✓	8
Fluctuation of prices of materials and/or equipment	Economic	✓	✓			✓			✓		✓	✓		✓				✓	8

* Reference: 1: Adam et al. (2017a), 2: Odediran and Windapo (2018), 3: Santoso and Soeng (2016), 4: Aziz and Abdel-Hakam (2016), 5: Taghipour et al. (2015), 6: Marzouk and El-Rasas (2014), 7: Mahendra et al. (2013), 8: Banaitiene and Banaitis (2012), 9: Fang et al. (2012), 10: Kuo and Lu (2013), 11: Nieto-Morote and Ruz-Vila (2011), 12: Ehsan et al. (2010), 13: Zayed et al. (2008), 14: Saqib et al. (2008), 15: Zou et al. (2007), 16: Assaf and Al-Hejji (2006), 17: Dey (2001).

Figure 2.3 shows that the major or most cited disruptive events caused cost overruns and time delay in the construction of infrastructure projects by previous literature with larger nodes, of which the top major events are the weather, availability of materials, inaccurate management or supervision and availability of skilled labour (larger nodes). Also, Figure 2.3 disclosed that the most disruptive events that affect the cost and time of projects belong to the technical, financial, legal, social, environmental, political and economic factors. Table 2.5 revealed that while 14 out of 20 most cited disruptive events in the reviewed literature are classified under technical factors and three are classified under financial, one event which is most cited by literature (weather) is classified under environment, and one each under legal and economic. These suggest that the technical disruptive events are the key events in the construction of infrastructure projects from both the perspective of the number of events and high level of citation by previous literature. However, due to the infrequent occurrence of disruptive events and the difficulty of measuring the outcome, there are very few quantitative studies that assess the impact of disruptive events on cost and time of infrastructure projects (Moret and Einstein, 2016, Renuka et al., 2014, Barker and Haimes, 2009, El Khalek et al., 2016).

2.8.3.1 *Economic factors*

Economic factors involve issues or concerns associated with the macroeconomic impact of the community and region in which the construction project is to be located. Various literature identifies fluctuation in prices of materials and equipment, monopoly of material and equipment suppliers, saturated market and fluctuation in foreign exchange rate as the key economic risks affecting the project performance (Banaitiene and Banaitis, 2012, Kuo and Lu, 2013, Wang and Yuan, 2011, Zavadskas et al., 2010, Saqib et al., 2008, Iyer and Jha, 2005, Dey, 2001, Tah and Carr, 2000, Aziz and Abdel-Hakam, 2016, Odediran and Windapo, 2018).

2.8.3.2 *Environmental factors*

Environmental factors involve issues associated with environmental problems, concerns, and activities confronting the project. Weather, natural disasters, remote location cost and terrain/topological condition of the site were identified in the literature as important environmental risk factors that impact on construction project performance (Banaitiene and Banaitis, 2012, Ehsan et al., 2010, Wang and Yuan, 2011, Saqib et al., 2008, Iyer and Jha, 2005, Tah and Carr, 2000, Aziz and Abdel-Hakam, 2016)

2.8.3.3 *Financial factors*

Financial factors involve issues associated with project financing. Several researchers identify tax and legal fees, cash flow difficulties, poor financial control, lack of capital, high tender price, high cost of materials, equipment and labour as the important financial risk factors affecting construction project performance (Taghipour et al., 2015, Banaitiene and Banaitis, 2012, Ehsan et al., 2010, Fang et al., 2012, Zayed et al., 2008, Saqib et al., 2008, Dey, 2001, Shen et al., 2001, Tah and Carr, 2000, Bunni, 2003, Aziz and Abdel-Hakam, 2016, Odediran and Windapo, 2018).

2.8.3.4 *Legal factors*

Legal factors involve concerns associated with the significant legal consequences that flow from legal actions attributable to the project. Right of way acquisition, deficient documentation, difficulties in importing equipment and materials, changes in government regulations and laws, unclear arbitration process for legal disputes between construction parties, changing of bankers' policies for loans, ineffective delay penalties, type of contracts, and problems in dispute settlement due to law and contract failure are identified in the literature as the legal risk factors that affect construction project performance (Zou et al., 2007, Shen et al., 2001, Bunni, 2003, Aziz and Abdel-Hakam, 2016).

2.8.3.5 *Political factors*

Political factors involve issues associated with the local, regional, and national political and regulatory situation confronting the project. Political risk factors identified in the literature as affecting the performance of infrastructure projects comprise the political situation, encroachment problems and human-made disasters (Taghipour et al., 2015, Banaitiene and Banaitis, 2012, Ehsan et al., 2010, Zavadskas et al., 2010, Zayed et al., 2008, Saqib et al., 2008, Iyer and Jha, 2005, Baloi and Price, 2003, Dey, 2001, Tah and Carr, 2000, Aziz and Abdel-Hakam, 2016, Odediran and Windapo, 2018).

2.8.3.6 *Social factors*

Social factors are associated with the social and cultural impacts of the community and region in which the construction projects are to be located. The Literature cites cultural heritage issues, personal conflicts among labour, social and cultural impacts, rehabilitation of affected people, diseases, security and corruption as the important social risks impacting on construction project performance (Kuo and Lu, 2013, Wang and Yuan, 2011, Zavadskas et al., 2010, Saqib et al., 2008, Aziz and Abdel-Hakam, 2016).

2.8.3.7 *Technical factors*

Technical factors are associated with the technology used on the construction project by the different stakeholders during construction. These technical risk factors are further identified according to general issues as labour, material, equipment, technology, specialist consultants and contractors. Various researchers support technical risks as major factors affecting the performance of infrastructure projects (Mahendra et al., 2013, Banaitiene and Banaitis, 2012, Ehsan et al., 2010, Fang et al., 2012, Nieto-Morote and Ruz-Vila, 2011, Wang and Yuan, 2011, Zavadskas et al., 2010, Zayed et al., 2008, Saqib et al., 2008, Dikmen et al., 2007, Dey, 2001, Shen et al., 2001, Tah and Carr, 2000, Bunni, 2003, Aziz and Abdel-Hakam, 2016, Marzouk and El-Rasas, 2014, Odediran and Windapo, 2018).

To verify the existence of these uncertain events in highway construction projects, the research conducted further investigations into the disruptive events in Chapter Five.

2.9 ESTIMATION OF COST AND TIME IN INFRASTRUCTURE PROJECTS

The cost and time required to construct an infrastructure project is a key piece of information for assessing the project feasibility and alternatives. The importance of the estimation process of the construction cost and duration of infrastructure projects is highlighted in the literature, such as Moret and Einstein (2016); APM (2012), Leonard (2009).

Estimation of cost and time of a project is a critical process of the integrated project management because it is a most important and reliable input data for pre-investment decision for assessing and selecting the preferred infrastructure project alternatives and it is an essential in the definition of project performance targets, which are evaluated during the project appraisal (Halpin et al., 2017). PMI (2013) defined the cost and time estimation as the process of developing an approximation of the monetary resources and the work periods needed to complete the project. Project estimation interacts with other activities related to the general project management process, is executed at the concept phase of the project and is refined at feasibility, planning and construction phases when more information is available (American Association of Cost Engineers, 2016).

2.9.1 Estimation evolution and accuracy

Cost and time estimation are the predicting of the required resources and time based on the available data at a given phase of the project and they should be refined during the project to reflect additional information to improve the accuracy and reliability of the estimation (PMI, 2013). An accurate estimation allows better decision-making and ultimately increases the project's probability of success (Leonard, 2009). The American Association of Cost Engineers (2016) classified the estimation into five classes according to maturity level of the project and purpose of estimate and each estimate class has an associated expected accuracy range, as summarised in Table 2.6.

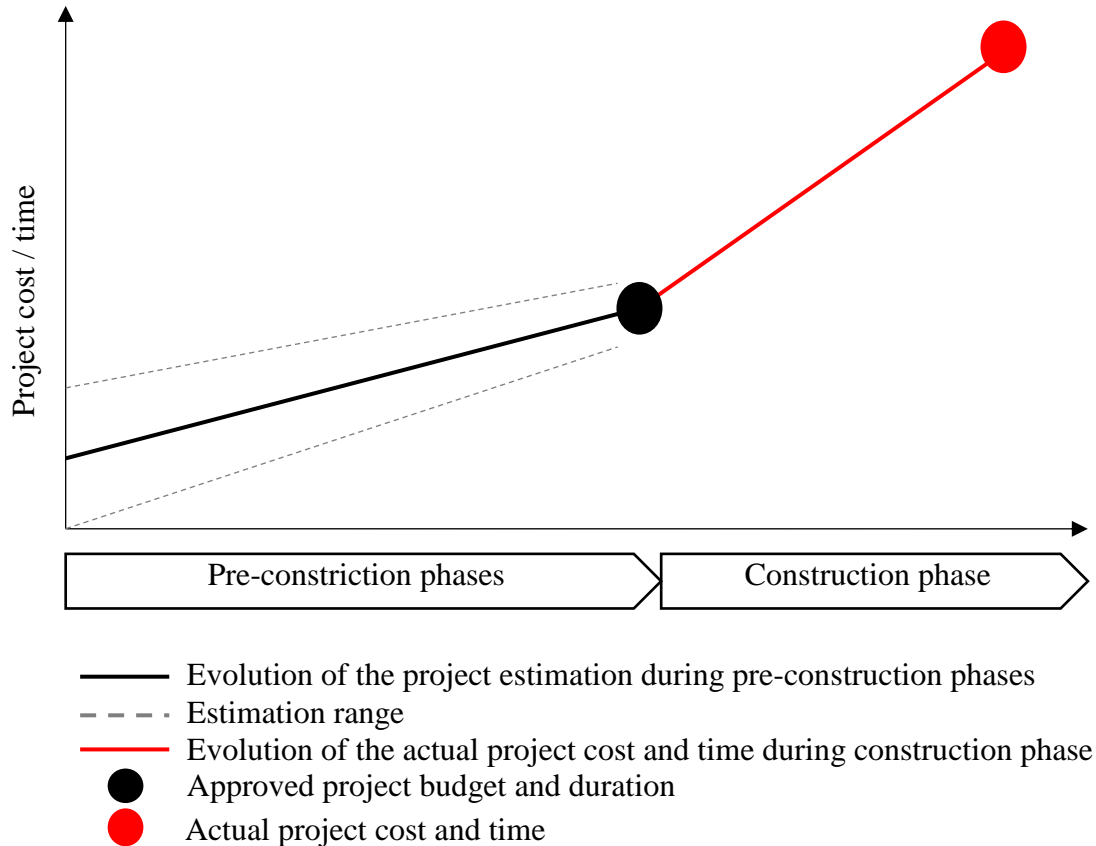
Table 2.6: Estimation classification

Estimate class	Maturity level of project	Purpose of estimate	Expected accuracy range
Class 5	0% to 2%	Concept	Low: -20% to -50% High: +30% to +100%
Class 4	1% to 15%	Feasibility	Low: -15% to -30% High: +20% to +50%
Class 3	10% to 40%	Budget or control	Low: -10% to -20% High: +10% to +30%
Class 2	30% to 75%	Control or bid	Low: -5% to -15% High: +5% to +20%
Class 1	65% to 100%	Check estimate or bid	Low: -3% to -10% High: +3% to +15%

Source: American Association of Cost Engineers (2016)

Table 2.6 shows that the more mature, the project, the higher the expected accuracy range. The expected levels of accuracy provided by AACE are fully consistent with other project management

and construction management literature, such as Smith (2017) PMI (2013), Leonard (2009) and Kim et al. (2004), which emphasise that the estimation evolution suggests that the mean value of estimation should be closer to the expected actual value (accuracy), while the standard deviation (precision) should be reduced as the project progresses into more advanced phases. This phenomenon denominated as the cone of uncertainty in Leonard (2009) is shown in Figure 2.4.



Source: Leonard (2009)

Figure 2.4: Project estimation maturity and evolution

As presented in Figure 2.4, the black line shows the evolution of the project estimation during the pre-construction (concept, feasibility, planning, and design) phases. The dotted lines represent the range of the estimation. The red line represents the evolution of the actual project cost and time, during the construction phase. The difference between the actual project cost and time and the approved project budget and duration is understood as the cone of uncertainty (Leonard, 2009). Figure 2.4 shows that the actual project cost and time increase sharply once the project moves into the construction phase. Several public reports and researches, such as Flyvbjerg et al. (2002); Flyvbjerg (2007); UK (2010) and Cantarelli et al. (2013) emphasise that cost and time underestimation is still a crucial problem in infrastructure projects due to poor prediction and capturing the risks and uncertainties in the construction process of projects.

2.9.2 Estimation methods

Several techniques and methods for the estimation of the impact of risk and uncertainty on construction cost and duration of infrastructure projects have been developed by practitioners and researchers, in which the use and suitability of each technique depends on the purpose for which it is employed and the amount of available data at the project phase of estimation. Leonard (2009) grouped different estimation techniques into: expert judgment, analogous, engineering build-up, parametric and hybrid model.

2.9.2.1 Expert judgment estimation

Expert judgment, guided by historical information, provides valuable insight about the environment and information from previous similar projects. Expert judgment can also be used to determine whether to combine methods of estimating and how to reconcile differences between them. Expert judgement models use algorithms, heuristics, expert system programming, and fuzzy logic techniques.

According to Leonard (2009) the advantages of expert judgment is: it can be used when no historical data are available; it takes minimal time and is easy to implement; an expert may give a different perspective or identify factors not previously considered leading to a better understanding of the project; it can help in cross-checking for estimation relations that require data significantly beyond the data range; it can be combined with other estimation techniques; and it can be applied in all project phases. However, the expert judgment has the following disadvantages: its lack of objectivity; and it is not very accurate or valid as a primary estimation method.

2.9.2.2 Analogous estimation

Analogous estimation is a technique for estimating the duration or cost of an activity or a project using historical data from a similar activity or project. Analogous estimating uses parameters from a previous, similar project, such as duration, budget, size, weight, and complexity, as the basis for estimating the same parameter or measure for a future project. Analogous estimating is frequently used to estimate a value when there is a limited amount of detailed information about the project (Chou and Yang, 2012). Analogous estimating is generally less costly and less time consuming than other techniques, but it is also less accurate. It can be used in conjunction with other estimating methods. Analogous estimating is most reliable when the previous activities are similar in fact and not just in appearance, and the project team members preparing the estimates to have the needed expertise (Chou and Yang, 2012).

The analogy method has the following advantages: it can be used before the detailed project is known; if the analogy is strong, the estimate will be defensible; an analogy can be developed quickly and at minimum cost; and the tie to historical data is simple enough to be readily understood. Analogy also has some disadvantages: an analogy relies on a single data point; it is often difficult to find the detailed cost, technical details required for analogies; there is a tendency to be too subjective about the technical parameter adjustment factors; difficulties in the measure

of the concept of degree of similarity, and the difficulty of incorporating the effect of technological progress and of context factors. (Leonard, 2009).

2.9.2.3 Engineering build-up estimation

Engineering estimating is based on the detailed analysis and features of the project. The estimated variables of the project are estimated in a very analytical way. This model is done at the lowest level of details. Because of the high level of detail, each step of the work flow should be identified, measured and tracked and the results for each outcome should be summed to make the point estimate (Peurifoy and Oberlender, 2002).

The advantages of the engineering estimating include: the estimator's ability to determine exactly what the estimate includes and whether anything was overlooked; its unique application to the specific project; it gives a good insight into major project variables contributions; and easy transfer of results to another project. Some disadvantages of this approach are: it can be expensive to implement and is time consuming; it is not flexible enough to what-if questions; new estimates must be built for each alternative; the project specification must be well known and stable; all variations and changes must be reflected in the estimate; some errors can grow into large errors during the summations; and some elements can be omitted by accident. (Leonard, 2009).

2.9.2.4 Parametric estimating

Parametric estimating utilises a statistical relationship between relevant historical data and other variables to calculate the cost or duration of a project. This technique produces high levels of accuracy depending upon the sophistication and underlying data built into the model (Peurifoy and Oberlender, 2002). Activity durations and cost can be quantitatively determined by multiplying the quantity of work to production rate and unit cost respectively. Parametric techniques such as regression, Bayesian, case-based reasoning, neural networks, statistical models, Monte Carlo simulation, and decision rules, can be used, in conjunction with other estimating methods.

The parametric estimating approach has several advantages compared to the other estimation approaches: if the data are available, parametric relationships can be derived at any level; if the design or specification of project changes, estimation can be quickly modified and used to answer what-if questions and design alternatives; it can produce sensitivity analysis for varying input parameters; parametric relationships derived from statistical analysis generally have both objective measures of validity and a calculated standard error that can be used in risk analysis; and it relies on historical data which increase the estimate's defensibility. However, the disadvantages of parametric estimating include: the underlying database must be consistent and reliable and it may be time consuming to normalise the data; the database must be updated from time to time to capture most current cost, technical details; using data outside the database range causes errors; and complicated estimation techniques, such as nonlinear analysis may make it difficult for others to readily understand the relationship independent variables and estimated cost and time (Leonard, 2009).

Artificial intelligence, such as case-based reasoning (CBR), neural networks (NNs), genetic algorithms (GA) and variations of such, is able to facilitate the parametric estimation. Much research has been carried out in exploring the applicability of AI methodologies in cost and time estimating, specifically NNs and CBR (Leśniak and Zima, 2018, Kim et al., 2004, Hsiao et al., 2012). The AI parametric approaches offer powerful abilities to estimate construction costs and time accurately (Wauters and Vanhoucke, 2016, Ebrat and Ghodsi, 2014, Odeyinka et al., 2013, Ji et al., 2018).

The AI parametric model has the following advantages: it can be adjusted to best fit the hardware or software being estimated; estimates are based on a database of historical data; and it can be calibrated to match a specific project environment. However, the parametric model includes the following disadvantages: the results depend on the quality of the underlying database; they require many inputs that may be subjective; and accurate calibration is required for valid results (Leonard, 2009).

2.9.2.5 Hybrid estimating models

The concept of hybrid estimating models are to combine unique features of each estimating technique to capture different patterns or features in the data set to improve the reliability of estimation by assessing precisely the risk and uncertainty (Leonard, 2009). A hybrid estimating model is especially useful when it is not clear which model would provide a more accurate estimation (Arashpour et al., 2016).

As discussed in Section 2.7, in construction projects, there are three main sources of uncertainty: variabilities in cost and time, correlation between the costs, times and cost-time and disruptive event (also known as risk, unforeseen events).

Variability in cost and time of projects are modeled with PERT (Programme Evaluation and Review Technique), APRAM (Advanced Programmatic Risk Analysis and Management Model) and CSRAM (Construction Risk Analysis Model) (Ökmen and Öztaş, 2010). Touran (1993b); Bakhshi and Touran (2012); Moret and Einstein (2011b) and Firouzi et al. (2016) modeled the correlation between project cost and times variables. For instance, Firouzi et al. (2016) developed a hybrid generic copula-based Monte Carlo model and assessed the correlations between the construction costs. Very few models are available to assess the impact of disruptive events (risk, unforeseen) on construction cost and duration. WSDOT (2012) developed CEVP (Cost Estimation Validation Process) to model risk events in construction projects by employing impact matrix.

There is evidence that available hybrid estimating models improve the estimation of construction project by quantifying the impact of variability, correlation, and disruptive events in project cost and time. However, none of these estimating models is capable of modelling the three sources of uncertainty and assessing their cumulative impact on construction projects cost and time (Moret and Einstein, 2016). In the subsequent section, the Cost Estimate Validation Process (CEVP), as the one of the most advanced risk-based estimating tool, is discussed.

2.9.3 Cost Estimation Validation Process (CEVP)

Cost Estimate Validation Process (CEVP) has been developed to identify, quantitatively analyse and evaluate the risk that could impact cost and/or time during infrastructure project execution (WSDOT, 2018). CEVP is the most advanced estimating tool pursuing the risk strategy with its more comprehensive strategies proposed by the transportation community to counteract the risk factors causing cost underestimation and time delays in infrastructure construction projects (WSDOT, 2018). It is a tool especially suited to risk identification and risk analysis, the first and second phases of the risk strategy. In this section, the goals and the two central processes of the CEVP, the validation process and the risk identification process, are discussed.

According to WSDOT (2018) the main goal of CEVP is estimating ranges of project cost and time by modelling risk in the negative and positive forms of opportunities and threats, thus favouring interval probabilistic ranges over single deterministic estimates. The other goal of CEVP are to establish consistency in the practice of risk-based estimations and to provide a flexible and scalable estimating tool that can be adapted depending on the size, location and complexity of the project.

In CEVP, cost or time estimates are given by the base estimation (deterministic) and the risk estimation (interval probabilistic range). The base estimation is the most probable estimation that can be expected in the case of the project developing as planned. It is estimated during the validation process by eliminating contingencies from the initial estimate. The risk estimation is given by risk events, defined by their probability of occurrence, severity and their impact. It is determined and quantified during the risk identification process (WSDOT, 2012).

When CEVP was introduced in 2002, an initial negative reaction of the public turned into acceptance and gratitude for more realistic estimates: within a short period of time; both the larger estimates and the concept that ranges are a more sensible representation of estimates than single numbers were accepted by the public (Reilly et al., 2004).

The efficacious use of CEVP depends on one main condition: the project owner is interested in knowing the potential factual estimation of the project (WSDOT, 2012). This observation is tightly connected to the body of literature that identified the causes of cost escalation in inadequate estimation tools, optimism bias and economic-political interests. CEVP is an advanced tool to estimate risk in cost and time; it can address biases in the risk identification process with the help of the risk analyst, but it cannot address politically motivated cost and time underestimations that aim at obtaining approval for a project by accentuating benefits and reducing costs and times. In order to guarantee the professionalism in cost and time estimates, CEVP binds the participants to a code of ethics in ten points that cover issues such as the highest standards of practice in the industry, honest and effective communication, accountability, broad participation in the process without exercising pressure when developing estimates, consideration for public funds, and strengthening the understanding of risk and of cost/time estimation (WSDOT, 2012).

The project team and estimator specialists conduct the cost validation process, starting from an initial phase of the project to determine the base estimation. The project team briefs the estimator

specialist on the project scope and the risks included in the project estimate. Then, successively the project scope, cost and time are reviewed. Unit costs and production rates are also reviewed; the contingencies in the unit costs and production rates are removed. Finally, an agreed upon base estimation for cost and time of the project are calculated, which is the base to which the risk estimations are added (Idrus et al., 2011).

In the process of risk identification, project team members and experts identify risks, led by an experienced risk analyst who is acquainted with uncertainty theory, debiasing techniques, and the cost and risk models (Reilly et al., 2004). The three main goals of the risk identification process of CEVP are: identify the risks; quantify the risks; and model the risk of infrastructure project cost and time.

Prior to the formal risk identification process, the participants are calibrated, trained (although briefly) on relevant risk concepts and biases. The calibration requires three points of input: a graphical display of the project plan and strategy, a preliminary list of risks and opportunities, and the base estimation from the validation processes (WSDOT, 2012).

CEVP utilises the Monte Carlo procedure to develop a probabilistic model and provide the probability distributions of project cost and time from validated base estimation and risk estimation. Such distributions are used to communicate ranges of probable cost and time to the public. The quantitative analysis, as well as the risk identification, are iterative, since some risks are mitigated or eliminated, and others arise (Idrus et al., 2011).

According to WSDOT (2012), a main advancement of CEVP compared to the other estimating tools is that it provides a range of project cost and time, which is a more sensible representation of uncertain outcomes, since no one can predict the future accurately. However, Reilly et al. (2004) considered a practical downside of CEVP cost and time ranges for planning purposes, that is, a single number estimate is needed to gain legislature endorsement, because results presented as ranges cause communication difficulties and the project appears too expensive and unrealistic if the decision-makers focus on the extreme values of the ranges.

To avoid these difficulties the WSDOT (2012) indicated the 90th percentile of the probability distribution of estimated cost and time ranges for approval and legislating purposes. However, when the budget for the Dubai metro was allocated, it included a range for the construction costs of $\pm 20\%$ of estimated cost from CEVP (Johnson and Babu, 2018)

Other risk identification and analysis tools similar to CEVP are Highways Agency Risk Management (HARM) and the Public-Sector Comparator (PSC). In both tools, risks are first identified and prioritised, and then they are analysed with quantitative risk analysis. In particular, HARM aims at creating full-fledged risk management including, besides risk identification and analysis, also risk mitigation and risk allocation. Differently, the special feature of PSC is the capability of comparing total project cost, including the entire project life cycle (FHWA, 2005).

The focus on the two phases of risk strategy and CEVP as the most advanced risk-based estimation tool is needed since the uncertainty model proposed in this thesis allows one to identify and analyse uncertainty in an infrastructure construction project.

2.10 SUMMARY OF THE CHAPTER

The literature presented in this chapter examined holistically the costs underestimation and time delays in infrastructure construction projects and identified various causes and proposed various solutions for these underestimations and delays.

The concept, of five risk strategy phases (risk identification, risk analysis, risk mitigation and planning, risk allocation and risk monitoring and controlling) was discussed. Three main sources of uncertainty in the construction of infrastructure projects, the variability in the construction cost and time of the infrastructure process, the correlations between construction activities costs and times; and disruptive events were identified.

Furthermore, different types of correlations in the construction of linear infrastructure projects were identified. Also, seven main factors, namely: economic, environmental, financial, legal, political, social and technical were established from literature. Lastly, the evolution and accuracy of estimation in construction were discussed and available estimation methods for assessing the impact of risk and uncertainty on cost and time of infrastructure projects were reviewed.

CHAPTER THREE: THEORETICAL AND CONCEPTUAL FRAMEWORK

3.1 INTRODUCTION

This chapter provides an overview of the theoretical perspectives on cost and time estimation on infrastructure projects and modern portfolio theory, to highlight a knowledge gap on assessing uncertainty and to form the basis, along with reviewed literature, for developing the research conceptual framework. Furthermore, this chapter outlines the research hypotheses which were tested to answer the research objectives in Chapter Six.

3.2 THEORETICAL PERSPECTIVES ON ESTIMATION OF COST AND TIME OF INFRASTRUCTURE PROJECTS

Blischke and Murthy (2011) defined estimation as a symbolic formation of a system, and the content of it is defined using the factors affecting the construction cost and duration of projects such as risk and uncertainty. Since the 1950s, efforts have been made to identify the relation between the level of available information and construction cost and time to develop models to estimate construction cost and duration accurately. WSDOT stated that estimating is a maturation process that follows project development.

Generally, the theories of cost and time estimation are classified into two main groups: deterministic and probabilistic.

3.2.1 Deterministic theory

Deterministic theory focuses on the values and durations which are qualified with all variables that exactly known or can be estimated accurately (Benjamin and Cornell, 2014). Deterministic theory, also known as base estimation, provides a single cost and duration and neglects to consider the risk and uncertainty in the estimate of cost and time.

The base estimation process is the most common estimation technique in the construction industry developed based on deterministic theory. The base estimation considers the project construct at the point of the idea and calculates the cost and time of activity based on the normal (mode) value and duration (Khamooshi et al., 2012). The base estimation employs several methods to estimate the cost and time of projects, such as global estimation, composite estimating, unit rate estimating, first principles estimating, and unit rates/first principles estimation. Base estimation is an estimation process developed from deterministic theory.

The base cost estimate is the sum of two key components: the client (public) costs and construction (indirect, direct, margin) costs, while the base time estimate is obtained by the construction (indirect, direct) time as at the applicable base date and which should cover all phases of the project (Development, 2017). The base estimate is prepared based on the estimator's best assessment of the quantities, market rates and production rates that will be required for a given scope of work at the time the estimate is prepared. Allowance, contingency or escalation do not form part of the base estimate which means the project must be constructed in ideal conditions. Total project cost

attained by the simple summation of all activities' cost and the total project time is obtained by the simple summation of all critical activities' time.

The nature of the deterministic estimation of cost and time is independent of the method employed for obtaining the initial values (Kumar and Varaiya, 2015) Thus, deterministic cost and time estimations are derived from an analysis of historical data of past projects or expert opinions. Considering the project to be constructed in ideal conditions is the main weakness of the deterministic (base estimation) theory, which systematically disregards the occurrence of any uncertainty and unforeseen conditions during the construction of the project.

Therefore, deterministic estimation methods such as base estimation yield higher cost and time differentials (underestimation) and do not allow planners to incorporate the risk and uncertainty that define the characteristics and uniqueness of each construction project. The estimation models, which used deterministic theory, such as the single value estimation model and base cost estimation, are considered unreliable and lead in underestimation of construction cost and duration of projects (Odoh and Ihedigbo, 2014).

3.2.3 Probabilistic theory

Probabilistic theory, also known as risk-based estimation is based on the ideology of the random nature of the construction cost and time of activities, and initial values of a specific statistic distributions (Benjamin and Cornell, 2014). Probabilistic theory incorporates the risk and the uncertainty that surrounds each construction project and, consequently, it provides a method representative of the project characteristics and uniqueness.

Probabilistic theory accepts that although the values of some variables are not absolutely certain, they can be calculated. The main advantage of probabilistic theory compared to deterministic theory its ability to provide insight into the accuracy of the estimate and the impact of risk and uncertainty (AASHTO, 2013). The concept of probabilistic theory shown in Figure 3.1.

Several estimating methods have been developed based on probabilistic theory such as: expected value, variance, central limit theorem, PERT, and Monte Carlo. These probabilistic methods represent the construction project cost and time as full probability distributions, and incorporate new information as the construction progresses. The main difficulty of models using probabilistic theory lies in the necessity of reliable expert estimation data, and the effort of obtaining and incorporating reliable data into estimation models have been identified as the main problems of this approach (Ross, 2013). Even when reliable data is available, some other challenges, such as selection of the appropriate probability distributions to describe the cost and time elements, and the determination and quantification of correlation among cost and time variables involved in the construction project, are difficult to address (Kumar and Varaiya, 2015).

The models based on probabilistic theory have not been widely employed in the construction industry, because there is not a real demand for quantitative modelling of uncertainty among projects planners and decision makers, and existing probabilistic models do not provide a realistic

and accurate estimate due to not properly assessing the impact of risk and uncertainty (Eastman, 2018).

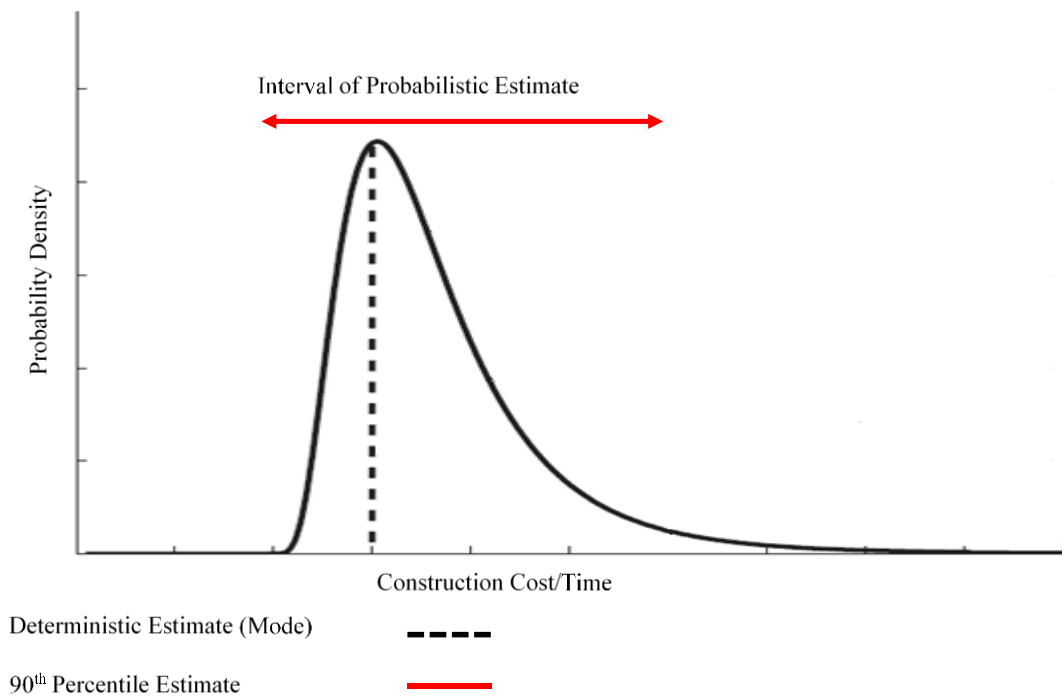


Figure 3.1: Probabilistic theory concept

3.3 MODERN PORTFOLIO THEORY

Modern portfolio theory is the most influential of economic and management theories dealing with finance and investment, and is based on the idea that risk averse investors can construct a portfolio to optimise expected output based on a given level of risk and uncertainty, emphasising that risk is an inherent part of the higher reward (Omisoro et al., 2011). Modern portfolio theory reflects how to assess the uncertainty/risk and the compensations of all possible elements combinations and identify all efficient items combinations and, hence, discard all items costing that is instead found, by comparison, to be inefficient. (Fabozzi and Markowitz, 2011).

The main idea of modern portfolio theory is that the uncertainty/risk, probability of occurrence and impact are directly linked, and the theory argues that uncertainty/risk, probability of occurrence and impact should not be viewed alone but should be evaluated by the overall portfolio's risk/uncertainty and output (Odoh and Ihedigbo, 2014). Another main idea of modern portfolio theory is that, through diversification across a wide variety of uncertainties and risk, the portfolio's overall uncertainty can be assessed accurately. Modern portfolio theory is an appropriate method to establish the uncertainty portfolio of projects and maintain this portfolio in order to ensure that the uncertainty portfolio of the project is constant to achieve the project goal (Omisore et al., 2011). The concept of modern portfolio theory shown in Figure 3.2.

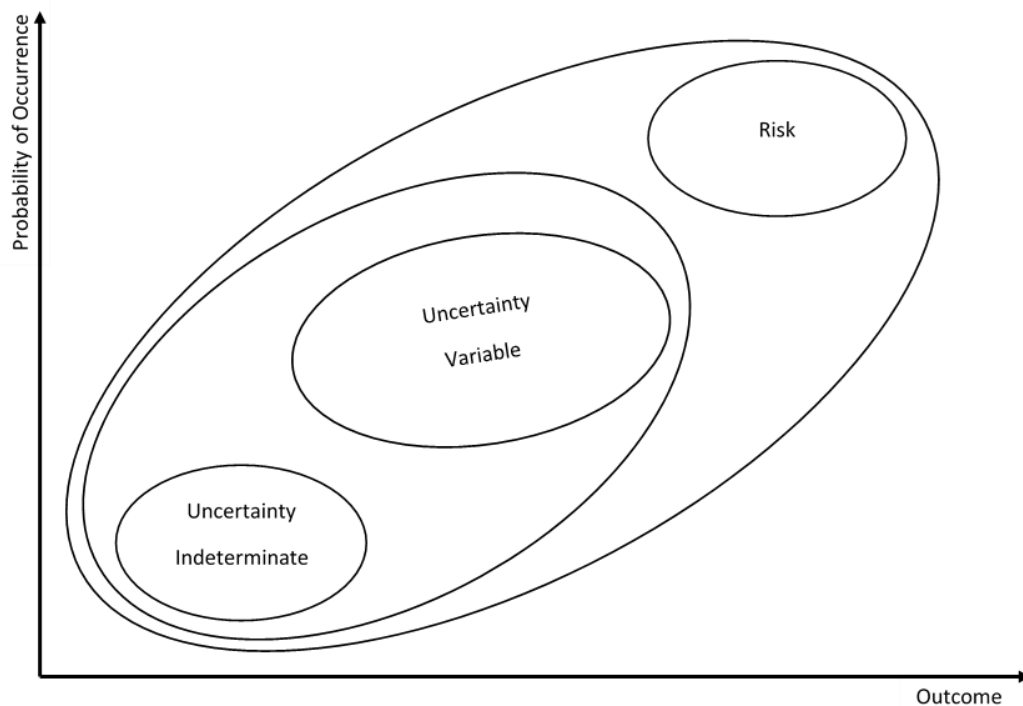


Figure 3.2: Modern portfolio theory concept

Very few researchers employed the modern portfolio theory in the field of construction management (Lee and Eid Junior, 2018, Cattell et al., 2011). Cattell et al. (2011) examined the relationship between risks and unbalanced estimation and developed a framework by which all risks of work items adopted modern portfolio theory. Lee and Eid Junior (2018) developed portfolio construction and risk management based on modern portfolio theory to evaluate the asset management companies in Brazil and determine the best financial practice on investment on construction projects.

3.4 CONCEPTUAL FRAMEWORK OF THE STUDY

As deliberated previously from literature in Chapter Two, cost and time underestimation due to uncertainty is a global phenomenon in infrastructure projects, and construction of infrastructure

projects are subject to various uncertainties that affect construction cost and duration differently (El Khalek et al., 2016). The impact of uncertainties depends on the features (size, nature, and complexity) of the infrastructure project.

Various researcher (Touran and Lopez, 2005, Moret and Einstein, 2016, Ang and De Leon, 2005, Arestegui Carvajal, 2014, El Khalek et al., 2016) attempted to tackle this phenomenon by developing different estimating models (fuzzy logic, artificial neural network, fault tree analysis) and techniques (Monte Carlo, Bayesian, decision analysis) based on probabilistic theory; however, till now none of these models and methods have provided a realistic and accurate estimate because of an inaccurate assessment of the impact of uncertainties on cost and time. While modern portfolio theory stipulates that uncertainty/risk, probability and outcome have a direct relationship and the uncertainty and risk should be assessed in the uncertainty portfolio (Omisore et al., 2011). Modern portfolio theory has been used by a few researchers in the field of construction management, and none of them employed this theory in the field of construction cost and time estimation. Therefore, this study adopted the principles of modern portfolio theory and combined it with the philosophy of probabilistic theory and infrastructure characteristics to tackle assessing the uncertainty and risk in construction projects and to address the phenomenon of the underestimation of infrastructure cost and time.

This research is based in the field of construction economics, cost and time estimating of infrastructure projects and construction management. This study aims to develop a hybrid estimation model by adopting unique features of probablistics theory and the modern portfolio concept, which reflects how to assess the uncertainty and the compensations of all possible elements' cost and time combinations in the uncertainty portfolio of a project and identify all efficient items' cost and time combinations and hence discard all items' cost and time that are instead found, by comparison, to be inefficient. The review of literature (AASHTO 2009, Molenaar 2010, Yoe 2011) perspectives provides conceptual evidence that there is an association between infrastructure project characteristics, impacts of uncertainties and accurate estimation of cost and time of the infrastructure project. Therefore, the study embedded the philosophy of the modern portfolio theory in probabilistic theory in developing a conceptual framework for understanding the relationship between different sources of uncertainty in the construction process, infrastructure project characteristics and estimation of cost and time to address the infrastructure cost and time underestimation phenomenon. The conceptual framework of the study (uncertainty portfolio) is shown in Figure 3.3.

The process is hinged on integrated infrastructure project characteristics as variables to develop an uncertainty estimation model using the uncertainty portfolio concept to assess the impact of different sources of uncertainty to improve the accuracy of estimation of infrastructure cost and time. Due to the peculiar nature of uncertainty, the impact of uncertainty is assessed in the uncertainty portfolio of the project.

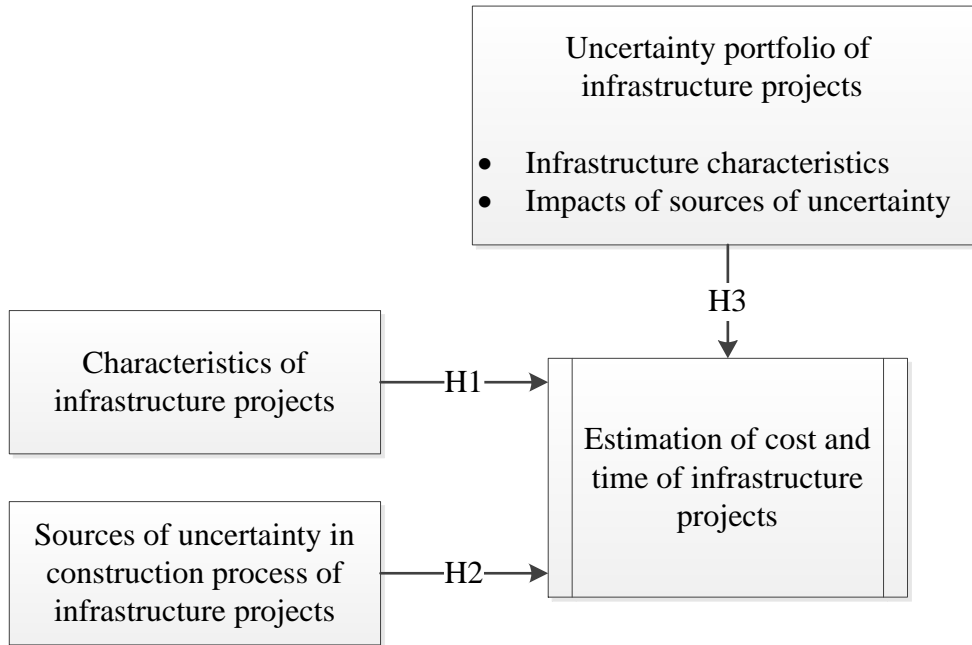


Figure 3.3: Conceptual framework of the study

The conceptual framework considered three basic premises: 1. the estimation of infrastructure cost and time should not be assessed by itself, but by how it contributes to an uncertainty portfolio of the infrastructure project; 2. the impact of uncertainty on cost and time of project should consider the nature of infrastructure activities and project; and 3. the variance of cost and time of an infrastructure project is a function not only of the variance of each individual activity due to uncertainty (variability), but also of the covariance (correlation) between activities and the unforeseen (disruptive events).

The key insight of the conceptual framework developed is that the estimation of infrastructure cost and time should assess the different sources of uncertainty in the uncertainty portfolio of the infrastructure project by using probabilistic theory. Another important argument of the conceptual framework is that the impact of uncertainty on the cost and time of projects should be evaluated at the level of the single activity and the cumulative impact considered as the uncertainty portfolio of the infrastructure.

Based on the three premises of the conceptual framework it can be expected that variability uncertainty of some activities increases while at the same time the variability uncertainty of other activities decreases. The premises of the framework suggest that the relationship among the respective activities in infrastructure projects activities are positively correlated (Touran and Lopez, 2006) and thus increasing cost or time in one activity is associated with increasing cost or time of the other and vice versa, this significantly reduces the risk of double cost or time underestimation error of the infrastructure projects. Also, the conceptual framework considers the principles of probabilistic theory on occurrence of disruptive events in each activity.

The uncertainty portfolio conceptual framework proposed that the uncertainty portfolio of the infrastructure project is steady, and that the uncertainty portfolio concept provides a reliable platform on which to develop a hybrid estimation model for assessing the uncertainty portfolio of projects and improving the accuracy of infrastructure cost and time estimation.

Furthermore, the coverage of the two common estimation theories on predicting the total construction cost and time investigated in this research, namely: deterministic theory (base estimation) and probabilistic theory (risk-based estimation), compares to the estimation coverage of proposed uncertainty portfolio concept (uncertainty estimation model) illustrated in Figure 3.4.

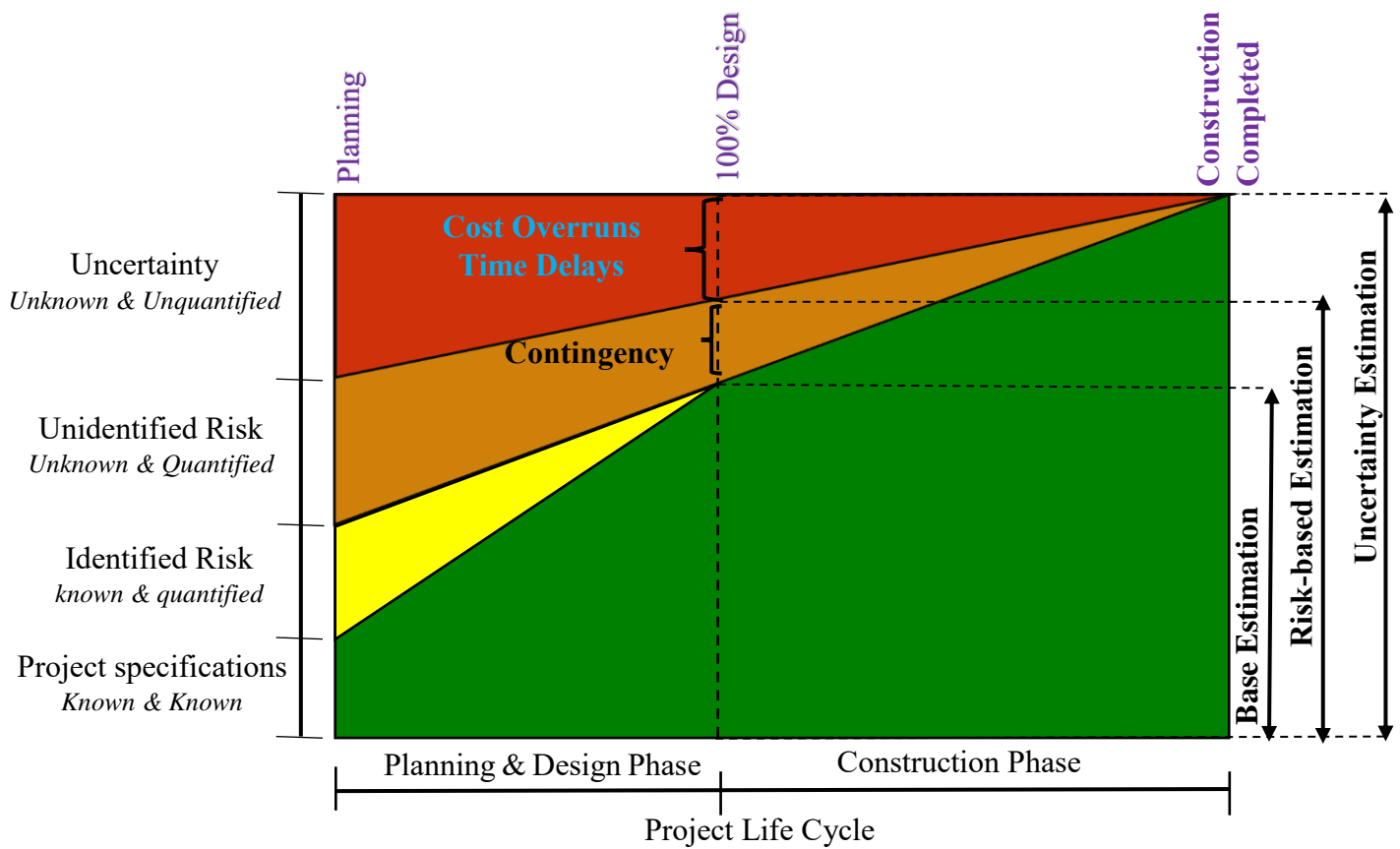


Figure 3.4: Assessment of coverage of three estimation approaches

The base estimation includes all of the known items (project specifications) and other items that are known and quantified at the point of starting the construction phase (identified risk) using the deterministic method. Risk-based estimation includes the base estimation items along with other items needed to construct the project but have yet to be fully identified and can be quantified (unidentified risk) using some probabilistic methods. The difference between uncertainty estimation with the risk-based estimation is, instead of applying percentage contingency to the cost and time of infrastructure projects to cover cost and time of uncertainty (Shen et al. 2015), all of the inherent uncertainty in the process of infrastructure construction are identified and carefully

divided to the risk and uncertainty-variable and the impact of each one simulated using an uncertainty portfolio of project and probability distribution. Furthermore, the conceptual model depicts the relationship between the project characteristics and the uncertainty in the construction of an infrastructure project, based on the project maturity and uncertainty within the project life cycle.

As presented in Figure 3.4, the level of project uncertainty reduces when more and better data and information become available, and the project progresses into the project life cycle. This is an integrated conceptual model of the philosophy behind the current research and the research hypotheses that are discussed in the next section and were tested and validated through the case study in Chapters Six and Seven.

3.5 HYPOTHESES DEVELOPMENT

The previous section presented the two major estimation theories in the construction industry and determined the drawback of each theory in assessing risk and uncertainty. To overcome these drawbacks the study developed an uncertainty portfolio conceptual framework by incorporating modern portfolio theory to probabilistic theory and underpinned the association between uncertainty and construction cost and duration of projects, characteristics of infrastructure project, impacts of uncertainty, and accurate cost and time estimation.

Prior to employing the uncertainty portfolio model, the three premises of this concept should be hypothetically tested using empirical data. The current section provides a further theoretical background to develop and lend support to the research hypotheses to be tested.

3.5.1 The association between project characteristics, cost and duration of infrastructure projects

The cost and time of infrastructure projects depend on the size, nature and different structures of the infrastructure project (Zavadskas et al., 2010). According to Flyvbjerg (2007), the impact of uncertainty on the cost and time of infrastructure projects is larger than on other construction projects because of the unique features of these projects. These features include complexity in the relationship between major construction activities and structures, the long duration of construction, the dynamic process of construction, the repetition within linear infrastructure projects, and the risks associated with any mobile construction site.

Very limited research examined the influence of characteristics of different structures of an infrastructure project on the relevant structure cost and time. Moret and Einstein (2016) proved that the impact of uncertainty on cost and time is varied in the different structure of rail line infrastructure projects.

In order to answer Research Question 2 (what is the association between the characteristics of infrastructure project and cost and time of infrastructure project?) and address Research Objective 2, a research hypothesis was formulated to test the association between the characteristics of different structures of an infrastructure project and the cost and time of infrastructure projects.

Hypothesis 1: There is a significant association between project characteristics, cost and duration of infrastructure projects.

Null Hypothesis 1.1: There is no significant association between project characteristics and cost of infrastructure projects.

Alternative Hypothesis 1.1: There is a significant association between project characteristics and cost of infrastructure projects.

Null Hypothesis 1.2: There is no significant association between project characteristics and duration of infrastructure projects.

Alternative Hypothesis 1.2: There is a significant association between project characteristics and duration of infrastructure projects.

3.5.2 The association between the impacts of different sources of uncertainty and the cost of infrastructure projects.

Construction of infrastructure projects are subject to uncertainties and risks (El Khalek et al., 2016). Various uncertainties exist in the construction process of infrastructure projects that affect construction cost and duration differently (Moret and Einstein, 2016). Infrastructure projects are some of the most dynamic, challenging and complex construction projects because they are exposed to various uncertainties and risks (El Khalek et al., 2016)

Uncertainties in construction of infrastructure projects impact the cost and time of the project through a combination of the following factors: the cost and time of the activity vary from repetition to repetition, which causes the cost and time of project to change; the costs and times of construction activities are correlated, which causes the standard deviation of the total cost and time to increase; and during the construction of infrastructure, some unforeseen incidents occur, which influence the construction cost and duration of the projects.

Three sources of uncertainty, namely: variability in the construction cost and time of the infrastructure process, the correlations between construction costs, times and cost/time activities, and disruptive events, have been adopted and expanded from Moret and Einstein (2016).

To answer Research Questions 4 (what is the association between the impacts of different sources of uncertainty and the cost and time of infrastructure projects?) and address Research Objectives 4, a research hypothesis was formulated to test the association between the impact of different sources of uncertainty and the cost and time of infrastructure projects.

Hypothesis 2: There is a significant association between the impacts of different sources of uncertainty, cost and duration of infrastructure projects.

Null Hypothesis 2.1: There is no significant association between the impacts of different sources of uncertainty and cost of infrastructure projects.

Alternative Hypothesis 2.1: There is a significant association between the impacts of different sources of uncertainty and cost of infrastructure projects.

Null Hypothesis 2.2: There is no significant association between the impacts of different sources of uncertainty and duration of infrastructure projects.

Alternative Hypothesis 2.2: There is a significant association between the impacts of different sources of uncertainty and duration of infrastructure projects.

3.5.3 The difference between the estimations of cost and time and actual cost and time of the construction of infrastructure projects

The review of the existing solutions to counteract cost underestimation and time delays in Chapter Two showed two limitations: the lack of an in-depth understanding of the construction process and its uncertainties, and modelling risks only without capturing the cumulative effect of different sources of uncertainty. To address these two limitations which are aligned with Research Question 6 (What is the difference in the construction cost and time of infrastructure projects before and after applying the uncertainty model?) and Research Objective 6, the following research hypotheses were formulated to test the relationship between the assessment of uncertainty and accurate estimation of cost and time of the project.

Hypothesis 3.1: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using uncertainty model.

Null Hypothesis 3.1.1: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using the variability model.

Alternative Hypothesis 3.1.1: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using the variability model.

Null Hypothesis 3.1.2: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using the correlation model.

Alternative Hypothesis 3.1.2: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using the correlation model.

Null Hypothesis 3.1.3: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using the disruptive events model.

Alternative Hypothesis 3.1.3: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using the disruptive events model.

Hypothesis 3.2: There is a significant difference between the accuracy of estimations of construction cost and duration by deterministic methods and the uncertainty model.

Null Hypothesis 3.2.1: There is no significant difference between the initial estimations of construction cost and duration and actual construction cost and duration.

Alternative Hypothesis 3.2.1: There is a significant difference between the initial estimations of construction cost and duration and actual construction cost and duration.

Null Hypothesis 3.2.2: There is no significant difference between the uncertainty estimations of construction cost and duration and actual construction cost and duration.

Alternative Hypothesis 3.2.2: There is a significant difference between the uncertainty estimations of construction cost and duration and actual construction cost and duration.

3.6 SUMMARY OF THE CHAPTER

This chapter investigated the two estimation theories commonly used in the construction industry and determined the drawbacks and limitations of these theories. To address the drawbacks and limitations of existing theories, the conceptual framework for the research (uncertainty portfolio) was developed by employing the features of probabilistic theory and modern portfolio theory which support the research ideology.

To test the relationship between the infrastructure characteristics, different sources of uncertainty, impact of uncertainty on infrastructure cost and time and accurate estimation of infrastructure cost and time were proposed by uncertainty portfolio theory with empirical data and three research hypotheses developed. Furthermore, based on the uncertainty portfolio theory framework, the research conceptual framework was drawn. The developed conceptual framework presented the relationship of uncertainty with cost and time underestimation. It also proposed that the characteristics of an infrastructure project, the cumulative impacts of different sources of uncertainty, and accurate estimation were related concepts.

The developed conceptual model and formulated research hypothesis will be used in the analysis of a case study in Chapter Six.

CHAPTER FOUR: RESEARCH DESIGN AND METHODOLOGY

4.1 INTRODUCTION

Modelling the uncertainty of cost and time in infrastructure projects is a complex process requiring appropriate methodological approaches to collecting and analysing the data to achieve a reliable model that estimates the cost and time of infrastructure projects with clarity and accuracy. Creswell and Creswell (2017) affirmed that methodology is one of the more important requirements for any research. Research methodology is a way to solve the research problem systematically. This chapter explains the justification for the research methodology and design used in the study and delineates the logical sequence to connect empirical data to research questions and, eventually, to the research results. It also presents the philosophical underpinning of the research paradigms and research approach considered and discusses the design of the data collection instrument, the unit of analysis, techniques of data analysis, and criteria for judging the quality of the research design. Lastly, the ethical principles considered in conducting the study are discussed. A graphic summary of the research methodology is presented in Figure 4.1.

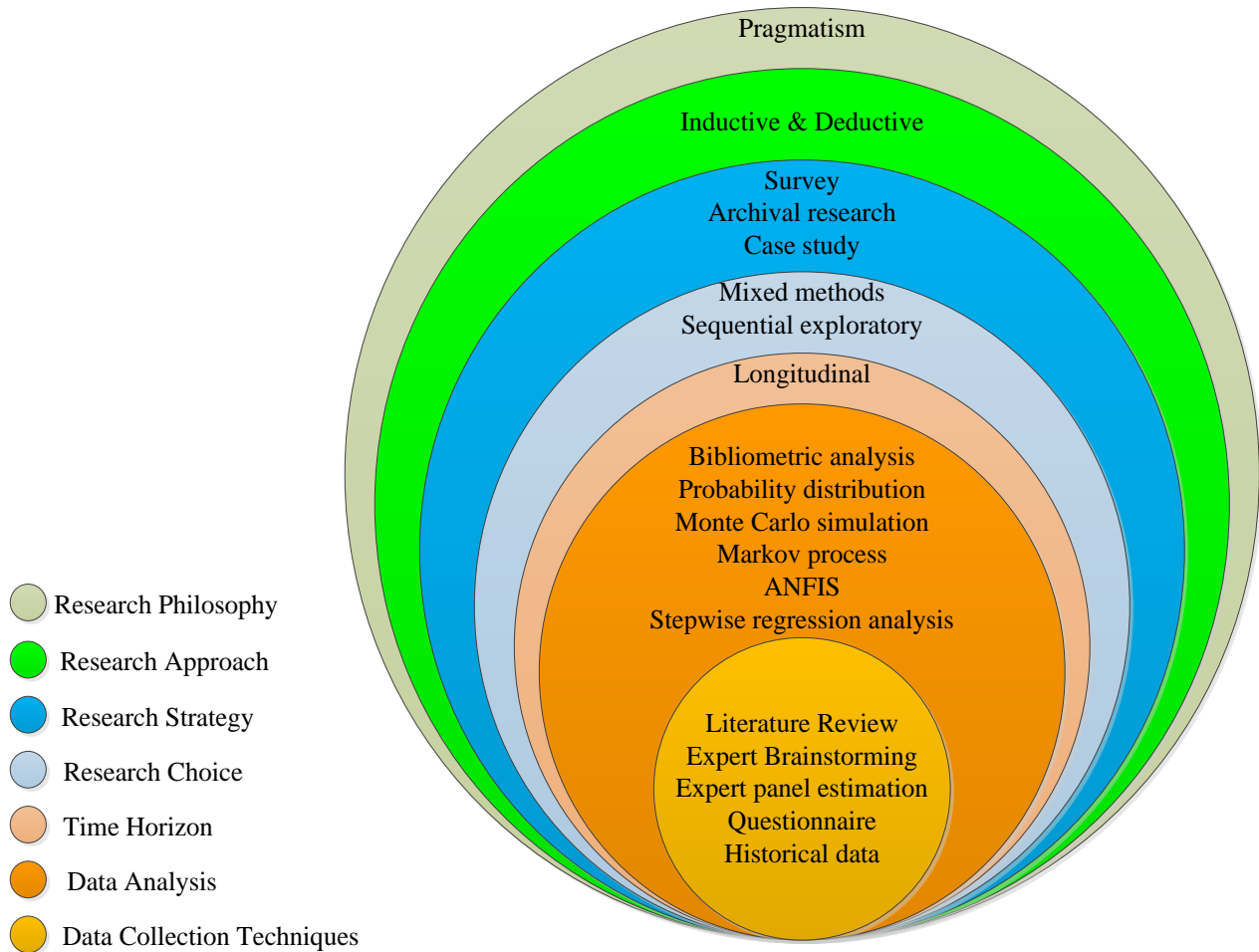


Figure 4.1: Summary of research methodology of the study

4.2 RESEARCH PHILOSOPHY

Research philosophy is a principle about the technique by which data about a phenomenon should be collected and analysed (Holt and Goulding, 2014). Scheurich (2014) acknowledged that the research philosophy involves establishing some fundamental beliefs and assumptions on how to approach a research problem and hence, its methodological design. Understanding the philosophical aspects of research assists the researcher to clarify research design, to recognise the suitable designs and to create an innovative design that is outside their previous experience (Robson and McCartan, 2016). The three major philosophical schools of thought about research are ontology, epistemology and axiology (Killam, 2013).

4.2.1 Ontology

Ontology is concerned with the nature of reality and raises the questions of the assumptions the researcher has about the way the world functions and commitment from the particular perspectives. (Easterby-Smith et al., 2012). It describes the study or science being undertaken and develops this description for the social sciences to encompass allegations about what exists, what it looks like, what factors make it up, and how these factors interact with each other (Killam, 2013). Ontology has two aspects, namely, objectivism (positivist) and subjectivism (interpretivist). Objectivism describes the position that social entities occupy external to social actors concerned with their existence, while subjectivism considers that social phenomena are generated from the perceptions and consequent actions of those social actors involved with their presence (Creswell and Creswell, 2017).

The study undertaken is based on the objectivist paradigm because the focus of the study was on construction cost and time of infrastructure projects and emphasised the sources of uncertainty that disrupted the construction of infrastructure projects causing cost overruns and time delays. The research questions, research hypotheses conjecture and the survey information to answer must be real and external to social actors concerned with their existence.

4.2.2 Epistemology

Epistemology concerns what constitutes acceptable knowledge in a field of study firmly joined with ontology and its consideration of what constitutes reality. It considers opinions about the most proper ways of enquiring into the nature of the world (O'Leary, 2017) and “what is knowledge, what are the sources and what are the limits of knowledge” (Scheurich, 2014). O'Leary (2017) defines epistemology as the science or theory of the method, or grounds of knowledge expanding this into a set of assumptions or claims about the ways in which it is possible to gain knowledge of reality, what exists may be known, what can be known, and what criteria must be satisfied in order to be expressed as knowledge. Questions of epistemology begin to consider the research method, how knowledge is possible to know, and the need to consider practices and standards through which verifiable and reliable knowledge is produced, can be generated and argued for (Killam, 2013).

Epistemologically, this research is deductive, and objectivism-ontology inclined. In order to continue the inquiry, an alternative to the needed archival data was sought. Sourceable primary data from construction participants as an alternative to achieved data redirected the focus of the research from archival sources to individual infrastructure project managers. The study employed a series of expert panels' estimation, and the survey method used the closed-end structured questionnaire in the collection of quantitative data. Furthermore, facts were focused on, sources of uncertainty and disruptive events evaluated, disruptive events were localised to the research area and classified, and hypotheses formulated from the research questions were tested for confirmations.

4.2.3 Axiology

Axiology judges the value. Although this may comprise values in the areas of ethics and aesthetics, it is the process of social enquiry (Hartman, 2011).

The axiology aims to depict the level of reliability, consistency, or otherwise reconstructing or extending the previously held theories or construction. Axiology urges congruence between epistemological and ontological assumptions (Killam, 2013). It plays an essential role in establishing the requirements and standards of an adequate research approach and research techniques (Creswell and Creswell, 2017). Making the axiology explicit assists in setting and clarifying the guiding tone and difficulty for action in research (O'Leary, 2017).

In this study, the following research elements assumed great importance: the construction cost and duration of infrastructure projects were examined in a single study because of correlation between cost and time; data were collected by allowing the experts and respondents to supply data freely; and respondents were given the privacy of delving into files to qualitatively rate the probability of occurrence and severity of disruptive events in infrastructure projects.

4.3 THE RESEARCH PARADIGMS IN CONSTRUCTION MANAGEMENT

The research paradigm indicates the logical tendency and the nature of the research, which provides a philosophical, methodological and conceptual outline in order to solve the research problem and answer the research questions (Johnson and Onwuegbuzie, 2004). Positivism, realism, interpretivism and pragmatism are the four main paradigms regarding research development (Creswell, 2009) (See Table 4.1).

To adopt the appropriate research paradigm for the study, the philosophical positions of four dominant paradigms used in construction management research are compared and summarised in Table 4.1.

Table 4.1: Comparison of research paradigms in construction management

	Positivism	Realism	Interpretivism	Pragmatism
Ontology (Nature of reality)	One reality; knowable within a specified level of probability	Rejects cultural relativism; recognises the various of reality based on social positioning; conscious recognition of consequences of privileging versions or reality	Multiple, socially constructed realities	Asserts that there is a single reality and that all individuals have their own unique interpretation of reality
Epistemology (Nature of knowledge)	Objectivity is important; the researcher manipulates and observes in a dispassionate objective manner	Interactive link between researcher and participants; knowledge is socially and historically situated; need to address issues of power and trust	Subjective meanings and social phenomena; focus upon the details of situation; a reality behind these details; subjective meanings motivating actions	Relationships in research are determined by what the researcher deems as appropriate to that particular study
Axiology (Nature of ethical behaviour)	Respect privacy; informed consent; minimise harm (beneficence); justice/equal opportunity	Respect for cultural norm; beneficence is defined in terms of the promotion of human rights and increase in social justice; reciprocity	Balanced representation of views raises participants' awareness; community rapport	Gain knowledge in pursuit of desired ends as influenced by the researcher's values and politics
Methodology (Approach to systematic inquiry)	Quantitative, interventionist decontextualised	Qualitative, but quantitative and mixed methods can be used; contextual and historical factors are described, especially as they related to oppression	Qualitative; Hermeneutical; Dialectical; contextual factors are described	Match methods to specific questions and purpose of research; mixed methods can be used as researcher works back and forth between various approaches
Data collection techniques	Highly structured; large samples; measurement, quantitative, but can use qualitative	Method chosen must fit the subject matter; quantitative or qualitative	Small samples; in-depth investigations; qualitative	Mixed or multiple method designs; quantitative and qualitative

Source: Adapted from Mertens (2014)

4.3.1 Positivism

Positivism is a research approach that employs empirical methods, makes extensive use of quantitative analysis, or develops logical analyses to build formal explanatory theory (Neuman, 2013). Positivism assumes an epistemological position that promotes the application of the methods of the natural sciences to the study of social reality, as opposed to the post-positivism approach, which aims to examine in-depth phenomena from a qualitative prospect (Bryman, 2016).

The positivist paradigm is known to be efficient in explaining behavioural aspects, as well as measuring the descriptive aspects of built environment research, particularly construction management (Amaratunga et al., 2002). Dainty (2008) found that the positivist approach appears to be one of the dominant research approaches in construction management.

Hammond (2011) used the positivism approach to understand the social world of emerging contractors within the construction sector in South Africa. Adediran (2018) employed the positivism quantitative approach to empirically validate the pre-existing assumption or theory that targeting SMCs and increasing their participation in government contracts stimulates their growth performance and development.

4.3.2 Realism

Realism relates to scientific enquiry: the nature of realism is that what the senses present to the researcher as reality is the truth; that objects have an existence independent of the human mind (Easterby-Smith et al., 2012).

The focus of the realism approach is on experiments that would unravel the inherent underlying structures either within an object or between objects (Bhaskar, 2008). Two reasons have contributed to the lack of popularity of realism in construction management researches: its multiple conceptualisations and associating it with positivism (Johnson and Duberley, 2006).

4.3.3 Interpretivism

Interpretivism propounds that it is essential for researchers to recognise differences between human roles as social actors. This emphasises the differences between conducting a study among people rather than objects. Interpretivism is concerned with the meanings that people attach to rules, values and norms that regulate their interactions and care is taken not to impose previous knowledge of values, rules and norms on others, but rather to understand their actions and beliefs from their point of view. The emphasis is not only on what they tell the researcher directly about the reasons for their actions and beliefs, but also on the social practices that underlie them (Mertens, 2014).

According to Dainty (2008), the main advantage of the interpretivism approach lies in allowing a researcher to obtain rich, in-depth data from participants, and this advantage makes the interpretivism approach one of the prevalent research approaches used in construction management researches.

4.3.4 Pragmatism

Pragmatism considers that the most critical determinant of the epistemology, ontology, and axiology adopted is the research question. The philosophical view underpinning pragmatism arises out of situations, actions and consequences rather than antecedent conditions. Pragmatist theorists do not believe that some pre-determined frameworks or theories form truth and knowledge, nor can people create reality out of nothing (Easterby-Smith et al., 2012). Pragmatic emphasises tackling current and pressing problems to generate constructive knowledge, and the ensuing

transformation of the developed knowledge into action (Fendt et al., 2008). Hence, it is a widely accepted philosophical foundation for the mixed methods approach, which argues for the successful combination of positivist and constructivist philosophical stances (Creswell, 2009). However, this distinguishes pragmatism from qualitative or quantitative approaches that are founded on interpretivism and positivist paradigms, respectively.

In the construction management discipline, the interpretivism paradigm and the positivism paradigm are the dominant research paradigms in use (Holt and Goulding, 2014). According to Dainty (2008), due to the high level of complexities that are involved in construction management research resulting from a convergence of social and natural sciences, no single paradigm could independently address the problems in this field. Amaratunga et al. (2002) and Fellows and Liu (2015) affirmed that the pragmatic paradigm is an appropriate and desirable research paradigm for construction management research. The pragmatic paradigm utilises the multi-dimensional methodology (combining both positivist and interpretivist paradigms) and allows the collection of data from both qualitative and quantitative sources in a single research study.

Based on the discussion above and the comparison of the four research paradigms in Table 4.1, the study employed a pragmatic mixed methods approach. Pragmatism is viewed here as a valuable dimension in the current research since it focuses more on the main problem and its practical solution, rather than deploying the specific designs and methods (Creswell, 2014). The pragmatic paradigm utilises all three approaches to improve the perception of the research problem and provide a comprehensive approach to the results and, therefore, more profound outcomes of the research project that are particularly relevant to studies of construction management.

4.4 RESEARCH APPROACH

Construction management research is a multidisciplinary field, which combines various knowledge in social science, natural science, engineering and management, such as technical, legal, political, environmental, financial, and human and non-human resources (Fellows and Liu, 2015, Dainty, 2008). Each research approach has its features, advantages and drawbacks and the adoption depends on how each approach relates to the nature of the research and experience of the researcher. Creswell and Creswell (2017) classified research approaches in the social sciences and management into three categories: qualitative, quantitative and mixed method.

4.4.1 Qualitative research approach

The qualitative research approach focuses on understanding human or social problems and its methods generate words and arguments information, rather than numerical data for analysis. The qualitative approach involves contextual questions, collecting data in small-sized samples, and general inductive content analysis. It aims to answer questions about the “how”, “why”, or “what” of a phenomenon instead of “how much” or “how many” (Myers, 2013). In qualitative evaluations, contexts, solutions, events, interactions and conditions cannot be replicated to any extent nor can generalisation be made with confidence to a broader context than that studied. The individuality, richness and subjective reality of a participant’s or participants’ understanding, and perspective

are not agreeable to the usual criteria of the conventional standard of reliability and validity (Rasinger, 2013). However, these do not make such understanding any less valid or real for that participant(s), and their explanatory purpose for a person's behaviour is extremely predictive. The qualitative approach relies on the interpretivism paradigm

In conducting qualitative research, the following common methods are used: grounded theory (inductively creating a theory describing a phenomenon) (Glaser and Strauss, 2017); phenomenology (describing individual experience of phenomena) (Cilesiz, 2011); narrative (describing an individual person's life) (Cortazzi, 2014); ethnography (describing cultural characteristics of a group of people over a period of time) (Fetterman, 2010); and case study (addressing research questions through in-depth analysis) (Yin, 2017).

The current research adopts the phenomenological approach where group experts' brainstorming (rapid idea generation) and linguistic questionnaire were conducted to verify the existence of disruptive events in South African highway construction and obtain more detailed knowledge on the probability and severity of disruptive events using qualitative scales, which could not be addressed by the quantitative methods (Creswell, 2009). Expert group interviews were done based on the pre-determined events and unit price and production rate based on the historical data, which helped to minimise/eliminate the bias.

Yin (2017) and Gerring (2006) described the case study approach as either an investigation of reality about a problem or exploratory inquiry of a problem. Gerring (2006) classified the case study forms into two groups: single-case and multiple-case study. Stake (2013) stated that the choice between these groups relies on the research aim, the availability of appropriate cases, and funds. However, the current study employed the single-case approach due to the nature of the case study (investigation of the reality of the estimation problem), scale of the case study, and in-depth analysis and availability of data. The results of the case study were cross-checked and validated with the actual data of the case study project and three other comparable projects.

4.4.2 Quantitative research approach

The quantitative research approach focuses on examining objective models by verifying the relation among the variables, which are usually measured by an instrument and analysed by numerical and statistical methods (Creswell and Creswell, 2017). The models are tested deductively, emphasising the protection in contradiction of bias and the generalisation and replication of findings. The quantitative approach relies on the positivist and post-positivist paradigms (Anderson et al., 2018). Creswell and Creswell (2017) classified the quantitative research approach into two types: experimental quantitative research (single subject experimental, quasi-experimental, or applied behavioural) and non-experimental quantitative research (typically, survey). The quantitative research approach provides the relationships between several study groups according to the cause and the recipient.

Lately, the quantitative research approach has been elaborated to incorporate more complex statistical and numerical techniques in data analysis, such as machine learning, logistic regression

and structural equation modelling (Creswell and Creswell, 2017). The main strength of the quantitative method is that it can yield statistical inference forms survey with predetermined scales (Anderson et al., 2018). Data collected and analysed quantitatively are very reliable and precise, and the findings obtained could be generalised to the entire population.

The current research employed a series of expert group estimations to estimate the variability in the unit cost and production rate of activities as well as determine the types and coefficient of potential correlation in the case study project. Moreover, the research utilised a closed-ended questionnaire to determine the probability and severity of disruptive events which fall into a non-experimental quantitative approach.

4.4.3 Mixed method research approach

The mixed method approach focuses on collecting both qualitative and quantitative data while using different methods and designs that may contain both paradigms and philosophical assumptions (Creswell, 2009). The fundamental assumption of the mixed method research approach is that the combination of both qualitative (positivist) and quantitative (interpretivist) approaches provide a thorough understanding of the research problem (Mertens, 2014). The mixed method approach relies on the pragmatism paradigm (Creswell, 2014), such as the increasing demand for cost-effective research and the quest to move away from theoretical research to research which meets practitioners' and policymakers' needs (Mertens, 2014).

According to Holt and Goulding (2014), there are four types of mixed method research: development (the results from one approach is used to develop or inform the other approach); initiation (the result from one approach is recast to questions or results from the other approach); complementary (combines the results of one approach with the results of the other approach); and expansion (in which a different approach is used to extend the range of research). Furthermore, Creswell (2014) classified mixed methods research approaches into nine types with different design intent and approach characteristics as summarised in Table 4.2.

As presented in Table 4.2, each mixed methods research approach differs in terms of its priority, which refers to the relative importance of the quantitative and qualitative components for addressing the purpose of the research. For example, the quantitative and qualitative components of the convergent parallel approach are both equally important, while the quantitative and qualitative components of other approaches are an unequal priority (one of the components has greater importance, while the other component has a lesser priority) (Creswell, 2014).

To collect and analyse data accurately this study adopted the sequential exploratory research approach. The sequential exploratory mixed method design is described as the procedure to collect and analyse qualitative and quantitative data at sequential timing by connecting from each phase to inform the later phases aimed at developing and evaluating a complex model (Holt and Goulding, 2014) adopted.

Table 4.2: Overview of the design intent and characteristics of the different mixed method research approaches

Mixed method approach	Design intent	Characteristics
Convergent parallel	To develop a complete and valid understanding	<ul style="list-style-type: none"> • Concurrent timing • Equal priority • Merging the quantitative results and qualitative findings during analysis and/or interpretation
Sequential explanatory	To explain the mechanisms or reasons behind quantitative results	<ul style="list-style-type: none"> • Sequential timing • Unequal priority • Connecting from the quantitative results to shape the qualitative data collection
Sequential exploratory	To test or generalise qualitative findings	<ul style="list-style-type: none"> • Sequential timing • Unequal priority • Connecting from the qualitative findings to form the quantitative data collection
Embedded experiment	To enhance a quantitative experimental study by including a secondary qualitative component to explore the procedures or process of the experiment	<ul style="list-style-type: none"> • Concurrent or sequential timing • Quantitative priority • Embedding a qualitative component into a quantitative experimental design
Embedded case study	To enhance a qualitative case study by including a secondary quantitative component to enrich the interpretation of the case study	<ul style="list-style-type: none"> • Concurrent or sequential timing • Qualitative priority • Embedding a quantitative component into a qualitative case study design
Concurrent conversion	To identify quantitative relationships among variables that include at least one variable that is a quantification of qualitative findings	<ul style="list-style-type: none"> • Concurrent timing • Quantitative priority • Converting qualitative findings into a new quantitative variable and analysing that new variable statistically with other quantitative data
Concurrent multilevel	To examine multiple levels (for example, students, teachers, principals, and districts)	<ul style="list-style-type: none"> • Concurrent timing • Equal or unequal priority • Merging the quantitative results and qualitative findings from each level during analysis and/or interpretation
Multiphase	To conduct a programme of studies aimed at achieving an overall objective, such as developing and evaluating a programme	<ul style="list-style-type: none"> • Concurrent and sequential timing • Varies for each study in the programme • Connecting from each study to inform the later steps of the programme development
Transformative	To conduct research that empowers individuals and advocates for social justice	<ul style="list-style-type: none"> • Concurrent or sequential timing • Equal or unequal priority • Embedding a mixed-methods design in a social justice framework, which shapes all the design decisions

Source: Adopted from Plano Clark and Creswell (2014)

4.4.4 Research approach adopted in this study

To provide background knowledge on selecting a suitable mixed method approach, the design and characteristics of different mixed method approaches were described in the previous sections. Selecting the most appropriate research approach is one of the important stages in the process of research, since the correct research approach provides the correct direction to solving the research

problem. However, the selection of the most proper research approach depends on the nature and elements of the research, such as the research problem, type of data required, and the analysis of the data (Creswell, 2014).

For the achievement of the aim of this research, which is to examine the sources of uncertainty in the construction process of infrastructure projects, the types of uncertainty sources considered during cost estimation, and whether there are key uncertainties in the process that impact on project cost and time, were pursued by quantitatively modelling uncertainties and determining the cumulative impact of different sources of uncertainty on infrastructure project cost and time.

Previous researchers in this field have used a mainly quantitative research approach (Anderson et al., 2009, Flyvbjerg, 2008, Flyvbjerg et al., 2002) or mixed method (sequential or concurrent) research approach (AASHTO, 2013, Molenaar, 2010). Having considered the abovementioned factors, the researcher determined that a mixed methods approach was most appropriate, as a combination of the strengths of both an interpretivist qualitative approach and a positivist quantitative approach, addresses the research objectives of the current research. Due to various analytical and inherent complexities involved in modelling the uncertainty, the study adopted a sequential exploratory mixed method approach that goes beyond the basic mixed method approaches through the combination of sequential and concurrent aspects.

The first phase of the study adopted a qualitative research approach, which is effective in identifying and explaining behavioural aspects of construction management research to determine the sources of uncertainty in infrastructure projects (Dainty, 2008). The second phase of the research contained three concurrent pieces of research. To evaluate the variability in different activities, evaluate the correlation between the cost/time of different activities and to identify the disruptive events, verify the existence of the disruptive events in South Africa, and assess the impact of disruptive events the positivist quantitative research approach was used. Phases three and four of the study adopted a positivist quantitative research approach to determine the cumulative impact of different sources of uncertainty in infrastructure projects and test and validate the developed model. Figure 4.2 depicts the sequential exploratory mixed methods research approach employed in this study.

Utilising a sequential exploratory mixed method research approach represents a significant improvement from the basic mixed method approaches employed in previous studies (AASHTO, 2013, Molenaar, 2010, Moret and Einstein, 2016). This makes the designed research approach used in the current study one of the significant contributions of the study to the body of knowledge of modelling cost and time in the field of construction management.

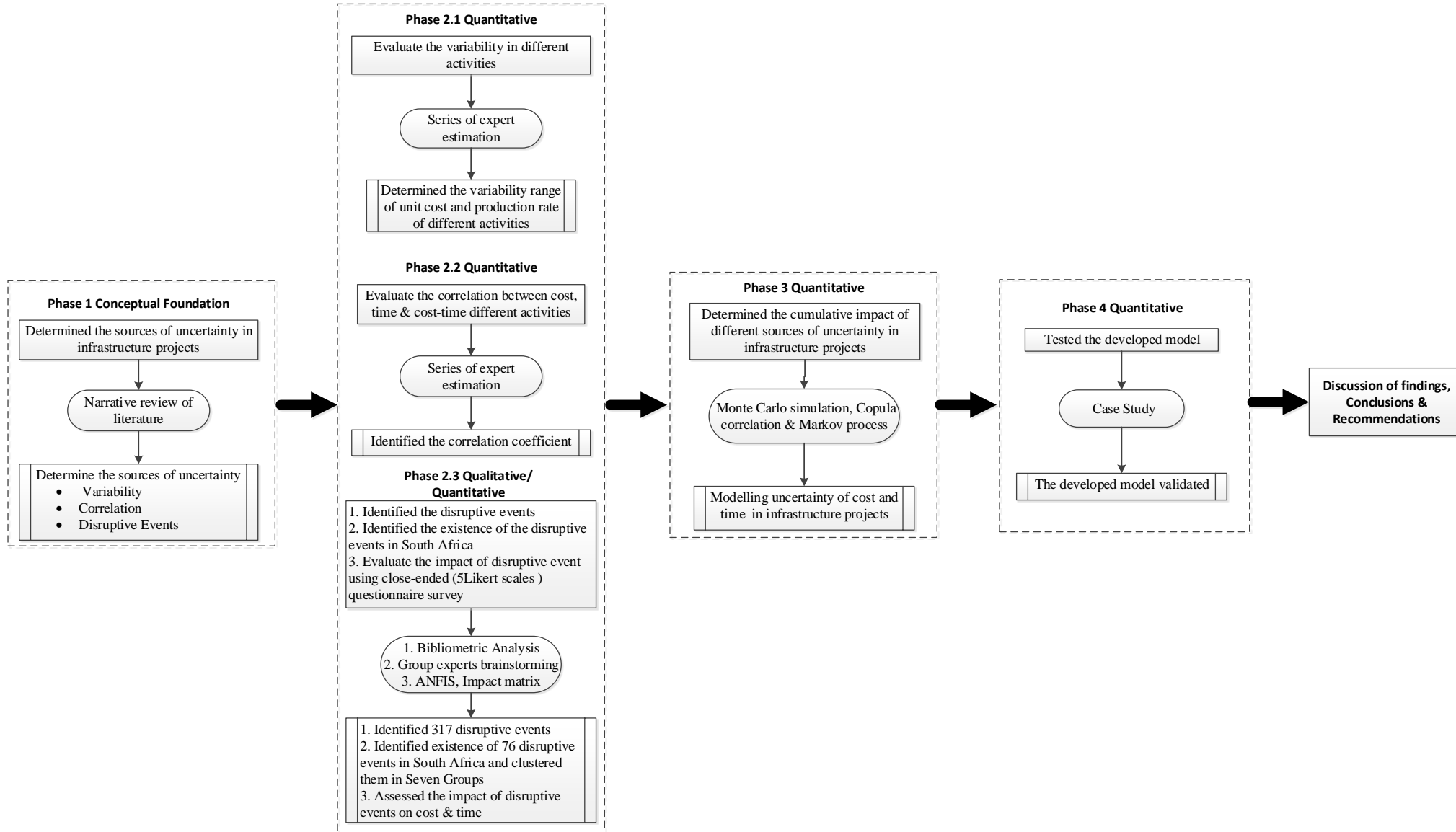


Figure 4.2: Sequential exploratory mixed method research approach design for the study

4.5 STUDY POPULATION

The study population for the qualitative strand in Phase 2.3 comprises the professional highway construction managers with a minimum of 20 years' experience in the construction of highway projects in South Africa. To determine the population for the study, the total number of highway construction projects under construction in 2017 was obtained from the South African National Road Agency Ltd (SANRAL). According to SANRAL, in 2017, there were 37 highway construction projects under construction in South Africa. However, five highway construction managers of these projects did not meet the general conditions of the research survey (either with less than 20 years' experience in construction of highway projects in South Africa or not registered as a professional engineer).

4.6 SAMPLING TECHNIQUE AND SAMPLE SIZE

Due to the small size of the study population (32 professional highway construction managers with more than 20 years' experience), a census survey was employed to gather data. Census is a systematic survey method that collects the data from the entire population of the study with a sampling error of zero (Creswell and Creswell, 2017). A census eliminates sampling error and provides data of all the individuals in the small population. Therefore, all 32 highway construction managers were invited to participate in the study. To analyse the questionnaire, the need for a large population is well acknowledged. However, Central Limit Theorem (CLT) considered a population size with 30 observations as adequate for non-parametric analysis (Ritchie et al., 2013); the 32 respondents for this study were thus considered adequate.

The expert panel used in the series of experts' estimation Phases 2.1 and 2.2 and expert brainstorming in Phase 2.3 included five highway experts working as highway consultants and estimators in South Africa with a minimum of 20 years' experience in highway estimation.

The panel of earthwork experts included a highly qualified expert in the field of earthwork with more than 30 years of experience in earthwork and two experts in highway cost and time estimation. The panel of bridge experts comprised an expert in the field of constructing highway bridges with 32 years of experience and two experts in the field of highway estimation. The pavement panel experts included an expert in the field of pavement with more than 35 years of experience and two other experts in the field of estimation of highway projects with 25 years of experience.

4.7 UNIT OF ANALYSIS

The study implements and tests the developed uncertainty model on the construction of a highway as a case study for which archival data of cost and construction durations should be most suitable. According to Ritchie et al. (2013), the unit of analysis refers to the phenomenon being investigated, and the data are collected and analysed.

The three research variables for this study were the variability of construction cost and duration of highway construction projects in Phase 2.1, the correlation between the construction activities' costs/times and cost-time in Phase 2.2 and probability and severity of uncertainty events in the highway construction projects in Phase 2.3. This information was retrieved from archives and directory from the professional highway construction managers who participated in the study.

The participants of the expert estimation in Phases 2.1 and 2.2 and group expert brainstorming in Phase 2.3 were the highway experts with over 30 years' experience in their respective fields. An expert is described as a very skilful person who underwent extensive training and is very knowledgeable in a specific field. From expert knowledge, expert opinion can be deduced in the process of expert estimation. The expert opinion is the formal judgment of the expert on a matter that requires advice (Ayyub, 2001). The research constructs evaluated within the unit of analysis were the probability distributions of unit cost and production rate of activities, correlations between the costs/times and cost-time of every 100 linear metres for earthwork and pavement structures, and the bridge structure activities repeated over 16.5 kilometres of the case study project.

According to Holt and Goulding (2014), unit of analysis in qualitative research comprise of selected cases the data of which are expected to provide answers to the research problem. In Phase 2.3, the units of analysis for questionnaire survey were the probability of occurrence and severity of 76 uncertainty events existing in the construction of a highway in South Africa which is clustered in seven major groups by the experts' panel, using rapid idea generation and mind mapping techniques. The group experts' brainstorming map is illustrated in Figure 4.3.

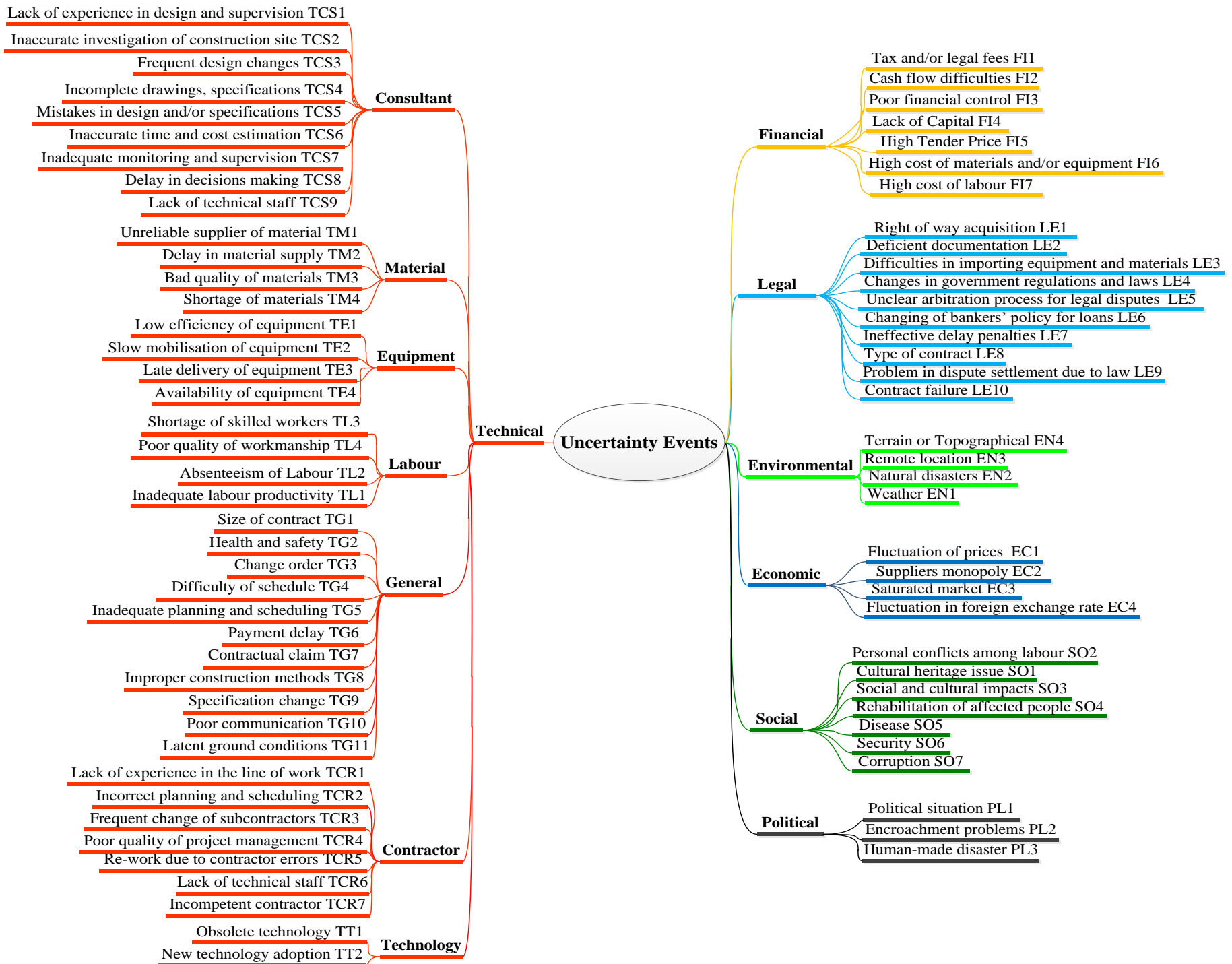


Figure 4.3: Disruptive events in South African highway construction

4.8 METHOD OF DATA COLLECTION

Data collection is a process of collecting information from relevant and reliable sources to answer the research problem, test the research hypothesis and evaluate the research outcomes (Creswell, 2014b). Various methods and techniques have been used in the process of collecting data in the study to increase the reliability of collected data.

4.8.1 Questionnaire

To guarantee that all study populations were able to complete the questionnaire survey, different methods of delivery and completion, such as self-administered questionnaire, telephone calls and emails to the targeted respondents, were used as methods of data collection. Earlier studies (Odediran, 2016, Israel, 2011) established that online questionnaire surveys' response rates are low; therefore, the study focused on delivery by presumed email, self-administration, and telephone calls to collect the responses from the targeted respondents. The personal follow up, email reminders and telephone calls to participate helped completed questionnaire collection with a 100% response rate.

The designed questionnaire contains two parts: Part 1. Introductory Information and Part 2. Technical Information

- In part 1, The general information of participants was collected through some introductory questions such as age, education, profession, position, and experience of respondents related to the construction of highway projects.
- In Part2, participants assessed the probability of occurrence and severity of different uncertainty events on the construction cost and time of the respondents past three projects.

4.8.2 Experts' estimation

The expert's estimation is a specific type of expert-opinion technique which assumes that some people have more knowledge than others about a certain topic; and if this knowledge is collected from a group of experts, the results will exceed the outcomes obtained from one expert (Porter et al., 2011). Expert's estimation can provide technical, economic, social and environmental perspectives that could be difficult to collect by other standard instruments.

The expert's estimation method is used when historical data are not available or insufficient. Since there is no reliable database on the costs and the duration of construction projects in South Africa, the study considered the expert estimation as the primary source of data collection for modelling the variability of cost and time of activities and correlation between costs/times and cost-time (Phase 2.1 and Phase 2.2).

The process of collecting data in experts' estimation (variability and correlation) consisted of three sessions: feasibility check, panel estimation, and validation. In the first session, each group of experts was asked to read and familiarise themselves with the estimation protocols and if they agreed to participate in the expert estimation process. In the second session, after calibration of the experts was conducted, the three panels estimated their particular structure, while the researcher

was available for any further explanations or responding to the experts' questions. In the third session, each expert panel's estimated values were clarified, and their result validated against the three comparable projects.

4.8.2.1 Panel estimation of variability

The panel estimations of the cost and time variability were obtained by means of two estimation sessions with the panel of experts. In the first session, the experts estimated the lower, most likely and higher unit cost and production rate of each construction activity of three main structures of the case study in different geological conditions. In the second session, their estimation was cross-checked with some historical data to minimise the error and improve the accuracy of estimation.

4.8.2.2 Panel estimation of correlation

The panel estimation of the correlations between the costs and times of activities were obtained from three estimation sessions. In the first session, the panel of experts were agreed on the common estimation conditions and general assumptions to estimate probabilistic correlation distribution accurately. In the second session, the experts determined the potential types of correlation in the construction of highway projects and estimated the correlation coefficient of identified types of correlation. In the third session, their estimated correlation coefficient was calibrated with some historical data.

4.8.3 Group experts' brainstorming

To verify the existence of disruptive events in South African highway construction from the list of identified events from the bibliometrics technique, rapid idea generation was integrated to the mind mapping technique. The brainstorming was conducted in two successive sessions. At the beginning of the first session, the experts had 10 minutes to read and familiarise themselves with the list of identified disruptive events. Subsequently, the rapid idea generation technique was employed to verify the existence of disruptive events in South African construction highway from the 317 identified events. In the second session, the panel experts clustered the verified events into the seven major groups of economic, environmental, financial, legal, political, social and technical, using the mind mapping technique. Lastly, the panel of experts reviewed the developed map and justified some events using the content analysis technique. By using this technique, overlapping events were either combined or eliminated, and 76 disruptive events affecting South African highway construction projects were identified.

4.9 METHODS OF DATA ANALYSIS

This study adopted the mixed method research approach in which both qualitative and quantitative data were collected. Therefore, several techniques were employed to analyse and evaluate the collected data so as to improve the reliability and validity of the research results.

4.9.1 Qualitative data analysis

Qualitative analysis is the range of processes which transform the obtained qualitative data into the form of understanding, explaining and interpretation. The study employed mind mapping to identify and classify the existence of disruptive events in South African infrastructure projects based on the panels of experts' opinions. Mind mapping is a visual form of note and link that depicts an overview of a concept and its complex information. A mind map is a graphical representation of hierarchical information around a central idea surrounded by branches of associated factors. Mind mapping engages both the analytical and artistic faculties of a participant's brain (Miles et al., 2014).

In this study, the process of mind mapping involved placing each disruptive event in South African infrastructure projects as a central concept and arranging and grouping identified events from literature around the central idea. To identify the existence of the disruptive events in South African infrastructure projects, the rapid idea generation techniques were employed. The rapid idea generation helped the panel of experts to evaluate the concept and examine each identified event from different perspectives. The mind map of the panel of experts is presented in Figure 4.3.

4.9.2 Quantitative data analysis

The study employed both descriptive and inferential statistical techniques to analyse the quantitative data collected. The descriptive statistics employed were percentiles, bibliometrics, probability distribution (lognormal and triangular), while the inferential statistics included the Chi-square test, Wilcoxon signed rank test and stepwise regression analysis (SRA). The statistical analyses were achieved using Statistical Packages for the Social Sciences (SPSS) software and MATLAB. To quantify the uncertainty in the construction of infrastructure projects, the probability distributions, Copula analysis, Monte Carlo simulation and Markov process were employed using MATLAB. A construction model of the highway project was also developed to understand the construction process of highway projects and assess the different sources of uncertainty at the level of activity of the construction model. This was done with the model a case study of the research and to validate the uncertainty portfolio concept presented in Chapter Three.

4.9.2.1 Construction model of the highway infrastructure project

The research developed a construction model to understand the process of construction of the case study (highway project) before quantifying the different sources of uncertainty on the cost and time of single construction activity. Construction of a highway contains three major structures: earthworks, bridges, and pavements. To model the construction of the highway, it is essential to analyse the construction processes of the project at the level of the single activities of each highway structure.

Three activity networks representing the specific construction processes of three main structures of the highway project were developed, which further assisted the estimation of the cost and time of the structures. The activity networks contained sub-networks that were repeated several times during the construction of the structures. Hence, the interconnection of the sub-networks models

of a structure and the interconnection of the three structure networks model the construction of the highway project. The mapping of the construction process of a project with activity networks boosts the understanding of the construction process of the highway, and it is the beginning stage to modelling the different sources of uncertainty.

Construction cost and time

To assess the uncertainty it was necessary to understand and evaluate these dependencies’ (different parameters such as the construction methods and the sequential, parallel and repeated activities in the construction process) relation and its impact on the cost and the time of highway construction. The construction of the highway was modelled as a sequence of the three main structures of highway construction: earthwork, bridge, and pavement structures. The construction model analysed every single activity and sub-activity in the construction processes of the three highway structures. Activity networks were developed in the highway construction model to represent the particular construction process and calculate the construction cost and time of the highway project.

Every structure was modelled as a sequence of activities, which are characterised by cost and time equations. Figure 4.4 shows the hierarchy of structures.

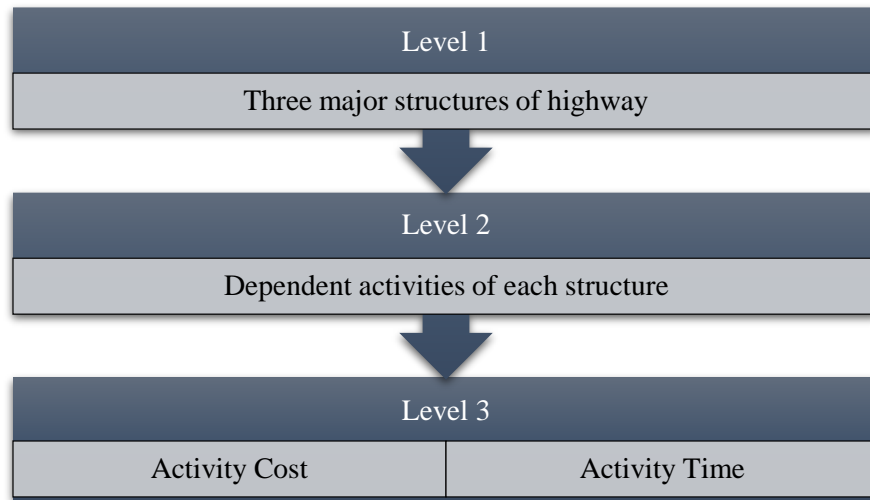


Figure 4.4: Structure hierarchy of a highway project

Assuming the construction of highway projects is unit cost based, the total construction cost of a highway project is estimated by the sum of the costs of the three major structures as shown in equation 4.1.

$$Highway\ project\ cost = \sum_{e=1}^n Cost_{earthwork} + \sum_{b=1}^n Cost_{bridge} + \sum_{p=1}^n Cost_{pavement} \quad [4.1]$$

Total time of a highway project is not equal to the sum of all activities' time because some activities are performed in parallel. The total construction time of a highway project is given by the sum of the critical activities which are located on the longest path:

$$\text{Highway project time} = \sum_{i=1}^n \text{Time}_{critical} \quad [4.2]$$

Activity network

An activity network is a diagram that models the sequential relationships of activities in the complex construction comprising many sub-activities. An activity network was used to model the construction of the three structures of the highway project. It was modelled with arrows showing the connection between nodes. They connect in series and parallel. In the series connection, an activity must wait for the preceding activity to be completed before being started, while, in the parallel connection, activities are started simultaneously, as illustrated in Figures 4.5 and 4.6.

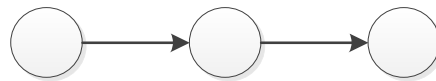


Figure 4.5: Series activities

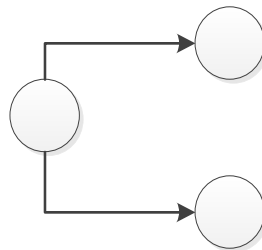
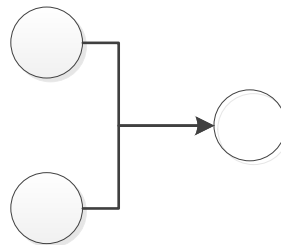


Figure 4.6: Parallel activities

Nodes differentiate into OR and AND nodes depending on the starting of the activity following the node. The OR node activates starting the following activity immediately as any of the preceding activities are completed, while the AND node must wait for all preceding activities to be completed before starting the following activity. The OR nodes model sequences activities while the AND nodes model parallels activities, as shown in Figures 4.7 and 4.8.



○ *OR node*

Figure 4.7: OR node activity



Figure 4.8: AND node activity

Dummy activities are used when AND and OR nodes are not adequate to model the logical relationship between activities in the process. Dummy activities are created for the sole purpose of demonstrating a specific relationship; they do not strictly contribute to the process of the project. Figure 4.9 illustrates an example of a dummy activity. The third activities at the bottom path depend on the first and the second activities of the top path. This is modelled with a dummy activity connecting the end of the activities in the top path to the start of the activities in the bottom path.

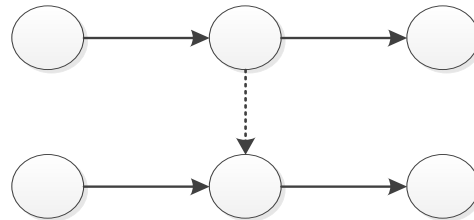


Figure 4.9: Dummy Activity

Modelling earthwork structure

The earthwork structure was modelled with two constructions: cutting (excavation) and filling (embankment). The construction of a cut was modelled as a sequence of the three following activities: clearing the topsoil, excavation, and improving the area and stabilising the trench as illustrated in the cross-section of cut activity in Figure 4.10.

