EVALUATION OF THE ELECTRICAL DENSITY GAUGE FOR IN-SITU MOISTURE AND DENSITY DETERMINATION

BY

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To my mother, for having the utmost faith in me.

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ABSTRACT

Densification of soil during construction of earth structures is achieved through the process of compaction by application of mechanical energy to obtain the required engineering properties of the soil for a particular project such as hydraulic conductivity, soil strength and compressibility. These properties are dependent on attainment of high compaction densities normally achieved at specific moisture contents for a given compactive effort. The optimum moisture content and maximum dry density for a particular soil is determined by means of Proctor tests in the laboratory. A relative compaction index is then used to correlate the laboratory values with the field compaction values obtained using in-situ tests.

The Sand Cone (SC) and Nuclear Density Gauge (NDG) are the common field tests used to the dry density and moisture content of the soil for purposes of quality control of the compaction process. The sand cone is a laborious test that involves excavation of part of the compacted layer and requires a 24-hour waiting period to obtain the moisture content of the soil through the laboratory oven method. The NDG on the other hand is less laborious, however it uses a radioactive source that is a potential health hazard and therefore requires strict handling, storage and maintenance of the equipment to maintain safety standards. The Electrical Density Gauge (EDG) is an alternative in-situ test that is quicker, safer and easier to maintain since it uses electric current to measure the compaction characteristics of the soil.

The objective of the study was to determine the repeatability, accuracy and applicability of the EDG on South African soils by comparing its measurements for dry density and moisture content in the laboratory and in the field to the results from the sand cone and oven method. In the laboratory, a clean sand and a clayey sand were tested at the optimum moisture content and at ± 3% of the optimum moisture content. The soils were compacted to 200 mm using the RT74 rammer and the compaction values first tested using the EDG then followed by the sand cone test at the centre of the EDG test spot. The moisture content of the excavated sample from the sand cone test was determined using the oven method. For the field tests, the compaction characteristics of a sandy gravel and three uniformly graded sands were tested in-situ using the EDG followed by the sand cone test.

Overall, the EDG measurements were repeatable based on test-retest comparison of the paired measurements. EDG results for moisture content were consistent with the values obtained from the laboratory oven method especially in the uniformly graded sands. However, the density measurements differed from the results of the sand cone test, which was considered the reference test for determination of field soil density. It is recommended that the EDG calibration relationship for bulk density be revised in order to improve the accuracy of the density measurements.

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NOTATIONS

Symbols	Description	Units
ρ	Density	*kg/m*^{3}
γ_m	Bulk density	*kN/m*^{3}
γ_d	Dry density	*kN/m*^{3}
ξ	Relative amount of energy lost on collision	_
θ , P_s	Phase difference	^{0}
σ_s	Cross-sectional area	*barns*
μ	Linear absorption coefficient	*cm*$^{-1}$
μ_p	Photoelectric effect	_
μ_{pp}	Pair production effect	_
ω	Natural frequency $(2\pi f)$	*Hz*
A	Atomic weight	_
b	Intercept of equation	_
E_n	Neutron energy after n collisions	*MeV*
f	Frequency	*Hz*
I_s	Soil current	*A*
m	Slope of equation	_
N	Avogadro's number	6.02×10^{23}
n	Number of collisions	no.
r	Repeatability limit	
RC	Relative compaction index	%
R^2	Co-efficient of determination	_
R_s	Soil resistance	Ω
T	Temperature	^0C
V	Volume	*cm*^{3}
V_s	Soil voltage	*V*
W	Weight of compacted soil	*kg*
w	Moisture content	%
w_o	Optimum moisture content	%

W_w	Weight of water per unit volume	kN/m^3
Z_s	Soil impedance	Ω
Z	Atomic mass number	no.