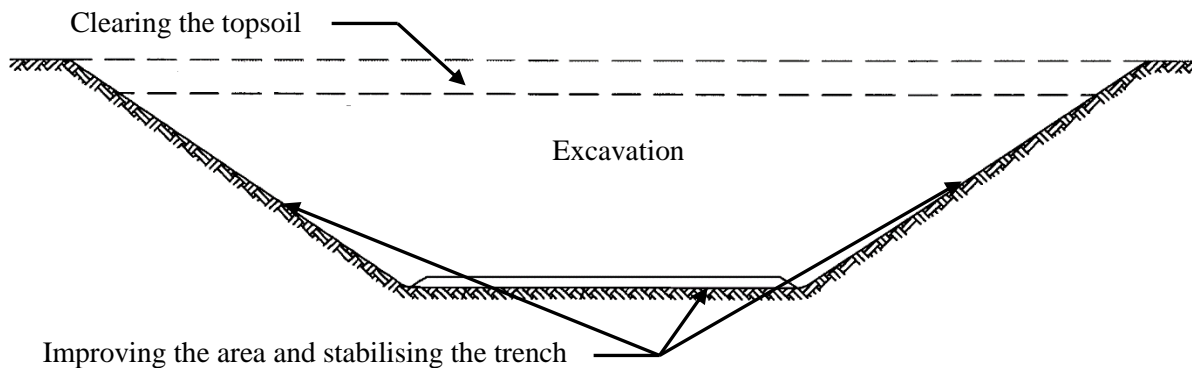


Figure 4.10: Cross section of cutting activity

Similarly, the construction of a filling was modelled as a sequence of the three following activities: clearing the topsoil, improving the area, and embankment as shown in the cross-section of filling in Figure 4.11.

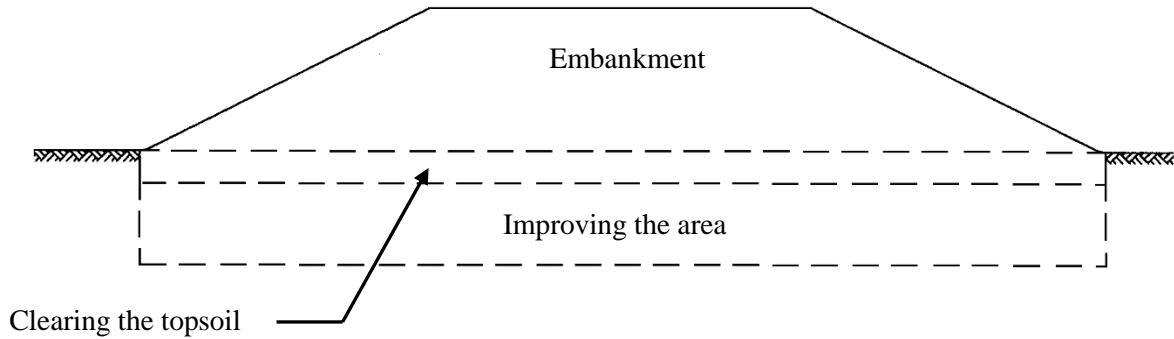


Figure 4.11: Cross section of the filling activity

The construction of a cut is started from either end or both ends of the cut segment, and is advanced sequentially, possibly in parallel layers at different depths as illustrated in Figure 4.12.

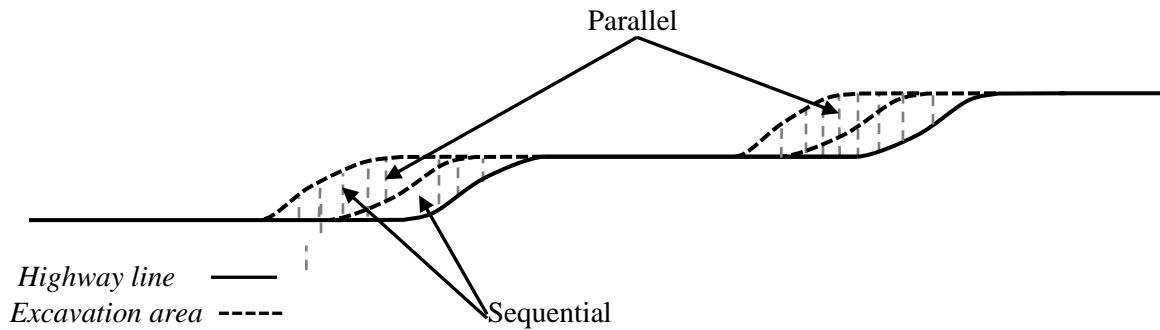


Figure 4.12: Sequential and parallel excavation in the construction of a cut

The construction of filling is started from any point, and also advances sequentially, possibly in parallel layers at different heights as illustrated in Figure 4.13.

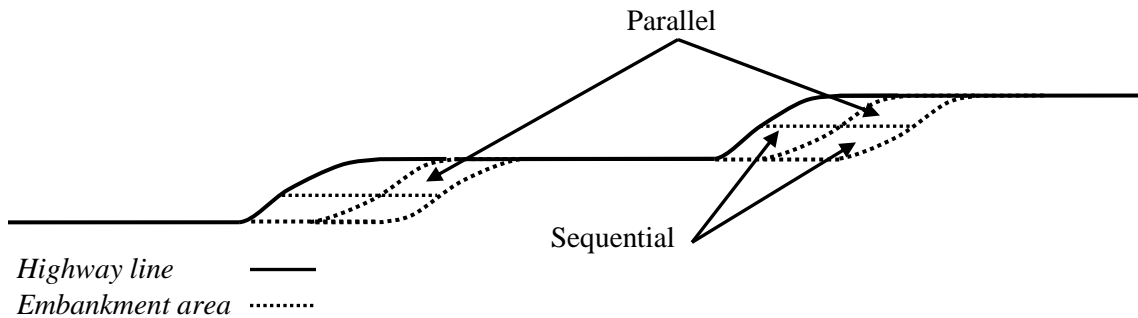


Figure 4.13: Sequential and parallel embankment in the construction of filling

Depending on site access and equipment used, fillings are constructed sequentially not only longitudinally, but also laterally as shown in Figure 4.14.

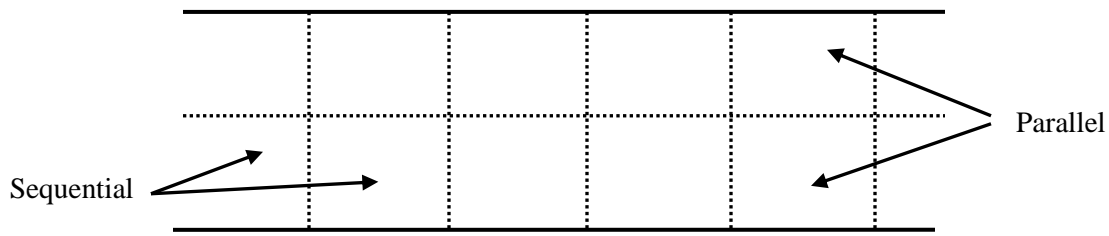
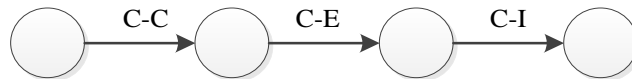


Figure 4.14: Lateral sequential and parallel embankment in the construction of filling

The activity network of cutting was modelled with a sequence of three activities in a construction (see Figure 4. 15).



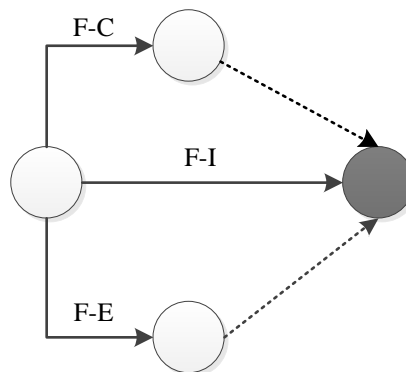
C-C: Clearing the topsoil

C-E: Excavation

C-I: Improving the area and stabilising the trench

Figure 4.15: Activity network of cutting construction

The activity network of fillings was modelled with the parallel of three activities in filling construction (see Figure 4.16).



F-C: Clearing the topsoil

F-I: Improving the area

F-E: Embankment

Figure 4.16: Activity network of filling construction

The construction cost and time of cutting were dependent on the geological condition of excavation. Based on the class of soil, the geology was classified into four groups namely, fine (silt and clay), soft (sand and gravel), hard (cobble and boulders) and rock. Differently, the construction of filling was characterised by recycling the good materials from excavation in the

cuttings, which was reused in the fillings. Thus, only one cost and time were considered for filling activities.

The cost and time of the different activities in earthwork structures were characterised by quantifying of each activity in each construction as a function of the unit cost, the production rate and the volume, as formulated in Equations 4.3 and 4.4.

$$\text{Activity cost} = \text{cost per unit volume of activity} \times \text{volume of activity} \quad [4.3]$$

$$\text{Activity time} = \frac{\text{volume of the activity}}{\text{production rate of activity}} \quad [4.4]$$

The total cost of cutting and filling constructions was given by the sum of all the activities costs in the cutting and filling construction according to Equations 4.5 and 4.6.

$$\begin{aligned} \text{Cutting cost} &= \sum_{i=1}^n \text{clearing the topsoil}_i \\ &+ \sum_{i=1}^n \text{excavation}_i \\ &+ \sum_{i=1}^n \text{improving the area and stabilising the trench}_i \end{aligned} \quad [4.5]$$

$$\begin{aligned} \text{Cutting cost} &= \sum_{i=1}^n \text{clearing the topsoil}_i \\ &+ \sum_{i=1}^n \text{improving the area}_i + \sum_{i=1}^n \text{embankment}_i \end{aligned} \quad [4.6]$$

The total time of cutting and filling constructions was given by the sum of the times of all the critical activities (located on the critical path) in the cut and fill construction work according to Equations 4.7 and 4.8.

$$\begin{aligned} \text{Cutting time} &= \sum_{i=1}^n \text{clearing the topsoil}_i \\ &+ \sum_{i=1}^n \text{excavation}_i \\ &+ \sum_{i=1}^n \text{improving the area and stabilising the trench}_i \end{aligned} \quad [4.7]$$

$$\text{Filling time} = \sum_{i=1}^n \text{improving the area}_i \quad [4.8]$$

The sub-networks activities of cuttings and fillings were combined in an activity network of the project with the following conditions:

- The segment i of construction (cutting or filling) was constructed before the segment $i+1$: in a sequence of two cuttings and fillings (see Figure 4.18).
- The activities within a cutting structure were modelled with a series of sub-networks, while the activities in filling structures were modelled with parallel sub-networks and dummy activities, connecting the end of the preceding filling activity with the start of the following activity.
- The cutting and filling sub-networks were repeated as many times as the number of cuttings and fillings in the earthwork structure.

For clarity, the construction of two cuttings and two fillings between 2 culverts was modelled jointly in one activity network as shown in Figure 4.18.

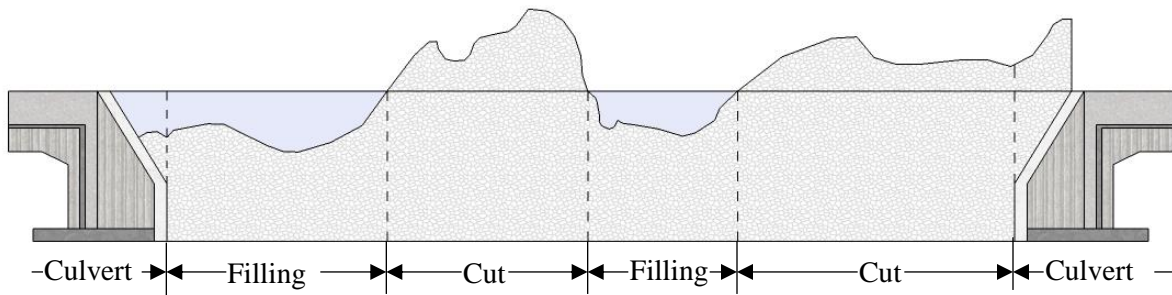


Figure 4.17: Sequence of two cuttings and two fillings between two culverts

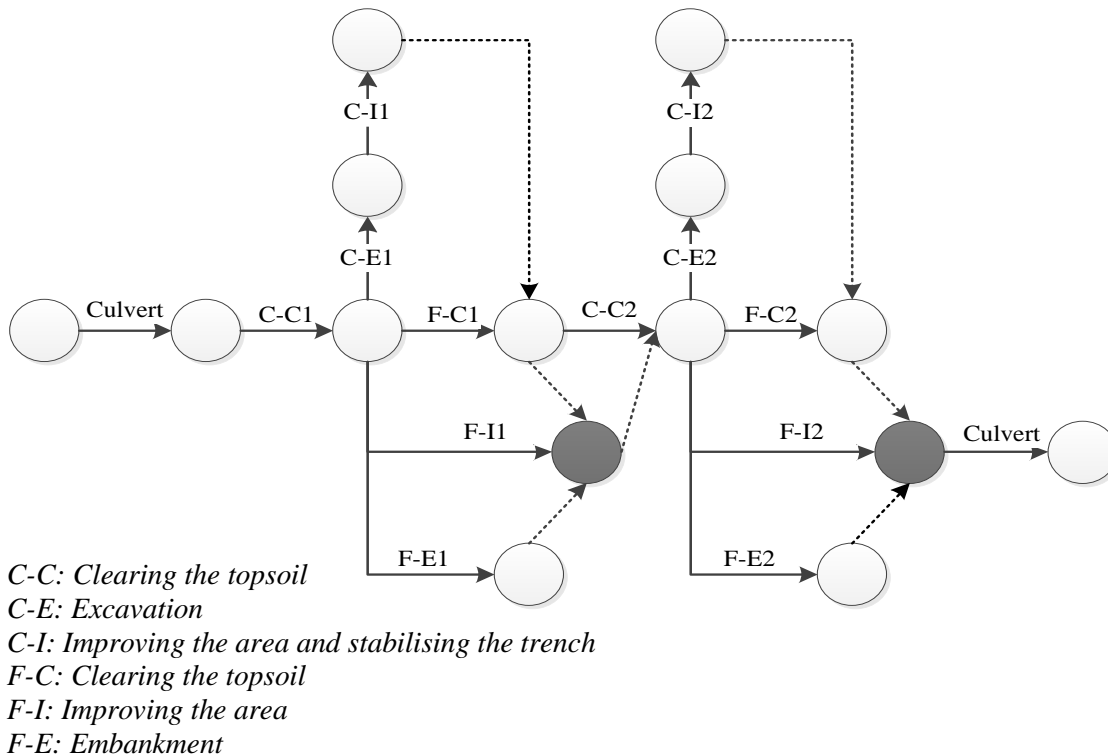


Figure 4.18: Activity network of two cuttings construction and two fillings construction

Modelling bridge structure

The construction of a bridge was modelled with an activity network, which depends on the construction method of two most common bridge components used in highway projects, namely the box culvert and the slab bridge, and their activity networks include the cost and time equations of the activities as previously discussed.

Box culvert

The construction of a box culvert bridge was modelled with a combination of the following six activities: set up the site, culvert bedding, set up the precast culvert, the footing of wing wall, wing wall, and backfilling. Elements of a box culvert are illustrated in Figure 4.19.

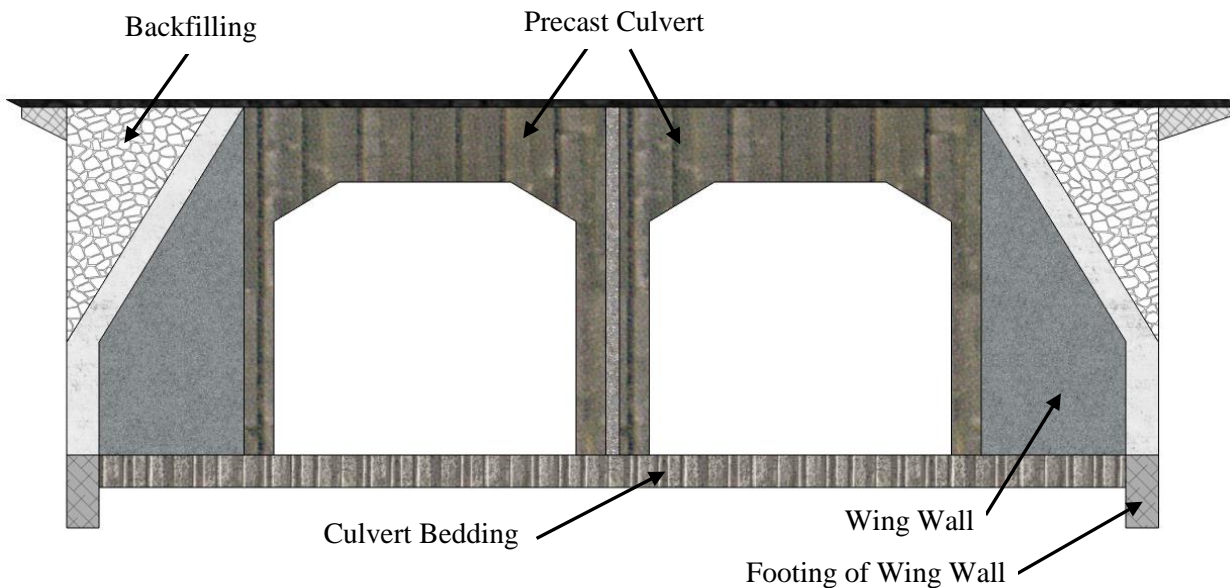


Figure 4.19: Elements of box culvert

In the box culvert method (Figure 4.19) the construction was started with the setup of the site. Then the culvert bedding and footing of the wing wall were constructed, followed by the wing wall and the setup of the precast culvert. The final activity was backfilling the backs of the wing walls. The culvert activity network is presented in Figure 4.20.

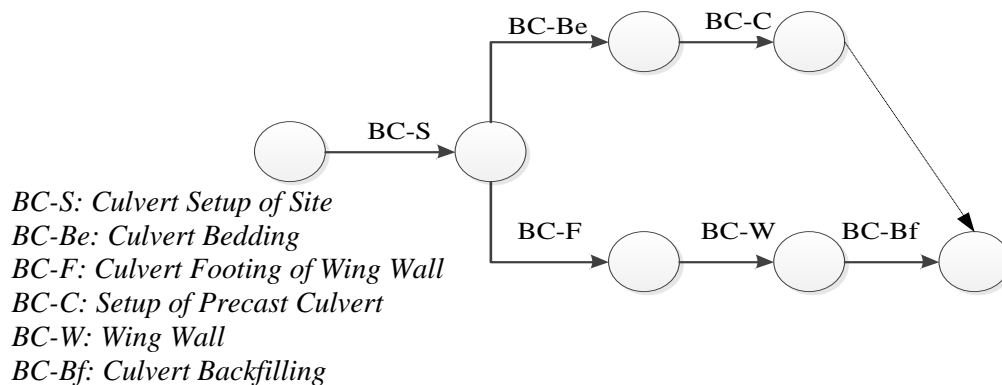


Figure 4.20: Activity network of a box culvert

Slab bridge

There are two main types of slab bridge: single span bridge, and multispan slab bridge with pier. The construction of the single span slab bridge was modelled with a combination of seven activities: set up the site, footing of the abutment, abutment, the footing of the wing wall, wing wall, set up the precast deck and backfilling (See Figure 4.21).

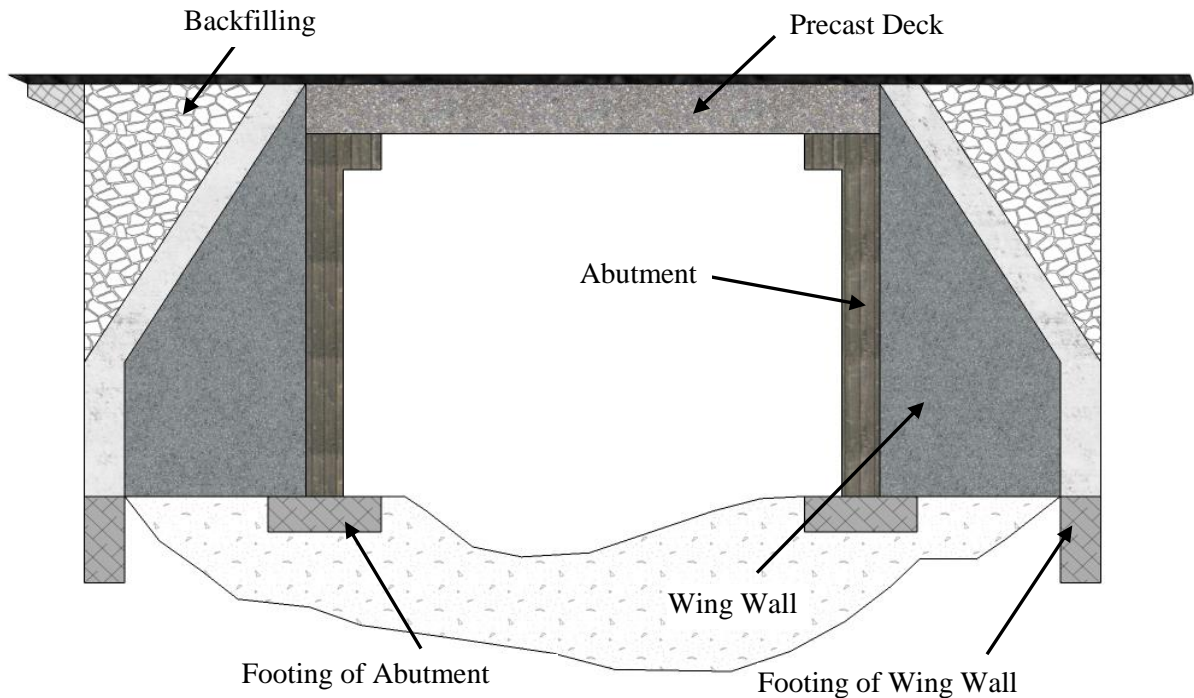
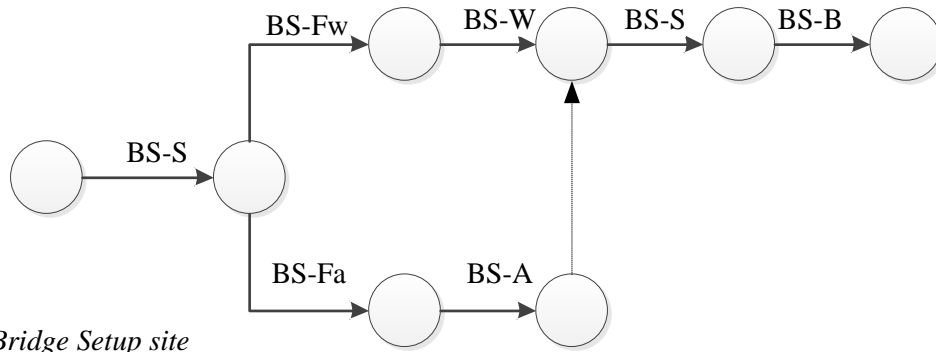


Figure 4.21: Elements of a single span slab bridge

In the single span slab bridge construction, the construction was started with setup of the site. Then the footing of the wing wall and abutment were constructed, followed by construction of abutment and wing wall. The deck section was constructed by attaching and post-tensioning precast concrete elements to the abutments, and finally, backfilling. The activity network of a single span slab bridge is shown in Figure 4.22.

The construction of a multispan slab bridge was modelled with a combination of the following nine activities: set up the site, construct the footing of the abutment, construct the abutment, the footing of the pier, the pier, the footing of the wing wall, construct the wing wall, set up the precast deck, and complete backfilling (See Figure 4.23).



BS-S: Slab Bridge Setup site
BS-Fa: Slab Bridge Footing of the abutment
BS-Fw: Slab Bridge Footing of Wing Wall
BS-A: Slab Bridge Abutment
BS-W: Slab Bridge Wing wall
BS-S: Slab Bridge Slab
BS-B: Slab Bridge Backfilling

Figure 4.22: Activity network of a single span slab bridge

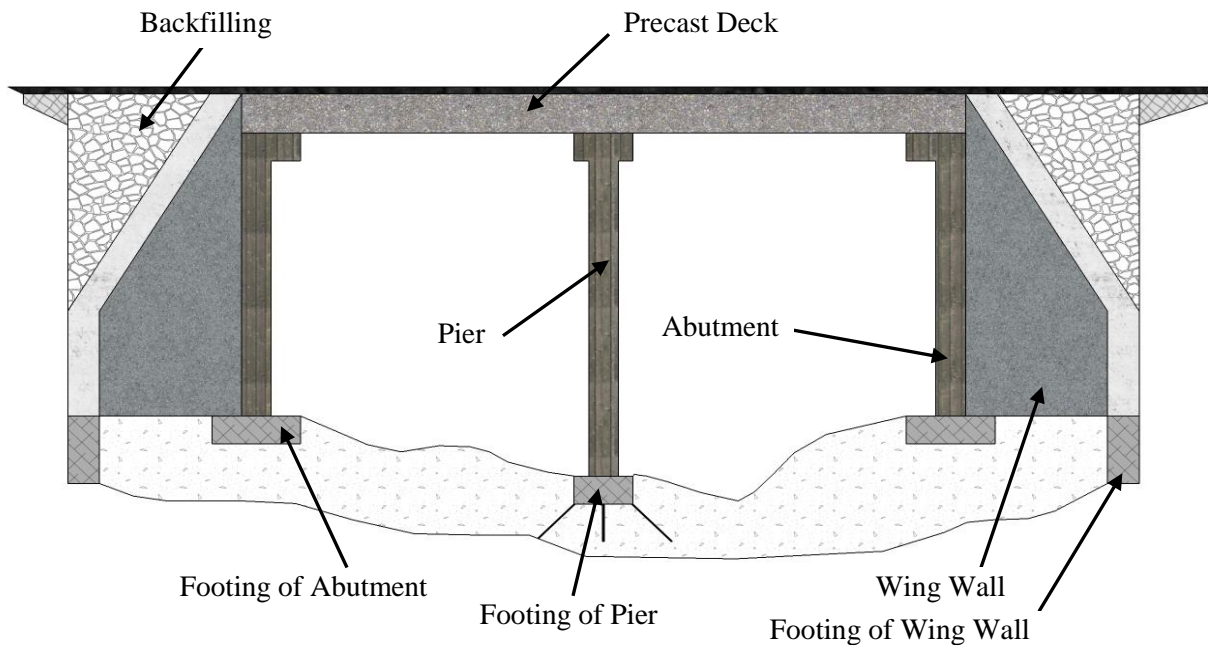
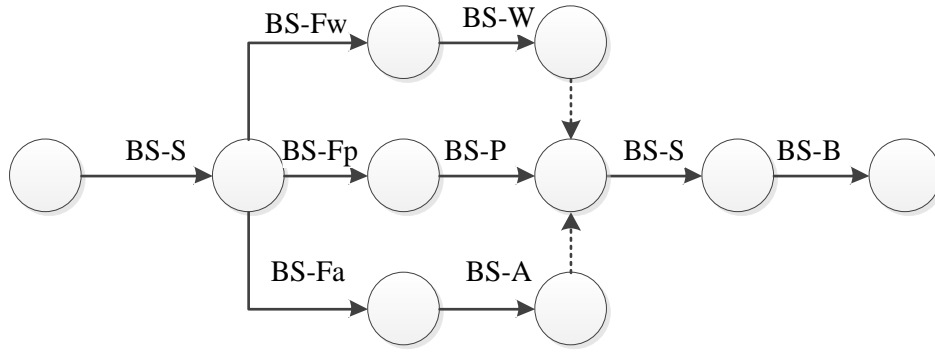


Figure 4.23: Elements of a multispan slab bridge

In the multispan slab bridge, the construction was started with a setup of the site, then construction of the footing of the pile, footing of the wing wall and footing of the abutment, followed by construction of the pier, abutment and wing wall. The deck section was constructed by attaching and post-tensioning precast concrete elements on both sides of the pier and followed by backfilling. The activity network of a multispan slab bridge is illustrated in Figure 4.24.



- BS-S: Slab Bridge Setup of Site*
- BS-Fa: Slab Bridge Footing of the Abutment*
- BS-Fw: Slab Bridge Footing of the Wing Wall*
- BS-Fp: Slab Bridge Footing of the Pier*
- BS-A: Slab Bridge Abutment*
- BS-W: Slab Bridge Wing Wall*
- BS-P: Slab Bridge Pier*
- BS-S: Slab Bridge Slab*
- BS-B: Slab Bridge Backfilling*

Figure 4.24: Activity network of a multispan slab bridge

The construction models presented here modelled the box culvert and slab bridges construction at the activity level. The construction cost and time of both bridges are dependent on the geological condition of the site and geometric parameters of the bridge. Therefore, the construction of each element was modelled with one activity, which was characterised by cost and time equations. The cost and time of different types of bridge construction are quantified by the cost and the time of each bridge activity. The cost and time of bridge construction were mathematically modelled, as shown in Equations 4.9 and 4.10.

$$Bridge\ cost = \sum_{i=1}^n activity\ cost_i \quad [4.9]$$

$$Bridge\ time = \sum_{i=1}^n critical\ activity\ time_i \quad [4.10]$$

For instance, the cost and time of a box culvert were calculated using equations 4.11 and 4.12.

$$Culvert\ cost = \sum \begin{matrix} setup\ site + bedding + footing\ of\ wing\ wall + wing\ wall \\ + backfilling \end{matrix} \quad [4.11]$$

$$Culvert\ time = \sum \begin{matrix} setup\ site + footing\ of\ wing\ wall + wing\ wall \\ + backfilling \end{matrix} \quad [4.12]$$

The cost and time of a single span slab bridge and a multispan slab bridge are estimated from Equations 4.13-4.14 and Equations 4.15-4.16, respectively.

$$\begin{aligned}
 & \textit{Single span slab bridge cost} \\
 & = \sum \textit{setup site} + \textit{footing of wing wall} + \textit{fotting of abutment} \\
 & \quad + \textit{wing wall} + \textit{abutments} + \textit{precast deck} + \textit{backfilling}
 \end{aligned}
 \tag{4.13}$$

$$\begin{aligned}
 & \textit{Single span slab bridge time} \\
 & = \sum \textit{setup site} + \textit{footing of wing wall} + \textit{wing wall} \\
 & \quad + \textit{precast deck} + \textit{backfilling}
 \end{aligned}
 \tag{4.14}$$

$$\begin{aligned}
 & \textit{Multispan slab bridge cost} \\
 & = \sum \textit{setup site} + \textit{footing of wing wall} \\
 & \quad + \textit{fotting of abutment} + \textit{footing of pier} + \textit{wing wall} \\
 & \quad + \textit{abutments} + \textit{pier} + \textit{precast deck} + \textit{backfilling}
 \end{aligned}
 \tag{4.15}$$

$$\begin{aligned}
 & \textit{Multispan slab bridge time} \\
 & = \sum \textit{setup site} + \textit{footing of pier} + \textit{pier} + \textit{precast deck} \\
 & \quad + \textit{backfilling}
 \end{aligned}
 \tag{4.16}$$

Modelling pavement structure

The pavement structure was modelled as a sequence of the four following layers: Subgrade, Subbase, Base, and Surface as shown in the cross-section in Figure 4.25.

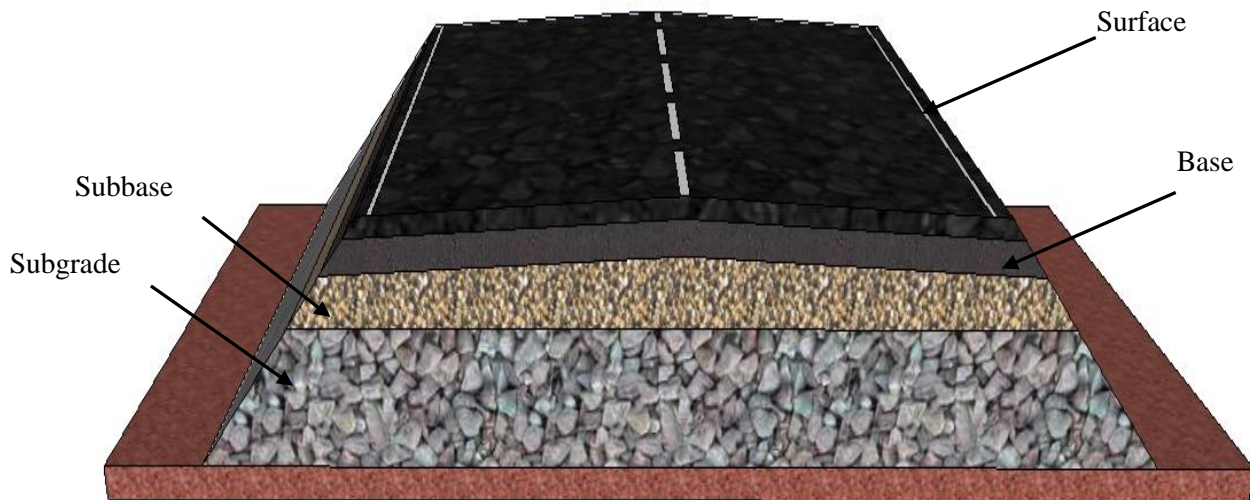


Figure 4.25: Cross section of the pavement structure

The construction of pavement is started from either end or both ends of each segment and is advanced sequentially, possibly in parallel layers at different segments as illustrated in Figure 4.26.

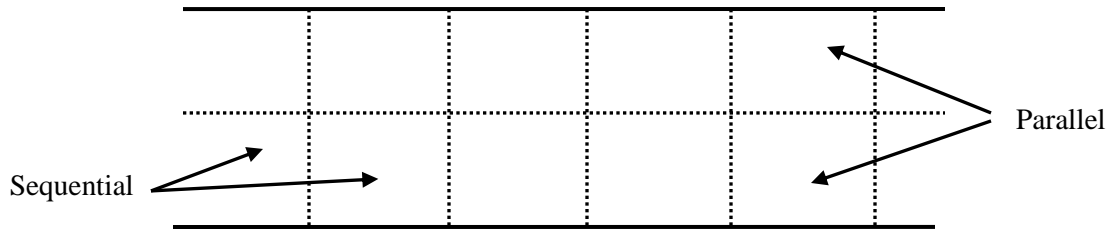
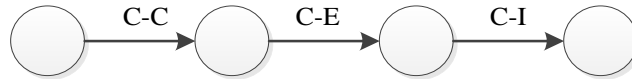


Figure 4.26: Sequential and parallel layers in the pavement structure

The activity network of pavement was modelled with a sequence of the four activities in pavement structure (See Figure 4.27).



C-C: Clearing the topsoil

C-E: Excavation

C-I: Improving the area and stabilising the trench

Figure 4.27: Activity network of the pavement structure

Similarly, to the fill construction, all constructions of pavement structure are independent of the geological condition of the site due to work prior to the pavement (earthwork or bridge). Therefore, only one-unit cost and production rate were considered for each pavement activity.

The cost and time of the paving structure were characterised by quantifying the cost and time of each layer as a function of the unit cost, the production rate, and the volume. The total cost of the pavement structure was given by the sum of costs of all the four activities in the pavement structure according to Equation 4.17.

$$Pavement\ cost = \sum_{i=1}^n subgrade_i + \sum_{i=1}^n subbase_i + \sum_{i=1}^n base_i + \sum_{i=1}^n surface_i \quad [4.17]$$

Similarly, to the total cost of pavement structure, the time of pavement structure was also given by the sum of the all the four activity times (linear structure) in the pavement structure according to Equation 4.18.

$$Pavement\ time = \sum_{i=1}^n subgrade_i + \sum_{i=1}^n subbase_i + \sum_{i=1}^n base_i + \sum_{i=1}^n surface_i \quad [4.18]$$

4.9.2.2 Bibliometrics

Bibliometrics is a quantitative method to examine the knowledge structure and development of research fields based on analysis of related publications using statistical methods, such as frequency of repetition in different literature; in other words, the use of publication trends to identify technology trends (Borgatti et al., 2018). In this study, bibliometrics was employed to determine the disruptive events ascribed to scholars in the construction of infrastructure projects.

4.9.2.3 Probability distribution

Probability distribution is a mathematical function that provides a random phenomenon in terms of the probabilities of events. Probability distributions are grouped into two classes: a discrete probability distribution and continuous probability distribution (Ang and Tang, 2007). Discrete probability distribution, known as a probability mass function, models the discrete list of the probabilities of the outcomes. On the other hand, continuous probability distribution models the range of real numbers of the probabilities of the outcomes and is described by probability density function (PDF). The normal distribution is a commonly encountered continuous probability distribution. More complex experiments, such as those involving stochastic processes defined in continuous time, may demand the use of more general probability measures.

In this study, the lognormal probability distribution and triangular probability distribution and their distribution parameters, such as minimum, mode and maximum, were employed to identify the lower, most likely and higher possible cost and time of activities.

Lognormal distribution

Lognormal distribution is a continuous probability distribution of a random variable which exponentially is normally distributed. For instance, if Y is a normal distribution, then the exponential function of Y is a lognormal distribution. Lognormal distribution takes only positive real values (Ross, 2013, Benjamin and Cornell, 2014). The lognormal distribution is used to model continuous random variables when the distribution is believed to be skewed, such as with construction cost (see Figure 4.28).



Figure 4.28: Lognormal probability distribution

The lognormal distribution function and probability density function is given as:

$$F(x) = \Phi\left(\frac{\ln(x) - \mu}{\sigma}\right), x > 0 \quad [4.19]$$
$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln(x) - \mu)^2}{2\sigma^2}\right), x > 0$$

Where: Φ is the standard normal distribution function with mean and standard deviation.

The lognormal distribution is the selected probability to model cost variables in this study since it often underlies the distribution of construction cost variables (Touran and Lopez, 2006).

The probabilistic costs of activities were calculated using Equations 4.20 and 4.21.

The cost distributions C_i is defined as:

$$C_i \sim \text{Lognormal}(\mu, \sigma^2) \quad [4.20]$$

where μ and σ are the mean, and the standard deviation of the corresponding normal distribution and the μ and σ are calculated by solving the following system of equations

$$\begin{cases} \text{Mode} - \text{Mean} = \exp(\mu - \sigma^2) \\ 0.98 = 0.5 \times \left[1 + \text{erf} \left(\frac{\ln(\text{high value} - \text{min}) - \mu}{\sigma\sqrt{2}} \right) \right] \end{cases} \quad [4.21]$$

where *Min*, *Mode*, and *High* values are the minimum, the mode and the value that can be exceeded with 2% probability, respectively, of the lognormal distribution.

Triangular distribution

In this study, the time of construction is modelled with triangular distribution since it often underlies the distribution of construction time variables (Love et al., 2013).

The time distribution, T_i is defined as:

$$T \sim \text{Triangular}(\text{min}, \text{mode}, \text{max}) \quad [4.22]$$

where *Min*, *Mode*, *Max* are the minimum, the mode and the maximum, respectively, of the triangular distribution.

Triangular distribution is a continuous probability distribution with a triangle-shaped probability density function as shown in Figure 4.29.



Figure 4.29: Triangular probability distribution

Triangular distribution is defined by three values: the lower limit, upper limit and mode.

The triangular probability density function is given as:

$$\left\{ \begin{array}{ll} 0 & \text{for } x < a \\ \frac{2(x-a)}{(b-a) \times (c-a)} & \text{for } a \leq x < c \\ \frac{2}{b-a} & \text{for } x = c \\ \frac{2(b-x)}{(b-a) \times (b-a)} & \text{for } c < x \leq b \\ 0 & \text{for } b < x \end{array} \right. \quad [4.23]$$

Where: a , b and c are the lower limit, upper limit and mode of distribution respectively

4.9.2.4 Copula analysis

A copula generates correlated varieties with the desired Spearman correlation coefficients. It is a multivariate distribution function defined on the unit cube $[0, 1]^2$, with uniformly distributed marginals (Vrac et al., 2012). The copula primary generates random numbers from a uniform distribution; then, through two transformations, it obtains random numbers correlated with the desired correlations and distributed with the desired probability distribution. In this study, the correlation is measured with the Spearman correlation coefficient, and modelled with Gaussian copula. The Gaussian copula is a distribution over the unit cube $[0,1]^d$. It is constructed from a multivariate normal distribution over R^d by using the probability integral transform.

For a given correlation matrix the Gaussian copula with parameter matrix R is described as:

$$C_R^{gaussian} = \Phi_R(\Phi^{-1}(u_1), \dots, \Phi^{-1}(u_d)) \quad [4.24]$$

Where: Φ^{-1} is the inverse cumulative distribution function of a standard normal and Φ_R is the joint cumulative distribution function of a multivariate normal distribution with mean vector zero and covariance matrix equal to the correlation matrix R

Copula was generated for the unit costs and production rates of the highway activities, which are correlated, then these were summed to obtain the total cost and total time of the activities. The copula generation and the summing of the unit costs and production rates of all activities were repeated for each simulation run. With the copula generation, the uncertainty in each unit of activities was modelled, as well as the correlation between the costs and times of the activities.

4.9.2.5 Monte Carlo analysis

Monte Carlo analysis is a mathematical simulation tool that generates random samples from probability distributions (Robert and Casella, 2013). Different probability distributions are utilised for modelling input variables, such as normal, lognormal, uniform, and triangular. Different iterations or simulations are run for generating paths, and the outcome is arrived at by using suitable numerical computations. Monte Carlo simulation is used when a model has uncertain parameters, or a dynamic complex system needs to be analysed. It is a probabilistic method for modelling risk and uncertainty in a system. Monte Carlo analysis provides a better model of uncertainty compared to the deterministic analysis (Zio, 2013). It gives the expected outcome as

well as the probability of an outcome. Monte Carlo simulation is also able to model the correlation between variables.

Monte Carlo analysis was employed in this study to generate the probability distributions for the variability in unit cost and production rate of activities. The variability of unit cost is modelled with a lognormal distribution and a triangular distribution for production rate. By simulating all project activities repetitively, it generates probability distributions for total cost and time of the project.

4.9.2.6 The Markov process

The Markov process is a stochastic model defining a series of possible events in which the probability of an event depends on the probability of the previous event (Gamerman and Lopes, 2006). This process has three properties: the number of possible outcomes is finite, the outcome at any stage depends only on the outcome of the previous stage, and the probabilities are constant over time (Gamerman and Lopes, 2006).

Disruptive events occur with a probability of occurrence and cause additional construction cost and time on projects. The occurrence of the disruptive event was modelled with a Markov process based on transition probability for a unit of the three structures of the highway project and a random number was generated from a uniform distribution [0, 1] as illustrated in Figure 4.30.

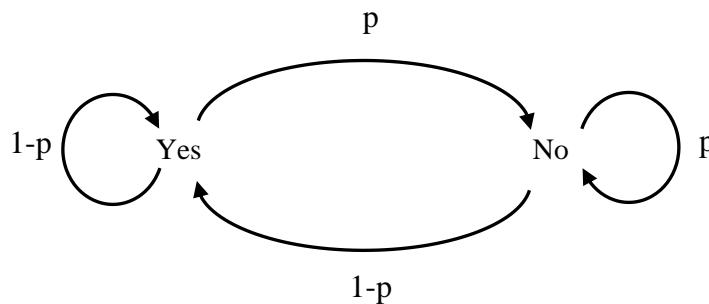


Figure 4.30: Markov process based on the transitional probability for the probability of occurrence and non-occurrence of an event

$$P = \begin{bmatrix} P_{AA} & P_{AB} \\ P_{BA} & P_{BB} \end{bmatrix} \quad [4.25]$$

The states of the Markov process are “no” for when the disruptive event does not occur and “yes” for when the disruptive event does occur. The transition probability from state “no” to state “yes” is equal to the probability of occurrence of the disruptive event, p , while the transition probability from state “yes” to state “no” is equal to one minus the probability of occurrence of the disruptive event, $(1 - p)$ as illustrated in Figure 4.30.

Since each simulation run was different, the occurrence of the disruptive event was changed. It may not occur, it may occur once, or it may occur more than once.

If the generated number was larger than the probability of occurrence, the event has not occurred, and the simulation proceeded to the next unit. Otherwise, if the generated number was smaller or equal to the probability of occurrence, the event has occurred in the unit of structure, and its time and cost impacts were calculated.

4.9.2.7 *Stepwise regression analysis*

Stepwise Regression Analysis (SRA) is an extension of multiple regression analysis. The SRA model is a mathematical model used in estimating the relationship between a dependent variable and independent variables with a strong mathematical background. SRA measures how two or more independent variables influence the actions of a dependent variable (Draper and Smith, 2014).

To assess the magnitude of influence of disruptive events from two parameters, probability of occurrence and severity of the event, SRA was employed. Since each of the independent variables can have low correlation with the dependent variable, the SRA model was used in this study to evaluate the impact size of disruptive events on the cost and time of construction projects.

The predictive strength or fitness of predicted impact size to real data was measured using a correlation coefficient value (R Square). Furthermore, to measure the differences between values predicted by the SRA model and the real values, two error tests, the Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) were used.

4.9.2.8 *Wilcoxon signed rank test*

The Wilcoxon signed rank test is a non-parametric hypothesis test designed for use with repeated measures when variables are measured under two different conditions. It is the non-parametric alternative to the repeated measures t-test, but, instead of comparing means, the Wilcoxon converts scores to the ranks and compares them at condition 1 and condition 2 (Field, 2013).

$$W = \sum_{i=1}^n [\text{sgn}(x_{2,i} - x_{1,i}) \times R_i] \quad [4.26]$$

Where *sgn* is the sign function, R_i is the rank

$$Z = \frac{W - 0.5}{\sqrt{\frac{n(n+1)(2n+1)}{6}}} \quad [4.27]$$

The effect size for the Wilcoxon test can be calculated to an approximate value of *r* using *z* value as shown in Equation 4.28.

$$r = \frac{Z}{\sqrt{n}} \quad [4.28]$$

where $r=0.1$ indicates a small effect size, $r=0.3$ a medium effect size and $r=0.5$ a large effect size. The Wilcoxon signed rank test was employed to test the 1st and 3rd research hypotheses of the study and validate the developed uncertainty portfolio concept.

4.9.2.9 *Chi-Square test for independence*

The Chi-square test is a nonparametric hypothesis test that used to determine if there is a significant association between categorical variables. This test compares the observed frequencies or proportions of cases that occur in each of the categories, with the values that would be expected if there was no association between the two variables being measured. It is based on a crosstabulation table, with cases classified according to the categories in each variable (McKight and Najab, 2010).

The null hypothesis for this test assumes that there is no significant association between the variables and the alternative hypothesis assumes that there is a significant association between the variables.

$$\chi^2 = \sum_{i=1}^n \sum_{j=1}^n \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \quad [4.29]$$

Where O_{ij} is observed value of two nominal variables and E_{ij} is expected value of two nominal variables.

4.9.3 Mixed data analysis

Mixed data analysis is technique that analyses the data from both the qualitative and quantitative approaches. To quantify the impact of disruptive events on construction cost and time of infrastructure projects from the qualitative data obtained from survey participants, the ANFIS (adaptive neuro-fuzzy inference system) was employed.

4.9.3.1 ANFIS

The adaptive neuro-fuzzy inference system (ANFIS) is an intelligent machine learning technique, which combines the strengths of the artificial neural network (ANN) with fuzzy inference systems (FIS) to create an efficient mixed technique for analysing the impact of risks and disruptive incidents on performance (Ebrat and Ghodsi, 2014). ANFIS, trained to develop fuzzy rules and determine membership functions (MF) for input and output variables of the system (Huang et al., 2002), is an intelligent system, which is able to estimate the variables and fuzzy rules intelligently and does not require a systematic method for design of fuzzy systems. ANFIS has the capability to handle uncertainty, nonlinearity, and complexity problems which are involved in most construction management decision-making processes (Jin, 2010). Also, ANFIS interprets human knowledge to a mathematical model (Singh et al., 2013).

The fuzzy inference system (FIS) is used in modelling qualitative aspects without employing precise quantitative analyses; it provides standard practical methods for transformation into a rulebased system, as well as effective methods for turning membership functions (MF) for better performance index, and it is instrumental in undertaking complex problems (Carr and Tah, 2001). The schematic representation of the fuzzy system is shown in Figure 4.31.

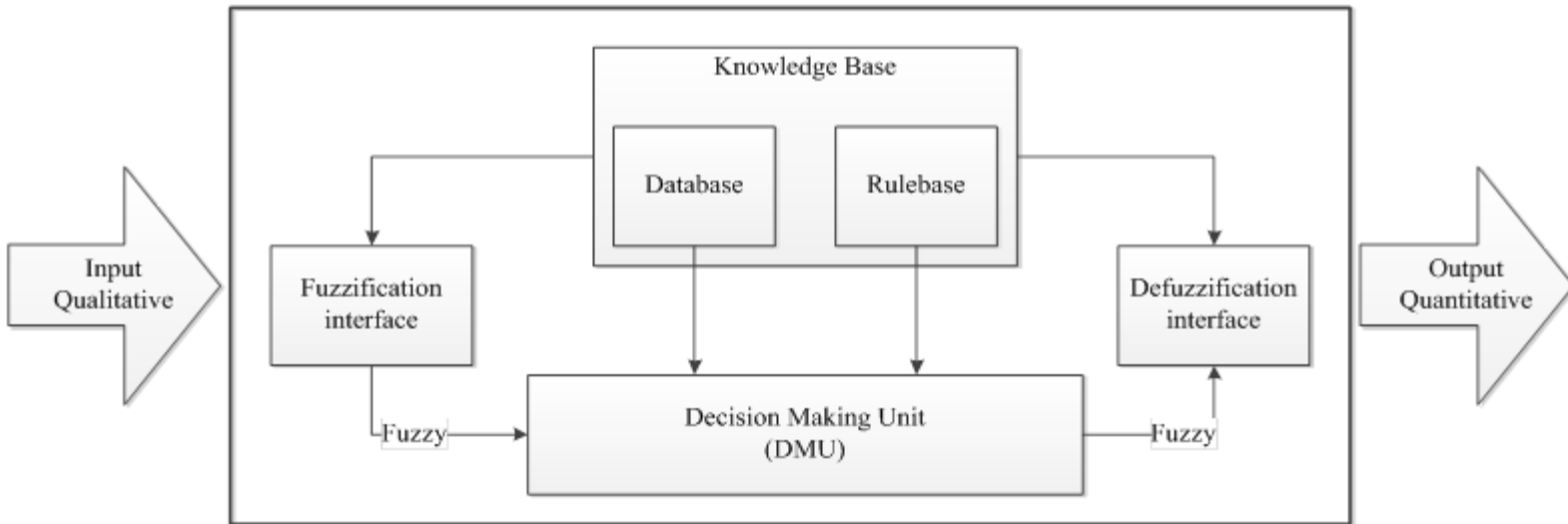


Figure 4.31: Fuzzy system diagram

Over and above the positive points of the fuzzy system, one of its most positive points is that there is no need for a systematic method for the design of fuzzy systems. Hence, a neural network-based method intelligently designs fuzzy systems. The intelligent design of these systems originates from the fact that system parameters and fuzzy rules are estimated by neural networks intelligently (Ebrat and Ghodsi, 2014). A neuro-fuzzy system solves the difficulty of fuzzifier and defuzzifier systems. Also, neuro-fuzzy systems can interpret the human knowledge in a mathematical formula well. The neural network can be used in the design of fuzzy systems because of the ability of neural networks to learn by network train parameters.

This study employed ANFIS to assess the magnitude of influence of disruptive events from qualitative parameters (probability of occurrence and severity of the event). Similar to SRA, the predictive strength of ANFIS was measured using a correlation coefficient value (R Square) and the modelling error was measured by RMSE and MAPE. The details and discussion of predicting the impact size of disruptive events on construction cost and time of infrastructure projects are presented in Chapter Six.

4.9.4 Modelling of variability in the construction process

Variability is the change in a variable under normal conditions and regular processes, such as the change in the cost of excavation of one meter of the bridge and the next meter of the bridge in the same geology and construction environment. Variability is the first source of uncertainty that was modelled with probability distributions: the lognormal distribution for the variability in cost variables and the triangular distribution for the variability in time variables. The lognormal distribution was the selected probability distribution to model cost variables since it often underlies the distribution of construction cost variables (Ang and Tang, 2007, Touran and Lopez, 2006). Time variables were modelled with the triangular distribution for four main reasons: it is closed-

ended in the lower tail (time variables are positive); it can be either skewed to the left or skewed to the right; the minimum, mode, and maximum parameters can be relatively easily estimated by an expert; and it is often used in construction modelling (Love et al., 2013, Devore, 2011).

Differently from the deterministic cost and time estimate, which corresponds to one point, modelling the variability of costs and times provides the range of the possible total cost and total time by a cloud of points. The cloud of points visually represents the variability of the resulting total cost and total time. The variability in the cost and the time of infrastructure projects was modelled for each unit of the construction activities in all infrastructure structures using the lower, most likely and higher estimated value (estimated by a panel of experts) and historical data of three comparable projects. Figure 4.32 presents the flowchart of modelling variability in construction cost and time of an infrastructure project.

As mentioned earlier, the variability in the construction process was modelled with a lognormal distribution for cost, and a triangular distribution for time. From the probability distribution, one cost and time for a unit of construction activities were generated per simulation with a Monte Carlo simulator. The number generation was repeated for every unit of construction activities until all the activities of all three structures in different geological conditions had been completed. At the end of each simulation run, the costs and the times, respectively, were summed up to calculate the total cost and the total time of the construction activity for the particular simulation run.

The procedure was repeated for every simulation run until the standard deviation of total cost and total time of activity bound within $\pm 1\%$ in 10 out of 10 simulations. The total cost and the total time were the expressions of the accumulated uncertainties in the construction of all units of construction activities. Since generated cost and time change from simulation to simulation due to the construction process uncertainty, the cost-time scatterplot is represented by a different point for every simulation run (cloud of points).

Finally, the construction time and cost of all three structures and the total highway project were simulated considering only the variability in the construction cost and time and the variability cost PDF, time PDF and cost-time PDF were plotted against the deterministic total cost and total time of each structure and the overall project.

4.9.5 Modelling of correlation between construction activities' cost/time

Correlation measures and describes the strength and direction of the relationship between two variables (Benjamin and Cornell, 2014). The correlation varies between -1 (fully negatively correlated) and +1 (fully positively correlated), and for a correlation equal to 0, the two variables are uncorrelated. If the value of one variable is above average, the value of the second variable tends to be above average when they are positively correlated, while it tends to be below average when they are negatively correlated (Ökmen et al., 2010). In this study, the correlation was measured with the non-parametric Spearman correlation coefficient, and it is modelled with the Gaussian copula. A copula is a multivariate distribution function defined on the unit cube $[0, 1]^2$, with uniformly distributed marginals (Vrac et al., 2012).

The choice of the Spearman correlation from amongst the available correlation measures and the Gaussian copula from amongst the available correlation models was because, differently from a random number generator, a copula first generates random numbers from a uniform distribution, then, through two transformations, it obtains random numbers correlated with the desired correlations and distributed with the desired probability distribution. Also, a Copula generates the unit costs and production rates of the construction activities, which are correlated, then these are summed to obtain the total cost and total time of the activities. In other words, copulas allow the generation of correlated costs and times with the desired Spearman correlation matrix and with the desired marginal distribution, and, because of the availability of both marginal distributions and the correlation matrix for this study, the copula was employed. Figure 4.33 presents the flowchart of modelling correlation in a highway project.

The study identified five potential types of correlation in construction of infrastructure projects, namely:

1. correlation between the costs/times of a repeated activity in a structure,
2. correlation between the costs/times of different activities in a structure,
3. correlation between the costs/times of activities in adjacent structures,
4. correlation between the costs/times of same activities in same type of structures,
5. correlation between the costs and the times of activity.

The Gaussian copula generation and the summing of the unit costs and production rates of all activities were repeated for each simulation run. With the copula generation, the uncertainty in each unit of construction activities was modelled, as well as the correlation between the costs and times of the activities. At the end of each simulation run, the costs and the times, respectively, were summed up to calculate the correlated total cost and total time of activities for the particular simulation run. The correlation process was repeated for every simulation run by Monte Carlo until the standard deviation of total cost and total time of activity bound within $\pm 1\%$ in 10 out of 10 simulations.

A positive correlation causes the standard deviation of the sum of the correlated variables to increase, since cost and time correlations in construction are usually positive (Bakhshi and Touran, 2012, Moret and Einstein, 2011b, Flyvbjerg, 2008). Compared to the total cost and the total time when modelling only the variability, the correlated cost and time are expected to increase the range of possible total costs and total times of the project, which causes the cloud of points to expand in the total cost and total time directions.

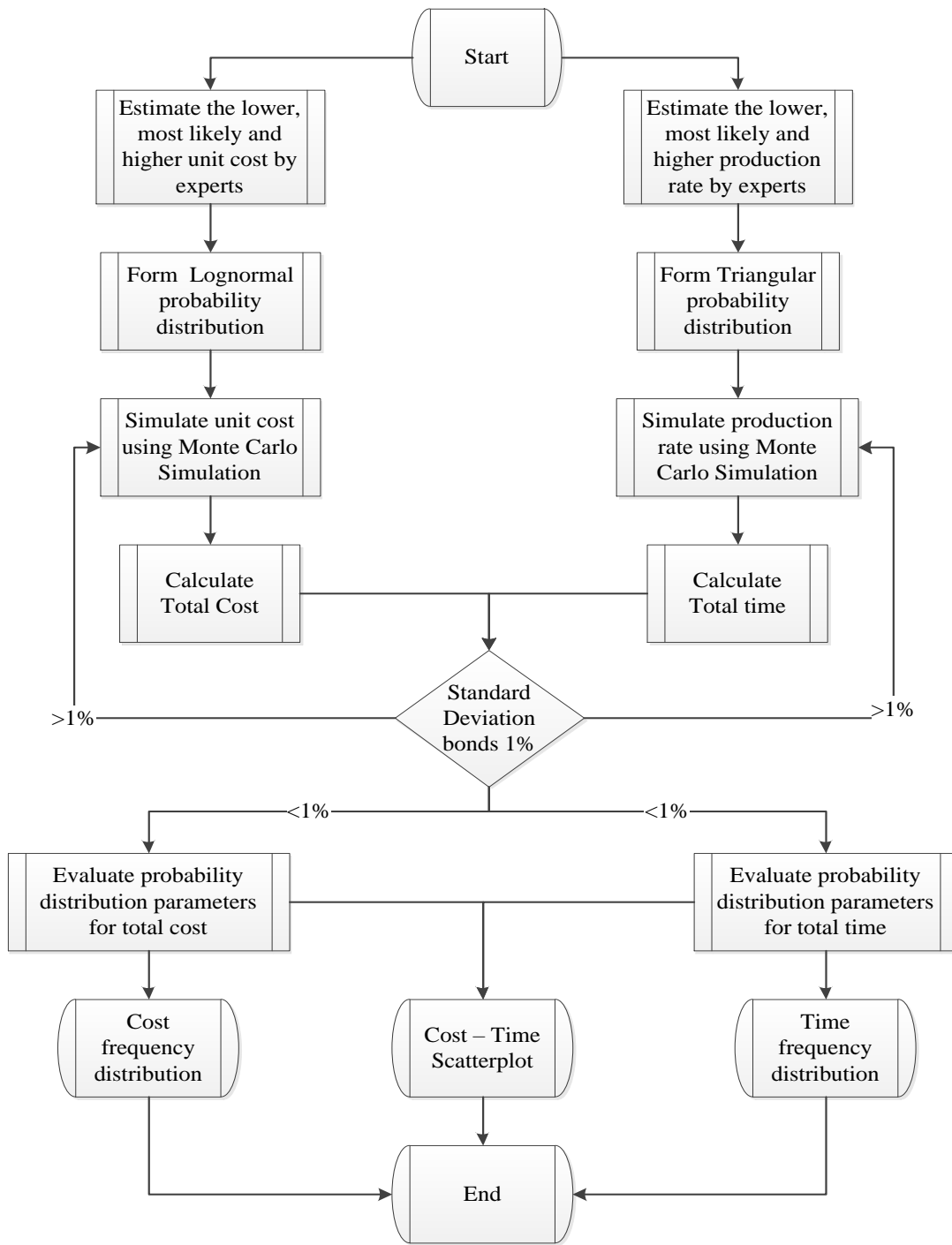


Figure 4.32: Variability model flowchart

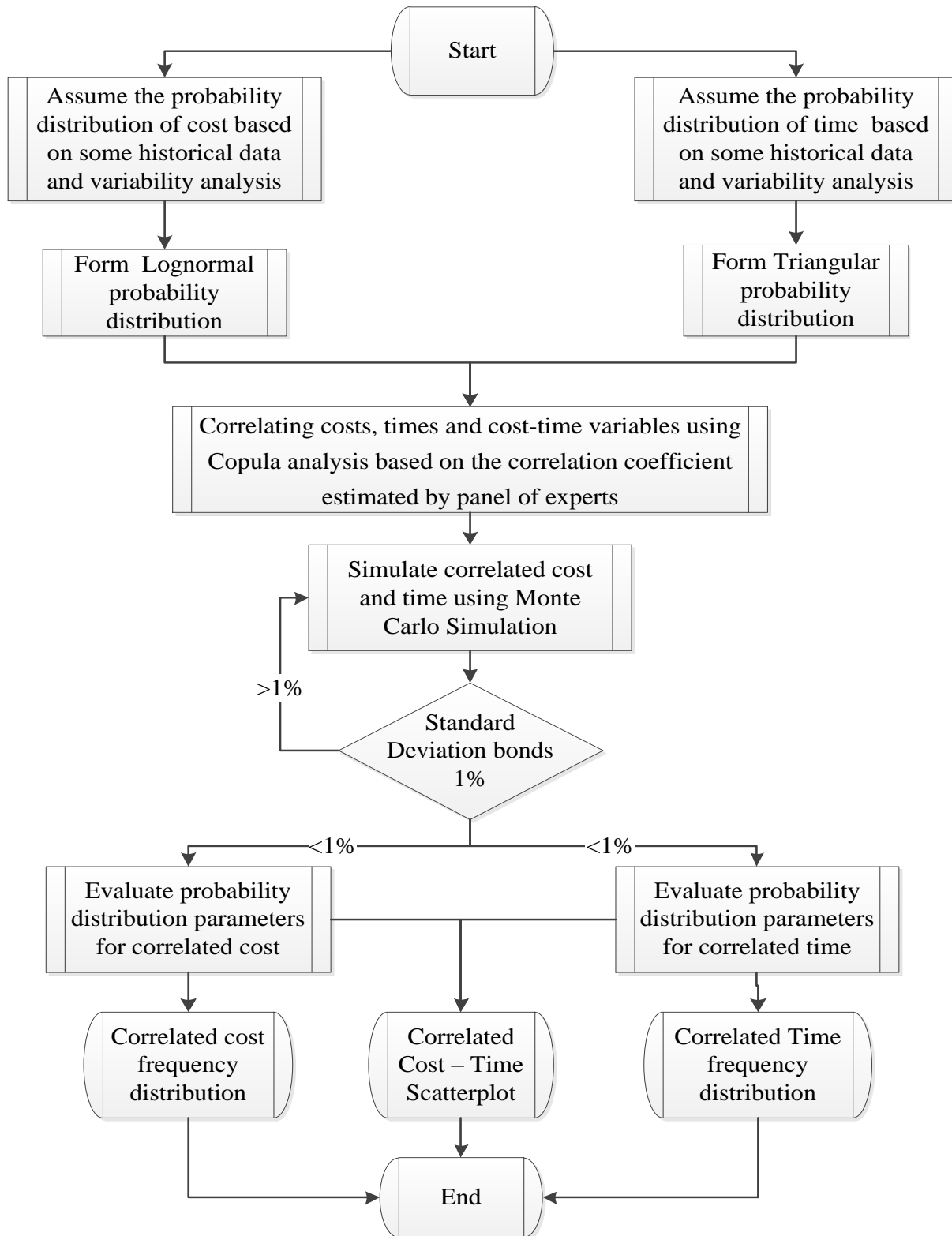


Figure 4.33: Correlation model flowchart

4.9.6 Modelling of disruptive events

An uncertainty event is an event with an unknown outcome and no background information (Ökmen and Öztaş, 2010). Due to the rare occurrence of uncertainty events and difficulty of measuring the outcome, there are, in general, no studies on the underlying impact of uncertainty events on the cost and time of highway projects.

By gathering enough reliable and appropriate data and assigning meaningful probabilities to the information the uncertainty events transform to disruptive events (Winch 2012). The impact of disruptive events on cost and time can be assessed by modelling the probability of occurrence and severity of the disruptive event (PMI, 2013, ISO, 2018).

To assess the impact size of disruptive events on construction cost and duration of infrastructure projects, the qualitative values of probability of occurrence and severity of event were obtained from the questionnaire survey and were inserted into the ISO 31000 impact size matrix as shown in Figure 4.34 the input variables and impact in the Linguistic value.

		Severity of event				
		Insignificant	Minor	Moderate	Major	Catastrophic
Probability of occurrence	Rare	Minimal	Minimal	Low	Low	Moderate
	Unlikely	Minimal	Low	Moderate	Moderate	High
	Possible	Low	Moderate	Moderate	High	High
	Likely	Low	Moderate	High	High	Extreme
	Almost Certain	Moderate	High	High	Extreme	Extreme

Figure 4.34: Impact size matrix

The occurrence of a disruptive event was modelled with the Markov process a random number generation by uniform distribution [0,1] at every unit of an infrastructure project. If the generated number was larger than the probability of occurrence of an event obtained from the survey, the disruptive event did not occur, and the simulation proceeded to the next unit of the infrastructure project. On the other hand, if the generated number was smaller or equal to the probability of occurrence obtained from the survey, the disruptive event occurred in the unit of the project, and its cost and time impacts were simulated.

4.9.6.1 Modelling the impact size of disruptive events using intelligent machine learning

To quantify the impact sizes of disruptive events on the cost and time of the construction activities, the ANFIS, as an intelligent machine learning technique, was employed. According to Asgari et al. (2016) quantification of these factors with classical methods, such as probability analysis and influence diagrams, are very difficult. Efficient applications and quantification techniques are difficult and complex, and furthermore, exact data are required (Chen and Zhang, 2014). Unfortunately, such data relevant to this study either do not exist at all or are hard to obtain.

Moreover, most of the classical mathematical assessment methods, such as differential equations, are not able to examine the relationship between input variables and an output variable and they are not well suited for uncertainty problems (Zhang et al., 2009).

Also, these methods are based on statistical or computing techniques, and they cannot cover qualitative data which are used in the evaluation of uncertainties. The fuzzy inference system (FIS), on the other hand, is used in modelling the qualitative aspects without employing precise quantitative analyses; it provides standard practical methods for transformation into rulebased, as well as effective methods for turning membership functions (MF) for better performance index, and it is very useful in undertaking complex problems (Carr and Tah, 2001).

As discussed, earlier ANFIS combines the strengths of the artificial neural network with fuzzy inference systems and provides uncertainties capability to handle uncertainty, nonlinearity, and complex problems an efficient method for analysing the impact of uncertainties and risks

The magnitude of influence of disruptive events was assessed using two variables, probability of occurrence and severity of the event. Figure 4.35 illustrates the developed fuzzy system for assessing the disruptive events in the study.

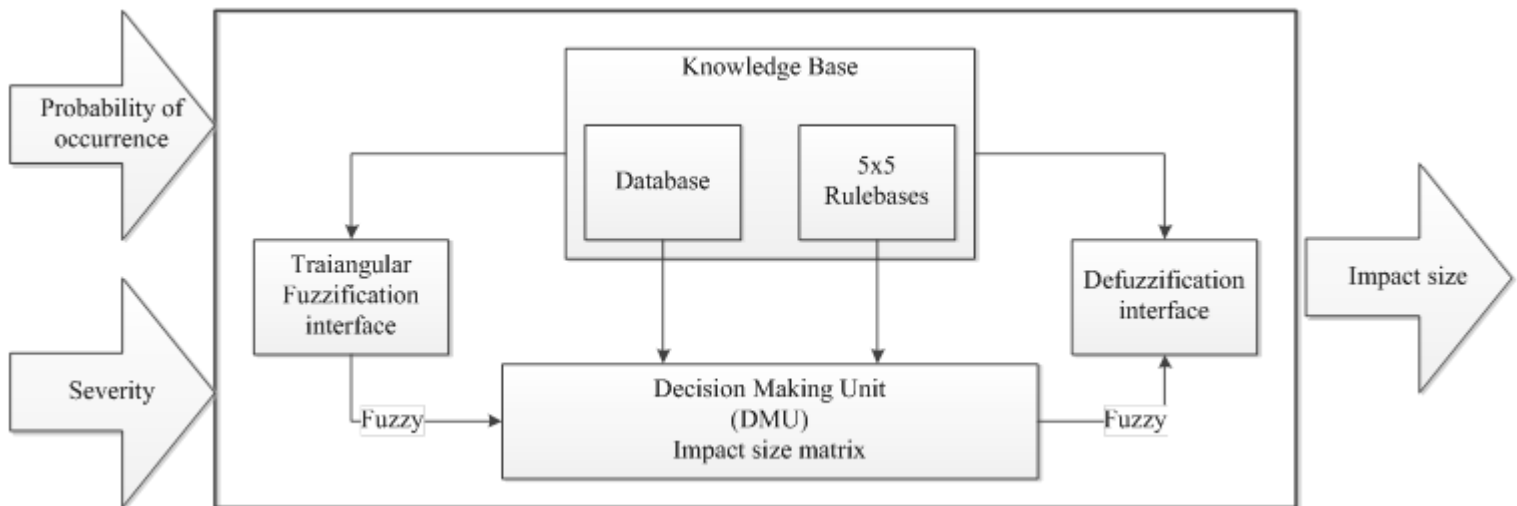


Figure 4.35: Fuzzy system for disruptive events assessment

The value of probability of occurrence and severity of each event on the cost and time of activity were obtained from the 5-point Likert scale closed-ended questionnaire (Database, 5x5 rulebases). In the next step, the linguistic values of probability of occurrence, the severity of the event, and the impact size of the event were converted to fuzzy values. To convert a linguistic value to a fuzzy value, triangular fuzzy numbers were used, since the probability of occurrence and time variables underlie triangular distribution (Tang and Ang, 2007). The fuzzy values and fuzzy graphical diagram of each of these linguistic variables in terms of the probability of occurrence, severity, and impact are shown in Table 4.3.

Table 4.3: Linguistic and fuzzy values of the probability, severity, and impact size

	Linguistic value	Fuzzy value	Fuzzy graphical diagram
Probability of occurrence	Rare	(-0.1, 0.1, 0.3)	
	Unlikely	(0.1, 0.3, 0.5)	
	Possible	(0.3, 0.5, 0.7)	
	Likely	(0.5, 0.7, 0.9)	
	Almost Certain	(0.7, 0.9, 1.1)	
Severity of event	Insignificant	(-1, 1, 3)	
	Minor	(1, 3, 5)	
	Moderate	(3, 5, 7)	
	Major	(5, 7, 9)	
	Catastrophic	(7, 9, 11)	
Impact size	Minimal	(0, 1, 2)	
	Low	(1, 2, 3)	
	Moderate	(2, 3, 4)	
	High	(3, 4, 5)	
	Extreme	(4, 5, 6)	

After converting the linguistic values of variables into the fuzzy values, the center of area (COA) method was used to defuzzify the fuzzy values into a numerical value using best non-fuzzy performance (BNP) (Chen and Lu, 2001). The deterministic values of probability of occurrence, severity, and impact size of all 76 disruptive events for cost and time calculated by BNP using Equation 4.30 is outlined in Table 4.4.

$$M_A = \frac{a_l + 2a_m + a_u}{4} \quad [4.30]$$

Where: $\tilde{A} = (a_l + a_m + a_u)$

Table 4.4: Conversion value of linguistic to numerical

Probability of Occurrence		Severity of Event		Impact Size	
Linguistic value	Numerical Value	Linguistic Code	Numerical Value	Linguistic Code	Numerical Value
Rare	0.1	Insignificant	1	Minimal	1
Unlikely	0.3	Minor	3	Low	2
Possible	0.5	Moderate	5	Moderate	3
Likely	0.7	Major	7	High	4
Almost Certain	0.9	Catastrophic	9	Extreme	5

Table 4.3 shows the numerical values of probability of occurrence, the severity of the event, and impact size based on Table 4.4 fuzzy values.

4.9.6.2 Developing ANFIS structure

The Takagi and Sugeno ANFIS model was used for a systematic approach to generating fuzzy rules from a given input-output dataset. In this study, the first-order Sugeno fuzzy inference system proposed by Takagi and Sugeno (1983) was employed to assess the impact size of disruptive events in construction cost and duration of highway projects. In this inference system, the output of each rule is a linear combination of two input variables (occurrence and severity of event) added to by a linear term of “AND” logic. The final output is the weighted average of each rule’s output (Buragohain and Mahanta, 2008). Figure 4.36 illustrates the Takagi and Sugeno ANFIS structure in 5 layers which were developed for assessing the impact of disruptive events on the cost and time of highway structures. To model each ANFIS, the following 25 fuzzy rules, “If-Then”, were considered.

$$\text{If } (P | p_i) \text{ AND } (S | s_i) \text{ Then } f_i = ap_i + bs_i + r_i \quad [4.31]$$

Where P and S are numerical inputs while p_i and s_i are numerical variables. Membership functions identify these variables. Also, a_i , b_i , and r_i are parameters that determine the relationship between input and output.

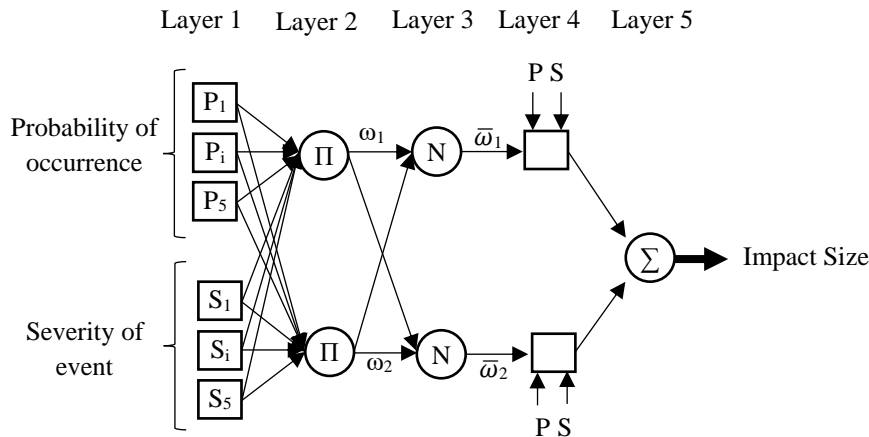


Figure 4.36: Proposed Takagi and Sugeno ANFIS structure

1st layer – Input layer: Designates the numerical input values, probability of occurrence (P) and severity of event (S) to the different fuzzy set.

$$\begin{aligned} \mu_{p_i}(p) \quad i = 1,2,3,4,5 \\ \mu_{s_i}(s) \quad i = 1,2,3,4,5 \end{aligned} \quad [4.32]$$

Where, p and s are the membership functions for fuzzy sets of probability and severity. There are eight membership functions which are shown in Tables 4.10 and 4.11.

2nd layer – Inference layer: The “AND” operator was used for achieving the output (firing strength), which shows the degree of satisfaction of each 25 fuzzy rules in a different value of two input variables.

$$\omega_i = \mu_{p_i}(p) \cdot \mu_{s_i}(s) \quad i = 1,2,3,4,5 \quad [4.33]$$

3rd layer – Implication layer: The firing strengths were normalised in this layer.

$$\bar{\omega}_i = \frac{\omega_i}{\sum \omega_i} \quad i = 1,2,3,4,5 \quad [4.34]$$

4th layer – Aggregation layer: The normalised firing strengths were multiplied with the function of the Sugeno fuzzy rules which the consequent parameter set that was adjusted with the hybrid learning algorithm.

$$\bar{\omega}_i f_i = \bar{\omega}_i (a p_i + b s_i + r_i) \quad i = 1,2,3,4,5 \quad [4.35]$$

Where a_i , b_i and r_i are the consequent parameters set that adjusted with the learning algorithm.

5th layer – Defuzzification layer: The weighted averaged method was used to perform the process of defuzzification, which transforms the fuzzy result into a single numerical (crisp) output.

$$F = \sum \bar{\omega}_i f_i \quad i = 1,2,3,4,5 \quad [4.36]$$

The designed ANFIS structure for this study was modelled in the MATLAB environment to forecast the impact size of disruptive events on the cost and time of highway construction projects. Eighty percent of the data collected from the census of South African highway project managers was used for training of the system, while the balance of 20% was used for checking the neural network which sets the system parameters. The model structure of the ANFIS that was designed for this study is illustrated in Figure 4.37

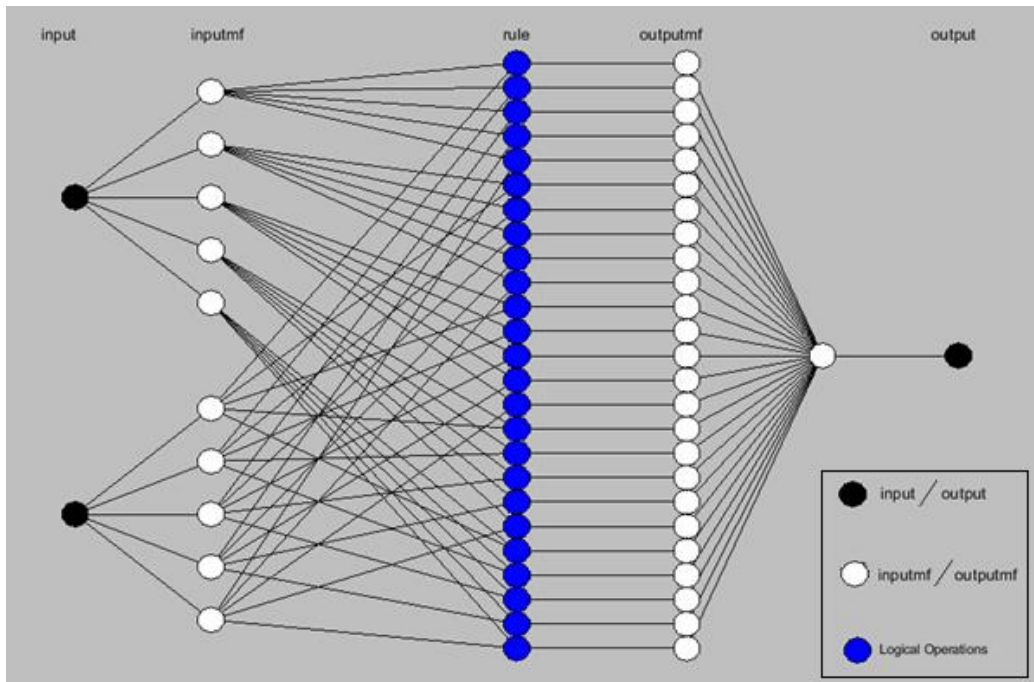


Figure 4.37: Proposed ANFIS structure model

Figure 4.37 illustrates the five membership functions of each input variable, 25 rules (AND rules), 25 membership functions for output variables, and a single output of the disruptive event in an impact assessment model in ANFIS.

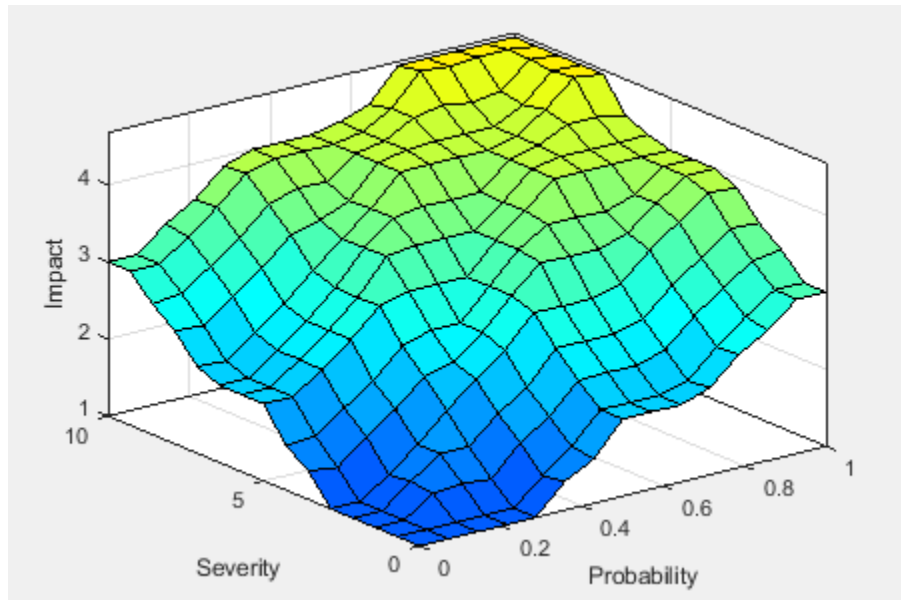


Figure 4.38: 3D Surface Diagram of Rules in the FIS.

From the surface 3D diagram in Figure 4.38, it can be inferred that, with an increase in the probability of occurrence and the effect of the severity of the event, the impact size of the disruptive event on the cost and completion time of the highway construction projects was increased, which was aligned with the risk impact matrix shown in the Figure 4.38. The capability of neural networks in learning by train and adapting the network's parameters with training data is the main advantage of using a neural network in the design of fuzzy systems (Carr and Tah, 2001). To train FIS and determine the relationship between input and output variables of the current study, the hybrid learning algorithms were used.

To identify the best membership function, the designed ANFIS was modelled with the eight more common membership functions namely: Triangular (Trimf), Trapezoidal (Trapmf), Generalized bell-shaped (Gbellmf), Gaussian curve (Gaussmf), Gaussian combination (Gauss2mf), II-shaped (Pimf), Difference between two sigmoidal (Dsigmf), and Product of two sigmoidal (Psigmf). The performance of each model for cost and time was evaluated by four types of error tests namely RMSE (Root Mean Square Error), NRMSE (Normalised Root Mean Square Error), MAPE (Mean Absolute Percentage Error), MSE (Mean Squared Error) and correlation coefficient value between the real data and predicted data as shown in Tables 4.5 and 4.6. The model with the least errors and R-Value closest to 1 is chosen as the best membership function.

As shown in Table 4.5, the Gaussian membership function (Gaussmf) had the least errors among all four tests and also the R-Value closest to 1 for the time variable. On the other hand, Table 4.6 revealed that Triangular membership function (Trimf) had the least errors and R-Value closest to 1 for the cost variable.

Table 4.5: ANFIS membership functions for performance evaluation for cost

Model	Membership Function	RMSE	NRMSE	MAPE	MSE	R-Value*
1	Trimf	3.12E-07	7.83E-08	4.35E-08	2.14E-14	0.999999999999997
2	Trapmf	2.41E-07	7.17E-08	3.74E-08	2.07E-14	0.999999999999996
3	Gbellmf	1.47E-07	7.36E-08	3.60E-08	2.17E-14	0.999999999999998
4	Gaussmf	1.14E-07	5.84E-08	2.23E-08	1.07E-14	0.999999999999999
5	Gauss2mf	1.28E-07	6.41E-08	2.98E-08	1.65E-14	0.999999999999999
6	Pimf	1.47E-07	7.36E-08	3.77E-08	2.17E-14	0.999999999999998
7	Dsigmf	1.34E-07	6.68E-08	3.17E-08	1.78E-14	0.999999999999998
8	Psigmf	1.85E-07	7.12E-08	3.53E-08	2.95E-14	0.999999999999996

* The R-Values are presented with 15 decimals to show the closeness to 1

Table 4.6: ANFIS membership functions for performance evaluation for time

Model	Membership Function	RMSE	NRMSE	MAPE	MSE	R-Value*
1	Trimf	1.26E-07	6.28E-08	2.90E-08	1.58E-14	0.999999999999999
2	Trapmf	1.30E-07	6.49E-08	3.08E-08	1.68E-14	0.999999999999999
3	Gbellmf	1.47E-07	7.36E-08	3.60E-08	2.17E-14	0.999999999999998
4	Gaussmf	1.49E-07	7.45E-08	3.68E-08	2.22E-14	0.999999999999998
5	Gauss2mf	1.28E-07	6.41E-08	2.98E-08	1.65E-14	0.999999999999999
6	Pimf	1.47E-07	7.36E-08	3.77E-08	2.17E-14	0.999999999999998
7	Dsigmf	1.34E-07	6.68E-08	3.17E-08	1.78E-14	0.999999999999998
8	Psigmf	1.33E-07	6.64E-08	3.22E-08	1.77E-14	0.999999999999999

* The R-Values are presented with 15 decimals to show the closeness to 1

The low value of test error indicated the reliability of the model for impact assessment and the closeness of the R-value to 1 verified the fitness of the model for impact evaluation. Therefore, Trimf and Gaussmf were selected as the best membership functions to model and assess the impact size of disruptive events on construction cost and time of highway construction projects, respectively.

Since disruptive events affect construction cost and duration of infrastructure projects, the cost and time of the unit of the project, where the event occurred, were larger than the cost and time of a unit project, where the disruptive event did not occur. The cost and time of all unit lengths were summed up to obtain the total cost and time of a highway project for a simulation run, which was one point in the cost-time scatterplot. Since each simulation run was different, the occurrences of the disruptive event were changed: it may not occur, it may occur once, or it may occur more than once.

When modelling the disruptive event in addition to the variability and correlations, the cloud of points is expected to expand, and the range of possible total costs and total time increases dramatically. Figure 4.39 presents the flowchart of modelling disruptive events in infrastructure projects.

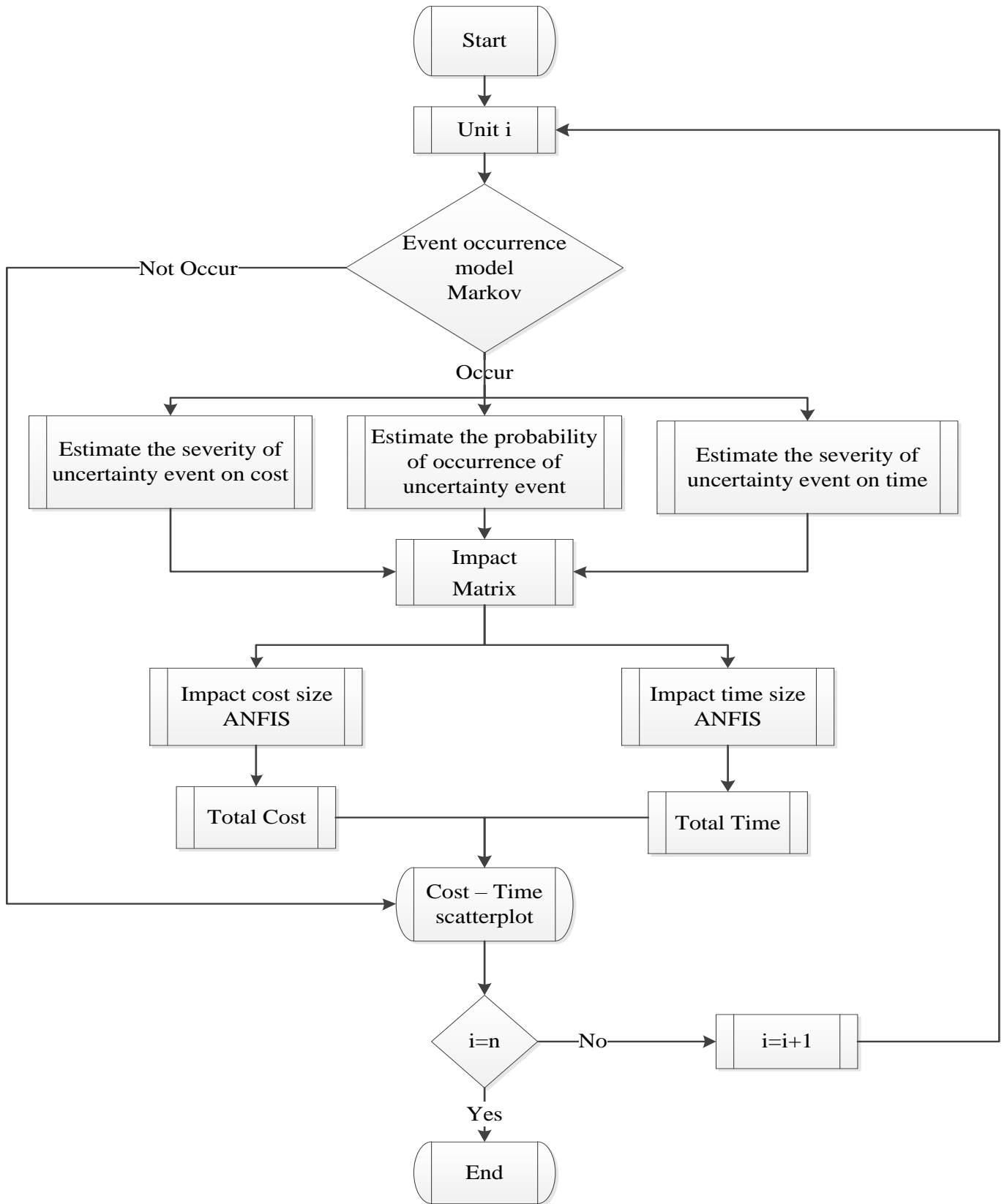


Figure 4.39: Disruptive event model flowchart

4.10 INSTRUMENTS OF DATA COLLECTION

This section discusses the procedures employed for collecting data in the current research. As outlined in Section 4.3, this study adopted a sequential exploratory mixed method research approach to collect and analyse the data. The details of data collection in both the qualitative and quantitative strands are provided in the subsequent sections.

4.10.1 Quantitative strand

Collecting quantitative data depends on a structured data collection instrument that fits diverse experience into predetermined response categories. Quantitative data collection methods produce numerical results that are easy to summarise, analyse and generalise (Creswell and Creswell, 2017). Statistical data, the closed-ended questionnaire, expert estimation, sampling and census data are the most common quantitative data collection instruments.

Two quantitative instruments used to collect data for the study were a close-ended questionnaire and experts' estimation. The data collection procedure of each instrument is discussed in the subsequent sections.

4.10.1.1 Questionnaire

The questionnaire instrument employed in the survey to accurately collect information on the probability and severity of disruptive events on construction cost and time (Appendix A) was designed in the uniform closed-ended format in five-point Likert scale. This was to reduce difficulties in clarity and completion time that affect the accuracy of the data gathered from the respondents.

It has been described as a simple technique that allows respondents to compare and establish relationships among the independent variables by ranking questions using numerical or categorical scales (Creswell and Creswell, 2017). The following subsections discuss further details on questionnaire constructs, questionnaire design and measuring techniques used in the questionnaire survey.

Constructs and variables used in the questionnaire

The verified disruptive events in the area of study, the probability of occurrence of disruptive events in infrastructure projects, and the severity of disruptive events on construction cost and duration of infrastructure projects are the three main constructs used in designing the questionnaire, together with their variables.

The disruptive events used in designing the questionnaire survey for this study were obtained through the systematic review of extant literature using bibliometrics in Chapter Two, and the justification for their inclusion was obtained using the expert panel brainstorming technique. The panel of experts verified the existence of 76 disruptive events in the construction of highway projects in South Africa and clustered these events in seven major groups.

Questionnaire design and measuring techniques

The questionnaire was designed in three main sections, which were preceded by an introduction about the research and respondent's consent to participate in the study. The first section sought the background information of the respondents, such as the highest qualification, years of experience in highway projects, and registration with professional bodies.

The second and third sections of the questionnaire included seven subsections. The respondents were asked to rate the probability of occurrence of disruptive events on a five-point Likert scale based on their two latest completed projects in the second section. The rating scales for the probability of events ranged through rare, unlikely, possible, likely and almost certain.

Similarly, the respondents evaluated the perceived severity of each disruptive event on construction cost and duration of their two latest projects using a five-point Likert scale. The evaluation scales of the severity of events ranged through insignificant, minor, moderate, major and catastrophic.

Pre-test of the questionnaire

The quality and suitability of the questionnaire for analysis as a data collection instrument should be pre-tested (Fellows and Liu, 2015). The pre-testing of the questionnaire is crucial to confirm the simplicity and clarity of the designed questions required to be answered.

Pre-testing of the questionnaire of this study was done by five members of the expert panel of the study. All the advice and suggestions of members of the panel were incorporated into the final draft of the questionnaire. Furthermore, the Ethics in Research Committee of UCT also approved the initial draft of the questionnaire at the beginning of the data collection process (See Appendix B).

4.10.1.2 Expert estimation

The uncertainty model considers three sources of uncertainty which require a significant amount of input data. The research work presented in this study is based on historical data and expert opinions. However, there is no reliable database on the costs and the duration of construction projects in South Africa. Therefore, the study considered the expert estimation as the main source of data collection for modelling the variability of cost and time of activities and correlation between costs/times and cost-time (Phase 2.1 and Phase 2.2).

The study selected a panel of five highly qualified experts in the construction of highway projects in South Africa with more than 30 years' experience with diverse specialities: an expert in earthwork, an expert in the construction of a highway bridge, an expert in paving and two experts in highway cost and time estimation. All of them had passed several special pieces of training in the field of estimation of construction cost and time of projects.

When using expert estimation to obtain data, particular validation and care were employed in the data gathering process in order to guarantee the data quality. In the following subsections, the main

aspects of expert estimation are discussed. In particular, biases are described, and expert calibration is presented.

Variables evaluated in the expert estimations

To assess the variability of cost and time of activities and evaluate the correlation between the cost and duration of activities in the construction of highway projects, five selected knowledgeable highway experts were assigned in three estimation groups of earthwork, bridge and pavement. Each estimation group contained an expert in its field and the two highly qualified experts in highway cost and time estimation.

Expert estimation of variability variables

The three expert groups estimated the lowest possible, the highest possible and most possible unit costs and production rates of each activity in the different geological conditions and geometric design in their specific structure of the highway project (earthwork, bridge and pavement). The results of variability estimations by the experts are presented in Section 5.3.1.

Expert estimation of correlation variables

Prior to the estimation of correlation by each estimation group the experts' panel agreed on the following assumptions:

- The labour and plants were assumed to be performing similarly at all times.
- All required material was assumed to be available.
- The cost fluctuations and delivery delay were modelled as the disruptive events.
- Weather-related events were assumed to be included in the disruptive events as well.

Given the above assumptions, the panel of experts determined the five potential types of correlation in the construction of highway projects:

1. Correlation between the costs/times of a repeated activity in a structure
2. Correlation between the costs/times of the various activities in a structure
3. Correlation between the costs/times of activities in adjacent structures
4. Correlation between the costs/times of the same activities in the same type of structures
5. Correlation between the costs and the times of an activity

The estimated correlation coefficients of different types of correlation by the three estimation groups are presented in Section 5.3.2.

4.10.2 Qualitative strand

The qualitative research approach answers questions of "how and why". Qualitative research relies on the view of participants and obtains more detailed and in-depth information about a problem (Creswell and Creswell, 2017). Brainstorming, interviews focus groups and observations are the most common methods of data collection in qualitative research. In the current research, group experts brainstorming was employed as the main qualitative instruments to collect data from the panel of experts.

Group brainstorming, also described as brain-netting of the group, consists of a small number of highly knowledgeable experts that are drawn together for the purpose of generating new ideas and solutions for a specific domain (Parks, 2018). Group brainstorming is a data collection process used by qualitative researchers to collect both the views of the specific participants and a shared understanding from several individuals (Creswell and Creswell, 2017).

Group brainstorming is a robust tool for solving a complex problem because it develops a solution in greater depth. Group brainstorming allows gathering a diverse panel with different expertise and specialities; this diversity is vital to the effect of this technique (Parks, 2018). The group brainstorming was conducted by the expert panel of the study which consisted of five experts with more than 30 years of experience in construction of linear infrastructure projects to verify the existence of disruptive events in the construction of highway projects in South Africa among the 317 uncertainty and risk events determined from the literature review and clustered these events (See Figure 4.3).

4.10.3 Criteria for judging the quality of research design

Validity and reliability are the two criteria that can be used to measure the quality of a research design at various research stages (Yin, 2017). The concept of validity is different in quantitative and qualitative research, although in both approaches it is used to ensure or check the quality of data, the results, and their interpretation (Creswell and Creswell, 2017). Quantitative researchers design their studies to reduce the threats to internal and external validity of the instrument used. This section assesses the quality of research design or potential adoption of both quantitative and qualitative approach design.

4.10.3.1 Validity and reliability in quantitative research

Internal validity

Internal validity is the degree to which a measured and observed effect among research variables can be said to be due to a causal relationship (Fellows and Liu, 2015). Internal validity is the extent to which the relational and causal effects, which the researcher observes between the research variables, may be the correct evidence for the conclusions (Creswell and Creswell, 2017).

Also, Creswell (2014b) described internal validity as the rate at which a researcher can draw correct conclusions that there are causes and relational effects among variables, which might be influenced by attributes of the participants, and maturity and biases in the selection process. Internal validity is also referred to as content validity, which examines whether variables are representative of possible items, and criterion-related or construct validity, which examines whether scores relate to an external standard or measure as intended. This can be done by means of statistical procedures, or consulting external experts (Creswell and Clark, 2017).

In this study, the consideration for internal validity focused on the quality of and relation between scores obtained from the results of the questionnaire survey, preventing potential biases in the expert estimations, and how the quality of the questionnaire responses and expert estimations

influenced the quality of findings and conclusions. It becomes imperative to consider content, criterion-related and construct validity, because the main concern of questionnaire survey designs with regard to internal validity has to do with the quality of the scores obtained from the questionnaire.

Content validity refers to the extent to which questionnaire items are representative of all facets of the constructs being measured. The current research ensured content validity through an in-depth review of extant literature and adopting the impact matrix (ISO, 2018) from which the questionnaire items (probability of occurrence and surety of events) were derived. Criterion-related validity describes whether the obtained sources link to some external standard, such as the score on a similar instrument and construct validity measures what they are intended to measure (Holt and Goulding, 2014). This validity was addressed by employing universal linguistic scales of measurement for the questionnaire items, to collect valid scores from the respondents.

According to Fellows and Liu (2015), the regression analysis and Spearman Rho correlation coefficient are two instruments to evaluate the criterion-related and construct validity. In this study, the Spearman correlation between two parts of the questionnaire survey (part 2.1: the probability of occurrence and part 2.2: degree of severity of events) for both cost and time was calculated and is shown in Tables 4.7 and 4.8.

According to Tables 4.3 and 4.4, positive and significant correlation was found between part 2.1 and part 2.2 of both costs ($r=0.81$; $p<0.01$) and time ($r=0.74$; $p<0.01$).

Table 4.7: Spearman correlation between Part 2.1 and 2.2 of cost questionnaire

		Part 2.1	Part 2.2
Part 2.1	Correlation Coefficient	1.000	0.81**
	Sig. (2-tailed)	.	0.000
	N	32	32
Part 2.2	Correlation Coefficient	0.81**	1.000
	Sig. (2-tailed)	0.000	.
	N	32	32

** . Correlation is significant at the 0.01 level (2-tailed).

Table 4.8: Spearman correlation between Part 2.1 and 2.2 of time questionnaire

		Part 2.1	Part 2.2
Part 2.1	Correlation Coefficient	1.000	0.74**
	Sig. (2-tailed)	.	0.000
	N	32	32
Part 2.2	Correlation Coefficient	0.74**	1.000
	Sig. (2-tailed)	0.000	.
	N	32	32

** . Correlation is significant at the 0.01 level (2-tailed).

In order to further evaluate the quality and relation among of scores obtained from the results of the questionnaire survey, the researcher took into account biases that could lead to errors in the estimation of probabilities. Biases are caused by the incorrect use of heuristics or rules of thumb by experts during estimating (Cantarelli et al., 2013). Biases in expert estimations are outlined in detail in the literature in Chapter Two.

The most common biases encountered in the estimation process (Hallowell and Gambatese, 2010) were:

Availability - the experts tend to base their estimates on the ease, which enables them to retrieve the information from their short-term memory; Anchoring - the experts arrange their estimate of a probability to an initial value and adjust, but with an inadequate adjustment; Contrast - the expert's perception of a variable was influenced (enhanced/diminished) by the exposure to a (larger/lower) value of the immediately preceding variable; Overconfidence - experts tend to give narrower confidence intervals compared to real intervals.

The optimism bias did not apply to the experts in this specific study, since none of them was a planner or a promoter of the case study project. Biases were avoided with calibration by experts and careful preparation of the estimation protocols. Calibration methods involved instructing the experts on the correct use of estimation values, probability concepts, and biases. Care was also taken to, inform the experts about the use of their estimation's results in the uncertainty model to estimate total construction cost and time of the case study project; to improve the knowledge of the experts with the advanced probability distributions and correlations in the construction of projects by discussing and visualising patterns; to warn the experts about the existence of availability and anchoring biases in the process of estimation, and their effects on the estimation results; to discuss the overconfidence bias when estimating the lowest and the highest values or small and large correlations, to prevent the experts from committing the same type of error; and to prevent the contrast bias by randomisation of the sequence of the activities' estimations in the estimation protocol.

Additionally, the estimation exercised the outside view, by not allowing the experts to focus on the details of the project, but instead, it provided estimation and opinion from extensive experience.

External validity

External validity relates to the degree to which the results of the survey can be generalised to the population (population validity) and possibly other research settings or contexts (ecological validity) (Yin, 2017). External validity is essential to quantitative research using some standardised procedures in selecting a sample as representative of the population study (Creswell and Creswell, 2017).

Since this study used a nonbiased population and employed standard procedures for selecting an appropriate population (professional construction managers of highway projects under construction in 2017 in South Africa, with more than 20 years' experience) and used a census survey (data collection from the whole population), automatically the population validity of

external validity was fully satisfied, and no further test was required. Although there was no wrong or right answer to any question in the questionnaire, the ecological validity was ensured as well.

Reliability

Reliability in quantitative research measures the internal consistency of the data collected from the respondents. It is assessed by the statistical reliability coefficient (Creswell and Clark, 2017).

Cronbach's alpha is the most common statistical test to check the internal consistency of a research variable (Field, 2013). Cronbach's alpha determines the degree of internal consistency or average correlation of items in a survey instrument from 0 to 1: the closer to 1, the greater the internal consistency of the items in the scale (Tavakol and Dennick, 2011).

Tavakol and Dennick (2011) provide the following classification for Cronbach's alpha coefficient range shown in Table 4.9.

Table 4.9: Cronbach's alpha coefficient range

Cronbach's alpha coefficient range	Internal consistency
$\alpha \geq 0.9$	Excellent
$0.9 > \alpha \geq 0.8$	Good
$0.8 > \alpha \geq 0.7$	Acceptable
$0.7 > \alpha \geq 0.6$	Questionable
$0.6 > \alpha \geq 0.5$	Poor
$0.5 > \alpha$	Unacceptable

The internal consistency of each group of disruptive events for both cost and time variables was estimated. Tables 4.10 and 4.11 summarise the results from Cronbach's alpha test obtained for cost and time.

Table 4.10: Reliability value of disruptive events for the cost component

Uncertainty group	Disruptive event	Cronbach's alpha
Economic	<ol style="list-style-type: none"> 1. Fluctuation of prices of materials and/or equipment 2. Monopoly of material and/or equipment suppliers 3. Saturated market 4. Fluctuation in foreign exchange rate 	0.927
Environmental	<ol style="list-style-type: none"> 1. Weather 2. Natural disasters 3. Remote location cost 4. Terrain (or topographical site) 	0.872
Financial	<ol style="list-style-type: none"> 1. Tax and/or legal fees 2. Cash flow difficulties 3. Poor financial control 4. Lack of capital 5. High tender price 6. High cost of materials and/or equipment 7. High cost of labour 	0.777
Legal	<ol style="list-style-type: none"> 1. Right of way acquisition 2. Deficient documentation 	0.721

		<ol style="list-style-type: none"> 3. Difficulties in importing equipment and materials 4. Changes in government regulations and laws 5. Unclear arbitration process for legal disputes between construction parties 6. Changing of bankers' policies for loans 7. Ineffective delay penalties 8. Type of contract 9. Problem in dispute settlement due to law 10. Contract failure 		
Political		<ol style="list-style-type: none"> 1. Political situation 2. Encroachment problems 3. Human-made disaster 	0.926	
Social		<ol style="list-style-type: none"> 1. Cultural heritage issue 2. Personal conflicts among labour 3. Social and cultural impacts 4. Rehabilitation of affected people 5. Disease 6. Security 7. Corruption 	0.869	
Technical	General	<ol style="list-style-type: none"> 1. Size of contract 2. Health and safety 3. Change order (change in the scope of the project) 4. Difficulty of schedule 5. Inadequate planning and scheduling 6. Payment delay 7. Contractual claim 8. Improper construction methods 9. Specification change 10. Poor communication/coordination between construction parties 11. Latent ground conditions 	0.773	0.707
	Labour	<ol style="list-style-type: none"> 1. Inadequate labour productivity 2. Absenteeism of labour 3. Shortage of skilled workers 4. Poor quality of workmanship 		0.712
	Material	<ol style="list-style-type: none"> 1. Unreliable supplier of material 2. Delay in material supply 3. Bad quality of materials 4. Shortage of materials 		0.794
	Equipment	<ol style="list-style-type: none"> 1. Low efficiency of equipment 2. Slow mobilisation of equipment 3. Late delivery of equipment 4. Availability of equipment 		0.876
	Technology	<ol style="list-style-type: none"> 1. Obsolete technology 2. New technology adoption 		0.814
	Consultant	<ol style="list-style-type: none"> 1. Lack of experience in design and supervision 2. Inaccurate investigation of construction site 3. Frequent design changes 4. Incomplete drawings, specifications 5. Mistakes in design and/or specifications 6. Inaccurate time and cost estimation 7. Inadequate monitoring and supervision 8. Delay in decision-making 9. Lack of technical staff 		0.732
	Contractor	<ol style="list-style-type: none"> 1. Lack of experience in the line of work 		0.829

		<ol style="list-style-type: none"> 2. Incorrect planning and scheduling 3. Frequent change of subcontractors 4. Poor quality of project management 5. Re-work due to contractor errors 6. Lack of technical staff 7. Incompetent contractor/subcontractor 		
Overall		Total: 76 events	0.759	

Table 4.11: Reliability value of disruptive events for the time component

Uncertainty group		Disruptive event	Cronbach's alpha	
Economic		<ol style="list-style-type: none"> 1. Fluctuation of prices of materials and/or equipment 2. Monopoly of material and/or equipment suppliers 3. Saturated market 4. Fluctuation in foreign exchange rate 	0.914	
Environmental		<ol style="list-style-type: none"> 1. Weather 2. Natural disasters 3. Remote location cost 4. Terrain (or topographical site) 	0.851	
Financial		<ol style="list-style-type: none"> 1. Tax and/or legal fees 2. Cash flow difficulties 3. Poor financial control 4. Lack of capital 5. High tender price 6. High cost of materials and/or equipment 7. High cost of labour 	0.753	
Legal		<ol style="list-style-type: none"> 1. Right of way acquisition 2. Deficient documentation 3. Difficulties in importing equipment and materials 4. Changes in government regulations and laws 5. Unclear arbitration process for legal disputes between construction parties 6. Changing of bankers' policies for loans 7. Ineffective delay penalties 8. Type of contract 9. Problem in dispute settlement due to law 10. Contract failure 	0.718	
Political		<ol style="list-style-type: none"> 1. Political situation 2. Encroachment problems 3. Human-made disaster 	0.901	
Social		<ol style="list-style-type: none"> 1. Cultural heritage issue 2. Personal conflicts among labour 3. Social and cultural impacts 4. Rehabilitation of affected people 5. Disease 6. Security 7. Corruption 	0.875	
Technical	General	<ol style="list-style-type: none"> 1. Size of contract 2. Health and safety 3. Change order (change in the scope of the project) 4. Difficulty of schedule 5. Inadequate planning and scheduling 6. Payment delay 7. Contractual claim 8. Improper construction methods 	0.761	0.711

		9. Specification change 10. Poor communication/coordination between construction parties 11. Latent ground conditions		
	Labour	1. Inadequate labour productivity 2. Absenteeism of labour 3. Shortage of skilled workers 4. Poor quality of workmanship		0.704
	Material	1. Unreliable supplier of material 2. Delay in material supply 3. Bad quality of materials 4. Shortage of materials		0.756
	Equipment	1. Low efficiency of equipment 2. Slow mobilisation of equipment 3. Late delivery of equipment 4. Availability of equipment		0.865
	Technology	1. Obsolete technology 2. New technology adoption		0.802
	Consultant	1. Lack of experience in design and supervision 2. Inaccurate investigation of construction site 3. Frequent design changes 4. Incomplete drawings, specifications 5. Mistakes in design and/or specifications 6. Inaccurate time and cost estimation 7. Inadequate monitoring and supervision 8. Delay in decisions making 9. Lack of technical staff		0.741
	Contractor	1. Lack of experience in the line of work 2. Incorrect planning and scheduling 3. Frequent change of subcontractors 4. Poor quality of project management 5. Re-work due to contractor errors 6. Lack of technical staff 7. Incompetent contractor/subcontractor		0.822
	Overall	Total: 76 events		0.735

As presented in Tables 4.10 and 4.11, the results of the reliability test indicate acceptable to excellent internal consistency for both cost and time components with reliability coefficients ranging from 0.7 to 0.9.

4.10.3.2 *Validity and reliability in qualitative research*

There is greater emphasis on validity than on reliability in qualitative research to determine whether information provided by the participants is accurate and credible (Leung, 2015) the study employed different approaches to improve the validity of the qualitative data collected. The careful selection of five expert panel members was used to address population validity. Internal validity was enhanced through the use of the standard rapid idea generation brainstorming process (See Section 4.9.3). Several strategies of validation such as group review and justification, were used to collect a valid set of disruptive events from the list of identified uncertainty and risk events in the construction process of infrastructure projects.

Furthermore, the developed research hypotheses based on the research conceptual framework were tested in order to validate the uncertainty portfolio concept. Finally, to enhance the replicability of the expert group brainstorming a detailed mind map of the existence of disruptive events in the construction of South African highway projects was prepared (See Figure 4.3).

4.11 ETHICAL CONSIDERATIONS

The integrity of research and described findings is protected by adopting ethical principles, Therefore, the planning and conducting of the research hinged on ethical norms such as integrity, honesty, informed consent, confidentiality, care and right to privacy (Richey and Klein, 2014). Ethical elements considered in the conducting and execution of this research included ensuring that all participants were informed about the purpose of the research and the nature of the data and information required from them before their participation in the research. The researcher ensured that participants' details remained confidential and protected any proprietary information throughout the study. The participants were permitted to accept or reject participation or to withdraw their participation without providing a reason at any time (Appendix A).

Furthermore, the study received the approval of the Ethics in Research Committee of the Engineering and the Built Environment Faculty at the University of Cape Town on December 22 2016 before data collection commenced (Appendix B).

4.12 SUMMARY OF THE CHAPTER

This chapter discussed and justified the research philosophy, research approach, instrument of data collection and methods of data analysis adopted by the study. The chapter recognised that the study is primarily deductive, but also requiring an interpretivist paradigm, which is suitable for addressing the complex issue of uncertainty impact on construction cost and duration of infrastructure projects. Hence, a pragmatist (multi-methodology) research approach, which draws from the strength of both the qualitative and quantitative approaches, was adopted. The research, therefore, employed a sequential exploratory mixed methods approach that relied on both qualitative and quantitative data in four sequential phases. The main data collection instrument was expert panel estimation, complemented by a questionnaire survey and supported by expert panel brainstorming and documentary evidence.

The study was carried out longitudinally across a period of time to gather the required data to answer the research question, since data was gathered at three different points in time: 1. Identified the source of uncertainty and disruptive events; 2. Estimated the unit costs and production rates and determined the existence of disruptive events in South African infrastructure projects; and 3. Obtained the probability of occurrence and the effect of the severity of disruptive events. The collected data were analysed with ANFIS and validated by stepwise regression analysis and nonparametric inferential statistics techniques.

CHAPTER FIVE: DATA PRESENTATION AND ANALYSIS

5.1 INTRODUCTION

To test and evaluate the capabilities and potential applicability of the developed uncertainty model on estimating construction cost and time of infrastructure projects, a specific case study was selected, and the description of the highway project chosen is presented in this chapter. The chapter also develops the construction model for highway projects and presents the obtained input data for modelling the uncertainty of the construction of highway projects.

5.2 CASE STUDY PROJECT

5.2.1 Description of the case study

The selected case study was a 16.5-kilometre section from a new highway infrastructure project with six lanes and controlled-access, which was constructed on both flat and hilly terrain in South Africa between 2014 and 2016. Construction of the highway project contained three major structures, namely: earthworks, bridges, and pavements. The initial estimated total construction cost of this section was ZAR 809,504,922.80 and total duration of 340 days. The construction of the project comprised: 2,973,692 cubic metres of earthworks in four different geological conditions, namely: fine, soft, hard and rock, 46 precast concrete bridges (box culvert and precast slab bridge) and 1,015,340 cubic metres of asphalt pavements.

See the highway plan (horizontal alignment), highway profile (vertical alignment) and highway cross sections of the project in Appendix C.

Construction of the study highway project encountered cost overrun and time delay. The initial cost and time estimation of each structure and overall highway project and the actual construction cost and duration of the project are summarised in Table 5.1.

Table 5.1: Initial estimation and actual construction cost and time of study highway project

		Earthwork	Bridge	Pavement	Overall Project
Initial estimation	Cost (ZAR)	244,292,292.83	70,952,700.00	494,259,930.00	809,504,922.83
	Time (Days)	215	340	217	340
Actual	Cost (ZAR)	410,415,938.89	96,543,919.84	657,775,942.64	1,164,735,801.37
	Time (Days)	431	539	320	539
Underestimation	Cost (ZAR)	166,123,646.06	25,591,219.84	163,516,012.64	355,230,878.57
	Time (Days)	216	199	103	199

As shown in Table 5.1, the study highway project was constructed with a 355,230,878.57 ZAR cost overrun and 199 days' time delay. According to the records of the project, the main causes of cost overrun and time delays were some unseen technical and social issues, such as the changing condition of the ground, some changes in design and specifications, and constraints caused by the community surrounding the project.

To evaluate and model the uncertainty at the level of single construction activities, the construction process of the highway project was modelled as described in the next section.

5.3 DATA ANALYSIS

In this section, the collected data from the series of expert panels' estimation, expert brainstorming, questionnaire survey and historical data are arranged and presented in order of the three sources of uncertainty as follows: variability of earthwork, bridge and pavement; correlation on earthwork, bridge and pavement; and disruptive events.

5.3.1 Variability in construction process of highway project

In the uncertainty model, variability is one of the three sources of uncertainty. The variability is the change in a variable under normal conditions. As discussed in Chapter Four, variability was modelled with probability distributions. Modelling the variability presents the range of the possible total cost and total time. To model the variability of costs and times and compare it to the deterministic cost and time of activity, the deterministic and variability distribution of unit costs and production rates of each construction activity of the project were needed.

The deterministic unit cost and production rate of all construction activities of the three structures were extracted from the case study project estimation. However, the possible ranges of unit cost and production rate of all construction activities of the three structures were not available. Therefore, these data were obtained by means of the series of expert panel estimations and validated by historical data of three comparable projects. This section presents the deterministic cost and time of activities as input data for modelling the variability of cost and time of a highway project.

5.3.1.1 Deterministic estimation of earthwork structure

The construction of the earthwork structure was restricted to cutting and filling constructions, with each construction involving its three activities (See Section 4.10.2.1). Along the cutting construction, the unit cost was varied according to the geological conditions. The geological conditions were distinguished between fine, soft, hard and rock. The time taken by an activity is a function of activity production rate. Therefore, to calculate the deterministic time of an activity, it is necessary to identify the production rate of each activity. Likewise, the deterministic cost and the production rates of the cutting activities were estimated as a function of the four geological conditions. The deterministic unit costs, the production rates, and the volumes of cutting where these geological conditions were encountered are given in Table 5.2, while only a unit cost and production rate were estimated for filling construction regardless of the geological conditions (Table 5.3).

The unit costs and production rates were extracted from the case study cost and time data bill of quantity and time schedule. The volume along the cuttings and fillings, where the geological conditions were encountered has been estimated, based on the horizontal plan and vertical profile plan of the highway case study.

Table 5.2: Deterministic unit costs and production rates of cutting activities in the different types of geological conditions

Activity	Geology	Volume	Unit Cost	Cost	Total Cost	Production Rate	Time	Total Time
		M ³	ZAR/M ³	ZAR	ZAR	M ³ /Day	DAY	DAY
Clearing the topsoil	Fine	327,591	14.05	4,602,653.55	12,916,937.60	14,000	24	34
	Soft	467,163	14.05	6,563,640.00		14,000	34	
	Hard	124,601	14.05	1,750,644.05		14,000	9	
	Rock	84,062	0	0		0	0	
Excavation	Fine	327,591	43.59	14,279,691.70	53,759,045.73	10,200	33	50
	Soft	467,163	48.44	22,629,376.00		9,500	50	
	Hard	124,601	50.03	6,233,788.03		4,570	28	
	Rock	84,062	126.29	10,616,190.00		2,960	29	
Improving the area and stabilising the trench	Fine	327,591	21.17	6,935,101.47	19,895,796.35	8,700	38	56
	Soft	467,163	20.14	9,408,663.00		8,400	56	
	Hard	124,601	18.88	2,352,466.88		7,900	16	
	Rock	84,062	14.27	1,199,565.00		7,200	12	
Total		86,571,779.68			140			

Table 5.3: Deterministic unit costs and production rates of filling activities

Activity	Unit Cost	Total Cost	Production Rate	Total Time
	ZAR/M ³	ZAR	M ³ /Day	DAY
Volume	1,970,275			
Clearing the topsoil	14.05	27,682,363.75	14,000	141
Improving the area	17.50	34,479,812.5	9,200	215
Embankment	48.50	95,558,337.5	12,500	158
Total	157,720,513.8		215	

5.3.1.2 Variability estimation of earthwork structure

The variability cost and time of earthwork activities stem from the estimation of the earthwork expert panel.

The variability unit costs and production rates of the three cutting activities (clearing the topsoil, excavation and improving the area, and stabilising the trench) in the four different geological conditions were estimated by a panel of experts and are summarised in Table 5.4.

Table 5.4: Variability unit cost of cutting activities in the different types of geological conditions

Activity	Geology	Variability	Unit Cost	Production Rate
			ZAR/M ³	M ³ /Day
Clearing the topsoil	Fine	Lower	13.78	12,760.00
		Most Likely	14.50	14,500.00
		Higher	15.95	15,660.00
	Soft	Lower	13.78	12,760.00
		Most Likely	14.50	14,500.00
		Higher	15.95	15,660.00
	Hard	Lower	13.78	12,760.00
		Most Likely	14.50	14,500.00
		Higher	15.95	15,660.00
Excavation	Fine	Lower	40.85	8,800.00
		Most Likely	43.00	10,000.00
		Higher	47.30	10,800.00
	Soft	Lower	46.08	8,008.00
		Most Likely	48.50	9,100.00
		Higher	53.35	9,828.00
	Hard	Lower	47.41	3,960.00
		Most Likely	49.90	4,500.00
		Higher	54.89	4,860.00
	Rock	Lower	119.89	2,550.00
		Most Likely	126.20	2,900.00
		Higher	138.82	3,130.00
Improving the area and stabilising the trench	Fine	Lower	19.86	7,480.00
		Most Likely	20.90	8,500.00
		Higher	22.99	9,180.00
	Soft	Lower	18.81	7,040.00
		Most Likely	19.80	8,000.00
		Higher	21.78	8,640.00
	Hard	Lower	17.58	6,600.00
		Most Likely	18.50	7,500.00
		Higher	20.35	8,100.00
	Rock	Lower	13.59	6,160.00
		Most Likely	14.30	7,000.00
		Higher	15.73	7,560.00

The variability unit costs and production rates of filling activities are summarised in Table 5.5.

Table 5.5: Variability unit cost of filling activities

Activity	Variability	Unit Cost	Production Rate
		Rand	M ³ /day
Clearing and removing the topsoil	Lower	13.77	13,340.00
	Most likely	14.50	14,500.00
	Higher	15.95	16,240.00
Embankment	Lower	16.43	8,280.00
	Most likely	17.30	9,000.00
	Higher	19.03	10,080.00
Improving the area	Lower	45.79	11,132.00
	Most likely	48.20	12,100.00
	Higher	53.20	13,552.00

5.3.1.3 *Deterministic estimation of bridge structure*

Two bridge methods were used in this highway project: precast concrete box culvert and precast slab bridge. The construction cost and time of bridges are dependent on the geological condition of the site and geometric parameters of the bridge. Along the 16.5-km case study highway, 46 bridges were constructed. The quantity and specification of the different types of bridges (box culvert, slab bridge) in the four geological conditions (fine, soft, hard and rock) were determined from the horizontal plan and vertical profile of the project and are listed in Table 5.6.

Table 5.6: Number of bridges with different geometry in four geological conditions

Bridge Type	Geology	Geometry	Number
Culvert	Fine	1x1x1 perpendicular	4
		1x1x1 skewed	12
	Soft	1x1x1 perpendicular	5
		1x1x1 skewed	20
		2x1x1 skewed	1
Slab bridge	Hard	1x2x2 perpendicular	1
		3x4x1 perpendicular	1
	Rock	1x2x2 perpendicular	1
		1x2x2 skewed	1

The deterministic construction cost of different bridge activities was estimated as a function of the four geological conditions and bridge geometry; however, due to very small differences of construction time of each activity in different geological conditions the deterministic construction time of the bridge activities was considered to be independent of geological conditions. The deterministic construction cost and time of each bridge activity is summarised in Tables 5.7 and 5.8, respectively. The deterministic cost and time of different bridges were extracted from the case study cost and time data.

Table 5.7: Deterministic costs and times of box culvert activities with different geometry in the different types of geological conditions.

Activity	Geometry	Cost		Time
		Fine	Soft	Day
		ZAR		
Set up Site	All	15,000.00		2
Bedding	1x1x1 perpendicular	162,000.00	144,000.00	14
	1x1x1 skewed	202,500.00	180,000.00	15
	2x1x1 skewed	-	300,000.00	17
Set Up culvert	1x1x1 perpendicular	720,000.00		6
	1x1x1 skewed	900,000.00		7
	2x1x1 skewed	1,800,000.00		9
Footing of wing wall	1x1x1 perpendicular	237,600.00	204,000.00	15
	1x1x1 skewed	297,000.00	255,000.00	16
	2x1x1 skewed	-	255,000.00	16
Wing wall	1x1x1 perpendicular	84,000.00		12
	1x1x1 skewed	100,800.00		14
	2x1x1 skewed	100,800.00		14
Backfilling	1x1x1 perpendicular	26,250.00		1
	1x1x1 skewed	31,500.00		1
	2x1x1 skewed	31,500.00		1
Total	1x1x1 perpendicular	1,244,850.00		30
	1x1x1 skewed	1,546,800.00		33
	2x1x1 skewed	2,502,300.00-		33

Table 5.8: Deterministic costs and time of slab bridge activities with different geometry in the different types of geological conditions

Activity	Geometry	Cost		Time
		Hard	Rock	
		ZAR		DAY
Set up Site	All	30,000.00		3
Footing of abutment	1x2x2 perpendicular	384,000.00	302,400.00	17
	1x2x2 skewed	480,000.00	378,000.00	18
	3x4x1 perpendicular	1,344,000.00	1,166,400.00	16
Abutment	1x2x2 perpendicular	324,000.00	300,000.00	17
	1x2x2 skewed	405,000.00	375,000.00	18
	3x4x1 perpendicular	600,000.00	576,000.00	14
Footing of pier	3x4x1 perpendicular	1,440,000.00	1,252,800.00	18
Pier	3x4x1 perpendicular	960,000.00	912,000.00	15
Footing of wing wall	1x2x2 perpendicular	172,800.00	144,000.00	17
	1x2x2 skewed	216,000.00	180,000.00	18
	3x4x1 perpendicular	172,800.00	144,000.00	15
wing wall	1x2x2 perpendicular	84,000.00	84,000.00	16
	1x2x2 skewed	100,800.00	100,800.00	17
	3x4x1 perpendicular	95,100.00	95,100.00	14
Precast deck	1x2x2 perpendicular	144,000.00	144,000.00	17
	1x2x2 skewed	186,000.00	186,000.00	18
	3x4x1 perpendicular	1,152,000.00	1,152,000.00	23
Backfilling	1x2x2 perpendicular	26,250.00		1
	1x2x2 skewed	31,500.00		1
	3x4x1 perpendicular	26,250.00		1
Total	3x4x1 perpendicular	1,165,050.00	1,030,650.00	55
	1x2x2 perpendicular	1,449,300.00	1,281,300.00	58
	1x2x2 skewed	5,820,150.00	5,354,550.00	60

5.3.1.4 Variability estimation of bridge structure

The range of variability costs and time of different bridge activities in both box culvert and slab bridge structures with different geometry and in different geological conditions stem from the panel of bridge experts. The lower, most likely and higher possible costs and times of culvert activities and slab bridge activities with different geometry and in different geological conditions are shown in Tables 5.9 and 5.10, respectively.

Table 5.9: Variability costs of culvert activities with different geometry in different geological conditions

Activity	Geometry	Cost						Time		
		Fine			Soft			Lower	Most Likely	Higher
		Lower	Most Likely	Higher	Lower	Most Likely	Higher			
		ZAR			ZAR			Day		
Set up Site	All	13,650.00	15,000.00	17,250.00	13,650.00	15,000.00	17,250.00	2	2	2
Bedding	1x1x1 perpendicular	146,510.00	161,000.00	185,150.00	130,585.00	143,500.00	165,025.00	11	13	15
	1x1x1 skewed	183,820.00	202,000.00	232,300.00	162,890.00	179,000.00	205,850.00	12	14	16
	2x1x1 skewed				273,455.00	300,500.00	345,575.00	15	17	20
Set Up culvert	1x1x1 perpendicular	656,565.00	721,500.00	829,725.00	656,565.00	721,500.00	829,725.00	5	6	7
	1x1x1 skewed	820,820.00	902,000.00	1,037,300.00	820,820.00	902,000.00	1,037,300.00	6	7	8
	2x1x1 skewed				1,639,820.00	1,802,000.00	2,072,300.00	7	8	9
Footing of wing wall	1x1x1 perpendicular	214,760.00	236,000.00	271,400.00	184,275.00	202,500.00	232,875.00	12	14	16
	1x1x1 skewed	269,815.00	296,500.00	340,975.00	231,140.00	254,000.00	292,100.00	13	15	18
	2x1x1 skewed				231,140.00	254,000.00	292,100.00	13	15	18
Wing wall	1x1x1 perpendicular	75,985.00	83,500.00	96,025.00	75,985.00	83,500.00	96,025.00	11	13	15
	1x1x1 skewed	91,000.00	100,000.00	115,000.00	91,000.00	100,000.00	115,000.00	12	14	16
	2x1x1 skewed				91,000.00	100,000.00	115,000.00	12	14	16
Backfilling	1x1x1 perpendicular	24,570.00	27,000.00	31,050.00	24,570.00	27,000.00	31,050.00	1	1	1
	1x1x1 skewed	28,210.00	31,000.00	35,650.00	28,210.00	31,000.00	35,650.00	1	1	1
	2x1x1 skewed				28,210.00	31,000.00	35,650.00	1	1	1
	1x1x1 skewed	1,407,315.00	1,546,500.00	1,778,475.00	1,347,710.00	1,481,000.00	1,703,150.00	28	32	37
	2x1x1 skewed				2,277,275.00	2,502,500.00	2,877,875.00	28	32	37
Total	1x1x1 perpendicular	1,132,040.00	1,244,000.00	1,430,600.00	1,085,630.00	1,193,000.00	1,371,950.00	26	30	35
	1x1x1 skewed	1,407,315.00	1,546,500.00	1,778,475.00	1,347,710.00	1,481,000.00	1,703,150.00	28	32	37
	2x1x1 skewed				2,277,275.00	2,502,500.00	2,877,875.00	28	32	37

Table 5.10: Variability costs and times of slab bridge activities with different geometry in different geological conditions

Activity	Geometry	Cost						Time		
		Hard			Rock			Lower	Most Likely	Higher
		Lower	Most Likely	Higher	Lower	Most Likely	Higher			
		ZAR			ZAR			DAY		
Set up Site	All	27,300.00	30,000.00	34,500.00	27,300.00	30,000.00	34,500.00	2	3	4
Footing of abutment	1x2x2 perpendicular	348,530.00	383,000.00	440,450.00	274,820.00	302,000.00	347,300.00	14	16	19
	1x2x2 skewed				342,615.00	376,500.00	432,975.00	15	17	20
	3x4x1 perpendicular	1,223,950.00	1,345,000.00	1,546,750.00				14	16	19
Abutment	1x2x2 perpendicular	295,295.00	324,500.00	373,175.00	273,910.00	301,000.00	346,150.00	16	18	21
	1x2x2 skewed				341,705.00	375,500.00	431,825.00	17	19	22
	3x4x1 perpendicular	546,910.00	601,000.00	691,150.00				12	14	16
Footing of pier	1x2x2 perpendicular	1,312,220.00	1,442,000.00	1,658,300.00				17	19	22
Pier	1x2x2 skewed	871,325.00	957,500.00	1,101,125.00				12	14	16
Footing of wing wall	1x2x2 perpendicular	156,520.00	172,000.00	197,800.00	130,585.00	143,500.00	165,025.00	16	18	21
	1x2x2 skewed				164,710.00	181,000.00	208,150.00	17	19	22
	3x4x1 perpendicular	156,520.00	172,000.00	197,800.00				12	14	16
Wing wall	1x2x2 perpendicular	77,350.00	85,000.00	97,750.00	77,350.00	85,000.00	97,750.00	14	16	19
	1x2x2 skewed				91,000.00	100,000.00	115,000.00	15	17	20
	3x4x1 perpendicular	85,995.00	94,500.00	108,675.00				13	15	18
Precast deck	1x2x2 perpendicular	131,950.00	145,000.00	166,750.00	131,950.00	145,000.00	166,750.00	16	18	21
	1x2x2 skewed				168,350.00	185,000.00	212,750.00	17	19	22
	3x4x1 perpendicular	1,049,685.00	1,153,500.00	1,326,525.00	-	-	-	21	24	28
Backfilling	1x2x2 perpendicular	24,570.00	27,000.00	31,050.00	24,570.00	27,000.00	31,050.00	1	1	1
	1x2x2 skewed				28,210.00	31,000.00	35,650.00	1	1	1
	3x4x1 perpendicular	24,570.00	27,000.00	31,050.00				1	1	1
Total	3x4x1 perpendicular	1,061,515.00	1,166,500.00	1,341,475.00	940,485.00	1,033,500.00	1,188,525.00	49	56	66
	1x2x2 perpendicular				1,163,890.00	1,279,000.00	1,470,850.00	52	59	69
	1x2x2 skewed	5,298,475.00	5,822,500.00	6,695,875.00				54	61	71

5.3.1.5 *Deterministic estimation of pavement structure*

The unit cost and production rate of each layer of pavement were extracted from the case study cost and time data, and the volume of layers has been estimated based on the horizontal plan and vertical profile plan of the highway case study. The deterministic unit cost and production rate volume of the various pavement layers are listed in Table 5.11.

Table 5.11: Deterministic unit costs and production rate volume of pavement activities

Activity	Volume	Unit Cost	Total Cost	Production Rate	Time
	M ³	ZAR/M ³	ZAR	M ³ /DAY	DAY
Subgrade	183,688	205.00	37,656,040.00	6,400	29
Subbase	402,412	320.00	128,771,840.00	6,070	67
Base	268,275	535.00	143,527,125.00	4,250	64
Surface	160,965	1,145.00	184,304,925.00	2,860	57
Total			494,259,930.00		217

5.3.1.6 *Variability estimation of pavement structure*

The ranges of unit costs and production rates for the different pavement activities estimated by the pavement experts are shown in Table 5.12.

Table 5.12: Variability unit costs and production rates of pavement activities

Activity	Unit Cost			Production Rate		
	Lower	Most likely	Higher	Lower	Most likely	Higher
	ZAR			M ³ /DAY		
Subgrade	201.60	210.00	226.80	5,715	6,350	6,731
Subbase	303.36	316.00	341.28	5,445	6,050	6,413
Base	515.52	537.00	579.96	3,915	4,350	4,611
Surface	1,101.12	1,147.00	1,238.76	2,565	2,850	3,021

The deterministic and possible ranges of unit costs and production rates of activities estimated by the experts were employed to model the variability of cost and time, and evaluate the impact of variability on total cost and total time of the highway project, described in Chapter Six.

5.3.2 **Correlation between the activities cost and times of the highway project**

In the uncertainty model, cost and time correlations are one of the three sources of uncertainty. In this section, the input data for modelling correlation of costs and times of three structures of a highway project are presented. To evaluate the impact of correlations on the distributions of total cost and total time, a correlated probabilistic analysis was required. The unit cost and production rate data of each activity were presented in Section 5.2.

In the following sections, the estimations of the expert panel for identified correlations of the three main structures of the case study are presented.

5.3.2.1 *Correlation between the costs/times of a repeated activity in a structure*

As discussed earlier the costs and times of a repeated activity are expected to be positively correlated because of the repetitiveness of the processes in a structure. To analyse the impact of repeated activities in cost/time of activities of each highway structure, the following three correlation scenarios are considered:

Scenario 1. Every unit is independent, $\rho=0$.

Scenario 2. Intermediate scenarios include all positive correlations, $\rho=(0, 1)$.

Scenario 3. Every unit is perfectly correlated, $\rho=1$.

Furthermore, the panel of experts identified the relationship of repeating activities cost and time of different structures of highway projects with the geometry and geological conditions.

Correlation between the repeated activity in the earthwork structure

Cutting construction: The activities, clearing the topsoil, excavation and improving the area and stabilising the trench, were repeated in the construction of a cutting. The activity cut (excavation) may change along the cutting if geology changes.

Filling construction: The activities, clearing the topsoil, embankment and improving the area, were repeated in the construction of a filling.

Correlation between the repeated activity in the bridge structure

Box culvert: The activities, set up the site, bedding, set up the culvert, wing wall footing, wing wall and backfilling, were repeated in the construction of the same geometry culvert. The activities bedding and, wing wall footing, may change along the same geometry culvert if geology changes.

Slab bridge: The activities, set up the site, the footing of the abutment, abutment, the footing of the pier, pier, the footing of wing wall, wing wall, decking and backfilling, were repeated in the construction of a same geometry slab bridge. The activities, wing wall footing, footing of abutment and footing of the pier, may change along the same geometry bridge if geology changes.

Correlation between the repeated activity in the pavement structure

The activities, subgrade, subbase, base and surface, are repeated in the construction of pavement which was independent of the geology.

5.3.2.2 *Correlation between the costs/times of the various activities in a structure*

To evaluate the correlation between the various activities in each of the three structures of the highway project, the expert panel considered that the costs/times of the various activities in a structure were positively correlated because these activities were subjected to the same type of constraints. Associated activities in each structure are correlated. Activities changed from structure to structures therefore, this correlation was analysed one structure at a time.

Correlation between the various activities in earthwork structure

Cutting construction: Based on the panel of earthwork experts' opinion regarding clearing the topsoil, excavation and improving the area and stabilising the trench activities in cutting construction, the cost/time of the excavation and improving the area and stabilising the trench were subject to the geological conditions, unlike the cost and time of clearing the topsoil. In other words, if the cost/time of excavation were changed due to geological and/or access conditions of the site, similarly the cost and time of improving the area and stabilising the trench would be changed and vice versa. The expert panel evaluated the association between costs/time of the cutting construction based on their opinions, then they validated their estimated correlation coefficient by analysing three comparable projects and recommended the $\rho = +0.75$ Spearman correlation coefficient between the activities of cutting construction.

Filling construction: The expert panel stated that the cost and time of the embankment and improving the area activities are subject to site access constraints. It means, if the site access was difficult when constructing the embankment, similarly it was difficult for the activity of improving the area. The earthwork expert panel suggested the $\rho = +0.8$ correlation coefficient between the cost/time of the construction of embankment and improving the area activities due to site access, using their previous experience and evaluation of the three available highway projects.

Correlation between the various activities in bridge structure

Box culvert: The construction of a culvert was modelled with the set up of the site, bedding, set up the culvert, wing wall footing, wing wall and backfilling activities. The cost and time of the bedding, wing wall and wing wall activities were subject to the geological and site access conditions. It means that, if the cost and time of one of these three activities were changed due to geological and/or site access conditions, similarly the cost and time of the other two activities were changed. The bridge expert panel evaluated the relationship between costs/time of the box culvert construction of the three highway projects and they recommended the $\rho = +0.7$ correlation coefficient between the bedding, wing wall and wing wall activities based on their analysis and experience.

Slab bridge: The construction of a slab bridge was modelled with set up site, footing of the abutment, abutment, footing of pier, pier, footing of wing wall, wing wall, decking and backfilling activities. Similarly, to the culvert construction, the cost and time of footing of abutment, abutment, the footing of pier, pier, footing of wing wall and wing wall are related to the geological and site access conditions. Thus, the bridge expert panel estimated $\rho = +0.65$ correlation coefficient between footing of abutment, abutment, footing of pier, pier, footing of wing wall and wing wall activities of the slab bridge construction, based on their opinions and evaluating the correlation between the costs/times of activities of slab bridges of the three similar projects.

Correlation between the various activities in pavement structure

The structure of pavement was modelled with subgrade, subbase, base and surface activities. The expert panel specified that the costs/times of the subgrade, subbase and base activities were subject

to site access constraints. If the site access is difficult for the subgrade activity, similarly it will be difficult for the subbase and base activities. Thus, the expert panel calculated a positive correlation between the costs/times of the subgrade, subbase and base activities correlated due to site access. Similar to the earthwork and bridge structures, the expert panel suggested $\rho = +0.85$ as the correlation coefficient between the costs/times of various activities in pavement structure based on their experience and analysing the costs/times of the three highway projects.

5.3.2.3 *Correlation between the costs/times of activities in adjacent structures*

Typical adjacent structures in highway projects are: cutting-filling, filling-bridges, cutting-pavement, filling-pavement, bridge-pavement. It is possible but unusual to have adjacent cutting and bridge. Activities change from structure to structure; therefore, this correlation was analysed for a pair of typical adjacent structures at a time.

Cutting-Filling: The construction of cutting and the construction of a filling share the clearing the topsoil activities. The expert panel considered the following two situations:

If clearing the topsoil of the cuts was done separately from clearing the topsoil of the fills so that clearing the topsoil was interrupted between the cut and the fill, cost/time of clearing the topsoil of the cutting construction was independent of the cost/time of clearing the topsoil of the filling construction. Alternatively, if the clearing the topsoil activity was repeated without interruption from the beginning to the end of the cut and fill sequence, the costs and times should be modelled as correlated costs/times of repeated activity in the same structure.

Filling-Bridge, Cutting-Pavement, Filling-Pavement, Bridge-Pavement: Although these pairs of structures are adjacent, they do not share any activities. Furthermore, the geology was considered differently because the costs and times of filling and pavement activities were independent of geological conditions. Therefore, the expert panel considered there to be no correlation between the costs/times of each these pairs.

Cutting-Bridge: The cutting and the bridge are excavated in the same geology so that correlations between the costs/times of the cut activity (excavating) and the cost of the bridge activity (bedding, footings) are expected. The cost/time distribution of a cut and the cost/time distribution of a bridge were functions of the geology in the sense that different cost/time distributions apply for different geologies with different excavation methods. Thus, the expert panel considered there to be no correlation between the costs/times of excavation of cutting and bridge due to the different methods of excavation.

5.3.2.4 *Correlation between the costs/times of same activities in the same type of structures*

Positive correlations between the costs and times of the same type of structures (between bridge i and bridge j, between cut i and cut j, between fill i and fill j) were expected if the geology (cut, bridge) and geometry (bridge) were similar. The cost and time distribution of a bridge and cut structure were a function of the geology and the cost and time of a bridge were a function of the geometry so that similar geologies and geometry determined similar cost and time distributions.

The expert panel agreed that the costs and times of the same activities in the same type of structures were assumed to be independent, since the simulation should be assigned new numbers from the input cost and time distributions, when the construction of a new structure was started. Thus, the underlying assumption is that structures were in different locations and/or using different construction methods.

5.3.2.5 *Correlation between the cost and time of an activity*

Due to the difficulty of measuring the association between the cost and time of an activity, all members of the expert panel agreed to use $\rho=+0.8$ as correlation coefficient to model the correlation between the cost and time of activities. To model the correlations on the construction cost and duration of activities and evaluate the impact of the identified three correlations on the total cost and total time of the project, a correlated probabilistic analysis was required (See Chapter Six). Essentially, the probabilistic distributions data of the cost and time variables were not available. Therefore, to model the correlation with copula, the following marginal distribution assumptions were constructed by the panel of experts, based on the results of the variability of cost and time estimation sessions, to generate a correlation probability distribution of costs and times.

- The underlying distributions of cost variables and time variables are lognormal and triangular, respectively.
- The modes of the cost and time distribution are assumed equal to the deterministic cost and time.
- The minimum value of the cost and time distributions are 80% of the mode of each variable's distribution.
- There is a probability of 2% of exceeding the High Value, which is assumed to be 150% of the mode, of the cost distributions.
- The maximum of the time distributions is assumed to be 130% of the mode of the time distributions.

5.3.3 Disruptive events

To model the impact of 76 justified disruptive events on construction cost and time of highway projects in South Africa, the questionnaire survey was used (See Appendix A). The two sets of required data, the probability of occurrence and the effect of the severity of events, were obtained from the closed-ended questionnaires completed by 32 project managers of highway construction projects in South Africa. The study sought to know the probability of occurrence and severity of each disruptive event based on their last three completed highway projects. The data collected are presented and analysed in the following sub-section.

5.3.3.1 *General profile of the project managers surveyed*

As highlighted in Chapter Four the survey respondents of the study comprised of 32 project managers of highway construction projects under construction in 2017 with a minimum 20 years of experience in South African highway construction projects and registered as professional

engineers or construction project managers with the appropriate Built Environment Registration Council.

The profile of the participating project managers is presented in Table 5.13. Results from the descriptive statistics analysis captured the project managers' age, experience/years in the construction of a highway project, their highest level of qualification, and registration status.

Table 5.13: General profile of surveyed project managers

Description	Frequency (N)	Valid percentage (%)	Cumulative Percentage (%)
Age (Years old)			
40-49	7	21.9%	21.9%
50-59	15	46.9%	68.8%
60-69	9	28.1%	96.9%
>69	1	3.1%	100.0%
Experience/years in the construction of highway projects (Years)			
20-25	17	53.1%	53.1%
25-30	11	34.4%	87.5%
>30	4	12.5%	100.0%
Highest level of qualification			
Bachelor	12	37.5%	37.5%
Honours	17	53.1%	90.6%
Master'	3	9.4%	100.0%
Registered professional			
Pr civil engineering	23	71.9%	71.9%
Pr civil engineering & Pr construction project manager	9	28.1%	100.0%

The results show that 21.9% of surveyed project managers are 40 to 49 years old, 46.9% are 50 to 59 years old, 28.1% are 60 to 69 years old and 3.1% are above 69 years old. Regarding experience, 53.1%, 34.4% and 12.5% of project managers have 20 to 25 years', 25 to 30 years' and more than 30 years' experience in construction of highway projects, respectively. Furthermore, 37.5% of surveyed project managers hold a Bachelor's degree, 53.1% hold an Honours degree, and 9.4% hold a Master's degree. Table 5.13 also shows that 71.9% of the project managers are registered as professional civil engineers, while 28.1% of project managers are registered as professional civil engineers and professional construction project managers.

5.3.3.2 *The probability of occurrence and the effect of the severity of an event*

To quantify the impact of the disruptive events on construction cost and duration of highway projects, the surveyed project managers were asked to assess the two input variables using a five-point Linguistic Likert scale.

The prevalence results of the questionnaire for the probability of occurrence and the effect of the severity of events on the cost and time of project are summarised in Table 5.14.

Table 5.14: Frequencies of response for input on disruptive events

Code	Event	Probability of occurrence					Effect of severity on cost					Effect of severity on time				
		Rare	Unlikely	Possible	Likely	Almost certain	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
EC1	Fluctuation of prices of materials and/or equipment	0%	9%	22%	44%	25%	0%	3%	34%	47%	16%	6%	31%	41%	22%	0%
EC2	Monopoly of material and/or equipment suppliers	0%	3%	19%	53%	25%	0%	19%	50%	31%	0%	9%	53%	38%	0%	0%
EC3	Saturated market	9%	31%	53%	6%	0%	0%	31%	44%	25%	0%	38%	41%	22%	0%	0%
EC4	Fluctuation in foreign exchange rate	0%	3%	31%	50%	16%	0%	6%	66%	28%	0%	53%	44%	3%	0%	0%
EN1	Weather	0%	0%	34%	50%	16%	25%	47%	28%	0%	0%	3%	22%	47%	28%	0%
EN2	Natural disasters (earthquake, floods, hurricane, etc.)	0%	50%	44%	6%	0%	0%	0%	0%	44%	56%	0%	0%	6%	41%	53%
EN3	Remote location cost	0%	0%	16%	44%	41%	0%	0%	50%	47%	3%	0%	56%	41%	3%	0%
EN4	Terrain or topographical	0%	0%	13%	47%	41%	0%	78%	19%	3%	0%	34%	59%	6%	0%	0%
FI1	Tax and/or legal fees	9%	50%	41%	0%	0%	0%	0%	47%	53%	0%	56%	44%	0%	0%	0%
FI2	Cash flow difficulties	0%	6%	47%	47%	0%	0%	13%	59%	28%	0%	0%	28%	50%	22%	0%
FI3	Poor financial control	0%	9%	47%	44%	0%	0%	9%	63%	28%	0%	13%	59%	28%	0%	0%
FI4	Lack of capital	3%	47%	47%	3%	0%	0%	0%	31%	44%	25%	0%	6%	56%	38%	0%
FI5	High tender price (higher than estimate)	0%	13%	50%	38%	0%	0%	0%	41%	56%	3%	53%	41%	6%	0%	0%
FI6	High cost of materials and/or equipment	0%	6%	59%	34%	0%	0%	0%	41%	50%	9%	41%	50%	9%	0%	0%
FI7	High cost of labour	0%	6%	53%	41%	0%	0%	0%	66%	28%	6%	66%	28%	6%	0%	0%
LE1	Right of way acquisition (land acquisition)	0%	0%	44%	50%	6%	0%	38%	59%	3%	0%	0%	22%	53%	25%	0%
LE10	Contract failure - new contract establishment cost	0%	34%	50%	16%	0%	0%	3%	59%	38%	0%	0%	19%	66%	16%	0%
LE2	Deficient documentation	3%	31%	56%	9%	0%	0%	44%	44%	13%	0%	6%	53%	34%	6%	0%
LE3	Difficulties in importing equipment and materials	53%	47%	0%	0%	0%	13%	50%	38%	0%	0%	0%	25%	50%	25%	0%
LE4	Changes in government regulations and laws	6%	38%	56%	0%	0%	0%	9%	50%	41%	0%	0%	22%	50%	28%	0%
LE5	Unclear arbitration process for legal disputes between construction parties	0%	34%	63%	3%	0%	3%	53%	44%	0%	0%	0%	38%	53%	9%	0%
LE6	Changing of bankers' policies for loans	19%	56%	25%	0%	0%	0%	0%	28%	34%	38%	13%	44%	41%	3%	0%
LE7	Ineffective delay penalties	0%	38%	56%	6%	0%	9%	63%	28%	0%	0%	0%	19%	59%	22%	0%
LE8	Type of contract	3%	44%	47%	6%	0%	0%	28%	56%	16%	0%	0%	38%	59%	3%	0%
LE9	Problem in dispute settlement due to law	0%	0%	47%	44%	9%	0%	66%	34%	0%	0%	0%	0%	66%	34%	0%
PL1	Political situation	0%	0%	41%	47%	13%	0%	16%	59%	25%	0%	0%	9%	47%	44%	0%
PL2	Encroachment problems	0%	16%	56%	28%	0%	0%	50%	47%	3%	0%	0%	34%	56%	9%	0%
PL3	Human-made disaster (war, protest, strike, etc.)	0%	0%	6%	31%	63%	0%	0%	63%	38%	0%	0%	0%	9%	59%	31%
SO1	Cultural heritage issue	0%	0%	38%	53%	9%	31%	63%	6%	0%	0%	3%	34%	59%	3%	0%
SO2	Personal conflicts among labour	0%	3%	66%	31%	0%	50%	44%	6%	0%	0%	28%	63%	9%	0%	0%
SO3	Social and cultural impacts	0%	0%	13%	41%	47%	0%	56%	44%	0%	0%	0%	34%	63%	3%	0%
SO4	Rehabilitation of affected people	0%	0%	3%	53%	44%	0%	72%	28%	0%	0%	0%	0%	6%	47%	47%
SO5	Disease (HIV, Ebola, etc.)	0%	0%	19%	59%	22%	0%	0%	44%	47%	9%	0%	0%	25%	59%	16%
SO6	Security	0%	0%	6%	53%	41%	0%	44%	53%	3%	0%	0%	50%	47%	3%	0%
SO7	Corruption	0%	0%	0%	53%	47%	0%	3%	69%	28%	0%	6%	53%	34%	6%	0%
TCR1	Lack of experience in the line of work	9%	50%	41%	0%	0%	0%	22%	59%	19%	0%	3%	31%	63%	3%	0%

TCR2	Incorrect planning and scheduling by contractor	0%	6%	59%	34%	0%	0%	63%	38%	0%	0%	0%	44%	50%	6%	0%
TCR3	Frequent change of subcontractors	0%	16%	47%	38%	0%	13%	59%	28%	0%	0%	3%	38%	47%	13%	0%
TCR4	Poor quality of project management	0%	0%	31%	53%	16%	0%	34%	53%	13%	0%	0%	16%	44%	41%	0%
TCR5	Rework due to contractor errors	0%	0%	34%	59%	6%	0%	16%	59%	25%	0%	0%	13%	47%	41%	0%
TCR6	Lack of technical staff	0%	6%	41%	50%	3%	0%	59%	41%	0%	0%	0%	50%	47%	3%	0%
TCR7	Incompetent contractor/subcontractor	0%	28%	59%	13%	0%	3%	50%	47%	0%	0%	3%	41%	53%	3%	0%
TCS1	Lack of experience in design and supervision	6%	50%	41%	3%	0%	9%	53%	38%	0%	0%	9%	47%	41%	3%	0%
TCS2	Inaccurate investigation of construction site	0%	3%	53%	41%	3%	0%	3%	75%	22%	0%	3%	28%	59%	9%	0%
TCS3	Frequent design changes	0%	0%	50%	47%	3%	0%	3%	63%	34%	0%	0%	6%	47%	47%	0%
TCS4	Incomplete drawings, specifications	0%	0%	25%	63%	13%	0%	41%	53%	6%	0%	0%	16%	59%	25%	0%
TCS5	Mistakes in design and/or specifications	0%	28%	59%	13%	0%	0%	34%	50%	16%	0%	0%	19%	50%	31%	0%
TCS6	Inaccurate time and cost estimation	0%	0%	6%	41%	53%	0%	0%	22%	38%	41%	0%	0%	0%	34%	66%
TCS7	Inadequate monitoring and supervision	0%	34%	59%	6%	0%	13%	47%	41%	0%	0%	0%	44%	53%	3%	0%
TCS8	Delay in decisions making	0%	0%	6%	63%	31%	50%	47%	3%	0%	0%	6%	41%	47%	6%	0%
TCS9	Lack of technical staff	0%	0%	66%	34%	0%	63%	34%	3%	0%	0%	3%	72%	22%	3%	0%
TE1	Low efficiency of equipment	0%	6%	38%	56%	0%	22%	66%	13%	0%	0%	6%	22%	59%	13%	0%
TE2	Slow mobilisation of equipment	25%	69%	6%	0%	0%	53%	47%	0%	0%	0%	19%	56%	25%	0%	0%
TE3	Late delivery of equipment	0%	41%	56%	3%	0%	63%	34%	3%	0%	0%	16%	50%	28%	6%	0%
TE4	Availability of equipment	0%	25%	69%	6%	0%	66%	34%	0%	0%	0%	9%	53%	38%	0%	0%
TG1	Size of contract	34%	59%	6%	0%	0%	28%	72%	0%	0%	0%	19%	72%	9%	0%	0%
TG10	Poor communication/coordination between construction parties	0%	6%	38%	56%	0%	78%	22%	0%	0%	0%	9%	72%	13%	6%	0%
TG11	Latent ground conditions	0%	0%	3%	22%	75%	0%	0%	0%	22%	78%	0%	0%	0%	34%	66%
TG2	Health and safety	0%	0%	9%	53%	38%	16%	66%	19%	0%	0%	13%	63%	19%	6%	0%
TG3	Change order (change in the scope of the project)	0%	0%	9%	59%	31%	0%	53%	47%	0%	0%	9%	34%	50%	6%	0%
TG4	Difficulty of schedule	0%	6%	59%	34%	0%	0%	53%	47%	0%	0%	0%	0%	9%	44%	47%
TG5	Inadequate planning and scheduling	0%	0%	0%	44%	56%	25%	44%	31%	0%	0%	0%	0%	9%	47%	44%
TG6	Payments delay	0%	6%	41%	50%	3%	0%	28%	59%	13%	0%	3%	13%	59%	25%	0%
TG7	Contractual claim	0%	63%	38%	0%	0%	0%	6%	31%	47%	16%	6%	34%	50%	9%	0%
TG8	Improper construction methods	0%	6%	69%	25%	0%	22%	41%	38%	0%	0%	13%	16%	59%	13%	0%
TG9	Specification change	0%	0%	6%	72%	22%	3%	31%	50%	16%	0%	0%	6%	28%	53%	13%
TL1	Inadequate labour productivity	0%	0%	13%	63%	25%	0%	56%	44%	0%	0%	6%	19%	63%	13%	0%
TL2	Absenteeism of labour	0%	3%	72%	25%	0%	66%	34%	0%	0%	0%	13%	53%	34%	0%	0%
TL3	Shortage of skilled workers	0%	0%	41%	59%	0%	22%	63%	16%	0%	0%	3%	6%	63%	28%	0%
TL4	Poor quality of workmanship	0%	0%	69%	31%	0%	16%	38%	47%	0%	0%	6%	25%	63%	6%	0%
TM1	Unreliable supplier of material	0%	3%	59%	38%	0%	28%	59%	13%	0%	0%	6%	13%	69%	13%	0%
TM2	Delay in material supply	0%	0%	66%	34%	0%	53%	47%	0%	0%	0%	0%	3%	38%	56%	3%
TM3	Bad quality of materials	0%	0%	41%	59%	0%	0%	16%	69%	16%	0%	0%	13%	56%	25%	6%
TM4	Shortage of materials	0%	3%	72%	25%	0%	16%	50%	34%	0%	0%	0%	9%	34%	50%	6%
TT1	Obsolete technology	0%	0%	59%	41%	0%	0%	9%	47%	44%	0%	0%	9%	38%	38%	16%
TT2	New technology adoption	0%	0%	81%	19%	0%	0%	9%	44%	47%	0%	0%	6%	31%	59%	3%

Table 5.14 presented the assessment frequency of project managers for the input variables of disruptive events in a five-point Linguistic Likert scale.

Table 5.14 shows that the latent ground conditions (TG11) have the highest probability of occurrence (75% almost certain, 22% likely, 3% possible), followed by the effect of severity on construction cost (78% catastrophic, 22% major) and time (66% catastrophic, 34% major) in

highway projects in South Africa. On the other hand, difficulties in importing equipment and materials (LE3), slow mobilisation of equipment (TE2) and size of contract (TG1) have the lowest probability of occurrence (47% unlikely, 53% rare), effect of severity on construction cost (47% minor, 53% insignificant) and time (9% moderate, 72% minor, 19% insignificant).

5.4 SUMMARY OF THE CHAPTER

This chapter presented the description and construction model of the selected project to test the uncertainty model. Furthermore, the chapter summarised and presented the obtained input data for modelling the three sources of uncertainty, which were collected through a series of expert panel estimation sessions, group experts' brainstorming and questionnaire survey.

The construction model of the project and obtained input data are employed to model the uncertainty and assess the impact of uncertainties on total cost and total time of construction of the highway project, the obtained Linguistic values of probability of occurrence and the severity of events are converted to fuzzy values and used in modelling the impact of disruptive events, in Chapter Six.

CHAPTER SIX: APPLICATION OF THE UNCERTAINTY MODEL TO AN INFRASTRUCTURE PROJECT

6.1 INTRODUCTION

This chapter applies the developed construction and uncertainty models to the construction of a new highway project as a case study and presents the impacts of the three sources of uncertainty and their cumulative impacts on construction cost and time of the highway project. The collected input data used in this chapter were obtained from a series of expert panel estimations, expert brainstorming, a questionnaire survey and historical data employed to model variability, correlation and disruptive events on the selected construction of the highway project.

The chapter is arranged and presented in order of the three sources of uncertainty as follows: variability, correlation and disruptive events on earthwork, bridge, and pavement structures, respectively. Lastly, the chapter presents the cumulative impacts of three sources of uncertainty and the results of testing the research hypotheses.

6.2 MODELLING VARIABILITY IN THE CONSTRUCTION PROCESS OF HIGHWAY PROJECTS

This section describes the process of modelling of variability in three main structures of highway projects and assesses the impact of variability in each activity of structures and total cost and total time of highway projects.

6.2.1 Variability related to the earthwork structure

The construction of the earthwork structure was modelled with two constructions: cutting and filling. The construction of cutting was modelled as a sequence of three activities: clearing the topsoil, excavation, and improving the area and stabilising the trench (See Figure 4.15) while the construction of filling was modelled as a parallel of three activities: clearing the topsoil, improving the area, and embankment (See Figure 4.16).

6.2.1.1 Modelling variability of the cost of the earthwork structure

The variability of the cost of the earthwork activities stemmed from the estimations of the earthwork expert panel and historical data (See Chapter Five). The cost parameters estimated by the panel were used to produce the lognormal probability distributions, which were utilised to model the cost variability of the earthwork constructions. The lower estimated cost was considered as the minimum point of the lognormal probability distribution function (PDF), most likely estimated cost was considered as the mode, and the higher estimated cost was considered as maximum lognormal PDF.

The total variability of cost for each activity of the two constructions (cutting, filling) of the earthwork structure was calculated using the total variability unit costs estimated by the earthwork expert panel (Tables 5.4 and 5.5) and volume of each activity (Equation 4.1).

For instance, the cost of the activity, clearing the topsoil in fine geology, was calculated as Equation 6.1.

$$\begin{aligned} \text{Cost of clearing the topsoil in fine geology} &= 14.05 \times 327,591 \\ &= \text{ZAR}4,602,653.55 \end{aligned} \quad [6.1]$$

The total cost of cutting and filling construction was calculated by the sum of all the activities costs in the cutting and filling constructions according to Equations 4.5 and 4.6, and the results are summarised in Table 6.2.

Table 6.1: Total variability of cost of cutting and filling construction and earthwork structure

	Geology	Cost variability (ZAR)		
		Minimum	Mode	Maximum
Cutting construction	Fine	24,398,977.68	25,683,134.40	28,251,447.84
	Soft	36,747,041.58	38,681,096.40	42,549,206.04
	Hard	9,812,951.76	10,329,422.90	11,362,365.19
	Rock	11,220,175.45	11,810,711.00	11,810,711.00
Total cutting construction		82,179,146.47	86,504,364.70	95,154,801.17
Total filling construction		149,740,900.00	157,622,000.00	173,384,200.00
Total earthwork structure		231,920,046.47	244,126,364.70	268,539,001.17

The cost variability model (lognormal) of the earthwork structure is presented in Figure 6.1.

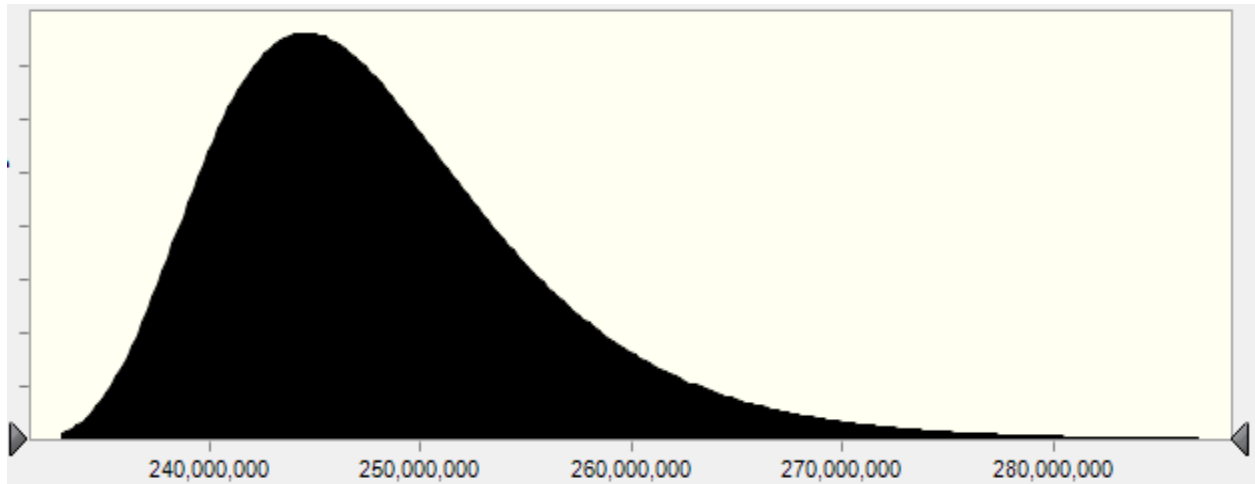


Figure 6.1: Cost variability model of the earthwork structure

As shown in the cost variation model of the earthwork structure (Figure 6.1), the cost distribution is skewed to the right, which attests that the probability that cost underestimation is substantially larger than the probability of cost overestimation, as illustrated by the cumulative cost distribution of the structure (Figure 6.2).

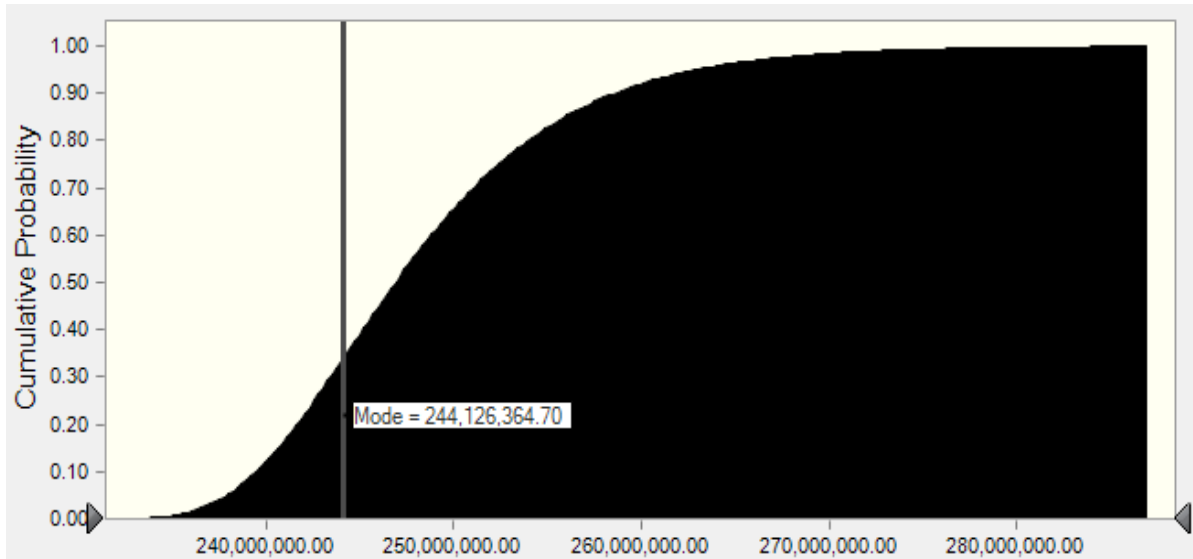


Figure 6.2: Cumulative cost distribution of the earthwork structure

6.2.1.2 *Modelling variability of time of the earthwork structure*

Similarly, to variability of cost, the production rate assessed by the panel of experts was used to obtain the triangular variability distribution. The triangular variability distribution was utilised to model the time variability of different constructions of the earthwork structure. The lower estimated production rate was considered as the minimum point of triangular PDF, most likely estimated production rate was considered as the mode, and the higher estimated production rate was considered as maximum PDF. The total variability of time of the cutting and filling constructions and overall time variability of the earthwork structure was calculated by Equation 4.2, using the production rate estimated by the earthwork experts (Tables 5.4 and 5.5) and volume of each construction.

The total time of cutting and filling constructions was given by the sum of all the critical activities (located on the critical path) as formulated in Equations 4.7 and 4.8 and are presented in Table 6.2.

Table 6.2: Total variability of time of cutting and filling construction and the earthwork structure

	Geology	Time variability (DAY)		
		Minimum	Mode	Maximum
Cutting construction	Fine	87	94	107
	Soft	132	142	162
	Hard	49	53	61
	Rock	38	41	47
Total cutting construction		132	142	162
Total filling construction		203	219	249
Total earthwork structure		203	219	249

The time variability model (triangular) of the earthwork structure is presented in Figure 6.3.

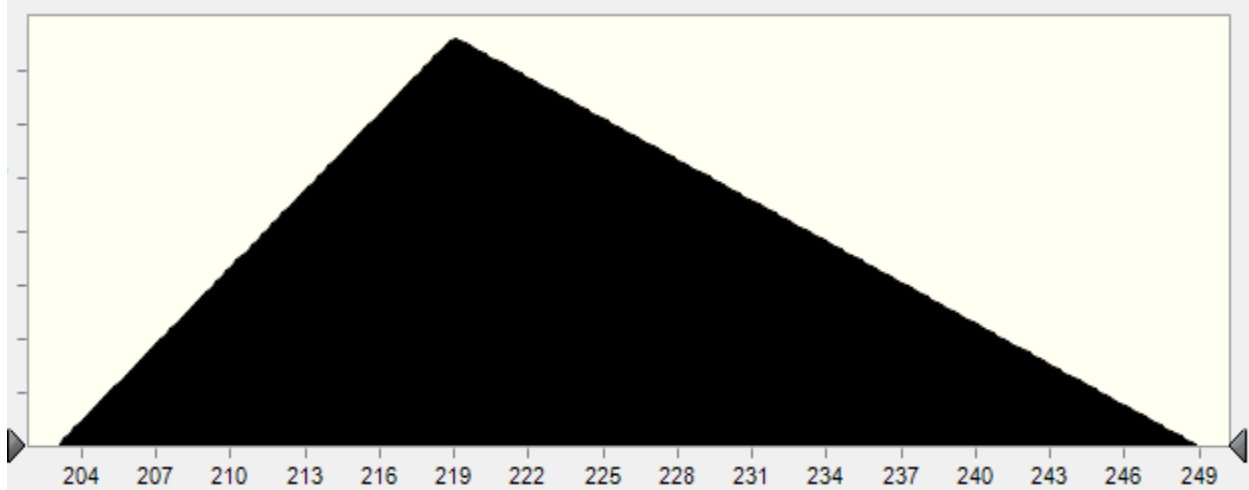


Figure 6.3: Time variability model of the earthwork structure

As shown in the time variation model of the earthwork structure (Figure 6.3), the time distribution was slightly skewed to the right, which means the probability of time underestimation was substantially larger than the probability of time overestimation, as also illustrated in the cumulative distribution of time (Figure 6.4).

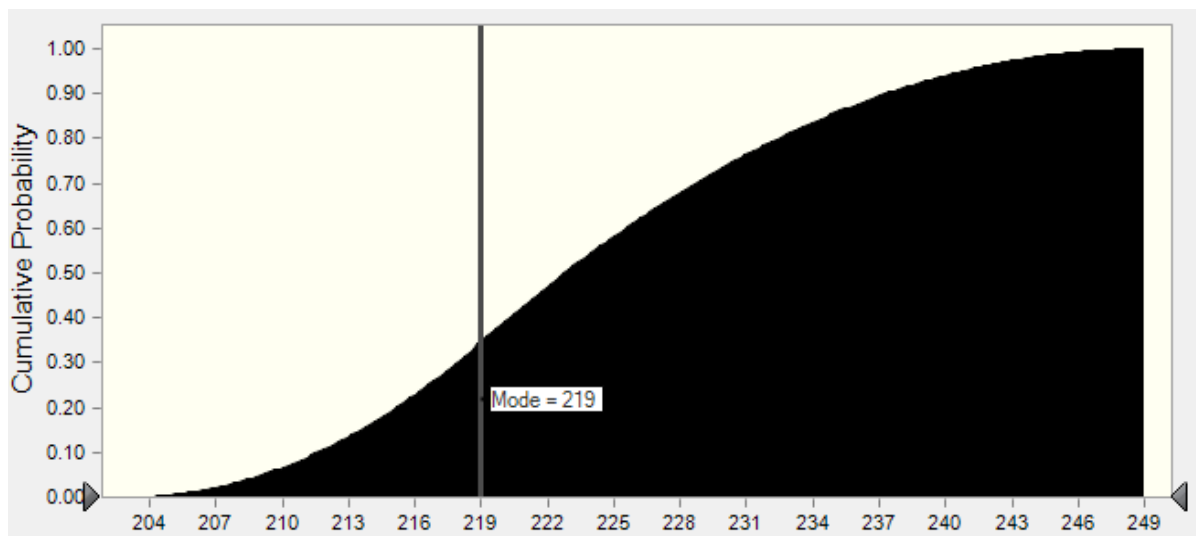


Figure 6.4: Cumulative distribution of time in earthwork structure

6.2.2 Variability related to the bridge structure

The construction of a bridge structure was modelled with an activity network, which depended on the construction method of the bridge. The two most common bridge components used in highway projects are a precast concrete box culvert and a precast slab bridge, which were both used in the case study project. The construction of a culvert bridge was modelled with a combination of the following six construction activities: set up site, culvert bedding, set up culvert, footing of wing wall, wing wall, and backfilling (See Figure 4.19). The construction of the slab bridge was modelled with a combination of the following nine construction activities: set up site, footing of abutment, abutment, footing of pier, pier, footing of wing wall, wing wall, set up precast deck, and

backfilling (See Figures 4.21 and 4.23). The construction cost and time of bridges is dependent on the geological condition of the site and geometric parameters of the bridge.

6.2.2.1 *Modelling variability of cost of the bridge structure*

The probabilistic data estimated by the bridge experts were used to obtain the lognormal variability distribution, which was utilised to model the variability of the cost of culverts, slab bridges and overall bridge structure. The lower, most likely and higher costs estimated by the experts were considered as the minimum, mode and maximum points of lognormal cost PDF, respectively. The total variability of costs for culverts construction and slab bridges construction was calculated by inserting the culvert and bridge variability of cost estimated by the bridge experts (Tables 5.9 and 5.10) and quantity of each bridge (Table 5.6) to the Equations 4.11, 4.13 and 4.15, and the results are presented in Table 6.4.

Table 6.3: Total variability of cost of culverts, slab bridges and overall bridge structure

	Minimum	Mode	Maximum
	ZAR		
Culvert construction	56,075,565.00	61,621,500.00	70,864,725.00
Slab bridge construction	8,464,365.00	9,301,500.00	10,696,725.00
Bridge structure	64,539,930.00	70,923,000.00	81,561,450.00

The cost variability model (lognormal) of the bridge structure is illustrated in Figure 6.5.

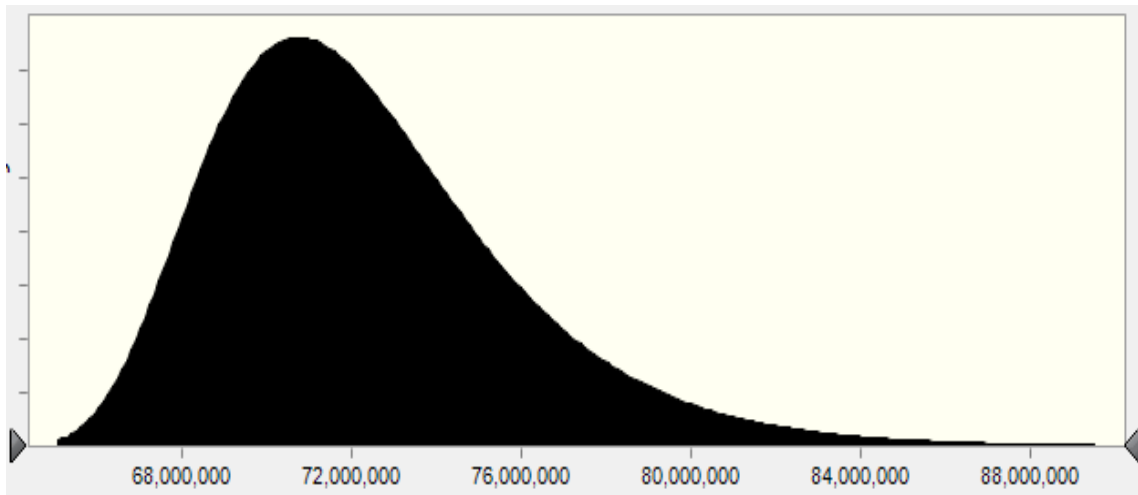


Figure 6.5: Cost variability model of the bridge structure

Similar to the earthwork cost variation, the cost variation model of the bridge structure showed the cost distribution skewed to the right, which confirms that the probability of cost underestimation was substantially larger than the probability of cost overestimation in the bridge structure, as illustrated in the cumulative cost distribution of the bridge structure (Figure 6.6).

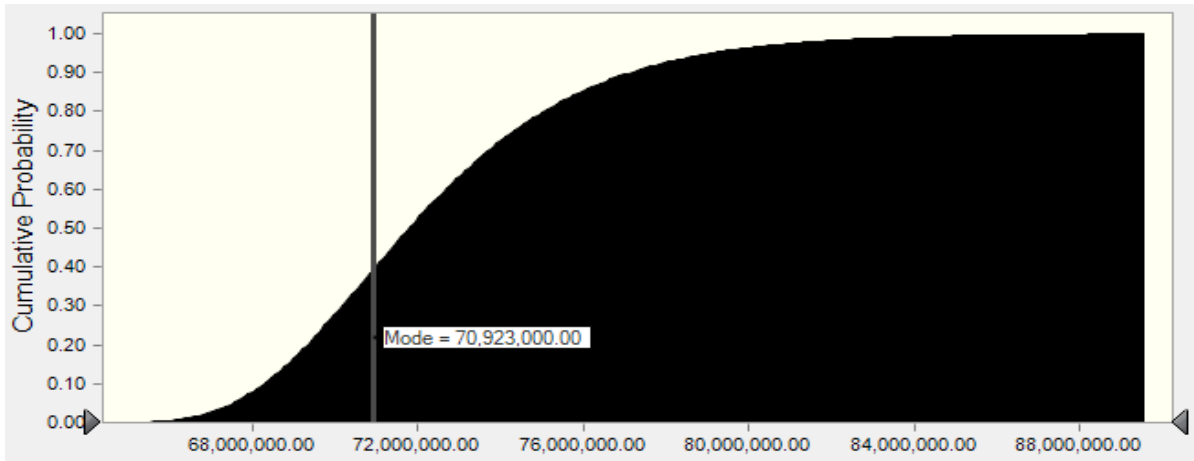


Figure 6.6: Cumulative cost distribution of the bridge structure

6.2.2.2 *Modelling variability of time of the bridge structure*

The variability of the duration of different bridge activities stemming from the bridge experts' panel (Tables 5.9 and 5.10) were used to obtain the triangular variability distribution. The triangular variability distributions were utilised to model the time variability of culvert and slab bridge and overall bridge structure.

The total variability of times of the culvert and slab bridge and overall time variability of the bridge structure were computed using Equations 4.12, 4.14 and 4.16 and are presented in Table 6.4.

Table 6.4: Total variability of time parameters of the culvert, slab bridge and overall bridge structure

	Minimum	Mode	Maximum
	DAY		
Culvert	296	336	393
Slab bridge	204	232	271
Bridge structure	296	336	393

The triangular time variability model of the bridge structure is presented in Figure 6.7.

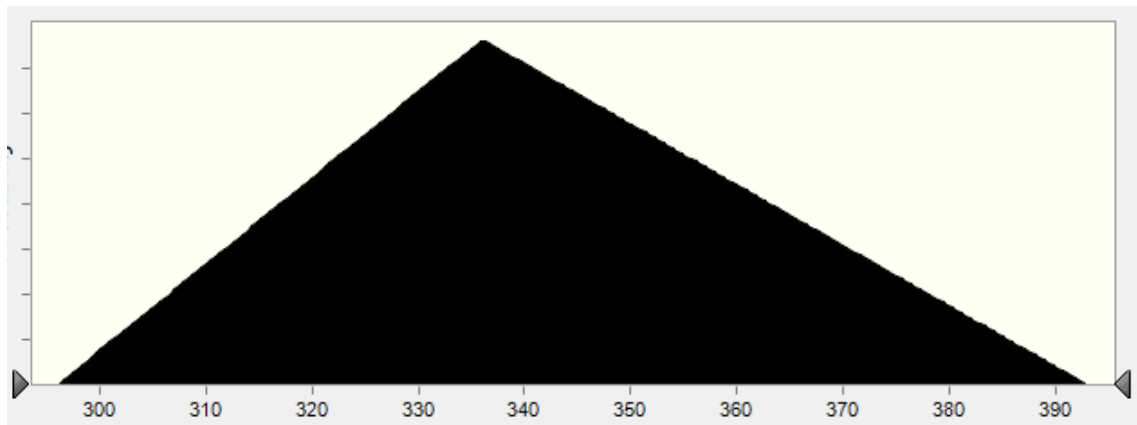


Figure 6.7: Time variability model of the bridge structure

The skewing of the time variation model to the right (Figure 6.7) and the larger portion of the times in the right side of the deterministic time of bridge structure (Figure 6.8) proved that the probability of time underestimation by considering the deterministic time was substantially larger than the probability of time overestimation.

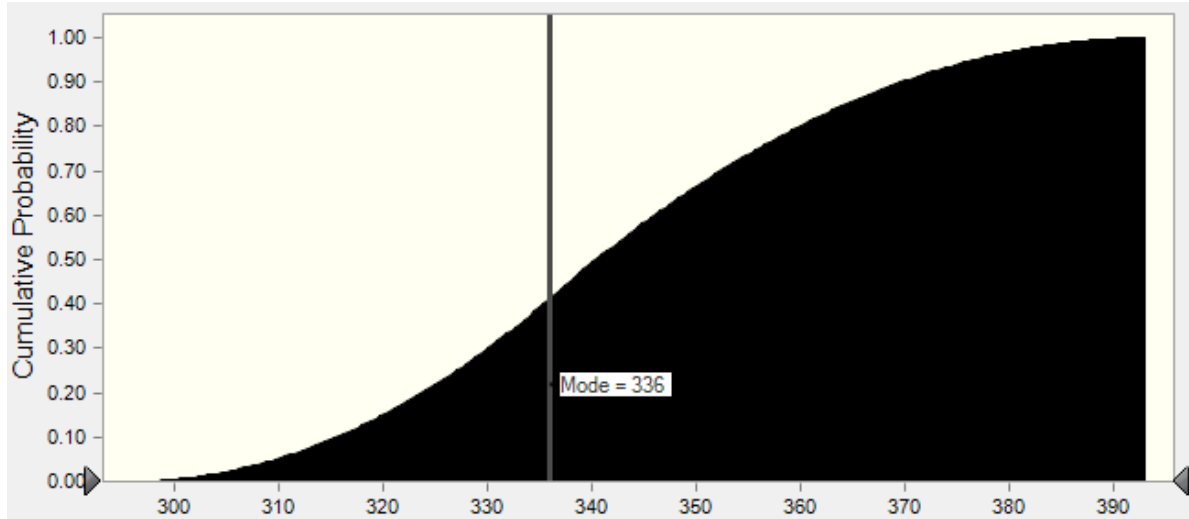


Figure 6.8: Cumulative time distribution of the bridge structure

6.2.3 Variability related to the pavement structure

The construction of the pavement was modelled as a sequence of the following four construction activities: subgrade, subbase, base, and surface (See Figure 4.27). Similarly, to the earthwork structure, the cost and time of the paving structure were characterised by quantifying the cost and time of each layer as a function of the unit cost, the production rate and the volume (Equation 4.1). Similarly to the fill construction, all constructions of the pavement structure are independent of the geological condition of the site, due to work done before the pavement (earthwork or bridge); therefore, only one-unit cost and production rate were considered for each pavement activity.

6.2.3.1 Modelling variability of cost of the pavement structure

The range of costs estimated by the pavement experts was employed to generate the lognormal variability distribution, which was utilised to model the cost variability of the pavement structure. The total variability of cost for the pavement activities was calculated using Equation 4.17 employing the variability unit cost estimated by the pavement experts (Tables 5.12) and volume of each layer as summarised in Table 6.5.

Table 6.5: Total variability of cost of pavement activities and overall pavement structure

	Minimum	Mode	Maximum
	ZAR		
Subgrade	37,031,500.80	38,574,480.00	41,660,438.40
Subbase	122,075,704.32	127,162,192.00	137,335,167.36
Base	138,301,128.00	144,063,675.00	155,588,769.00
Surface	177,241,780.80	184,626,855.00	199,397,003.40
Pavement structure	474,650,113.92	494,427,202.00	533,981,378.16

The cost variability model of the pavement structure is presented in Figure 6.9.

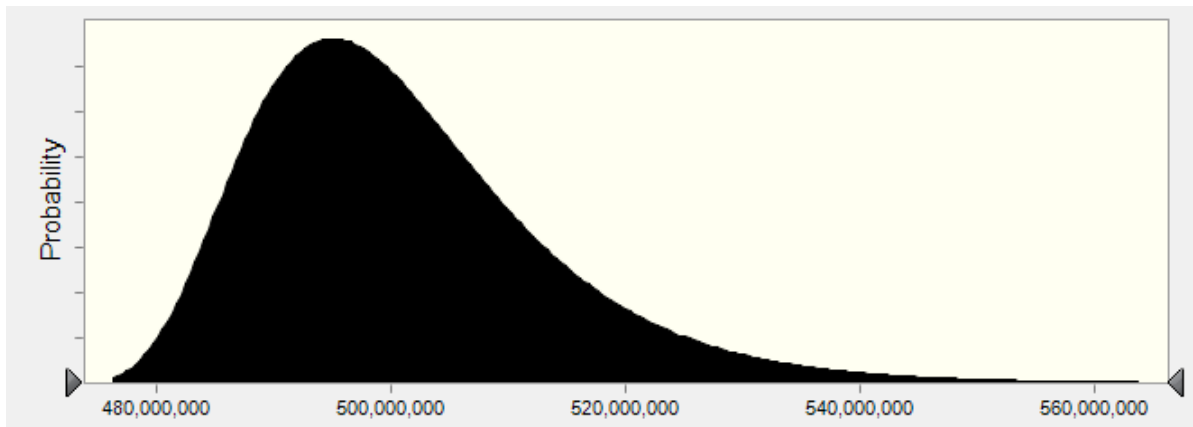


Figure 6.9: Cost variability model of the pavement structure

As shown in the cost variation model of the pavement structure (Figure 6.9), the cost distribution is skewed to the right, which confirms that the probability of cost underestimation is substantially higher than the probability of cost overestimation in the pavement structure as, illustrated by the cumulative cost of the pavement structure (Figure 6.10).

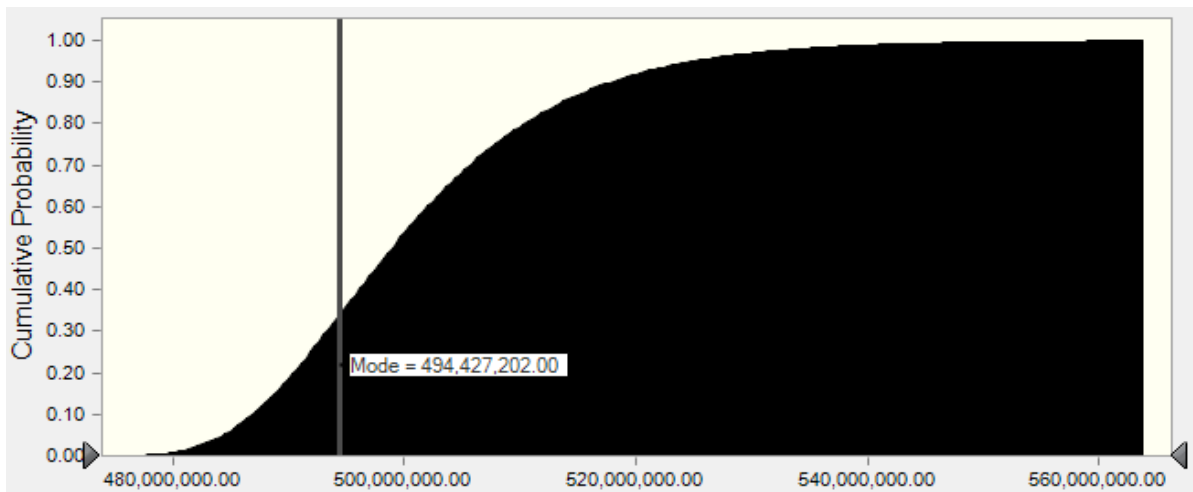


Figure 6.10: Cumulative cost of the pavement structure

6.2.3.2 *Modelling variability of time of the pavement structure*

Similar to the pavement variability of costs, the pavement experts panel estimated the variety range of the production rate (lower, most likely, higher) of different pavement activities (See Table 5.12). Due to the sequential construction of pavement activities, the total time of the pavement structure was calculated by the sum of all the pavement activities (See Equation 4.18). The total variability of time of the pavement activities and overall time variability of the pavement structure were calculated using the production rate estimated by the earthwork experts and volume of each pavement activity as summarised in Table 6.6.

Table 6.6: Total variability of time of pavement activities and pavement structure

	Time (DAY)		
	Minimum	Mode	Maximum
Subgrade (m ³)	27	29	32
Subbase (m ³)	63	67	74
Base (m ³)	58	62	69
Surface (m ³)	53	56	63
Pavement Structure (m ³)	201	214	238

The triangular time variability model of the pavement structure is presented in Figure 6.11.

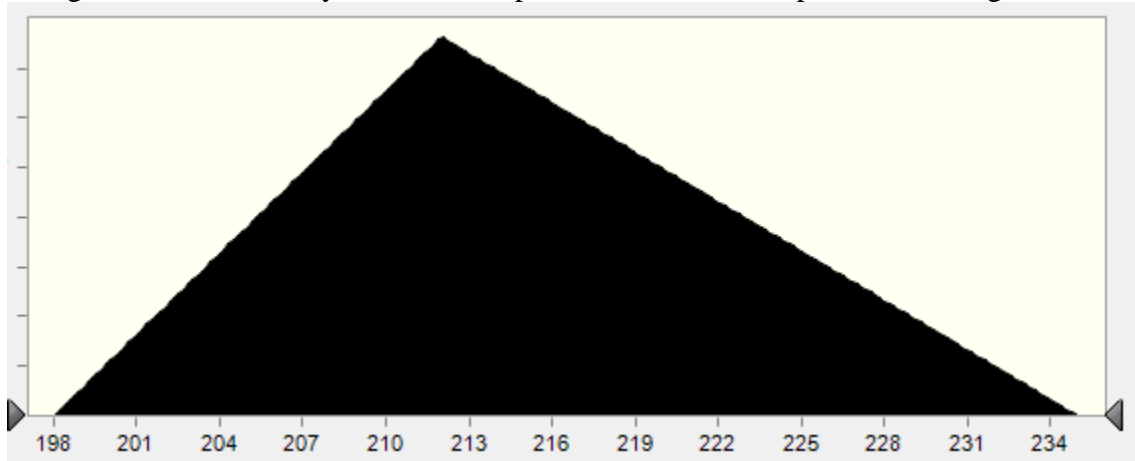


Figure 6.11: Time variability model of the pavement structure

As shown in the time variation model of the pavement structure (Figure 6.11), the distribution is skewed to the right, which shows that the probability of time underestimation was higher than the probability of time overestimation in the pavement structure. This is also illustrated by the cumulative time distribution (Figure 6.12).

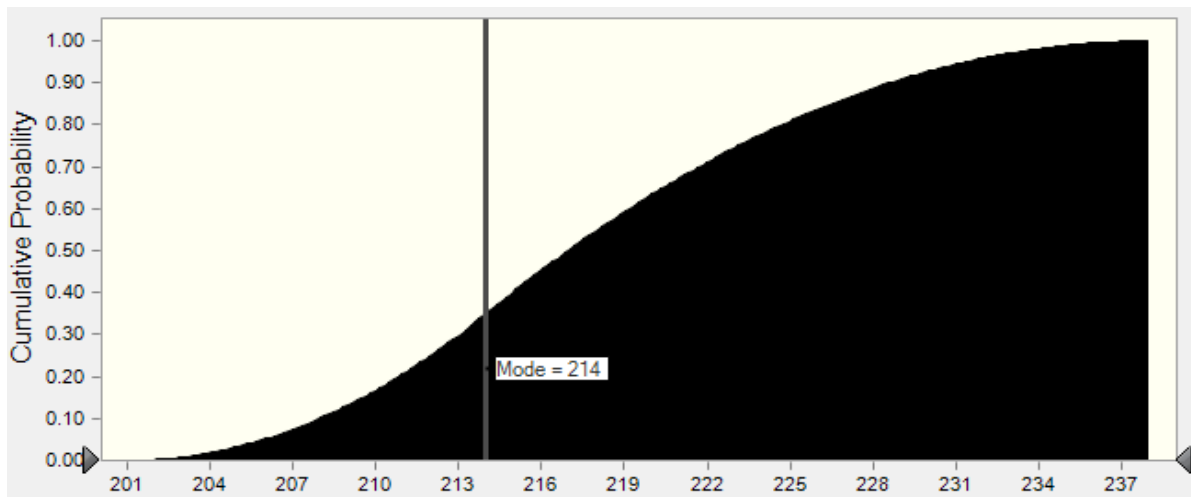


Figure 6.12: Cumulative time distribution of the pavement structure

6.2.4 Assessment of the variability impact on the overall project

The construction of the highway was modelled as a sequence of three structures: earthwork, bridge and pavement. The total deterministic cost of the project was given by the sum of the total deterministic cost of the three main structures of the project (See Equation 4.1). The total deterministic time of the highway project was not the sum of the deterministic time of all structures' time because all three structures were constructed concurrently (parallel construction). Therefore, the total construction time of a highway project is equal to the longest time structure which is bridge structure. The total deterministic cost and total deterministic time of project are summarised in Table 6.7.

Table 6.7: Deterministic total cost and time of project

	Deterministic Cost	Deterministic Time
	ZAR	Day
Highway project	809,504,922.8	340

Also, the total variable cost of the project was estimated by the sum of the variability of cost of the three main structures of the project (See Equation 4.1). However, the total variability of time of the highway project was equal to the variability of time of bridge structure (critical structure). The variability ranges of cost and time of the project are listed in Table 6.8.

Table 6.8: Total variability of cost and time of project

	Variability cost			Variability time		
	Minimum	Mode	Maximum	Minimum	Mode	Maximum
	ZAR			Day		
Highway project	771,110,090.39	809,476,566.70	884,081,829.33	296	336	393

The cost variability model and time variability model of the highway project are also illustrated in Figures 6.13 and 6.14.

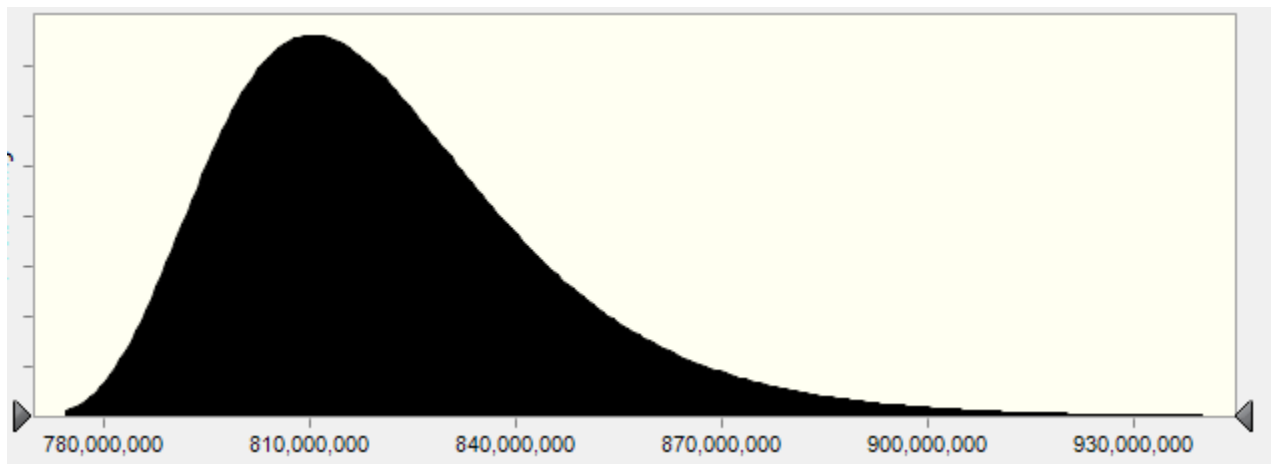


Figure 6.13: Cost variability model of the overall project

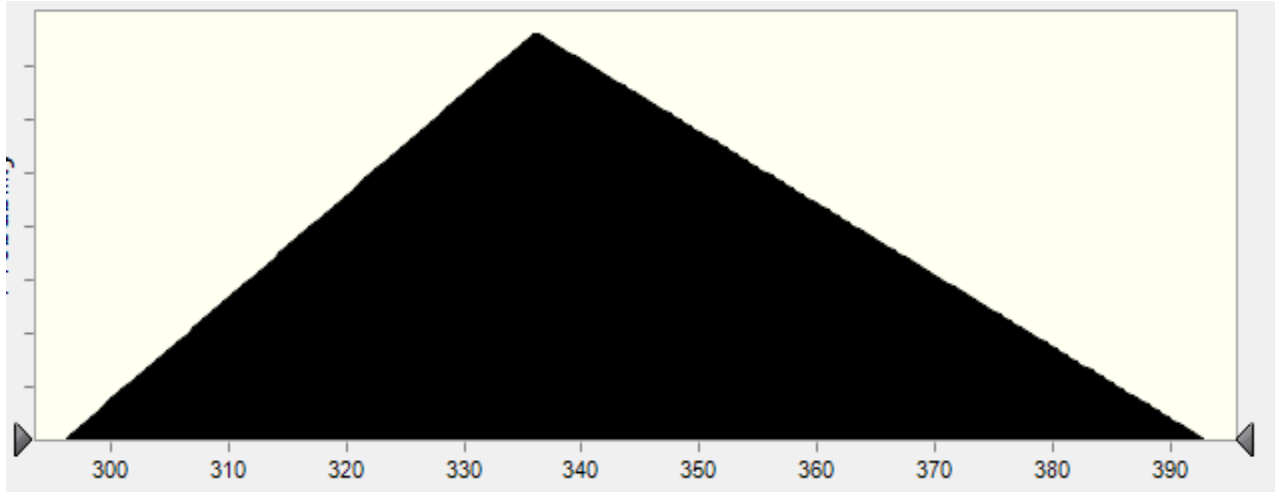


Figure 6.14: Time variability model of the overall project

Comparably to the cost and time of the three structures, the distributions cost and time of both variation models of the overall project (See Figures 6.13 and 6.14), are skewed to the right. This verifies that the probability of cost and time underestimation was higher than the probability of cost and time overestimation in the project by more than 60% for cost and 50% for time, as illustrated by the red lines in the cumulative distributions in Figures 6.15 and 6.16.

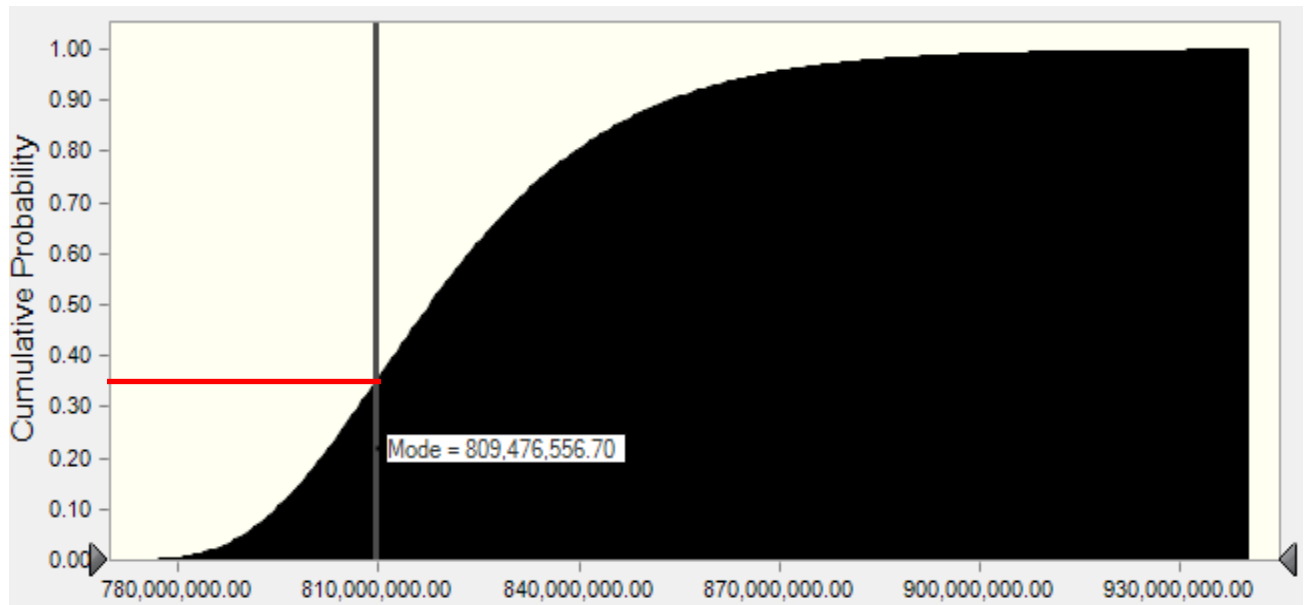


Figure 6.15: Cumulative cost distribution of the project

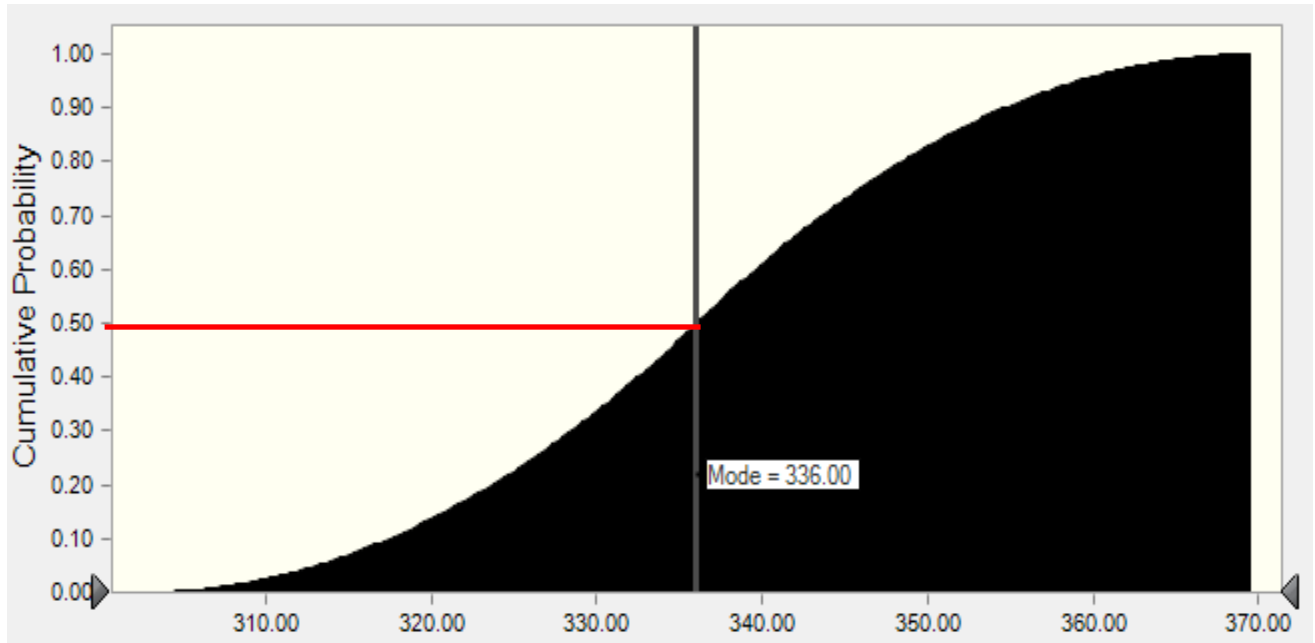


Figure 6.16: Cumulative time distribution of the project

6.2.5 Assessment of the impact of variability of cost and time

In this section, the impact of variability on the cost and time of each of the three structures of the highway project, and on the overall project, is assessed. In order to evaluate the impact of variability, the established deterministic total cost and total time of highway structures (earthwork, bridge and pavement) were compared to the 90th percentile of the developed lognormal models for cost variability and triangular models for time variability of highway structures. The 90th percentiles of the cost and time of variability models were estimated by simulating the cost and time of the activities and overall project, generated by the Monte Carlo simulation. The Monte Carlo simulation was run until the total of the standard deviation of structures was bounded within $\pm 1\%$ in 10 out of 10 sample simulations. The deterministic total cost and time (red) and the samples of Monte Carlo simulation of variability of cost and time of earthwork structure (25,100 runs), bridge structure (17,500), pavement structure (21,700) and overall (52,800) project (black) are illustrated respectively in Figures 6.17 to 6.20.