Abbreviations	**Desciption**
ANOVA	Analysis of variance
ASTM	American Standard Test Method
BS	British Standard
CI	Confidence interval
DCP	Dynamic cone penetration
DDL	Diffuse double layer
EDG	Electrical density gauge
FHWA	Federal Highway Administration
GTI	Gas Technology Institute
LO	Laboratory oven
LoA	Limits of agreement
LWD	Light weight deflectometer
MDD	Maximum dry density
NDG	Nuclear density gauge
OMC	Optimum moisture content
QA	Quality Assurance
QC	Quality control
RIC	Rapid impact compaction
RDSO	Research Designs and Standards Organisation
SC	Sand cone
SD	Standard deviation
TRB	Technical Research Bureau

CHAPTER 1 INTRODUCTION

1.1 Background to the study

The construction of earth structures such as earth dams, embankments and retaining walls requires compaction of the soil material in order to improve its engineering properties. Compaction is one of the most important ground improvement methods used in geotechnical engineering to improve soil strength (Xia, 2014). The compaction process increases the density of soil, which consists of the solid particles, air and water, by reducing the volume of air through application of mechanical energy. The energy is applied through pressure (rolling), impact (tamping) or vibration (Raj, 1999).

The aim of compaction is to attain high densities at specific moisture content values that aid in the densification process. Inadequate compaction of soil in earth structures has often resulted in the failure of the structures; leading to loss of lives and property. One example is a 4 m high embankment dam at Driefontein wastewater treatment works in Johannesburg, South Africa that failed in 1998 due to erosion of the earth fill resulting from inadequate compaction (Scheurenberg, 1999). It was determined that insufficient tests to measure the compaction attained were undertaken. It is important therefore that tests to measure compaction characteristics of soil are conducted and that the standard specifications are adhered to in order to mitigate such failures.

Tests used to measure compaction characteristics include volume replacement tests such as the sand cone, water balloon and the drive cylinder. These tests have been documented as providing a good level of accuracy of results. However, they are time consuming as they require a 24-hour waiting period for moisture content determination using the oven method and involve excavation of the compacted soil hence the tests are laborious and destructive thereby increasing project duration and costs due to the need to patch up the excavated holes (Islam et al., 2012). The other test is the nuclear density gauge (NDG) test, which is quicker and non-destructive. Nonetheless, the NDG uses radioactive materials that may be hazardous to the health of operators if mishandled (Zhuang, 2011). Operators using this equipment therefore require prior radiation safety training before handling it in order to avoid radiation poisoning. Furthermore, there are strict regulations governing the transportation of the NDG and high financial costs associated with its ownership (Brown, 2007). Consequently, there has been a need for alternative tests that are both safe and provide quick results which led to the development of the Electric Density Gauge, EDG in 2002 (Anderson et al., 2005). The EDG is a non-destructive test that is considered safe, quick and easy to use on site resulting in reduced project duration. This study investigated the suitability of the EDG test for measurement of compaction characteristics with a particular focus on the South African soils.

1.2 Relevance of study

Information pertaining to the accuracy of EDG measurements in the African context as compared to volume replacement tests is necessary to facilitate their adaptability for compaction testing of soils on the continent. The EDG requirement that a soil model be built for a particular soil type before use implies that its accuracy is soil property dependent due to variations in chemical composition, particle grading, soil structure and texture between different soils.

Meehan and Hertz, (2011), Cho et al. (2012) and Mejias-Santiago et al. (2013a and 2013b) calibrated the EDG using the NDG and found the EDG to have less accuracy than the NDG and volume replacement tests for measurement of soil density. However, the NDG does not have a 1:1 plot with volume replacement tests, which may have led to the inaccuracies in the EDG density measurements based on calibration with the NDG.

The EDG was found to have better accuracy for values of moisture content when calibrated using the laboratory oven (Cho et al., 2012). It was anticipated therefore that a better understanding of the level of accuracy of the EDG for both soil density and moisture content measurements would be obtained through the calibration of the EDG using volume replacement tests.

1.3 Justification

This study offers an understanding of the performance of the EDG for measuring compaction characteristics in South African soils. Compaction specifications can be made to include the EDG in the construction industry resulting in reduced project time as the test is quick and there will be less requirement for safety training compared to the hazardous NDG. Accordingly, the results from the study will contribute towards knowledge for development of standards for the use of the EDG in South Africa, thereby promoting its use on the African continent.

1.4 Research objectives

The main objective of this research was to evaluate the efficiency of the EDG test in measurement of compaction characteristics. The specific objectives included determining the repeatability, as well as the accuracy of EDG measurements for moisture content, bulk density and dry density relative to the conventional tests particularly the oven method for moisture content determination and sand cone test for bulk density and dry density determination. This involved assessing if the results from the measurements using the EDG were equal to the values obtained from the conventional tests or if a systematic difference existed between the tests. In order to establish the applicability of the EDG for measuring compaction characteristics, the statistical significance of the differences as well as their engineering relevance was examined and discussed. Different soils around Cape Town were tested to determine the effect of soil type on EDG measurements.

1.5 Scope and limitations of the study

The study evaluated the efficiency of the EDG measurement of density and moisture content of compacted soil. The EDG compaction values were compared to results from the sand cone test for bulk density and dry density, and the laboratory oven method for moisture content. The compaction measurements were conducted on samples in a laboratory physical compaction model and at three different field sites in Cape Town covering representative areas in the northern suburbs, the southern suburbs and the central business district of the city.

1.6 Thesis outline

Chapter 1 introduces the background to the study and identifies the existing knowledge gaps. The literature relevant to the study is reviewed in two chapters. Chapter 2 covers the mechanism of compaction and expounds on the importance of compaction and the processes involved. Chapter 3 focuses on the different density-based tests for measuring compaction characteristics and a review of previous research work relevant to the study to establish a basis for accomplishing the objectives of this study.

The materials used and the methodology adopted in executing the study are covered in Chapter 4. The chapter details the equipment, material description and properties, and the testing procedure.

Chapter 5 is a presentation of the results and analyses of the study. The statistical significance and engineering relevance of the results is assessed to establish the accuracy and precision of the EDG, and therefore the efficiency of the EDG test for compaction measurement. The observed trends in the results as well as the practical application of the EDG test are discussed in Chapter 6. Finally, a summary of the findings of the study is presented under Chapter 7 in the conclusions and some recommendations for future research are discussed at the end.

CHAPTER 2 COMPACTION OF SOIL

2.1 Introduction

Earth structures such as dams, embankments and retaining walls require the placement of fill soil in its densest state in order to optimise its engineering properties. Compaction as a means of densifying soil by reducing the air void space, and not the water content, is achieved through the application of an external compactive effort to improve the engineering properties of loose soil that are highly dependent on the macrostructure of the soil (Beckett et. al, 2013). The mechanical behaviour of unsaturated soils, particularly those with clay, is complex due to the presence of air and water in the pore space (Romero and Simms, 2008). It is therefore vital to understand the macrostructure of clays and its effect on their engineering properties (West, 2010).

2.2 Structure and engineering properties of compacted clay

Several significant studies (Lambe, 1958a; Lambe, 1958b; Seed and Chan, 1959; Lambe, 1962; and Foster, 1962) have been conducted to explain the compaction characteristics of clay. According to Lambe (1958a), compaction induces variations in the structure of clay.

2.2.1 Structure of compacted clay

The effect of compaction on the structure of clay is shown in Figure 2-1a). Lambe (1958a) found that clay compacted dry of optimum has a flocculent structure while that compacted wet of optimum has a dispersed structure. Lambe (1958a) attributed the structure of clay at the different water contents to the effect of the diffuse double layer (DDL). The DDL is well-developed at high moisture contents and there is greater repulsion between the particles forming a dispersed structure. Therefore, the density of the soil increases as more particles can fit in a given volume. However, literature (Mitchell, 1993; Powrie, 1997; and Oweis and Khera, 1998) suggests that the behaviour of compacted clays can be described by other theories besides the DDL theory, for example the aggregation of particles (Sridharan et al., 1971; McGown and Collins 1975; Delage et al., 1996; Romero and Simms, 2008; Lee and Zhang, 2009; and Monroy et al., 2010). Delage et al. (1996) attributes the increase in density of soil to the formation of aggregate particles with large inter-aggregate pores Figure 2-1b). These become easier to break as the water content approaches the optimum moisture content. However, Delage et al. (1996) used silty clay as opposed to clay that was used by Lambe (1958a).