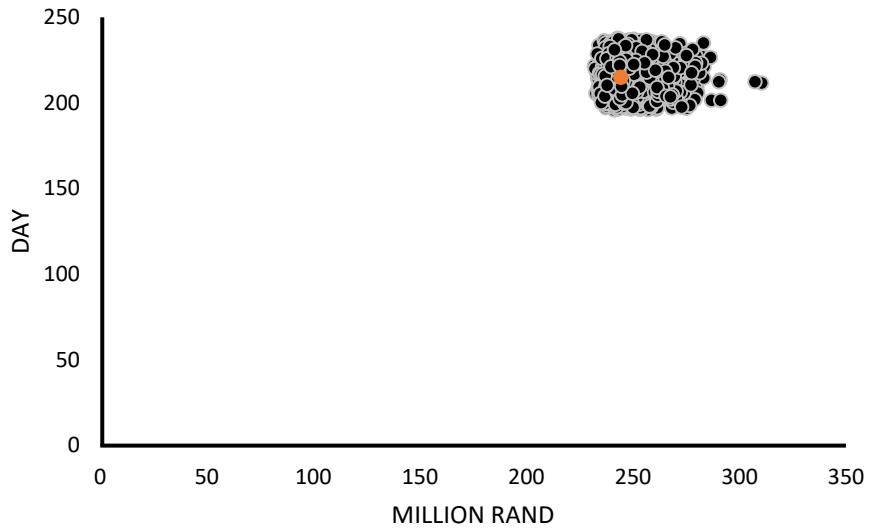


Figure 6.17: Deterministic and variation cost and time of the earthwork structure

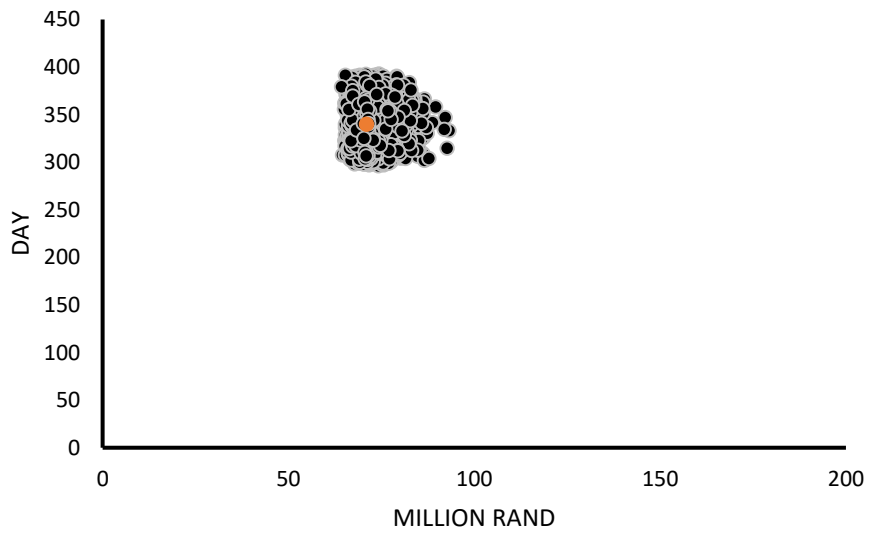


Figure 6.18: Deterministic and variation cost and time of the bridge structure

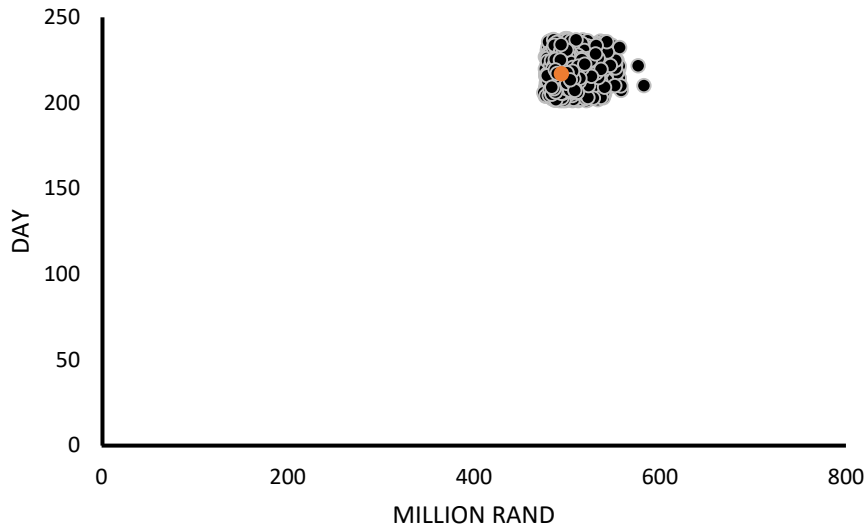


Figure 6.19: Deterministic and variation cost and time of the pavement structure

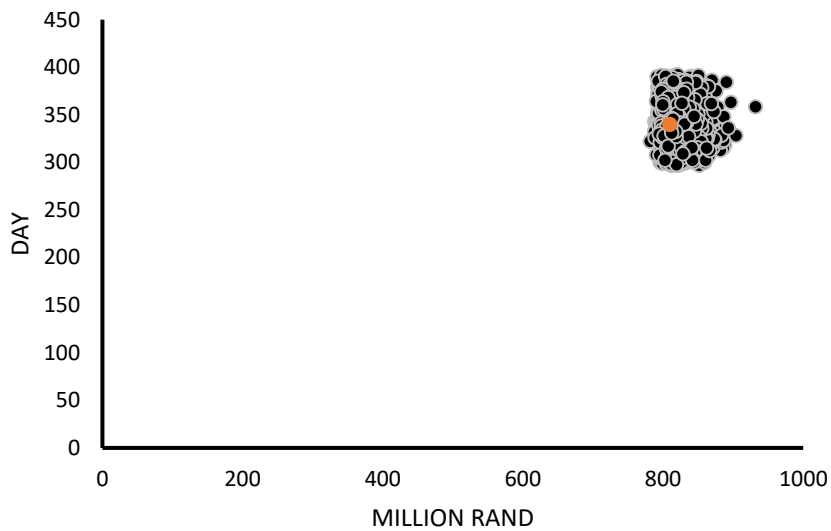


Figure 6.20: Deterministic and variation cost and time of the project

The deterministic cost and time were a single value (red dot), while the results of modelling variability of cost and time were a cloud of values (black cloud dots). The 90th percentiles of the total cost and total time of variation models were selected to compare with the deterministic total cost and total time of the main structures of the highway project, because the 90th percentile is located in the upper tail of both lognormal and triangular distribution models, which covers a large part of the variability distributions; also the 90th percentile shows that there is only a 10% chance that the deterministic cost or time of structures is higher than the total cost and total time of modelled variabilities, which is assumed to be acceptable.

The 90th percentile is employed as the standard point by transportation agencies such as the South African National Roads Agency (SANRAL) to evaluate and budget for highway projects (decision statistic point) (Reilly et al., 2004, Caltrans, 2012, WSDOT, 2018).

The 90th percentile of lognormal distribution (cost) and the 90th percentile of triangular distribution (time) were calculated with Equations 6.2 and 6.3, respectively.

$$Cost P_{90th} = 1.28 \times [(\exp(\sigma^2) - 1)(\exp(2\mu + \sigma^2))] + \exp(\mu + \sigma^2) \quad [6.2]$$

$$Time P_{90th} = \frac{ab - c(a+b-1.8) - 0.81}{(c-a) \times (c-b)} \quad [6.3]$$

Where μ and σ are respectively the mean and standard deviation of the modelled cost variability (lognormal) and a , b and c are the minimum, mode and maximum of the modelled time variabilities (triangular) respectively.

The increases in total cost and time of the highway structures were quantified by comparing the 90th percentiles of the total cost and total time variation models with the deterministic total cost and total time of the structure as shown with Equations 6.4 and 6.5:

$$Increase_c \% = \frac{C_{p90} - C_d}{C_d} \quad [6.4]$$

$$Increase_T \% = \frac{T_{p90} - T_d}{T_d} \quad [6.5]$$

Where C_{p90} is the 90th percentile of the total cost variation model, C_d is the deterministic total cost, T_{p90} is the 90th percentile of the total time variation model and T_d is the deterministic total time.

The cost variation and time variation of the three structures of the project and overall highway were calculated and are presented in Table 6.9.

Table 6.9: Deterministic cost and time and variability distributions parameters of the three structures and the project

		Earthwork	Bridge	Pavement	Overall project
Deterministic	Cost	244,292,292.83	70,952,700.00	494,259,930.00	809,504,922.80
	Time	215	340	217	340
Mean	Cost	248,195,137.45	72,341,460.00	501,019,564.69	821,556,162.14
	Time	223.67	341.67	217.67	341.67
Standard division	Cost	8.80	19.59	6.62	19.59
	Time	7,916,743.40	3,714,411.20	12,692,110.77	15,431,225.89
90thpercentile	Cost	258,410,039.21	76,883,575.67	517,582,030.41	841,927,264.18
	Time	228.76	369.48	228.53	368.64
Increased 90thpercentile	Cost	5.78%	8.36%	4.72%	4.01%
	Time	6.40%	8.67%	5.31%	8.42%
Modified variation	Cost	4.12%	6.28%	3.31%	2.48%
	Time	2.28%	8.14%	4.99%	7.89%

As shown in Table 6.9, the variability of cost and time (90th percentile) of all three structures and the overall project were larger than the relevant deterministic cost and time (mode cost and time). The investigation of deterministic cost and time and estimated variation cost and time from simulation revealed the following:

- The deterministic cost and time were a single value (red dot), while the results of modelling variability of cost and time were a cloud of values (black cloud dots). This cloud of values revealed that the variability of cost and time were uncertain values and proved that variability was one of the main sources of uncertainty of cost and total time of the three structures and overall highway project.
- The deterministic values of all three structures and the overall project were located in the left part of the variability cloud values since the deterministic costs were closer to the most likely cost estimated by experts (mode is smaller than the mean in lognormal distribution).
- The time variability models of the three structures and overall project were skewed to the right because the most likely duration for these structures and overall project were less than the mean of modelled variability of time. Therefore, the deterministic times are located at lower parts of the variability cloud values.

For all three structures and the overall project, the 90th percentiles of the cost and time distributions were larger than the mode of cost and time variability model (cost and time deterministic were estimated based on the mode). These variations in cost and time were the main reason for creating the cloud of values in scatterplots and the magnitude of uncertainty in the variability of cost and time. For instance, the size of this variation in the time (8.42%) of the overall project was larger than the cost (4.01%) dispersion. Thus, the clouds of the overall project were scattered wider along the Y-axis (time) compared to the X-axis (cost), which means the magnitude of uncertainty in the time of the project is higher than its cost.

Similarly, the magnitude of uncertainty in the time of all three structures is higher than the uncertainty in their cost (earthwork 5.78% - 6.40%, bridge 8.36% - 8.67%, pavement 4.72% - 5.53%). Further investigation of the cost dispersion and time dispersion of the three structures disclosed that the bridge structure has the highest magnitude of uncertainty among other structures at 8.36% in cost and 8.67%, in time. This observation manifested that the bridge structure drives the cost and time variability uncertainty in a highway project.

The practice of calculating the deterministic total cost and total time solely based on the mode (most likely) input cost and time (Molenaar, 2010, and WSDOT, 2012) is controversial, because the deterministic total cost and total time estimated based on the mode are smaller than the mean of possible variability modelled, due to positive skewing of both lognormal and triangular distributions, as shown in the cumulative distribution of cost and time of the three structures and overall project. Thus, the total cost and time should be estimated based on the mean of variability ranges.

By improving the basis of estimation of cost and time from mode (most likely) to the mean of variability, the range of uncertainty of the total cost and total time can be reduced. For instance, the magnitude of variability uncertainty in the earthwork structure could be reduced from 5.78% to 4.12% in cost and from 6.40% to 2.28% in time.

6.3 MODELLING CORRELATION IN CONSTRUCTION OF HIGHWAY PROJECTS

In the uncertainty model, cost and time correlations are one of the three sources of uncertainty. This section presents the cost and time correlations, the model and generation of correlations, and the impact on construction cost and duration is discussed. As discussed in Chapter Five, three types of correlations have been considered in the construction process of highway projects. The types and the coefficients of correlations that are used in this study are indicated in Table 6.10.

Table 6.10: Correlations types and coefficients between the cost and time in the construction of highway projects

Structure		Correlation between a repeated activity in a structure		Correlation between the various activities in a structure		Correlation between the cost and the time of an activity
		Cost	Time	Cost	Time	Cost -Time
Earthwork	Cut	$\rho = 0$	$\rho = 0$	$\rho = +0.75$	$\rho = +0.75$	$\rho = +0.8$
	Fill			$\rho = +0.8$	$\rho = +0.8$	
Bridge	Culvert	$\rho = (0, 1)$	$\rho = (0, 1)$	$\rho = +0.7$	$\rho = +0.7$	
	Slab bridge	$\rho = 1$	$\rho = 1$	$\rho = +0.65$	$\rho = +0.65$	
Pavement				$\rho = +0.85$	$\rho = +0.85$	

6.3.1 Correlations in the earthwork structure

All three types of correlations were modelled and the impact of each correlation on costs and times of earthwork structure was assessed as set out in this section.

6.3.1.1 Modelling probabilistic cost and time of the earthwork structure

The necessary parameters to model the three types of correlations in the construction of highway projects were calculated based on the section 6.2 (variability) result, and the calculated cost and time parameters for cutting and filling activities are summarised in Tables 6.11 and 6.12.

Table 6.11: Probability costs and time parameters of cutting activities in different types of geological conditions

Activity	Geology	Cost					Time		
		Min	Mode	Higher	Mean	Standard Deviation	Min	Mode	Higher
Clearing the topsoil	Fine	3,682,122.84	4,602,653.55	6,903,980.33	5,062,918.91	1,354,984.52	19.2	24	31.2
	Soft	5,250,912.00	6,563,640.00	9,845,460.00	7,220,004.00	1,932,283.30	27.2	34	44.2
	Hard	1,400,515.24	1,750,644.05	2,625,966.08	1,925,708.46	515,375.65	7.2	9	11.7
Excavation	Fine	11,423,753.36	14,279,691.70	21,419,537.55	15,707,660.87	4,203,827.41	26.4	33	42.9
	Soft	18,103,500.80	22,629,376.00	33,944,064.00	24,892,313.60	6,661,907.91	40.0	50	65
	Hard	4,987,030.42	6,233,788.03	9,350,682.05	6,857,166.83	1,835,177.51	22.4	28	36.4
	Rock	8,492,952.00	10,616,190.00	15,924,285.00	11,677,809.00	3,125,321.71	23.2	29	37.7
Improving the area and stabilising the trench	Fine	5,548,081.18	6,935,101.47	10,402,652.21	7,628,611.62	2,041,638.59	30.4	38	49.4
	Soft	7,526,930.40	9,408,663.00	14,112,994.50	10,34,9529.30	2,769,835.39	44.8	56	72.8
	Hard	1,881,973.50	2,352,466.88	3,528,700.32	2,587,713.57	692,547.50	12.8	16	20.8
	Rock	959,652.00	1,199,565.00	1,799,347.50	1,319,521.50	353,142.37	9.6	12	15.6
Total	Fine	20,653,957.38	25,817,446.72	38,726,170.08	28,399,191.39	7,600,450.52	76.0	95	123.5
	Soft	30,881,343.20	38,601,679.00	57,902,518.50	42,461,846.90	11,364,026.60	112.0	140	182
	Hard	8,269,519.17	10,336,898.96	15,505,348.44	11,370,588.86	3,043,100.66	42.4	53	68.9
	Rock	9,452,604.00	11,815,755.00	17,723,632.50	12,997,330.50	3,478,464.09	32.8	41	53.3

Table 6.12: Probability costs and time parameters of filling activities

Activity	Cost					Time		
	Min	Mode	Higher	Mean	Standard Deviation	Min	Mode	Higher
Clearing the topsoil	22,145,891	27,682,363.8	41,523,545.63	30,450,600	8,149,467	112.8	141	183.3
Improving the area	27,583,850	34,479,812.5	51,719,718.75	37,927,794	10,150,582	172	215	279.5
Embankment	76,446,670	95,558,337.5	143,337,506.3	105,114,171	28,131,613	126.4	158	205.4
Total	126,176,411	157,720,514	236,580,770.6	173,492,565	46,431,662	172	215	279.5

6.3.1.2 *Modelling the correlation between a repeated activity in the earthwork structure*

To model this correlation, the expert panel suggested considering the following three scenarios for all repeated activities in the earthwork structure and comparing the results to the base case, in order to determine the key correlation in each activity.

Base Case: Every unit of activity is uncorrelated (results from variation model).

Scenario 1. Every unit is independent, $\rho_r = 0$, so that the cost and time are randomly selected for each unit.

Scenario 2. Intermediate scenarios include all positive correlations, $\rho_r = (0, 1)$, which correspond to the case where the cost and time are randomly selected for each unit, and if one cost or time per unit is above average, the next cost or time per metre will tend also to be above average.

Scenario 3. Every unit is perfectly correlated; $\rho_r = 1$ once a cost and time per unit are randomly selected, which remains constant for the entire activity.

Some of the earthwork activities, such as excavation, were related to the geological condition, and the cost and time of activity were changed if geology changed. Activity i was repeated n_i times, activity j was repeated n_j times. As the geology changed, activity i and activity j were considered independent. For instance, the excavation of cut in fine geological conditions was repeated 327,591 times. Thus, the activity was repeated 327,591 times and the costs and times of the 327,591 repetitions were correlated. The range of total cost and total time for each construction activity of the earthwork was estimated for the above three scenarios. The probabilistic calculation was based on Monte Carlo simulations, which were run until the total of the standard deviation of activity bounded within $\pm 1\%$ in 10 out of 10 sample simulations.

Scenario 1: The cost and time of every constructing unit were independent of the cost and time of the preceding and the following units, as illustrated in matrix ρ_{r1} below.

$$\rho_{r1} = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & 0 & \vdots \\ \vdots & 0 & 1 & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix}$$

Scenario 2: The cost and time of every construction unit were positively dependent on the cost and time of the preceding and following units. The correlation decreases by 0.01 for unit activity as shown in matrix ρ_{r2} below.

$$\rho_{r2} = \begin{bmatrix} 1 & 0.99 & \dots & 0 \\ 0.99 & 1 & 0.99 & \vdots \\ \vdots & 0.99 & 1 & 0.99 \\ 0 & \dots & 0.99 & 1 \end{bmatrix}$$

Scenario 3: The cost and time of every construction unit were fully correlated with the cost and time of construction of the preceding and following units, as presented in Matrix ρ_{r3} .

$$\rho_{r3} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & 1 & 1 & \vdots \\ \vdots & 1 & 1 & 1 \\ 1 & \dots & 1 & 1 \end{bmatrix}$$

The Gaussian copula was employed to generate the correlated costs and times with the desired Spearman correlation coefficients, and it was modelled with the Gaussian copula in the MATLAB environment.

To generate the correlated variables, first the random numbers from a uniform distribution were produced, then the two transformations were obtained from random numbers and correlated with the desired Spearman correlation coefficients matrix. Lastly, the correlation probability distributions of costs and times were modelled using the marginal distribution assumptions provided by a panel of experts (See Chapter Five).

Modelling correlation between a repeated activity in different geologies of cutting construction

The range of means and the standard deviations of total cost and total time of cutting construction and its three activities for the three correlation scenarios in the four different geological conditions are summarised in Table 6.13. The variation of the mean and standard deviation of each scenario from the base case was calculated using Equations 6.6 and 6.7.

$$\Delta_M = \frac{M_s - M_b}{M_b} \quad [6.6]$$

where M_s is the mean of the scenario and M_b is the mean of the base case.

$$\Delta_S = \frac{S_s - S_b}{S_b} \quad [6.7]$$

where S_s is the mean of the scenario and S_b is the mean of the base case.

Table 6.13: Correlation between a repeated activity in different geologies of cutting construction

Activity	Geology	Scenario	Cost (ZAR)				Time (Days)			
			Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Topsoil	Fine	Base Case	5,061,286.90	0.00%	123,976.25	0.00%	24.79	0.00%	0.72	0.00%
		Scenario 1	5,062,172.30	0.02%	124,175.75	0.16%	24.80	0.03%	0.72	-0.69%
		Scenario 2	5,064,121.44	0.06%	683,973.40	451.70%	24.87	0.34%	2.45	244.63%
		Scenario 3	5,069,024.42	0.15%	706,734.40	470.06%	24.84	0.21%	2.47	248.52%
	Soft	Base Case	7,215,779.77	0.00%	147,091.83	0.00%	35.14	0.00%	0.85	0.00%
		Scenario 1	7,222,301.64	0.09%	148,463.76	0.93%	35.12	-0.04%	0.85	0.40%
		Scenario 2	7,217,664.27	0.03%	922,621.29	527.24%	35.15	0.05%	3.43	303.22%
		Scenario 3	7,243,172.48	0.38%	1,016,101.57	590.79%	35.02	-0.32%	3.56	318.71%
	Hard	Base Case	1,924,985.46	0.00%	76,525.15	0.00%	9.30	0.00%	0.42	0.00%
		Scenario 1	1,924,841.95	-0.01%	77,195.16	0.88%	9.30	0.00%	0.43	0.89%
		Scenario 2	1,918,479.12	-0.34%	258,501.69	237.80%	9.29	-0.13%	0.92	117.12%
		Scenario 3	1,925,972.70	0.05%	273,833.65	257.83%	9.29	-0.14%	0.92	119.19%
Excavation	Fine	Base Case	15,709,849.75	0.00%	380,821.59	0.00%	34.08	0.00%	0.83	0.00%
		Scenario 1	15,704,054.29	-0.04%	384,256.33	0.90%	34.08	0.02%	0.83	0.65%

		Scenario 2	15,692,303.18	-0.11%	2,059,310.59	440.75%	34.11	0.09%	3.23	290.21%
		Scenario 3	15,778,534.14	0.44%	2,197,998.12	477.17%	33.99	-0.24%	3.40	310.09%
	Soft	Base Case	24,884,290.62	0.00%	500,557.95	0.00%	51.67	0.00%	1.02	0.00%
		Scenario 1	24,893,569.28	0.04%	504,378.71	0.76%	51.64	-0.05%	1.03	0.98%
		Scenario 2	24,834,055.27	-0.20%	3,146,349.51	528.57%	51.73	0.11%	5.00	390.28%
		Scenario 3	24,900,687.19	0.07%	3,524,683.28	604.15%	51.66	-0.01%	5.22	411.56%
	Hard	Base Case	6,851,722.33	0.00%	280,195.39	0.00%	28.94	0.00%	0.77	0.00%
		Scenario 1	6,858,358.46	0.10%	281,595.55	0.50%	28.94	0.00%	0.77	0.03%
		Scenario 2	6,854,521.65	0.04%	947,090.01	238.01%	28.99	0.20%	2.84	270.68%
		Scenario 3	6,863,572.96	0.17%	947,108.65	238.02%	28.88	-0.19%	2.89	277.67%
	Rock	Base Case	11,694,947.26	0.00%	584,638.64	0.00%	29.95	0.00%	0.78	0.00%
		Scenario 1	11,682,122.25	-0.11%	587,483.13	0.49%	29.97	0.05%	0.78	0.31%
Scenario 2		11,656,129.24	-0.33%	1,594,623.54	172.75%	29.88	-0.25%	2.98	282.85%	
Scenario 3		11,701,848.15	0.06%	1,635,641.25	179.77%	30.03	0.28%	2.92	275.05%	
Trench	Fine	Base Case	7,632,850.70	0.00%	183,864.74	0.00%	39.25	0.00%	0.89	0.00%
		Scenario 1	7,630,388.70	-0.03%	185,279.07	0.77%	39.28	0.06%	0.90	0.79%
		Scenario 2	7,620,599.20	-0.16%	1,007,465.73	447.94%	39.24	-0.02%	3.84	331.98%
		Scenario 3	7,621,074.53	-0.15%	1,041,550.18	466.48%	39.27	0.05%	3.94	343.73%
	Soft	Base Case	10,350,038.22	0.00%	209,267.36	0.00%	57.86	0.00%	1.07	0.00%
		Scenario 1	10,349,430.24	-0.01%	211,021.55	0.84%	57.88	0.03%	1.08	0.76%
		Scenario 2	10,318,290.25	-0.31%	1,303,952.50	523.10%	57.82	-0.07%	5.57	419.67%
		Scenario 3	10,362,408.03	0.12%	1,453,190.17	594.42%	57.94	0.13%	5.72	434.05%
	Hard	Base Case	2,587,858.29	0.00%	105,654.45	0.00%	16.52	0.00%	0.58	0.00%
		Scenario 1	2,590,328.63	0.10%	105,797.61	0.14%	16.54	0.10%	0.58	0.81%
		Scenario 2	2,592,974.72	0.20%	355,299.47	236.28%	16.52	0.02%	1.62	179.47%
		Scenario 3	2,596,055.95	0.32%	361,116.71	241.79%	16.55	0.16%	1.62	180.15%
	Rock	Base Case	1,317,467.67	0.00%	65,174.17	0.00%	12.40	0.00%	0.50	0.00%
		Scenario 1	1,320,816.47	0.25%	65,344.01	0.26%	12.39	-0.05%	0.50	0.66%
		Scenario 2	1,318,892.43	0.11%	180,422.58	176.83%	12.40	0.00%	1.22	146.33%
		Scenario 3	1,317,817.08	0.03%	180,365.56	176.74%	12.41	0.05%	1.26	153.92%
Total Cutting	Fine	Base Case	28,396,575.70	0.00%	438,377.04	0.00%	98.15	0.00%	1.39	0.00%
		Scenario 1	28,393,415.77	-0.01%	440,127.19	0.40%	98.19	0.04%	1.40	0.98%
		Scenario 2	28,402,457.75	0.02%	2,397,975.41	447.01%	98.15	0.00%	5.64	306.52%
		Scenario 3	28,375,653.38	-0.07%	2,511,065.89	472.81%	98.09	-0.06%	5.78	316.60%
	Soft	Base Case	42,459,716.39	0.00%	565,981.56	0.00%	144.68	0.00%	1.74	0.00%
		Scenario 1	42,479,809.52	0.05%	570,028.05	0.71%	144.68	0.00%	1.75	0.11%
		Scenario 2	42,505,748.13	0.11%	3,487,226.57	516.14%	144.61	-0.05%	8.14	367.12%
		Scenario 3	42,384,249.89	-0.18%	3,810,606.74	573.27%	144.74	0.05%	8.45	384.91%
	Hard	Base Case	11,371,742.99	0.00%	306,345.75	0.00%	54.77	0.00%	1.04	0.00%
		Scenario 1	11,372,643.10	0.01%	307,733.66	0.45%	54.77	0.01%	1.04	0.26%
		Scenario 2	11,372,894.28	0.01%	1,034,954.54	237.84%	54.72	-0.08%	3.34	221.62%
		Scenario 3	11,401,745.53	0.26%	1,086,634.70	254.71%	54.66	-0.20%	3.45	232.66%
	Rock	Base Case	12,985,740.64	0.00%	577,909.85	0.00%	42.37	0.00%	0.94	0.00%
		Scenario 1	13,008,362.10	0.17%	582,101.43	0.73%	42.37	0.01%	0.94	0.54%
		Scenario 2	12,974,766.87	-0.08%	1,587,553.39	174.71%	42.31	-0.13%	3.08	228.91%
		Scenario 3	13,021,817.97	0.28%	1,667,908.48	188.61%	42.39	0.05%	3.24	246.17%
Cutting Construction	Base Case	95231262.30	0.00%	963202.23	0.00%	144.67	0.00%	1.72	0.00%	
	Scenario 1	95254205.03	0.02%	966669.76	0.36%	144.69	0.01%	1.72	0.00%	
	Scenario 2	95148328.28	-0.09%	4645194.27	382.27%	144.53	-0.10%	7.96	362.79%	
	Scenario 3	95083118.49	-0.16%	5104989.72	430.00%	144.59	-0.06%	8.48	393.02%	

The correlated total cost and total time of cutting construction in overall geologies for the three scenarios were generated by copula and Monte Carlo simulation and were compared with the base case as illustrated in Figure 6.21. (See Appendix D for the results of cuttings in different geologies.)

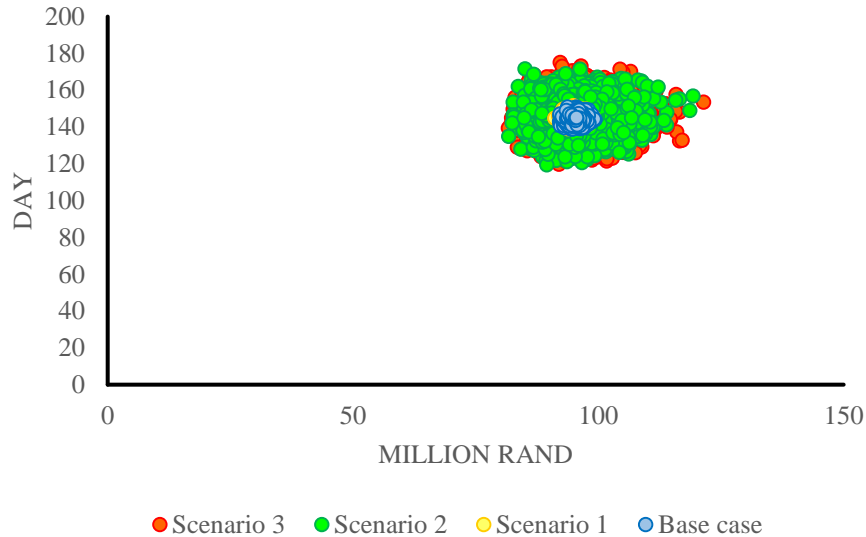


Figure 6.21: Overlay scatterplot of total cost and total time of base case and three correlation scenarios of cutting construction in overall geologies

The study found that the means of the total cost and time in four different geologies of cutting construction were equal to the sum of the costs means and the times of the same geology. The costs mean, and the time mean of cuts were not changed from scenario to scenario. Thus, the mean of the total cost and the mean of the total time of cuts were not expected to vary in the three scenarios, as confirmed by a constant centre of significance in the cost and time distribution plots.

On the other hand, the standard deviations of the total cost and total time of cuts were expected to increase from Scenario 1 (independent) to Scenario 3 (fully correlated) due to the correlation between a repeated activity. This expectation was confirmed in all four geological conditions, as illustrated in cost and time overlaying distributions plots (See Figure 6.21), which proved that the cost and time of construction cutting activities were positively correlated to the repetition.

The evaluation of the overlaying distribution costs and times of the three scenarios of correlation between repeated activity of cutting construction in different geologies shows that the standard deviations of the total cost and time of construction were increased dramatically due to the positive correlation between the number of repetitions of an activity in cutting construction (See Appendix D).

Modelling correlation between a repeated activity in filling construction

The means and the standard deviations of total cost and total time of three activities of filling construction were estimated by the Gaussian copula and summarised in Table 6.14. To evaluate

the variation of the mean and standard deviation of each scenario from the base case, Equations 6.6 and 6.7 were used.

Table 6.14: Correlation between a repeated activity in construction filling

Activity	Scenario	Cost				Time			
		Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Topsoil	Base Case	30,444,578.87	0.00%	428,952.09	0.00%	145.71	0.00%	2.08	0.00%
	Scenario 1	30,450,112.86	0.02%	427,265.02	-0.39%	145.64	-0.05%	2.1	0.96%
	Scenario 2	30,408,686.63	-0.12%	3,488,341.71	713.22%	145.67	-0.03%	13.44	546.15%
	Scenario 3	30,467,554.38	0.08%	4,339,385.87	911.62%	145.61	-0.07%	14.52	598.08%
Improving the area	Base Case	37,932,814.87	0.00%	531,416.34	0.00%	222.2	0.00%	2.58	0.00%
	Scenario 1	37,924,559.01	-0.02%	532,020.39	0.11%	222.13	-0.03%	2.60	0.78%
	Scenario 2	38,032,495.56	0.26%	4,422,407.82	732.19%	221.74	-0.21%	19.6	659.69%
	Scenario 3	37,860,309.58	-0.19%	5,226,962.86	883.59%	221.9	-0.14%	21.69	740.70%
Embankment	Base Case	105,126,905.37	0.00%	1,465,464.13	0.00%	163.29	0.00%	2.21	0.00%
	Scenario 1	105,136,016.19	0.01%	1,463,722.14	-0.12%	163.23	-0.04%	2.23	0.90%
	Scenario 2	105,486,724.65	0.34%	12,012,733.88	719.72%	163.35	0.04%	14.69	564.71%
	Scenario 3	105,361,965.01	0.22%	14,662,097.67	900.51%	163.03	-0.16%	16.13	629.86%
Total	Base Case	173,507,327.73	0.00%	1,611,379.94	0.00%	222.23	0.00%	2.62	0.00%
	Scenario 1	173,526,848.45	0.01%	1,614,514.32	0.19%	222.13	-0.05%	2.64	0.51%
	Scenario 2	173,898,952.63	0.23%	13,161,824.68	716.80%	222.26	0.01%	19.60	646.80%
	Scenario 3	173,359,259.52	-0.09%	16,086,507.06	898.31%	222.15	-0.04%	22.09	741.93%

The scatterplots of the base case and three Scenarios of correlated total costs and total times of construction filling were simulated using the Monte Carlo analysis as shown in Figure 6.22.

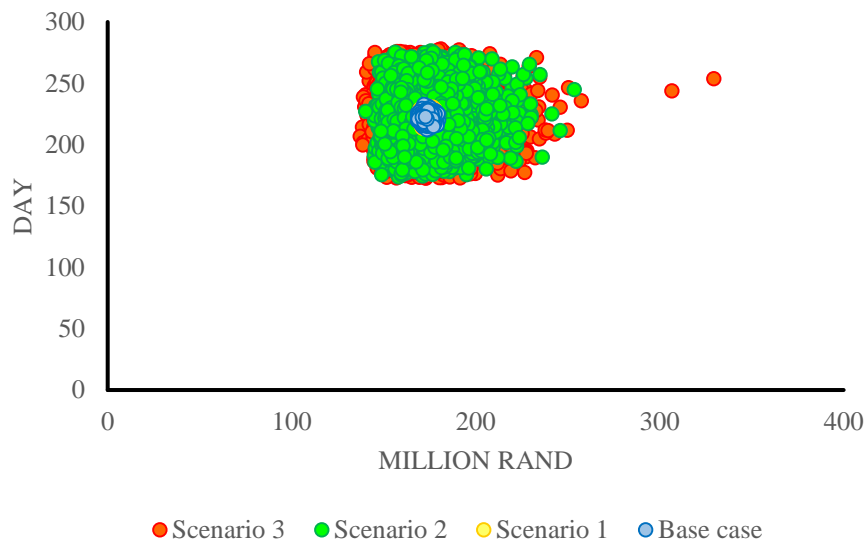


Figure 6.22: Overlay scatterplot of total cost and total time of base case and the three correlation scenarios of construction filling

Comparable to the cutting construction, the means of cost and the means of time were not changed from scenario to scenario in the construction filling component. Thus, the mean of the total cost and the mean of the total time of filling were not expected to vary in the three scenarios due to a

constant centre of significance. The standard deviations of the total cost and total time of construction filling increased from Scenario 1 (independent) to Scenario 3 (fully correlated) due to the correlation between a repeated activity, as illustrated in the overlay cost and time distributions plots, which revealed that the cost and time of activities in the construction of filling, as in cutting construction, were positively correlated to the repetition of an activity.

Regarding the overlay distribution costs and times of the three scenarios of correlation between repeated activities of construction filling, it was established that the standard deviations of the total cost and time of construction were increased dramatically due to the positive correlation between the number of repetitions of an activity (See Appendix D)

Overall modelling correlation between a repeated activity in the earthwork structure

The means, standard deviations and variation of means and standard deviation of the base case and the three different correlation scenarios are summarised in Table 6.15.

Table 6.15: The overall correlation between a repeated activity in the earthwork structure

	Scenario	Cost				Time			
		Mean	Δ_M	Standard Deviation	Δ_s	Mean	Δ_M	Standard Deviation	Δ_s
Earthwork Structure	Base Case	268726606.90	0.00%	1871424.00	0.00%	222.19	0.00%	2.61	0.00%
	Scenario 1	268692562.60	-0.01%	1883658.00	0.65%	222.19	0.00%	2.59	-0.93%
	Scenario 2	268608078.40	-0.04%	14106038.00	653.76%	222.32	0.06%	19.53	648.51%
	Scenario 3	268530325.90	-0.07%	17098391.00	813.66%	222.78	0.27%	22.40	758.26%

The scatterplot of the base case and three scenarios correlated total costs and total times of overall earthwork structure was simulated by the Monte Carlo analysis and is shown in Figure 6.23.

The analysis of the three scenarios of correlation between repeated activity in the earthwork structure proved that the standard deviations of the total cost and time were increased dramatically, due to a positive correlation between the number of repetitions of activities in the earthwork structure (See Appendix D)

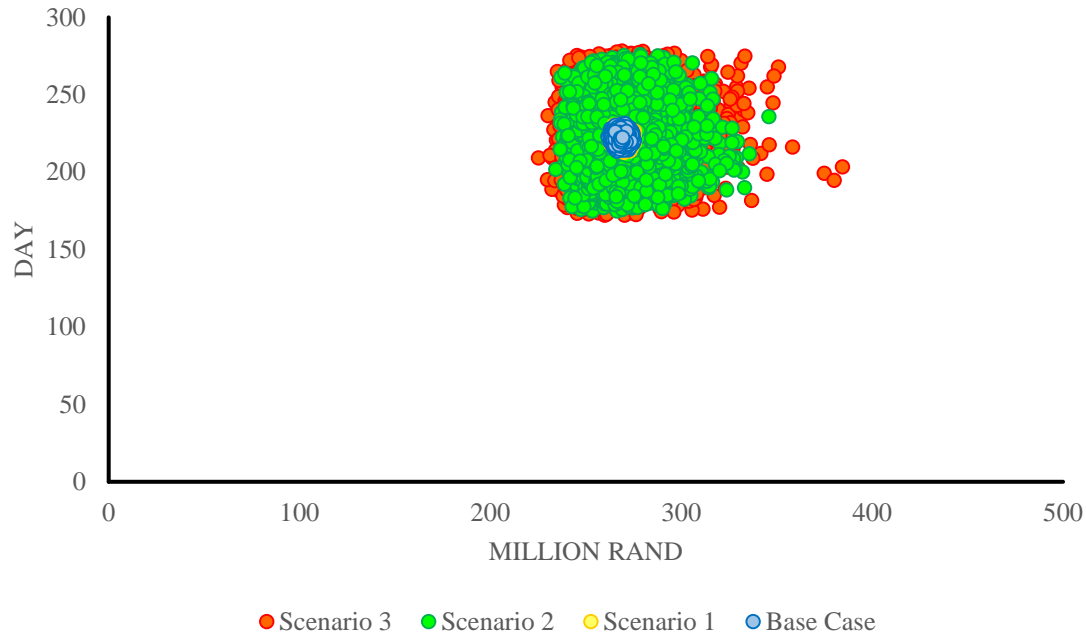


Figure 6.23: Overlay scatterplot of total cost and total time of the base case and the three correlation scenarios of the earthwork structure

Based on the overlaying scatterplots (See Figure 6.23), distribution plots (Appendix D) and the variation of means and standard deviations of total cost and total time of the three scenarios of correlations in cutting construction, filling construction and the earthwork structure (Appendix D), the following observations were made:

- i. The means of the total cost and total time are constant from scenario to the scenario, as a result of the constant centre of significance in the cost and time distribution plots, scatterplots and variation mean.
- ii. The base case and Scenario 1 are considered equal due to similar means, standard deviations, overlay distributions plots and scatterplots. The standard deviations were not exactly the same, but are considered equal because the variation was within the $\pm 1\%$ limit set.
- iii. The standard deviations of the total cost and total time were increased dramatically from Scenario 1 to Scenario 3 as shown in Tables 6.13, 6.14 and 6.15. The increases in total cost standard deviation and total time standard deviation are visible in the overlaying distribution cost and time plots, as well as in the scatterplots.
- iv. Scenario 1 was modelled independently of the repetition cost variables and time variables ($p_r = 0$), while Scenario 3 was modelled fully correlated with the repetition cost variables and time variables ($p_r = 1$). Therefore, Scenario 1 and Scenario 3 were considered the lower and upper bounds of the spectrum of possible correlated cost and time of the repeated activity.

- v. In the scatterplots and the overlay distribution plots of total cost and total time of Scenario 1 (independent), the sample was concentrated around the mean, whereas in Scenarios 2 and 3 (positively correlated) they were much more scattered, particularly on the right side, more than on the left side. It can be deduced that the input cost distributions were lognormal distributions, and the input time distributions were triangular distributions which skewed to the right (the mode input was smaller than the mean input).
- vi. The differences in total cost and total time standard deviations between Scenario 1 and Scenario 3 in all the geological conditions of cutting construction were more than one order of magnitude (100%) in total cost and more than two orders of magnitude (200%) in total time; for instance, the variations in total cost and time standard deviation of cutting in rock geology were 189% and 246%, respectively.
- vii. The difference in total cost and total time standard deviations between Scenario 1 and Scenario 3 of construction filling was more than eight orders of magnitude (800%) in total cost and more than six orders of magnitude (600%) in total time. For instance, the variation in total cost and time standard deviation of fill construction was 898% and 758%, respectively.
- viii. Scenario 2 was correlated positively the costs and times of repeated activities ($p_r = (0, 1)$), which is a correlation scenario between the extreme scenarios of independent ($p_r = 0$) and fully correlated ($p_r = 1$). This was reflected in the overlay distributions' cost and time plots as well as cost and time scatterplots, where the samples of Scenario 2 were more widely spread than the sample in Scenario 1, and more concentrated than the sample in Scenario 3 (Figure 6.23). This was confirmed by the magnitude of the variation in standard deviation, which was lower than in Scenario 3 (See Table 6.16).
- ix. The variations in the standard deviation of cost and time depended on the number of repetitions. For instance, the cutting construction in soft geology had the highest variation in standard deviation due to the highest number of repetitions.
- x. The means of total cost and total time were larger than the deterministic total cost and total time due to the following reasons:
 - Cost input distributions (lognormal) and time input distributions (triangular) were skewed to the right; in other words, the mean was larger than the mode.
 - The deterministic total cost and total time were the sums of the modes of the input distributions, while the probabilistic means of total cost and total time were equal to the sum of the means of the input distributions.

The impact of the three scenarios of correlation between repeated activities in the earthwork structure was further investigated with sensitivity analysis.

6.3.1.3 *Modelling correlation between the different activities in the earthwork structure*

This model represents a correlation between the costs and times of different activities in construction cutting and filling. Based on the earthwork expert panel’s opinion, it was assumed that the cost/time of the excavation activities and the trench activities in cutting construction were correlated due to the dependency of cost and time of these two activities to the geological conditions.

The expert panel suggested the correlation coefficient of $\rho_r=+0.75$, so that the correlation matrix of the elements in unit i of cutting between excavation and trench activities was:

$$R_{r\text{cut}} = \begin{bmatrix} 1 & 0.75 \\ 0.75 & 1 \end{bmatrix}$$

Similarly, according to the earthwork experts, the cost and time of improving the area activities and the embankment activities in filling construction are assumed to be correlated. The correlation was recommended to be $\rho_r=+0.8$ so that the correlation matrix of the elements in unit i of filling between improving the area and embankment activities was:

$$R_{r\text{fill}} = \begin{bmatrix} 1 & 0.8 \\ 0.8 & 1 \end{bmatrix}$$

The means, standard deviations and the variations of total correlated cost and total correlated time in the activities of cutting construction and filling construction, and the overall earthwork structure were estimated by the Gaussian copula using the marginal distribution assumptions and Spearman correlation coefficient matrix as summarised in Table 6.16.

Table 6.16: Correlation between the different activities in construction cutting and filling and overall earthwork structure.

		Cost				Time			
		Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Cutting Construction	Base Case	95231262.30	0.00%	963202.23	0.00%	144.67	0.00%	1.72	0.00%
	Correlated	95236541.18	0.01%	10890336.48	1030.64%	144.76	0.06%	14.49	740.03%
Construction Filling	Base Case	173507327.73	0.00%	1611379.94	0.00%	222.19	0.00%	2.61	0.00%
	Correlated	173430936.34	-0.04%	19290967.14	1097.17%	221.60	-0.27%	21.93	740.23%
Earthwork Structure	Base Case	268726606.90	0.00%	1871424.00	0.00%	222.19	0.00%	2.61	0.00%
	Correlated	268180187.90	-0.20%	22538485.66	1104.35%	222.15	-0.02%	22.22	751.45%

The scatterplots of the base case and correlated total costs and total times of construction cutting and filling and the overall earthwork structure were modelled with Monte Carlo simulation and are shown in Figures 6.24 to 6.26.

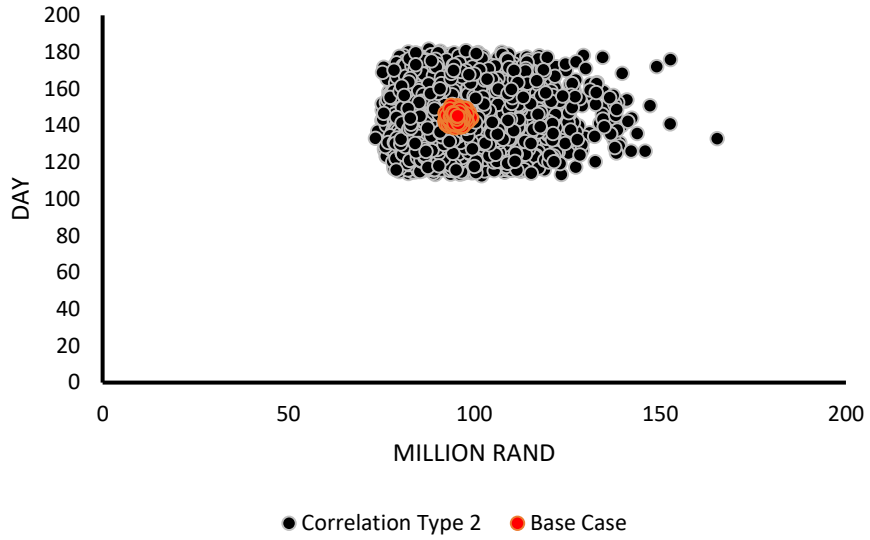


Figure 6.24: Scatterplot of correlated total cost and total time of construction cutting and the correlation between different activities (Type 2)

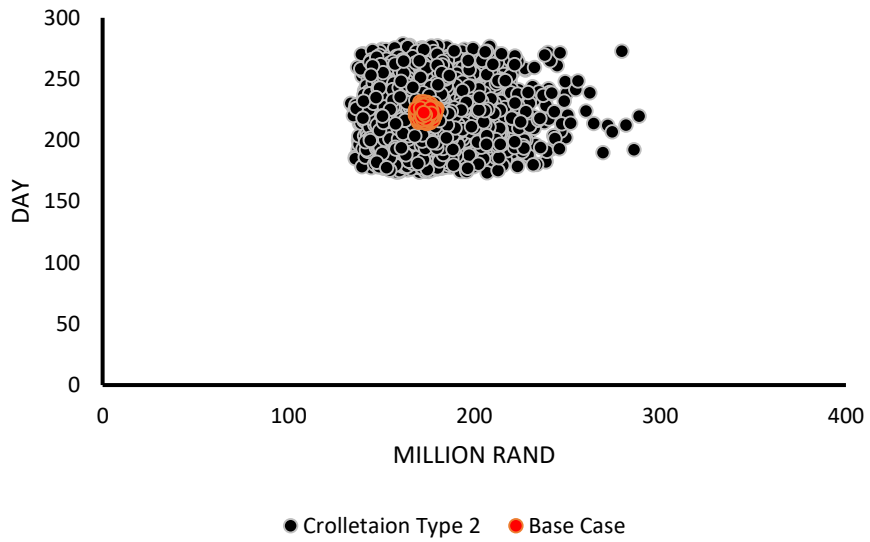


Figure 6.25: Scatterplot of correlated total cost and total time of construction filling and the correlation between different activities (Type 2)

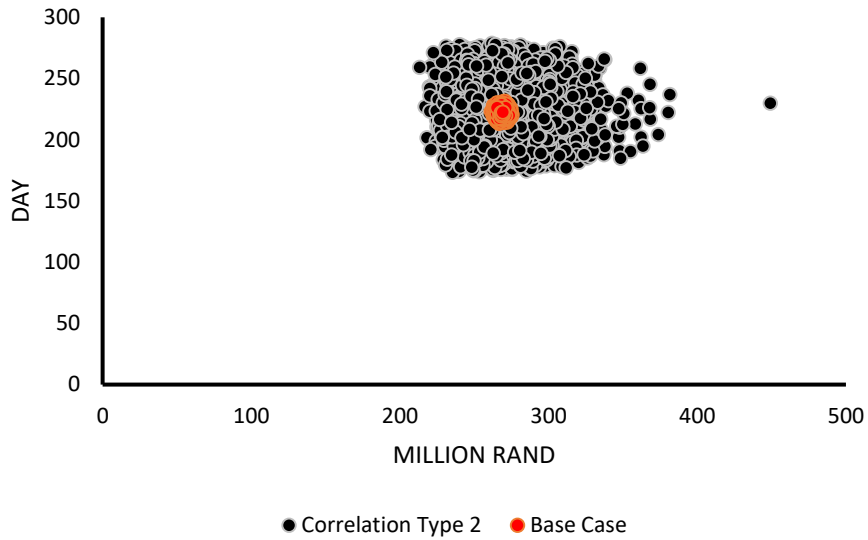


Figure 6.26: Scatterplot of correlated total cost and total time of earthwork construction, the correlation between different activities (Type 2)

The following deductions are made on the correlation between activities on the earthwork structure:

- i. The mean of the total cost and total time of construction cutting and filling overall earthwork structure are considered constant from the base case to correlated cost and time. This is confirmed by the constant centre of significance in the scatterplots (Figures 6.24 – 6.26), and variations of total cost mean, and time means (± 1) (See Table 6.17).
- ii. The means of total cost and total time of construction cutting, and filling and the overall earthwork structure were larger than the respective deterministic total cost and total time. (Cost input distributions and time input distributions were skewed to the right.)
- iii. The standard deviation of the total cost and total time were increased dramatically from base case (uncorrelated) to correlated between activities of construction of cuts, fills and earthwork structure. For instance, the standard deviations of the total cost and total time of the earthwork structure were increased by 1104.35% and 751.45%, respectively. These increases in total cost and total time standard deviations were barely visible in the scatterplot (See Figure 6.26).

The evaluation of the correlation between the cost and time activity in the structure of the earthwork structure with the base case (uncorrelated) proved that the standard deviations of the total cost and total time were increased dramatically, due to a positive correlation between the cost and time of activities in the earthwork structure. This aspect was further investigated using sensitivity analysis.

6.3.1.4 *Modelling correlation between the cost and the time of an activity in earthwork structure*

This correlation represented a correlation between the cost and time of each activity in the earthwork structure. The costs and times were independent of each other, but the cost and the time of each element *i* were correlated. The study assumed that the costs and times of all activities in cutting and filling construction are correlated. Based on knowledge provided by the earthwork expert panel, the correlation was assumed to be $\rho_r = +0.8$ so that the correlation matrix of the element *i* between the cost and the time of an activity is:

$$R_{r, cost - time} = \begin{bmatrix} 1 & 0.8 \\ 0.8 & 1 \end{bmatrix}$$

The means, standard deviations and the variations of correlated cost and time in construction cutting and filling, and in the overall earthwork structure are listed in Table 6.17.

Table 6.17: Correlation between the cost and time of activity in the construction cut and fill and the overall earthwork structure

		Cost				Time				Cost & time correlation
		Mean	Δ_M	S.D	Δ_s	Mean	Δ_M	S.D	Δ_s	
Cutting Construction	Base Case	95231262.30	0.00%	963202.23	0.00%	144.67	0.00%	1.72	0.00%	0.712
	Correlated	95,225,048.96	-0.01%	8,961,026.27	830.34%	144.69	0.02%	14.41	735.40%	
Construction Filling	Base Case	173507327.73	0.00%	1611379.94	0.00%	222.19	0.00%	2.61	0.00%	0.264
	Correlated	173418138.2	-0.05%	16384040.6	916.77%	222.312	0.05%	22.27	753.12%	
Earthwork Structure	Base Case	268726606.90	0.00%	1871424.00	0.00%	222.19	0.00%	2.61	0.00%	0.232
	Correlated	268784679.2	0.02%	18319948.86	878.93%	222.678	0.22%	22.34	756.05%	

The scatterplots of the base case and correlated total cost and total time of the earthwork structure were simulated by the Monte Carlo analysis and are shown in Figures 6.27- 6.29.

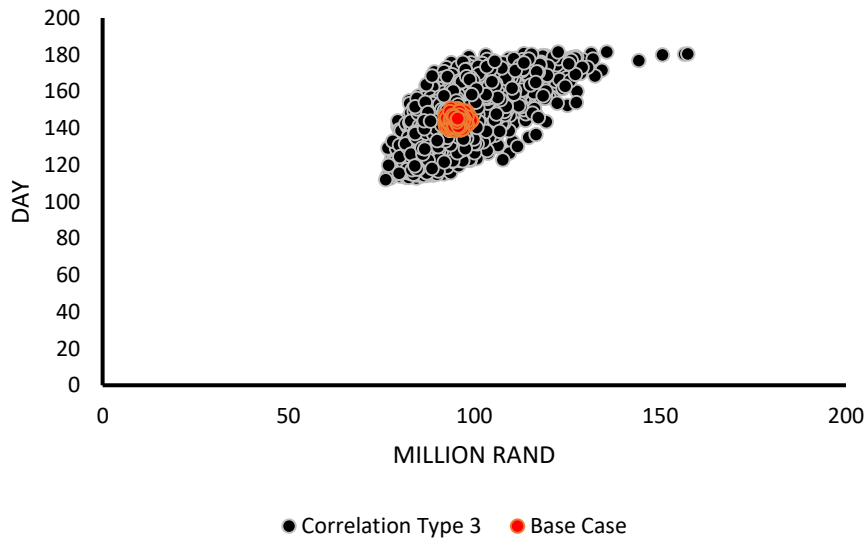


Figure 6.27: Scatterplot of correlated total cost and total time of the construction cutting, the correlation between cost and time (Type 3)

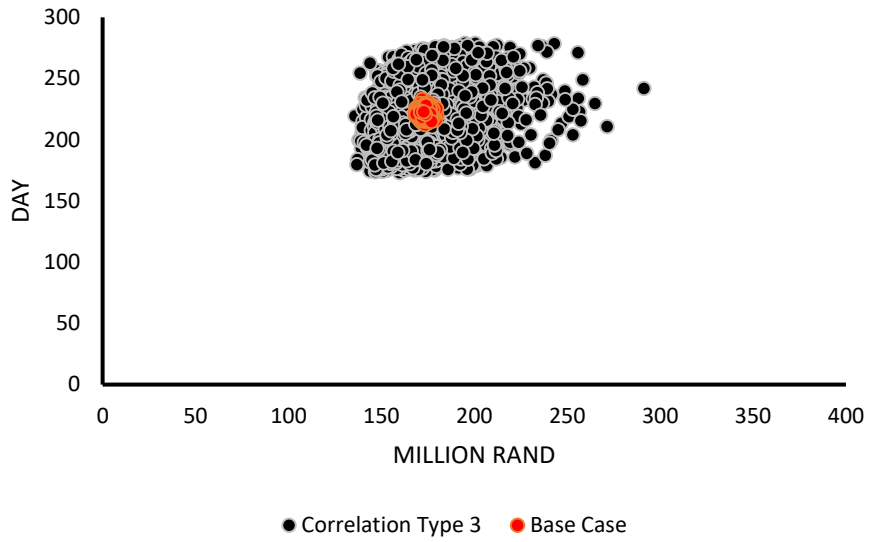


Figure 6.28: Scatterplot of correlated total cost and total time of the construction filling, the correlation between cost and time (Type 3)

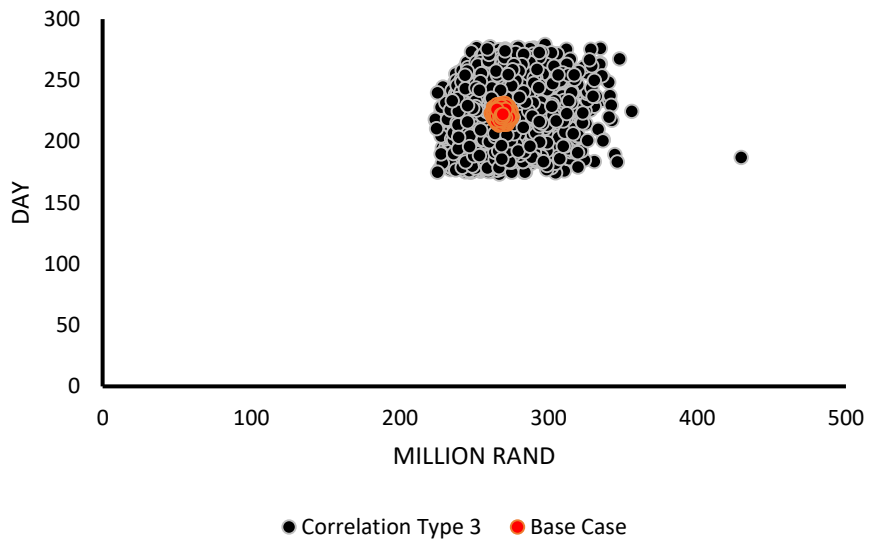


Figure 6.29: Scatterplot of correlated total cost and total time of the earthwork structure, the correlation between cost and time (Type 3)

Based on the analysis on the correlation between the cost and time of activities on the earthwork structure, the following deductions are made:

- i. The mean of the total cost and total time of both the construction cutting and filling and overall earthwork structure are constant from base case to correlated cost and time, due to the centre of importance/significance.
- ii. The means of total cost and total time of the earthwork constructions and overall structure were larger than the respective deterministic total cost and total time. (Cost distributions and time distributions were skewed to the right.)
- iii. Likewise, the correlation between the different activities in a structure and the standard deviation of the total cost and total time of correlation between the cost and the time of an activity were increased dramatically from base case (uncorrelated) to correlated between the cost and time of an activity.
- iv. The standard deviations of the total cost and total time of construction of the cutting construction were increased by 830% and 735%, respectively. Furthermore, there was a strong correlation, $p_r=+0.712$, between total cost and total time of the cutting construction, while the correlations between total cost and total time of the construction filling and earthwork structure were very weak ($p_r=+0.251$, $p_r=+0.222$) which are visible in the inclination of the cloud of data points in Figure 6.29.

The evaluation of the correlation between the different activities in the construction of the earthwork structure with the base case (uncorrelated) proved that the standard deviations of the total cost and total time were increased dramatically due to a positive correlation between the cost and time of activities in the earthwork structure. This aspect is further investigated with sensitivity analysis.

6.3.2 Correlations in the bridge structure

In this section, all three different types of correlations were modelled using the Gaussian copula and the impact of each correlation on costs and times of the box culvert construction, slab bridge construction and overall bridge structure were assessed.

6.3.2.1 Modelling probabilistic cost and time of the bridge structure

The total probabilistic cost and the total time of each activity of the bridge structures with different geometry and in different geological conditions were calculated using the same process (assumptions, equations) as the earthwork structure and the results are summarised in Tables 6.18 and 6.19.

Table 6.18: Probability costs and time parameters of box culvert activities with different geometry and geological conditions

Activity	Geometry	Geology	Cost					Time		
			Min	Mode	Higher	Mean	S.D	Min	Mode	Higher
Set up Site	All		12,000.00	15,000.00	22,500.00	16,500.00	4,415.88	1.60	2	2.60
Bedding	Box 1x1x1m Perpendicular	Fine	129,600.00	162,000.00	243,000.00	178,200.00	47,691.51	11.20	14	18.20
		Soft	115,200.00	144,000.00	216,000.00	158,400.00	42,392.45			
	Box 1x1x1m Skewed	Fine	162,000.00	202,500.00	303,750.00	222,750.00	59,614.39	12.00	15	19.50
		Soft	144,000.00	180,000.00	270,000.00	198,000.00	52,990.57			
	Box 2x1x1m Skewed	Fine	270,000.00	337,500.00	506,250.00	371,250.00	99,357.31	13.60	17	22.10
		Soft	240,000.00	300,000.00	450,000.00	330,000.00	88,317.61			
Set up culvert	Box 1x1x1m Perpendicular	Fine	576,000.00	720,000.00	1,080,000.00	792,000.00	211,962.26	4.80	6	7.80
		Soft	576,000.00	720,000.00	1,080,000.00	792,000.00	211,962.26			
	Box 1x1x1m Skewed	Fine	720,000.00	900,000.00	1,350,000.00	990,000.00	264,952.83	5.60	7	9.10
		Soft	720,000.00	900,000.00	1,350,000.00	990,000.00	264,952.83			
	Box 2x1x1m Skewed	Fine	1,440,000.00	1,800,000.00	2,700,000.00	1,980,000.00	529,905.65	7.20	9	11.70
		Soft	1,440,000.00	1,800,000.00	2,700,000.00	1,980,000.00	529,905.65			
Footing of wing wall	Box 1x1x1m Perpendicular	Fine	190,080.00	237,600.00	356,400.00	261,360.00	69,947.55	12.00	15	19.50
		Soft	163,200.00	204,000.00	306,000.00	224,400.00	60,055.97			
	Box 1x1x1m Skewed	Fine	237,600.00	297,000.00	445,500.00	326,700.00	87,434.43	12.80	16	20.80
		Soft	204,000.00	255,000.00	382,500.00	280,500.00	75,069.97			
	Box 2x1x1m Skewed	Fine	237,600.00	297,000.00	445,500.00	326,700.00	87,434.43	12.80	16	20.80
		Soft	204,000.00	255,000.00	382,500.00	280,500.00	75,069.97			
Wing wall	Box 1x1x1m Perpendicular	Fine	67,200.00	84,000.00	126,000.00	92,400.00	24,728.93	9.60	12	15.60
		Soft	67,200.00	84,000.00	126,000.00	92,400.00	24,728.93			
	Box 1x1x1m Skewed	Fine	80,640.00	100,800.00	151,200.00	110,880.00	29,674.72	11.20	14	18.20
		Soft	80,640.00	100,800.00	151,200.00	110,880.00	29,674.72			
	Box 2x1x1m Skewed	Fine	80,640.00	100,800.00	151,200.00	110,880.00	29,674.72	11.20	14	18.20
		Soft	80,640.00	100,800.00	151,200.00	110,880.00	29,674.72			
Backfilling	Box 1x1x1m Perpendicular	Fine	21,000.00	26,250.00	39,375.00	28,875.00	7,727.79	0.80	1	1.30
		Soft	21,000.00	26,250.00	39,375.00	28,875.00	7,727.79			
	Box 1x1x1m Skewed	Fine	25,200.00	31,500.00	47,250.00	34,650.00	9,273.35	0.80	1	1.30
		Soft	25,200.00	31,500.00	47,250.00	34,650.00	9,273.35			
	Box 2x1x1m Skewed	Fine	25,200.00	31,500.00	47,250.00	34,650.00	9,273.35	0.80	1	1.30
		Soft	25,200.00	31,500.00	47,250.00	34,650.00	9,273.35			
Total	Box 1x1x1m Perpendicular	Fine	995,880.00	1,244,850.00	1,867,275.00	1,369,335.00	366,473.92	24.00	30	39.00
		Soft	954,600.00	1,193,250.00	1,789,875.00	1,312,575.00	351,283.29			
	Box 1x1x1m Skewed	Fine	1,237,440.00	1,546,800.00	2,320,200.00	1,701,480.00	455,365.59	26.40	33	42.90
		Soft	1,185,840.00	1,482,300.00	2,223,450.00	1,630,530.00	436,377.30			
	Box 2x1x1m Skewed	Fine	2,065,440.00	2,581,800.00	3,872,700.00	2,839,980.00	760,061.34	26.40	33	42.90
		Soft	2,001,840.00	2,502,300.00	3,753,450.00	2,752,530.00	736,657.17			

Table 6.19: Probability costs and time parameters of slab bridge activities with different geometry and geological conditions

Activity	Geometry	Geology	Cost					Time		
			Min	Mode	Higher	Mean	S.D	Min	Mode	Higher
Set up Site	All		24,000.00	30,000.00	45,000.00	33,000.00	8,831.76	2.40	3	3.90
Footing of abutment	Slab 1x2x2m Perpendicular	Hard	307,200.00	384,000.00	576,000.00	422,400.00	113,046.54	13.60	17	22.10
		Rock	241,920.00	302,400.00	453,600.00	332,640.00	89,024.15			
	Slab 1x2x2m skewed	Hard	384,000.00	480,000.00	720,000.00	528,000.00	141,308.17	14.40	18	23.40
		Rock	302,400.00	378,000.00	567,000.00	415,800.00	111,280.19			
	Slab 3x4x1m Perpendicular	Hard	1,075,200.00	1,344,000.00	2,016,000.00	1,478,400.00	395,662.89	12.80	16	20.80
		Rock	933,120.00	1,166,400.00	1,749,600.00	1,283,040.00	343,378.86			
Abutment	Slab 1x2x2m Perpendicular	Hard	259,200.00	324,000.00	486,000.00	356,400.00	95,383.02	13.60	17	22.10
		Rock	240,000.00	300,000.00	450,000.00	330,000.00	88,317.61			
	Slab 1x2x2m skewed	Hard	324,000.00	405,000.00	607,500.00	445,500.00	119,228.77	14.40	18	23.40
		Rock	300,000.00	375,000.00	562,500.00	412,500.00	110,397.01			
	Slab 3x4x1m Perpendicular	Hard	480,000.00	600,000.00	900,000.00	660,000.00	176,635.22	11.20	14	18.20
		Rock	460,800.00	576,000.00	864,000.00	633,600.00	169,569.81			
Footing of pier	Slab 3x4x1m Perpendicular	Hard	1,152,000.00	1,440,000.00	2,160,000.00	1,584,000.00	423,924.52	14.40	18	23.40
		Rock	1,002,240.00	1,252,800.00	1,879,200.00	1,378,080.00	368,814.33			
Pier	Slab 3x4x1m Perpendicular	Hard	768,000.00	960,000.00	1,440,000.00	1,056,000.00	282,616.35	12.00	15	19.50
		Rock	729,600.00	912,000.00	1,368,000.00	1,003,200.00	268,485.53			
Footing of wing wall	Slab 1x2x2m Perpendicular	Hard	138,240.00	172,800.00	259,200.00	190,080.00	50,870.94	13.60	17	22.10
		Rock	115,200.00	144,000.00	216,000.00	158,400.00	42,392.45			
	Slab 1x2x2m skewed	Hard	172,800.00	216,000.00	324,000.00	237,600.00	63,588.68	14.40	18	23.40
		Rock	144,000.00	180,000.00	270,000.00	198,000.00	52,990.57			
	Slab 3x4x1m Perpendicular	Hard	138,240.00	172,800.00	259,200.00	190,080.00	50,870.94	12.00	15	19.50
		Rock	115,200.00	144,000.00	216,000.00	158,400.00	42,392.45			
Wing wall	Slab 1x2x2m Perpendicular	Hard	67,200.00	84,000.00	126,000.00	92,400.00	24,728.93	12.80	16	20.80
		Rock	67,200.00	84,000.00	126,000.00	92,400.00	24,728.93			
	Slab 1x2x2m skewed	Hard	80,640.00	100,800.00	151,200.00	110,880.00	29,674.72	13.60	17	22.10
		Rock	80,640.00	100,800.00	151,200.00	110,880.00	29,674.72			
	Slab 3x4x1m Perpendicular	Hard	76,080.00	95,100.00	142,650.00	104,610.00	27,996.68	11.20	14	18.20
		Rock	76,080.00	95,100.00	142,650.00	104,610.00	27,996.68			
Precast deck	Slab 1x2x2m Perpendicular	Hard	115,200.00	144,000.00	216,000.00	158,400.00	42,392.45	13.60	17	22.10
		Rock	115,200.00	144,000.00	216,000.00	158,400.00	42,392.45			
	Slab 1x2x2m skewed	Hard	148,800.00	186,000.00	279,000.00	204,600.00	54,756.92	14.40	18	23.40
		Rock	148,800.00	186,000.00	279,000.00	204,600.00	54,756.92			
	Slab 3x4x1m Perpendicular	Hard	921,600.00	1,152,000.00	1,728,000.00	1,267,200.00	339,139.62	18.40	23	29.90
		Rock	921,600.00	1,152,000.00	1,728,000.00	1,267,200.00	339,139.62			
Backfilling	Slab 1x2x2m Perpendicular	Hard	21,000.00	26,250.00	39,375.00	28,875.00	7,727.79	0.80	1	1.30
		Rock	21,000.00	26,250.00	39,375.00	28,875.00	7,727.79			
	Slab 1x2x2m skewed	Hard	25,200.00	31,500.00	47,250.00	34,650.00	9,273.35	0.80	1	1.30
		Rock	25,200.00	31,500.00	47,250.00	34,650.00	9,273.35			
	Slab 3x4x1m Perpendicular	Hard	21,000.00	26,250.00	39,375.00	28,875.00	7,727.79	0.80	1	1.30
		Rock	21,000.00	26,250.00	39,375.00	28,875.00	7,727.79			
Total	Slab 1x2x2m Perpendicular	Hard	932,040.00	1,165,050.00	1,747,575.00	1,281,555.00	342,981.43	44.00	55	71.50
		Rock	824,520.00	1,030,650.00	1,545,975.00	1,133,715.00	303,415.14			
	Slab 1x2x2m skewed	Hard	1,159,440.00	1,449,300.00	2,173,950.00	1,594,230.00	426,662.37	46.40	58	75.40
		Rock	1,025,040.00	1,281,300.00	1,921,950.00	1,409,430.00	377,204.51			

Slab 3x4x1m Perpendicular	Hard	4,656,120.00	5,820,150.00	8,730,225.00	6,402,165.00	1,713,405.77	48.00	60	78.00
	Rock	4,283,640.00	5,354,550.00	8,031,825.00	5,890,005.00	1,576,336.84			

6.3.2.2 Modelling correlation between a repeated activity in a bridge structure

To model this correlation on the bridge structure the three scenarios for repeated activities in the bridge (culvert, slab) activities were considered:

Base Case: Every unit of the activity was uncorrelated.

Scenario 1. Every unit of the activity was independent, $p_r = 0$.

$$R_{r1} = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & 0 & \vdots \\ \vdots & 0 & 1 & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix}$$

Scenario 2. Every unit of the activity is positively correlated, $p_r = (0, 1)$. The cost and time of every activity of a bridge are positively dependent on the cost and time of the preceding and following unit. The correlation decreases by 0.01 for a unit of activity.

$$R_{r2} = \begin{bmatrix} 1 & 0.99 & \dots & 0 \\ 0.99 & 1 & 0.99 & \vdots \\ \vdots & 0.99 & 1 & 0.99 \\ 0 & \dots & 0.99 & 1 \end{bmatrix}$$

Scenario 3. Every unit of the activity is perfectly correlated, $p_r = 1$.

$$R_{r1} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & 1 & 1 & \vdots \\ \vdots & 1 & 1 & 1 \\ 1 & \dots & 1 & 1 \end{bmatrix}$$

Certain bridge activities' costs and time, such as footings, were changed if the geology changed. The ranges of total cost and total time for each construction activity of the bridge were estimated for the above three scenarios by the Gaussian copula using the marginal distribution assumptions and Spearman correlation coefficient matrix. The probabilistic calculation was simulated by the Monte Carlo simulations, which were run until the total of the standard deviation of activity was bounded within $\pm 1\%$ in 10 out of 10 sample simulations.

6.3.2.3 Modelling correlation between a repeated activity in different geologies of the culvert

The range of means and the standard deviations of total cost and total time of culvert activities with different geometry in the four geological conditions for the three correlation scenarios (independent, positively correlated and fully correlated) are summarised in Table 6.20. To evaluate the variation of the mean and standard deviation of each scenario from base case, the variation in mean and standard deviation of each scenario were also calculated.

Table 6.20: Correlation between a repeated activity in different geometry and geology of culvert construction

Activity	Geometry	Geology	Scenario	Cost				Time			
				Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Set up site	All		Base Case	16,501.23	0.00%	727.20	0.00%	2.07	0.00%	0.14	0.00%
			Scenario 1	16,500.10	-0.01%	720.19	-0.96%	2.06	-0.02%	0.15	0.52%
			Scenario 2	16,524.95	0.14%	2,221.18	205.44%	2.07	0.20%	0.21	42.85%
			Scenario 3	16,504.44	0.02%	2,303.80	216.80%	2.07	0.14%	0.21	43.61%
Bedding	1x1x1m Perpendicular	Fine	Base Case	177,998.12	0.00%	7,947.61	0.00%	14.46	0.00%	0.54	0.00%
			Scenario 1	178,048.99	0.03%	7,914.92	-0.41%	14.47	0.07%	0.54	0.00%
			Scenario 2	178,028.83	0.02%	23,946.20	201.30%	14.44	-0.14%	1.43	164.81%
			Scenario 3	177,977.41	-0.01%	24,833.78	212.47%	14.45	-0.07%	1.45	168.52%
		Soft	Base Case	158,410.05	0.00%	6,963.88	0.00%	14.46	0.00%	0.54	0.00%
			Scenario 1	158,380.87	-0.02%	7,003.80	0.57%	14.47	0.07%	0.54	0.00%
			Scenario 2	158,072.42	-0.21%	20,941.01	200.71%	14.44	-0.14%	1.43	164.81%
			Scenario 3	158,819.48	0.26%	22,168.91	218.34%	14.45	-0.07%	1.45	168.52%
	1x1x1m Skewed	Fine	Base Case	222,480.24	0.00%	9,691.98	0.00%	15.50	0.00%	0.54	0.00%
			Scenario 1	222,784.77	0.14%	9,768.66	0.79%	15.50	0.00%	0.55	0.93%
			Scenario 2	222,162.75	-0.14%	30,316.52	212.80%	15.50	0.00%	1.52	181.48%
			Scenario 3	222,832.70	0.16%	31,167.76	221.58%	15.53	0.19%	1.53	183.33%
		Soft	Base Case	198,034.42	0.00%	8,627.47	0.00%	15.50	0.00%	0.54	0.00%
			Scenario 1	198,038.22	0.00%	8,643.75	0.19%	15.50	0.00%	0.55	0.93%
			Scenario 2	197,657.32	-0.19%	27,397.16	217.56%	15.50	0.00%	1.52	181.48%
			Scenario 3	197,842.88	-0.10%	27,593.44	219.83%	15.53	0.19%	1.53	183.33%
	2x1x1m Skewed	Soft	Base Case	330,551.60	0.00%	14,912.12	0.00%	17.56	0.00%	0.59	0.00%
			Scenario 1	330,111.21	-0.13%	14,769.05	-0.96%	17.58	0.11%	0.59	0.00%
			Scenario 2	329,886.63	-0.20%	44,317.09	197.19%	17.60	0.23%	1.72	191.53%
			Scenario 3	329,229.33	-0.40%	46,084.68	209.04%	17.58	0.11%	1.76	198.31%
Set up culvert	1x1x1m Perpendicular	Fine & Soft	Base Case	791,871.09	0.00%	35,489.84	0.00%	6.20	0.00%	0.35	0.00%
			Scenario 1	792,281.15	0.05%	35,153.29	-0.95%	6.20	0.00%	0.35	0.00%
			Scenario 2	792,171.38	0.04%	109,211.93	207.73%	6.20	0.00%	0.61	74.29%
			Scenario 3	792,188.42	0.04%	112,362.44	216.60%	6.21	0.16%	0.62	77.14%
	1x1x1m Skewed	Fine & Soft	Base Case	990,477.20	0.00%	43,102.04	0.00%	7.23	0.00%	0.37	0.00%
			Scenario 1	989,800.56	-0.07%	43,112.82	0.03%	7.24	0.14%	0.37	-0.54%
			Scenario 2	990,930.31	0.05%	133,849.20	210.54%	7.24	0.14%	0.72	94.59%
			Scenario 3	987,801.32	-0.27%	135,965.80	215.45%	7.22	-0.14%	0.73	97.30%
	2x1x1m Skewed	Soft	Base Case	1,981,528.92	0.00%	86,886.43	0.00%	9.29	0.00%	0.42	0.00%
			Scenario 1	1,981,621.87	0.00%	86,123.64	-0.88%	9.30	0.11%	0.42	0.71%
			Scenario 2	1,978,354.83	-0.16%	266,048.69	206.20%	9.29	0.00%	0.93	121.43%
			Scenario 3	1,983,628.19	0.11%	276,577.09	218.32%	9.30	0.11%	0.93	121.43%
Footing of wing wall	1x1x1m Perpendicular	Fine	Base Case	261,185.96	0.00%	11,537.64	0.00%	15.49	0.00%	0.56	0.00%
			Scenario 1	261,516.78	0.13%	11,565.67	0.24%	15.50	0.06%	0.56	0.00%
			Scenario 2	261,119.92	-0.03%	35,304.89	206.00%	15.50	0.06%	1.51	169.64%
			Scenario 3	262,340.11	0.44%	36,646.45	217.63%	15.49	0.00%	1.54	175.00%
		Soft	Base Case	224,461.74	0.00%	9,913.40	0.00%	15.49	0.00%	0.56	0.00%
			Scenario 1	224,415.99	-0.02%	9,927.84	0.15%	15.50	0.06%	0.56	0.00%
			Scenario 2	224,357.94	-0.05%	30,928.18	211.98%	15.50	0.06%	1.51	169.64%
			Scenario 3	224,768.65	0.14%	31,822.84	221.01%	15.49	0.00%	1.54	175.00%
		Fine	Base Case	326,655.82	0.00%	14,436.82	0.00%	16.53	0.00%	0.59	0.00%

	1x1x1m Skewed		Scenario 1	326,825.40	0.05%	14,379.15	-0.40%	16.52	-0.06%	0.59	-0.85%	
			Scenario 2	325,454.27	-0.37%	42,924.87	197.33%	16.52	-0.06%	1.62	174.58%	
			Scenario 3	326,190.38	-0.14%	46,080.14	219.18%	16.54	0.06%	1.65	179.66%	
		Soft	Base Case	280,679.59	0.00%	12,467.17	0.00%	16.53	0.00%	0.59	0.00%	
			Scenario 1	280,531.69	-0.05%	12,371.23	-0.77%	16.52	-0.06%	0.59	-0.85%	
			Scenario 2	279,639.66	-0.37%	37,691.48	202.33%	16.52	-0.06%	1.62	174.58%	
	2x1x1m Skewed	Soft	Scenario 3	280,577.34	-0.04%	39,212.15	214.52%	16.54	0.06%	1.65	179.66%	
			Base Case	280,679.59	0.00%	12,467.17	0.00%	16.53	0.00%	0.59	0.00%	
			Scenario 1	280,531.69	-0.05%	12,371.23	-0.77%	16.52	-0.06%	0.59	-0.85%	
	Wing wall	1x1x1m Perpendicular	Fine & Soft	Base Case	92,444.77	0.00%	4,121.98	0.00%	12.39	0.00%	0.50	0.00%
				Scenario 1	92,465.41	0.02%	4,093.23	-0.70%	12.41	0.16%	0.50	0.80%
				Scenario 2	92,582.43	0.15%	12,710.66	208.36%	12.40	0.08%	1.24	148.00%
Scenario 3				92,697.77	0.27%	12,955.96	214.31%	12.39	0.00%	1.25	150.00%	
1x1x1m Skewed		Fine & Soft	Base Case	110,908.97	0.00%	4,874.46	0.00%	14.48	0.00%	0.53	0.00%	
			Scenario 1	110,894.45	-0.01%	4,909.03	0.71%	14.47	-0.07%	0.54	0.94%	
			Scenario 2	110,827.36	-0.07%	14,971.58	207.14%	14.46	-0.14%	1.44	171.70%	
			Scenario 3	110,808.83	-0.09%	15,336.62	214.63%	14.52	0.28%	1.45	173.58%	
2x1x1m Skewed		Soft	Base Case	110,908.97	0.00%	4,874.46	0.00%	14.48	0.00%	0.53	0.00%	
			Scenario 1	110,894.45	-0.01%	4,909.03	0.71%	14.47	-0.07%	0.54	0.94%	
			Scenario 2	110,827.36	-0.07%	14,971.58	207.14%	14.46	-0.14%	1.44	171.70%	
			Scenario 3	110,808.83	-0.09%	15,336.62	214.63%	14.52	0.28%	1.45	173.58%	
Backfilling	1x1x1m Perpendicular	Fine & Soft	Base Case	28,873.17	0.00%	1,280.20	0.00%	1.03	0.00%	0.10	0.00%	
			Scenario 1	28,892.14	0.07%	1,272.98	-0.56%					
			Scenario 2	28,849.10	-0.08%	3,892.40	204.05%					
			Scenario 3	28,909.71	0.13%	3,957.81	209.16%					
	1x1x1m Skewed	Fine & Soft	Base Case	34,697.16	0.00%	1,518.21	0.00%					
			Scenario 1	34,646.18	-0.15%	1,517.09	-0.07%					
			Scenario 2	34,527.72	-0.49%	4,707.27	210.05%					
			Scenario 3	34,618.34	-0.23%	4,760.64	213.57%					
	Box 2x1x1m (Skewed)	Soft	Base Case	34,697.16	0.00%	1,518.21	0.00%					
			Scenario 1	34,646.18	-0.15%	1,517.09	-0.07%					
			Scenario 2	34,527.72	-0.49%	4,707.27	210.05%					
			Scenario 3	34,618.34	-0.23%	4,760.64	213.57%					
Total	1x1x1m Perpendicular	Fine	Base Case	1,369,069.30	0.00%	37,133.45	0.00%	30.99	0.00%	0.80	0.00%	
			Scenario 1	1,369,614.34	0.04%	37,450.66	0.85%	30.98	-0.03%	0.79	-0.75%	
			Scenario 2	1,372,022.78	0.22%	116,349.26	213.33%	31.02	0.10%	2.99	273.75%	
			Scenario 3	1,370,538.98	0.11%	121,461.48	227.09%	31.00	0.03%	3.12	290.00%	
		Soft	Base Case	1,312,233.17	0.00%	37,178.11	0.00%	30.99	0.00%	0.80	0.00%	
			Scenario 1	1,312,321.83	0.01%	37,254.04	0.20%	30.98	-0.03%	0.79	-0.75%	
			Scenario 2	1,315,110.51	0.22%	116,077.24	212.22%	31.02	0.10%	2.99	273.75%	
			Scenario 3	1,312,590.55	0.03%	117,290.29	215.48%	31.00	0.03%	3.12	290.00%	
	1x1x1m Skewed	Fine	Base Case	1,700,942.45	0.00%	47,580.74	0.00%	34.09	0.00%	0.83	0.00%	
			Scenario 1	1,701,905.47	0.06%	47,252.66	-0.69%	34.08	-0.03%	0.82	-0.72%	
			Scenario 2	1,701,717.63	0.05%	146,880.61	208.70%	34.15	0.18%	3.27	293.98%	
			Scenario 3	1,703,119.81	0.13%	149,678.69	214.58%	34.10	0.03%	3.37	306.02%	
Soft	Soft	Base Case	1,630,984.21	0.00%	47,035.70	0.00%	34.09	0.00%	0.83	0.00%		
		Scenario 1	1,631,005.81	0.00%	46,687.43	-0.74%	34.08	-0.03%	0.82	-0.72%		
		Scenario 2	1,629,337.17	-0.10%	145,730.52	209.83%	34.15	0.18%	3.27	293.98%		
		Scenario 3	1,629,337.17	-0.10%	145,730.52	209.83%	34.15	0.18%	3.27	293.98%		

	2x1x1m Skewed	Soft	Scenario 3	1,632,263.68	0.08%	147,366.57	213.31%	34.10	0.03%	3.37	306.02%
			Base Case	2,753,023.43	0.00%	89,830.34	0.00%	34.09	0.00%	0.83	0.00%
			Scenario 1	2,753,742.98	0.03%	89,826.80	0.00%	34.08	-0.03%	0.82	-0.72%
			Scenario 2	2,755,548.17	0.09%	279,248.88	210.86%	34.15	0.18%	3.27	293.98%
			Scenario 3	2,758,080.28	0.18%	285,531.12	217.86%	34.10	0.03%	3.37	306.02%
Culvert construction			Base Case	67,781,462.00	0.00%	1,886,428.00	0.00%	351.26	0.00%	5.06	0.00%
			Scenario 1	67,831,759.00	0.07%	1,901,775.00	0.81%	351.40	0.04%	5.11	0.96%
			Scenario 2	67,812,300.00	0.05%	5,996,235.00	217.86%	351.60	0.10%	31.54	523.11%
			Scenario 3	67,824,920.00	0.06%	6,048,284.00	220.62%	351.46	0.06%	35.14	594.07%

The scatterplots of the base case and correlated total cost and total time of the three scenarios of culvert construction, with different geometries and geologies, were modelled with a Monte Carlo simulation, as illustrated in Figure 6.30.

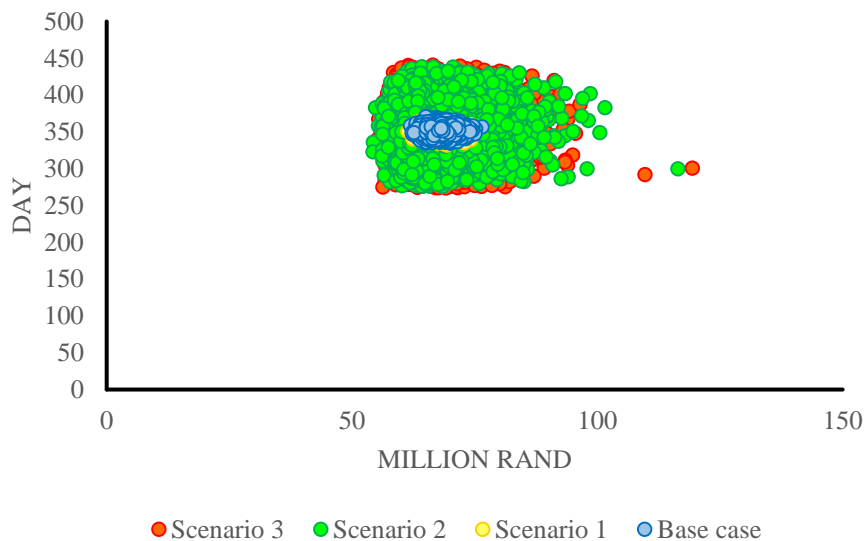


Figure 6.30: Overlay scatterplot of total cost and total time of the base case and the three correlation scenarios, for culvert construction

The mean of the total cost and the mean of the total time of culvert activities with different geometry and geological conditions were equal to the sum of the costs means and the times of same culvert geometry in the same geology, respectively. The costs mean and the times mean of activities were not changed from scenario to scenario. Thus, the mean of the total cost and the mean of the total time of culvert activities were not expected to vary in the three scenarios due to the constant centre of significance in the cost and time distribution plots.

On the other hand, the standard deviation of the total cost and total time of culvert activities were expected to increase from Scenario 1 (independent) to Scenario 3 (fully correlated) due to the correlation between a repeated activity. This expectation was confirmed in all types of culvert geometry in fine and soft geological conditions as illustrated in cost and time overlaying distribution plots (Figure 6.30), which revealed that the cost and time of culvert activities are positively correlated to the repeated activity.

The overlaying distribution costs and times of the three scenarios of correlation between the repeated activity of culvert construction proved that the standard deviation of the total cost and time of construction were increased dramatically due to a positive correlation between the number of repetitions of the activity in culvert construction (See Appendix. D.)

6.3.2.4 Modelling correlation between a repeated activity in the slab bridge construction

The means, standard deviations and variations of total cost and total time of bridge slab activities across the three correlation scenarios, with different geometries in hard and rock geological conditions calculated by copula, are summarised in Table 6.21.

Table 6.21: Correlation between a repeated activity in different geometries and geologies of slab bridge construction

Activity	Geometry	Geology	Scenario	Cost				Time			
				Mean	Δ_M	S.D	Δ_s	Mean	Δ_M	S.D	Δ_s
Setup site	All		Base Case	32,995.41	0.00%	1,453.10	0.00%	3.09	0.00%	0.18	0.00%
			Scenario 1	33,006.57	0.03%	1,463.85	0.74%	3.10	0.32%	0.18	0.79%
			Scenario 2	32,995.79	0.00%	4,454.28	206.54%	3.10	0.09%	0.31	72.13%
			Scenario 3	33,007.63	0.04%	4,477.24	208.12%	3.11	0.40%	0.31	76.12%
Footing of abutment	1x2x2m Perpendicular	Hard	Base Case	422,244.22	0.00%	18,572.90	0.00%	17.57	0.00%	0.59	0.00%
			Scenario 1	421,982.49	-0.06%	18,432.31	-0.76%	17.58	0.06%	0.59	-0.85%
			Scenario 2	423,037.22	0.19%	57,055.91	207.20%	17.56	-0.06%	1.74	194.92%
			Scenario 3	422,059.38	-0.04%	58,324.39	214.03%	17.57	0.00%	1.76	198.31%
		Rock	Base Case	332,819.45	0.00%	14,707.92	0.00%	17.57	0.00%	0.59	0.00%
			Scenario 1	332,563.99	-0.08%	14,673.70	-0.23%	17.58	0.06%	0.59	-0.85%
			Scenario 2	332,684.41	-0.04%	45,316.13	208.11%	17.56	-0.06%	1.74	194.92%
			Scenario 3	333,579.65	0.23%	45,414.73	208.78%	17.57	0.00%	1.76	198.31%
	1x2x2m skewed	Rock	Base Case	415,231.69	0.00%	17,983.13	0.00%	18.61	0.00%	0.62	0.00%
			Scenario 1	415,326.41	0.02%	18,094.16	0.62%	18.60	-0.05%	0.62	-0.81%
			Scenario 2	416,081.06	0.20%	55,796.53	210.27%	18.51	-0.54%	1.81	191.94%
			Scenario 3	415,879.33	0.16%	58,611.86	225.93%	18.58	-0.16%	1.85	198.39%
	3x4x1m Perpendicular	Hard	Base Case	1,479,241.02	0.00%	64,342.36	0.00%	16.54	0.00%	0.58	0.00%
			Scenario 1	1,478,217.53	-0.07%	64,900.17	0.87%	16.55	0.06%	0.58	0.00%
			Scenario 2	1,476,639.06	-0.18%	200,439.63	211.52%	16.55	0.06%	1.63	181.03%
			Scenario 3	1,483,714.52	0.30%	209,523.84	225.64%	16.55	0.06%	1.65	184.48%
Abutment	1x2x2m Perpendicular	Hard	Base Case	356,024.71	0.00%	15,380.26	0.00%	17.57	0.00%	0.60	0.00%
			Scenario 1	356,735.23	0.20%	15,460.66	0.52%	17.56	-0.06%	0.59	-0.92%
			Scenario 2	357,686.80	0.47%	49,408.48	221.25%	17.56	-0.06%	1.72	186.67%
			Scenario 3	357,565.38	0.43%	50,561.77	228.74%	17.60	0.17%	1.76	193.33%
		Rock	Base Case	329,866.56	0.00%	14,667.33	0.00%	17.57	0.00%	0.60	0.00%
			Scenario 1	330,390.33	0.16%	14,574.27	-0.63%	17.56	-0.06%	0.59	-0.92%
			Scenario 2	330,848.13	0.30%	45,388.81	209.46%	17.56	-0.06%	1.72	186.67%
			Scenario 3	329,875.11	0.00%	45,412.49	209.62%	17.60	0.17%	1.76	193.33%
	1x2x2m skewed	Rock	Base Case	412,580.06	0.00%	18,302.98	0.00%	18.59	0.00%	0.62	0.00%
			Scenario 1	412,686.31	0.03%	18,474.93	0.94%	18.61	0.11%	0.62	0.00%
			Scenario 2	412,835.15	0.06%	56,835.67	210.53%	18.59	0.00%	1.82	193.55%

			Scenario 3	412,544.80	-0.01%	59,444.03	224.78%	18.60	0.05%	1.84	196.77%	
	3x4x1m Perpendicular	Hard	Base Case	660,162.33	0.00%	28,902.29	0.00%	14.47	0.00%	0.54	0.00%	
			Scenario 1	660,191.02	0.00%	28,725.33	-0.61%	14.48	0.07%	0.55	0.93%	
			Scenario 2	658,779.99	-0.21%	89,197.20	208.62%	14.49	0.14%	1.42	162.96%	
			Scenario 3	659,979.99	-0.03%	93,889.20	224.85%	14.47	0.00%	1.46	170.37%	
Footing of pier	3x4x1m Perpendicular	Hard	Base Case	1,582,117.64	0.00%	69,609.67	0.00%	18.60	0.00%	0.61	0.00%	
			Scenario 1	1,583,515.26	0.09%	68,990.47	-0.89%	18.58	-0.11%	0.61	0.00%	
			Scenario 2	1,585,716.25	0.23%	220,986.46	217.47%	18.64	0.22%	1.81	196.72%	
			Scenario 3	1,582,113.87	0.00%	221,145.78	217.69%	18.65	0.27%	1.88	208.20%	
Pier	3x4x1m Perpendicular	Hard	Base Case	1,055,327.64	0.00%	46,358.06	0.00%	15.50	0.00%	0.56	0.00%	
			Scenario 1	1,055,188.82	-0.01%	45,929.82	-0.92%	15.50	0.00%	0.56	-0.54%	
			Scenario 2	1,053,896.42	-0.14%	143,997.12	210.62%	15.47	-0.19%	15.47	2662.50%	
			Scenario 3	1,056,754.41	0.14%	148,560.78	220.46%	15.50	0.00%	15.50	2667.86%	
Footing of Wing wall	1x2x2m Perpendicular	Hard	Base Case	190,009.50	0.00%	8,377.62	0.00%	17.58	0.00%	0.58	0.00%	
			Scenario 1	189,949.33	-0.03%	8,298.23	-0.95%	17.56	-0.11%	0.59	0.86%	
			Scenario 2	189,429.40	-0.31%	25,522.23	204.65%	17.56	-0.11%	1.71	194.83%	
			Scenario 3	189,686.23	-0.17%	26,259.06	213.44%	17.56	-0.11%	1.74	200.00%	
		Rock	Base Case	158,330.34	0.00%	6,923.75	0.00%	17.58	0.00%	0.58	0.00%	
	Scenario 1		158,215.82	-0.07%	6,865.29	-0.84%	17.56	-0.11%	0.59	0.86%		
	Scenario 2		157,926.75	-0.25%	21,519.90	210.81%	17.56	-0.11%	1.71	194.83%		
	Scenario 3		158,310.31	-0.01%	21,734.29	213.91%	17.56	-0.11%	1.74	200.00%		
		1x2x2m skewed	Rock	Base Case	197,985.84	0.00%	8,747.25	0.00%	18.62	0.00%	0.61	0.00%
	Scenario 1			198,147.34	0.08%	8,676.77	-0.81%	18.61	-0.05%	0.61	0.00%	
	Scenario 2			193,309.17	-2.36%	26,939.76	207.98%	18.62	0.00%	1.82	198.36%	
	Scenario 3			198,700.71	0.36%	27,465.54	213.99%	18.57	-0.27%	1.84	201.64%	
	3x4x1m Perpendicular	Hard	Base Case	190,009.50	0.00%	8,377.62	0.00%	15.50	0.00%	0.55	0.00%	
Scenario 1			189,949.33	-0.03%	8,297.23	-0.96%	15.50	0.00%	0.55	0.00%		
Scenario 2			189,429.40	-0.31%	25,522.23	204.65%	15.53	0.19%	1.52	176.36%		
Scenario 3			189,686.23	-0.17%	26,259.06	213.44%	15.53	0.19%	1.56	183.64%		
Wing wall	1x2x2m Perpendicular	Hard & Rock	Base Case	92,488.41	0.00%	4,071.36	0.00%	16.53	0.00%	0.59	0.00%	
			Scenario 1	92,371.15	-0.13%	4,083.42	0.30%	16.54	0.06%	0.58	-0.93%	
			Scenario 2	92,301.53	-0.20%	12,760.60	213.42%	16.51	-0.12%	1.62	174.58%	
			Scenario 3	92,549.19	0.07%	12,968.59	218.53%	16.51	-0.12%	1.64	177.97%	
		1x2x2m skewed	Rock	Base Case	110,808.72	0.00%	4,894.41	0.00%	17.56	0.00%	0.58	0.00%
	Scenario 1			110,717.10	-0.08%	4,876.91	-0.36%	17.55	-0.06%	0.58	0.00%	
	Scenario 2			110,728.15	-0.07%	14,817.36	202.74%	17.55	-0.06%	1.72	196.55%	
	Scenario 3			110,752.25	-0.05%	15,184.64	210.24%	17.55	-0.06%	1.74	200.00%	
		3x4x1m Perpendicular	Hard	Base Case	104,653.85	0.00%	4,666.70	0.00%	14.46	0.00%	0.55	0.00%
	Scenario 1			104,688.03	0.03%	4,632.63	-0.73%	14.47	0.07%	0.54	-0.99%	
	Scenario 2			104,386.52	-0.26%	14,086.52	201.85%	14.49	0.21%	1.42	158.18%	
	Scenario 3			104,299.85	-0.34%	14,228.44	204.89%	14.46	0.00%	1.43	160.00%	
Precast deck	1x2x2m Perpendicular	Hard & Rock	Base Case	158,176.50	0.00%	6,965.53	0.00%	17.56	0.00%	0.58	0.00%	
			Scenario 1	158,565.89	0.25%	7,006.10	0.58%	17.56	0.00%	0.58	0.69%	
			Scenario 2	158,939.88	0.48%	21,906.58	214.50%	17.57	0.06%	1.73	198.28%	
			Scenario 3	158,615.72	0.28%	22,188.39	218.55%	17.60	0.23%	1.75	201.72%	
		1x2x2m skewed	Rock	Base Case	204,811.94	0.00%	8,959.09	0.00%	18.58	0.00%	0.62	0.00%
	Scenario 1			204,500.70	-0.15%	8,876.80	-0.92%	18.60	0.11%	0.62	0.00%	
	Scenario 2			205,089.05	0.14%	28,540.62	218.57%	18.62	0.22%	1.83	195.16%	
	Scenario 3			204,814.67	0.00%	28,974.54	223.41%	18.62	0.22%	1.85	198.39%	
	Hard	Base Case	1,266,222.74	0.00%	56,430.09	0.00%	23.78	0.00%	0.69	0.00%		

	3x4x1m Perpendicular		Scenario 1	1,267,990.87	0.14%	55,876.25	-0.98%	23.77	-0.04%	0.69	0.00%	
			Scenario 2	1,269,195.54	0.23%	177,787.40	215.06%	23.76	-0.08%	2.32	236.23%	
			Scenario 3	1,267,764.76	0.12%	179,039.75	217.28%	23.79	0.04%	2.38	244.93%	
Backfilling	1x2x2m Perpendicular	Hard & Rock	Base Case	28,892.56	0.00%	1,283.99	0.00%	1.03	0.00%	0.10	0.00%	
			Scenario 1	28,870.45	-0.08%	1,271.48	-0.97%					
			Scenario 2	28,950.77	0.20%	3,937.12	206.63%					
			Scenario 3	28,872.48	-0.07%	4,038.03	214.49%					
	1x2x2m skewed	Rock	Base Case	34,657.37	0.00%	1,518.51	0.00%					
			Scenario 1	34,666.44	0.03%	1,507.83	-0.70%					
			Scenario 2	34,562.02	-0.28%	4,729.93	211.48%					
			Scenario 3	34,784.23	0.37%	4,842.02	218.87%					
	3x4x1m Perpendicular	Hard	Base Case	28,892.56	0.00%	1,283.99	0.00%					
			Scenario 1	28,870.45	-0.08%	1,271.48	-0.97%					
			Scenario 2	28,950.77	0.20%	3,937.12	206.63%					
			Scenario 3	28,872.48	-0.07%	4,038.03	214.49%					
Total	1x2x2m Perpendicular	Hard	Base Case	1,281,606.33	0.00%	27,280.38	0.00%	56.81	0.00%	1.05	0.00%	
			Scenario 1	1,281,416.08	-0.01%	27,014.70	-0.97%	56.84	0.05%	1.06	0.95%	
			Scenario 2	1,279,289.75	-0.18%	82,502.03	202.42%	56.85	0.07%	2.99	184.76%	
			Scenario 3	1,282,246.33	0.05%	86,377.47	216.63%	56.74	-0.12%	3.05	190.48%	
		Rock	Base Case	1,133,350.73	0.00%	23,265.83	0.00%	56.81	0.00%	1.05	0.00%	
			Scenario 1	1,133,422.09	0.01%	23,382.30	0.50%	56.84	0.05%	1.06	0.95%	
			Scenario 2	1,134,765.17	0.12%	73,442.76	215.67%	56.85	0.07%	2.99	184.76%	
			Scenario 3	1,135,187.39	0.16%	74,865.39	221.78%	56.74	-0.12%	3.05	190.48%	
	1x2x2m skewed	Rock	Base Case	1,409,529.15	0.00%	29,547.38	0.00%	59.92	0.00%	1.12	0.00%	
			Scenario 1	1,409,216.59	-0.02%	29,434.53	-0.38%	59.94	0.03%	1.11	-0.98%	
			Scenario 2	1,407,691.30	-0.13%	89,812.55	203.96%	59.90	-0.03%	3.10	176.79%	
			Scenario 3	1,411,801.39	0.16%	93,759.90	217.32%	59.92	0.00%	3.23	188.39%	
	3x4x1m Perpendicular	Hard	Base Case	6,402,858.71	0.00%	122,475.30	0.00%	62.02	0.00%	1.10	0.00%	
			Scenario 1	6,404,271.83	0.02%	122,341.68	-0.11%	61.99	-0.05%	1.11	0.91%	
			Scenario 2	6,395,745.71	-0.11%	380,678.72	210.82%	61.98	-0.06%	3.33	202.73%	
			Scenario 3	6,399,246.42	-0.06%	388,025.00	216.82%	62.08	0.10%	3.35	204.55%	
	Slab bridge construction			Base Case	10,227,333.00	0.00%	147,307.77	0.00%	235.65	0.00%	4.11	0.00%
				Scenario 1	10,230,238.00	0.03%	146,876.41	-0.29%	235.74	0.04%	4.08	-0.84%
				Scenario 2	10,224,098.00	-0.03%	461,460.37	213.26%	235.20	-0.19%	22.22	440.50%
				Scenario 3	10,230,989.00	0.04%	464,025.13	215.00%	235.50	-0.06%	23.52	472.18%

The scatterplots of the base case and three correlated total costs and total times of the overall slab bridge were modelled with a Monte Carlo simulation, and are presented in Figure 6.31.