It is probable therefore, that both the DDL theory and the aggregation of particles on compaction contribute to the structure of compacted soil. However, the dominant factor is dependent on the composition of the soil. In addition, the structure of the compacted soil is affected by the soil water interaction, which in turn affects the soil engineering properties (Barden and Sides, 1970; Mitchell, 1993; Nagaraj and Miura, 2001).

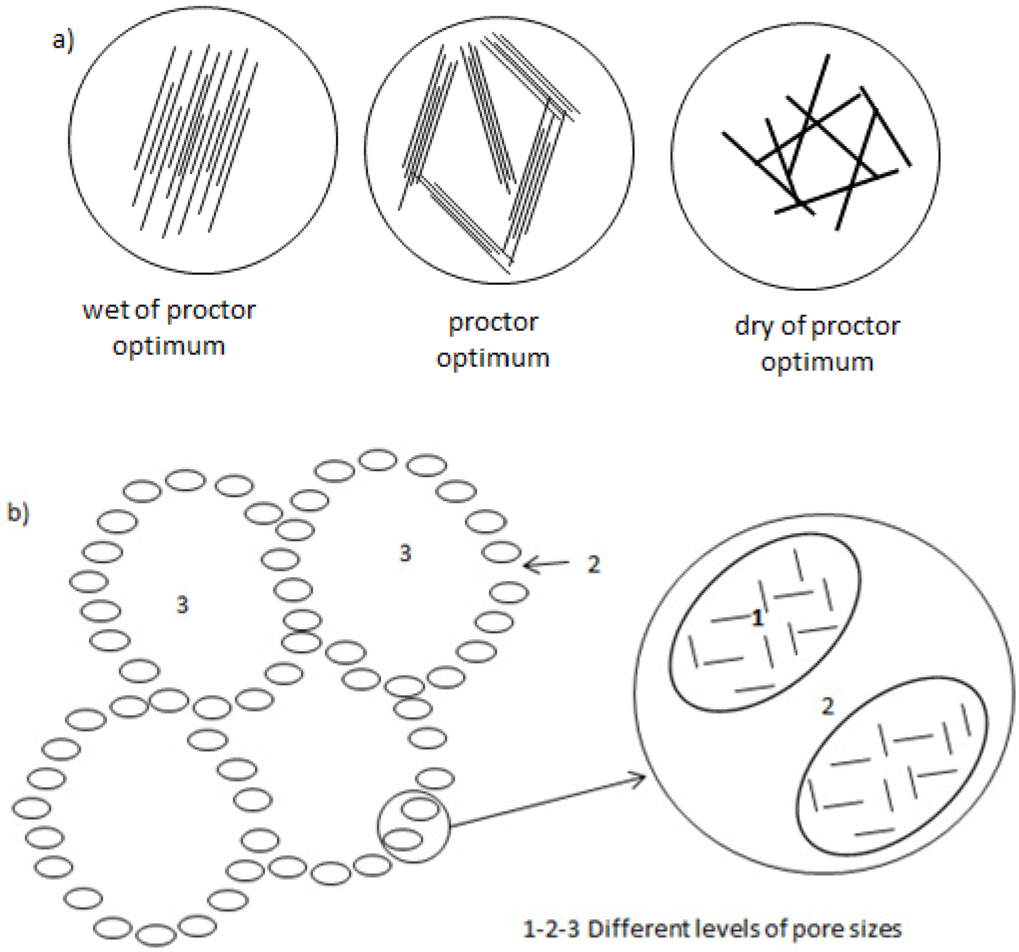


Figure 2-1: a) Orientation of clay particles at different Proctor moisture contents, b) Soil structure aggregation – 1: intra-aggregate pores (micro-pores), 2: inter-aggregate pores (meso-pores), 3: large enclosed inter-aggregate pores (macro-pores) (redrawn after Nagaraj and Miura, 2001)

2.2.2 Engineering properties of compacted clay

Compaction of soil results in orientation of particles, which affects the engineering properties of soil such as the hydraulic conductivity, compressibility, strength and volume change.