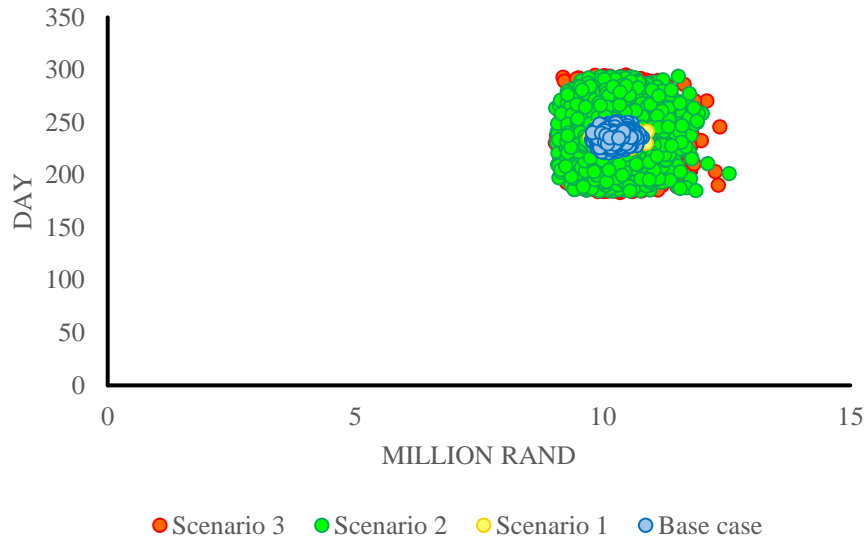


Figure 6.31: Overlay scatterplot of total cost and total time of the base case and three correlation scenarios of the slab bridge construction

Similar to the culvert construction, the costs mean, and the time mean of slab bridges were not changed from scenario to scenario, due to the constant centre of significance in the cost and time scatterplot. Conversely, the standard deviations of the total cost and total time of slab bridges were increased from Scenario 1 (independent) to Scenario 3 (fully correlated) due to the correlation between a repeated activity as illustrated in the overlay cost and time distributions plots, which proved that the cost and time of activities in the construction of slab bridge construction were positively correlated to the repetition of activity.

Comparable to the culvert construction, the standard deviations of the total cost and time in the slab bridge construction were increased dramatically, which confirmed the positive correlation between the number of repetitions of activity in the slab bridge construction (See Appendix D).

6.3.2.5 *Overall modelling correlation between a repeated activity in the bridge structure*

The means, standard deviations and variation of means, and standard deviation of the base case and the three correlation scenarios calculated from copula are summarised in Table 6.22.

Table 6.22: Overall correlation between a repeated activity in the bridge structure.

	Scenario	Cost				Time			
		Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Bridge structure	Base Case	78,030,393.34	0.00%	1,920,505.95	0.00%	351.35	0.00%	5.04	0.00%
	Scenario 1	78,044,588.91	0.02%	1,939,650.17	1.00%	351.36	0.00%	4.99	-0.84%
	Scenario 2	78,113,067.80	0.11%	6,014,085.33	213.15%	351.46	0.03%	32.81	551.42%
	Scenario 3	78,065,388.98	0.04%	6,159,085.32	220.70%	349.72	-0.46%	34.59	586.70%

The scatterplots of the base case and three correlated total costs and total times of the overall bridge structure generated by Monte Carlo simulation are shown in Figure 6.23.

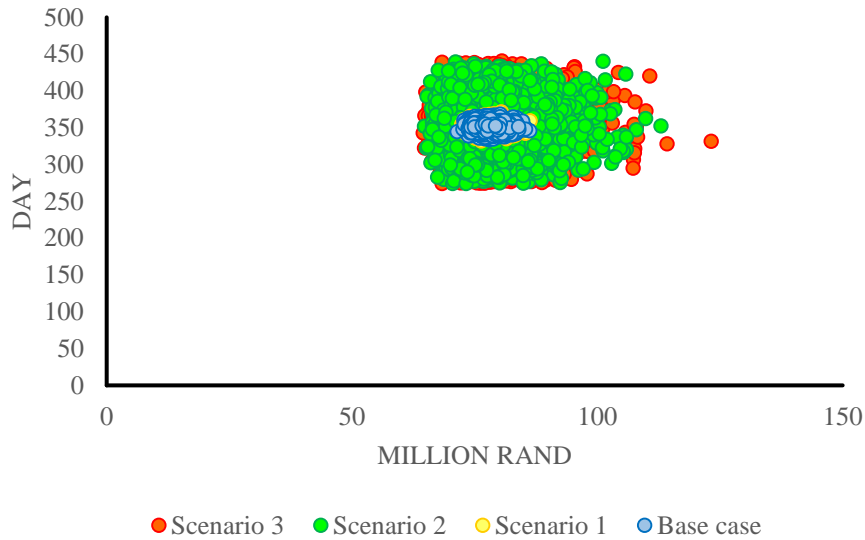


Figure 6.32: Overlay scatterplot of total cost and total time of the base case and the three correlation scenarios of the bridge structure

Based on the overlaying scatterplots (Figures 6.32), distribution plots (Appendix D) and the variation mean and standard deviation of total cost and total time of the base case and the three correlation scenarios for all culvert construction and slab bridge construction with different geometry in different geological conditions, the following deductions were made:

- i. The means of the total cost and total time are constant from scenario to scenario, as this is confirmed by a constant centre of significance in the cost and time distribution plots, scatterplots and variation mean.
- ii. Base case and Scenario 1 were similar. This was reflected in the means, standard deviations (within the $\pm 1\%$ limit set), overlay distribution plots and scatterplots.
- iii. The standard deviations of the total cost and total time were increased from Scenario 1 to Scenario 3 (See Table 6.23).
- iv. Scenario 1 and Scenario 3 were considered the lower and upper bounds of the spectrum of possible correlated cost and time of a repeated activity. Scenario 1 was modelled independently to the repetition cost and time variables of activities, while Scenario 3 was modelled fully correlated with the repetition cost variables and time variables of activities
- v. In Scenario 1, the sample was concentrated around the mean, whereas in Scenarios 2 and 3, there were much more scattered, particularly on the right side than on the left side, because the cost distributions were lognormal distributions and the time distributions were triangular distributions with positive skew.
- vi. The differences in total cost and total time standard deviations between Scenario 1 and Scenario 3 in all types of culverts were more than two orders of magnitude (200%), while

these differences in slab bridge construction were more than two orders of magnitude (200%) in total cost and more than one order of magnitude (100%) in total time.

- vii. The variation of the standard deviation of the total time for all types of culverts and slab bridge construction was larger than the variation of the standard deviation of the total cost, which reveals that the time variables were more independent than the cost variables.
- viii. Scenario 2 was correlated positively to the repetition cost variables and time variables of bridge activities. A correlation scenario between the extreme scenarios of independent (Scenario 1) and fully correlated (Scenario 3). This was reflected in the overlay distributions cost and time plots as well as cost and time scatterplots, where the sample of Scenario 2 was more spread than the sample in Scenario 1, and more concentrated than the sample in Scenario 3 (Figure 6.32). This was confirmed by the magnitude of the variation in standard deviation, which was lower than in Scenario 3 (See Table 6.23).
- ix. The variation in the standard deviation of cost and time depends on the number of repetitions. For instance, the construction of Box 2x1x1m skewed culvert in soft geology has the highest variation due to the highest number of repetitions (218% in cost and 306% in time).
- x. The means of total cost and total time were larger than the deterministic total cost and total time, for the following reasons:
 - Cost input distributions and time input distributions were positively skewed; in other words, the mean was larger than the mode.
 - The deterministic total cost and total time of culverts construction were the sums of the modes of the input distributions while the probabilistic means of total cost and total time of culvert were equal to the sum of the means of the input distributions.

The analysis of the three scenarios of correlation between repeated activities in the construction of a bridge structure proved that the standard deviation of the total cost and time are increased dramatically due to a positive correlation between the number of repetitions of activity in the bridge structure. This aspect is further investigated with sensitivity analysis.

6.3.2.6 *Modelling correlation between the different activities in the bridge structure*

This correlation represented a correlation between the costs and times of the different activities in culvert construction and slab bridge construction. Based on the historical data of three similar projects, the bridge expert panel suggested that the cost and time of the bedding activities, the footing of wing wall activities and the wing wall activities in culvert construction were correlated by $\rho_r = +0.7$ because of dependency of cost and time of these activities on the geological conditions and, moreover, these are critical activities of culvert construction.

$$R_{r,culvert} = \begin{bmatrix} 1 & 0.7 & 0.7 \\ 0.7 & 1 & 0.7 \\ 0.7 & 0.7 & 1 \end{bmatrix}$$

Similarly, the bridge expert panel estimated $\rho_r = +0.65$ correlation coefficient between the cost and time of the footing of abutment activities, abutment activities, footing of pier activities, pier activities, footing of wing wall activities and wing wall activities in slab bridge construction.

$$R_{r,culvert} = \begin{bmatrix} 1 & 0.65 & 0.65 \\ 0.65 & 1 & 0.65 \\ 0.65 & 0.65 & 1 \end{bmatrix}$$

The means, standard deviations and the variation of total correlated cost and total correlated time in the construction of culverts, slab bridge and overall bridge structure were estimated by the Gaussian copula, using the marginal distribution assumptions provided by the expert panel and above correlation coefficient matrix as summarised in Table 6.23.

Table 6.23: Correlation between the different activities in culvert construction, slab bridges construction and overall bridge structure.

		Cost				Time			
		Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Culvert construction	Base Case	67,781,462.00	0.00%	1,886,428.00	0.00%	351.26	0.00%	5.06	0.00%
	Correlated	67,813,553.35	0.05%	6,531,837.94	246.25%	351.38	0.03%	30.35	499.80%
Slab bridge construction	Base Case	10,227,333.00	0.00%	147,307.77	0.00%	235.65	0.00%	4.11	0.00%
	Correlated	10,205,836.00	-0.21%	1,052,897.03	614.76%	235.53	-0.05%	15.10	267.31%
Bridge structure	Base Case	78,030,393.34	0.00%	1,920,505.95	0.00%	351.35	0.00%	5.04	0.00%
	Correlated	77,890,401.00	-0.18%	6,425,163.00	234.56%	351.36	0.00%	30.15	498.24%

The simulated base case and correlated total costs and total time between different activities in culvert construction, slab construction and bridge structure from the Monte Carlo simulation are shown in Figures 6.33-6.35.

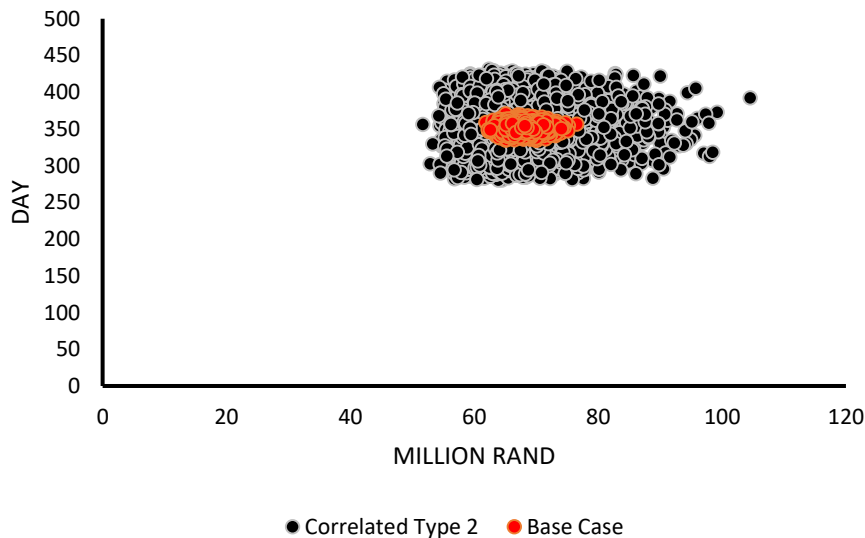


Figure 6.33: Scatterplot of correlated total cost and total time of the culvert construction, the correlation between different activities (Type 2)

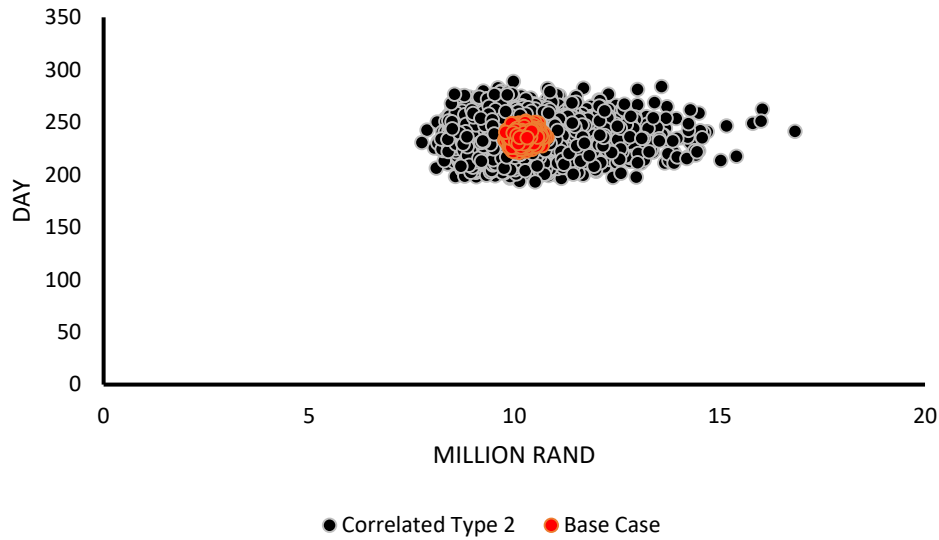


Figure 6.34: Scatterplot of correlated total cost and total time of the slab bridge construction, the correlation between different activities (Type 2)

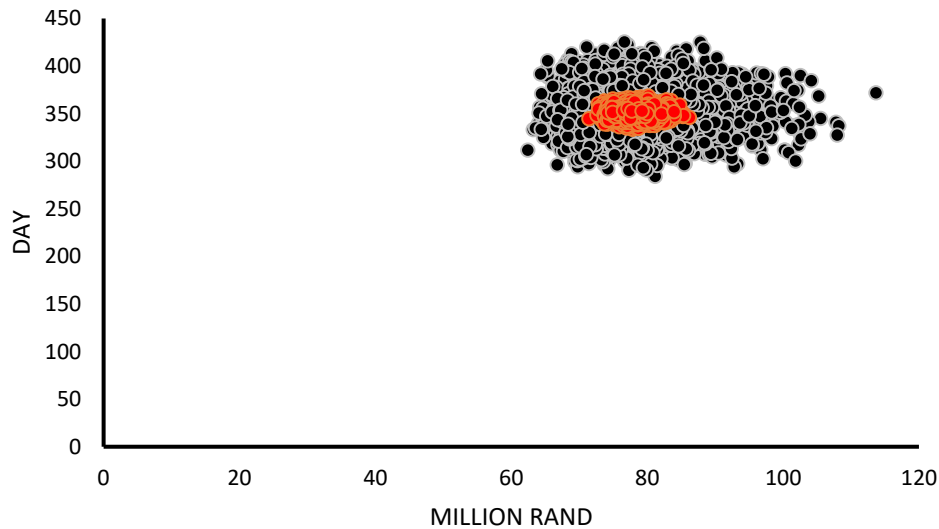


Figure 6.35: Scatterplot of correlated total cost and total time of the bridge structure, the correlation between different activities (Type 2)

The following inferences were made on the correlation between activities on the bridge structure:

- (i) The mean of the total cost and total time of culvert construction, slab construction and overall bridge structure were considered constant from base case to correlated cost and time, due to the constant centre of significance in the scatterplots and variations of total cost mean and time mean (± 1) (See Table 6.24).

- (ii) The means of total cost and total time of culvert construction, slab construction and overall bridge structure were larger than the respective deterministic total cost and total time for the same reasons explained for earthwork structure.
- (iii) The standard deviation of the total cost and total time increased dramatically from base case to correlated between activities in construction of culverts, slab bridges and bridge structure. For instance, the standard deviations of the total cost and total time of the bridge structure increased by 235% and 498%, respectively. These increases in total cost and total time standard deviation are barely visible in the scatterplot (See Figure 6.35).

The evaluation of the correlation between the cost and time of different activities in the bridge structure with the base case proved that the standard deviations of the total cost and total time were increased dramatically due to a positive correlation between the cost and time of activities in the bridge structure. This aspect is further investigated with sensitivity analysis technique.

6.3.2.7 Modelling correlation between the cost and the time of an activity in the bridge structure

This correlation represented a correlation between the cost and time of each activity in the structure of the bridge. A similar process as for the earthwork structure was used to correlate the cost and time of the activities in the bridge structure.

The means, standard deviations and the variation of correlated cost and time in the construction of culverts, slab bridges and overall bridge structure derived through the copula analysis are listed in Table 6.24.

Table 6.24: Correlation between the cost and time of activity in the construction of a culvert and a slab bridge and the overall bridge structure.

		Cost				Time				Total cost total time correlation
		Mean	Δ_M	Standard Deviation	Δ_S	Mean	Δ_M	Standard Deviation	Δ_S	
Culvert construction	Base Case	67,781,462.00	0.00%	1,886,428.00	0.00%	351.26	0.00%	5.06	0.00%	0.225
	Correlated	67848516.44	0.10%	6031310.19	219.72%	351.56	0.09%	22.70	348.53%	
Slab bridge construction	Base Case	10,227,333.00	0.00%	147,307.77	0.00%	235.65	0.00%	4.11	0.00%	0.659
	Correlated	10,236,918.64	0.09%	601,079.52	308.04%	235.92	0.11%	11.23	173.24%	
Bridge structure	Base Case	78,030,393.34	0.00%	1,920,505.95	0.00%	351.35	0.00%	5.04	0.00%	0.237
	Correlated	78,072,569.32	0.05%	6,191,307.31	222.38%	351.57	0.06%	22.61	348.55%	

The scatterplots of correlated costs and times of culvert and slab bridge construction and overall bridge structure were simulated by Monte Carlo analysis and are shown in Figures 6.36-6.38.

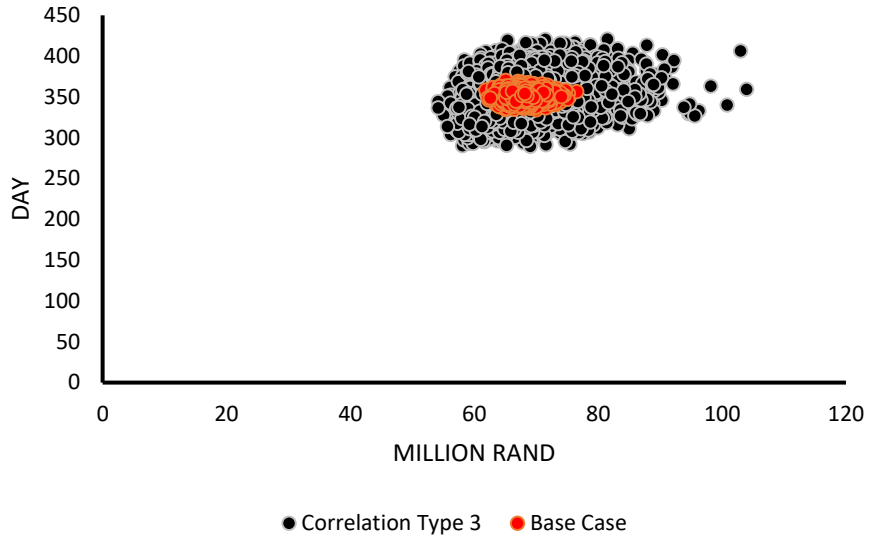


Figure 6.36: Scatterplot of correlated total cost and total time of culvert construction, the correlation between cost and time (Type 3)

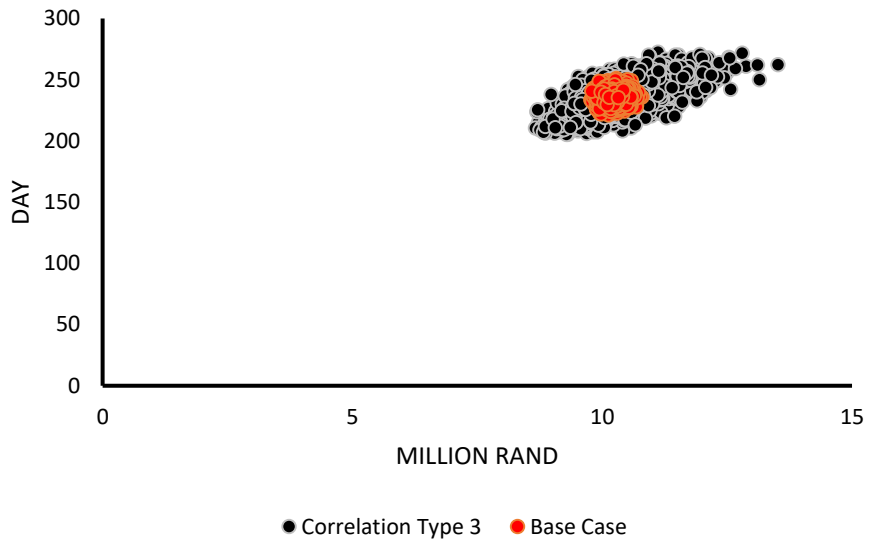


Figure 6.37: Scatterplot of correlated total cost and total time of the slab bridge construction, the correlation between cost and time (Type 3)

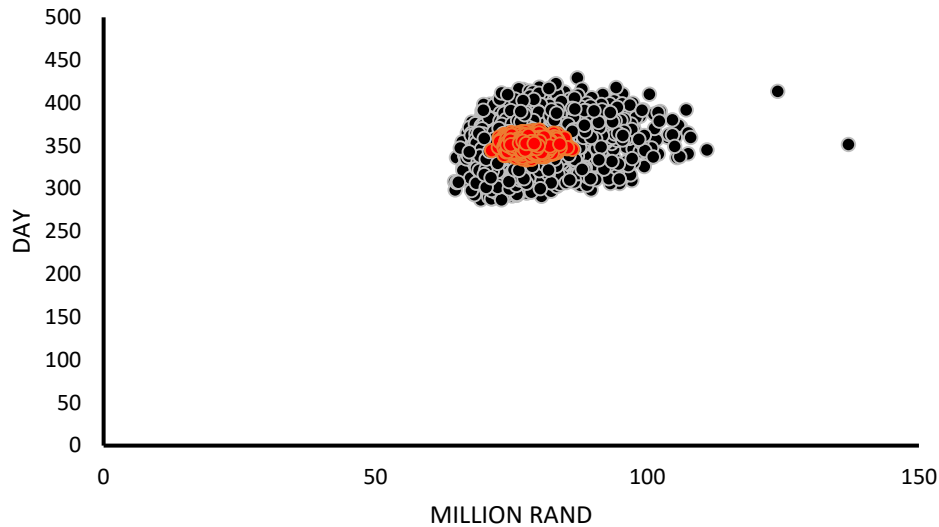


Figure 6.38: Scatterplot of correlated total cost and total time of the bridge structure, the correlation between cost and time (Type 3)

The following deductions were made on the correlation analysis between the cost and time of activity on the bridge structure:

- (i) The mean of the total cost and total time of culvert and slab construction and overall bridge structure were constant from base case to correlated cost and time for the same reason given in the correlation between the different activities in a structure.
- (ii) The means of total cost and total time of culvert and slab construction and overall bridge structure were larger than the respective deterministic total cost and total time for the same reasons explained in earthwork structure.
- (iii) Likewise, the correlation between the different activities in a structure, the standard deviation of the total cost and total time were increased dramatically from base case to correlated between the cost and time of an activity. For instance, the standard deviation of the total cost and total time of the culvert construction increased by 219.72% and 348.539%, respectively. Furthermore, the correlation between the total cost and total time of slab construction was strong with a correlation coefficient of 0.666, while the correlation between the costs and time of culvert construction and bridge structure were weak (0.220, 0.230) which are in the inclination of the cloud of data points shown in Figure 6.38.

The evaluation of the correlation between the different activities in the bridge structure with the base case proved that the standard deviation of the total cost and total time increased dramatically due to a positive correlation between the cost and time of activities in the bridge structure. This aspect is further investigated with sensitivity analysis.

6.3.3 Correlations in the pavement structure

In this section, the three types of correlations were modelled on pavement structure, and their impacts on the cost and time of pavement structure were assessed.

6.3.3.1 Modelling probabilistic cost and time of the pavement structure

The same marginal distribution assumptions and procedure as earthwork and bridge structures were considered to estimate the probabilistic cost and time of four pavement constructions by the Gaussian copula analysis. The probabilistic cost and time of pavement activities and pavement structures are summarised in Table 6.25.

Table 6.25: Probability costs and time parameters of the pavement structure

Activity	Cost					Time		
	Min	Mode	Higher	Mean	Standard Deviation	Min	Mode	Higher
Subgrade	30,124,832.00	37,656,040.00	56,484,060.00	41,421,644.00	11,085,638.02	24.00	29.00	38.00
Subbase	103,017,472.00	128,771,840.00	193,157,760.00	141,649,024.00	37,909,403.24	54.00	67.00	88.00
Base	114,821,700.00	143,527,125.00	215,290,688.00	157,879,837.67	42,253,241.75	52.00	64.00	84.00
Surface	147,443,940.00	184,304,925.00	276,457,388.00	202,735,417.67	54,257,901.03	46.00	57.00	75.00
Total	395,407,944.00	494,259,930.00	741,389,895.00	543,685,923.00	145,506,183.59	174.00	217.00	283.00

6.3.3.2 Modelling correlation between a repeated activity in the pavement structure

To model this correlation, three scenarios across repeated activities in the pavement structure are considered and compared with the base case:

Base Case: Every unit of an activity is uncorrelated.

Scenario 1. Every unit of activity is independent, $\rho_r = 0$.

$$\rho_{r1} = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & 0 & \vdots \\ \vdots & 0 & 1 & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix}$$

Scenario 2. Every unit of activity is positively correlated, $\rho_r = (0, 1)$

$$\rho_{r2} = \begin{bmatrix} 1 & 0.99 & \dots & 0 \\ 0.99 & 1 & 0.99 & \vdots \\ \vdots & 0.99 & 1 & 0.99 \\ 0 & \dots & 0.99 & 1 \end{bmatrix}$$

Scenario 3. Every unit of activity is perfectly correlated, $\rho_r = 1$

$$\rho_{r3} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & 1 & 1 & \vdots \\ \vdots & 1 & 1 & 1 \\ 1 & \dots & 1 & 1 \end{bmatrix}$$

The cost and time of the pavement structure did not depend on the geological conditions. The correlated costs and time for the different correlation scenarios were generated using the Gaussian

copula technique and using the expert panel’s marginal distribution assumptions and above correlation coefficient matrices. The ranges of total cost and total time for each construction activity of the pavement were estimated for the above three scenarios. The probabilistic calculation was based on Monte Carlo simulations, which were run until the total of the standard deviation of activity was bounded within $\pm 1\%$ in 10 out of 10 sample simulations.

The range of means and the standard deviations of total cost and total time of the pavement structure and its four activities for the three correlation scenarios were summarised in Table 6.26. To evaluate the deviation of the mean and standard deviation of each scenario from the base case, the variation in mean and standard deviation of each scenario were also calculated.

Table 6.26: Correlation between a repeated activity in the pavement structure

Activity	Scenario	Cost				Time			
		Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Subgrade	Base Case	41,430,013.65	0.00%	739,239.68	0.00%	29.96	0.00%	0.94	0.00%
	Scenario 1	41,414,170.71	-0.04%	732,929.73	-0.85%	29.97	0.03%	0.945	0.53%
	Scenario 2	41,362,318.50	-0.16%	5,043,743.19	582.29%	29.94	-0.07%	2.92	210.64%
	Scenario 3	41,374,004.60	-0.14%	5,664,118.63	666.21%	29.9	-0.20%	2.98	217.02%
Subbase	Base Case	141,662,170.65	0.00%	2,018,708.07	0.00%	69.2	0.00%	1.44	0.00%
	Scenario 1	141,664,013.18	0.00%	1,999,939.07	-0.93%	69.23	0.04%	1.454	0.97%
	Scenario 2	141,316,286.25	-0.24%	16,056,299.46	695.38%	69.04	-0.23%	6.66	362.50%
	Scenario 3	141,610,207.91	-0.04%	19,846,341.23	883.12%	69.26	0.09%	6.89	378.47%
Base	Base Case	157,866,538.32	0.00%	2,221,362.74	0.00%	66.14	0.00%	1.43	0.00%
	Scenario 1	157,887,981.53	0.01%	2,203,986.72	-0.78%	66.18	0.06%	1.417	-0.91%
	Scenario 2	157,539,195.19	-0.21%	17,502,049.48	687.90%	65.61	-0.80%	6.33	342.66%
	Scenario 3	157,420,383.55	-0.28%	21,672,390.47	875.63%	65.99	-0.23%	6.57	359.44%
Surface	Base Case	202,732,249.63	0.00%	2,891,744.05	0.00%	58.89	0.00%	1.34	0.00%
	Scenario 1	202,696,711.73	-0.02%	2,863,450.90	-0.98%	58.9	0.02%	1.34	0.00%
	Scenario 2	202,563,790.27	-0.08%	23,263,751.50	704.49%	58.52	-0.63%	5.75	329.10%
	Scenario 3	202,476,067.95	-0.13%	28,158,048.28	873.74%	58.83	-0.10%	5.82	334.33%
Total	Base Case	543,664,957.99	0.00%	4,174,001.38	0.00%	224.22	0.00%	2.64	0.00%
	Scenario 1	543,716,702.76	0.01%	4,170,151.60	-0.09%	224.28	0.03%	2.62	-0.76%
	Scenario 2	543,899,815.54	0.04%	33,572,597.99	704.33%	224.41	0.08%	11.13	321.59%
	Scenario 3	543,558,761.37	-0.02%	41,710,389.41	899.29%	224.24	0.01%	11.63	340.53%

The scatterplots of the base case and the three correlated total cost and total time of pavement activities were modelled by a Monte Carlo simulation, as shown in Figure 6.39.

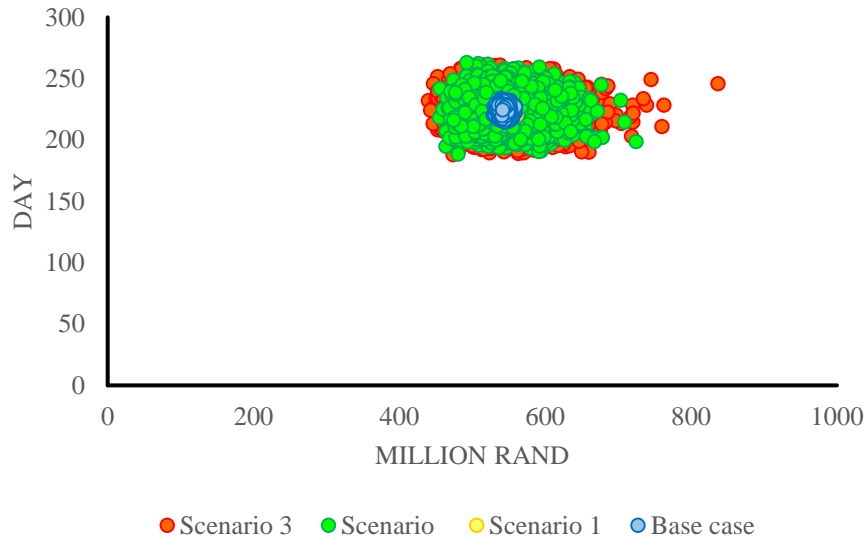


Figure 6.39: Overlay scatterplot of total cost and total time of the base case and the three correlation scenarios of the pavement structure

Figure 6.39 shows that the means of the total cost and time of the pavement structure were equal to the sum of the cost means and the time means, respectively. The cost mean, and the time mean of the pavement structure did not change from scenario to scenario. Thus, the mean of the total cost and the mean of the total time of the pavement structure do not vary in the three scenarios as confirmed by a constant centre of significance in the cost and time distribution plots.

On the other hand, the standard deviations of the total cost and total time of the pavement were expected to increase from Scenario 1 (independent) to Scenario 3 (fully correlated) due to the correlation between a repeated activity. This expectation was confirmed, as illustrated in the cost and time overlaying distribution plots below, which proved that the cost and time of activities in the pavement structure were positively correlated to the repetition activity.

Based on the overlaying distribution plots (Figure 6.39), scatterplot (Appendix D) and the variation mean and standard deviation of total cost and time of the pavement structure, the following inferences were made:

- i. Similar to the findings about earthwork and bridge structures, the mean of the total cost and total time were considered constant from scenario to scenario, due to the constant centre of significance in the correlated cost and time (distribution plots, scatterplots and variation mean).
- ii. The base case and Scenario 1 are similar.
- iii. The standard deviation of the total cost and total time increased dramatically from Scenario 1 to Scenario 3 (See Table 6.27).
- iv. Scenario 1 and Scenario 3 have lower and upper bounds of the spectrum of possible correlated cost and time of repeated activity for the same reason as explained in the

earthwork structure. Therefore, Scenario 2 was considered to have the most probable correlated cost and time for repeated activity in the pavement structure.

- v. In Scenario 1, the sample was concentrated around the mean, whereas, in Scenarios 2 and 3, the samples were skewed to the right (positively skewed on cost and time).
- vi. The differences in total cost and total time standard deviations between Scenario 1 and Scenario 3 were more than eight orders of magnitude (800%) in total cost and more than three orders of magnitude (300%) in total time. For instance, the variations in total cost and time standard deviation of pavement structure were 899% and 341%, respectively.
- vii. Scenario 2 samples for both cost and time were more widespread than the sample in Scenario 1 and more concentrated than the sample in Scenario 3 because of the positive correlation scenario between the extreme scenarios of independent (Scenario 1) and fully correlated (Scenario 3).
- viii. The variations in the standard deviation of cost and time in the pavement structure were dependent on the number of repetitions.
- ix. The means of total cost and total time of the pavement structure were larger than the deterministic total cost and total time because cost input distributions and time input distributions were positively skewed which meant they were larger than the mode.

The analysis of the three scenarios of correlation between repeated activity in the pavement structure proved that the standard deviations of the total cost and time increased dramatically due to a positive correlation between the number of repetitions of activities in the pavement structure. This aspect is further investigated using sensitivity analysis.

6.3.3.3 *Modelling correlation between the different activities in the pavement structure*

This correlation modelled a correlation between the costs and times of different activities in the pavement structure. Based on the pavement expert panel’s evaluation, the correlation coefficient between the costs/time of the subgrade activities, subbase activities and base activities were $p_r = +0.85$ due to the dependency of cost and time of these three activities on the conditions and accessibility of the site.

$$R_{r,pavement} = \begin{bmatrix} 1 & 0.85 & 0.85 \\ 0.85 & 1 & 0.85 \\ 0.85 & 0.85 & 1 \end{bmatrix}$$

The means, standard deviations and the variations of total correlated cost and total correlated time in the pavement structure calculated by copula are summarised in Table 6.27.

Table 6.27: Correlation between the different activities in the pavement structure

	Cost				Time			
	Mean	Δ_M	S.D	Δ_S	Mean	Δ_M	S.D	Δ_S
Base case	543,664,957.99	0.00%	4,174,001.38	0.00%	224.22	0.00%	2.64	0.00%
Correlated	543,853,187.64	0.03%	52,912,363.32	1167.67%	224.27	0.02%	13.23	401.14%

The scatterplots of the base case and correlated cost and time of pavement activities were simulated by a Monte Carlo analysis as presented in Figure 6.40.

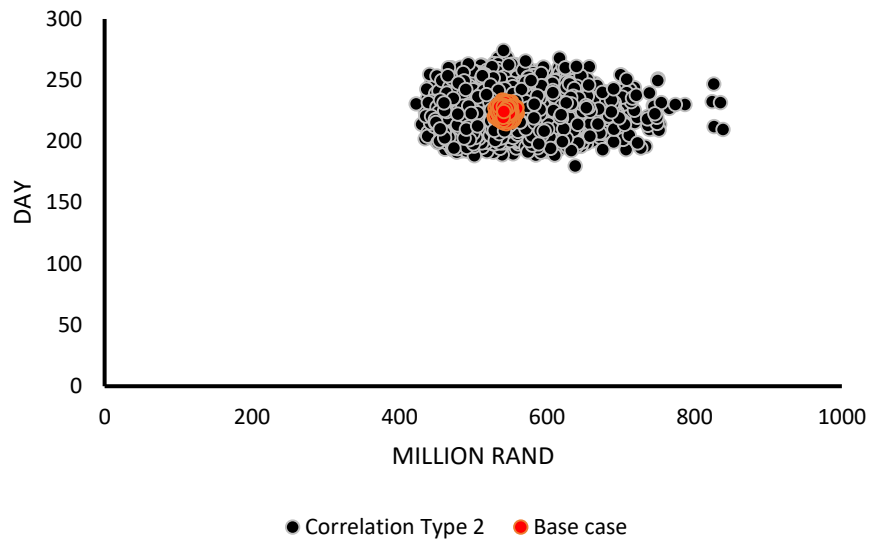


Figure 6.40: Scatterplot of correlated total cost and total time of the pavement structure, the correlation between different activities (Type 2)

The following deductions were made on the correlation between activities in the pavement structure.

- (i) The means of the total cost and total time of the pavement structure were considered constant from base case to correlated cost and time (centre of significance).
- (ii) The means of total cost and total time of the pavement structure were larger than the respective deterministic total cost and total time (positively skewed).
- (iii) The standard deviations of the total cost and total time of the pavement structure activities increased dramatically from base case to correlated cost and time. The standard deviations of the total cost and total time of the pavement structure were increased by 1168% and 401%, respectively, which were barely visible in the scatterplot.

The evaluation of the correlation between the cost and time of different activities in the pavement structure with the base case proved that the standard deviations of the total cost and total time were increased dramatically, due to a positive correlation between the cost and time of activities in the pavement structure. This aspect is further investigated with sensitivity analysis.

6.3.3.4 *Modelling correlation between the cost and the time of an activity in the pavement structure*

This correlation modelled the correlation between the cost and time of each activity in the structure of the pavement. Based on the pavement experts' opinion, the correlation is assumed to be $\rho_r=0.8$.

$$R_{r, cost - time} = \begin{bmatrix} 1 & 0.8 \\ 0.8 & 1 \end{bmatrix}$$

Table 6.28: Correlation between the cost and time of an activity in the pavement structure

	Cost				Time				Total cost total time correlation
	Mean	Δ_M	Standard Deviation	Δ_S	Mean	Δ_M	Standard Deviation	Δ_S	
Base case	543,664,957.99	0.00%	4,174,001.38	0.00%	224.22	0.00%	2.64	0.00%	0.769
Correlated	542,662,510.48	-0.18%	41,474,779.05	893.65%	223.93	-0.13%	11.59	339.02%	

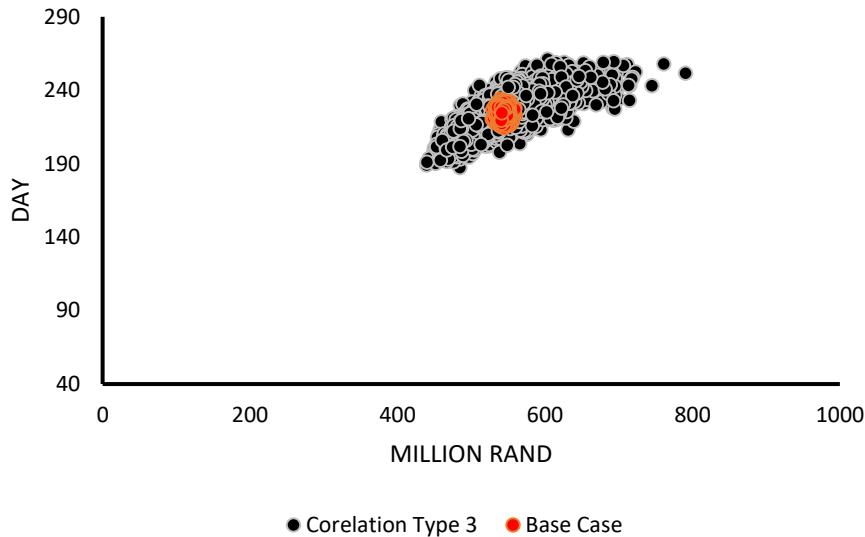


Figure 6.41: Scatterplot of correlated total cost and total time of the pavement structure, the correlation between cost and time (Type 3)

The following inferences were made on correlation between the cost and time of activity on the pavement structure:

- (i) The means of the total cost and total time of pavement structure were constant from base case to correlated cost and time.
- (ii) The means of total cost and total time of construction of the pavement structure were larger than the respective deterministic total cost and total time (positively skewed).
- (iii) Similarly, the correlation between the different activities in the pavement structure the standard deviation of the total cost and total time were increased dramatically from base case to correlated cost and time of an activity. The standard deviations of the total cost and total time of construction of the pavement increased by 894% and 339%, respectively. Furthermore, the association between the total cost and the total time of construction of the pavement was strong (0.763), which is visible in the inclination of the cloud of data points shown in Figure 6.41.

The evaluation of the correlation between the different activities in the pavement structure with the base case proved that the standard deviations of the total cost and total time increased

dramatically due to a positive correlation between the cost and time of activities in the pavement structure. This aspect is further investigated with a sensitivity analysis.

6.3.4 Sensitivity analysis of the different types of correlation

In the following section, the deterministic total cost and total time and the 90th percentiles of the correlated total cost and total time distributions of each highway structure were compared, to evaluate the impacts of the different types of correlation on the total cost and total time of each structure. Sensitivity analysis was employed to further examine the change in total cost and total time deviation in each structure as a function of each correlation type.

In order to evaluate the sensitivity of the total cost and time of each structure to the different types of correlation, the clustered bar of increases in the standard deviation and the 90th percentile for each correlation type were calculated and demonstrated. The bar lengths in standard deviation and 90th percentile represented the increase of standard deviation of total costs and times from the base case standard deviation, and the increase of the 90th percentile total cost and time from deterministic total cost and total time. The correlation with the largest increase in the 90th percentile and standard deviation (bar length) was considered as the dominant correlation in a structure. In other words, the structure was more sensitive to the changes of that type of correlation.

6.3.4.1 Evaluation of the impact of different types of correlation on the earthwork structure

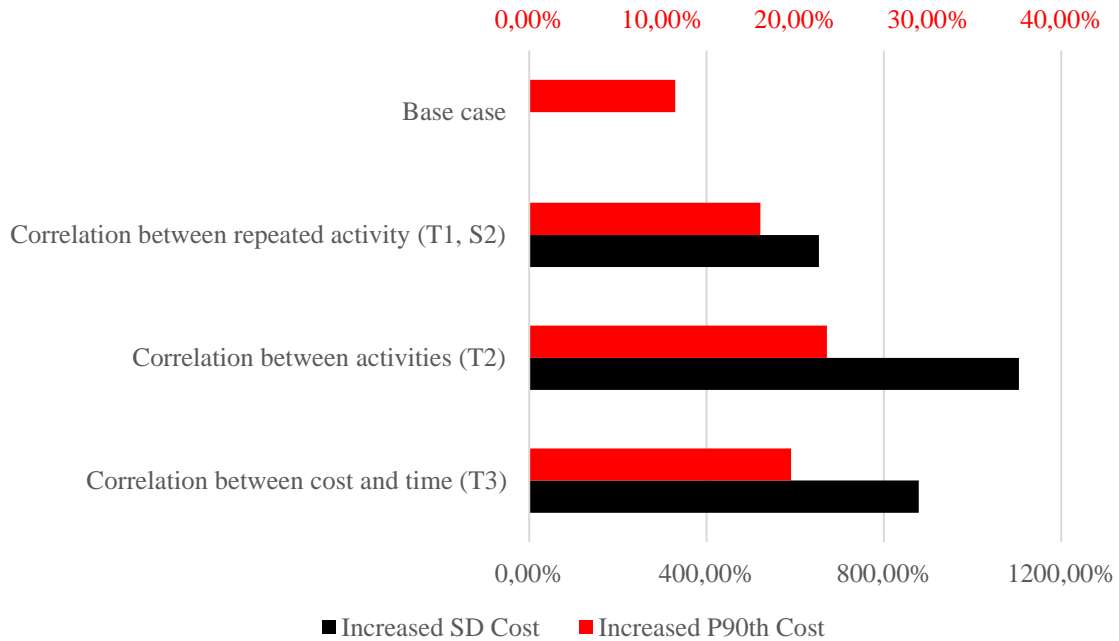
The deterministic total cost and total time of the earthwork structure were ZAR 244,292,292.8 and 215 days (See Table 6.10). The standard deviation and the 90th percentiles of the correlated total cost and total time distributions, and their increases for three types of correlations in the earthwork structure are summarised in Table 6.29.

Table 6.29: Impact of different types of correlations on total cost and total time of the earthwork structure

	Cost				Time			
	Standard Deviation	Increased Standard Deviation	P90 th (ZAR)	Increased P90 th	Standard Deviation	Increased Standard Deviation	P90 th (Day)	Increased P90 th
Base Case	1,871,424.42	0.00%	271,089,094.40	10.97%	2.61	0.00%	225.59	4.93%
Correlation between repeated activities (Type1, Scenario2)	14,106,037.74	653.76%	286,766,429.79	17.39%	19.53	648.51%	249.18	15.90%
Correlation between activities (Type2)	22,538,485.66	1,104.35%	298,968,508.46	22.38%	22.22	751.45%	253.63	17.97%
Correlation between cost and time (Type3)	18,319,948.86	878.93%	292,373,016.20	19.68%	22.34	756.05%	254.45	18.35%

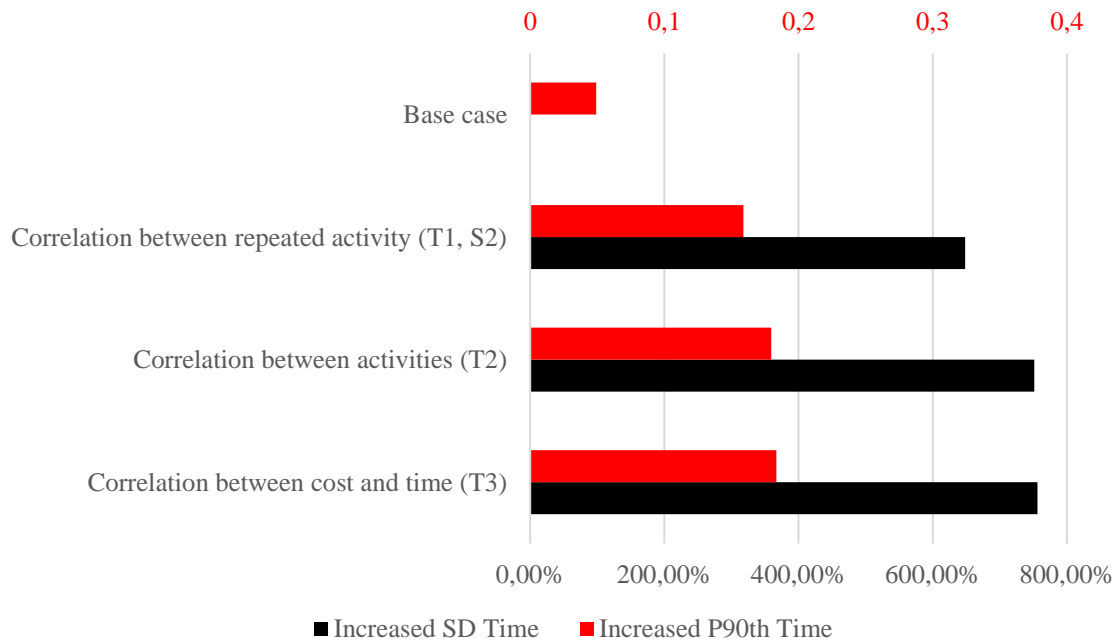
Key: P90th: 90th Percentile

The increases in standard deviation and increases in 90th percentile total cost and total time for the different types of correlations in the earthwork structure are displayed in Figures 6.42 and 6.43.



Key: T: Correlation Type; S: Correlation Scenario; SD: Standard Deviation; P90th: 90th Percentile

Figure 6.42: Impact of different types of correlations on the total cost of the earthwork structure



Key: T: Correlation Type; S: Correlation Scenario; SD: Standard Deviation; P90th: 90th Percentile

Figure 6.43: Impact of different types of correlations on the total time of the earthwork structure

Table 6.30 and clustered bar sensitivity graphs on cost and time (Figure 6.42 and 6.43) verify that correlation Type 2 (correlation between activities) caused the largest increase in standard deviation and 90th percentile of the total cost, which increased by 1,104.35% and 22.38%, respectively. The largest increase in standard deviation and 90th percentile of the total time was caused by correlation Type 3 (correlation between cost and time) with 756.05% and 18.35%, respectively. Therefore, correlation Type 2 and correlation Type 3 were considered as the dominant correlation on cost and time in the earthwork structure, respectively.

6.3.4.2 Evaluation of the impact of different types of correlations in the bridge structure

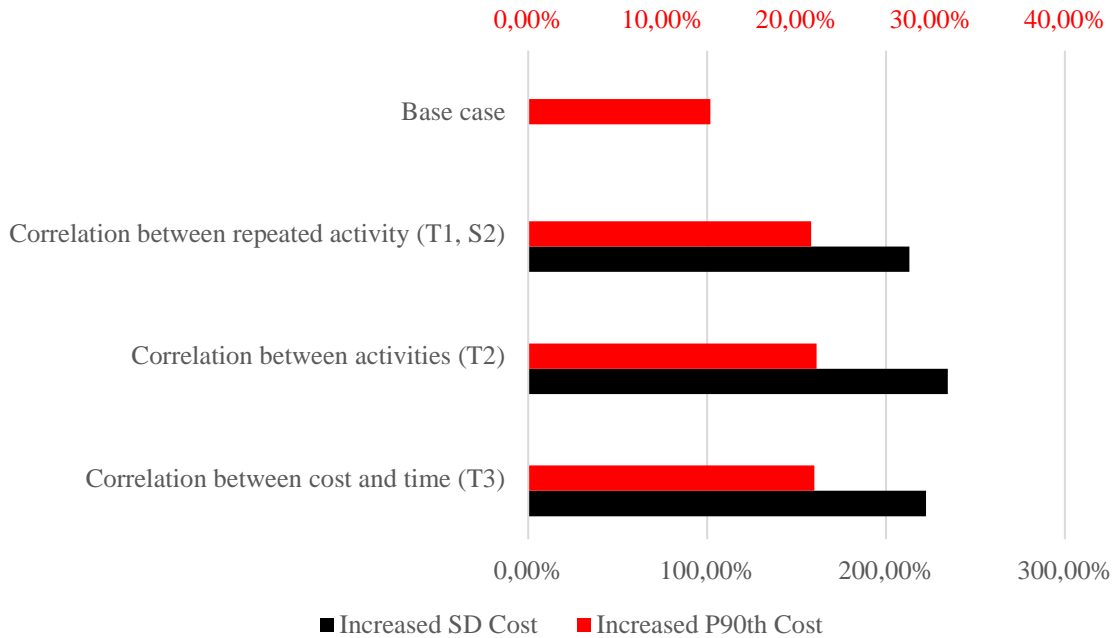
The deterministic total cost and total time of the earthwork structure are ZAR 70,952,700.00 and 340 days (See Table 6.10). The standard deviation and the 90th percentiles of the correlated total cost and total time distributions and their increases caused by the three types of correlations for the structure of the bridge are presented in Table 6.30.

The increases in the standard deviation of total cost and total time and increases in the 90th percentiles of total cost and total time for the different Types of correlations in the bridge structure are displayed in Figures 6.44 and 6.45.

Table 6.30: Impact of different types of correlations on total cost and total time of the bridge structure

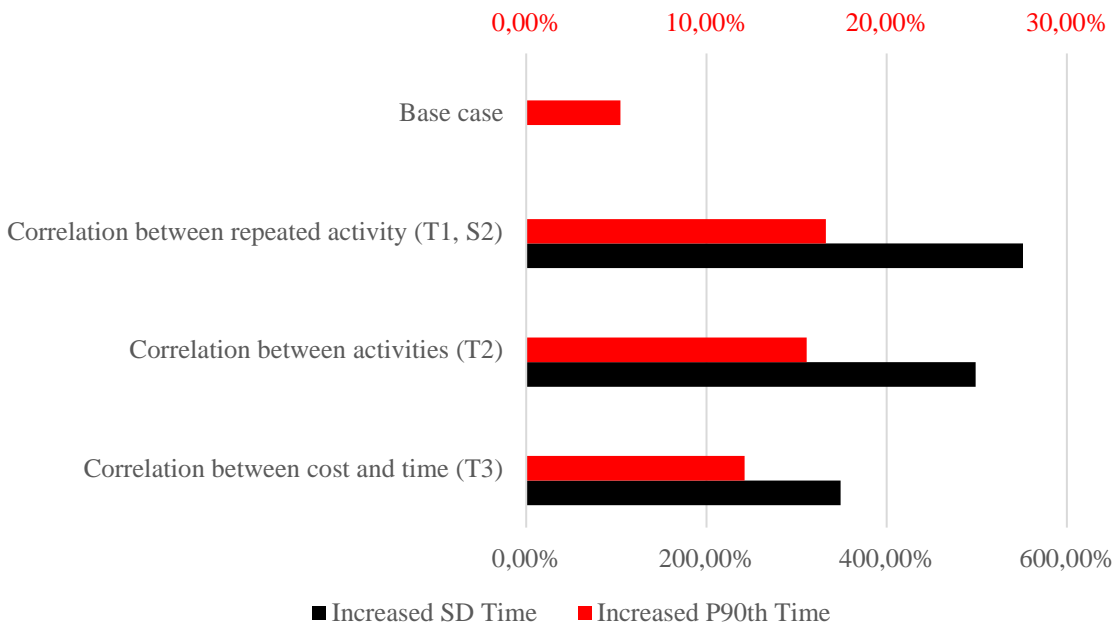
	Cost (ZAR)				Time (Day)			
	Standard Deviation	Increased Standard Deviation	P90th	Increased P90th	Standard Deviation	Increased Standard Deviation	P90th	Increased P90th
Base Case	1,920,505.95	0.00%	80577949.52	13.57%	5.04	0.00%	357.78	5.23%
Correlation between repeated activities (Type1, Scenario2)	6,014,085.33	213.15%	85,920,760.74	21.10%	32.81	551.42%	396.52	16.62%
Correlation between activities (Type2)	6,425,162.95	234.56%	86,205,928.64	21.50%	30.15	498.62%	392.89	15.56%
Correlation between cost and time (Type3)	6,191,307.31	222.38%	86,085,866.87	21.33%	22.61	348.84%	381.19	12.12%

Key: P90th: 90th Percentile



Key: T: Correlation Type, S: Correlation Scenario, SD: Standard Deviation, P90th: 90th Percentile

Figure 6.44: Impact of different types of correlations on the total cost of the bridge structure



Key: T: Correlation Type; S: Correlation Scenario; SD: Standard Deviation; P90th: 90th Percentile

Figure 6.45: Impact of different types of correlations on the total time of the earthwork structure

Table 6.31 and clustered sensitivity graphs in cost and time (Figures 6.44 and 6.45) illustrate that correlation Type 2 (correlation between activities) caused the largest increase in standard deviation and 90th percentile of the total cost of the bridge structure where they were increased by 234.56% and 21.50%, respectively. The largest increase in standard deviation and 90th percentile of the total time was caused by correlation Type 1 (correlation between repeated activities) with an increase of 551.42% and 16.62%, respectively. Thus, correlation Type 2 and correlation Type 1 were the principal correlation on cost and time in the bridge structure, respectively.

6.3.4.3 Evaluation of the impact of different types of correlations on the pavement structure

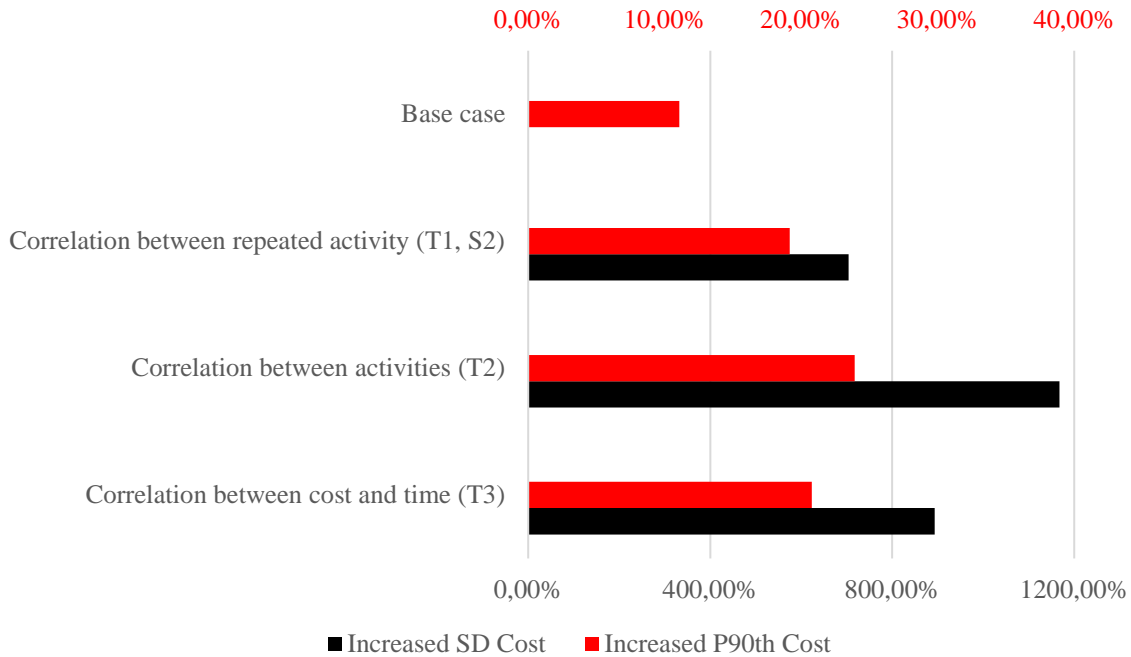
The deterministic total cost and total time of the pavement structure are ZAR 494,259,930.00 and 217 days (See Table 6.10). The standard deviation and the 90th percentiles of the correlated total cost and total time distributions, and their increases for the three types of correlations in the pavement structure are summarised in Table 6.31.

Table 6.31: Impact of different types of correlations on total cost and total time of the pavement structure

	Cost (ZAR)				Time (Day)			
	Standard Deviation	Increased Standard Deviation	P90th	Increased P90th	Standard Deviation	Increased Standard Deviation	P90th	Increased P90th
Base Case	4,174,001.38	0.00%	548,997,579.66	11.07%	2.64	0.00%	227.62	4.90%
Correlation between repeated activities (Type1, Scenario2)	33,572,597.99	704.33%	588,988,971.85	19.17%	11.13	321.59%	239.00	10.14%
Correlation between activities (Type2)	52,912,363.32	1167.67%	612,440,433.36	23.91%	13.23	401.14%	241.64	11.35%
Correlation between cost and time (Type3)	41,474,779.05	893.65%	596,935,711.88	20.77%	11.59	339.02%	239.16	10.21%

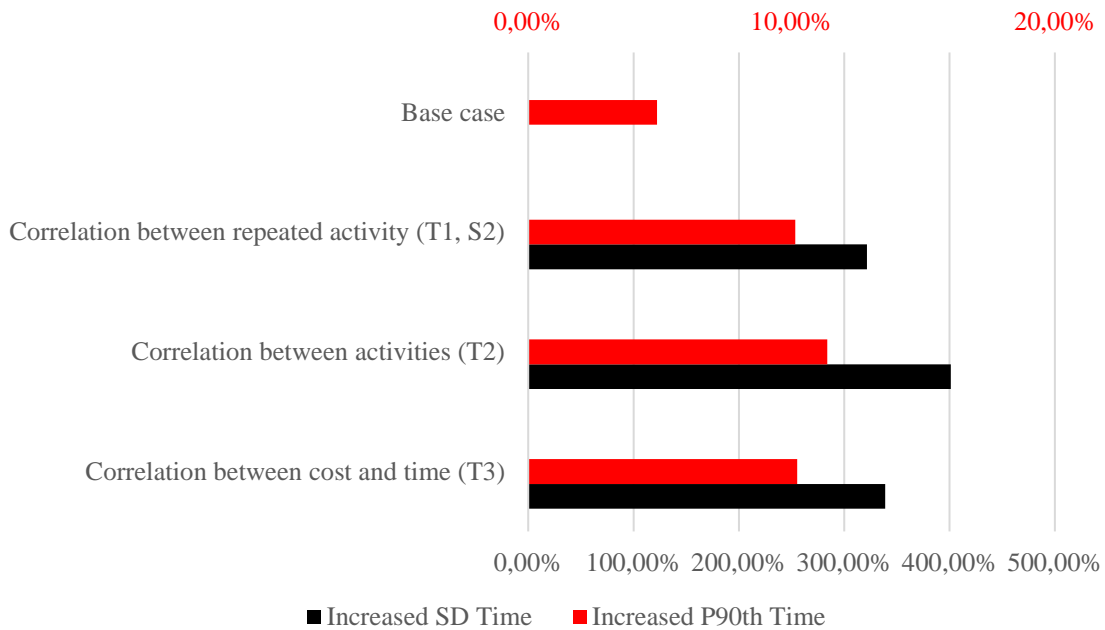
Key: P90th: 90th Percentile

The increases in the standard deviation of total cost and total time and increases in 90th percentiles of total cost and total time for the different Types of correlation in the pavement structure are displayed in Figures 6.46 and 6.47.



Key: T: Correlation Type; S: Correlation Scenario; SD: Standard Deviation; P90th: 90th Percentile

Figure 6.46: Impact of different types of correlations on the total cost of the pavement structure



Key: T: Correlation Type; S: Correlation Scenario; SD: Standard Deviation; P90th: 90th Percentile

Figure 6.47: Impact of different types of correlations on the total time of the pavement structure

Table 6.32 and the clustered sensitivity graph of cost and time (Figures 6.46 and 6.47) demonstrated that correlation Type 2 (correlation between activities) caused the largest increase in standard deviation and 90th percentiles of the total cost and total time of the pavement, which increased by 1167.67% and 23.91%, respectively, in total cost and 401.14% and 11.35%, respectively, in total time of the pavement structure. Hence, correlation Type 2 was considered as the key correlation on cost and time in pavement structure.

6.3.4.4 Evaluation of the impact of different types of correlations on the overall construction project

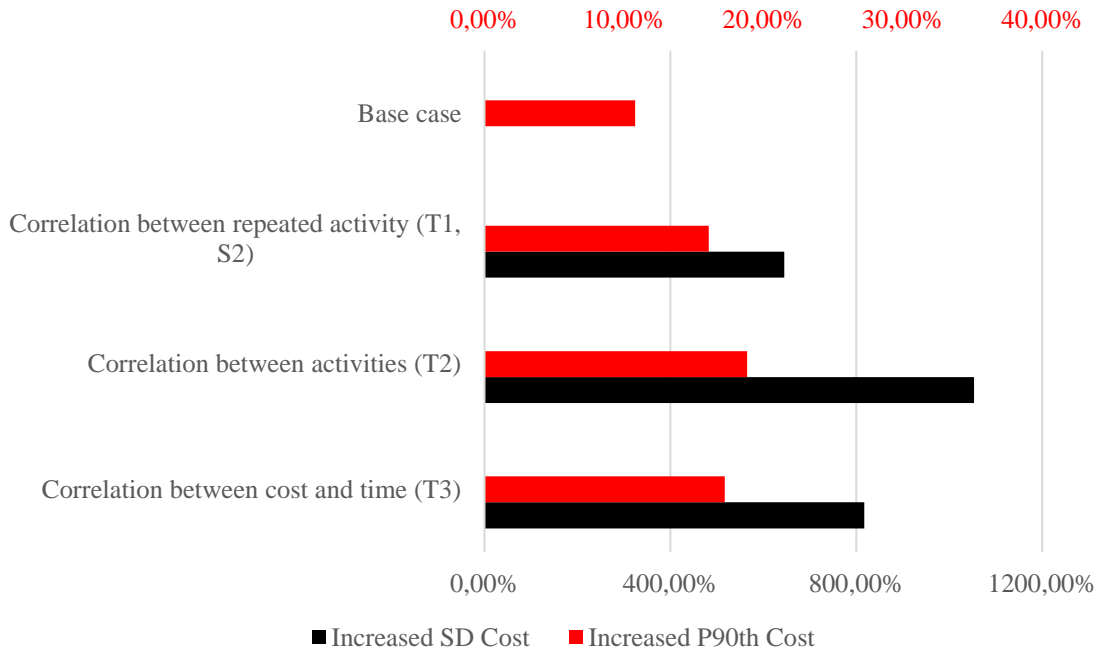
The deterministic total cost and total time of project are ZAR 809,504,922.8 and 340 days (See Table 6.10). The standard deviation and the 90th percentiles of the correlated total cost and total time distributions, and their increases for three types of correlations in the overall project are presented in Table 6.33.

The increases in the standard deviation of total cost and total time and increases in the 90th percentiles of total cost and total time for the different types of correlation of the overall project are displayed in Figures 6.48 and 6.49.

Table 6.32: Impact of different types of correlations on total cost and total time of the overall construction project

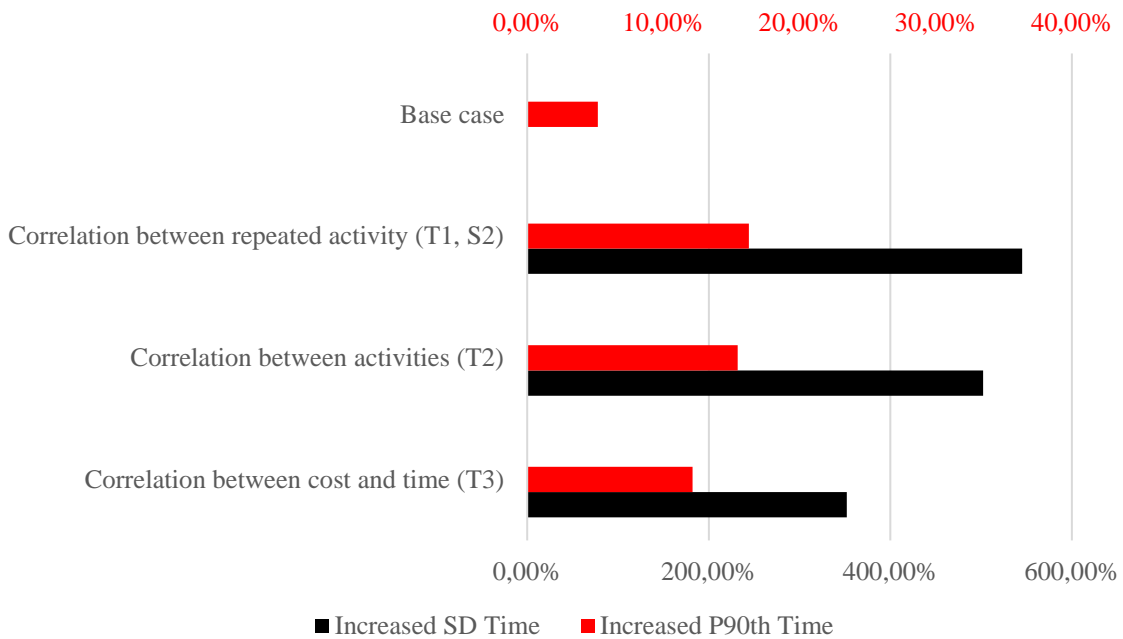
	Cost (ZAR)				Time (DAY)			
	Standard Deviation	Increased Standard Deviation	P90th	Increased P90th	Standard Deviation	Increased Standard Deviation	P90 th	Increased P90 th
Base Case	4935665.19	0.00%	896942973.77	10.80%	4.98	0.00%	357.67	5.20%
Correlation between repeated activities (Type1, Scenario2)	36756875.60	644.72%	939759672.15	16.09%	32.12	545.20%	395.32	16.27%
Correlation between activities (Type2)	56921248.85	1053.26%	962076539.65	18.85%	29.97	502.06%	392.52	15.45%
Correlation between cost and time (Type3)	45,274,510.91	817.29%	949067831.41	17.24%	22.50	352.03%	381.25	12.13%

Key: P90th: 90th Percentile



Key: T: Correlation Type; S: Correlation Scenario; SD: Standard Deviation; P90th: 90th Percentile

Figure 6.48: Impact of different types of correlations on the overall construction project cost



Key: T: Correlation Type; S: Correlation Scenario; SD: Standard Deviation; P90th: 90th Percentile

Figure 6.49: Impact of different types of correlations on the overall construction project time

Table 6.33 and the clustered sensitivity graph of cost and time (Figures 6.48 and 6.49) reveal that correlation Type 2 (correlation between activities) caused the largest increase in standard deviation and 90th percentile of the total cost of the project, which increased by 1053.26% and 18.85%, respectively. The largest increase in standard deviation and 90th percentile of the total time was caused by correlation Type 1 (correlation between repeated activities) with increases of 545.20% and 16.27%, respectively. Therefore, correlation Type 2 and correlation Type 1 were considered as the dominant correlations of cost and time, respectively, in the overall project.

6.4 DISRUPTIVE EVENTS IN THE CONSTRUCTION OF HIGHWAY PROJECTS

In the uncertainty model, the disruptive events occurring in projects are one of the three sources of uncertainty. In this section, disruptive events in South African highway construction were modelled using intelligent machine learning technique and were validated by classical statistics regression analysis. Finally, their impact on construction cost and duration of each structure and total cost and total time of the project were assessed.

6.4.1 Identification of disruptive events in highway construction projects

Through a systematic review of the literature using the bibliometrics technique, 317 disruptive events in construction projects were identified (See Chapter Two). A series of panels and a brainstorming meeting with the panel of experts with 30 years and more experience in South African highway construction projects were held. The highway expert panel reviewed the identified uncertainties and confirmed the existence of 76 disruptive events in South African highway construction projects. They grouped these 76 disruptive events into seven major uncertainty factors as shown in the disruptive events networks in Figure 6.50.

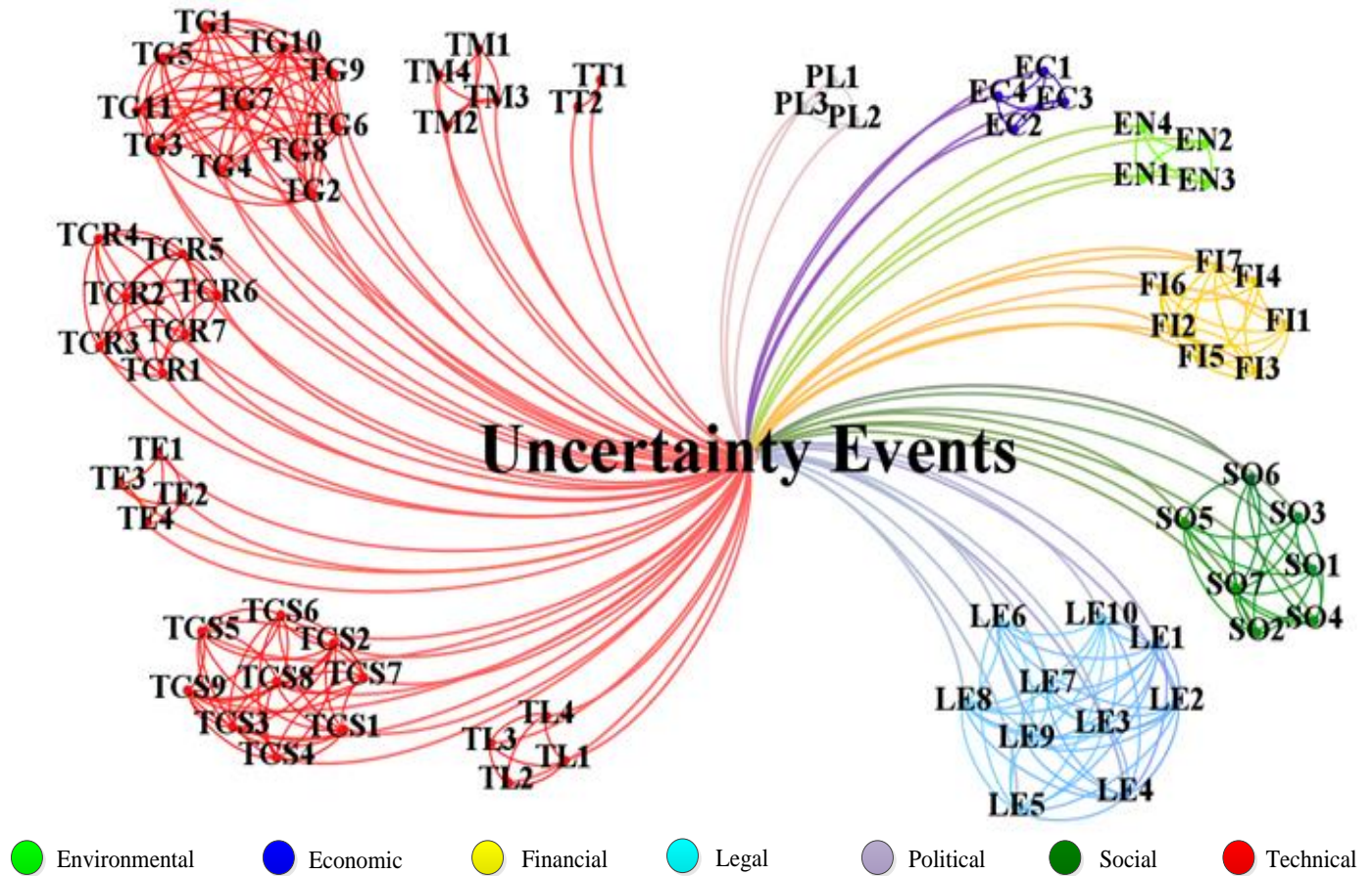


Figure 6.50: Disruptive events networks of South African highway construction projects

6.4.2 Modelling disruptive events

As discussed in Chapter Four, an Adaptive Neuro-Fuzzy Inference System (ANFIS) as advanced intelligent machine learning technique was developed and modelled in the MATLAB environment to predict accurately the impact size of disruptive events on cost and time of highway construction projects. In this section, the predicted impacts of disruptive events and the performance of the ANFIS are presented.

6.4.2.1 Prediction of disruptive events' impact on construction cost and time of highway projects

To identify the impact size of an event, the optimum (mean) values of two input variables' probability of occurrence and severity of event obtained from the census survey (Table 5.14) were input to the trained ANFIS rule viewers, and the relevant size of the impact of the event on time and cost variables were predicted by trained ANFIS models. For instance, the optimum probability of occurrence (0.66875) and severity time (4.5625) value of fluctuation of prices of materials and equipment (EC1) event were inserted into the input box of the rule viewer of the trained ANFIS,

and the model predicted the impact size of event (3.7) to the time of highway construction projects. (See Figure 6.51).

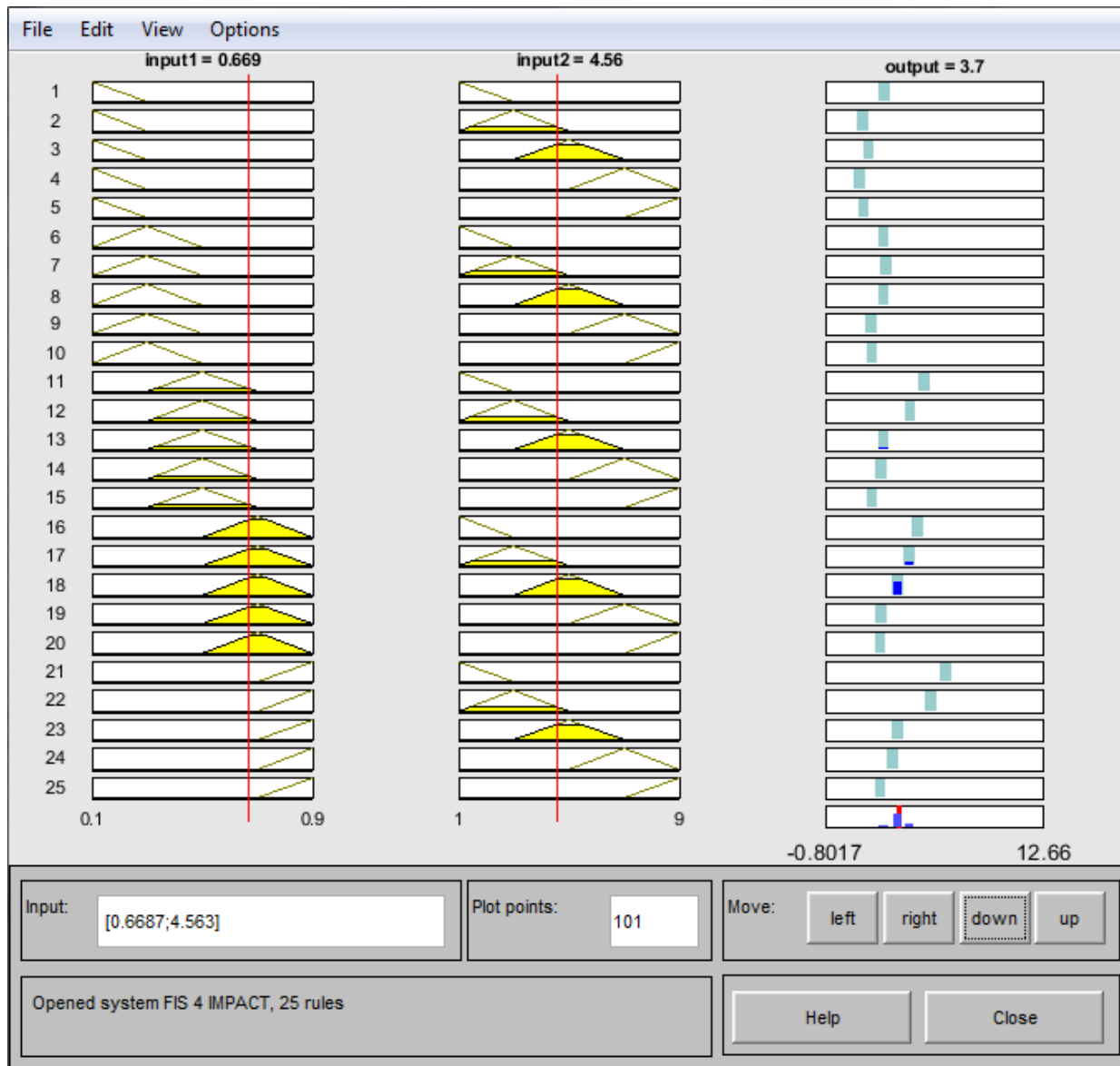


Figure 6.51: Rules viewer display for event, price of materials and equipment (EC1)

Figure 6.51 illustrates the total size of each numerical input (input 1: probability, input 2: severity) of event EC1 to triangular fuzzy memberships function and the predicted impact size of the event. Likewise, the predicted impact sizes of 76 disruptive events on the cost and time of highway construction projects were predicted and ranked and presented in Table 6.33. Results show that the ANFIS models predicted the size of impact of disruptive events on the cost and time of the highway project.

Table 6.33: ANFIS models predicted impact size of disruptive events on cost and time of a highway project

Event	Probability of Occurrence	Cost			Time		
		Severity of the event	Impact Size	Rank	Severity of the event	Impact Size	Rank
TG11	0.84375	8.5625	4.97	1	8.3125	4.95	1
TCS6	0.79375	7.375	4.59	2	8.3125	4.85	2
PL3	0.8125	5.75	4.27	3	7.4375	4.69	4
EN3	0.75	6.0625	4.21	4	3.9375	3.68	29
SO7	0.79375	5.5	4.17	5	3.8125	3.79	19
SO5	0.70625	6.3125	4.11	6	6.8125	4.06	8
EC2	0.7	5.5625	4.08	7	3.5625	3.32	40
EC1	0.66875	6.5625	4.02	8	4.5625	3.7	26
EC4	0.65625	5.4375	3.88	9	2.0	2.48	69
TG9	0.73125	4.5625	3.86	10	6.4375	4.18	6
EN2	0.4125	8.125	3.84	11	7.9375	3.8	17
SO6	0.76875	4.1875	3.82	12	4.0625	3.78	20
FI6	0.55625	6.375	3.8	13	2.375	2.68	67
PL1	0.64375	5.1875	3.77	14	5.6875	3.88	11
TCR5	0.64375	5.1875	3.77	14	5.5625	3.86	14
FI5	0.55	6.25	3.75	16	2.0625	2.53	68
SO3	0.76875	3.875	3.72	17	4.375	3.88	12
TCS3	0.60625	5.625	3.72	17	5.8125	3.77	21
TCR4	0.66875	4.5625	3.7	19	5.5	3.95	9
TG3	0.74375	3.9375	3.66	20	4.0625	3.71	25
FI7	0.56875	5.8125	3.65	21	1.8125	2.4	71
SO4	0.78125	3.5625	3.65	21	7.8125	4.68	5
TT1	0.58125	5.6875	3.65	21	6.1875	3.8	18
TCS4	0.675	4.3125	3.63	24	5.1875	3.92	10
TG5	0.8125	3.125	3.61	25	7.6875	4.75	3
TM3	0.61875	5.0	3.59	26	5.5	3.74	23
TCS2	0.5875	5.375	3.57	27	4.5	3.41	36
TL1	0.725	3.875	3.57	27	4.625	3.88	13
EN4	0.75625	3.5	3.52	29	2.4375	2.97	58
FI2	0.58125	5.3125	3.52	29	4.875	3.4	37
TT2	0.5375	5.75	3.51	31	6.1875	3.69	28
LE1	0.625	4.3125	3.49	32	5.0625	3.64	31
FI4	0.4	6.875	3.48	33	5.625	3.19	46
TG6	0.6	4.6875	3.47	34	5.125	3.54	32
TG2	0.75625	3.0625	3.31	35	3.375	3.47	34
TG7	0.375	6.4375	3.31	35	4.25	2.82	62
LE10	0.4625	5.6875	3.3	37	4.9375	3.01	55
LE9	0.625	3.6875	3.29	38	5.6875	3.81	16
TG4	0.55625	3.9375	3.25	39	7.75	4.15	7
FI1	0.3625	6.0625	3.22	40	1.875	1.7	75
TCR2	0.55625	3.75	3.22	40	4.25	3.29	42
PL2	0.525	4.0625	3.21	42	4.5	3.2	45
TL4	0.5625	3.625	3.2	43	4.375	3.32	41

LE4	0.4	5.625	3.19	44	5.125	3.04	53
LE6	0.3125	7.1875	3.15	45	3.6875	2.4	72
FI3	0.56875	5.375	3.13	46	3.3125	3.11	50
TM4	0.54375	3.375	3.12	47	6.0625	3.66	30
TCR3	0.54375	3.3125	3.1	48	4.375	3.26	43
TG8	0.5375	3.3125	3.1	48	4.4375	3.24	44
TCR6	0.6	3.8125	3.08	50	4.0625	3.37	38
TCS5	0.46875	4.625	3.05	51	5.25	3.11	51
TCR7	0.46875	3.875	3.04	52	4.125	3.06	52
EN1	0.6625	3.0625	3.03	53	5.0	3.81	15
LE2	0.44375	4.375	3.01	54	3.8125	2.94	60
EC3	0.4125	4.6875	2.98	55	2.6875	2.39	73
LE8	0.4125	4.75	2.98	55	4.3125	2.93	61
TCR1	0.3625	4.9375	2.98	55	4.3125	2.81	64
TL3	0.61875	2.875	2.93	58	5.3125	3.69	27
LE5	0.4375	3.8125	2.92	59	4.4375	3.0	56
TE1	0.6	2.8125	2.9	60	4.5625	3.46	35
TCS7	0.44375	3.5625	2.89	61	4.1875	2.99	57
TM1	0.56875	2.6875	2.84	62	4.75	3.35	39
LE7	0.4375	3.375	2.81	63	5.0625	3.02	54
TCS8	0.75	2.0625	2.75	64	4.0625	3.73	24
SO1	0.64375	2.5	2.73	65	4.25	3.52	33
TCS1	0.38125	3.5625	2.63	66	3.75	2.69	66
SO2	0.55625	2.125	2.56	67	2.625	2.81	63
TM2	0.56875	1.9375	2.46	68	6.1875	3.77	22
TCS9	0.56875	1.8125	2.4	69	3.5	3.17	47
TL2	0.54375	1.6875	2.34	70	3.4375	3.14	48
TG10	0.6	1.4375	2.21	71	3.3125	3.13	49
TE4	0.4625	1.6875	2.14	72	3.5625	2.97	59
TE3	0.425	1.8125	2.0	73	3.5	2.79	65
LE3	0.19375	3.5	1.7	74	5.0	2.47	70
TG1	0.24375	2.4375	1.5	75	2.8125	1.64	76
TE2	0.2625	1.9375	1.35	76	3.125	1.87	74

Table 6.33 shows the optimum value of probability of occurrence, the effect of the severity of the event on cost and time, and predicted impact size of each disruptive event on the cost and time of highway construction projects. The results presented in Table 6.33 show that the events with the highest values of probability of occurrence (almost certain) were latent ground conditions (TG11) (0.84375), inadequate planning and scheduling (TG5) (0.8125) and human-made disaster (PL3) (0.8125). However, the events with the highest values of effect of severity on time (catastrophic) were latent ground conditions (TG11) (8.3125) and inaccurate time and cost estimation (TCS6) (8.3125), while the events with the highest values of effect of severity on cost were latent ground conditions (TG11) (8.5625) and natural disasters (EN2) (8.125).

All 76 disruptive events were prioritised based on the predicted value output affecting cost and time, from ANFIS models (See Table 6.34). For instance, the latent ground conditions and inaccurate time and cost estimation events had the highest impact (1st and 2nd rank) on both time (4.95 & 4.85) and cost (4.97 & 4.59) of highway construction. Further investigation of the ANFIS model predicted impact size of disruptive events on the cost and time of highway project revealed that the impact of disruptive events on time was varied to the cost of the highway project. For instance, the inadequate planning and scheduling event had the third highest impact on time of highway projects by impact size of 4.75. However, the impact of this event on the cost of the project was ranked at 25th, with impact size of 3.65. The impact size of disruptive events on cost and time are visualised through the size of the nodes in the network analysis graphs in Figures 6.52 and 6.53, to provide useful view on impacts on each disruptive event on the cost and time of the project

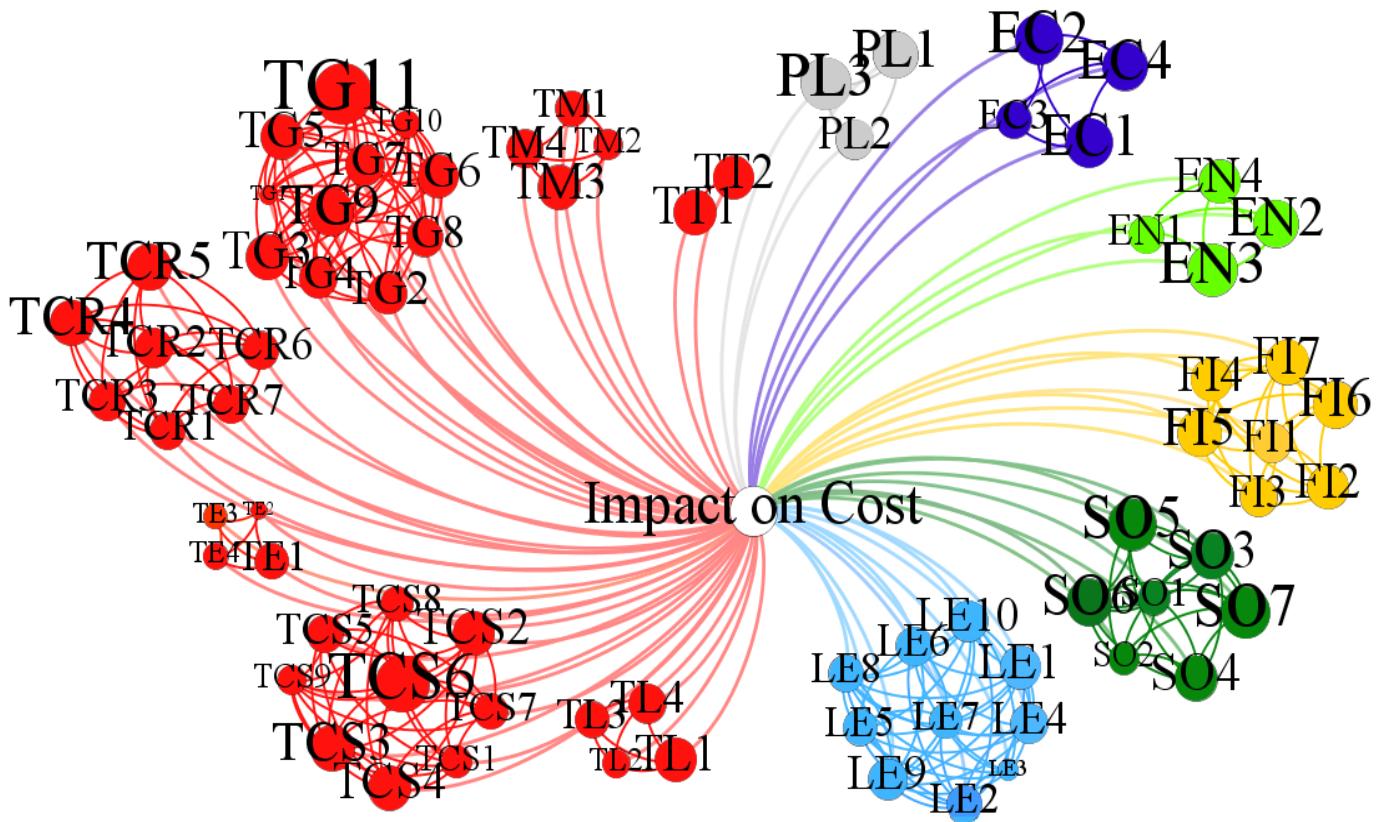


Figure 6.52: Impact size of disruptive events on the cost of highway projects

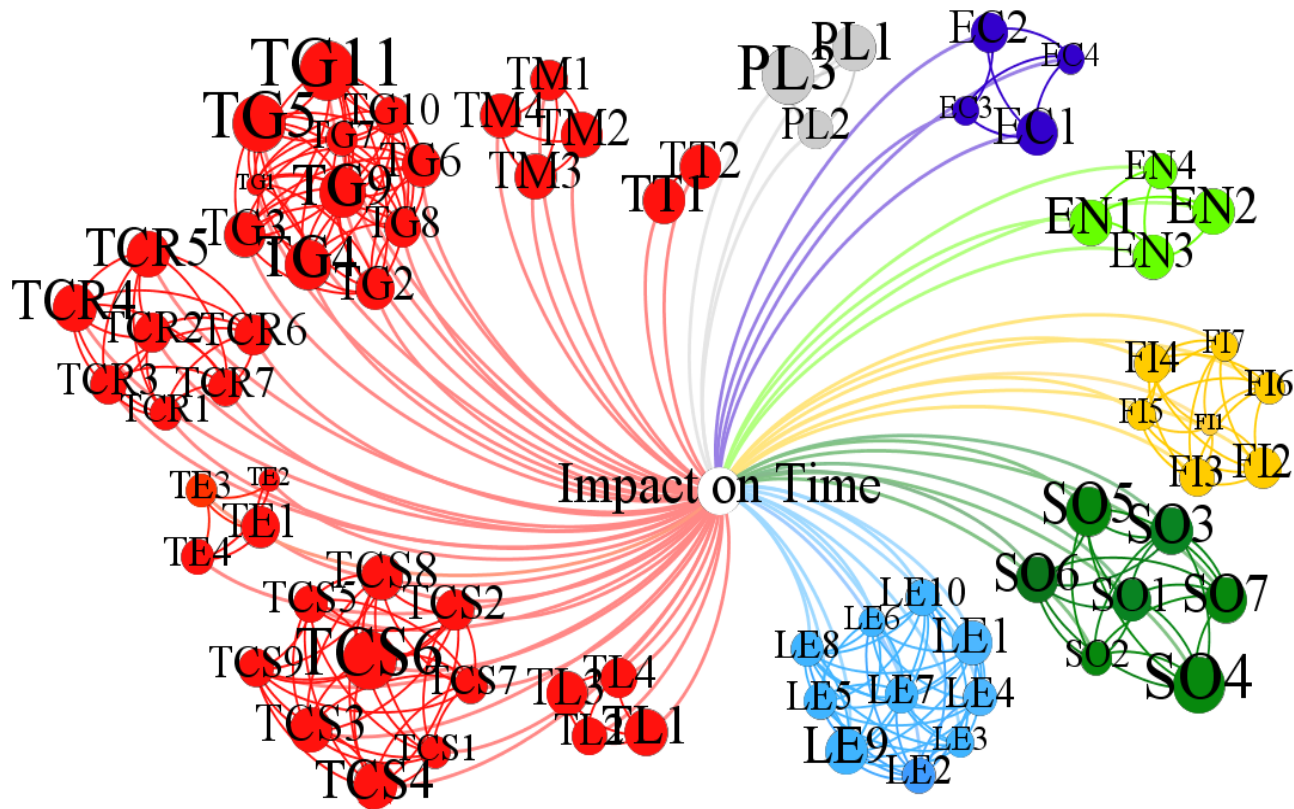


Figure 6.53: Impact size of disruptive events on the time of highway projects

6.4.2.2 Evaluation of the performance of predicted impact size

To evaluate the performance of predicted impact sizes on cost and time with ANFIS, the reliability of predicted sizes were tested using the Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) and the fitness of predicted impact size by ANFIS models to the real data checked by correlation coefficient value as shown in Table 6.34.

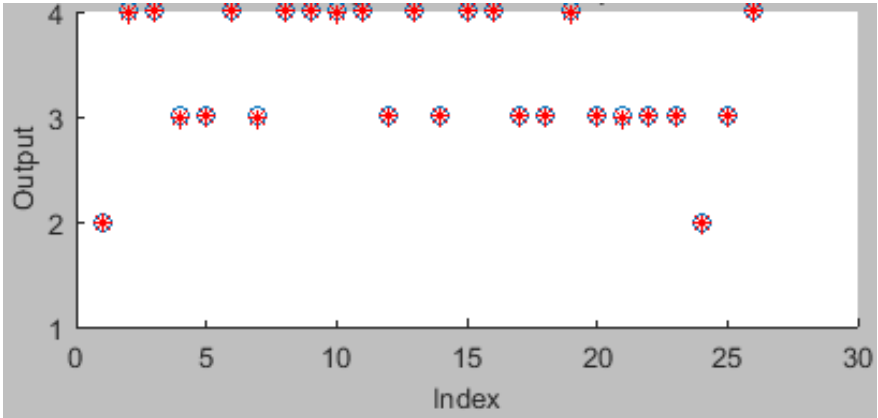
Table 6.34: ANFIS prediction cost and time performance evaluation

Event	Cost performance			Time performance		
	RMSE	MAPE	R Value	RMSE	MAPE	R Value
EC1	6.05E-08	1.35E-08	1.0000000000000000	8.74E-07	2.07E-07	0.9999999999999936
EC2	1.07E-07	1.73E-08	0.9999999999999999	7.76E-07	1.88E-07	0.9999999999999947
EC3	6.88E-08	2.14E-08	0.9999999999999999	6.00E-07	2.15E-07	0.9999999999999931
EC4	1.27E-07	2.06E-08	0.9999999999999999	7.22E-07	2.38E-07	0.9999999999999924
EN1	2.53E-07	6.02E-08	0.9999999999999994	9.20E-07	2.27E-07	0.9999999999999938
EN2	1.39E-08	2.94E-09	1.0000000000000000	9.73E-07	1.83E-07	0.9999999999999941
EN3	3.36E-08	7.08E-09	1.0000000000000000	8.36E-07	1.80E-07	0.9999999999999948
EN4	8.03E-08	1.62E-08	0.9999999999999999	7.78E-07	1.62E-07	0.9999999999999938
FI1	2.16E-08	6.59E-09	1.0000000000000000	4.03E-07	2.07E-07	0.9999999999999952
FI2	4.58E-08	1.05E-08	1.0000000000000000	1.02E-06	2.26E-07	0.9999999999999911
FI3	7.55E-08	1.43E-08	1.0000000000000000	7.97E-07	2.00E-07	0.9999999999999925

FI4	4.34E-08	1.03E-08	1.000000000000000	8.61E-07	2.14E-07	0.999999999999925
FI5	2.65E-08	6.07E-09	1.000000000000000	6.24E-07	1.63E-07	0.999999999999927
FI6	2.41E-08	5.99E-09	1.000000000000000	7.64E-07	1.98E-07	0.999999999999913
FI7	2.41E-08	5.69E-09	1.000000000000000	6.97E-07	1.63E-07	0.999999999999906
LE1	6.91E-08	1.49E-08	1.000000000000000	9.68E-07	2.04E-07	0.999999999999930
LE10	6.85E-08	1.06E-08	1.000000000000000	9.86E-07	2.38E-07	0.999999999999902
LE2	7.90E-08	2.45E-08	0.999999999999999	1.12E-06	2.84E-07	0.999999999999844
LE3	1.20E-07	4.82E-08	0.999999999999996	4.21E-07	1.74E-07	0.999999999999965
LE4	7.37E-08	1.42E-08	0.999999999999999	8.13E-07	2.57E-07	0.999999999999928
LE5	1.04E-07	3.05E-08	0.999999999999999	7.19E-07	1.83E-07	0.999999999999941
LE6	2.49E-08	6.99E-09	1.000000000000000	7.37E-07	2.62E-07	0.999999999999898
LE7	2.05E-07	4.97E-08	0.999999999999995	8.45E-07	1.99E-07	0.999999999999923
LE8	9.11E-08	2.47E-08	0.999999999999999	7.83E-07	2.22E-07	0.999999999999926
LE9	5.77E-08	1.40E-08	1.000000000000000	5.08E-07	1.26E-07	0.999999999999982
PL1	8.27E-08	1.33E-08	0.999999999999999	7.76E-07	1.73E-07	0.999999999999956
PL2	5.84E-08	1.66E-08	1.000000000000000	9.40E-07	2.36E-07	0.999999999999911
PL3	3.09E-08	5.91E-09	1.000000000000000	1.10E-06	1.70E-07	0.999999999999945
SO1	2.20E-07	5.87E-08	0.999999999999994	8.90E-07	1.86E-07	0.999999999999931
SO2	1.14E-07	4.53E-08	0.999999999999998	5.74E-07	1.58E-07	0.999999999999956
SO3	5.31E-08	1.40E-08	1.000000000000000	8.96E-07	1.80E-07	0.999999999999945
SO4	4.66E-08	1.17E-08	1.000000000000000	9.77E-07	1.43E-07	0.999999999999956
SO5	3.59E-08	7.38E-09	1.000000000000000	9.67E-07	1.85E-07	0.999999999999948
SO6	5.06E-08	1.26E-08	1.000000000000000	8.05E-07	1.49E-07	0.999999999999952
SO7	7.54E-08	7.99E-09	1.000000000000000	6.32E-07	1.48E-07	0.999999999999971
TCR1	5.54E-08	1.66E-08	1.000000000000000	7.00E-07	2.42E-07	0.999999999999932
TCR2	4.58E-08	1.43E-08	1.000000000000000	9.82E-07	2.03E-07	0.999999999999907
TCR3	1.70E-07	4.29E-08	0.999999999999996	1.02E-06	2.51E-07	0.999999999999901
TCR4	7.50E-08	1.70E-08	1.000000000000000	8.83E-07	2.04E-07	0.999999999999945
TCR5	8.73E-08	1.33E-08	0.999999999999999	8.86E-07	1.73E-07	0.999999999999947
TCR6	9.19E-08	2.05E-08	0.999999999999999	1.01E-06	2.53E-07	0.999999999999907
TCR7	1.65E-07	2.97E-08	0.999999999999997	9.08E-07	2.08E-07	0.999999999999906
TCS1	2.09E-07	5.16E-08	0.999999999999994	8.32E-07	2.88E-07	0.999999999999903
TCS2	7.36E-08	1.27E-08	1.000000000000000	8.78E-07	2.00E-07	0.999999999999934
TCS3	6.65E-08	9.68E-09	1.000000000000000	9.08E-07	1.82E-07	0.999999999999939
TCS4	8.04E-08	1.70E-08	0.999999999999999	1.03E-06	2.04E-07	0.999999999999924
TCS5	6.74E-08	1.74E-08	1.000000000000000	8.84E-07	2.38E-07	0.999999999999925
TCS6	4.79E-08	7.51E-09	1.000000000000000	8.71E-07	1.24E-07	0.999999999999967
TCS7	1.42E-07	3.29E-08	0.999999999999997	8.63E-07	2.06E-07	0.999999999999912
TCS8	1.38E-07	4.16E-08	0.999999999999998	1.03E-06	2.19E-07	0.999999999999921
TCS9	1.03E-07	4.14E-08	0.999999999999998	6.91E-07	1.41E-07	0.999999999999947
TE1	1.61E-07	4.83E-08	0.999999999999997	1.11E-06	2.30E-07	0.999999999999888
TE2	1.99E-07	6.60E-08	0.999999999999982	6.83E-07	2.40E-07	0.999999999999891
TE3	1.77E-07	6.00E-08	0.999999999999993	9.90E-07	2.70E-07	0.999999999999871
TE4	1.37E-07	5.85E-08	0.999999999999996	6.46E-07	2.01E-07	0.999999999999948
TG1	2.04E-07	6.61E-08	0.999999999999985	5.95E-07	2.11E-07	0.999999999999888
TG10	1.13E-07	5.83E-08	0.999999999999997	1.20E-06	2.32E-07	0.999999999999843
TG11	1.13E-08	1.78E-09	1.000000000000000	7.64E-07	9.70E-08	0.999999999999976
TG2	2.00E-07	4.46E-08	0.999999999999997	1.12E-06	2.14E-07	0.999999999999898
TG3	7.51E-08	1.55E-08	1.000000000000000	1.20E-06	2.51E-07	0.999999999999896

TG4	5.94E-08	1.58E-08	1.000000000000000	1.05E-06	1.97E-07	0.999999999999941
TG5	1.85E-07	3.93E-08	0.999999999999997	7.57E-07	1.23E-07	0.999999999999974
TG6	1.19E-07	2.61E-08	0.999999999999999	1.22E-06	2.68E-07	0.999999999999887
TG7	7.49E-08	1.50E-08	0.999999999999999	8.35E-07	2.40E-07	0.999999999999911
TG8	1.56E-07	4.83E-08	0.999999999999997	9.38E-07	2.25E-07	0.999999999999915
TG9	2.50E-07	3.44E-08	0.999999999999995	1.23E-06	2.16E-07	0.999999999999915
TL1	7.40E-08	1.55E-08	1.000000000000000	1.14E-06	2.51E-07	0.999999999999910
TL2	1.06E-07	4.38E-08	0.999999999999998	7.88E-07	1.98E-07	0.999999999999931
TL3	1.60E-07	4.30E-08	0.999999999999997	7.51E-07	1.74E-07	0.999999999999959
TL4	1.72E-07	4.30E-08	0.999999999999997	7.97E-07	1.89E-07	0.999999999999938
TM1	1.36E-07	4.53E-08	0.999999999999998	8.41E-07	2.20E-07	0.999999999999939
TM2	1.03E-07	3.99E-08	0.999999999999998	8.38E-07	1.74E-07	0.999999999999951
TM3	6.02E-08	1.20E-08	1.000000000000000	1.01E-06	1.96E-07	0.999999999999929
TM4	9.14E-08	2.90E-08	0.999999999999999	1.04E-06	2.11E-07	0.999999999999922
TT1	7.25E-08	1.20E-08	1.000000000000000	9.08E-07	1.95E-07	0.999999999999946
TT2	7.78E-08	1.20E-08	1.000000000000000	1.01E-06	1.79E-07	0.999999999999927

The very small error values and the extreme closeness of the R-Value to 1 of each disruptive event indicated the reliability of predicted impact sizes when using ANFIS, and the good fit between their value and the real data, as illustrated, for fluctuation of prices of materials and equipment (EC1) in Figure 6.54.



Training Data: ○
 FIS Output: *

Figure 6.54: Performance of FIS in prediction of EC1 event impact size

The illustrative Figure 6.54 demonstrates that the predicted impact size (FIS) of event EC1 on time of highway projects was extremely close to the real data (Training data). Examining the correlation coefficient value revealed that all 76 ANFIS-developed models of cost and time were able to estimate the impact size of events with strong fit ($r > .7$) to the real size of impact of the events on the cost and time of a highway project.

6.4.2.3 Validation of the ANFIS model

Validation and verification of a problem-solving method need the comparison with different problem-solving methods (Sargent, 2013). In this section, the predicted impact size of the ANFIS model was validated using a Stepwise Regression Analysis (RSA).

The impact size of a disruptive event is here described as the dependent variable, which is a function of two independent variables: the probability of occurrence and the severity of the relative event, as demonstrated in Equation 6.8.

$$\text{Uncertainty impact}_i = a_i p + b_i s + r_i \quad [6.8]$$

Where r_i is a constant value. a_i and b_i represent regression coefficients of independent variables.

Because each of the inputs can have a low correlation with the output variable, the SRA model was used in this study. Table 6.35 presents the values of the correlation coefficients between inputs and output variable of the model.

Table 6.35: Correlation coefficients among inputs and output variables

	Probability	Severity	Impact
Probability	1		
Severity	0.001411	1	
Impact	0.685061	0.67034	1

Table 6.36 shows the low correlation between independent variables and dependent variables (0.685061, 0.67034 < 0.7).

The general SRA model for impact size based on the matrix impact in Figure 4.8 was developed to evaluate the prediction of the impact size of disruptive events on the cost and time of highway construction projects. The SRA model test details are shown in Table 6.36.

Table 6.36: Regression Test Details

Regression Statistics				
Multiple R	0.968822			
R Squared	0.93861607			
Adjusted R Squared	0.93303571			
Standard Error	0.31622777			
	Coefficients	Standard Error	t Stat	P-value
Intercept	0.18	0.170294	1.056996	0.00301
Probability	2.9	0.223607	12.96919	8.82E-12
Severity	0.29	0.022361	12.96919	8.82E-12

Table 6.36 revealed the correlation coefficient value (R Square) of the model is close to 1 and there is a very low P-value (<0.05). The very low values of P-value indicated the statistically significant relation of each independent variable to the dependent variable of the model and the closeness of the R-value to 1 was verified by the close fit between the estimated output model and the real data. The developed Stepwise Regression Analysis (SRA) model for general disruptive event impact size is outlined in Equation 6.9.

$$\text{Uncertainty impact}_i = 2.9p + 0.29s + 0.18 \quad [6.9]$$

Similar steps were repeated to develop the SRA models for each disruptive event to determine their impact on construction time and cost of highway projects. To assess the optimum impact size of each disruptive event, the mean values of two independent variables (probability of occurrence and severity of the event) were input to develop SRA models. The developed model and impact size of all identified disruptive events on the completion time and cost of highway construction projects were estimated and ranked as presented in Table 6.37.

Table 6.37: Estimated impact size of disruptive events on time of highway projects

Event	Probability of occurrence	Severity of event	Cost			Time			
			Model	Impact	Rank	Severity of event	Model	Impact	Rank
TG11	0.84375	8.5625	$I=1.0567p+0.018041s+3.9227$	4.968767	1	8.3125	$I=1.6079P+0.068282S+3.0132$	4.93746	1
TCS6	0.79375	7.375	$I=2.0573p+0.26851+0.94919$	4.562433	2	8.3125	$I=1.9967p+0.21694s+1.3931$	4.781294	2
EC1	0.8125	5.75	$I=2.3608p+0.27278s+0.78734$	4.156244	3	4.5625	$I=2.6591p+0.29949s+0.3694$	3.40623	33
SO7	0.75	6.0625	$I=1.3749p+0.1707s+2.0636$	4.093777	4	3.8125	$I=2.832p+0.26974s+0.50137$	3.687476	21
EN3	0.79375	5.5	$I=2.0843p+0.23046s+1.1333$	4.093689	5	3.9375	$I=3.5439p+0.37035s-0.50399$	3.687471	24
PL3	0.70625	6.3125	$I=2.7914p+0.31902s-0.039877$	4.062501	6	7.4375	$I=2.7748p+0.21478s+0.80427$	4.656221	5
SO5	0.7	5.5625	$I=1.9856p+0.23424s+1.1503$	4.03127	7	6.8125	$I=2.9907p+0.29509s+0.06499$	4.18747	6
EC2	0.66875	6.5625	$I=1.7414p+0.15862s+1.8362$	3.937504	8	3.5625	$I=3.1463p+0.36829s-0.22439$	3.343736	37
EN2	0.65625	5.4375	$I=1.847p+0.25187s+1.0354$	3.843731	9	7.9375	$I=1.8779p+0.20912s+1.4539$	3.812581	10
FI6	0.73125	4.5625	$I=2.6883p+0.25637s+0.65151$	3.781236	10	2.375	$I=1.4841p+0.37124s+0.79306$	2.562498	68
SO6	0.4125	8.125	$I=2.6783p+0.28725s+0.51942$	3.781223	11	4.0625	$I=1.8938p+0.31086s+0.74612$	3.687523	21
FI5	0.76875	4.1875	$I=1.8217p+0.22481s+1.343$	3.749998	12	2.0625	$I=3.9764p+0.36809s-0.28745$	2.374998	69
TG9	0.55625	6.375	$I=2.5266p+0.30053s+0.5$	3.718744	13	6.4375	$I=2.4275p+0.22789s+0.88358$	4.156213	7
EC4	0.64375	5.1875	$I=2.1726p+0.20893s+1.1257$	3.687526	14	2	$I=0.84299p+0.36892s+1.2174$	2.59372	67
TCR5	0.64375	5.1875	$I=2.7724p+0.28101s+0.47627$	3.718742	14	5.5625	$I=2.0528p+0.21823s+1.2336$	3.84376	9
SO3	0.55	6.25	$I=2.1293p+0.21863s+1.2034$	3.687491	16	4.375	$I=2.7031p+0.24679s+0.68305$	3.812436	11
FI7	0.76875	3.875	$I=3.4697p+0.29765s-0.078475$	3.625008	17	1.8125	$I=3.465p+0.40544s-0.23769$	2.312488	71
PL1	0.60625	5.625	$I=2.6883p+0.29301s+0.34314$	3.593723	17	5.6875	$I=2.1309p+0.25781s+0.92834$	3.718751	17
TT1	0.66875	4.5625	$I=2.2059p+0.25327s+0.83987$	3.562523	19	6.1875	$I=2.481p+0.29985s+0.52521$	3.78124	12
TCS4	0.74375	3.9375	$I=2.8863p+0.2923s+0.35372$	3.562516	20	5.1875	$I=2.2434p+0.25897s+0.80167$	3.749963	17
TCS3	0.56875	5.8125	$I=2.8066p+0.24945s+0.45785$	3.562508	21	5.8125	$I=3.1541p+0.27735s+0.24167$	3.718719	19
TG3	0.58125	5.6875	$I=2.7156p+0.29586s+0.37782$	3.562496	21	4.0625	$I=2.8625p+0.30386s+0.27494$	3.656247	27

TM3	0.78125	3.5625	$l=3.4413p+0.25s+0.1832$	3.562504	21	5.5	$l=2.7229p+0.29398s+0.4$	3.718694	20
TG5	0.675	4.3125	$l=3.3461p+0.37391s-0.3559$	3.531275	24	7.6875	$l=2.3235p+0.25137s+0.89851$	4.718761	3
TCR4	0.8125	3.125	$l=2.5197p+0.23276s+0.78424$	3.531257	25	5.5	$l=2.3438p+0.28125s+0.75$	3.781232	14
TG6	0.61875	5	$l=3.01p+0.30933s+0.27527$	3.531254	26	5.125	$l=3.4577p+0.34975s-0.38905$	3.59377	31
TL1	0.725	3.875	$l=2.7604p+0.31597s+0.30556$	3.531234	27	4.625	$l=2.0923p+0.25482s+0.98332$	3.750036	14
TT2	0.5875	5.375	$l=2.5p+0.36111s+0.11111$	3.531243	27	6.1875	$l=3.0904p+0.27333s+0.1924$	3.687484	21
SO4	0.75625	3.5	$l=3.5682p+0.22983s-0.075199$	3.531227	29	7.8125	$l=2.6448p+0.26225+0.5412$	4.656278	4
TCS2	0.58125	5.3125	$l=2.931p+0.21865s+0.63401$	3.531216	29	4.5	$l=3.2586p+0.34138s-0.15345$	3.343738	35
FI3	0.5375	5.75	$l=2.6643p+0.25592s+0.60911$	3.500001	31	3.3125	$l=1.9336p+0.20369s+1.1677$	2.874926	58
EN4	0.625	4.3125	$l=3.698p+0.25896s-0.20298$	3.499993	32	2.4375	$l=2.7811p+0.32932s+0.13755$	3.093789	48
FI2	0.4	6.875	$l=3.0391p+0.32533s+0.005167$	3.499962	33	4.875	$l=3.4557p+0.3706s-0.42467$	3.375016	34
FI4	0.6	4.6875	$l=3.0112p+0.22677s+0.71004$	3.473564	34	5.625	$l=3.0851p+0.31383s+0.04787$	3.156255	43
LE1	0.75625	3.0625	$l=3.2374p+0.2814s+0.20058$	3.437493	35	5.0625	$l=3.438p+0.36616s-0.3456$	3.625013	29
LE10	0.375	6.4375	$l=2.1519p+0.22266s+1.0509$	3.312533	35	4.9375	$l=3.6134p+0.48111s-0.81155$	3.125014	47
TG2	0.4625	5.6875	$l=3.696p+0.38314s-0.68717$	3.281296	37	3.375	$l=3.0203p+0.32275s-0.08614$	3.406242	32
LE6	0.625	3.6875	$l=3.6782p+0.27755s+0.13692$	3.281248	38	3.6875	$l=0.8352p+0.37052s+1.1659$	2.312507	70
TG7	0.55625	3.9375	$l=2.6854p+0.26726s+0.55371$	3.281221	39	4.25	$l=2.9545p+0.33636s+0.25455$	2.750008	62
LE9	0.3625	6.0625	$l=2.519p+0.20015s+0.87509$	3.187518	40	5.6875	$l=2.0753p+0.21005s+1.2381$	3.781232	13
TCR6	0.55625	3.75	$l=2.0793p+0.26027s+0.94765$	3.187509	40	4.0625	$l=2.7804p+0.26577s+0.4889$	3.281246	40
FI1	0.525	4.0625	$l=3.2834p+0.21481s+0.6325$	3.125018	42	1.875	$l=3.8354p+0.33282s-0.15217$	1.781255	75
LE4	0.5625	3.625	$l=3.1167p+0.24502s+0.46885$	3.093768	43	5.125	$l=2.2727p+0.18182s+1.1364$	2.927981	55
TG4	0.4	5.625	$l=2.0362p+0.18611s+1.1971$	3.062544	44	7.75	$l=2.1685p+0.26421s+0.97812$	4.000024	8
EN1	0.3125	7.1875	$l=2.456p+0.36195s+0.32691$	3.062482	45	5	$l=2.7156p+0.29685s+0.42496$	3.65623	29
TCR2	0.56875	5.375	$l=2.3206p+0.1866s+1.0407$	3.031284	46	4.25	$l=2.0875p+0.28672s+0.73556$	3.15622	45
TCS5	0.54375	3.375	$l=2.1485p+0.21207s+1.0433$	3.031233	47	5.25	$l=2.6541p+0.22389s+0.75535$	3.187505	40
LE8	0.54375	3.3125	$l=2.483p+0.25441s+0.7673$	2.999985	48	4.3125	$l=1.8809p+0.24922s+1.0235$	2.843723	59
PL2	0.5375	3.3125	$l=2.0468p+0.18501s+1.1738$	2.999973	48	4.5	$l=2.6359p+0.20652s+0.94022$	3.156258	42
TL4	0.6	3.8125	$l=1.9118p+0.27059s+0.85$	2.906276	50	4.375	$l=2.178p+0.21259s+1.0412$	3.156247	44
TM4	0.46875	4.625	$l=1.8863p+0.25816s+1.0093$	2.906266	51	6.0625	$l=2.9284p+0.35082s+0.05304$	3.65628	26
LE2	0.46875	3.875	$l=2.7706p+0.23754s+0.63757$	2.906261	52	3.8125	$l=2.6163p+0.30814s+0.4593$	2.781255	61
EC3	0.6625	3.0625	$l=2.9994p+0.18899s+0.75188$	2.875023	53	2.6875	$l=4.4937p+0.24051s+0.14557$	2.281243	72
TL3	0.44375	4.375	$l=0.86987p+0.37907s+1.2157$	2.843758	54	5.3125	$l=2.782p+0.29132s+0.37744$	3.656283	25
TCR3	0.4125	4.75	$l=1.5185p+0.27778s+1.0667$	2.812531	55	4.375	$l=2.2382p+0.2279s+0.96459$	3.125038	46
TCR7	0.4125	4.6875	$l=1.6048p+0.22335s+1.226$	2.843731	55	4.125	$l=2.3684p+0.15526s+1.2079$	2.937471	54
TCS8	0.3625	4.9375	$l=4.2139p+0.47423s-1.326$	2.812524	55	4.0625	$l=2.9728p+0.27905s+0.2915$	3.656246	27
TG8	0.61875	2.875	$l=1.8352p+0.29224s+0.85803$	2.812495	58	4.4375	$l=0.10753p+0.15403s+2.3997$	3.093749	48
TCR1	0.4375	3.8125	$l=3.1113p+0.21146s+0.64055$	2.81248	59	4.3125	$l=2.9965p+0.33535s+0.19377$	2.656228	65
TCS7	0.6	2.8125	$l=2.4395p+0.29931s+0.63245$	2.78127	60	4.1875	$l=1.2956p+0.30142s+1.1396$	2.906282	55
SO1	0.44375	3.5625	$l=1.7292p+0.38599s+0.70311$	2.781258	61	4.25	$l=3.3733p+0.31378s-0.05009$	3.374987	35
TE1	0.56875	2.6875	$l=1.3346p+0.38614s+0.89447$	2.781249	62	4.5625	$l=3.8776p+0.35682s-0.58779$	3.343713	38

LE5	0.4375	3.375	$I=3.3022p+0.23056s+0.45751$	2.781233	63	4.4375	$I=3.0647p+0.25393s+0.40071$	2.933041	55
LE7	0.75	2.0625	$I=2.9176p+0.34533s+0.27679$	2.718729	64	5.0625	$I=1.1169p+0.33612s+1.2164$	2.999954	51
TM1	0.64375	2.5	$I=0.86043p+0.32745s+1.3181$	2.687491	65	4.75	$I=2.5957p+0.25258s+0.69772$	3.31249	39
TCS1	0.38125	3.5625	$I=3.0952p+0.36496s+0.051046$	2.531261	66	3.75	$I=2.384p+0.4346s+0.16002$	2.593748	66
SO2	0.55625	2.125	$I=0.50186p+0.3777s+1.387$	2.468772	67	2.625	$I=3.016p+0.29228s+0.30247$	2.687454	64
TM2	0.56875	1.9375	$I=4.1331E-16p+0.5s+1.5$	2.46875	68	6.1875	$I=2.6345p+0.20179s+0.92489$	3.750014	16
TCS9	0.56875	1.8125	$I=0.18817p+0.41129s+1.7366$	2.375041	69	3.5	$I=2.4404p+0.24334s+0.70037$	2.999963	50
TL2	0.54375	1.6875	$I=0.75812p+0.46931s+1.1083$	2.312488	70	3.4375	$I=1.7879p+0.26378s+1.0113$	2.937544	53
TG10	0.6	1.4375	$I=1.238p+0.52868s+0.65344$	2.156218	71	3.3125	$I=1.487p+0.25588s+1.2494$	2.999938	52
TE4	0.4625	1.6875	$I=3.6359p+0.49211s-0.41826$	2.093779	72	3.5625	$I=2.8513p+0.26021s+0.52394$	2.781263	60
TE3	0.425	1.8125	$I=3.9928p+0.42725s-0.50257$	1.968761	73	3.5	$I=0.47194p+0.3463s+1.5159$	2.687473	63
LE3	0.19375	3.5	$I=4.6622p+0.45355s-0.74071$	1.750016	74	5	$I=4.3125p+0.44375s-0.6125$	2.218774	73
TG1	0.24375	2.4375	$I=3.7222p+0.28704s-0.044444$	1.562502	75	2.8125	$I=1.6079P+0.068282S+3.0132$	1.718765	76
TE2	0.2625	1.9375	$I=3.8626p+0.40995s-0.46445$	1.343761	76	3.125	$I=4.4815p+0.46975s-0.72407$	1.90625	74

Table 6.38 lists the impact size of events on cost and time of highway project estimated by SRA models. For instance, the optimum probability of occurrence (0.84375) and severity (8.5625) value of latent ground conditions (TG11) were inserted on the developed cost SRA model ($I=1.6079P+0.068282S+3.0132$) and the impact size (4.97) of this event on the completion cost of highway construction projects was estimated.

Estimated impact size of disruptive events by SRA models revealed that the latent ground conditions (TG11) and inaccurate time and cost estimation (TCS6) were the two most impactful disruptive events, with catastrophic consequences on cost and time of highway construction projects. Likewise, the evaluation of the ANFIS, the RMSE, MAPE and correlation coefficient value of developed SRA models for cost and time of highway projects were calculated and are presented in Table 6.39.

Table 6.38: Evaluation of RSA cost and time of highway project performance models

Event	COST			TIME		
	RMSE	MAPE	R Value	RMSE	MAPE	R Value
EC1	0.213	0.0484	0.659	0.249	0.0525	0.846
EC2	0.246	0.0547	0.647	0.213	0.0576	0.882
EC3	0.268	0.0857	0.506	0.277	0.0952	0.821
EC4	0.247	0.0597	0.582	0.279	0.1043	0.807
EN1	0.301	0.0943	0.649	0.286	0.074	0.742
EN2	0.251	0.062	0.665	0.251	0.0621	0.626
EN3	0.228	0.0449	0.444	0.245	0.0619	0.746
EN4	0.222	0.0513	0.821	0.241	0.0646	0.868
FI1	0.253	0.0725	0.62	0.167	0.0706	0.954
FI2	0.254	0.0666	0.766	0.249	0.0667	0.761
FI3	0.249	0.0749	0.638	0.28	0.0847	0.587
FI4	0.241	0.0595	0.789	0.256	0.076	0.695

FI5	0.249	0.0623	0.739	0.231	0.0795	0.794
FI6	0.251	0.0613	0.785	0.253	0.0751	0.764
FI7	0.233	0.0535	0.799	0.206	0.0626	0.821
LE1	0.203	0.0472	0.851	0.25	0.0648	0.758
LE10	0.249	0.0535	0.856	0.259	0.0786	0.646
LE2	0.238	0.0607	0.801	0.256	0.0858	0.8
LE3	0.168	0.07	0.954	0.258	0.1179	0.797
LE4	0.243	0.0696	0.559	0.264	0.0752	0.803
LE5	0.321	0.1133	0.664	0.232	0.0702	0.61
LE6	0.278	0.0818	0.773	0.247	0.0697	0.837
LE7	0.28	0.0989	0.76	0.236	0.0669	0.731
LE8	0.244	0.072	0.644	0.25	0.0851	0.57
LE9	0.331	0.0959	0.78	0.253	0.0628	0.661
PL1	0.251	0.0633	0.718	0.251	0.0618	0.718
PL2	0.268	0.0761	0.78	0.257	0.0764	0.693
PL3	0.236	0.0502	0.803	0.255	0.0518	0.738
SO1	0.269	0.0868	0.694	0.243	0.0592	0.82
SO2	0.244	0.0668	0.784	0.272	0.0861	0.688
SO3	0.238	0.0554	0.782	0.24	0.0571	0.658
SO4	0.243	0.0618	0.782	0.262	0.0537	0.725
SO5	0.193	0.0337	0.816	0.245	0.0521	0.84
SO6	0.232	0.0539	0.739	0.258	0.0651	0.72
SO7	0.252	0.0559	0.61	0.256	0.0643	0.724
TCR1	0.166	0.0333	0.884	0.327	0.1214	0.724
TCR2	0.254	0.0733	0.615	0.254	0.0729	0.558
TCR3	0.26	0.0856	0.754	0.265	0.074	0.728
TCR4	0.253	0.0657	0.765	0.253	0.0632	0.661
TCR5	0.244	0.0604	0.748	0.237	0.0553	0.613
TCR6	0.267	0.0705	0.693	0.262	0.0776	0.693
TCR7	0.254	0.0811	0.785	0.276	0.0874	0.624
TCS1	0.28	0.0921	0.772	0.296	0.1009	0.738
TCS2	0.214	0.0503	0.833	0.27	0.0743	0.771
TCS3	0.248	0.0605	0.768	0.259	0.0669	0.7
TCS4	0.233	0.0486	0.842	0.253	0.0635	0.691
TCS5	0.25	0.079	0.73	0.256	0.075	0.724
TCS6	0.255	0.0524	0.81	0.249	0.0481	0.671
TCS7	0.281	0.0829	0.694	0.25	0.0824	0.615
TCS8	0.269	0.0931	0.752	0.282	0.0724	0.75
TCS9	0.155	0.0328	0.907	0.195	0.0478	0.451
TE1	0.25	0.084	0.757	0.268	0.0696	0.814
TE2	0.215	0.1304	0.855	0.159	0.0635	0.942
TE3	0.216	0.0733	0.896	0.293	0.0997	0.772
TE4	0.207	0.0812	0.858	0.285	0.0982	0.569
TG1	0.23	0.155	0.844	0.212	0.1162	0.875
TG10	0.195	0.0821	0.865	0.244	0.0638	0.784
TG11	0.145	0.0163	0.367	0.19	0.0278	0.441
TG2	0.241	0.0657	0.786	0.265	0.0621	0.826

TG3	0.25	0.0664	0.77	0.283	0.0689	0.793
TG4	0.26	0.0764	0.768	0.248	0.0557	0.703
TG5	0.259	0.0701	0.755	0.261	0.0533	0.694
TG6	0.291	0.0787	0.767	0.237	0.0551	0.832
TG7	0.255	0.0718	0.726	0.28	0.0999	0.773
TG8	0.237	0.0687	0.594	0.27	0.0787	0.802
TG9	0.257	0.0649	0.649	0.252	0.0556	0.705
TL1	0.252	0.0662	0.769	0.286	0.0729	0.703
TL2	0.16	0.0416	0.892	0.272	0.0828	0.634
TL3	0.281	0.0829	0.742	0.243	0.0533	0.815
TL4	0.275	0.0801	0.749	0.261	0.0723	0.761
TM1	0.24	0.0649	0.777	0.224	0.0572	0.867
TM2	0	6.94E-17	1	0.257	0.066	0.68
TM3	0.215	0.053	0.866	0.248	0.062	0.789
TM4	0.252	0.0768	0.63	0.254	0.065	0.741
TT1	0.255	0.0657	0.761	0.259	0.0664	0.739
TT2	0.261	0.0717	0.753	0.236	0.0564	0.766

The low value of two error tests proved the reliability of the developed models to estimate the impact of disruptive events on cost and time of a construction project. However, the fitness of the estimated impact size to real data varied from 0.367 to 1 for estimated impact cost and 0.442 to 0.954 for estimated impact time.

Further interrogation of the correlation coefficient value revealed that the 55 SRA-developed models on cost and 52 developed models on time were able to estimate the impact size of these events with a high degree of fit ($r > .7$) to the real impact size. Likewise, 22 SRA-developed models of cost and 19 developed models of time estimated the impact of these events, with a moderate fit ($.7 > r > .5$) of the real impact size. However, two SRA-developed models on cost and two models on time estimated the impact size of events, with a poor degree of fit ($.5 > r$) to the real size of the impact of events on the cost and time of a highway project.

The comparison of the performance of classical statistics in predicting the impact size of disruptive events on the cost and time of highway projects, with machine learning techniques, showed that the error values of ANFIS models in predicting the impact sizes were much smaller than the error values of SRA models. This verified that the predicted impact sizes using ANFIS models were more reliable than the SRA models. Furthermore, the correlation coefficient value of ANFIS models was significantly closer to 1 compared to SRA models, which showed that the accuracy of ANFIS models in predicting impact size was extremely high.

Thus, the performance comparison proved that ANFIS is a very accurate tool for predicting the impact of disruptive events on construction projects' time and cost. Therefore, the predicted impact size of intelligent machine learning was used to model and simulate the cost and time of disruptive events on all three structures of the highway construction project.

6.4.2.4 *Modelling the occurrence of disruptive events on construction of the highway project*

The effect values of disruptive events on cost and time of structures of a highway project were estimated by the highway expert panel based on the five groups of predicted impact sizes of events on cost and time from ANFIS models (See Table 6.34). The effect values obtained are presented in Table 6.39.

Table 6.39: Effect values of disruptive events on the cost and time of a construction project

Structure	Event impact	Impact size	Effect value on the cost	Effect value on time
Earth work	Minimal	$1 \leq 1$	1.0%	3.0%
	Low	$1 < 1 \leq 2$	3.0%	5.0%
	Moderate	$2 < 1 \leq 3$	5.0%	7.0%
	High	$3 < 1 \leq 4$	7.0%	10.0%
	Extreme	$4 < 1 \leq 5$	10.0%	15.0%
Bridge	Minimal	$1 \leq 1$	1%	1.0%
	Low	$1 < 1 \leq 2$	2%	2.0%
	Moderate	$2 < 1 \leq 3$	3%	4.0%
	High	$3 < 1 \leq 4$	4%	6.0%
	Extreme	$4 < 1 \leq 5$	5%	10.0%
Pavement	Minimal	$1 \leq 1$	0.5%	1.5%
	Low	$1 < 1 \leq 2$	1.0%	3%
	Moderate	$2 < 1 \leq 3$	1.5%	4%
	High	$3 < 1 \leq 4$	2%	5%
	Extreme	$4 < 1 \leq 5$	4%	7%

Table 6.39 shows that the highway expert panel estimated the effect values of disruptive events for five degrees of impact in the three structures of the highway project based on the historical data of three-comparative highway projects. For instance, if the disruptive events with predicted minimal impact size on cost and time occurred on the earthwork structure, it increased the cost of the structure by 1% and extended the time by 3%.

6.4.2.5 *Simulation of the effect of the cost and time of disruptive events on the highway structures*

The construction time and cost of three structures and the overall highway project were simulated by considering the variability in the construction process and the correlations between the times and costs of the activities in Sections 6.2 and 6.3. In this section, effect of the time and cost of disruptive events on the different structures of the highway project were simulated by using the ANFIS-predicted impact size and effect value of events estimated by the experts. For instance, if the latent ground conditions (TG11) occurred on the earthwork structure, the cost and time of this

structure were increased by ZAR7,095,270.00 and 51 days. The predicted cost increase and time expansion were added to the cost and time of the structure and were utilised as input to simulate the cost and time of disruptive events.

The total time and cost of highway structures were obtained from a simulated Monte Carlo analysis, equal to the structure’s volume runs. The mean, 90th percentile and standard deviation of the simulation result of each structure and overall project are summarised in Table 6.40.

Table 6.40: The distribution parameters of disruptive events

		Earthwork	Bridge	Pavement	Overall Project
Deterministic	Cost	244,292,292.83	70,952,700.00	494,259,930.00	809,504,922.80
	Time	215	340	217	340
Mean	Cost	354,312,747.94	89,142,843.70	630,565,944.98	1,038,796,512.20
	Time	354.12	474.56	287.74	473.85
Standard Deviation	Cost	42,359,044.36	6,793,815.23	27,539,618.81	86,913,377.51
	Time	52.80	52.25	26.94	51.86
90th Percentile	Cost	407,968,130.11	97,914,726.00	667,250,905.50	1,154,839,722.87
	Time	425.70	544.00	323.33	544.00

The scatterplots of the simulations of the earthwork, bridge, and pavement structures and the overall highway project are plotted in Figures 6.55-6.58, respectively.

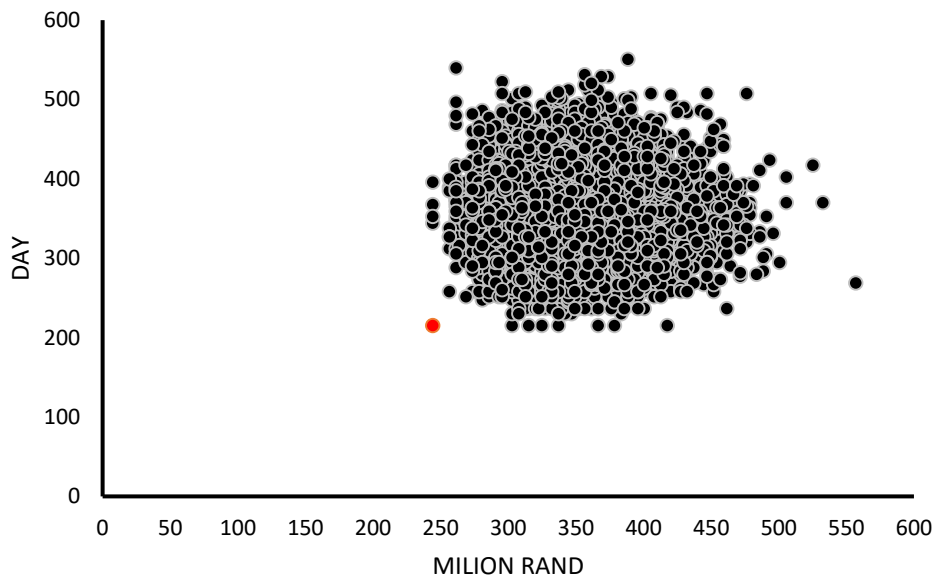


Figure 6.55: Scatterplot of total cost and total time of disruptive events on the earthwork structure

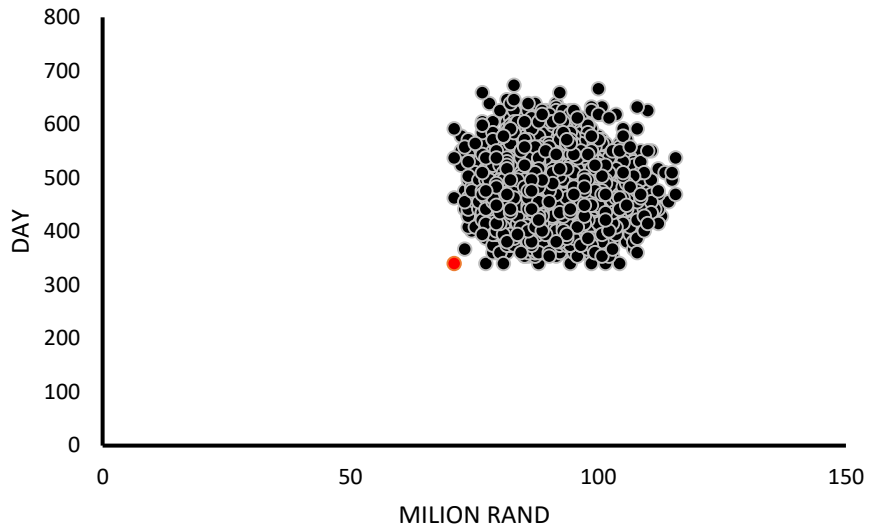


Figure 6.56: Scatterplot of total cost and total time of disruptive events on the bridge structure

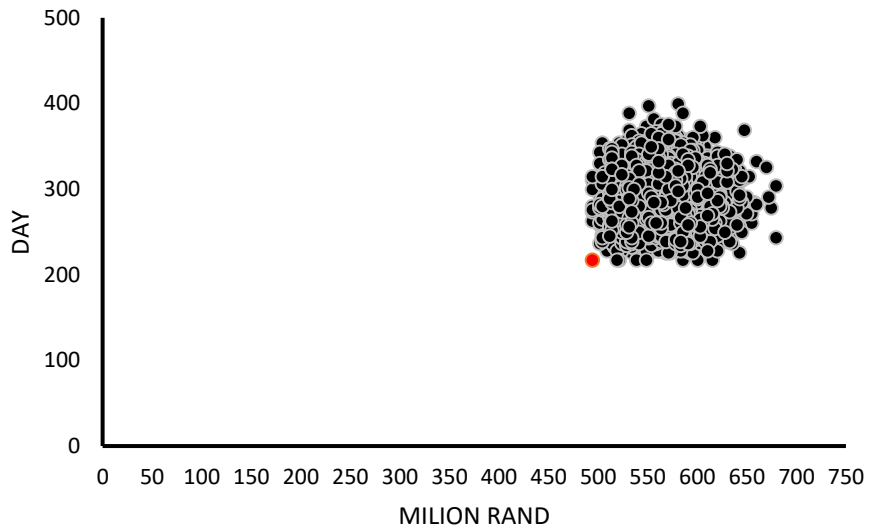


Figure 6.57: Scatterplot of total cost and total time of disruptive events on the pavement structure

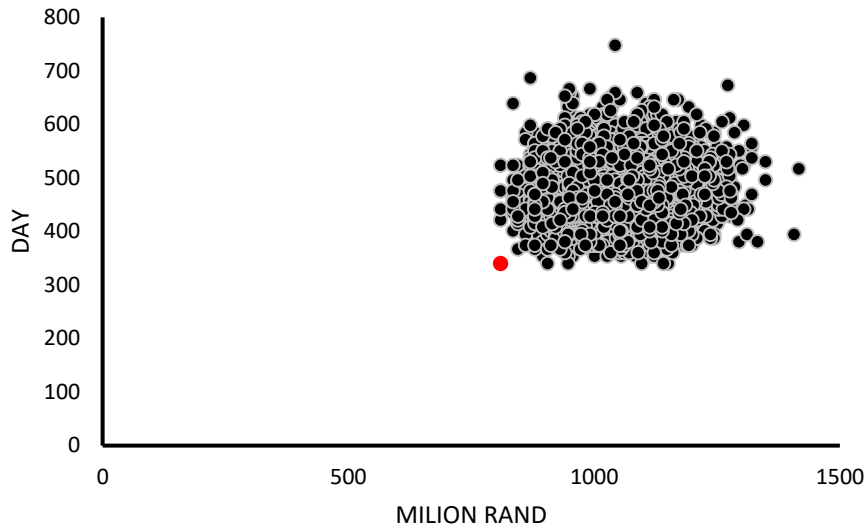


Figure 6.58: Scatterplot of total cost and total time of disruptive events on the overall construction project

From the analysis of the simulation results of disruptive events, the following were inferred:

- (i) The disruptive events had an impact on time and cost of the structure: the cost and time of the structures, where the disruptive event occurred, were significantly larger than the time and cost of a structure where the disruptive event did not occur. The increase in total cost and total time were visible in the scatterplots, that is, the black clouds versus the red dots.
- (ii) The total cost and the total time of structures were increased with different magnitudes (Figure 6.58) because of the different probability occurrence models generated with the Markov process.

6.5 CUMULATIVE IMPACTS OF THE UNCERTAINTY MODEL ON CONSTRUCTION COST AND TIME OF PROJECTS

In this section, the deterministic total cost and total time and the 90th percentiles (decision statistic point) of the total cost and total time distributions of all three structures of the highway construction project were compared to present the results of cumulative impacts of the uncertainty model on total construction time and cost of the project.

The increase in total cost and total time, due to the cumulative impacts of three sources of uncertainty in the construction of each structure of the highway project, was quantified by comparing the 90th percentiles of the total cost and total time distributions with the deterministic total cost and total time. The deterministic total cost and total time, the 90th percentiles of the total cost and total time distributions, and the increases in total cost and total time of each structure and the overall project are summarised in Table 6.41.

Table 6.41: Impact of uncertainty sources on construction cost and time

	Uncertainty source	Cost			Time		
		Deterministic	P90th	Increased P90th	Deterministic	P90th	Increased P90th
Earthwork	Variability	244,292,292.83	258,410,039.21	5.78%	215	228.76	6.40%
	Variability and Correlation		298,968,508.46	22.38%		254.45	18.35%
	Variability, Correlation and Disruptive events		407,968,130.11	67.00%		425.7	98.00%
Bridge	Variability	70,952,700.00	76,883,575.67	8.36%	340	369.48	8.67%
	Variability and Correlation		86,205,928.64	21.50%		396.52	16.62%
	Variability, Correlation and Disruptive events		97,914,726.00	38.00%		544	60.00%
Pavement	Variability	494,259,930.00	517,582,030.41	4.72%	217	228.53	5.31%
	Variability and Correlation		612,440,433.36	23.91%		241.64	11.35%
	Variability, Correlation and Disruptive events		667,250,905.50	35.00%		323.33	49.00%
Overall Project	Variability	809504922.8	841,927,264.18	4.01%	340	368.64	8.42%
	Variability and Correlation		962,076,539.65	18.85%		395.32	16.27%
	Variability, Correlation and Disruptive events		1,154,839,722.87	42.66%		544	60.00%

Key: P90th: 90th Percentile

The impact of sources of uncertainty on total cost and total time of each structure and overall project are in Figures 6.59 to 6.60.

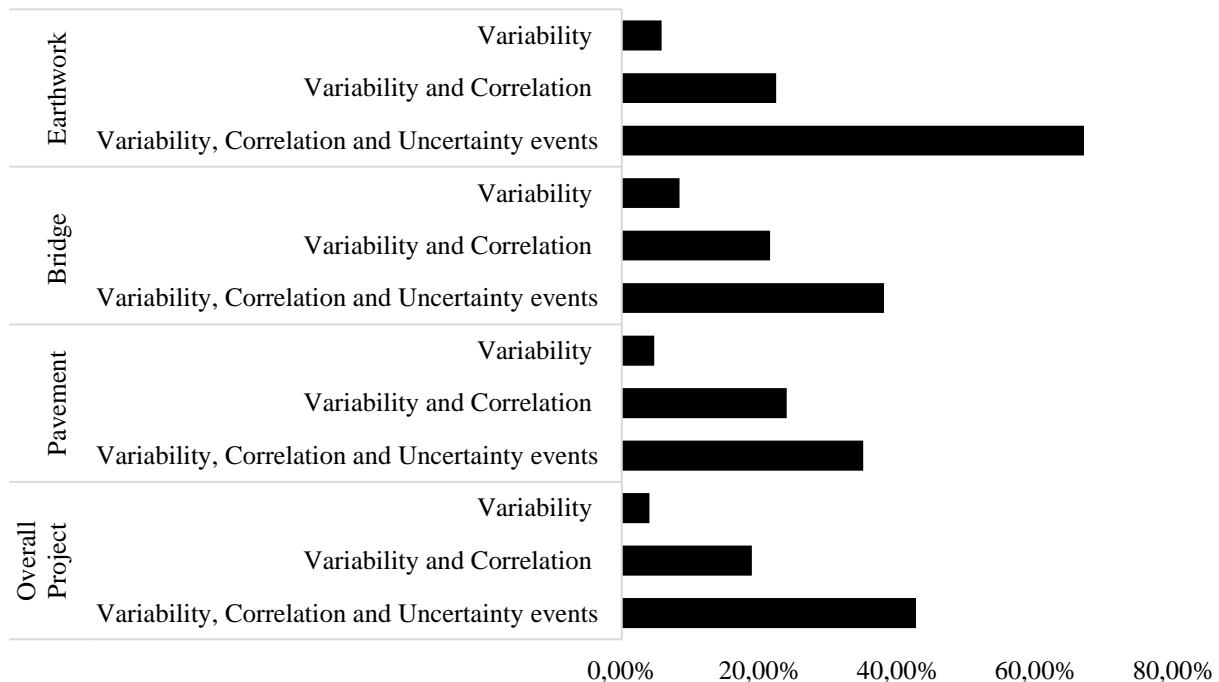


Figure 6.59: The impact of sources of uncertainty on total cost of the different structures and the overall construction project

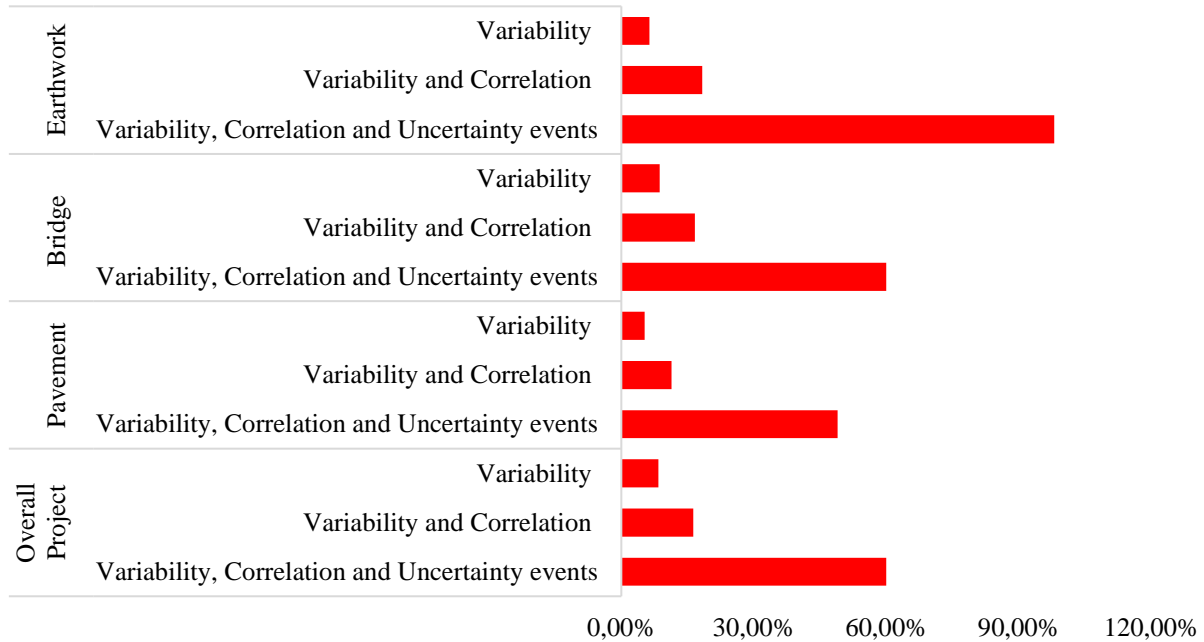


Figure 6.60: The impact of sources of uncertainty on the total time of the different structures and the overall construction project

Table 6.41 and Figures 6.59 and 6.60 established that the cumulative impact of all sources of uncertainty (variability, correlations, disruptive events) caused the largest increase on total cost and total time of the three highway structures and the overall project. For instance, the cumulative impact of the three sources of uncertainty on the total cost of the overall project was 42.66%, while the impact of variability and impact of correlation on the total cost of the overall project were 4.01% and 18.85%, respectively. Similarly, the cumulative impact of uncertainties on the total time of the overall project was 60%, while the impact of variability and correlation on the total time of the overall project were 8.42% and 16.27%, respectively.

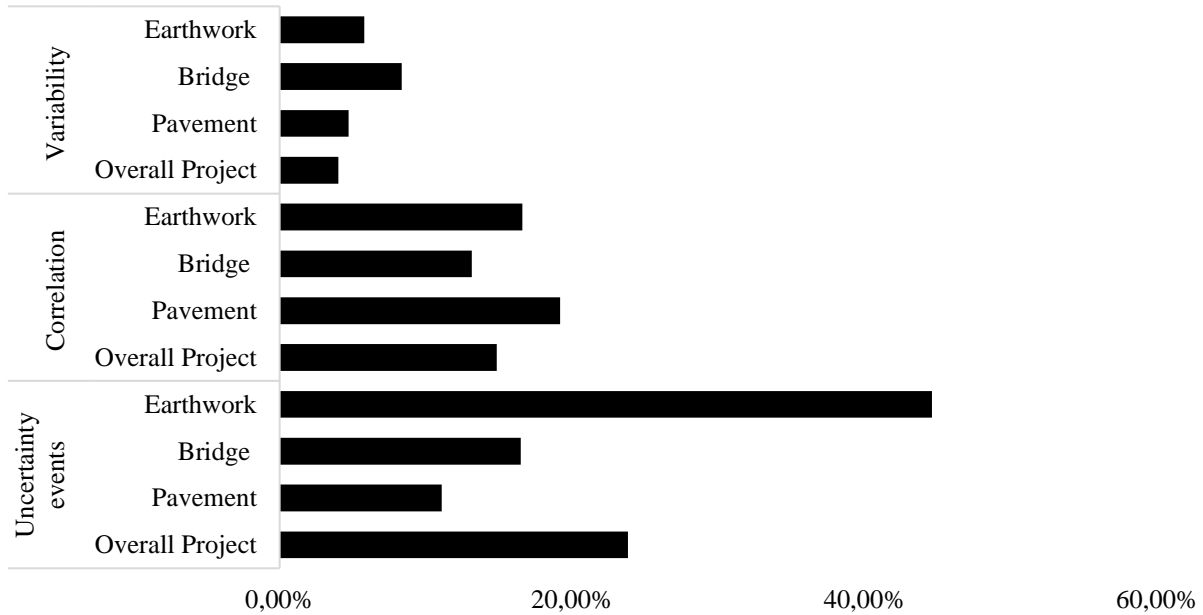


Figure 6.61: The impact of each source of uncertainty on total cost of the highway structures and the overall project

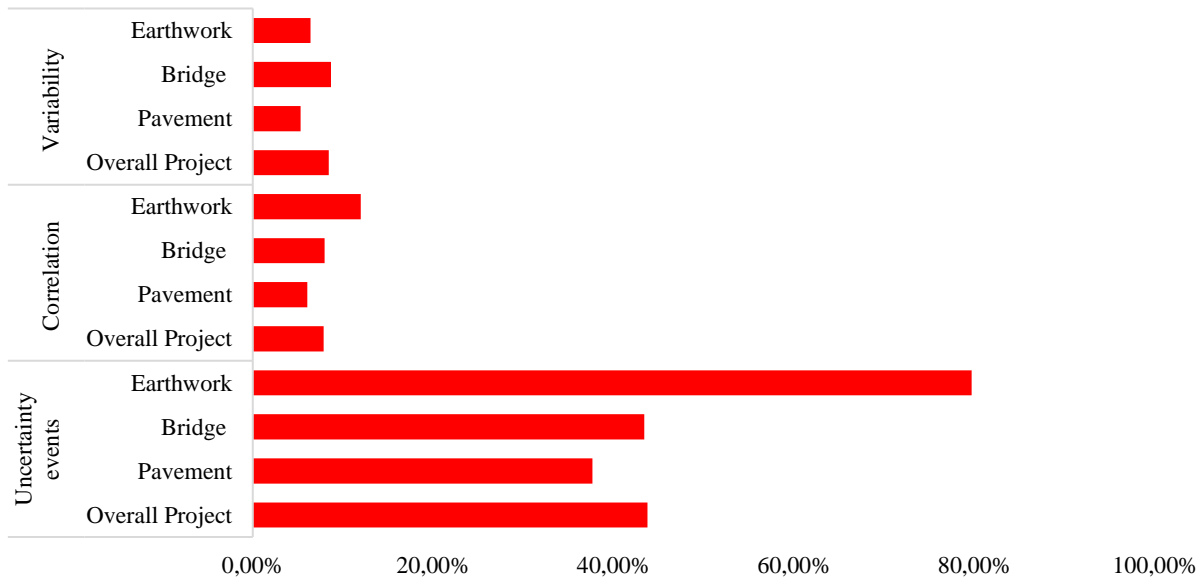


Figure 6.62: The impact of each source of uncertainty on the total time of the highway structures and the overall project

Further insight into the results of uncertainty models by considering the impact of three sources of uncertainty on construction cost and duration of each structure, and overall project, confirmed that the relevance of a source of uncertainty and its impact were dependent on the type of structure. The largest impact due to variability was observed on the total cost and total time of the bridge structure by 8.36% and 8.67%, respectively. The largest impact due to variability and correlations

was realised on the total cost of the pavement structure by 23.91% and the total time of the earthwork structure by 18.35%. The largest cumulative impact (variability, correlation and disruptive events) on total cost and total time was observed on the construction of the earthwork, for which the uncertainty cost was 67% and uncertainty time was 98% larger than the deterministic cost and time of construction due to the high impact of disruptive events in the earthwork structure.

6.6 TEST OF RESEARCH HYPOTHESES

This section presents the results of the research hypotheses outlined. Due to using the random samples and not normal distribution (lognormal, triangular), on generating the cost and time, Chi-square and Wilcoxon signed rank tests (non-parametric) were employed to test the research hypotheses.

6.6.1 The association between the characteristics of infrastructure projects and the cost and time of infrastructure projects

In order to address Research Objective 2 to determine the association between the characteristics of infrastructure projects and cost and time of infrastructure projects the Chi-square test was conducted to answer two sub-sets of Hypothesis 1.

Hypothesis 1: There is a significant association between project characteristics, cost and duration of infrastructure projects.

Null Hypothesis 1.1: There is no significant association between project characteristics and cost of infrastructure projects.

Alternative Hypothesis 1.1: There is a significant association between project characteristics and cost of infrastructure projects.

Null Hypothesis 1.2: There is no significant association between project characteristics and duration of infrastructure projects.

Alternative Hypothesis 1.2: There is a significant association between project characteristics and duration of infrastructure projects.

The difference between the initial estimation and the actual construction cost and duration of three main structures of infrastructure projects in the scale of data analysis (every 100 linear metres for earthwork and pavement structures and unit for bridge structure repeated over 16.5 kilometre infrastructure project) were fitted to the two Chi-square test and examined to ascertain whether there is a significant association between the characteristics of three highway structures and the cost and duration of each structure. The results of the two Chi-square test are presented in subsequent subsections.

Table 6.42: Chi-square test of hypothesis 1.1**Characteristics of Estimation of cost crosstabulation**

			Cost Estimation			Total
			Underestimation	Exact	Overestimation	
Structure	Earthwork	Count	155	9	1	165
		Expected Count	154.8	8.4	1.8	165.0
		% within Structure	93.9%	5.5%	0.6%	100.0%
		% within Cost	44.4%	47.4%	25.0%	44.4%
		% of Total	41.7%	2.4%	0.3%	44.4%
	Bridge	Count	36	6	0	42
		Expected Count	39.4	2.1	.5	42.0
		% within Structure	85.7%	14.3%	0.0%	100.0%
		% within Cost	10.3%	31.6%	0.0%	11.3%
		% of Total	9.7%	1.6%	0.0%	11.3%
	Pavement	Count	158	4	3	165
		Expected Count	154.8	8.4	1.8	165.0
		% within Structure	95.8%	2.4%	1.8%	100.0%
		% within Cost	45.3%	21.1%	75.0%	44.4%
		% of Total	42.5%	1.1%	0.8%	44.4%
Total	Count	349	19	4	372	
	Expected Count	349.0	19.0	4.0	372.0	
	% within Structure	93.8%	5.1%	1.1%	100.0%	
	% within Cost	100.0%	100.0%	100.0%	100.0%	
	% of Total	93.8%	5.1%	1.1%	100.0%	

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	11.289 ^a	4	.024
Likelihood Ratio	9.938	4	.041
Linear-by-Linear Association	.034	1	.854
N of Valid Cases	372		

a. 4 cells (44.4%) have expected count less than 5. The minimum expected count is .45.

Symmetric Measures

		Value	Approx. Sig.
Nominal by Nominal	Phi	.374	.024
	Cramer's V	.323	.024
N of Valid Cases		372	

Since the assumption of the Pearson Chi-square was violated (4 cells (44.4%) have expected count less than 5), the results of the Likelihood Ratio are considered to evaluate the result of the Chi-square test for cost. $G^2(4, n=372) = 9.938$, $\rho = .041$, $\Phi = .374$ (See Table 6.42).

Based on the deductions from Table 6.42, the ρ -value was less than the α -value, therefore the null hypothesis was rejected, and alternative hypothesis was accepted. The results of the Chi-square test supported the alternative hypothesis 1.1, which proved that there is a significant association

between project characteristics and cost of infrastructure projects with the medium effect ($.50 > \Phi = .374 > .30$) (Cohen, 1988).

6.6.1.2 Test of Hypothesis 1.2

Table 6.43: Chi-square test of hypothesis 1.2

Characteristics of Estimation of duration crosstabulation

			Time Estimation			Total
			Underestimation	Exact	Overestimation	
Structure	Earthwork	Count	151	11	3	165
		Expected Count	152.6	8.4	4.0	165.0
		% within Structure	91.5%	6.7%	1.8%	100.0%
		% within Time	43.9%	57.9%	33.3%	44.4%
		% of Total	40.6%	3.0%	.8%	44.4%
	Bridge	Count	35	5	2	42
		Expected Count	38.8	2.1	1.0	42.0
		% within Structure	83.3%	11.9%	4.8%	100.0%
		% within Time	10.2%	26.3%	22.2%	11.3%
		% of Total	9.4%	1.3%	.5%	11.3%
	Pavement	Count	158	3	4	165
		Expected Count	152.6	8.4	4.0	165.0
		% within Structure	95.8%	1.8%	2.4%	100.0%
		% within Time	45.9%	15.8%	44.4%	44.4%
		% of Total	42.5%	.8%	1.1%	44.4%
Total	Count	344.0	19.0	9.0	372.0	
	Expected Count	92.5%	5.1%	2.4%	100.0%	
	% within Structure	100.0%	100.0%	100.0%	100.0%	
	% within Time	92.5%	5.1%	2.4%	100.0%	
	% of Total	344.0	19.0	9.0	372.0	

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	9.867 ^a	4	.043
Likelihood Ratio	9.736	4	.045
Linear-by-Linear Association	.789	1	.375
N of Valid Cases	372		

a. 4 cells (44.4%) have expected count less than 5. The minimum expected count is 1.02.

Symmetric Measures

		Value	Approx. Sig.
Nominal by Nominal	Phi	0.363	0.043
	Cramer's V	0.315	0.043
N of Valid Cases		372	

Since the assumption of the Pearson Chi-Square (4 cells (44.4%) have expected count less than 5) was violated, therefore the results of the Likelihood Ratio are considered to evaluate the result of the test. $G^2(4, n=372) = 9.736, p = .045, \Phi = .363$ (See Table 6.43).

Based on the deductions from Table 6.43, the p -value was less than α -value the null hypothesis was rejected, and alternative hypothesis was accepted. The results of the Chi-Square independent test supported the Alternative Hypothesis 1.2, which proved that there is a significant association between project characteristics and duration of infrastructure projects, with the medium effect ($.50 > \Phi = .363 > .30$) (Cohen, 1988).

The results of two Chi-square tests proved that “*There is a significant association between project characteristics, cost and duration of infrastructure projects.*”

6.6.2 The association between the impacts of different sources of uncertainty and the cost of infrastructure projects

In order to address research Objective 4 to determine the association between the impacts of different sources of uncertainty and the cost and time of infrastructure projects the, Chi-square tests were conducted to answer the two sub-sets of Hypothesis 2.

Hypothesis 2: There is a significant association between the impacts of different sources of uncertainty, cost and duration of infrastructure projects.

Null Hypothesis 2.1: There is no significant association between the impacts of different sources of uncertainty and cost of infrastructure projects.

Alternative Hypothesis 2.1: There is a significant association between the impacts of different sources of uncertainty and cost of infrastructure projects.

Null Hypothesis 2.2: There is no significant association between the impacts of different sources of uncertainty and duration of infrastructure projects.

Alternative Hypothesis 2.2: There is a significant association between the impacts of different sources of uncertainty and duration of infrastructure projects.

The difference of the initial estimation cost and time of highway project and the forecasted impacts of three sources of uncertainty on the cost and time of the highway project in the scale of data analysis (100 linear metres for earthwork and pavement structures, and the unit for the bridge structure was repeated over 16.5 kilometre of the infrastructure project) were fitted to the two Chi-square tests and examined to ascertain whether there is a significant association between the impacts of different sources of uncertainty and the cost and time of a highway project. The results of the two Chi-square tests are presented in subsequent subsections.

Table 6.44: Chi-square test of Hypothesis 2.1**Uncertainty * Impact on Cost crosstabulation**

			Cost impact		Total
			Yes	No	
Sources of uncertainty	Variability	Count	155	10	165
		Expected count	151.7	13.3	165.0
		% within uncertainty	93.9%	6.1%	100.0%
		% within impact	34.1%	25.0%	33.3%
		% of Total	31.3%	2.0%	33.3%
	Correlation	Count	140	25	165
		Expected count	151.7	13.3	165.0
		% within uncertainty	84.8%	15.2%	100.0%
		% within impact	30.8%	62.5%	33.3%
		% of Total	28.3%	5.1%	33.3%
	Disruptive events	Count	160	5	165
		Expected count	151.7	13.3	165.0
		% within uncertainty	97.0%	3.0%	100.0%
		% within impact	35.2%	12.5%	33.3%
		% of Total	32.3%	1.0%	33.3%
Total	Count	455	40	495	
	Expected count	455.0	40.0	495.0	
	% within uncertainty	91.9%	8.1%	100.0%	
	% within impact	100.0%	100.0%	100.0%	
	% of Total	91.9%	8.1%	100.0%	

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	17.679 ^a	2	.000
Likelihood Ratio	17.312	2	.000
Linear-by-Linear Association	1.018	1	.313
N of Valid Cases	495		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 13.33.

Symmetric Measures

		Value	Approx. Sig.
Nominal by Nominal	Phi	.589	.000
	Cramer's V	.589	.000
N of Valid Cases		495	

Based on the deductions from Chi-square test result ($\chi^2(4, n=495) = 17.679, \rho = .000, \text{Phi} = .589$) (See Table 6.44), the ρ -value was less than α -value, therefore the null hypothesis was rejected, and the alternative hypothesis was accepted. The results of the Chi-Square test supported the Alternative Hypothesis 2.1, which proved that there is a significant association between the

impacts of different sources of uncertainty and cost of infrastructure projects with the high effect (Phi=.589>.50) (Cohen, 1988).

6.6.2.2 Test of Hypothesis 2.2

Table 6.45: Chi-square test of Hypothesis 2.2

Uncertainty * Impact on duration crosstabulation

			Time impact		Total
			Yes	No	
Sources of uncertainty	Variability	Count	156	9	165
		Expected count	153.0	12.0	165.0
		% within uncertainty	94.5%	5.5%	100.0%
		% within impact	34.0%	25.0%	33.3%
		% of Total	31.5%	1.8%	33.3%
	Correlation	Count	145	20	165
		Expected count	153.0	12.0	165.0
		% within uncertainty	87.9%	12.1%	100.0%
		% within impact	31.6%	55.6%	33.3%
		% of Total	29.3%	4.0%	33.3%
	Disruptive events	Count	158	7	165
		Expected count	153.0	12.0	165.0
		% within uncertainty	95.8%	4.2%	100.0%
		% within impact	34.4%	19.4%	33.3%
		% of Total	31.9%	1.4%	33.3%
Total	Count	459	36	495	
	Expected count	459.0	36.0	495.0	
	% within uncertainty	92.7%	7.3%	100.0%	
	% within impact	100.0%	100.0%	100.0%	
	% of Total	92.7%	7.3%	100.0%	

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	8.807 ^a	2	.012
Likelihood Ratio	8.355	2	.015
Linear-by-Linear Association	.179	1	.672
N of Valid Cases	495		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 12.00.

Symmetric Measures

		Value	Approx. Sig.
Nominal by Nominal	Phi	.533	.012
	Cramer's V	.533	.012
N of Valid Cases		495	

Based on the deductions from Chi-square test result ($\chi^2(2, n=495) = 8.807, \rho = .012, \text{Phi} = .533$) (See Table 6.45), the ρ -value was less than α -value the null hypothesis was rejected, and alternative hypothesis was accepted. The results of the Chi-Square independent test supported the Alternative

Hypothesis 2.2, which proved that there is a significant association between the impacts of different sources of uncertainty and duration of infrastructure projects, with the high effect ($\Phi=.533>.50$) (Cohen, 1988).

The results of the two Chi-square tests proved that “*There is a significant association between the impacts of different sources of uncertainty, cost and duration of infrastructure projects.*”

6.6.3 The difference between the estimations of cost and time and actual cost and time of the construction of infrastructure projects

To address Research Objective 6, to find out whether the uncertainty model is able to improve the accuracy of the estimation of cost and time of infrastructure projects required the testing of the two sets of Hypotheses 3.1, 3.2 and their sub-sets.

Hypothesis 3.1: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using uncertainty model.

Null Hypothesis 3.1.1: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using variability model.

Alternative Hypothesis 3.1.1: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using variability model.

Null Hypothesis 3.1.2: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using correlation model.

Alternative Hypothesis 3.1.2: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using correlation model.

Null Hypothesis 3.1.3: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using disruptive events model.

Alternative Hypothesis 3.1.3: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using disruptive events model.

Hypothesis 3.2: There is a significant difference between the accuracy of estimations of construction cost and duration by deterministic methods and the uncertainty model.

Null Hypothesis 3.2.1: There is no significant difference between the initial estimations of construction cost and duration and actual construction cost and duration.

Alternative Hypothesis 3.2.1: There is a significant difference between the initial estimations of construction cost and duration and actual construction cost and duration.

Null Hypothesis 3.2.2: There is no significant difference between the uncertainty estimations of construction cost and duration and actual construction cost and duration.

Alternative Hypothesis 3.2.2: There is a significant difference between the uncertainty estimations of construction cost and duration and actual construction cost and duration.

6.6.3.1 Test of hypothesis 3.1

The results of modelling variability (Table 6.10), correlation cost and time (Table 6.32) and disruptive events (Table 6.40) were fitted to the Wilcoxon signed rank tests and examined to ascertain whether there is a significant difference in construction cost and duration of the highway project before and after applying each of the uncertainty models. The results of the three Wilcoxon signed rank tests are presented in subsequent subsections.

Test of hypothesis 3.1.1

Table 6.46: Wilcoxon signed rank tests of Hypothesis 3.1.1

	Percentiles		
	25th	50th (Median)	75th
Deterministic Cost	114287598.21	369276111.42	730693674.60
Deterministic Time	215.50	278.50	340.00
Variability Cost	122265191.56	387996034.8100	760840955.74
Variability Time	228.59	299.12	369.60

Test Statistics ^a

	Variability Cost - Deterministic Cost	Variability Time - Deterministic Time
Z	-4.123 ^a	-4.123 ^a
Asymp. Sig. (2-tailed)	.000	.000

a. Wilcoxon signed ranks test

A Wilcoxon signed rank test revealed a statistically significant increase in construction cost and time of the project after applying the variability ($Z=-4.123$, $p=.000$). with the large effect size ($r=0.70709$) (See Table 6.46). The median score on the construction cost and time increased from deterministic cost and time ($Md_c=369276111.4150$, $Md_t=278.5$) to variability of cost and time ($Md_c=387996034.81$, $Md_t=299.12$), therefore the null hypothesis was rejected, and the alternative hypothesis was accepted. The results of the Wilcoxon signed rank test supported the Alternative Hypothesis 3.1.1, which proved that there is a significant difference between the estimated and forecasted construction cost and duration of the infrastructure project, using the variability model.

Test of hypothesis 3.1.2

A Wilcoxon Signed-rank test revealed a statistically significant increase in construction cost and time of the project after applying the correlation ($Z=-3.000$, $p=.003$), with the large effect size ($r=0.70711$) (See Table 6.47). The median score on the construction cost and time increased from deterministic cost and time ($Md_c=369276111.4150$, $Md_t=278.5$) to correlated cost and time ($Md_c=455704470.91$, $Md_t=324.885$), therefore the null hypothesis was rejected, and the alternative

hypothesis was accepted. The results of the Wilcoxon signed rank test supported the Alternative Hypothesis 3.1.2, which proved that there is a significant difference between the estimated and predicted construction cost and duration of an infrastructure project, using a correlational model.

Table 6.47: Wilcoxon signed rank tests of Hypothesis 3.1.2

	Percentiles		
	25th	50th (Median)	75th
Deterministic Cost	114287598.21	369276111.42	730693674.60
Deterministic Time	215.50	278.50	340.00
Correlation Cost	139396573.60	455704470.91	874667513.08
Correlation Time	244.84	324.89	396.22

Test Statistics ^a

	Correlation Cost - Deterministic Cost	Correlation Time - Deterministic Time
Z	-3.000 ^b	-3.000 ^b
Asymp. Sig. (2-tailed)	.003	.003

a. Wilcoxon signed rank test

b. Based on negative ranks

Test of hypothesis 3.1.3

Table 6.48: Wilcoxon signed rank tests of Hypothesis 3.1.3

	Percentiles		
	25th	50th (Median)	75th
Deterministic Cost	114287598.21	369276111.42	730693674.60
Deterministic Time	215.50	278.50	340.00
Disruptive events Cost	175428077.03	537609517.81	1032942518.53
Disruptive events Time	348.92	484.85	544.00

Test Statistics ^a

	Disruptive events Cost - Deterministic Cost	Disruptive events Time - Deterministic Time
Z	-3.742 ^b	-3.742 ^b
Asymp. Sig. (2-tailed)	.000	.000

a. Wilcoxon signed ranks test

b. Based on negative ranks

A Wilcoxon signed rank test revealed a statistically significant increase in construction cost and time of the project after applying the disruptive events ($Z=-3.742$, $\rho=.000$), with the large effect size ($r=0,70717$) (See Table 6.48). The median score on the construction cost and time increased from deterministic cost and time ($Md_c= 369276111.4150$, $Md_t=278.5$) to variability of cost and time ($Md_c=537609517.8050$, $Md_t=484.85$), therefore null hypothesis was rejected, and alternative hypothesis was accepted. The results of the Wilcoxon signed rank test supported the Alternative

Hypothesis 3.1.3, which proved that there is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using disruptive events model.

The results of the three Wilcoxon signed rank tests proved that “*There is a significant difference in the construction cost and duration of an infrastructure project before and after applying uncertainty modelling*”.

6.6.3.2 Test of hypothesis 3.2

The initial estimation of construction cost and time (Table 5.1), the predicted estimation of construction cost and time by the uncertainty model (Table 6.42) and the actual construction cost and time (Table 5.1) were fitted to the Wilcoxon signed rank tests and examined to find whether there is a significant difference between actual construction cost and duration (correct cost and time) and the deterministic estimation and the uncertainty estimation. The results of the three Wilcoxon signed rank tests are shown in Tables 6.49 and 6.50.

Test of hypothesis 3.2.1

Table 6.49: Wilcoxon signed rank tests of Hypothesis 3.2.1

	Percentiles		
	25th	50th (Median)	75th
Initial Cost Estimation	114287598.21	369276111.42	730693674.60
Initial Time Estimation	215.50	278.50	340.00
Actual Cost	176366376.75	538352944.00	1032140520.50
Actual Time	346.25	485.50	537.00

Test Statistics ^a

	Actual Cost – Deterministic Cost Estimation	Actual Time – Deterministic Time Estimation
Z	-1.826 ^b	-1.841 ^b
Asymp. Sig. (2-tailed)	.018	.016

a. Wilcoxon signed ranks test

b. Based on negative ranks

A Wilcoxon signed rank test revealed statistically significant differences between the deterministic construction cost and time of the project and the actual construction cost and time of the project ($Z_c=-1.826$, $p=.018$, $Z_t=-1.841$, $p=.016$). with the large effect size ($r_c=0.64589$, $r_t=0.65089$) (See Table 6.49). The median score on the construction cost and time significantly increased from deterministic cost and time estimation ($Md_c= 369276111.415$, $Md_t=278.5$) to variability of cost and time ($Md_c= 538352944$, $Md_t=484.5$), therefore the null hypothesis was rejected, and the alternative hypothesis was accepted. The results of the Wilcoxon signed rank test supported the Alternative Hypothesis 3.2.1, which proved that there is a significant difference between deterministic estimations of construction cost and duration and actual construction cost and duration. It can be inferred from these findings that deterministic estimation of construction cost and duration are not accurate.

Test of hypothesis 3.2.2

Table 6.50: Wilcoxon signed rank tests of Hypothesis 3.2.2

	Percentiles		
	25th	50th (Median)	75th
Uncertainty Cost Estimation	175428077.03	537609517.81	1032942518.53
Uncertainty Time Estimation	348.92	484.85	544.00
Actual Cost	176366376.75	538352944.00	1032140520.50
Actual Time	346.25	485.50	537.00

Test Statistics ^a

	Actual Cost – Uncertainty Cost Estimation	Actual Time – Uncertainty Time Estimation
Z	.000 ^b	-.368 ^c
Asymp. Sig. (2-tailed)	1.000	.713

a. Wilcoxon signed ranks test

b. The sum of the negative ranks equals the sum of the positive ranks.

c. Based on positive ranks.

A Wilcoxon signed rank test revealed no statistically significant difference between the uncertainty construction cost and time estimation of the project ($Md_c = 537609517.805$, $Md_t = 484.85$) and the actual construction cost and time of project ($Md_c = 538352944$, $Md_t = 485.5$), $Z_c = -.000$, $\rho = 1.000$, $Z_t = -.368$, $\rho = .713$ (See Table 6.50), therefore the null hypothesis was accepted, and the alternative hypothesis was rejected. The results of the Wilcoxon signed rank test supported the Null Hypothesis 3.2.2, which means there is no significant difference between the uncertainty estimation of construction cost and duration and actual construction cost and duration. Based on these findings, it can be inferred that the uncertainty estimation of construction cost and time were accurate.

The results of two Wilcoxon signed rank tests which rejected the Null hypothesis 3.2.1 and accepted the null Hypothesis 3.2.2 proved that “*There is a significant difference between the accuracy of estimations of construction cost and duration by deterministic methods and uncertainty model.*” Therefore, the study verified that the accuracy of the uncertainty model is significantly higher than the deterministic estimations.

Table 6.51: Summary of the results of the research hypotheses.

Hypothesis	Significance	Summary	Inference
<i>Hypothesis 1.1: There is no significant association between the characteristics of infrastructure projects and the cost of infrastructure projects.</i>	Reject the Null hypotheses and accept the Alternative hypotheses	<ul style="list-style-type: none"> There is a significant association between the characteristics of infrastructure projects and the cost and time of infrastructure projects. The characteristics of infrastructure projects have a medium effect on the cost and time of infrastructure projects. 	<ul style="list-style-type: none"> ➤ There is a significant medium association between the characteristics of infrastructure structures and the cost and duration of infrastructure projects. ➤ There is a significant high association between the impacts of different sources of uncertainty and the cost and duration of infrastructure projects. ➤ All three key sources of uncertainty significantly increase the cost and duration of infrastructure projects. ➤ The deterministic estimation of construction cost and duration are not accurate ➤ The uncertainty estimation of construction cost and duration are accurate.
<i>Hypothesis 1.2: There is no significant association between the characteristics of infrastructure projects and the time of infrastructure projects.</i>			
<i>Hypothesis 2.1: There is no significant association between the impacts of different sources of uncertainty and the cost of infrastructure projects.</i>	Reject the Null and the Alternative hypotheses	<ul style="list-style-type: none"> There is a significant association between the impacts of different sources of uncertainty and the cost and time of infrastructure projects. The impacts of different sources of uncertainty have a large effect on the cost and time of infrastructure projects. 	
<i>Hypothesis 2.2: There is no significant association between the impacts of different sources of uncertainty and the time of infrastructure projects.</i>			
<i>Hypothesis 3.1.1: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using variability model.</i>	Reject the Null hypotheses and accept the Alternative hypothesis	<ul style="list-style-type: none"> There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using uncertainty model 	
<i>Hypothesis 3.1.2: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using correlation model.</i>			
<i>Hypothesis 3.1.3: There is no significant difference between the estimated and forecasted construction cost and duration of infrastructure project using disruptive events model.</i>			
<i>Hypothesis 3.2.1: There is no significant difference between the initial estimations of construction cost and duration and actual construction cost and duration.</i>	Reject the Null hypothesis and accept the Alternative hypothesis	<ul style="list-style-type: none"> There is a significant difference between the deterministic estimations of construction cost and duration and actual construction cost and duration. The deterministic estimations significantly underestimated the construction cost and duration of the project There is no significant difference between the uncertainty estimations of construction cost and duration and actual construction cost and duration. The uncertainty model accurately estimates the construction cost and duration of the project 	
<i>Hypothesis 3.2.2: There is no significant difference between the uncertainty estimations of construction cost and duration and actual construction cost and duration.</i>	Accept the Null hypothesis and reject the Alternative hypothesis		

6.7 SUMMARY OF THE CHAPTER

The developed construction and uncertainty models were applied to the construction of the new highway project. The impacts of three sources of uncertainties and their cumulative impacts on construction cost and time of three structures of highway projects (earthwork, bridge and pavement) and for the overall project were quantified. Since the construction cost and duration of the construction project were uncertain, they were modelled and simulated taking into consideration the uncertainties associated with variability, correlations, and disruptive events and compared with the deterministic cost and time, which verified that the deterministic estimations of the project were inadequate because variability increased the ranges of the total cost and total time distributions, the cost and time correlations significantly grew the range of the total cost and time distributions, and disruptive events further increased the ranges of the total cost and total time distributions.

The results of the uncertainty model confirmed that the cumulative impacts of the three sources of uncertainty increased the 90th percentile of cost and time significantly. Moreover, the results of the case study application demonstrated that the cumulative impact of uncertainties varied from structure to structure. The results of the uncertainty model disclosed three sources of uncertainty, which caused an increase in the construction cost and duration of the project by 42.66% and 60% respectively. Therefore, it can be inferred that the three sources of uncertainty capture the ranges of the possible cost and time of construction project.

Furthermore, the established hypotheses in Chapter Three were tested using the deterministic cost and time and forecasted uncertainty cost and time against the actual construction cost and time of the case study. The hypotheses tests statistically prove that “*There is a significant association between the characteristics of infrastructure projects and the cost and time of infrastructure projects*”, and “*There is a significant association between the impacts of different sources of uncertainty and the cost and duration of infrastructure projects*” and “*There is a significant difference between the accuracy of estimations of construction cost and duration by deterministic methods and by the uncertainty model*”.

CHAPTER SEVEN: VALIDATION OF THE UNCERTAINTY MODEL AND DISCUSSION OF THE RESULTS AND FINDINGS

7.1 INTRODUCTION

This chapter contains two parts: validation of the forecasted results of the uncertainty model and discussion of the results and findings. In the first part, the forecasted results of uncertainty are validated using four orders of validation. In the second part, the results of the model are interpreted, and the findings of the study discussed and validated by relating them to the existing body of knowledge on cost overrun and time delays of infrastructure projects.

7.2 VALIDATION OF THE UNCERTAINTY MODEL

The validation of the model and its results (cost and time forecasting) was a core aspect to consider when analysing the capabilities of the developed uncertainty model and its potential applicability for forecasting the cost and time of other infrastructure projects. The evaluation of the validity helped to examine the applicability and generalisation of the uncertainty model.

McCabe and Dixon (2000) introduced four orders of model validation: first-order validation of inputs data and methods used in developing the model; second-order validation, which requires expert concurrence; third-order validation, which compares the model prediction with other observed data (data not used in the model construction); and fourth-order validation, which compares pre-implementation model predictions with observed events post-implementation. The four orders of uncertainty model validation are presented in this section.

7.2.1 First-order: validation of input data and methods used

The validity of the uncertainty model involved the precision of the process performed as internal validity, and the extent to which the model was generalisable as external validity. In assessing the internal validity and external validity, the study was not focussed exclusively on the results of the uncertainty model; the validation process was done on the inputs, as well as the process, which helped to improve the accuracy of the final results of the uncertainty model.

As discussed in Chapter Four, the validation of the input data was controlled in each stage of data collection using different methods. For example: Spearman correlation to determine the relationship between two parts of the questionnaire survey, Cronbach's alpha to test the internal consistency of the research variables, using the outside view of the panels of experts to estimate the unit cost and production rate and calibration of the estimation.

Moreover, regarding the modelling itself, the construction modelling and uncertainty modelling were integrated, and the standard approach was used for modelling different sources of uncertainty on the cost and time of each construction activity. Employing well-recognised (Monte Carlo analysis) and intelligent (ANFIS) methods and checking the validity of each process of analysing data was also controlled and validated by using proper methods, such as controlling the number of

simulations run in Monte Carlo, determining the performance of ANFIS, and cross-checking with SRA, all of which ensured the validity of the deployed model in this study.

Although the inputs and methods employed in developing the uncertainty model were validated entirely, the study recognised and considered the deficiency that affected the accuracy of the model results. In full agreement with Flyvbjerg and Glenting (2004), the researcher was aware of the influence of non-availability of data, different types of biases (availability, anchoring, contrast, overconfident optimism), ignorance, uncertainty associated with the assessment of model parameters, epistemic uncertainty in the model design, and calibration on the reliability of the final results of the uncertainty model. Considering all the above factors on input data and methods used in developing the uncertainty model assured that the study was provided with a valid model to forecast the accurate cost and time of the infrastructure projects.

7.2.2 Second-order: expert estimation validation

Subsequent to developing the uncertainty model and applying it to the case study, the comprehensive details of forecasted construction cost and duration of the three structures and the overall project were presented to the panel of experts for evaluation and validation of the uncertainty model results. Each panel of experts (earthwork, bridge, pavement) validated their particular structure results, and all the panels of experts validated the total cost and total time of the project. The expert panels compared the forecasted results to their own archive and experience.

During the validation sessions, all the comments and corrections recommended by the expert panels were applied to the model, and the adjusted results were presented to the panel of experts for validation. Ultimately, after several adjustments, all three expert' panels validated the accuracy of the forecasted construction cost and time of each structure and the overall project.

7.2.3 Third-order: comparing the model predictions with other observed data

The forecasted construction cost and time of each structure and the overall project from the uncertainty model were divided by the number of structures and the project to determine the unit cost and production rate of each structure and the overall project. The uncertainty model's unit cost and production rate were compared to the actual observed cost and time (cost was deflated to 2017 as a base year) of three comparable projects. The summary of the uncertainty model and three comparable projects is listed in Table 7.1.

The average variation between the forecasted construction cost and duration by the uncertainty model and average variation of the three comparable projects revealed that the range of variation was $\pm 1\%$, which proved that the uncertainty model was able to forecast accurately the actual construction cost and time of the identified projects.

Table 7.1: Comparison of the forecasted results with actual observed data of comparable projects

		Earthwork M ³	Bridge unit	Pavement M ³	Overall Project Km
Forecasted by uncertainty model	Cost (ZAR)	137.19	2,128,581.00	657.17	69,990,286.23
	Time (DAY)	6,985.42	11.82	3,140.55	32.97
Actual data of project 1	Cost (ZAR)	140.09	2,086,435.10	672.35	71,068,136.64
	Time (DAY)	7,080.42	11.52	3,201.79	33.56
Actual data of project 2	Cost (ZAR)	134.78	2,173,281.19	643.11	69,101,409.60
	Time (DAY)	6,845.01	12.11	3,069.93	32.48
Actual data of project 3	Cost (ZAR)	135.55	2,169,024.03	641.59	69,311,380.46
	Time (DAY)	6,916.96	12.05	3,062.04	32.63
Average variation	Cost (ZAR)	-0.283%	0.673%	-0.733%	-0.233%
	Time (DAY)	-0.543%	0.630%	-0.933%	-0.247%

7.2.4 Fourth-order: comparing pre-implementation model predictions with observed post-implementation model predictions

Modelling probabilistic estimation of cost and time is a complex process, to which validation measures must be applied, to obtain results from probability estimation that may be analysed with a certain level of confidence. This level of confidence must represent the phenomenon of interest with a degree of accuracy consistent with the intended use of the model (Sargent, 2009).

The most reliable and preferred method of validating the forecasted results was estimating the degree of accuracy for the developed uncertainty model. The degrees of accuracy were estimated for the cost and time of each structure and total cost and time of a project by comparing the actual cost and time with deterministic estimated cost and time and forecasted construction cost and duration. The deterministic estimated cost and time (Table 5.1), forecasted cost and time (Table 6.41), and observed actual construction cost and time (Table 5.1), presented with the estimated degree of accuracy for each structure, and the total cost and total time of the overall project, are summarised in Table 7.2.

As presented in Table 7.2, the margin of the error of the uncertainty model in total construction cost was 0.85%, and -0.93% in total construction time of the project. Moreover, the margins of the error of estimation accuracy of the uncertainty model in the three structures and the overall project were within $\pm 1\%$ (modelling conditions for stopping the simulation run of variability and correlation).

Furthermore, the uncertainty model improved the degrees of estimation accuracy significantly in all three structures and the overall project. For instance, the uncertainty model improved the degree of accuracy of the cost of earthwork, bridge, pavement and overall project by 39.88%, 25.09%, 23.42% and 31.35%, respectively. Also, the degree of accuracy of time of the three structures and the overall project (48.89%, 35.99%, 31.16%, 35.99%) were also improved when the uncertainty model was applied.

Table 7.2: Comparison of the forecasted results with actual results

		Earthwork	Bridge	Pavement	Overall Project
Deterministic estimation	Cost	244,292,292.83	70,952,700.00	494,259,930.00	809,504,922.83
	Time	215	340	217	340
Forecasted by the uncertainty model	Cost	407,968,130.11	97,914,726.00	667,250,905.50	1,154,839,722.87
	Time	425.7	544	323.3	544
Actual	Cost	410,415,938.89	96,543,919.84	657,775,942.64	1,164,735,801.37
	Time	431	539	320	539
Margin of error of deterministic estimation	Cost	40.48%	26.51%	24.86%	30.505
	Time	50.12%	36.92%	32.19%	36.69%
Degree of accuracy deterministic estimation	Cost	59.52%	73.49%	75.14%	69.50%
	Time	49.88%	63.08%	67.81%	63.08%
Margin of the error of the uncertainty model	Cost	0.60%	-1.42%	-1.44%	0.85%
	Time	1.23%	-0.93%	-1.04%	-0.93%
Degree of accuracy of the uncertainty model	Cost	99.40%	98.58%	98.56%	99.15%
	Time	98.77%	99.07%	98.97%	99.07%
Improved degree of accuracy of the uncertainty model	Cost	39.88%	25.09%	23.42%	31.35%
	Time	48.89%	35.99%	31.16%	35.99%

Furthermore, the uncertainty model improved the degrees of estimation accuracy significantly in all three structures and the overall project. For instance, the uncertainty model improved the degree of accuracy of the cost of earthwork, bridge, pavement and overall project by 39.88%, 25.09%, 23.42% and 31.35%, respectively. Also, the degree of accuracy of time of the three structures and the overall project (48.89%, 35.99%, 31.16%, 35.99%) were also improved when the uncertainty model was applied.

The validated uncertainty model and its forecasted cost and times results supported the main research hypotheses 3.1 and 3.2:

Hypothesis 3.1: There is a significant difference between the estimated and forecasted construction cost and duration of infrastructure project using the uncertainty model.

Hypothesis 3.2: There is a significant difference between the accuracy of estimations of construction cost and duration by deterministic methods and the uncertainty model.

7.3 DISCUSSION OF FINDINGS

This section presents a discussion of the findings of the study. The outline of this discussion of the findings corresponds sequentially with the research objectives stated in Section 1.6 of the thesis.

7.3.1 Construction model of the highway infrastructure projects development

The findings from evaluation of the deterministic theory (base estimation) and probabilistic theory (risk-based estimation) revealed that available estimation tools do not attempt to understand the construction process of a project and different sources of uncertainty and their cumulative impacts. Therefore, the study developed a hybrid estimation method consisting of two models: the construction model and the uncertainty model.

The construction model analysed the construction processes of the three main structures of a highway project, namely earthwork, bridge and pavement at the level of the single activities. It developed activity networks representing the specific construction processes of each structure and precisely calculated the construction cost and time of highway structures and total cost and time of a highway project. The representation of the construction process of highway projects with activity networks extended the understanding of the construction process and provided the starting point to identify the sources of uncertainty at the activity level in the construction process of highway projects.

The findings from analysis of the activity networks showed that there is a repetition of sub-networks during the construction of a structure. The interconnection of these sub-networks models one structure of highway, and the interconnection of the structure networks models the construction of the highway project. The findings also revealed that the complexity of the activity networks vary from the simplest three activity network of cutting and filling to the complex activity network of slab bridges. These findings of the study are in line with the research of Hassanein and Moselhi (2004).

7.3.2 Key sources of uncertainty in the construction process of infrastructure projects

The study identified three main sources of uncertainty in the construction process of infrastructure projects: variability on the construction process, the correlations between construction costs, times and cost-time and the occurrence of disruptive events.

The findings obtained from analysis of variability in the construction process proved that the lognormal and triangular probability distributions are the most reliable probability distribution to model the cost variable and the time variable respectively. This finding is supported by Touran (2003). The findings also showed that the generated range of the possible total cost and total time due to variability increased the cost and time of the project from the deterministic estimate (corresponds with one value). This finding is aligned with a study by Touran and Lopez (2006).

The findings from the analysis of the correlation in infrastructure projects revealed that there are five types of correlation between construction costs, times and cost-time of infrastructure projects namely: correlation between repeated activities in a structure, correlation between various activities in a structure, correlation between the activities in adjacent structures, correlation between the same activities in the same type of structures and correlation between cost and time of an activity; however due to the particular combinations of highway structures only the three following types of correlations are considered in the process of construction of highway projects: 1) correlation between the costs/times repeated activities in a structure, 2) correlation between the costs/times of the various activities in a structure, and 3) correlation between cost and time of an activity. Also, the findings indicated that the positive correlation in all three types of correlation in highway projects increase the range of possible construction cost and time. These findings are in line with the similar study by Moret et al. (2016).

The bibliometric analysis of uncertainty and risk events in the construction of infrastructure projects identified 317 events in the construction process, under seven main factors, namely: economic, environmental, financial, legal, political, social and technical. The study also found that the impact of disruptive events could be quantified by probability of occurrence and severity of the event. The findings from the analysis of disruptive events showed that the disruptive events have large impacts on the cost and time of a project and increase the cost and time significantly. These findings of the study are aligned with the outputs of ISO (2018) and (PMI, 2013).

7.3.3 Uncertainty model development

The study developed an uncertainty model to improve the accuracy of estimation of cost and time of infrastructure projects through assessing the different sources of uncertainty in the construction process of infrastructure projects; the study synthesised the probabilistic estimation theory with modern portfolio theory and developed the uncertainty portfolio concept for understanding the relationship between different sources of uncertainty, infrastructure project characteristics, and the risk-base cost estimate. The study employed both the quantitative and qualitative strands to collect the data. The findings from the panel of experts' estimation revealed the lower (minimum), most likely (mode) and higher (maximum) unit costs and production rates of different activities as well as the correlation coefficient of the three types of correlations in the main structures of highway projects. The findings from the group brainstorming of experts established a disruptive events map of the highway construction projects in South Africa. This map illustrates the 76 disruptive events existing in South African highway projects in seven major groups. The disruptive events survey conducted among project managers of highway construction projects in South Africa identified the probability of occurrence and severity of each event on construction cost and duration of highway projects.

Data obtained from both quantitative and qualitative approaches were analysed using various techniques. The probability distribution function of cost and time modelled the collected variability unit costs and production rates using lognormal and triangular probability distributions. The impact of variability on construction cost and time of a project was estimated by inserting the cost and time probability distributions into the Monte Carlo simulation. The impact of correlation on the cost and time of a project was calculated by using Copula analysis techniques and Monte Carlo simulation, while the impact of disruptive events on the construction cost and time of project was assessed by the Adaptive Neuro-Fuzzy Inference System (ANFIS) and Markov processes. The results from the uncertainty model proved that each of the three sources of uncertainty had different impacts on construction cost and duration of the infrastructure project. The details of findings on impacts of the three main sources of uncertainty and their cumulative impacts on cost and time of highway project are discussed in the subsequent sections.

7.3.3.1 Impacts of variability on construction cost and time of infrastructure projects

The analysis and modelling of the variability in the construction of highway projects determined that the variability cost and time of a project cannot be expressed with a single value estimate (deterministic cost and time) but rather with a range of possible costs and times. This range of

possible cost and time outcome proved that variability was one of the main sources of uncertainty on construction cost and total time of infrastructure projects. Moret and Einstein (2016), Salling and Leleur (2011), Chou (2009), Touran and Lopez (2006), Sovacool et al. (2014b) also confirmed variability as one of the main sources of uncertainty in estimating construction cost and duration of infrastructure projects.

Moreover, the modelling of variability verified that it caused the construction cost and time of the project (90th percentile) to be larger than the deterministic construction cost and duration of the project, due to estimating the deterministic cost and time being based on the mode. This was the main reason of positive skewing of both cost and time of variability distribution and proved that not considering variability on the construction estimation caused cost and time underestimation. This finding was aligned with findings of Moret and Einstein (2016), Touran and Lopez (2006), Isidore et al. (2002) which showed that not considering variability in the estimation process was one of the main reasons for cost and time underestimation in infrastructure projects.

Furthermore, the analysis of the variability cost and time variation revealed that the influence of variability on the time of the project was higher than its cost, which manifested that the construction time of an infrastructure project was more sensitive to variability than the construction cost of an infrastructure project. This finding of the study was supported with studies by Adeli and Karim (2014) and Molenaar (2005) that expressed the greater sensitivity of the construction time to the changes in normal conditions than the construction cost.

7.3.3.2 Impacts of correlation on the construction cost and time of infrastructure projects

The study analysed and modelled the following three types of correlation: correlation between costs/times of repeated activities in a structure, correlation between costs/times of various activities in a structure, and correlation between cost and time of an activity.

Modelling the three correlation scenarios (activities were independent, activities were positively correlated, activities were fully correlated) for correlation between repeated activities in a structure, demonstrated that the cost and time of a project were positively correlated to the number of repetitions of activities. The positive coefficient correlation due to repeated activities caused a larger variation on the cost of activities compared to the variation on the time of activities. The studies of Moret and Einstein (2011a), Emam et al. (2015) support this finding. The correlations cause the range of the total cost and time to increase on both sides of means which represent a threat as well as opportunity aspect of correlations.

The study also found that the cost and time of a project were increased dramatically due to the positive correlation between the costs and times of activities in a structure (Correlation Type 2). Similar to the correlation between repeated activities in a structure (Correlation Type 1), the influence of the correlation between the costs of activities was larger than the influence of correlation between the times of activities in the same structure. This finding is aligned with the findings of Ökmen and Öztaş (2010), Moret and Einstein (2011b), which stated that the structure with more activities has a higher chance of increasing the total cost and total time.

Modelling the correlation between cost-time of activity (Correlation Type 3) attested to the positive correlation between the cost and duration of the different activities and, consequently, the cost and time of the project. However, these positive correlations were varied in different structures of the project. There are very limited studies that have assessed this type of correlation (Touran, 1993, Purnus and Bodea, 2014) due to the difficulty of assessing the correlation between the cost-time of activity with the basic correlation techniques (Pearson, Spearman, Kendall).

The sensitivity analysis of the three types of correlation that was applied in this study on the different structures and overall project, verified that correlation between the activities in a structure (Correlation Type 2) caused the largest variation of the cost of all activities and the overall project. However, generalising the key correlation in relation to time was not possible due to the different combination of critical activities on the critical path, as shown in the construction model presented in Chapter Six. The correlation between the repeated activity in a structure (Correlation Type 1) was considered to be the key correlation on the time of the project because this correlation was the dominant correlation on the bridge structure as the critical component of the infrastructure project.

Furthermore, the study investigation of the sensitivity analysis of impacts of correlation on cost and time of each structure of a highway project and the overall highway project confirmed that the impact of different types of correlations on cost of the project was higher than their time, which revealed that the construction cost of an infrastructure project was more sensitive to variability than the construction time. The study of Bakhshi and Touran (2012) supports this finding.

7.3.3.3 Impacts of disruptive events on the construction cost and time of infrastructure projects

The study modelled the disruptive events using ANFIS models to assess the impact of each event on the cost and time of the construction project. This was a focus of the study because of the high capabilities of an artificial neural network in enabling the prediction, learning, and modelling of human knowledge.

A comparison of the performance of classical statistics versus the machine learning techniques, in predicting the impact of disruptive events, showed that the error values of ANFIS models were much smaller than the error values of Standard Regression (SR) models when predicting the size of the impact, which proved that the prediction of impact size using ANFIS models was more reliable than the prediction of SR models. Moreover, the correlation codefined value of ANFIS models was significantly closer to 1 compared to SR models, which strongly suggested that the accuracy of ANFIS models in predicting impact size was extremely high. Therefore, the performance comparison proved that ANFIS was a more accurate tool for predicting the impact of disruptive events. Convincingly, the predicted impact size from ANFIS models was accurately used to estimate and simulate the cost and time of disruptive events. This finding of the study is supported by Ebrat and Ghodsi (2014), Islam et al. (2017), Suveka and Priya (2016).

The results of the ANFIS modelling revealed that, from 76 disruptive events assessed in the study, eight events, namely latent ground conditions, inaccurate time and cost estimation, human made

disaster, remote location cost, corruption, disease, monopoly of materials and/or equipment suppliers and fluctuation of prices of materials and/or equipment had an extreme impact on cost. Forty-six (46) events had a high impact; 19 events had a moderate impact, and three events had a low impact, while none of the events had a minimal impact on the cost of the project. Similar to the cost, eight events had an extreme impact on time, namely latent ground conditions, inaccurate time and cost estimation, inadequate planning and scheduling, human made disaster, specification change, difficulty of schedule, disease and poor quality of project management had an extreme impact on time. Forty-eight (48) events had a high impact; 17 events had a moderate impact; three events had a low impact; and none of the events had a minimal impact on the completion time.

These results of the study were in accordance with several previous studies. For instance, the identification of latent ground conditions as having the highest predicted impact on cost and time of project was in line with the results of Aziz and Abdel-Hakam (2016), Adam et al. (2017), Taghipour et al. (2015), Fang et al. (2012), T. Zayed et al. (2008), Zou et al. (2007) Assaf and Al-Hejji (2006) and Baloi and Price (2003).

The study also revealed latent ground conditions, inaccurate time and cost estimation, were the two technical events that had an extreme effect on the costs of horizontal construction projects. While the latent ground conditions, inaccurate time and cost estimation, specification change, inadequate planning and scheduling, and difficulty of schedule were the four technical events among the total eight events that had an extreme effect on the time of construction projects. Technical events proved to be the most impactful as compared to the other identified causation of disruptive events and were put forward by other researchers. These technical events were also identified in the studies of Aziz and Abdel-Hakam (2016), Mahendra et al. (2013), Marzouk and El-Rasas (2014), Gosling, Naim, and Towill (2012), Ehsan et al. (2010), Saqib et al. (2008), Zou et al. (2007), Assaf and Al-Hejji (2006) Huang et al. (2002) and Bunni (2003).

The findings of Odediran and Windapo (2018), Aziz and Abdel-Hakam (2016) and Marzouk and El-Rasas (2014) were consistent with the findings of this study about the predicted impact of human-made disaster and disease, as political and social disruptive events that had an extreme impact on construction projects in developing countries in Africa, such as South Africa and Egypt. Furthermore, the findings of the study indicate that technical, social and political factors significantly impact on the cost and time of South African infrastructure construction projects. This outcome was aligned with the research results of Aziz and Abdel-Hakam (2016) and Marzouk and El-Rasas (2014).

Finally, the study also found that 54 events (71.1%) and 56 events (73.7%) had an extreme or high impact on the cost and time of highway construction projects, respectively. This indicated that the cost and particularly the time of infrastructure construction projects in South Africa are very sensitive to disruptive events.

7.3.3.4 *Cumulative impacts of different sources of uncertainty on construction cost and time of infrastructure projects*

The analysis of the cumulative impact of all three sources of uncertainty on construction cost and time of a project proved that each of the three sources of uncertainty increased the cost and time of a project differently. However, the study verified that the magnitude of the cumulative impacts of the three sources of uncertainty was significantly larger than the impact of each individual source, and if the impact of all sources of uncertainties were not modelled as the key driver of increasing cost and time in the estimation of an infrastructure project, the ranges of the possible construction cost and duration were underestimated. The studies of Flyvbjerg et al. (2002), Touran (2003), Moret (2011) fully support this finding of the study.

As presented in Chapter Six, each source of uncertainty had a different impact on total cost and total time of structures (See Table 6.42 and Figures 6.58, 6.59 and 6.60). Therefore, these different impacts of uncertainties on the total cost and total time of structures required differentiated strategies to be applied for the different structures of the project.

In earthwork structure, the disruptive events were the key source of uncertainty due to the highest magnitudes of impact on both cost and time of activities of earthwork structure. This finding is supported by Goodwin and Wright (2010) and Moret et al. (2016), who verified that the occurrence of disruptive events was the main source of cost overruns and time delays in the construction of infrastructure projects. Therefore, the focus should be on mitigation strategies for disruptive events, including identifying and quantifying all disruptive events that impact the cost and time of earthwork and bridge structures.

In bridge and pavement structures, the correlation between the cost of different activities and disruptive events were the key sources of uncertainty in relation to the cost and time of bridge and pavement structures respectively. This finding is aligned with Purnus and Bodea (2014), who stated that not considering the high correlation between the cost of the pavement activities caused the underestimation of the actual cost of the pavement structures. Therefore, the emphasis should be on measuring and modelling the cost of correlations between activities in the bridge and pavement structures, and on mitigation strategies to deal with disruptive events related to construction time of these structures.

In the infrastructure project, the focus should be on the disruptive events and correlation between the cost of activities, since they had the largest impact on the total cost of the project. In order to estimate the total time of the infrastructure project accurately, attention should be on the disruptive events with particular focus on the bridge structure, since the duration of bridge activities determined the total time of the overall project due to its critical structures.

Furthermore, the study also verified that the cumulative impact of uncertainties on the construction time of the infrastructure project was larger than the cumulative impact on the construction cost of the infrastructure project, which is aligned with the finding of Adeli and Karim (2014) that sensitivity of construction time to uncertainty was higher than that of the construction cost.