2.2.2.1 Hydraulic conductivity

The hydraulic conductivity of soil is a measure of the soil's ability to transmit water when subjected to a hydraulic gradient. Figure 2-2 illustrates the variation of the hydraulic conductivity of clay with water content. The hydraulic conductivity is least when close to optimum, such that any further increase in moisture results in a slight increase in hydraulic conductivity. Hence soil compacted wet of optimum exhibits lower hydraulic conductivity (Romero, 2013). This trend for hydraulic conductivity was explained using the DDL theory. However, if the stress level and chemical composition of the percolating fluid are varied, the hydraulic conductivity trend will differ (Schmitz, 2006) from that presented in Figure 2-2. It is therefore necessary to determine the chemical composition of the percolating fluid, stress level experienced by the soil and the soil structure before conclusions are drawn about a soil's hydraulic conductivity.

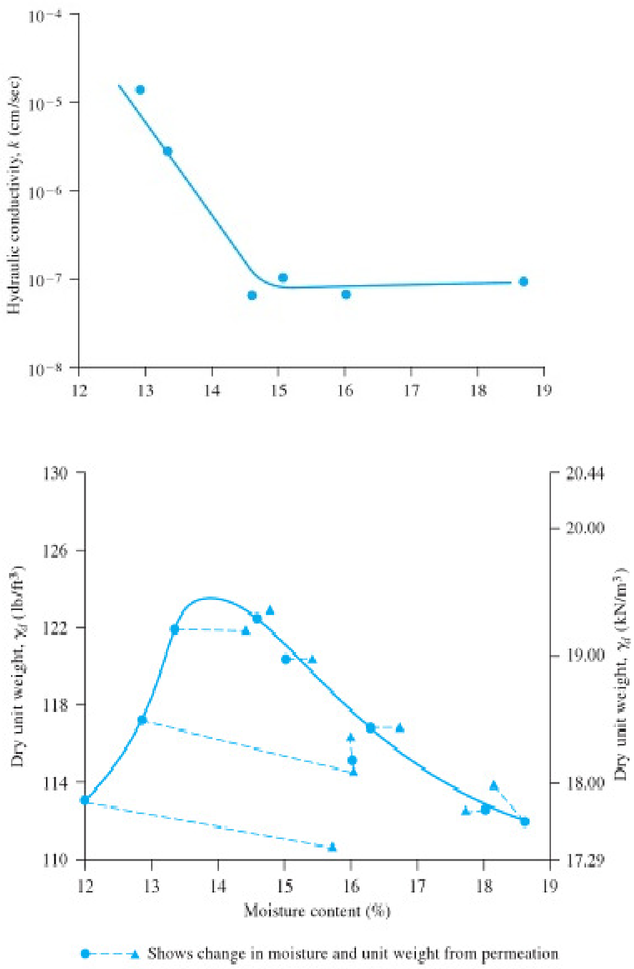


Figure 2-2: Effect of compaction on the hydraulic conductivity of clay

(redrawn after Lambe, 1958b (Das and Sobhan, 2013))

2.2.2.2 Compressibility

Compressibility refers to a reduction in the volume of soil due to the expulsion of water through the application of a static load. The compressibility of soil varies with the pressure applied. At low pressure (Figure 2-3); a soil that is compacted wet of optimum is more compressible than one compacted dry of optimum. This is because the microstructure (micro- and meso- pores) of soil remains unchanged on load application when a soil is compacted dry of optimum (Thom et al., 2007; Lee and Zhang, 2009; and Alonso et al., 2012). At low water contents, the aggregated soil particles exhibit very high stiffness, therefore resist low pressures. However, this applies to low plasticity soils and is not the case for sensitive clays (CH) (Monroy et al., 2010).

The aggregated soil particles thus need higher pressures to allow for compression (Figure 2-4). For this reason, a soil compacted dry of optimum is more compressible at high pressure than one compacted wet of optimum. Santucci de Magistris and Tatsuoka (2004) also found that the compression index changes moderately with water content from wet to dry conditions, except for states close to the modified Proctor optimum. Hence lower compression is experienced in soils wet of optimum.