7.3.4 Improving the estimation of construction cost and time of infrastructure projects by incorporating the construction model and uncertainty model

The findings obtained through incorporating the construction model and uncertainty model verified that the impacts of variability, correlations, and disruptive events on the cost and time distributions were varied depending on the construction activities and activity networks of each structure. The application of the construction model and the uncertainty model to the construction of the three structures of the new highway project attested to the accuracy of the proposed incorporated models in capturing and assessing the uncertainties in construction cost and time of infrastructure projects.

Furthermore, it emerged that integrating the construction model with the uncertainty model significantly improved the estimation of the construction cost of the transportation infrastructure project by 42.66%, which result was very close to the capital expenditure increase for roads infrastructure projects (45%) at the 90th percentile suggested by Flyvbjerg et al. (2003), as well as the estimated 90th percentile of cost escalation (42%) in the road construction infrastructure projects. Also, the improvement of the uncertainty model on the forecasted construction time of the infrastructure project was 60%, which was in the middle of the range of the different time underestimations reported by Ahsan and Gunawan (2010) (55.69%), Singh (2010) (117.5%), Assaf and Al-Hejji (2006) (10% - 50%), Ngacho and Das (2014) (87%), Kaliba et al. (2009) (86.7%) and Moret and Einstein (2016) (23.5%-94.4%).

7.4 SUMMARY OF THE CHAPTER

This chapter validated the forecasted results of the uncertainty model using the four orders of validation. The validated results of the model supported the two main research hypotheses.

This chapter also presented a discussion on the findings of the study on the impact of uncertainties on construction cost and duration of infrastructure projects and improving the estimation of construction cost and time of infrastructure projects by relating the findings of the study to the existing body of knowledge.

CHAPTER EIGHT: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

This chapter outlines the key research findings from the study and presents the extent to which the research objectives have been met, conclusions are drawn, and the contributions to knowledge are described, while the research limitations are clarified. Appropriate recommendations based on the findings and conclusions are outlined, and areas for future research are suggested.

The study examined the impacts of uncertainties on the estimation of construction cost and time of infrastructure projects. In particular, the study developed a construction model and an uncertainty model for the construction of infrastructure projects and applied them to the construction of a new highway construction project to answer the main research question, “*What are the key sources of uncertainty in the construction process of infrastructure projects and what are the levels of impacts of these uncertainties individually and cumulatively on the cost and time of infrastructure projects?*”

Answering this question involved a series of research processes that included the identification of causes and solutions to cost and time underestimation in infrastructure projects through a review of extant literature in the field of cost and time estimation. Through the review of literature, the research concepts and three sources of uncertainty in the construction process of infrastructure projects were determined. The research concepts helped in generating the research questions and hypotheses to guide the study in the proper direction. The research hypotheses were tested to determine how sources of uncertainty impact on construction cost and duration of infrastructure projects.

A mixed-methods research approach was utilised to collect and analyse the data. Both the qualitative approach (a semi-structured interview and group brainstorming) and quantitative approach (a series of expert panels’ estimations and questionnaire survey) were employed to collect the essential data. Data collected were modelled and analysed using descriptive and inferential statistics, probability distribution and machine learning to predict the impact size of three sources of uncertainties on construction cost and time, in the case study infrastructure project.

8.2 RESTATING THE AIM AND OBJECTIVES OF THE STUDY

The aim of this research was to examine the impacts of various sources of uncertainty in the construction process of infrastructure projects and whether the incorporation of the construction and uncertainty models improve the accuracy of the estimation of cost and duration of the projects. This was done by capturing the cumulative impact of the construction and uncertainty models on the cost and time of the infrastructure project.

In order to achieve the research, aim and summarise the key findings derived from this study in line with the objectives, the research objectives are revisited:

Research objective 1: Investigate the construction process of infrastructure projects and develop a representative construction model.

Research objective 2: Determine the association between the characteristics of infrastructure projects and the cost and duration of infrastructure projects.

Research objective 3: Identify the key sources of uncertainty in the construction process of projects that impact on cost and duration of infrastructure projects.

Research objective 4: Determine the association between the impacts of different sources of uncertainty and the cost and duration of infrastructure projects.

Research objective 5: Develop an uncertainty model, which will be used to forecast the impact size of different sources of uncertainty and model their cumulative impacts to improve the accuracy of construction cost and duration of infrastructure projects.

Research Objective 6: Apply the uncertainty model in the construction of infrastructure projects, validate and measure the effect of applying the model on the estimation of cost and duration of highway infrastructure projects.

8.3 SUMMARY OF RESEARCH FINDINGS

This section summarises the key findings that emerged from the study in line with the research objectives.

8.3.1 Objective 1:

Investigate the construction process of infrastructure projects and develop a representative construction model.

The study identified the three main structures of highway infrastructure projects, namely, earthwork, bridge and pavement, to model the new highway construction at the activity level and the interactions between activities. The construction of the infrastructure project was modelled with activity networks in a bottom-up approach: single activities were connected into sub-networks modelling the repetitive processes, sub-networks were connected into structure networks modelling the construction of each structure, and structure networks were connected into the construction network modelling the construction of the entire project. It emerged that the construction process of infrastructure projects involves earthwork structure (cutting, filling), pavement structure (subgrade, subbase, base, surface) and bridge structure (culvert, slab bridge) and which are also activities on the critical path.

8.3.2 Objective 2:

Determine the association between the characteristics of infrastructure projects and the cost and duration of infrastructure projects.

The study found that the characteristics of infrastructure project had significant associations with cost and time of infrastructure project. The study further revealed this association had a medium effect on both cost (0.374) and time (0.363) of the infrastructure project. It can be inferred that the

characteristics of infrastructure projects were a predictor of the cost and time of infrastructure projects.

8.3.3 Objective 3:

Identify the key sources of uncertainty in the construction process of projects that impact on cost and duration of infrastructure projects.

The study identified the variability in construction cost and time, correlation between the construction activities costs and times, and the disruptive events occurring, as the key sources of uncertainty in the construction process of infrastructure projects. The study found that, when the activity was repeated in the construction process of an infrastructure project, the cost and time of the activity is changed from one repetition to the other under normal conditions. Therefore, the study adopted the variability of the activity cost and time as one of the key sources of uncertainty in the construction process of infrastructure projects.

Moreover, the study found that the correlations between the cost and duration of an activity changed the standard deviation of the total cost and time of the activity. It emerged that, among the five possible correlations between costs and duration of activities in construction projects, the correlation between costs and the duration of a repeated activity in a structure, correlation between the costs and duration of different activities in a structure, and correlation between the cost and the time of an activity are the essential correlations in the infrastructure projects.

Furthermore, the study found that the disruptive events occurring in the process of construction caused a large impact on cost and time, thus increasing the total cost and total time of the project. The study revealed that, among the 317 disruptive events in construction projects, 76 occurred in South African infrastructure projects. These 76 were categorised under seven major uncertainty factors namely, economic, environmental, financial, legal, political, social and technical which prevail in the construction of infrastructure projects.

The study also examined these three sources of uncertainty to determine the most suitable methods and techniques for quantifying and assessing the impact of each source of uncertainty on cost and time of infrastructure projects. The study found that the lognormal and triangular probability distributions were the most appropriate methods for quantifying the impact of variability on construction cost and duration of a project, while the Spearman correlation coefficient and impact matrix were the most reliable techniques to compute the impact of correlation and disruptive events on cost and time of a project, respectively.

8.3.4 Objective 4:

Determine the association between the impacts of different sources of uncertainty and the cost and duration of infrastructure projects.

The study found that the impacts of three key sources of uncertainty (variability, correlation and disruptive events) had significant associations with cost and time of infrastructure project. The study further revealed this association had a high effect on both cost (0.589) and time (0.533) of

infrastructure project. It can be inferred that the impacts of different sources of uncertainty was a predictor of the cost and time of infrastructure projects.

8.3.5 Objective 5:

Develop an uncertainty model, which will be used to forecast the impact size of different sources of uncertainty and model their cumulative impacts to improve the accuracy of construction cost and duration of infrastructure projects.

The study investigated the performance of the three key sources of uncertainty in the construction process of infrastructure projects to identify the most suitable methods and techniques for modelling and analysing each source of uncertainty. Based on this investigation, an uncertainty model was developed to forecast the impact of each source of uncertainty at the activity level.

Therefore, the following uncertainty models were developed in the study: the variability of activity cost and time with probability distributions; the correlations between activities' costs and times with Gaussian copula; the occurrence of the disruptive events with the Markov process and the impacts of disruptive events on construction cost and time of the project with ANFIS. The study simulated the cumulative impact of three sources of uncertainty on construction cost and time of an infrastructure project, using the Monte Carlo method of analysis, and determined the 90th percentile of cost and time of each structure of the infrastructure project as a decision statistic point.

8.3.6 Objective 6:

Apply the uncertainty model in the construction of infrastructure projects, validate and measure the effect of applying the model on the estimation of cost and duration of highway infrastructure projects.

The study applied the construction and uncertainty models to the construction of a highway project (case study) to assess the feasibility of the models and their effectiveness in capturing the uncertainty in the construction process of an infrastructure project. The study found that there is a significant difference between the estimated and forecasted cost and time of infrastructure project using uncertainty model. The study further found that the 90th percentile of the simulated cumulative impact of uncertainties on construction cost and duration of the project were significantly larger than the deterministic construction cost and time: In the earthwork structure, the uncertainty cost and time were 67% and 98% higher than deterministic cost and time estimated. In the bridge structure, the uncertainty cost and time were 38% and 60% higher than deterministic cost and time estimated. In the pavement structure, the uncertainty cost and time were 35% and 49% higher than deterministic cost and time estimated. In the overall project, the uncertainty cost and time were 42.66% and 60% higher than deterministic cost and time estimated.

Furthermore, the study found that there is a significant difference between the accuracy of estimation of construction cost and time by deterministic methods and uncertainty model. Through the validation of the results of the uncertainty model with the actual cost and duration of the project,

the study found that the uncertainty model improved the accuracy of the estimation of construction cost and time of the project: In the earthwork structure, the accuracy of estimation of cost and time was 99.40% and 98.77%, which improved the accuracy of estimation of cost and time by 39.88% and 48.89%, respectively. In the bridge structure, the accuracy of estimation of cost and time was 98.58% and 98.07%, which improved the accuracy of estimation of cost and time by 25.09% and 35.99%, respectively. In the pavement structure, the accuracy of estimation of cost and time was 98.58% and 98.97%, which improved the accuracy of estimation of cost and time by 23.42% and 31.16%, respectively. In the overall project, the accuracy of estimation of cost and time was 99.15% and 99.07%, which improved the accuracy of estimation of cost and time by 31.35% and 35.99%, respectively.

8.3.5 Revisiting the hypotheses of the study

There were three main research hypotheses, which were formulated to answer the research question and to address research objectives.

Hypothesis 1 and its two sub-hypotheses, which were formulated to answer research Question 1 and to address the research Objective 2 are restated as follows:

Hypothesis 1: There is a significant association between project characteristics, cost and duration of infrastructure projects.

Null Hypothesis 1.1: There is no significant association between project characteristics and cost of infrastructure projects.

Alternative Hypothesis 1.1: There is a significant association between project characteristics and cost of infrastructure projects.

Null Hypothesis 1.2: There is no significant association between project characteristics and duration of infrastructure projects.

Alternative Hypothesis 1.2: There is a significant association between project characteristics and duration of infrastructure projects.

All two sub-hypotheses formulated to answer Hypothesis 1 were tested and agreed with the two alternative hypotheses 1.1 and 1.2.; therefore, it can be deduced that the characteristics of infrastructure projects are significant predictors of the cost and time of infrastructure projects.

Hypothesis 2 and its two sub-hypotheses, which were formulated to answer research Question 4 and to address research Objective 4, are restated as follows:

Hypothesis 2: There is a significant association between the impacts of different sources of uncertainty, cost and duration of infrastructure projects.

Null Hypothesis 2.1: There is no significant association between the impacts of different sources of uncertainty and the cost of infrastructure projects.

Alternative Hypothesis 2.1: There is a significant association between the impacts of different sources of uncertainty and cost of infrastructure projects.

Null Hypothesis 2.2: There is no significant association between the impacts of different sources of uncertainty and duration of infrastructure projects.

Alternative Hypothesis 2.2: There is a significant association between the impacts of different sources of uncertainty and duration of infrastructure projects.

The two alternative hypotheses 2.1 and 2.2 were accepted; therefore, it can be deduced that the impacts of different sources of uncertainty are the significant predictor of the cost and time of infrastructure projects.

Two Hypotheses 3.1 and 3.2 and their sub-hypotheses, which were formulated to answer research Question 6 and to address research objective 6 are restated as follows:

Hypothesis 3.1: There is a significant difference between the estimated and forecasted construction cost and duration of an infrastructure project, using the uncertainty model.

Null Hypothesis 3.1.1: There is no significant difference between the estimated and forecasted construction cost and duration of an infrastructure project, using the variability model.

Alternative Hypothesis 3.1.1: There is a significant difference between the estimated and forecasted construction cost and duration of an infrastructure project, using the variability model.

Null Hypothesis 3.1.2: There is no significant difference between the estimated and forecasted construction cost and duration of an infrastructure project, using the correlation model.

Alternative Hypothesis 3.1.2: There is a significant difference between the estimated and forecasted construction cost and duration of an infrastructure project, using the correlation model.

Null Hypothesis 3.1.3: There is no significant difference between the estimated and forecasted construction cost and duration of an infrastructure project, using the disruptive events model.

Alternative Hypothesis 3.1.3: There is a significant difference between the estimated and forecasted construction cost and duration of an infrastructure project, using the disruptive events model.

Hypothesis 3.2: There is a significant difference between the accuracy of estimations of construction cost and duration by deterministic methods and the uncertainty model.

Null Hypothesis 3.2.1: There is no significant difference between the initial estimations of construction cost and duration and the actual construction cost and duration.

Alternative Hypothesis 3.2.1: There is a significant difference between the initial estimations of construction cost and duration and the actual construction cost and duration.

Null Hypothesis 3.2.2: There is no significant difference between the uncertainty estimations of construction cost and duration and the actual construction cost and duration.

Alternative Hypothesis 3.2.2: There is a significant difference between the uncertainty estimations of construction cost and duration and the actual construction cost and duration.

Three sub-hypotheses formulated to answer hypothesis 3.1 were tested and accepted the alternative hypotheses; therefore, it can be deduced that all there is a significant difference between the estimated and forecasted construction cost and time of infrastructure project using uncertainty model (variability model, correlation model and disruptive events model).

Furthermore, the alternative sub-hypothesis 3.2.1 and the null sub-hypothesis 3.2.2 was accepted; therefore, it can be deduced that the hybrid uncertainty model developed based on the uncertainty portfolio concept was able to capture the cumulative impacts of uncertainties on construction cost and time of different structures of the infrastructure project and improve the accuracy of the estimation of the final construction cost and time.

8.4 CONCLUSIONS

The following conclusions were drawn based on the findings of the study:

Using improper estimation methods and lack of understanding of the construction process and its uncertainties, and modelling only risks without capturing the cumulative impact of different sources of uncertainty in the projects are the main causes of cost and time underestimations in infrastructure construction projects, particularly in transportation infrastructure projects. In the construction of these kinds of projects, the cost overruns are mostly significantly larger than the assigned contingency, while the time overruns in these projects are almost twice the estimated construction time.

Analysing single activities and sub-activities in the construction processes of the main structures of projects and their interconnection in the construction network proved that the construction model (type) of infrastructure project will influence the construction cost and duration of projects, and that there is a significant association between project characteristics, cost and duration of infrastructure projects. Moreover, the study concludes that the activities networks of infrastructure projects at the level of the single activities are essential for identification and forecasting the impacts of uncertainties on construction cost and time of the projects.

There are three major sources of uncertainty in the construction process of infrastructure projects, namely variability in the construction process, correlations between the costs, time and cost-time of construction activities and disruptive events. The impact of these three sources of uncertainty (variability, correlations and disruptive events) varies from structure to structure of the infrastructure project, and there is a significant association between the impacts of different sources of uncertainty, cost and duration of infrastructure projects.

The total cost and total time of infrastructure projects are uncertain. Using a deterministic estimation cost and time approach that allocates a single number to the construction cost and duration of infrastructure projects is inadequate. The construction model and the uncertainty model will accurately forecast the impact of the variability activity, correlations, and disruptive events, as well as the cumulative impact of these three sources of uncertainty in construction cost and time of infrastructure projects.

Furthermore, the research concludes that the disruptive event is the main cause of cost overruns and time delays in infrastructure projects. In the scale of activity, the correlation between the costs of different activities in the same structure causes the largest increase in the cost of the activity, while the correlation between the times of repeated activity in the same structure causes the largest increase in the time of the activity. The cumulative impact of these three sources of uncertainty will significantly increase the construction cost and duration of infrastructure projects.

The study further deduces that forecasting the impact of different sources of uncertainty and assessing their cumulative impact on construction projects' cost and time will significantly mitigate the cost and time underestimations in infrastructure projects. Furthermore, the study concludes that the improvement in the accuracy of cost and time estimation of infrastructure projects depends on a combination of classical probability estimation techniques and simulations, and intelligent techniques, such as machine learning.

Finally, combining the classical probability estimation techniques and simulations with intelligent techniques, such as machine learning, will significantly increase the accuracy and reliability of estimated cost and time of infrastructure projects. This model will therefore significantly reduce the difference between the estimated and final construction cost and duration of infrastructure projects.

8.5 CONTRIBUTION TO KNOWLEDGE

The current study makes several contributions to the body of knowledge of cost and time infrastructure projects estimation and the infrastructure construction management knowledge area which are most commonly characterised by cost and time underestimation.

- The study contributed to the understanding of the sources of uncertainty through a review of extant literature conducted on risk and uncertainty in construction projects. The result of the review provided a clear definition of uncertainty and revealed the variability in activity cost and time, the correlation between the activities' costs and times and disruptive events, as the three key sources of uncertainty in the construction process of infrastructure projects.
- The study provided an in-depth understanding of the construction process of linear infrastructure projects, particularly the construction of highway projects, and provided a tailor-made construction model for linear transportation infrastructure projects. The construction of highway projects is modelled as a sequence of earthwork, bridge and

pavement, as three main structures of highway projects. The construction process of each structure is examined down to the construction activity level and the interconnection between the construction activities. The depiction of the infrastructure construction project through activity networks contributes to the understanding of the construction process and provides insight into how to adapt to the sources of uncertainty on construction cost and duration of an infrastructure project, which was fundamental for modelling of the uncertainty at the activity level.

- Through an in-depth understanding of the uncertainty in the construction of infrastructure projects, in a novel approach, three sources of uncertainty in construction cost and time of a project were modelled jointly at the activity level: variation in the cost and the time of an activity; the cost and time of the activity were correlated with the costs and times of other activities; the occurrence of several disruptive events was analysed. The cumulative impacts of three sources of uncertainty in construction cost and duration of the infrastructure project were quantitatively estimated.
- The construction model and the uncertainty model are joined together and implemented in the Monte Carlo simulation and an Adaptive Neuro-Fuzzy Inference System (ANFIS) to improve the accuracy of estimation of uncertainty impacts on cost and time of the project. From a practical point of view, the uncertainty model and the implementation of the Monte Carlo simulation and ANFIS represent an advanced new tool to model uncertainties, and to cover positive and negative aspects of uncertainty in the construction cost and duration of highway and other linear/networked infrastructure projects.
- The application of the construction model and the uncertainty model to the construction of a highway project proved the effectiveness of the developed models in accurately estimating the impact of uncertainties in construction cost and time and the practicality of their application to linear transportation infrastructure projects. The construction model was applied to the different structures of the project with activity networks to simulate the construction process and estimate the deterministic construction cost and time, while the uncertainty model was applied to model three sources of uncertainty in the construction of different structures of the project and assess their impact on construction cost and time of each structure and the overall project.
- The study provided a comprehensive list of disruptive events in the construction process of the infrastructure projects, as well as the specific 76 disruptive events related to the context of South African infrastructure projects.
- Beyond the estimation of the impact of uncertainty in construction cost and duration of infrastructure projects, the uncertainty model has two other purposes: it is the preparatory point for allocation of budget, and it is used to update the impact of the uncertainties and to evaluate the effectiveness of countermeasures to mitigate their threats.

8.6 RECOMMENDATIONS

Based on the findings and conclusions from the study presented, the following recommendations are outlined to enlighten infrastructure project stakeholders and project planners and provide necessary knowledge and support to the construction infrastructure estimators on how to model appropriately and estimate accurately the impacts of uncertainties on the construction process of infrastructure projects.

Recommendations to the project planners:

- Utilise reliable estimation techniques, such as the uncertainty model to estimate the accurate cost and time of infrastructure projects for allocation of the budget instead of exercising contingency. (Mostly, the cost overruns are significantly larger than the assigned contingency, while the time overruns are almost twice the estimated construction time).
- Engage knowledgeable external estimators for modelling the construction of infrastructure and uncertainties, to avoid inside underestimation of cost and time of infrastructure projects (prevent psychological, optimism biases).

Recommendations to the estimators:

- Employ both the construction and uncertainties models in the estimation of construction cost and duration of infrastructure projects to forecast accurately the impacts of uncertainties on construction cost and time of different activities and structures of the infrastructure projects.
- Utilise the advantages of intelligent estimation techniques, such as machine learning and fuzzy logic, on the estimation process to improve the accuracy of the estimation and reduce the level of the data required.
- Exploit the required estimation data, such as the possible range of unit costs and production rates from experts' panels, instead of using the idea of an individual expert.
- Calibrate the expert panel through training sessions and validate their estimations using previous projects' data.
- Accumulate a technical library to record previous project data, such as unit cost, production rate, disruptive events and lessons learned.

Recommendations to the highway project managers:

- Assess and analyse the project uncertainties by using appropriate tools, such as the uncertainty model, from time to time to update the impact of the uncertainties, and evaluate the effectiveness of countermeasures to mitigate their threats on construction of infrastructure projects.

Recommendations to the highway contractors:

- The earthwork contractor should focus on mitigating the occurrence of disruptive events, such as latent ground conditions and human made disasters to keep both total cost and total time within the target.
- The bridge and pavement contractors should apply measures of cost correlation between the activities in their structures and mitigation of the impact of disruptive events on time to contain costs and meet deadlines.
- The general contractor must consider all three sources of uncertainty (variability, correlation, disruptive events) to contain the total cost, and focus on the technical and financial disruptive events to contain the total time. In order to minimise the total cost of the entire project, the focus of the general contractor should be on the correlation between the activities and disruptive events, since they have the largest impact on total overall cost, while in order to minimise total time, attention should be paid to the disruptive events that occur during the execution of the bridge structure, since the time taken by the bridge structure determines the critical path of the project.

Recommendations to the government agencies:

- The government agencies such as SANRAL and cidb as the policy makers should to establish and implement some regulations and policies to prevent or minimise the impacts of the legal, economic and social disruptive events such as corruption and fluctuation of prices of materials and equipment.
- Establish the national standard unit cost and production rate for infrastructure projects.

8.7 RESEARCH LIMITATIONS

Developing and applying the construction model and uncertainty model, although satisfactory, are subject to some limitations.

Due to the non-availability of data and commonality, the study application of the construction and uncertainties models was limited to new construction of a highway project in South Africa in which data was available, to demonstrate the effectiveness of the newly developed model in capturing the impact of uncertainty on the construction cost and duration of infrastructure projects.

The application of the construction model was limited to one resource in the earthwork structure, the material excavated in the cutting activity was reused in the filling activity, and two types of common bridges, culvert box and precast slab bridges.

Due to the higher probability and commonality of underestimation of cost and time in transportation infrastructure projects, the highway expert panel emphasised only the disruptive events with negative impact on cost and time.

Although the results of the model were significant and supported theoretically, some adjustments should be considered before generalising the results of the study to other types of infrastructure projects and geographical areas.

8.8 FUTURE RESEARCH

Corresponding to the research findings and limitations deliberated, the study provides the following potential areas for future research:

- The construction model and uncertainty model should be applied to other types of infrastructure projects to validate the applicability of the developed uncertainty model in different types of infrastructure projects.
- All the actual resources in the various structures of infrastructure projects should be included in the construction model of the project.
- If the national input data, such as unit cost and production rate, are available in the area of the study, they should be considered.
- The positive impact of disruptive events should be modelled.
- The impact of using modern construction methods and new materials in infrastructure projects should be investigated.

8.9 CRITICAL REFLECTION ON THE STUDY

The goal of this section is to reflect on the level of knowledge of the phenomenon at the commencement of the research endeavour and the advancement in such levels through to the end of the research project.

The apparent gap in the estimation of construction cost and time of infrastructure projects and a long list of infrastructure projects, which encountered enormous cost and time underestimation, gave the impression that an intelligent hybrid estimation model could address this gap and improve the accuracy of cost and duration of infrastructure projects. However, there were some challenges regarding the availability of initial data and the validation of the model.

The preliminary discussions with experts in the field of transportation infrastructure projects provided very useful advice on various aspects of the data collection: interviews with infrastructure project managers, and considering a wide range of disruptive events and not ignoring any events. All of these experts showed an interest in the subject and approach of the research, which was promising.

However, in these discussions, they clearly highlighted that there is no infrastructure database available in South Africa. This challenge compelled the use of expert opinion, experts' estimation, and a project manager survey as primary data, and the use of the limited historical data of infrastructure projects in South Africa as secondary data.

Through modelling each structure of the highway project, the importance of integrating the construction model of the project to the estimation model was clearly realised, which guaranteed that the correct specifications and details in the estimation modelling were used. Furthermore, the existing review and study of uncertainty and risk provided a clear difference between the

uncertainty and risk and helped the author in selecting a proper intelligent analysis technique for modelling each source of uncertainty.

The research was split into four phases to manage the complexity of the research problem, which facilitated dealing with each phase in detail and being able to develop the single-phase methodology components separately. This is based on the fact that estimation modelling development happens through the different defined phases and these phases were the basis of the dynamic systems development method. Due to the different characteristics of each phase, the methodology had to be projected as four single-phase methodologies. However, this research experienced no contradictions to the discrete nature of the phases, and it was observed that the phases are congruent to the entire dynamic systems development method. The sequence of distinct stages produced a continuous stream of modelling development, which forced the realisation that the transition over the phases had to be there; that data transformation from one phase to the next had to be foreseen.

A challenge encountered in the study was to find the right software that is able to integrate different techniques. Hence, a basic construction project was tested and modelled in PYTHON, R and MATLAB environments to determine the feasibility and potential of each modelling environment. A tailormade simulation, which enabled the integration of the construction and uncertainty models to simulate the uncertainty in the construction of a highway project was developed in a MATLAB environment because of the availability of various probability distribution functions and machine learning techniques in MATLAB.

Finally, the things, which would have been done differently in this research, would have been to analyse the disruptive events more comprehensively and model the positive outcome of disruptive events on cost and time of infrastructure projects and the mitigation measures applied in the case study to limit the disruptive events.

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APPENDIX A: QUESTIONNAIRE



UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Department of Construction Economic & Management
Faculty of Engineering and the Built Environment.
University of Cape Town, Rondebosch,
Cape Town, South Africa.

Dear Madam/Sir,

MODELLING UNCERTAINTY OF COST AND TIME IN INFRASTRUCTURE PROJECTS

Good Day, my name is Alireza Moghayedi, and I am conducting research towards a doctoral degree in Construction Economics and Management at the University of Cape Town. The research examines the uncertainty in the construction process of infrastructure projects and would like to invite you to participate in this research because you are project manager ofhighway project and your knowledge and experience as an professional highway project manager can contribute much to assessing the uncertainties in infrastructure projects.

Completing and providing information to this questionnaire should take about 35 minutes of your valuable time.

If you accept to participate in this study, the questionnaire form will be provided to you. If you do not wish to answer any of the questions, you may skip them and move on to the next question.

This questionnaire contains two parts: Part 1. Introductory Information and Part 2. Technical Information

- In part 1, you will provide information to some introductory questions such as your age, education, profession, position, and your experience related to the construction of highway projects
- In Part2, you will assess the probability of occurrence and severity of different disruptive events to the construction cost and time of your last three projects.

All the information provided is confidential, your name will not be included on the forms, only a number will identify you. No information that you provide about your projects will be shared with anybody outside, and nothing will be attributed to you by name. Data collected will be collected in an aggregate form and identification information will never be used in a publication or presentation.

Please understand that your participation in this research is entirely voluntary. The choice to participate is yours alone. If you choose not to participate, there will be no negative consequence. If you choose to participate but wish to withdraw at any time, you will be free to do so without any negative consequence. However, I would be grateful if you would participate in this study.

There is a risk that you may share some personal or confidential information by chance, or that you may feel uncomfortable, you do not have to answer any question or take part in the questionnaire if you feel the question(s) are too personal or if talking about them makes you uncomfortable. There is not any risk of emotional, upset, or stigmatisation that you encounter during this survey.

There is no direct benefit to you by participating in this research. The knowledge gained may benefit the public in the future. The knowledge that obtained from this research will be shared with you before it is made widely available to the public. Also, you will receive a summary of the results if you indicated this on the questionnaire.

This document acknowledges you understand of your rights as a participant in this study, which the researcher has explained to you prior to signing the document.

I acknowledge that the researcher has explained my rights, the requirements of this study, and the potential risks involved in participating in this study. I understand there is no compensation for or direct benefit of participating in this study. By signing below and providing my contact information, I am indicating that I consent to participate in this study that I am at least 18 years of age, and I am eligible to participate in this study.

Name of participant Date
Signature of participant
Contact Information

Thank you for your participation,

You may withdraw from this study at any time by notifying researcher by email. If you have concerns regarding your participation in this research study, you may contact research supervisor.

Researcher: Alireza Moghayedi
Email Address: MGHALI001@myuct.ac.za

Research Supervisor: Professor Abimbola Windapo
Email Address: abimbola.windapo@uct.ac.za

Questionnaire

Thank you for agreeing to take part in this survey which investigates the Uncertainties in Construction Cost and Time of Highway Projects. The goal of this survey is to identify the probability of occurrence and severity of disruptive events to the construction cost and time of your last three highway projects.

Please answer the following questions which should take about 35 minutes.

All responses will remain confidential and used only by the Researcher.

Thank you in advance for your help.

Part 1. Introductory Information:

Please provide the following introductory information

What is your age?

	25-34	35-44	45-54	55-64	65>
Years old					

What is the highest degree or level of education you have completed? (related to the highway construction)

	Bachelor	Master	PhD
Degree/Level			

What is the main source of your profession?

	Engineering	Construction Management	Other / Please Specify
Profession			

How many years have you been working at highway construction projects?

	5-9	10-14	15-19	20-24	25>
Years					

How many highway projects have you been engaged as project manager role?

	1	2-5	6-10	11-15	15>
Project					

Part 2. Technical Information:

Part 2.1: Please assess the probability of occurrence of each following disruptive events on highway projects based on your last three projects.

Please specify the probability of occurrence of each economical disruptive events during construction of highway projects.

Disruptive events	Probability of Occurrence				
	Rare	Unlikely	Possible	Likely	Almost Certain
Fluctuation of prices of materials and/or equipment					
Monopoly of material and/or equipment suppliers					
Saturated market					
Fluctuation in foreign exchange rate					

Please specify the probability of occurrence of each environmental disruptive events during construction of highway projects

Disruptive events	Probability of Occurrence				
	Rare	Unlikely	Possible	Likely	Almost Certain
Weather					
Natural disasters					
Remote location cost					
Terrain (or topographical site)					

Please specify the probability of occurrence of each financial disruptive events during construction of highway projects

Disruptive events	Probability of Occurrence				
	Rare	Unlikely	Possible	Likely	Almost Certain
Tax and/or legal fees					
Cash flow difficulties					
Poor financial control					
Lack of capital					
High tender price					
High cost of materials and/or equipment					
High cost of labour					

Please specify the probability of occurrence of each legal disruptive events during construction of highway projects

Disruptive events	Probability of Occurrence				
	Rare	Unlikely	Possible	Likely	Almost Certain
Right of way acquisition					

Deficient documentation					
Difficulties in importing equipment and materials					
Changes in government regulations and laws					
Unclear arbitration process for legal disputes between construction parties					
Changing of bankers' policy for loans					
Ineffective delay penalties					
Type of contract					
Problem in dispute settlement due to law					
Contract failure					

Please specify the probability of occurrence of each political disruptive events during construction of highway projects

Disruptive events	Probability of Occurrence				
	Rare	Unlikely	Possible	Likely	Almost Certain
Political situation					
Encroachment problems					
Human made disaster					

Please specify the probability of occurrence of each social disruptive events during construction of highway projects

Disruptive events	Probability of Occurrence				
	Rare	Unlikely	Possible	Likely	Almost Certain
Cultural heritage issue					
Personal conflicts among labour					
Social and cultural impacts					
Rehabilitation of affected people					
Disease					
Security					
Corruption					

Please specify the probability of occurrence of each technical disruptive events during construction of highway projects

Disruptive events	Probability of Occurrence				
	Rare	Unlikely	Possible	Likely	Almost Certain
General					
Size of contract					
Health and Safety					

Change order (change in the scope of the project)					
Difficulty of schedule					
Inadequate planning and scheduling					
Payment delay					
Contractual claim					
Improper construction methods					
Specification change					
Poor communication/coordination between construction parties					
Latent ground conditions					
Labour					
Inadequate labour productivity					
Absenteeism of labour					
Shortage of skilled workers					
Poor quality of workmanship					
Material					
Unreliable supplier of material					
Delay in material supply					
Bad quality of materials					
Shortage of materials					
Equipment					
Low efficiency of equipment					
Slow mobilisation of equipment					
Late delivery of equipment					
Availability of equipment					
Technology					
Obsolete technology					
New technology adoption					
Consultant					
Lack of experience in design and supervision					
Inaccurate investigation of construction site					
Frequent design changes					
Incomplete drawings, specifications					
Mistakes in design and/or specifications					
Inaccurate time and cost estimation					
Inadequate monitoring and supervision					
Delay in decisions making					
Lack of technical staff					
Contractor					
Lack of experience in the line of work					
Incorrect planning and scheduling					
Frequent change of subcontractors					
Poor quality of project management					
Re-work due to contractor errors					
Lack of technical staff					
Incompetent contractor/subcontractor					

Part 2.2: Please assess the severity of each following disruptive events on construction cost and time of highway projects based on your last three projects.

Please specify the severity of each economical disruptive events on construction cost and time of highway projects.

Disruptive events	Severity on Cost					Severity on Time				
	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
Fluctuation of prices of materials and/or equipment										
Monopoly of material and/or equipment suppliers										
Saturated market										
Fluctuation in foreign exchange rate										

Please specify the severity of each environmental disruptive events on construction cost and time of highway projects.

Disruptive events	Severity on Cost					Severity on Time				
	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
Weather										
Natural disasters										
Remote location cost										
Terrain (or topographical site)										

Please specify the severity of each financial disruptive events on construction cost and time of highway projects.

Disruptive events	Severity on Cost					Severity on Time				
	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
Tax and/or legal fees										
Cash flow difficulties										
Poor financial control										
Lack of capital										
High tender price										
High cost of materials and/or equipment										
High cost of labour										

Please specify the severity of each legal disruptive events on construction cost and time of highway projects.

Disruptive events	Severity on Cost	Severity on Time
-------------------	------------------	------------------

	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
Right of way acquisition										
Deficient documentation										
Difficulties in importing equipment and materials										
Changes in government regulations and laws										
Unclear arbitration process for legal disputes between construction parties										
Changing of bankers' policy for loans										
Ineffective delay penalties										
Type of contract										
Problem in dispute settlement due to law										
Contract failure										

Please specify the severity of each political disruptive events on construction cost and time of highway projects.

Disruptive events	Severity on Cost					Severity on Time				
	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
Political situation										
Encroachment problems										
Human made disaster										

Please specify the severity of each social disruptive events on construction cost and time of highway projects.

Disruptive events	Severity on Cost					Severity on Time				
	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
Cultural heritage issue										
Personal conflicts among labour										
Social and cultural impacts										
Rehabilitation of affected people										
Disease										
Security										
Corruption										

Please specify the severity of each technical disruptive events on construction cost and time of highway projects.

Disruptive events	Severity on Cost				Severity on Time					
	Insignificant	Minor	Moderate	Major	Catastrophic	Insignificant	Minor	Moderate	Major	Catastrophic
General										
Size of contract										
Health and Safety										
Change order (change in the scope of the project)										
Difficulty of schedule										
Inadequate planning and scheduling										
Payment delay										
Contractual claim										
Improper construction methods										
Specification change										
Poor communication/coordination between construction parties										
Latent ground conditions										
Labour										
Inadequate labour productivity										
Absenteeism of labour										
Shortage of skilled workers										
Poor quality of workmanship										
Material										
Unreliable supplier of material										
Delay in material supply										
Bad quality of materials										
Shortage of materials										
Equipment										
Low efficiency of equipment										
Slow mobilisation of equipment										
Late delivery of equipment										
Availability of equipment										
Technology										
Obsolete technology										
New technology adoption										
Consultant										
Lack of experience in design and supervision										
Inaccurate investigation of construction site										
Frequent design changes										
Incomplete drawings, specifications										
Mistakes in design and/or specifications										
Inaccurate time and cost estimation										
Inadequate monitoring and supervision										
Delay in decisions making										
Lack of technical staff										
Contractor										

Lack of experience in the line of work									
Incorrect planning and scheduling									
Frequent change of subcontractors									
Poor quality of project management									
Re-work due to contractor errors									
Lack of technical staff									
Incompetent contractor/subcontractor									

APPENDIX B: ETHICS APPROVAL

Application for Approval of Ethics in Research (EIR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:

Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form before collecting or analysing data. The objective of submitting this application prior to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the EBE Ethics in Research Handbook (available from the UCT EBE Research Ethics website) prior to completing this application form: <http://www.ebe.uct.ac.za/ur/eberesearch/ethics.pdf>

APPLICANT'S DETAILS	
Name of principal researcher, student or external applicant	
Alreza Moghayedl	
Department	
Construction Economics and Management	
Preferred email address of applicant:	
MGHALIDD1@myuct.ac.za	
If a Student	Your Degree: e.g., MSc., PhD, etc.,
	Name of Supervisor (if supervised):
PhD	
A Professor Abimbola Windapo	
If this is a research contract, indicate the source of funding/sponsorship	
Click here to enter text.	
Project Title	
Modeling Uncertainty of Cost and Time in Infrastructure Projects	

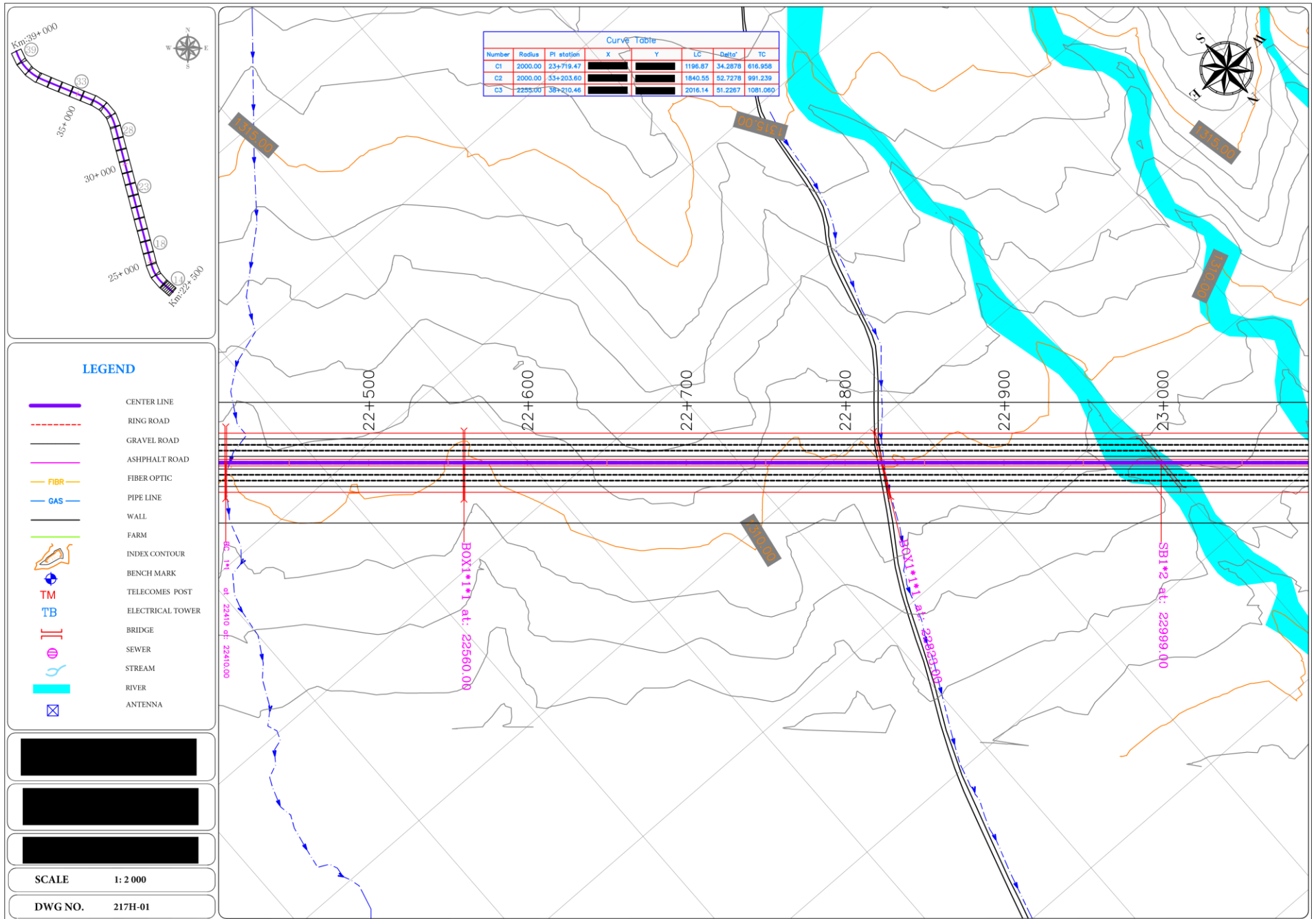
I hereby undertake to carry out my research in such a way that:

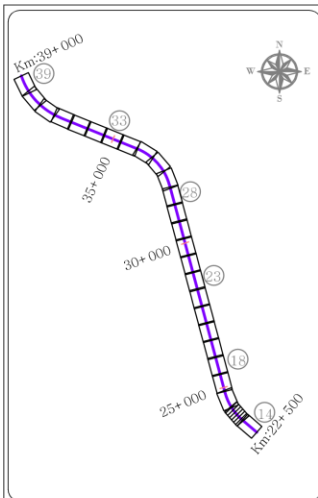
- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/ External applicant	Alreza Moghayedl		23 Nov 2018

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	A/Professor Abimbola Windapo		24 Nov 2018
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).	Click here to enter text.		
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	G. SITHOLE Click here to enter text.		22/12/2018 Click here to enter a date.

APPENDIX C: PLAN AND PROFILE OF HIGHWAY PROJECT





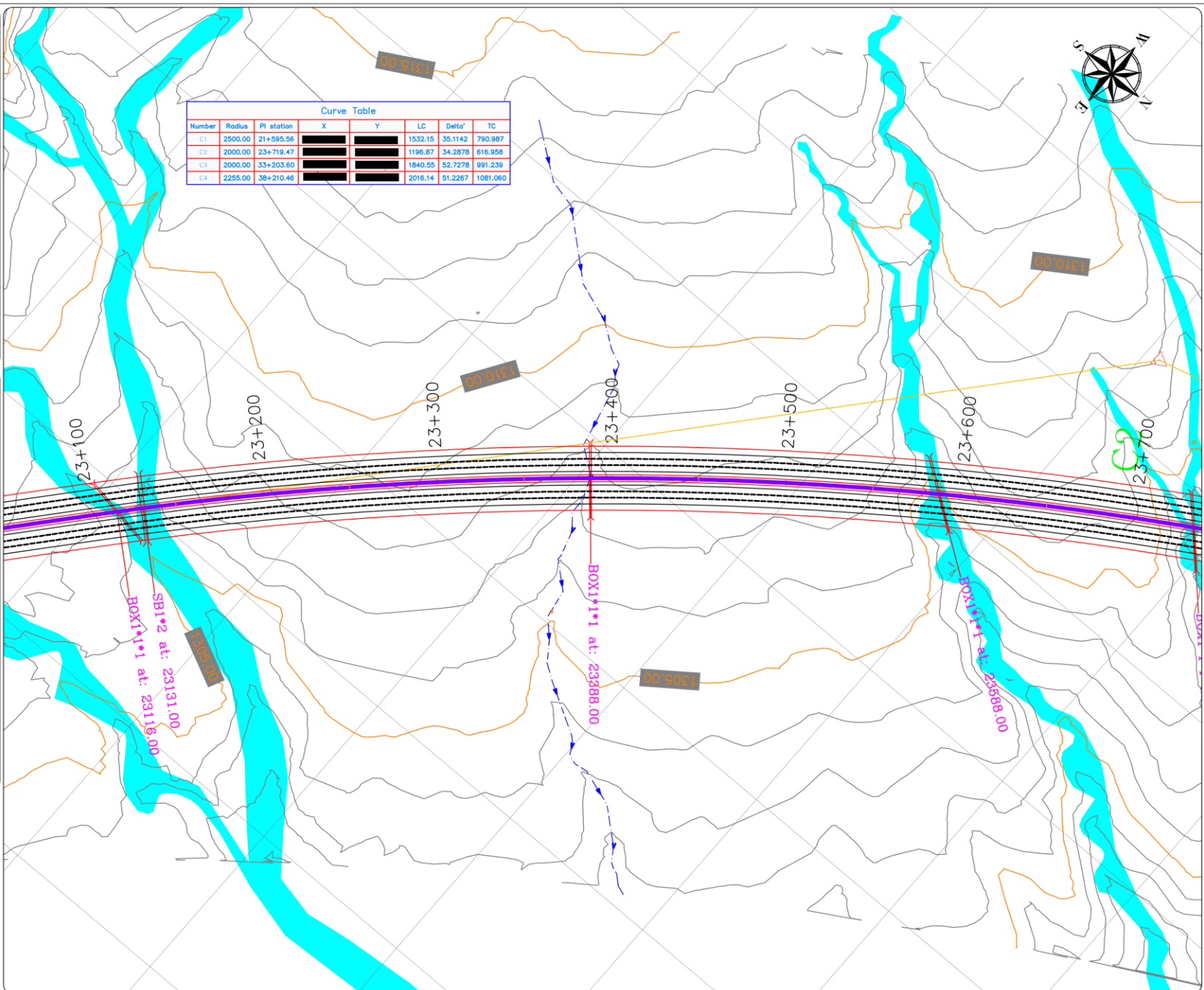
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C2	2000.00	23+719.47			1196.87	34.2878	616.958
C3	2000.00	33+203.60			1840.55	52.7278	991.239
C4	2255.00	38+210.46			2016.14	51.2267	1081.060

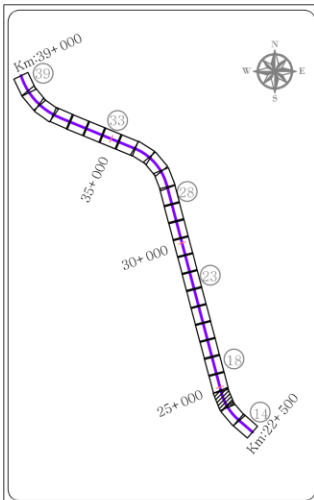
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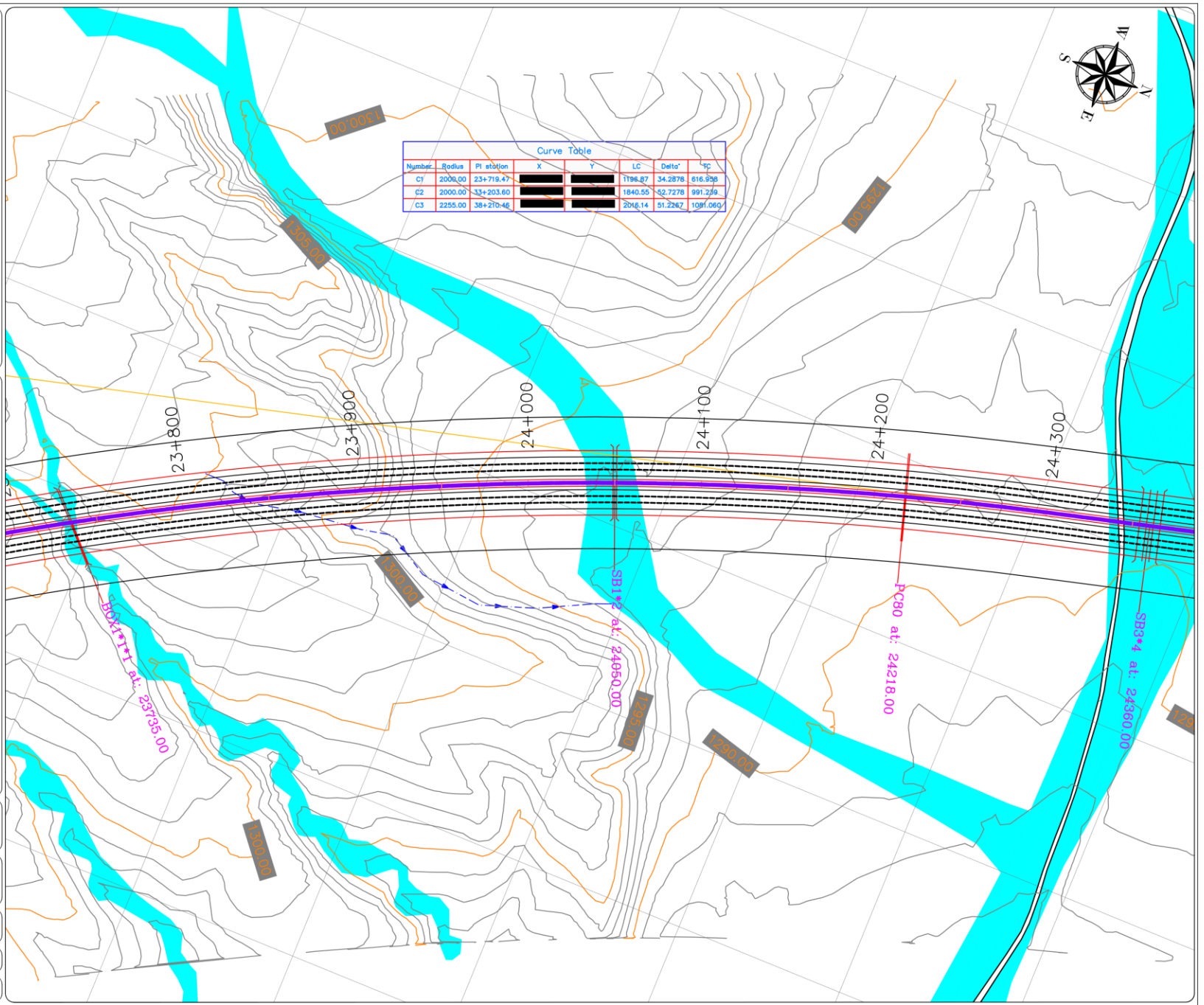
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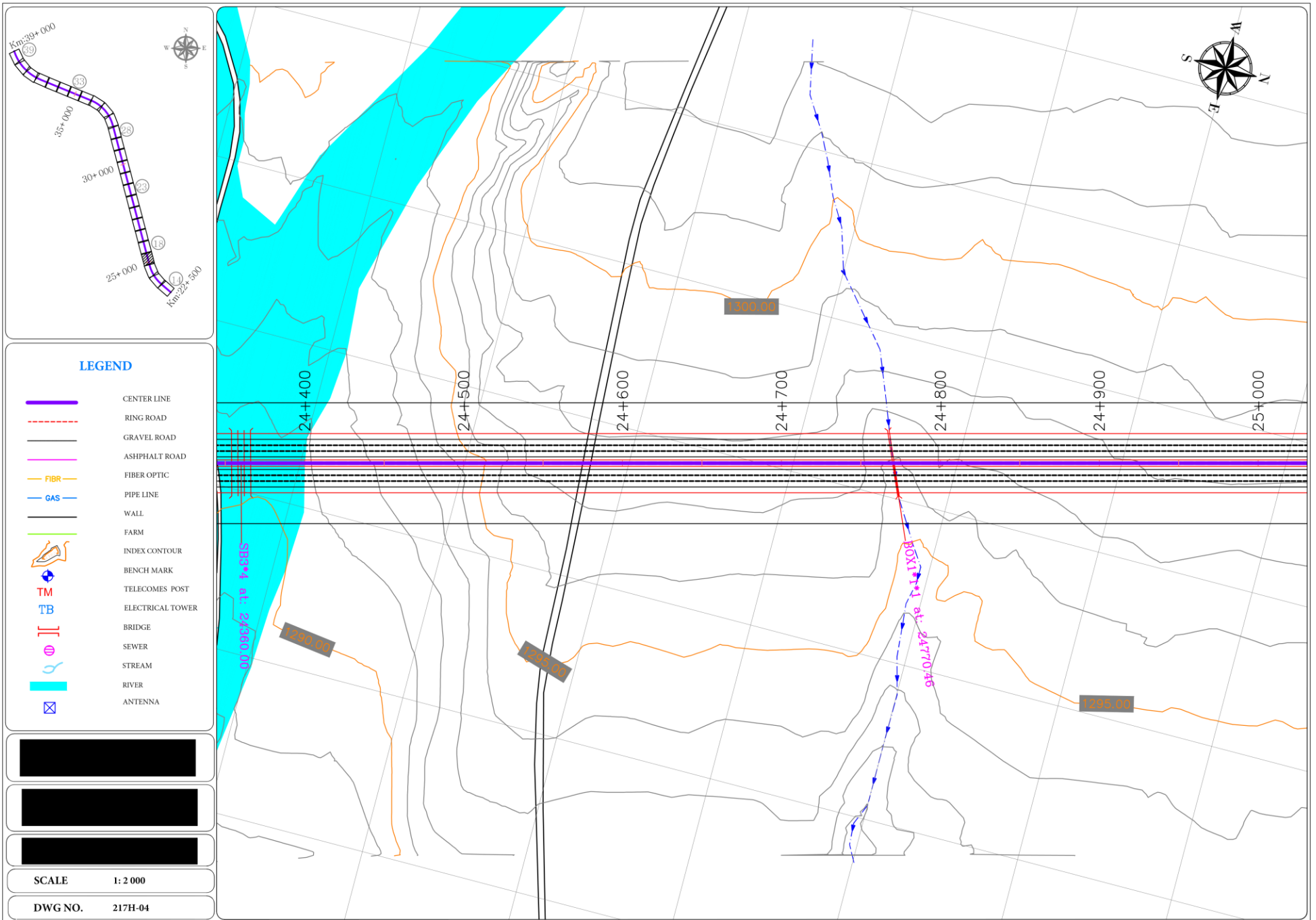


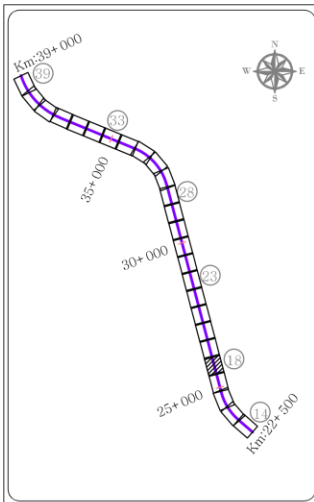
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Curve Table							
Number	Radius	PI station	X	Y	LC	Delta'	sc
C1	2006.00	23+719.47			1196.87	34.2876	616.938
C2	2000.00	33+203.60			1840.56	52.7276	991.259
C3	2255.00	38+270.46			2046.14	51.2267	1091.060



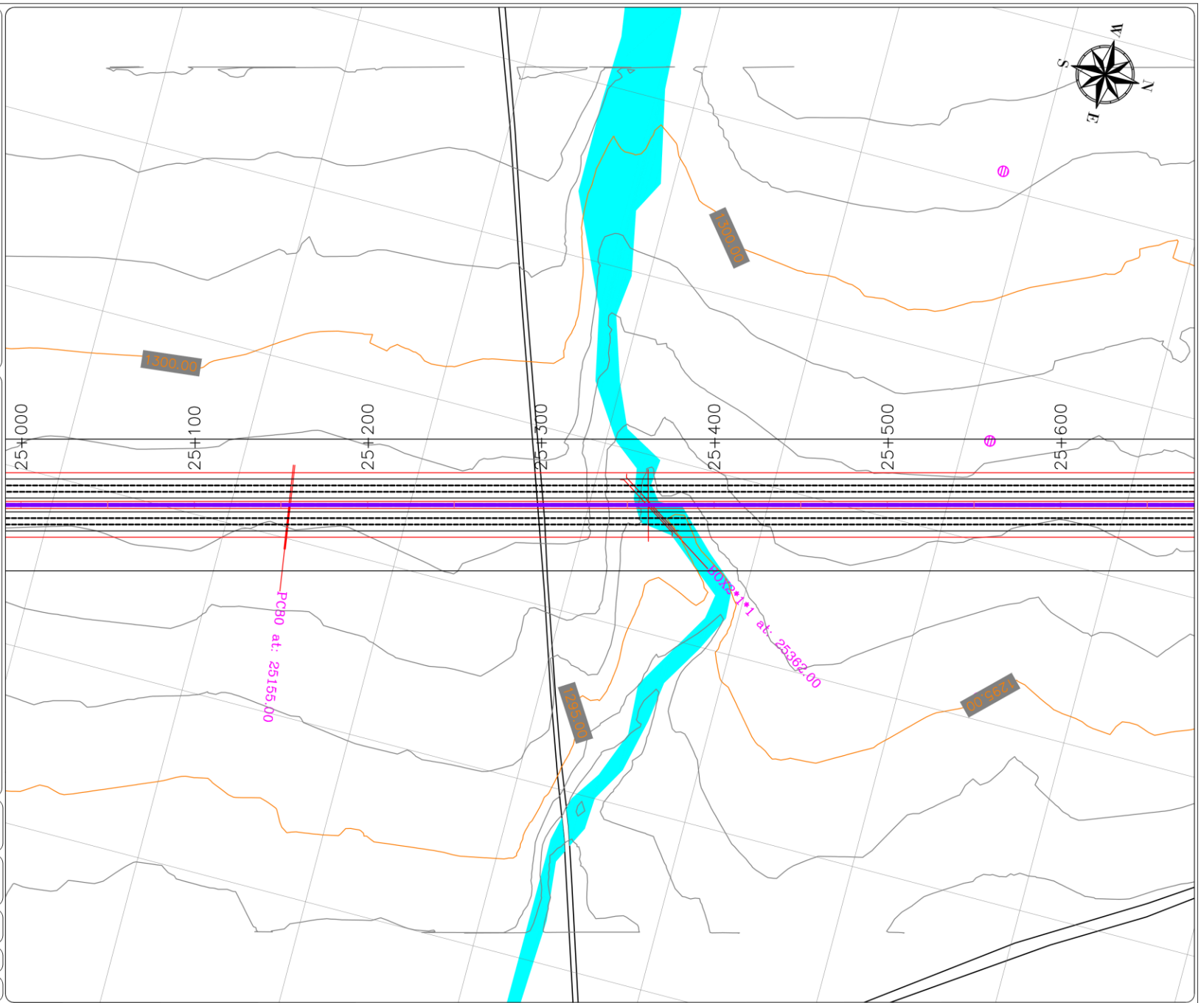


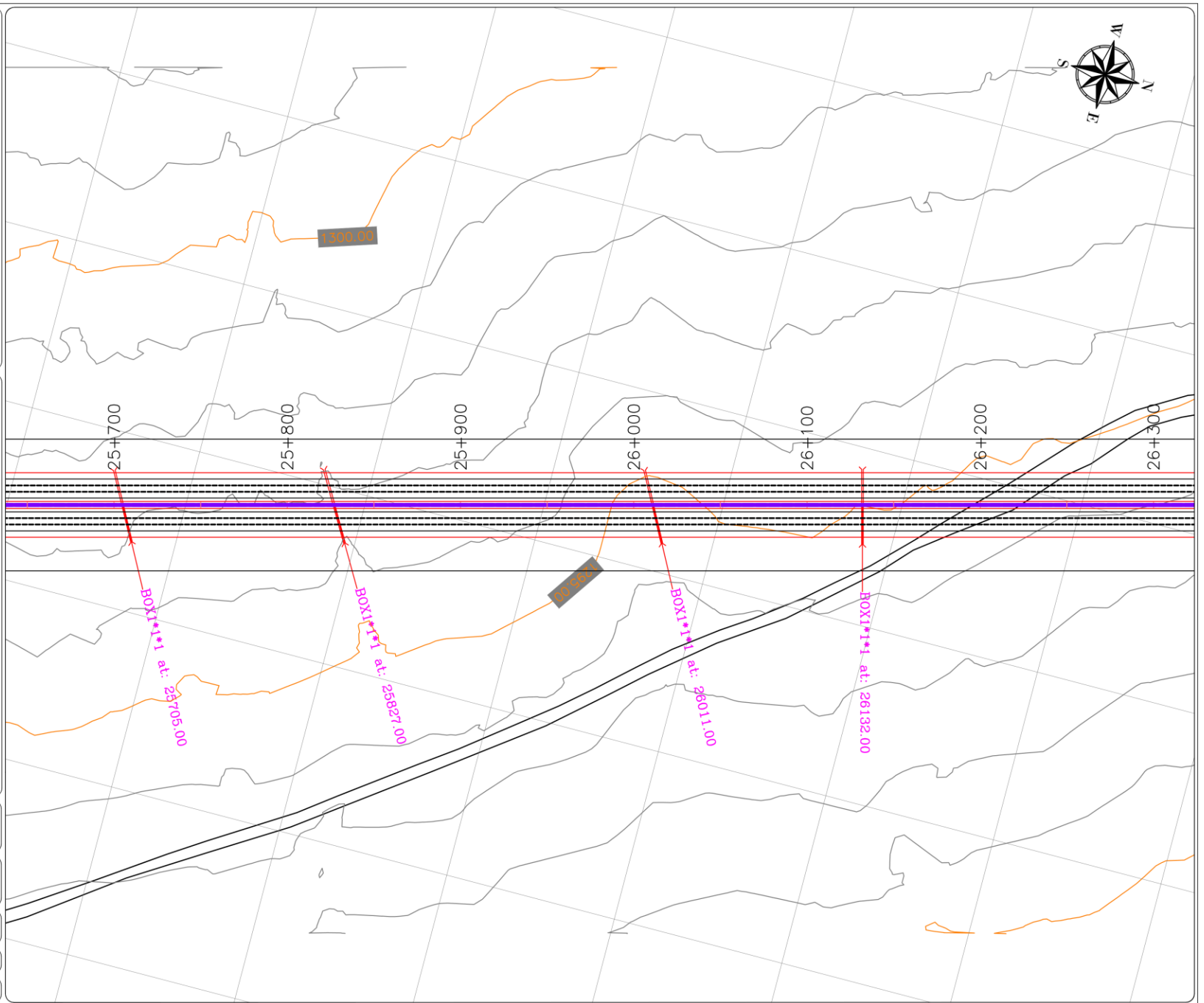
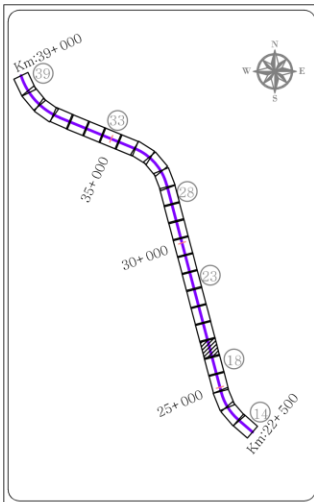
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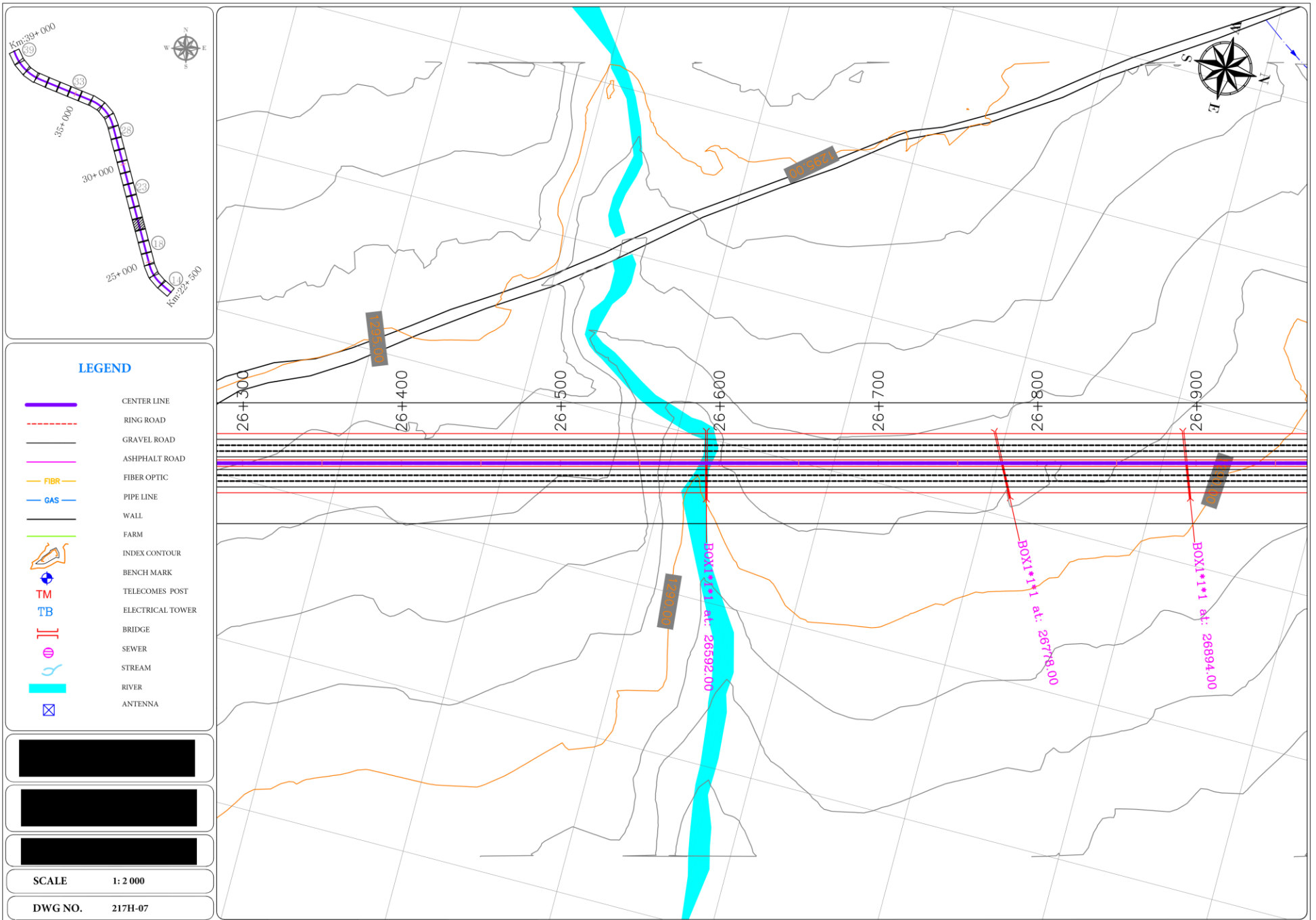


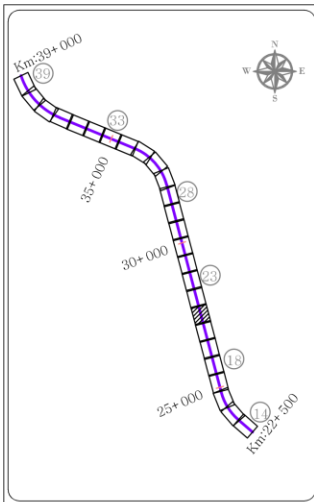


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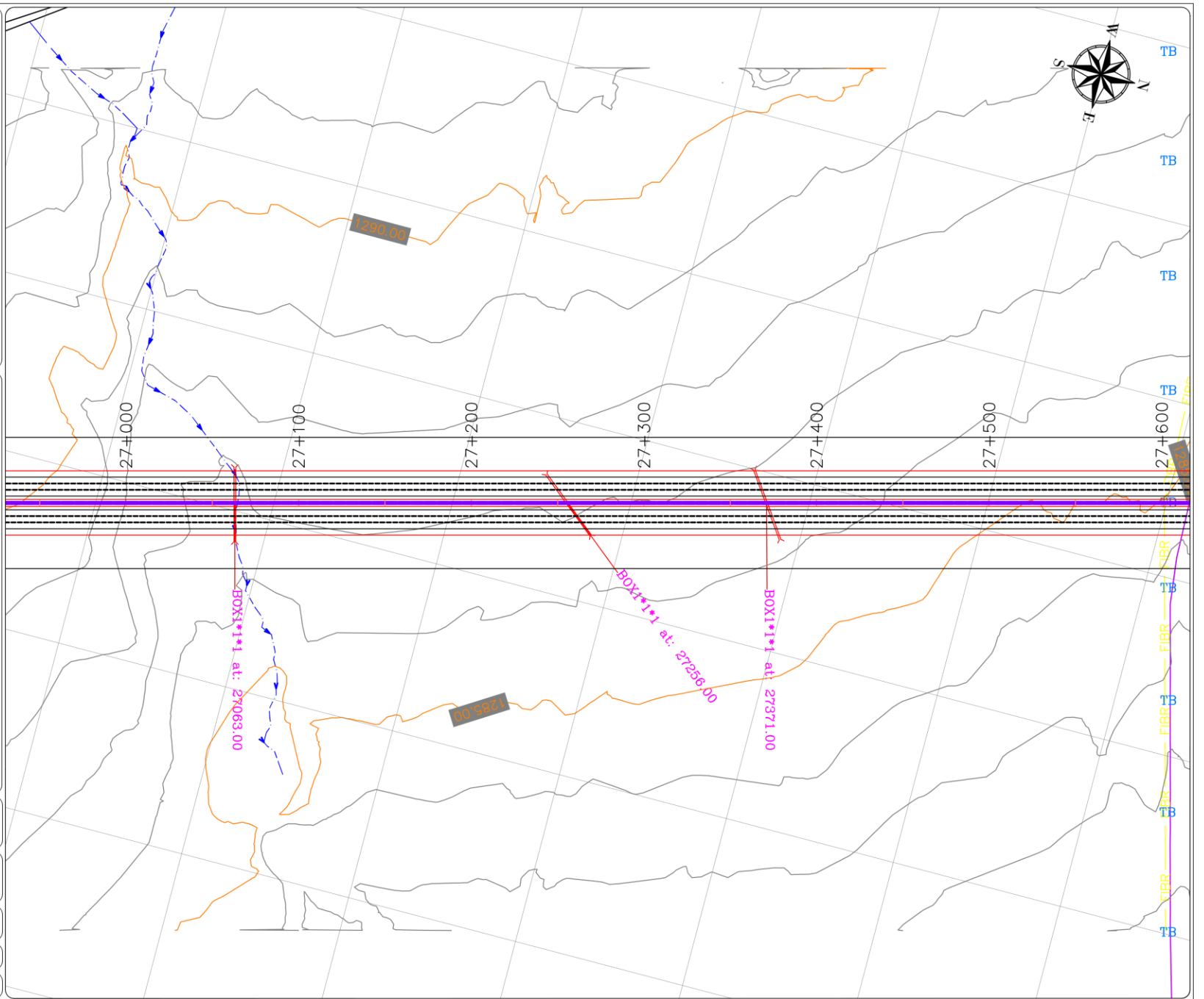
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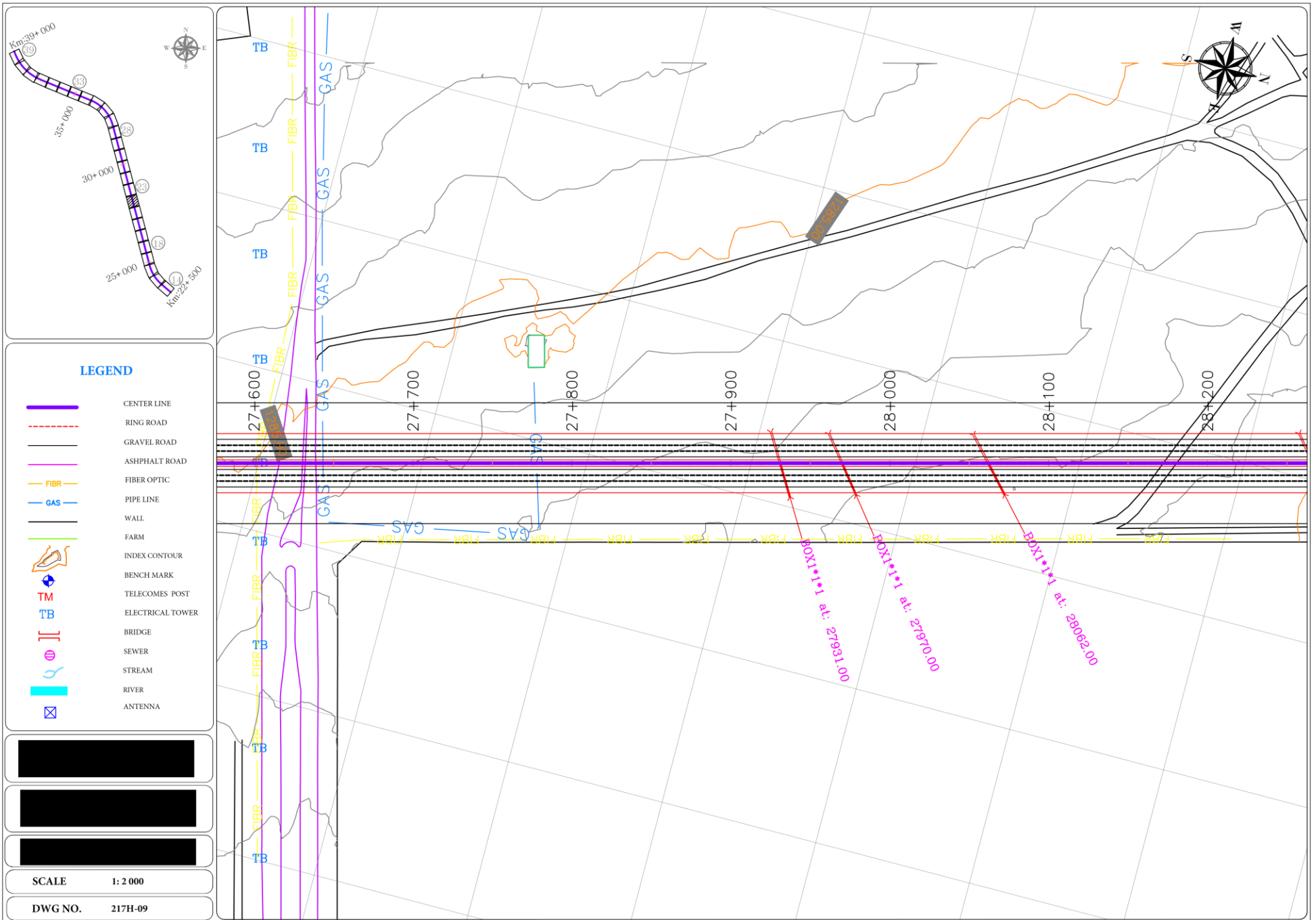
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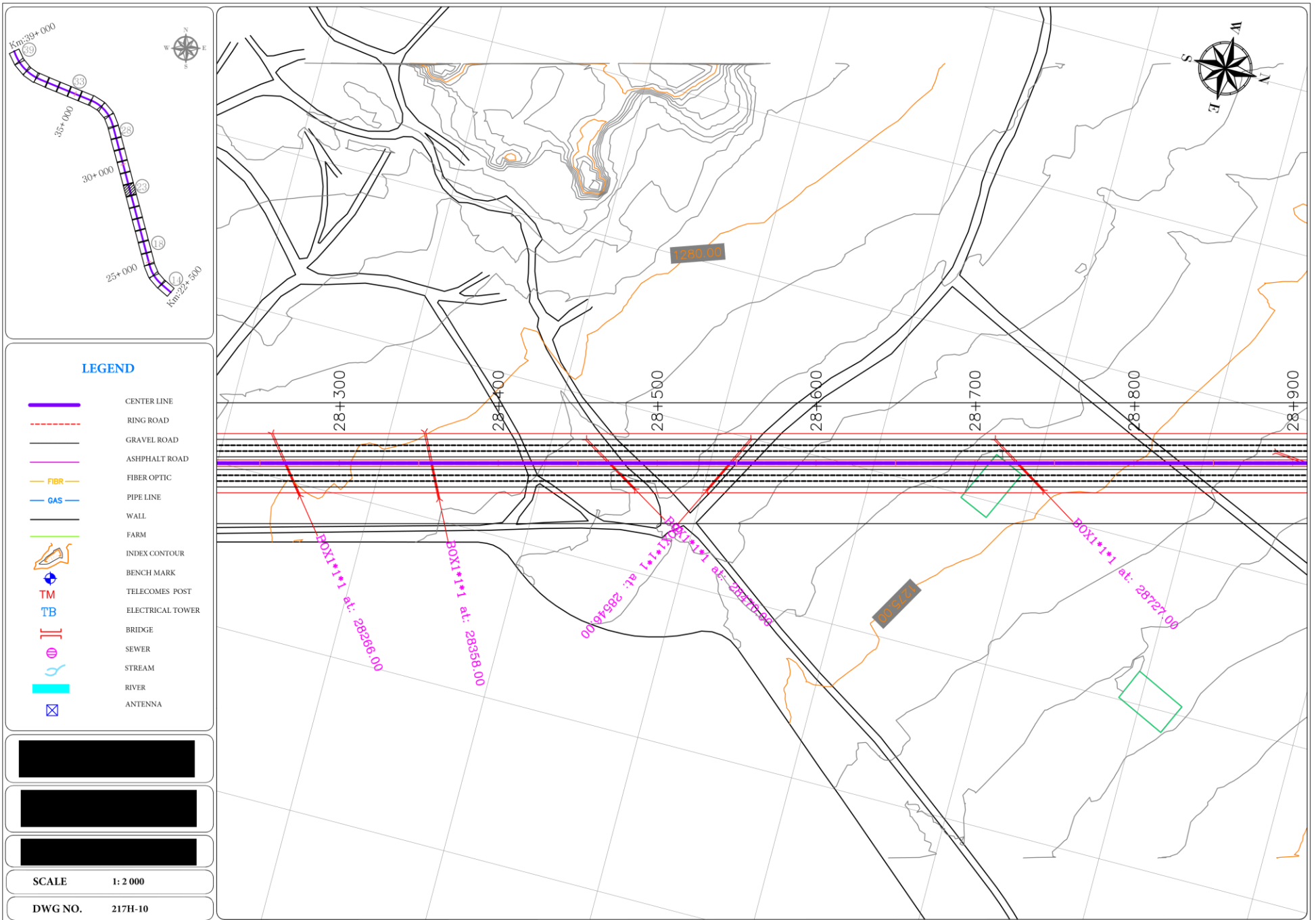


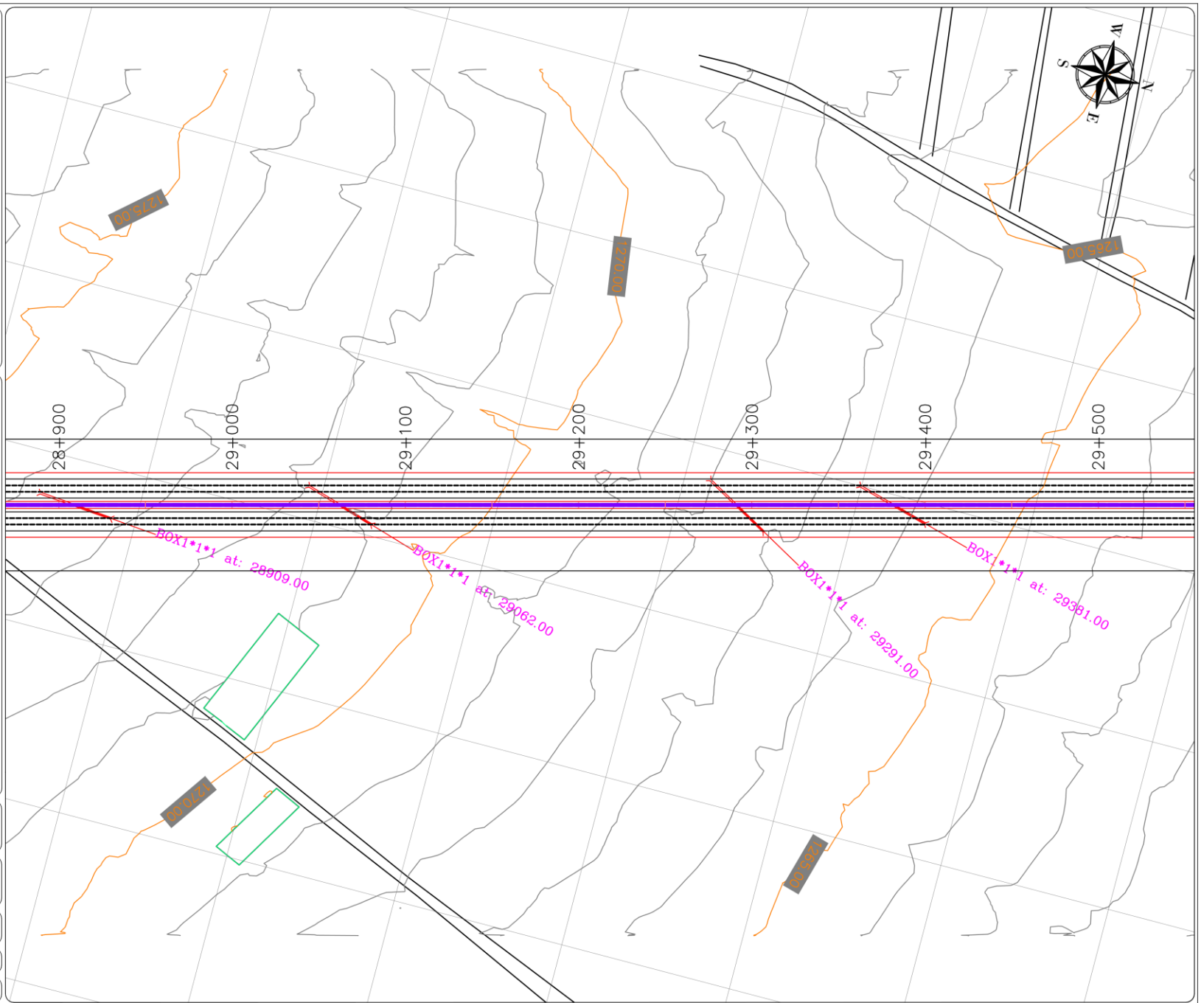
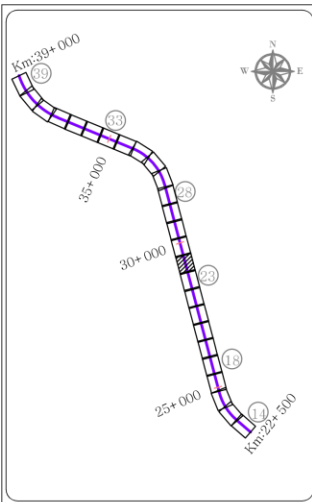
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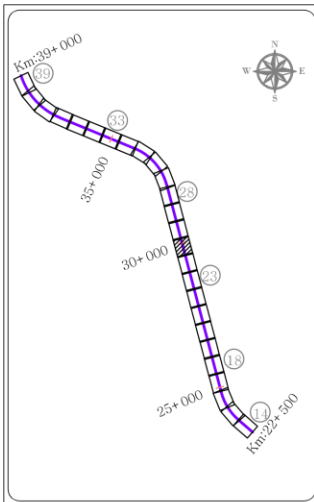





















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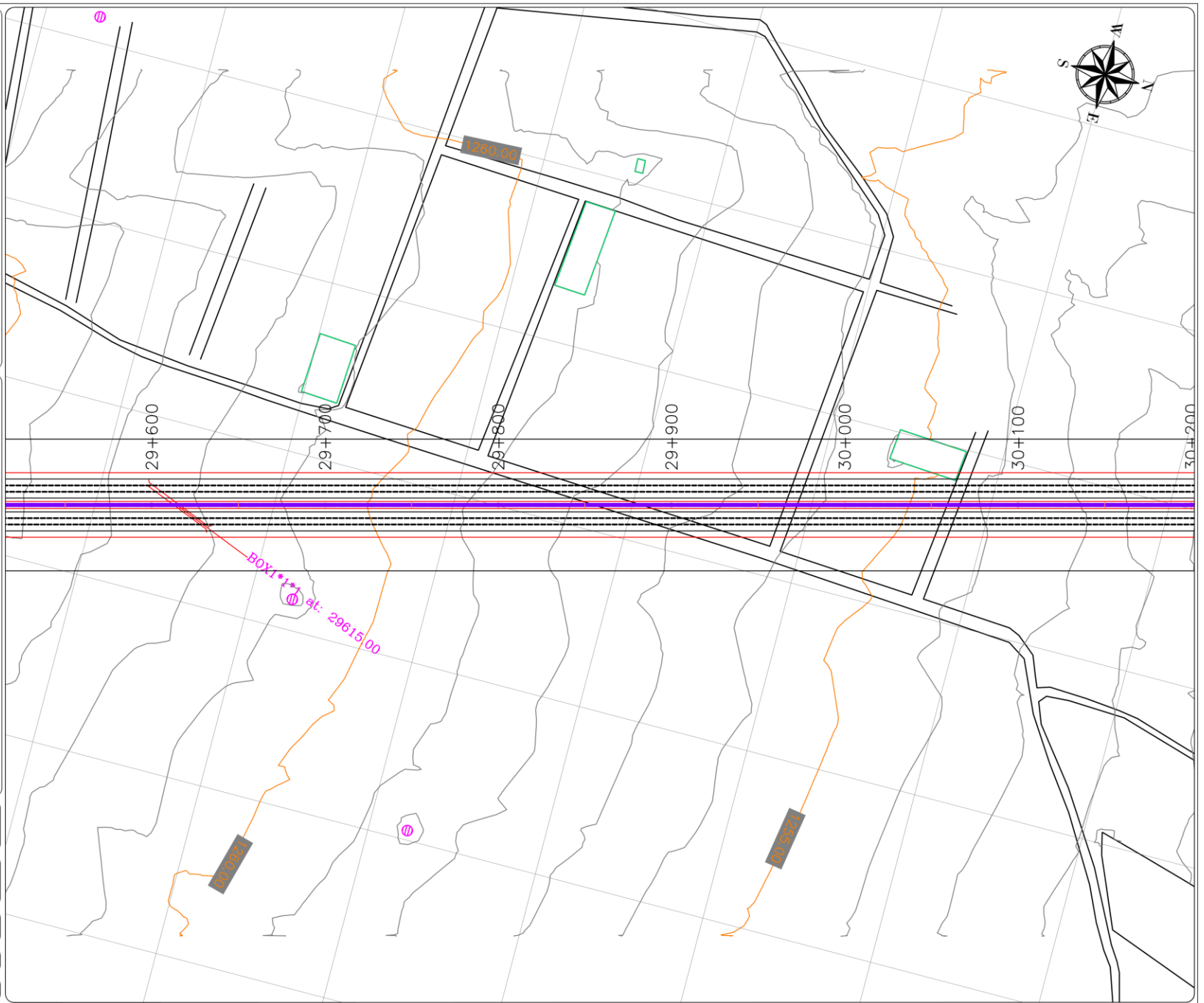
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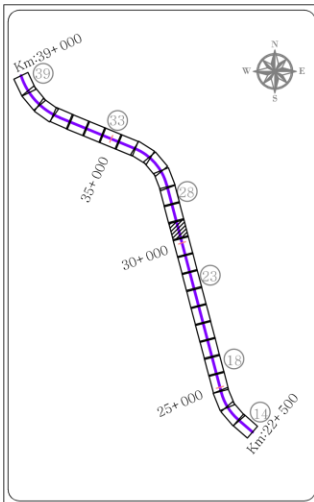


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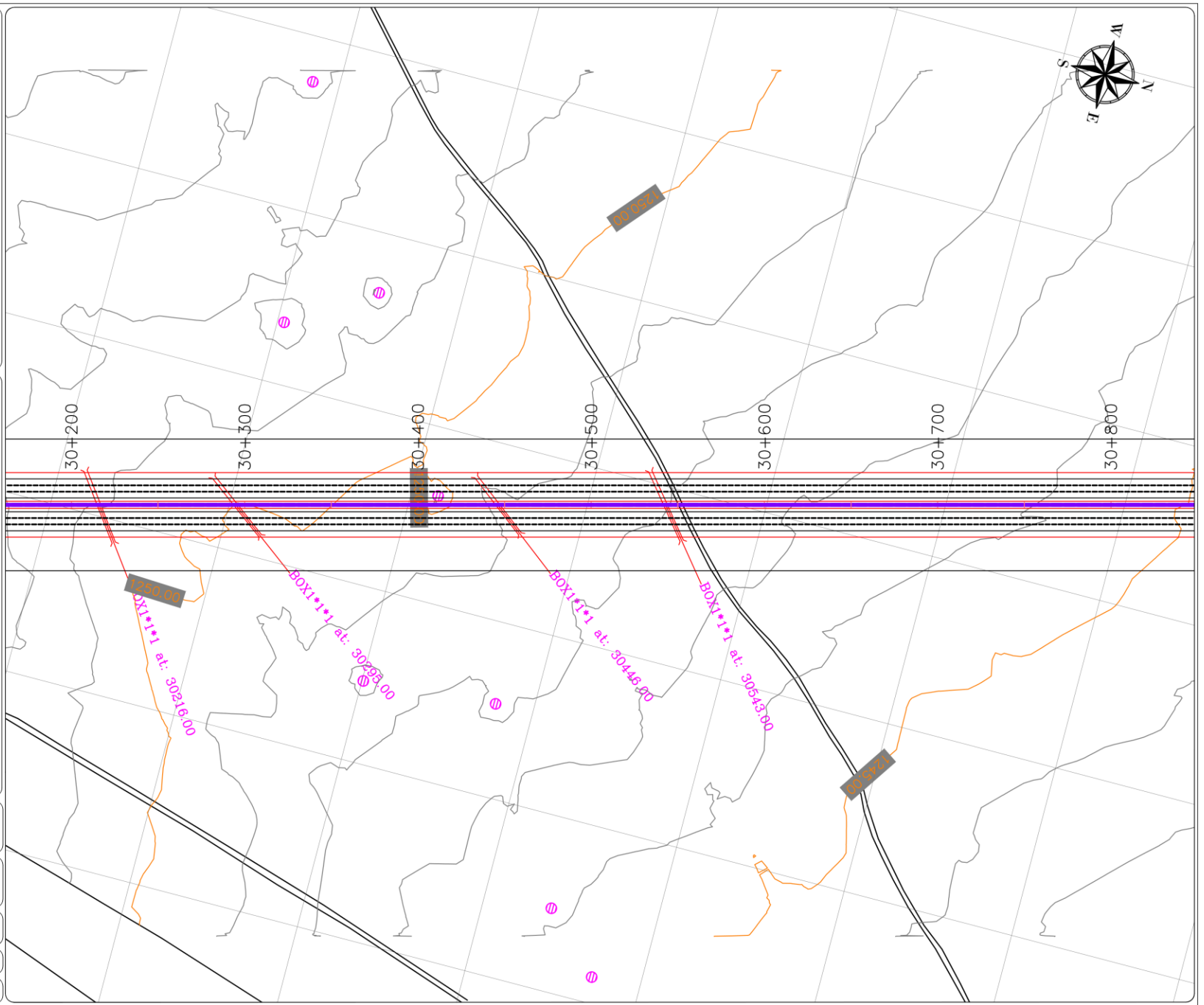


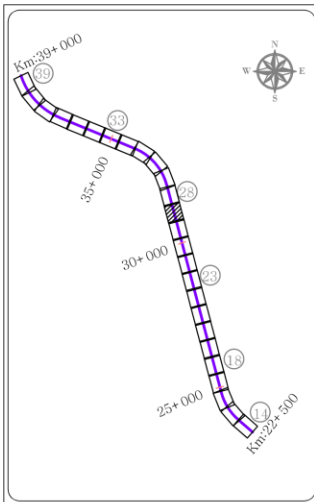


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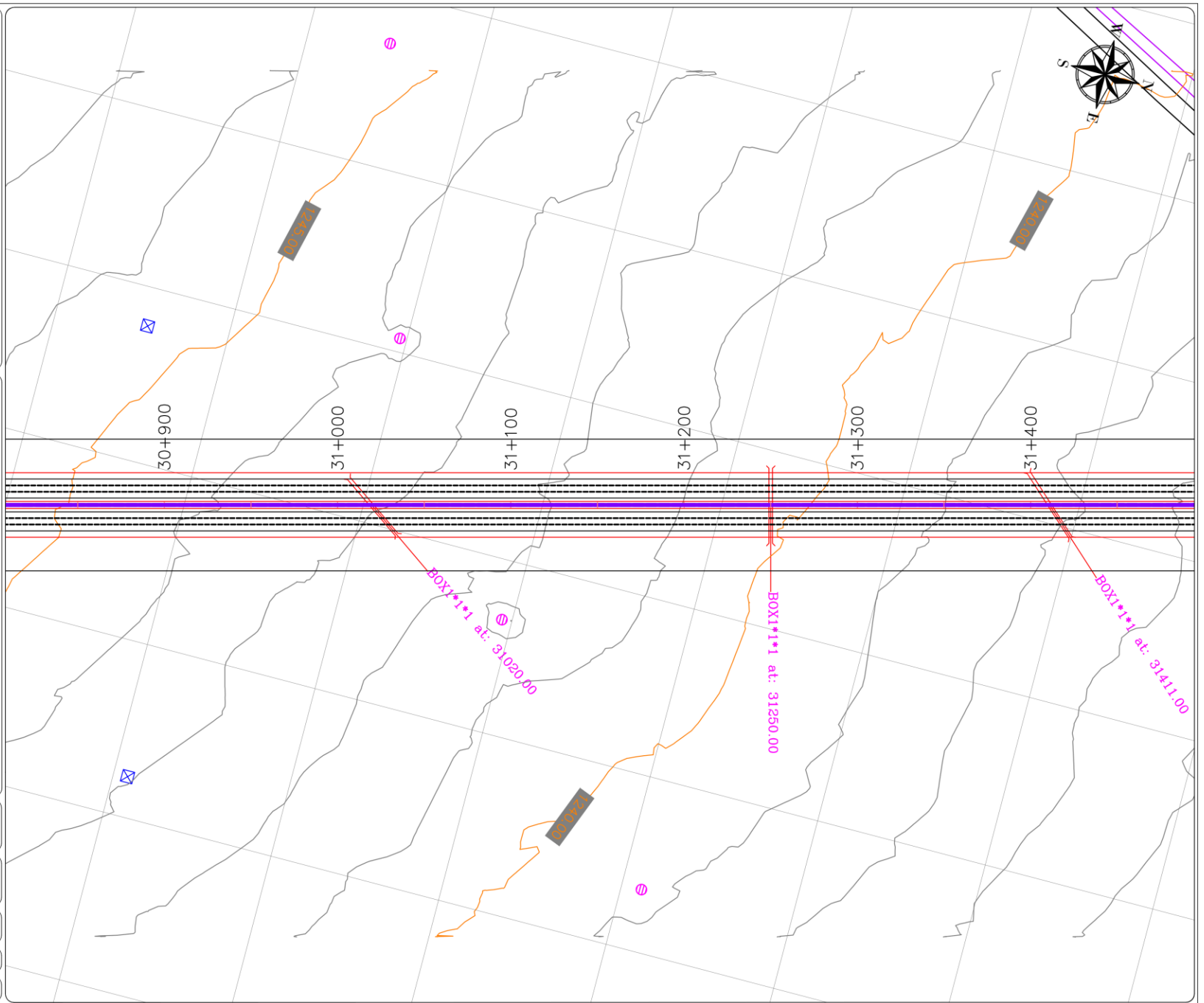


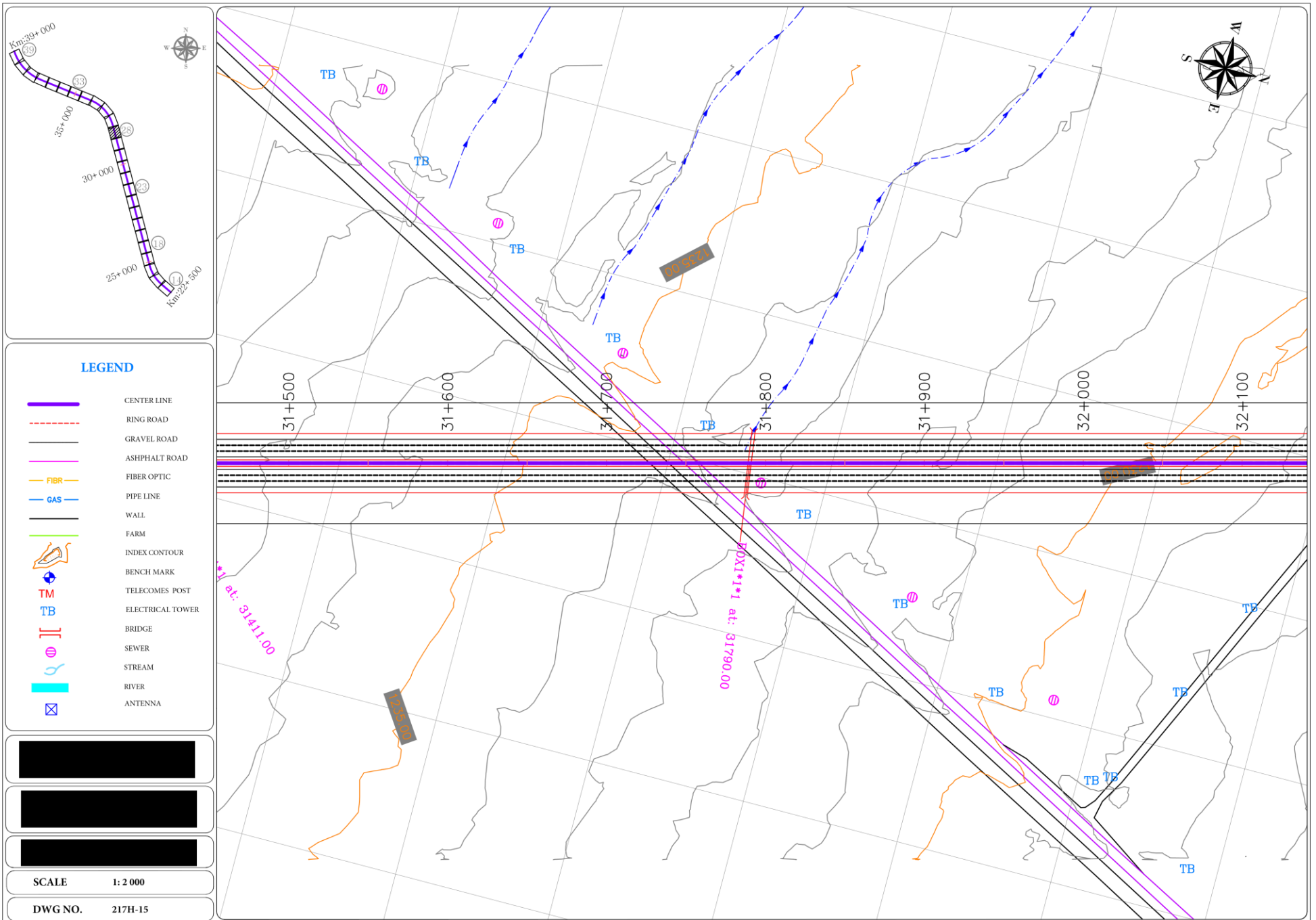
LEGEND

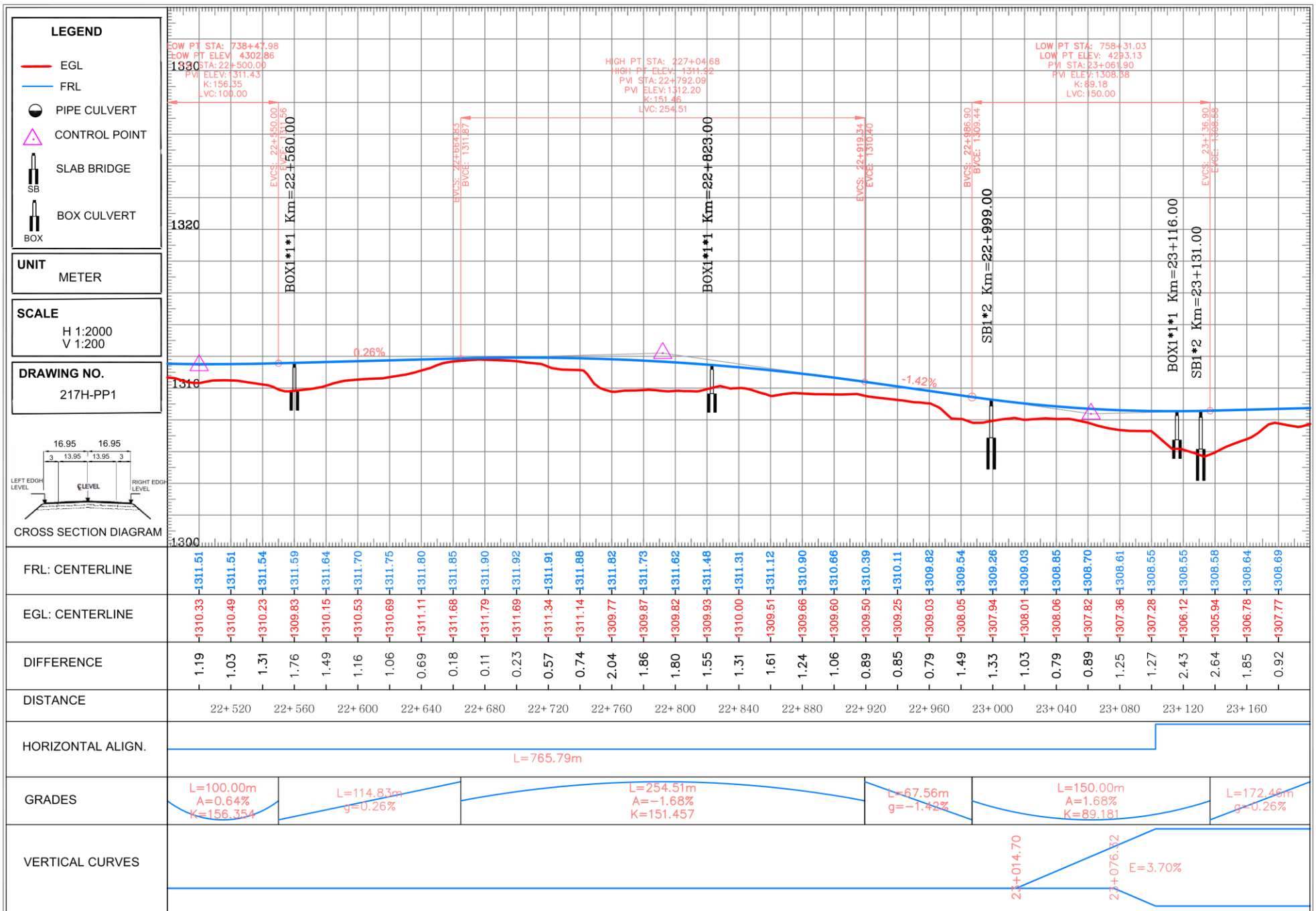
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	RING ROAD
	GRAVEL ROAD
	ASHPHALT ROAD
	FIBER OPTIC
	PIPE LINE
	WALL
	FARM
	INDEX CONTOUR
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	TELECOMES POST
	ELECTRICAL TOWER
	BRIDGE
	SEWER
	STREAM
	RIVER
	ANTENNA

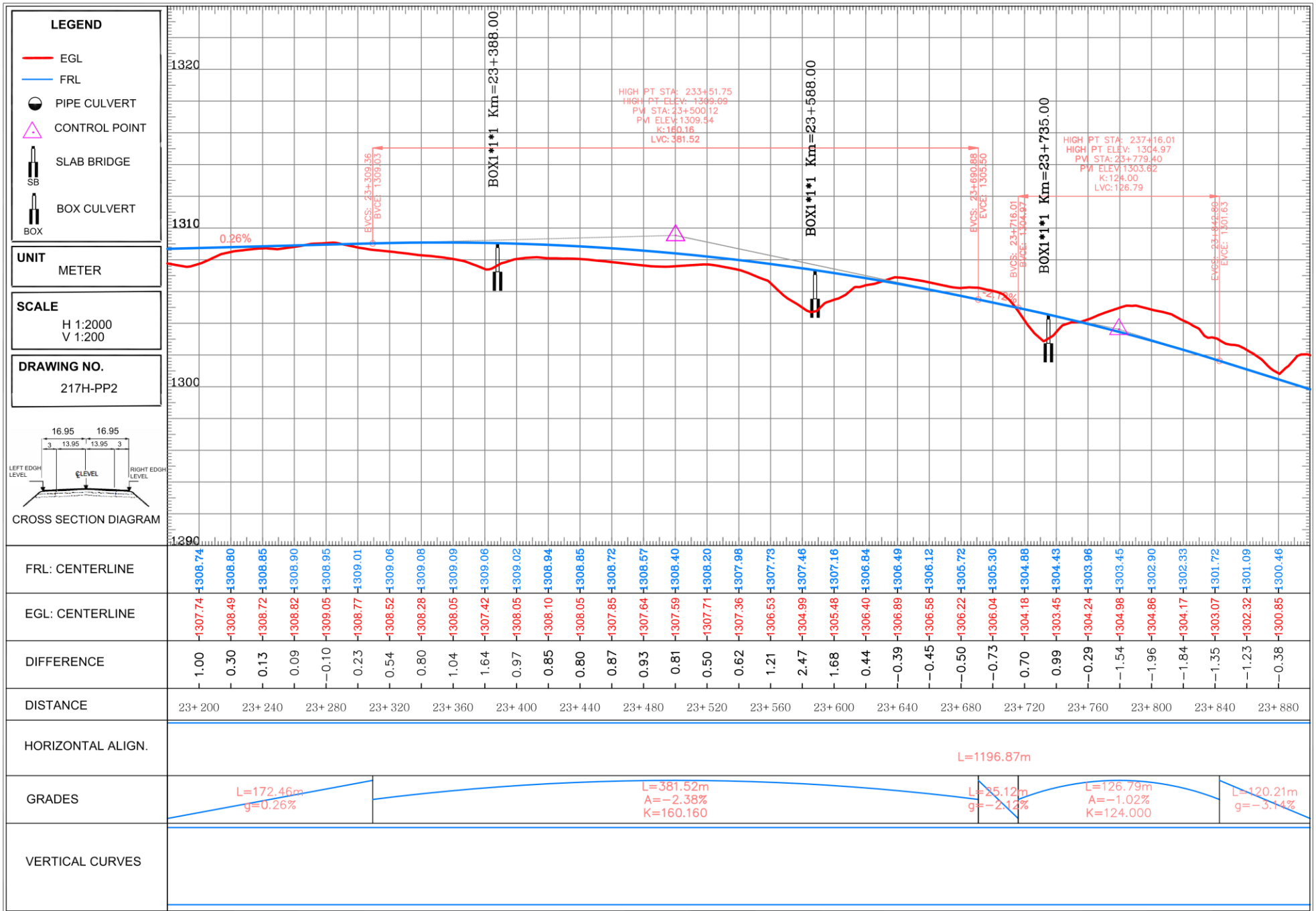
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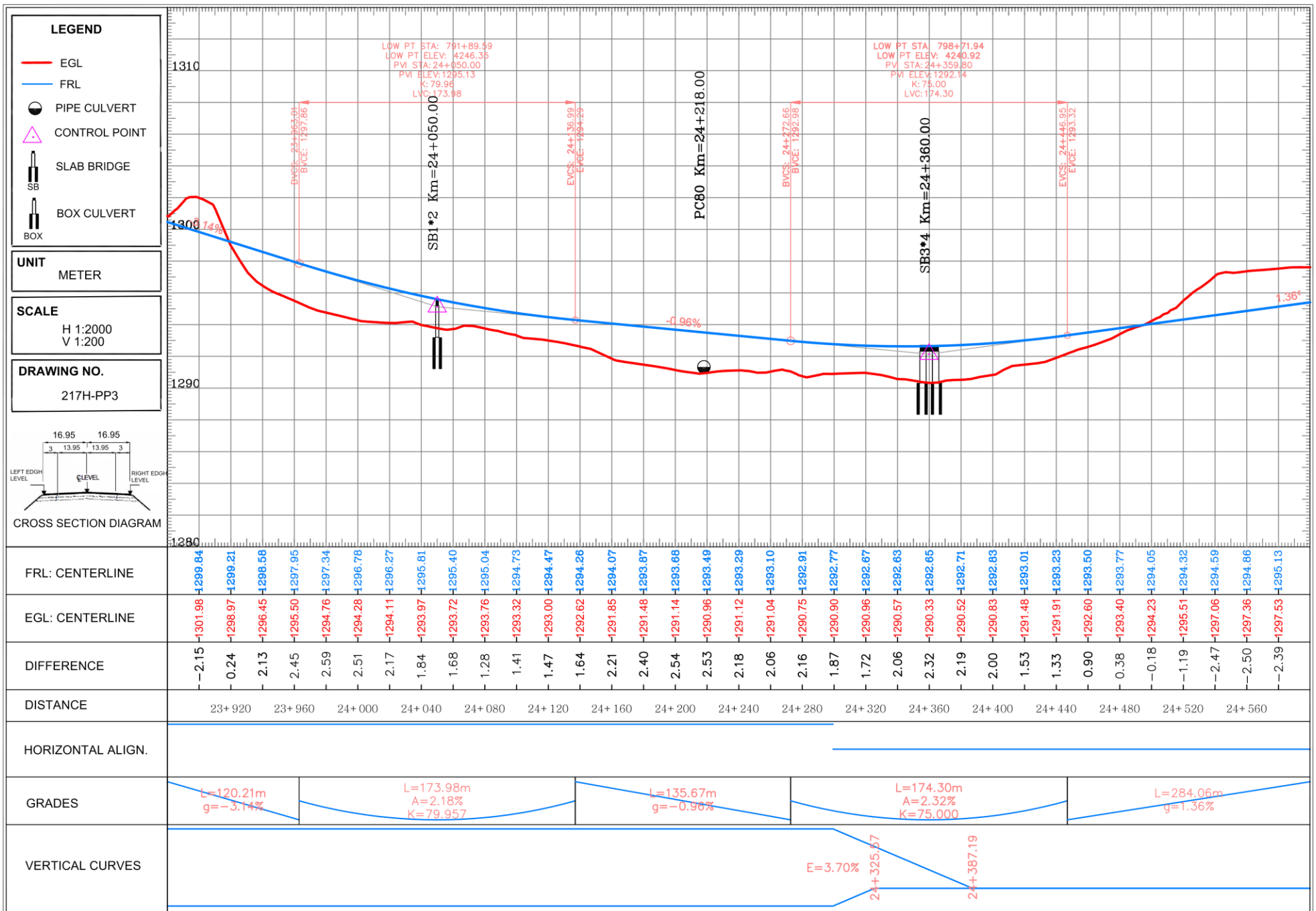
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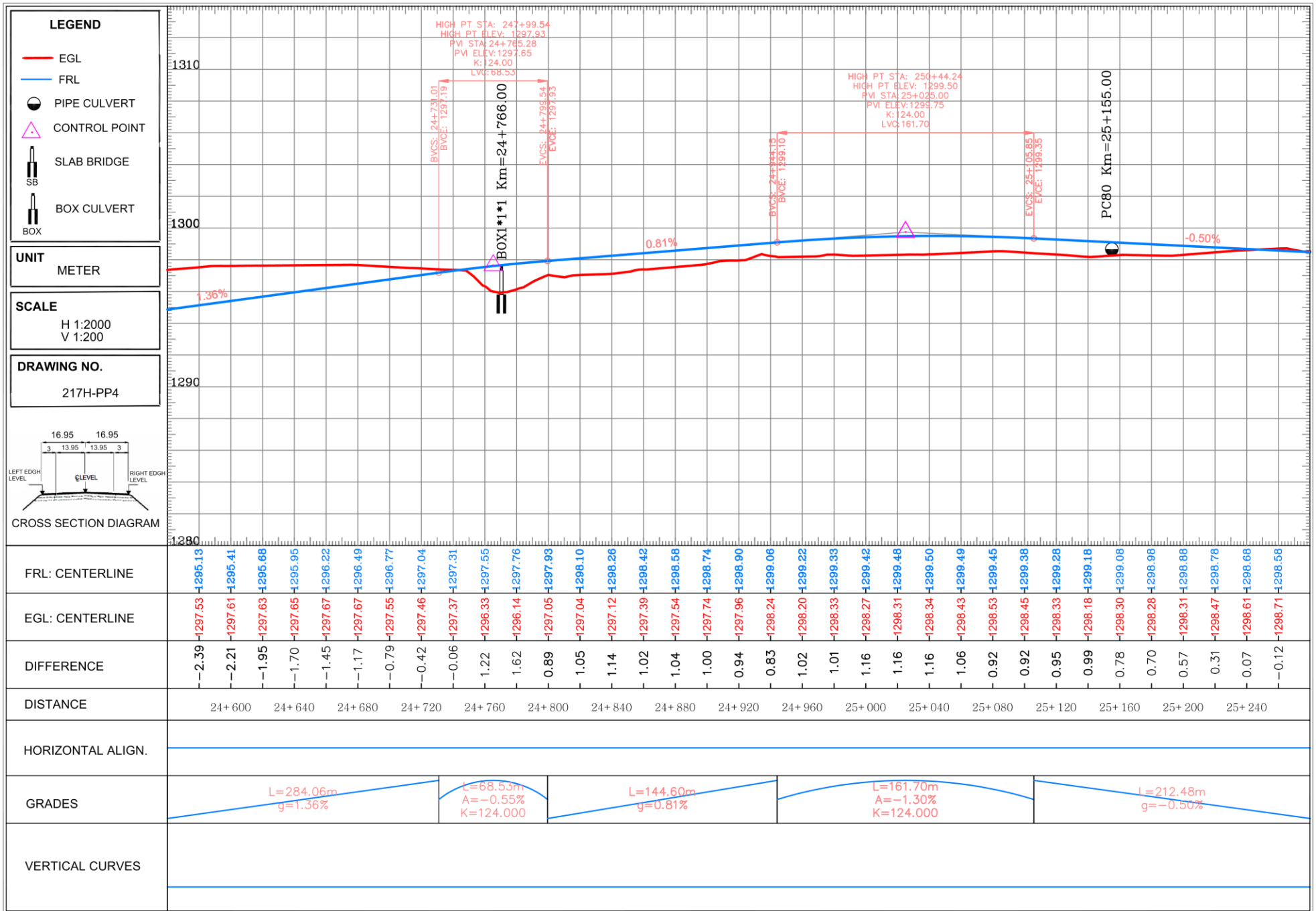


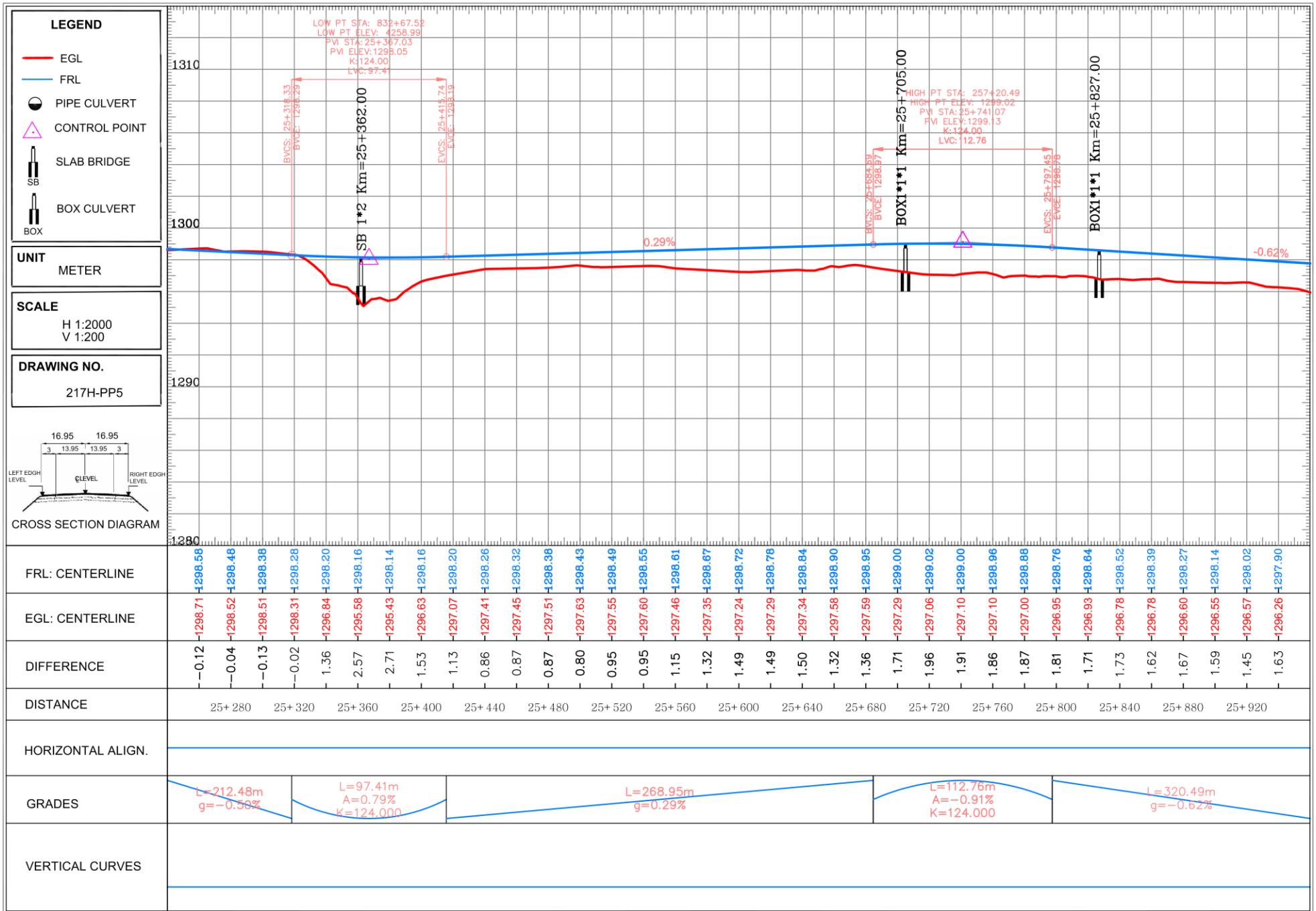


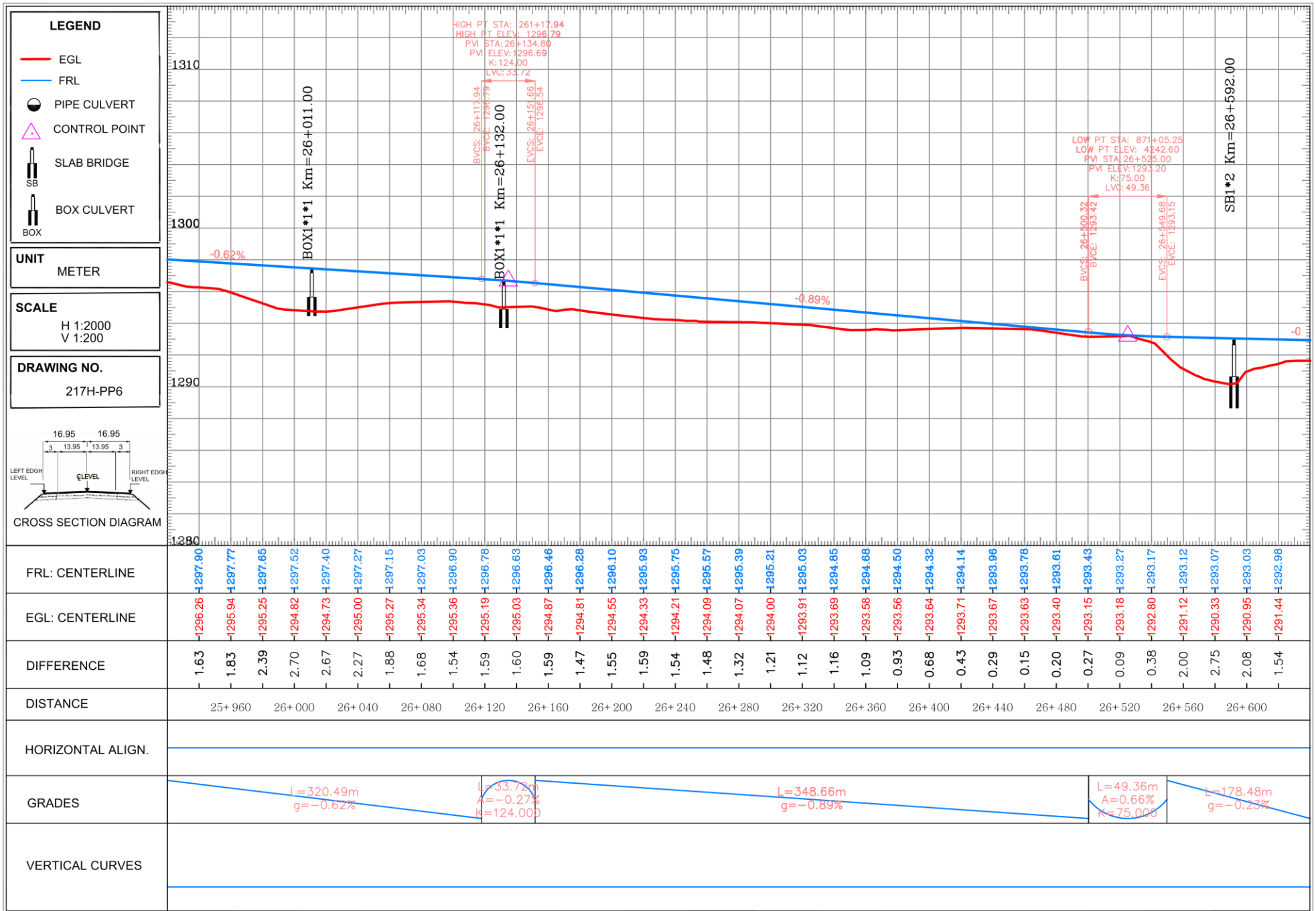


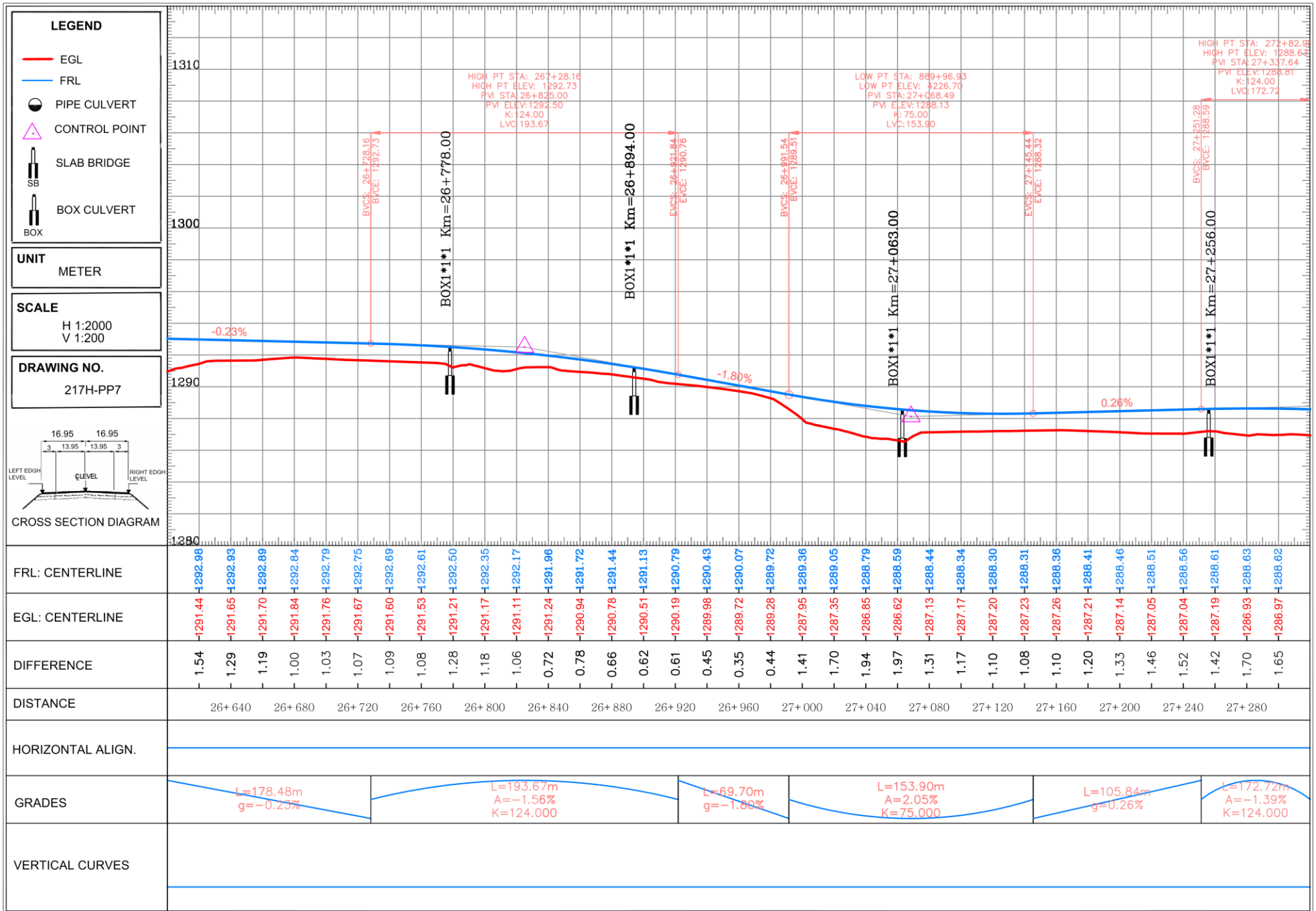


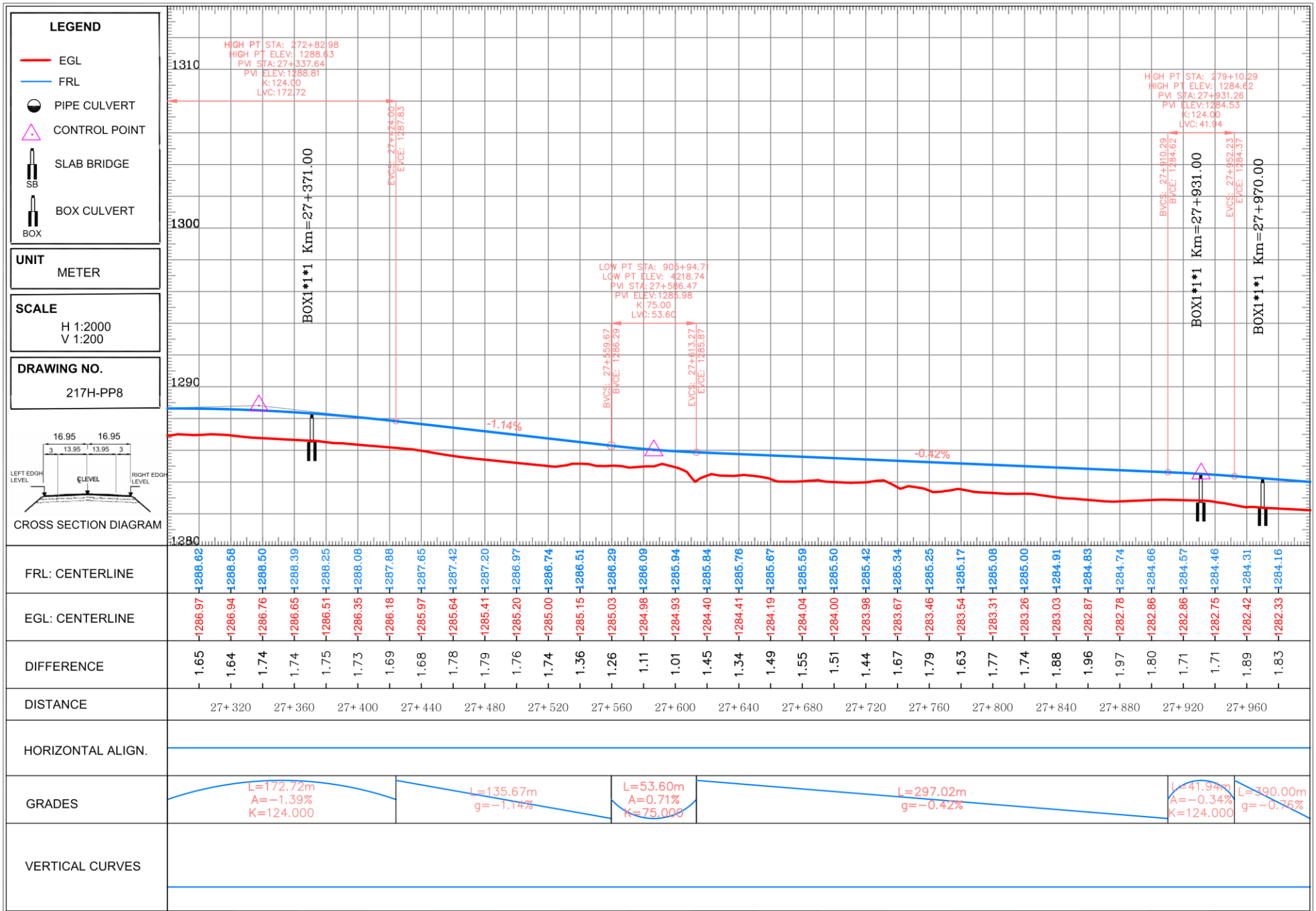


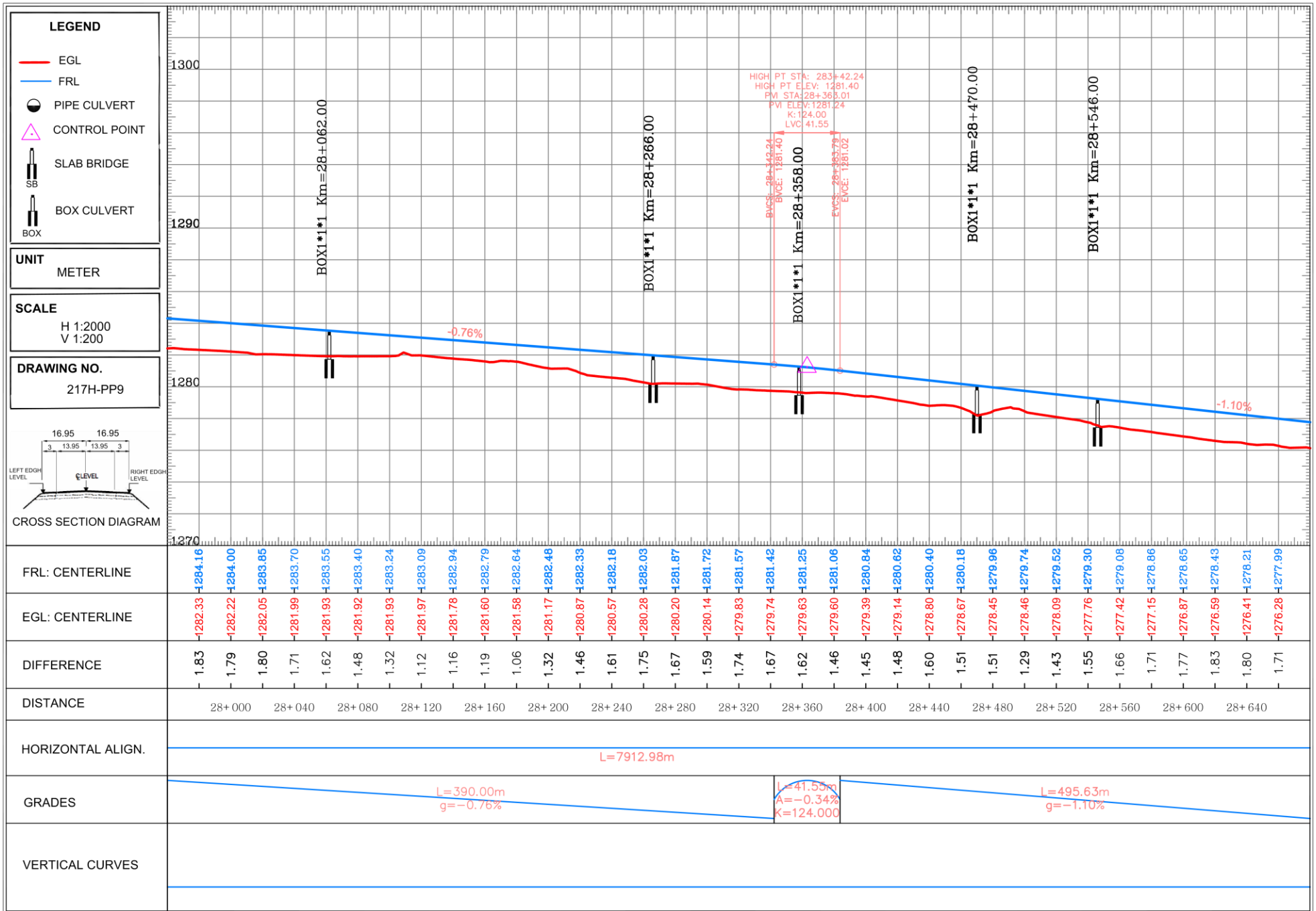


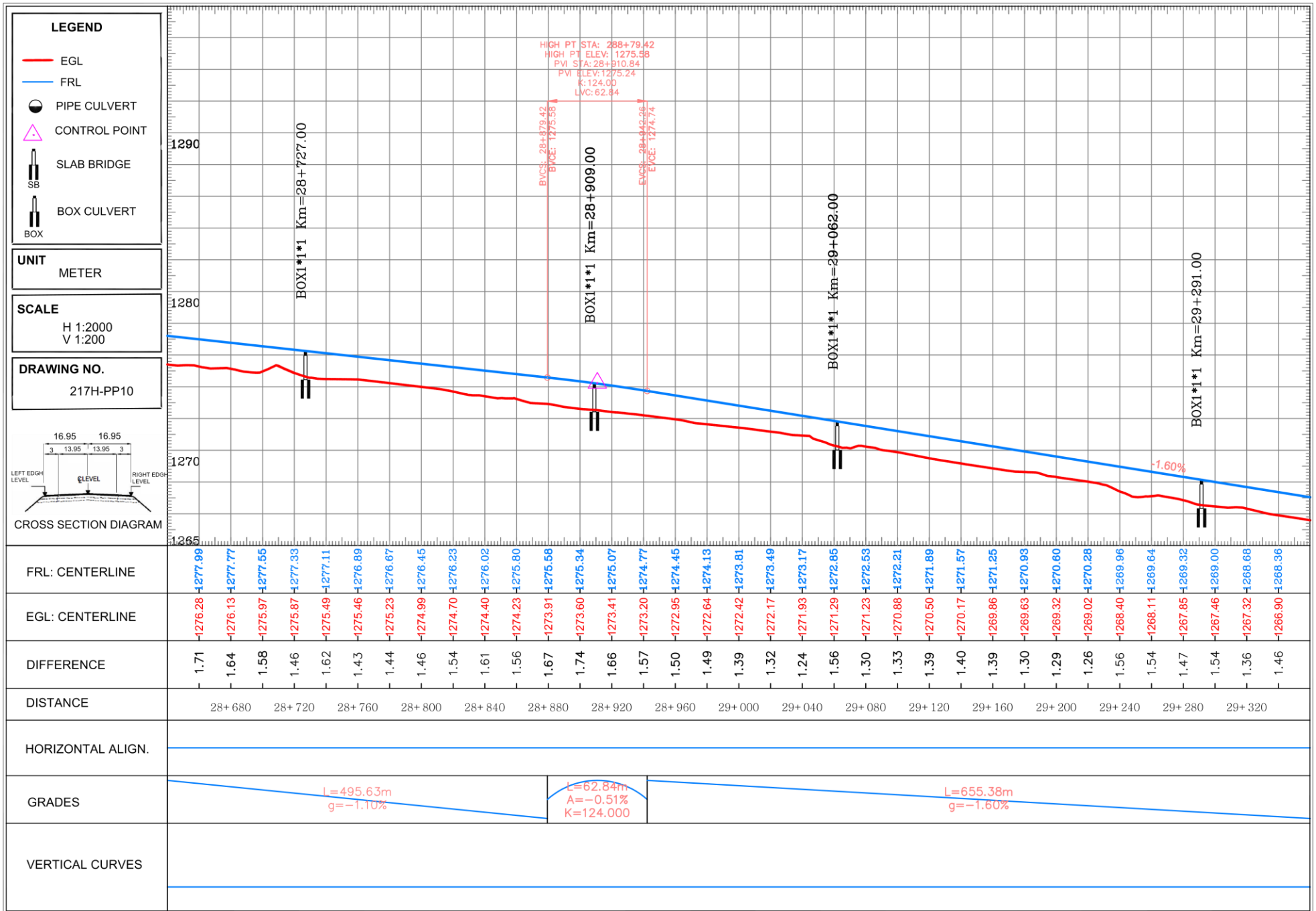


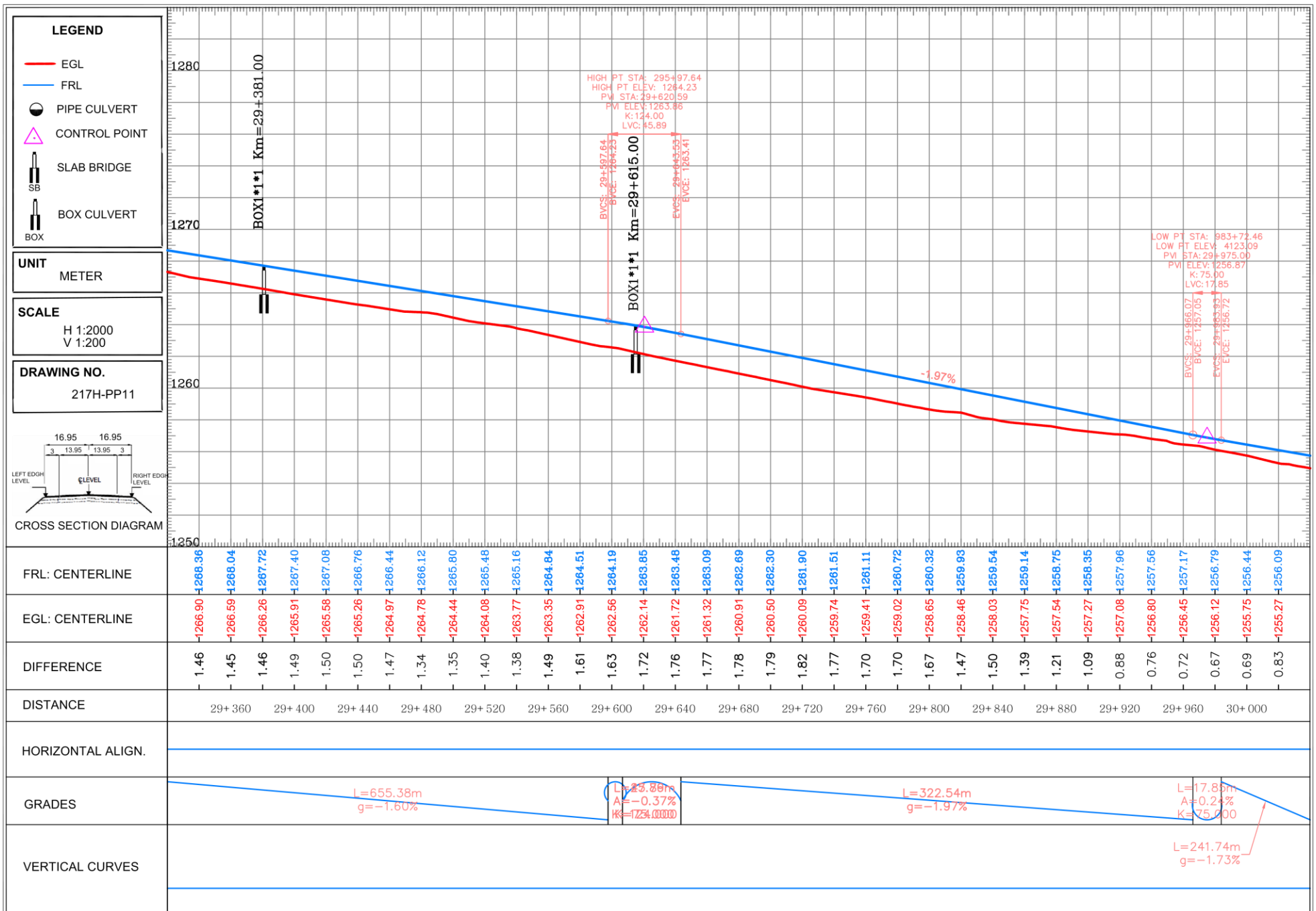


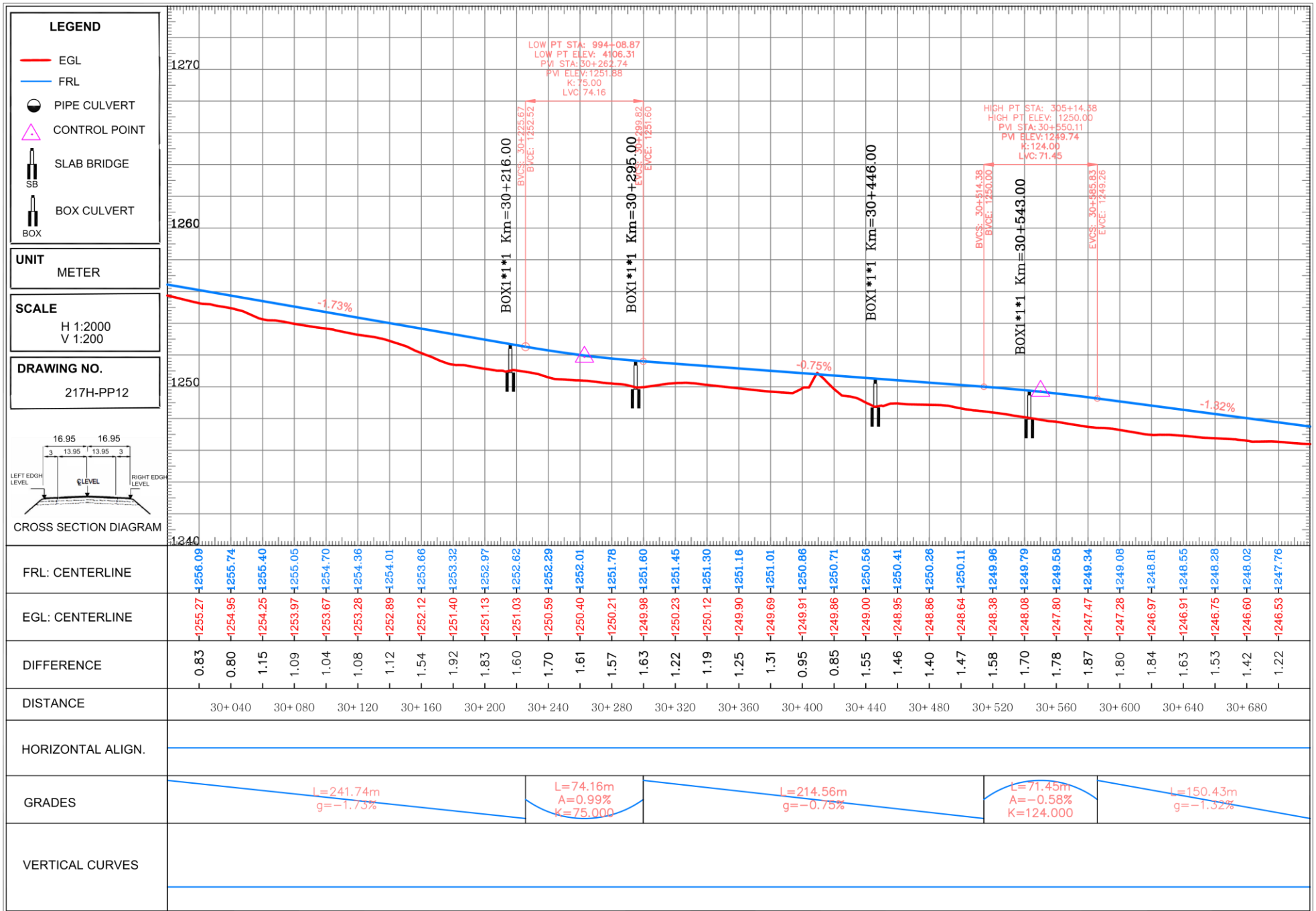


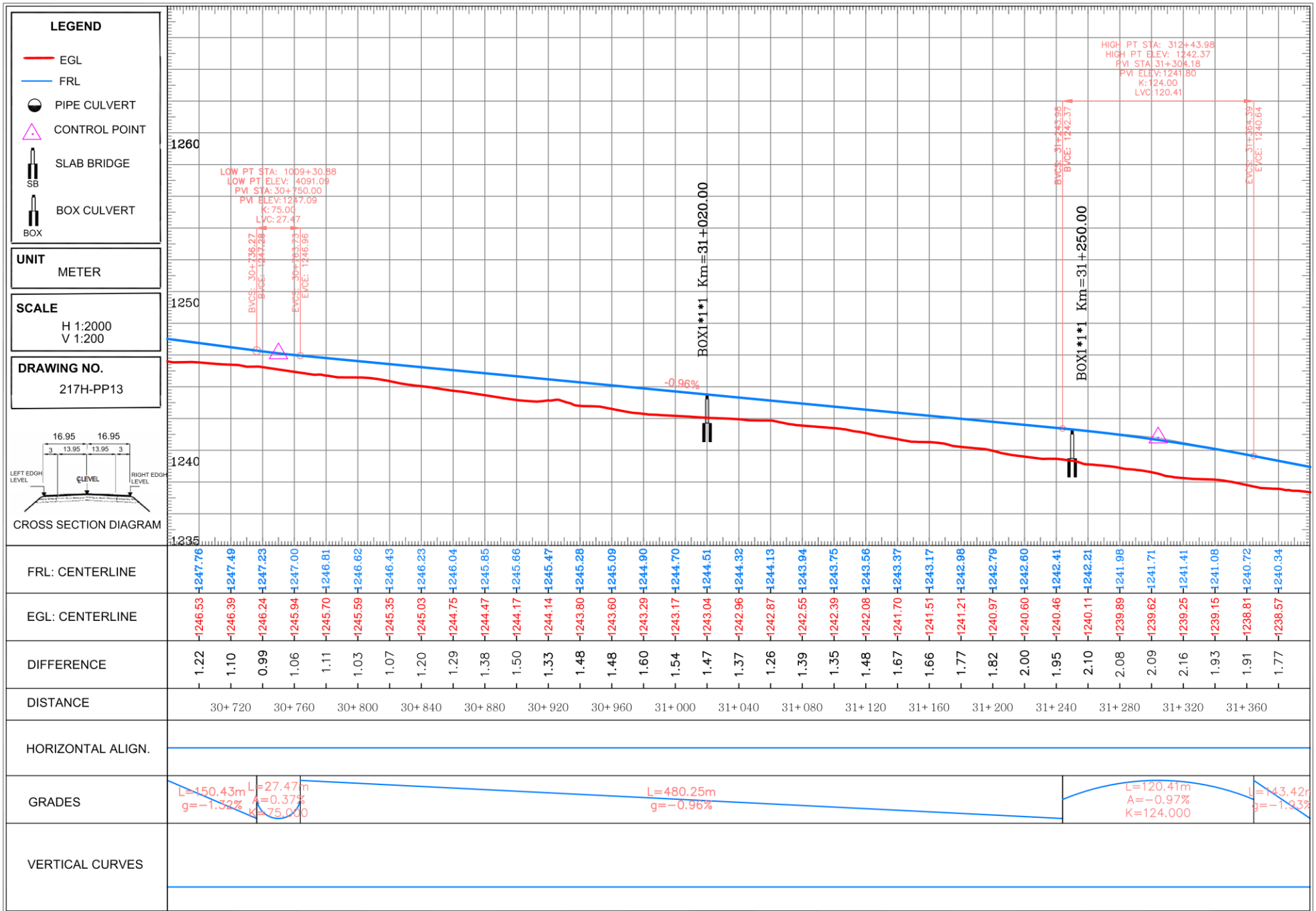


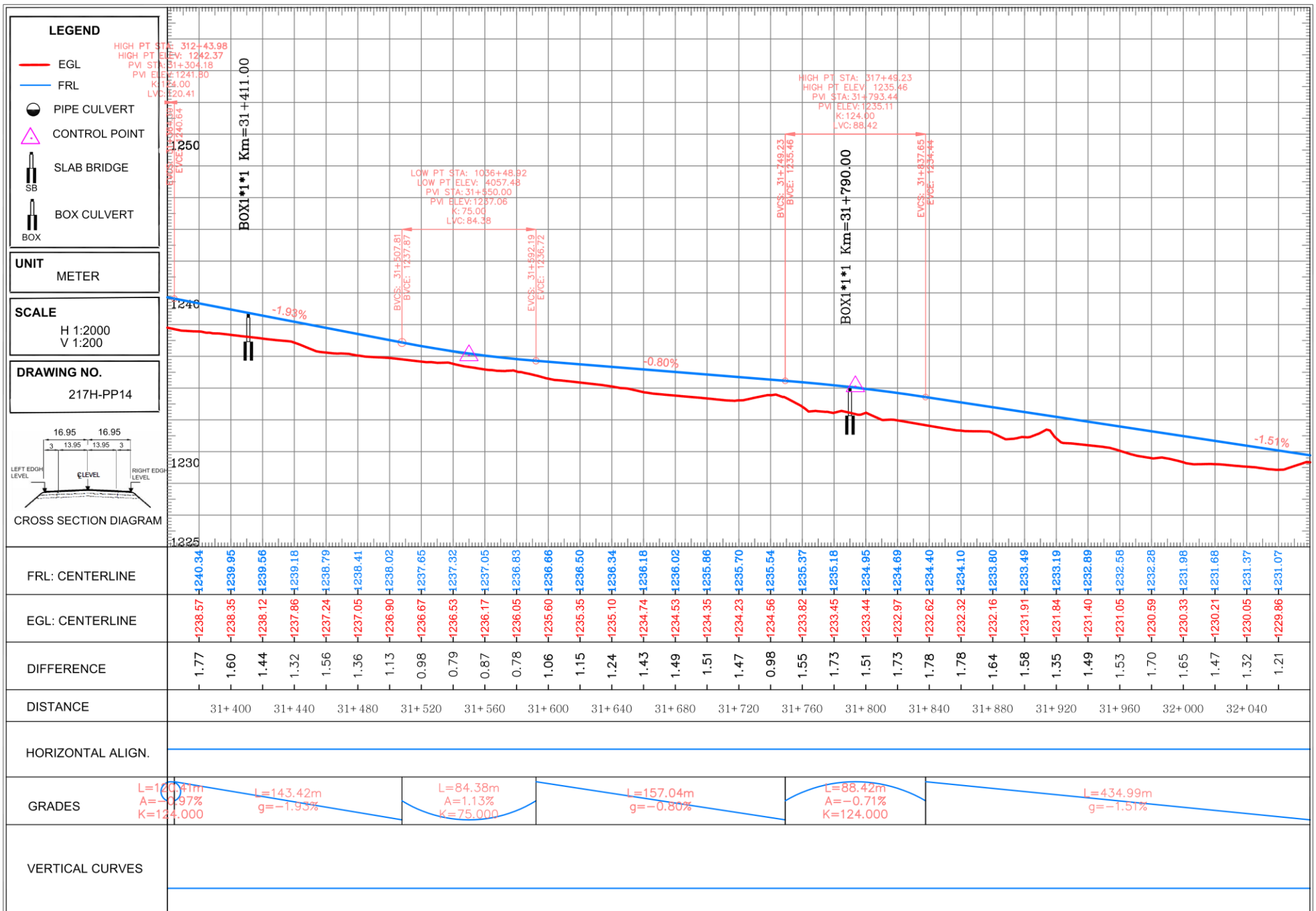


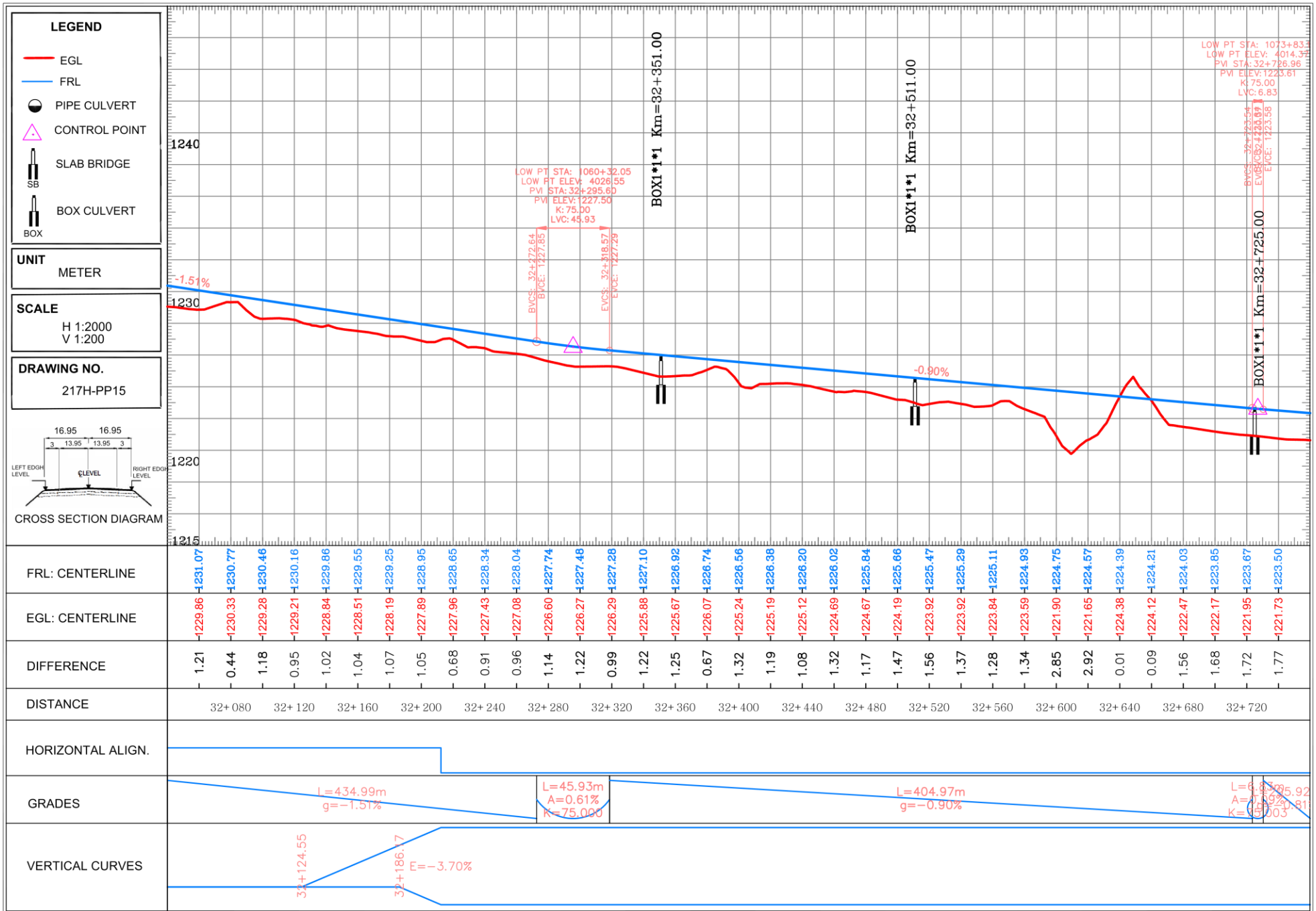




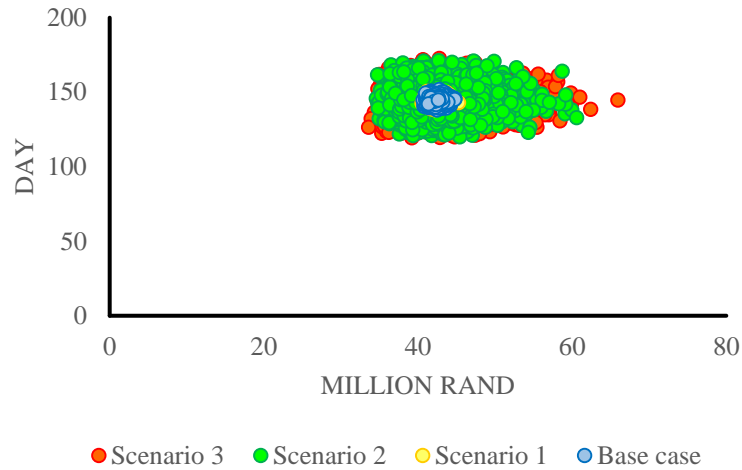




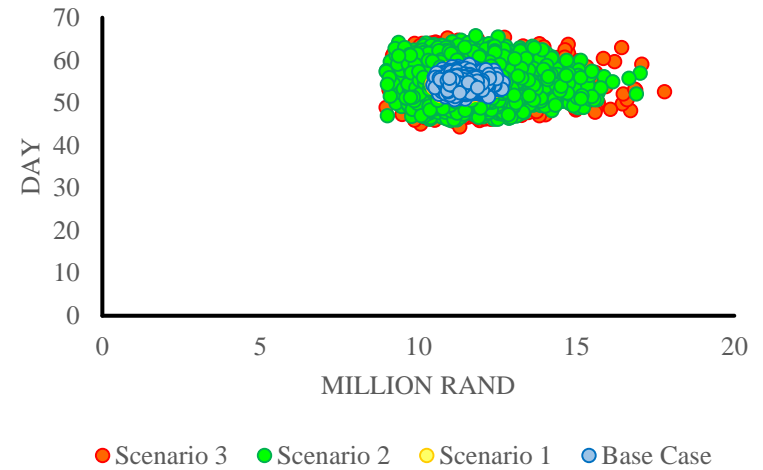




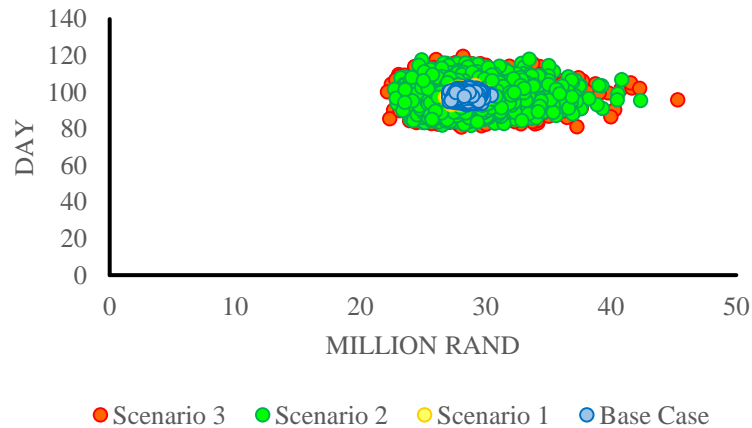
APPENDIX D: ADDITIONAL GRAPH



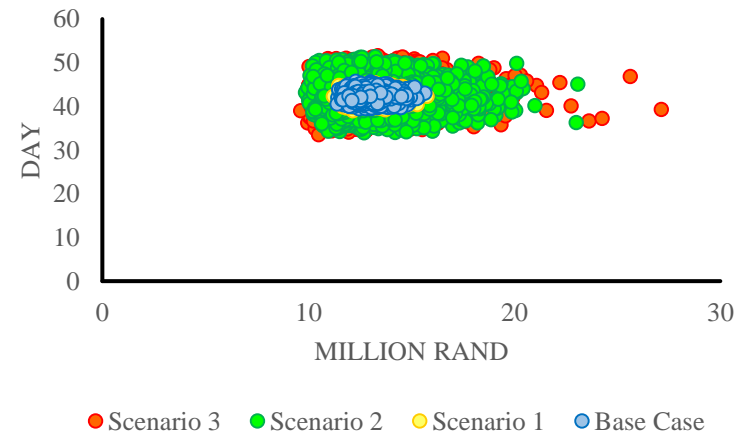
Overlay scatterplot of total cost and total time of base case and three correlation scenarios of cut construction in fine geology



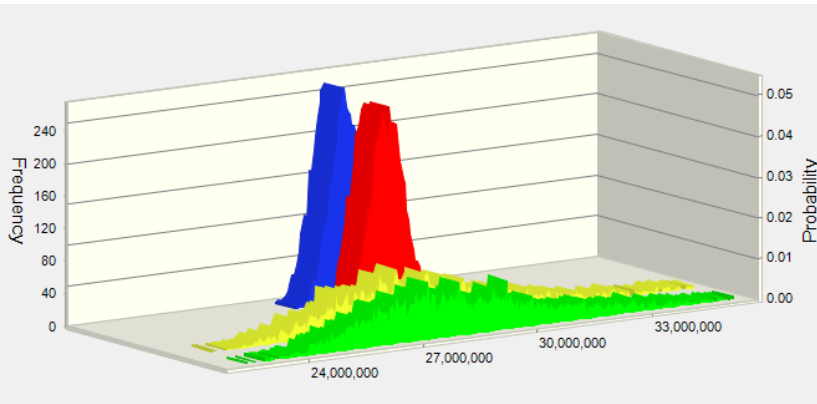
Overlay scatterplot of total cost and total time of base case and three correlation scenarios of cut construction in hard geology



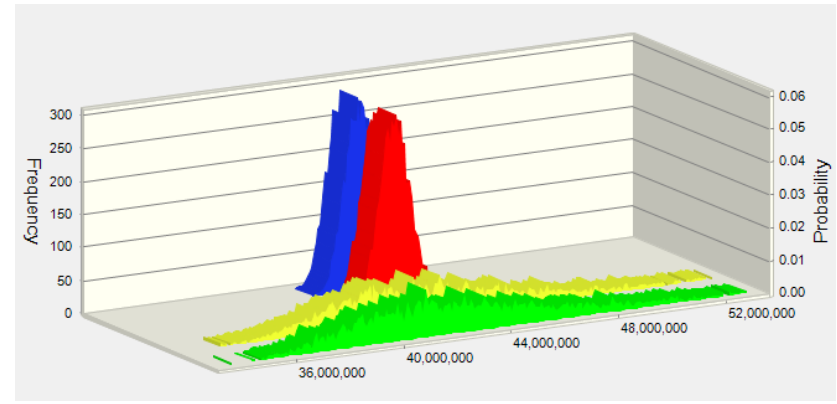
Overlay scatterplot of total cost and total time of base case and three correlation scenarios of cut construction in soft geology



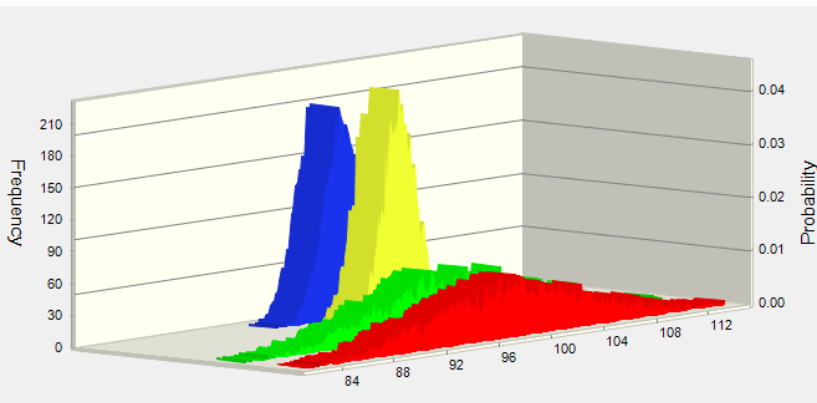
Overlay scatterplot of total cost and total time of base case and three correlation scenarios of cut construction in rock geology



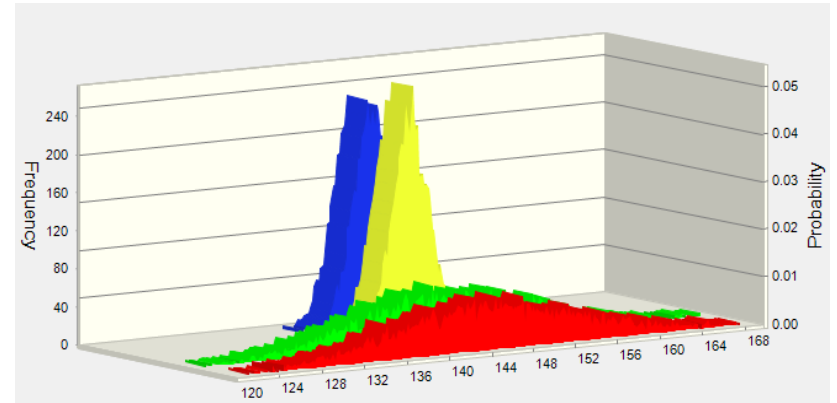
Overlaying total cost distribution of base case and three correlation scenarios of cut construction in fine geology



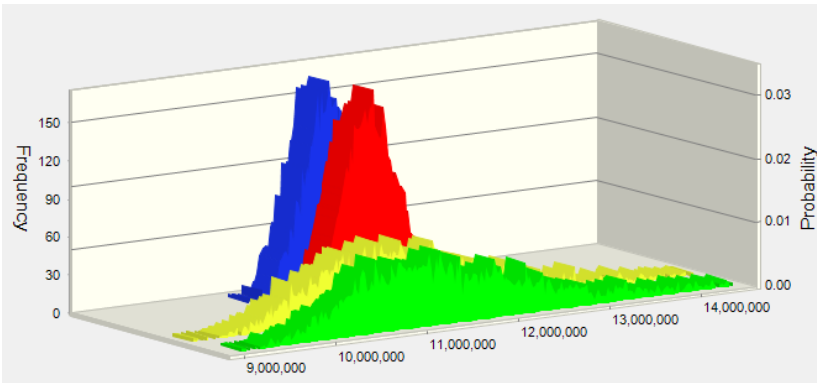
Overlaying total cost distribution of base case and three correlation scenarios of cut construction in soft geology



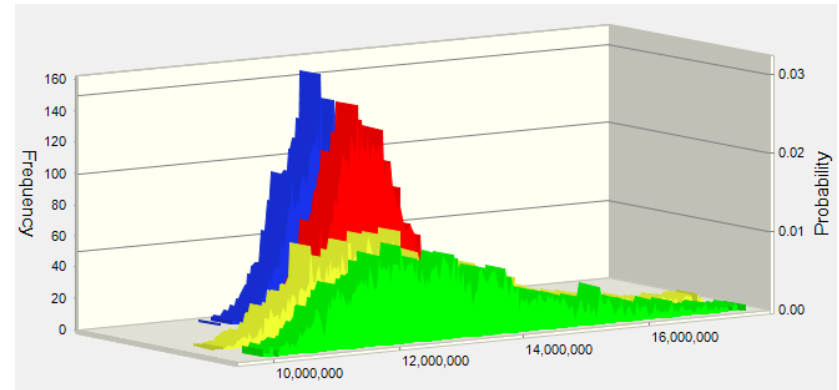
Overlaying total time distribution of base case and three correlation scenarios of cut construction in fine geology



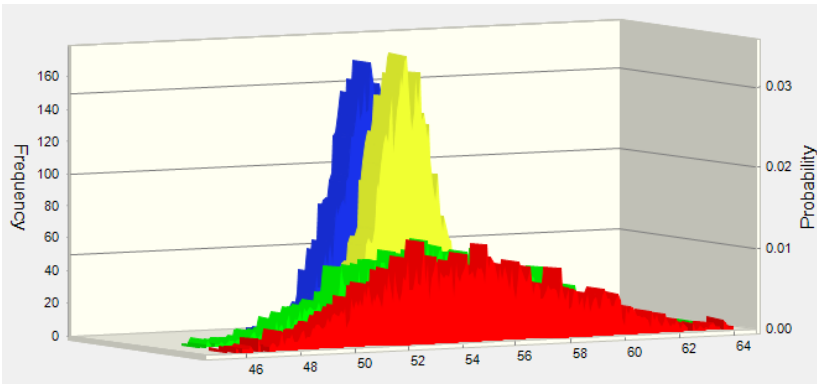
Overlaying total time distribution of base case and three correlation scenarios of cut construction in soft geology



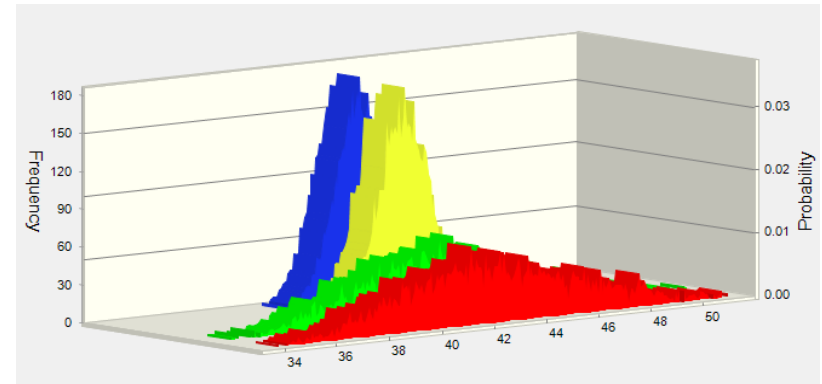
Overlaying total cost distribution of base case and three correlation scenarios of cut construction in hard geology



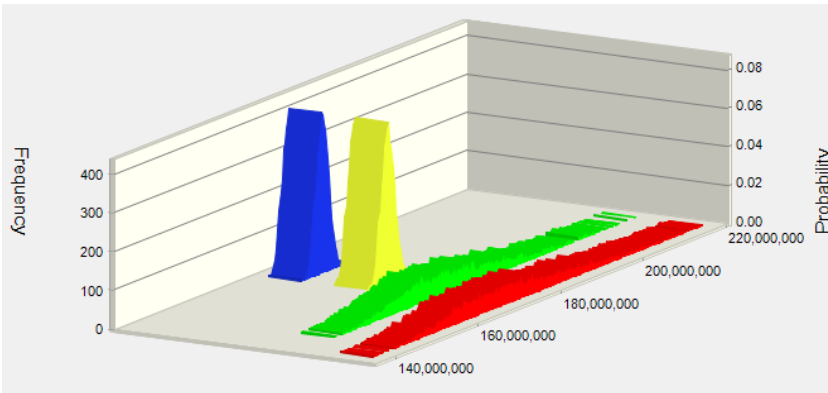
Overlaying total cost distribution of base case and three correlation scenarios of cut construction in rock geology



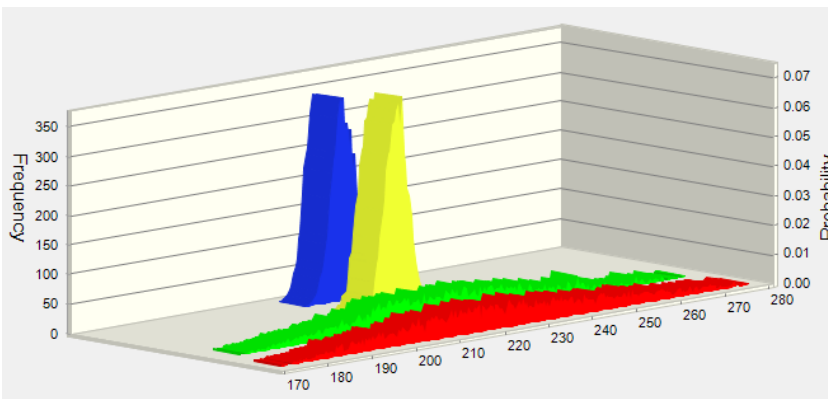
Overlaying total time distribution of base case and three correlation scenarios of cut construction in hard geology



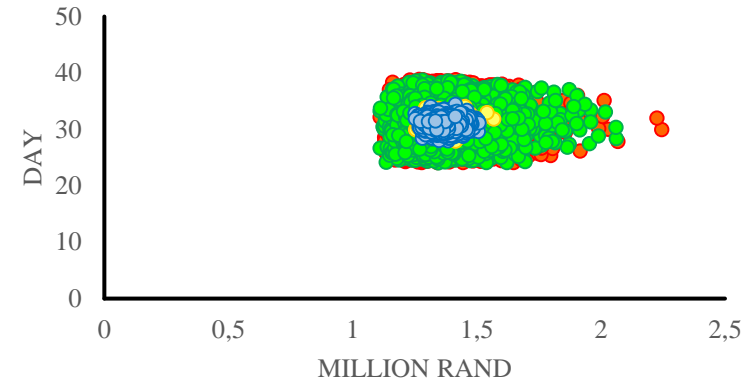
Overlaying total time distribution of base case and three correlation scenarios of cut construction in rock geology



Overlaying total cost distribution of base case and three correlation scenarios of fill construction

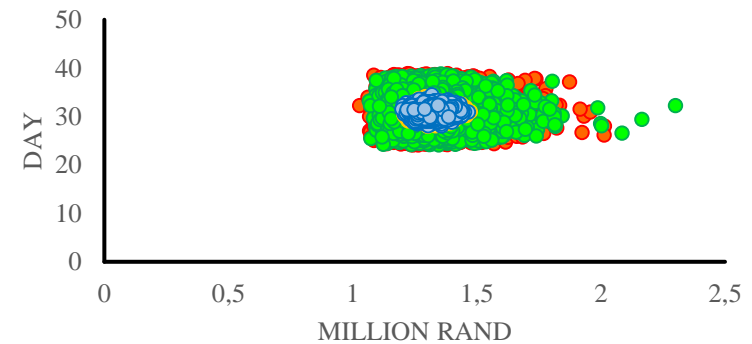


Overlaying total time distribution of base case and three correlation scenarios of fill construction



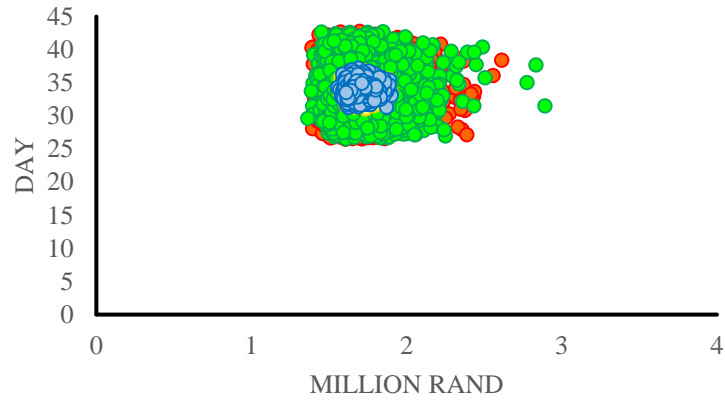
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of culvert 1x1x1 perpendicular in fine geology



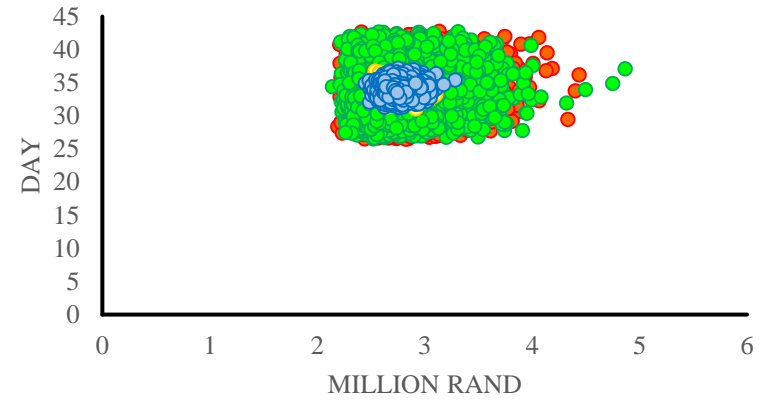
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of culvert 1x1x1 perpendicular in soft geology



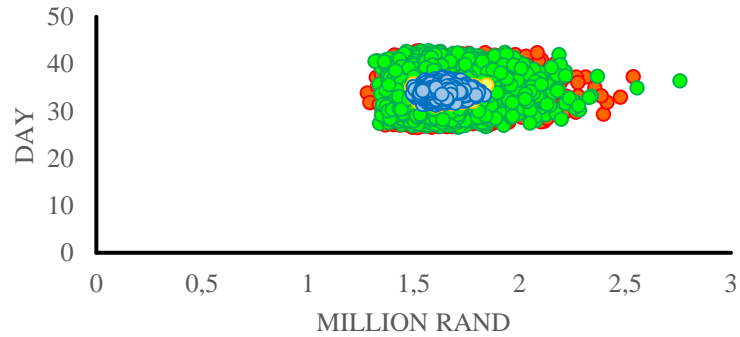
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of culvert 1x1x1 skewed in fine geology



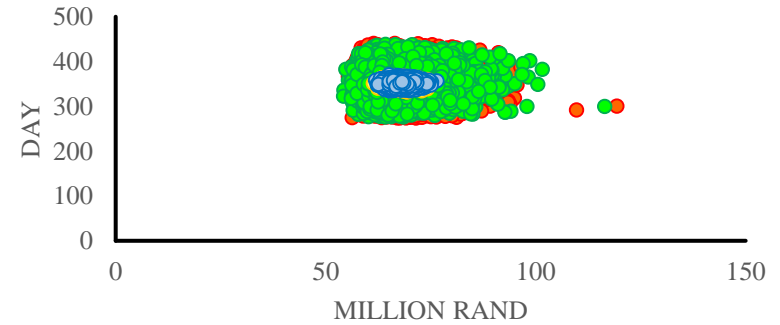
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of culvert 2x1x1 skewed in fine geology



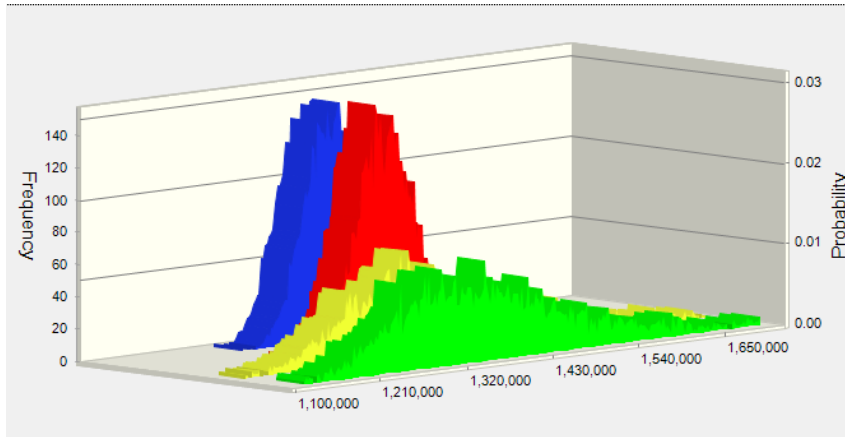
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of culvert 1x1x1 perpendicular in soft geology

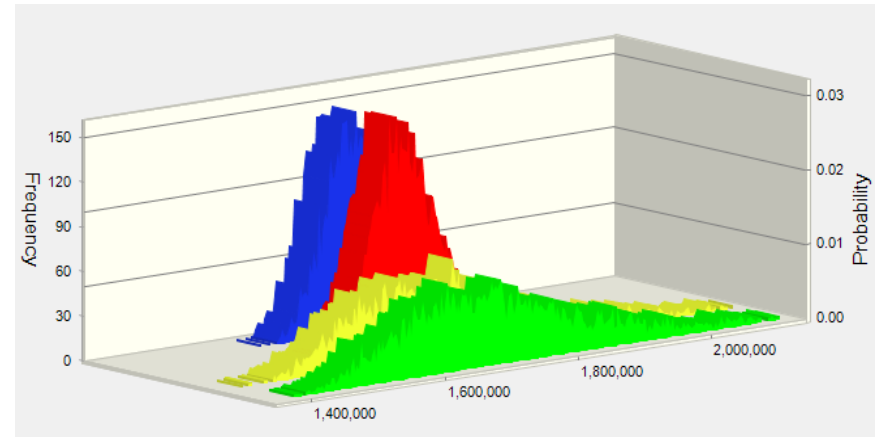


● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

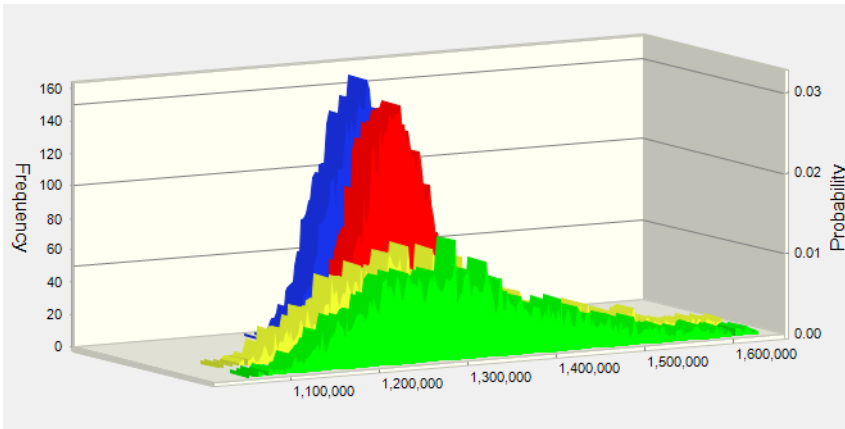
Overlay scatterplot of total cost and total time of base case and three correlation scenarios of culvert construction



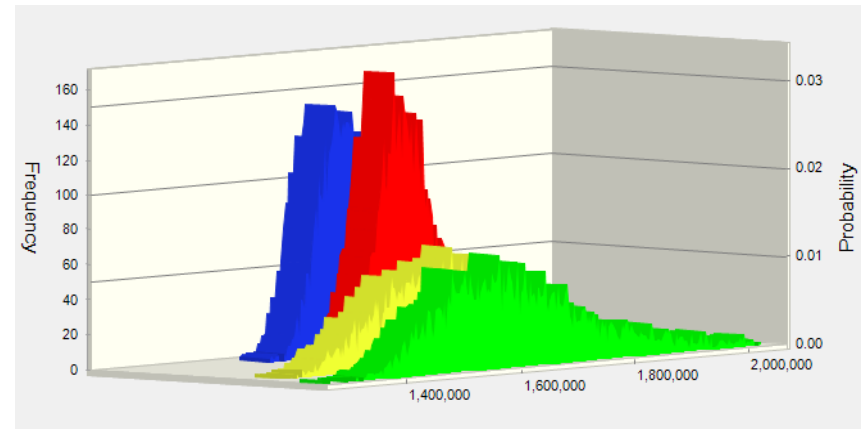
Overlaying total cost distribution of base case and three correlation scenarios of culvert 1x1x1 perpendicular in fine geology



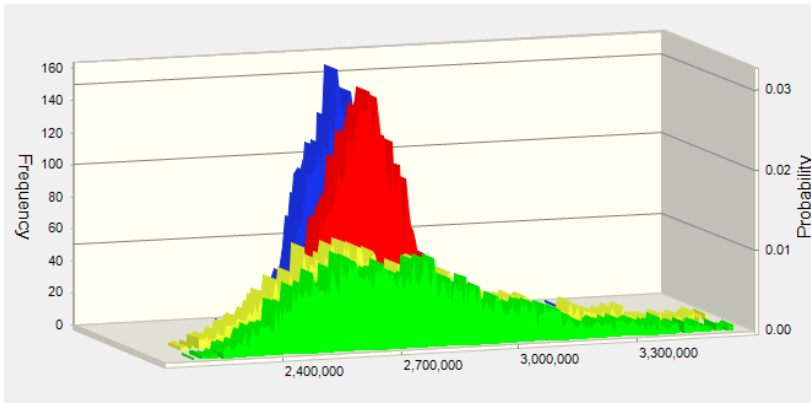
Overlaying total cost distribution of base case and three correlation scenarios of culvert 1x1x1 skewed in fine geology



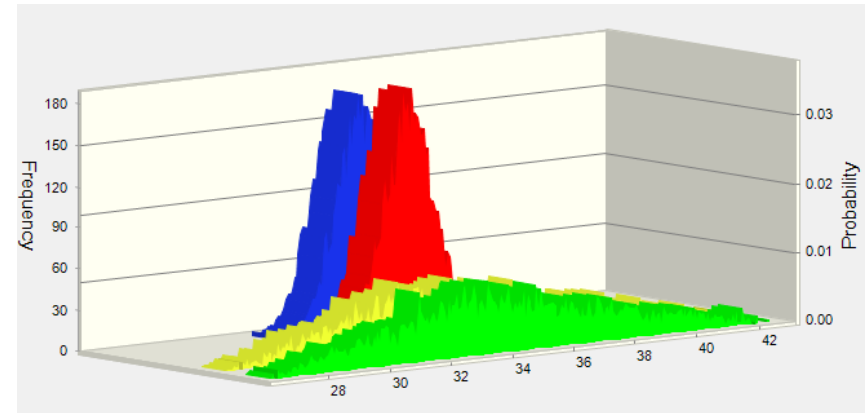
Overlaying total cost distribution of base case and three correlation scenarios of culvert 1x1x1 perpendicular in soft geology



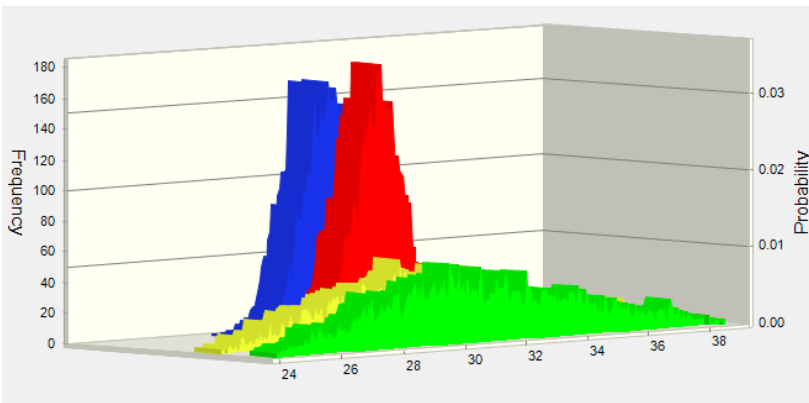
Overlaying total cost distribution of base case and three correlation scenarios of culvert 1x1x1 skewed in soft geology



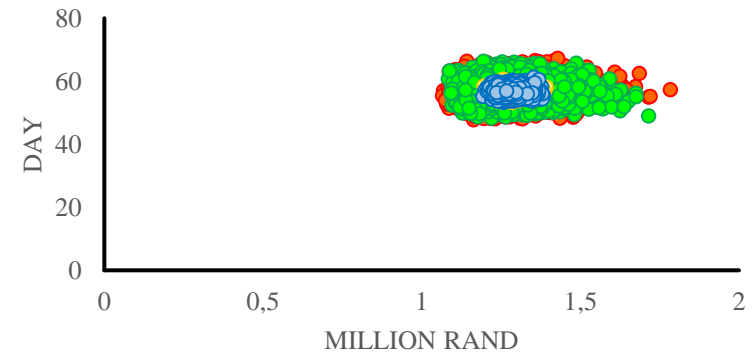
Overlaying total cost distribution of base case and three correlation scenarios of culvert 2x1x1 skewed in fine geology



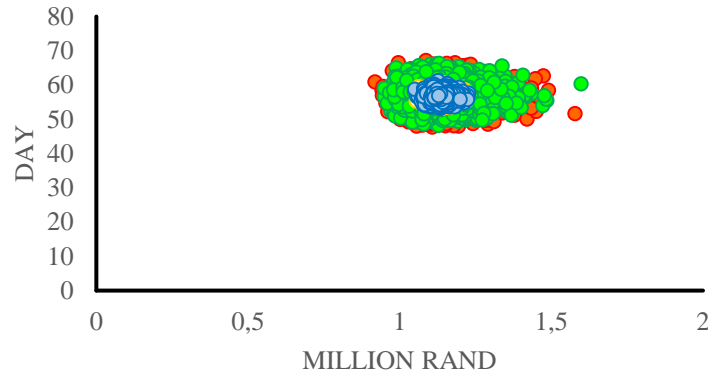
Overlaying total time distribution of base case and three correlation scenarios of culvert 1x1x1 skewed and culvert 2x1x1 skewed



Overlaying total time distribution of base case and three correlation scenarios of culvert 1x1x1 perpendicular

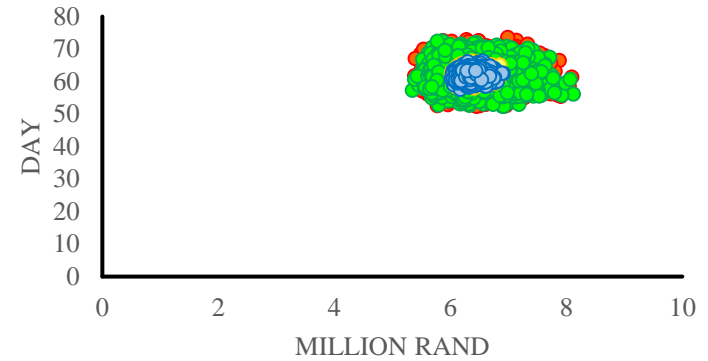


Overlay scatterplot of total cost and total time of base case and three correlation scenarios of slab bridge 1x2x2 perpendicular in hard geology



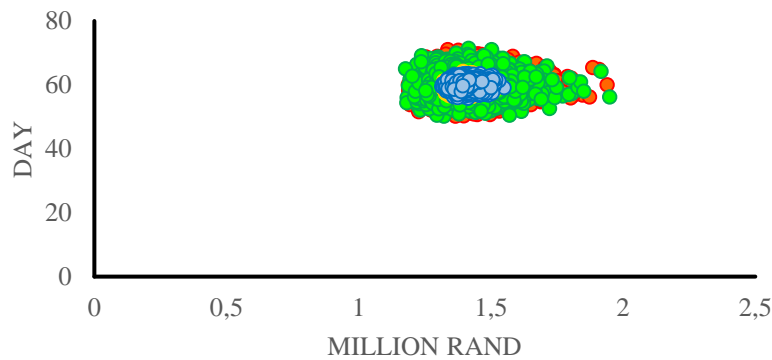
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of slab bridge 1x2x2 perpendicular in rock geology



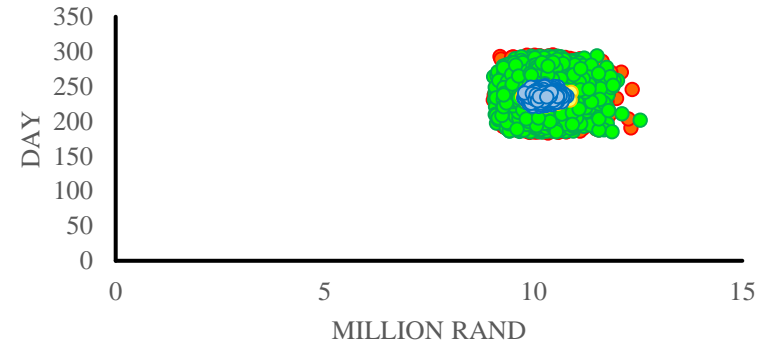
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of slab bridge 3x4x1 perpendicular in hard geology



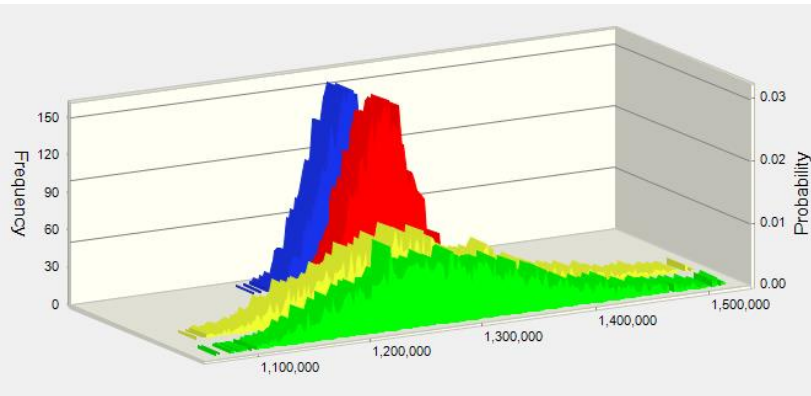
● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

Overlay scatterplot of total cost and total time of base case and three correlation scenarios of slab bridge 1x2x2 skewed in rock geology

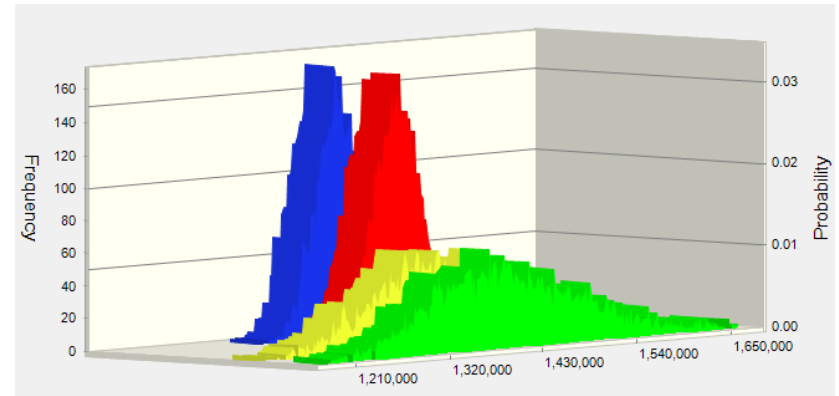


● Scenario 3 ● Scenario 2 ● Scenario 1 ● Base case

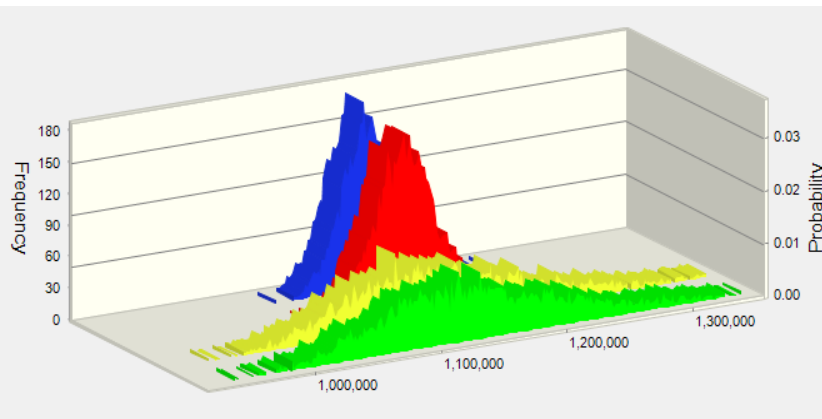
Overlay scatterplot of total cost and total time of base case and three correlation scenarios of slab bridges construction



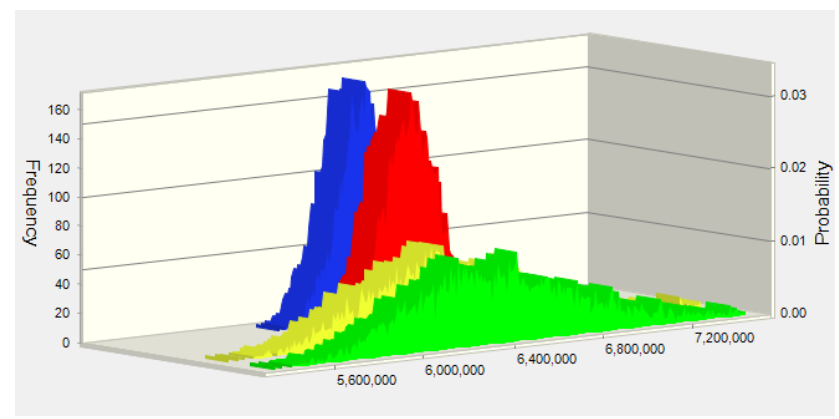
Overlaying total cost distribution of base case and three correlation scenarios of slab bridge 1x2x2 perpendicular in hard geology



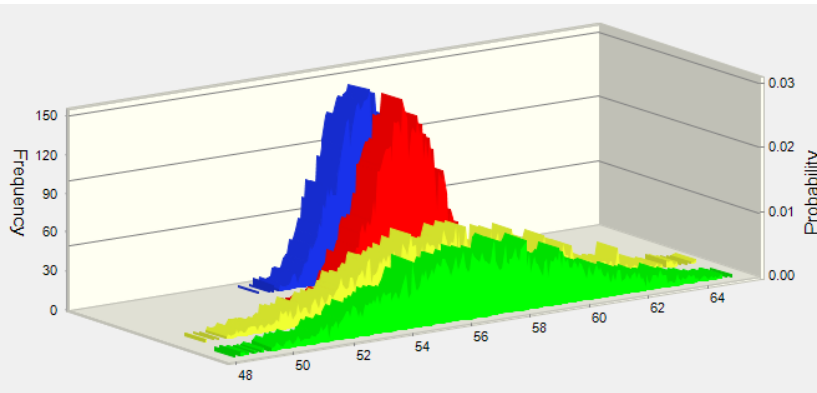
Overlaying total cost distribution of base case and three correlation scenarios of slab bridge 1x2x2 skewed in hard geology



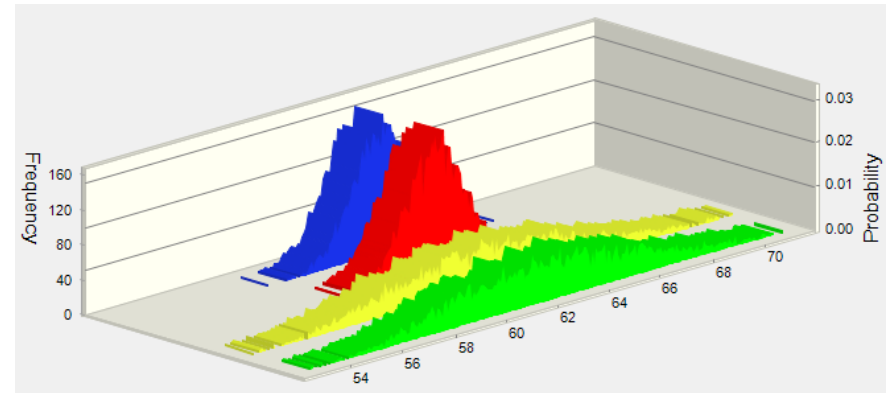
Overlaying total cost distribution of base case and three correlation scenarios of slab bridge 1x2x2 perpendicular in rock geology



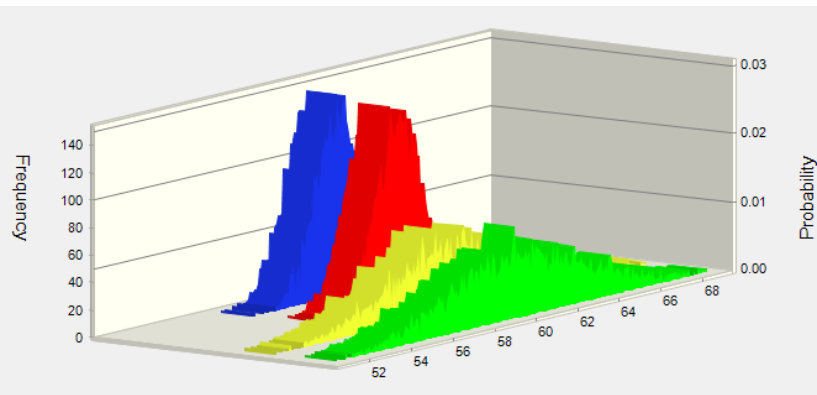
Overlaying total cost distribution of base case and three correlation scenarios of slab bridge 3x4x1



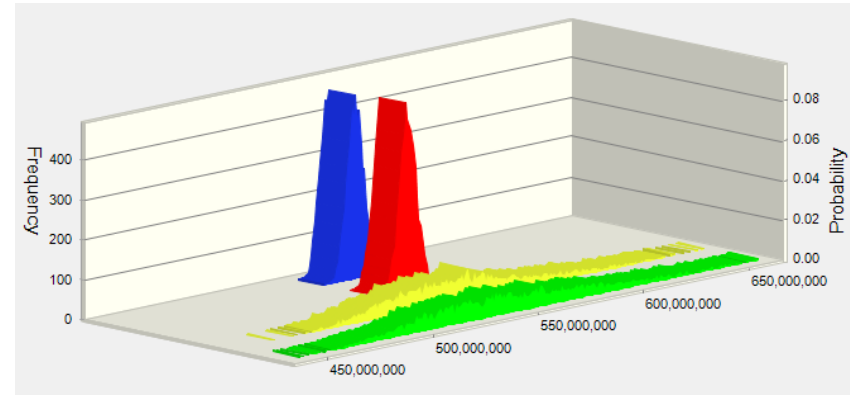
Overlaying total time distribution of base case and three correlation scenarios of slab bridge 1x2x2 perpendicular



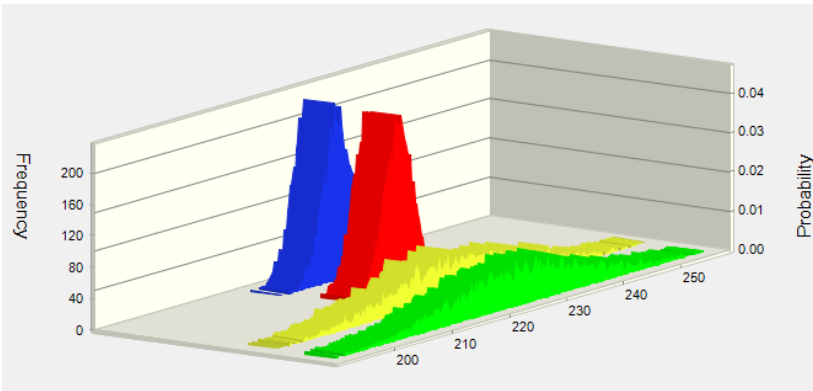
Overlaying total time distribution of base case and three correlation scenarios of slab bridge 3x4x1 perpendicular



Overlaying total time distribution of base case and three correlation scenarios of slab bridge 1x2x2 skewed



Overlaying total cost distribution of base case and three correlation scenarios of pavement structure



Overlaying total time distribution of base case and three correlation scenarios of pavement structure