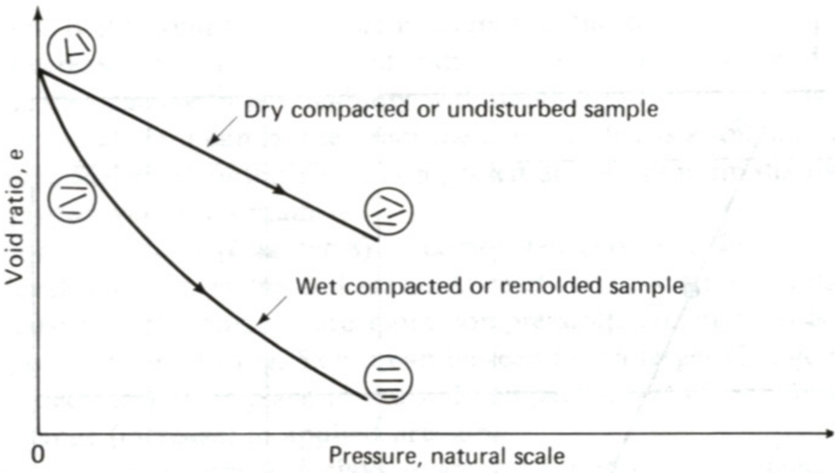


Figure 2-3: Low-pressure consolidation (Source: Lambe and Whitman, 1979)

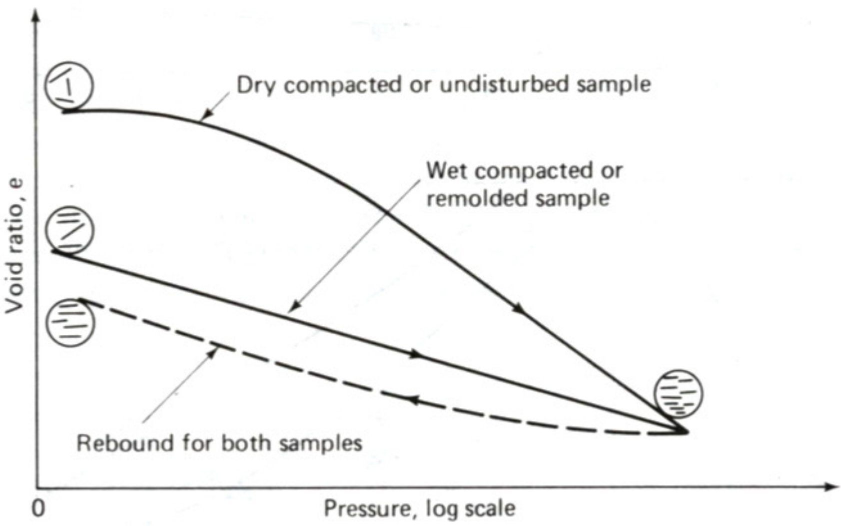


Figure 2-4: High-pressure consolidation (Source: Lambe and Whitman, 1979)

2.2.2.3 Strength

The shear strength of soil depends on the friction angle and cohesion. According to Çokça et al. (2004) the friction angle decreases with increase in water content, while cohesion increases with increase in water content up to a point close to the optimum and then decreases. However, some researchers (Ismail and Ryden, 2014; Luo et al., 2014; Tabet et al., 2014) observed that both the cohesion and friction angle vary parabolically with increasing moisture content. These researchers used silty clay while Çokça et al. (2004) used unsaturated clay. It is probable therefore, that the presence of silt in the soil contributes to the increase of the friction angle in silty clays.

Generally, shear strength is greatest close to the dry side of optimum. Tabet et al. (2014) found that samples compacted dry of optimum were stronger and stiffer. However, larger clod samples were stronger and stiffer than smaller clod samples. Therefore, the increase in shear strength is greater in soils with large particle sizes. Nonetheless, the large clod samples behaved as the small clod samples when exposed to water and saturated. They were also more easily deformed. Accordingly, it is important to control the moisture content of soil in order to preserve its strength.

2.2.2.4 Volume changes

Clay undergoes volume changes through swelling on adsorption of water, and shrinkage on loss of water. Figure 2-5 depicts the effect of varying water content and dry density on shrink and swell of compacted clay. The swell potential of clays increases with reduction in water content (Mishra et al., 2008). At low water contents, soil has a high affinity for water due to matric suction (Chen, 1988) thus swells more. However, Ashayeri and Yasrebi (2009) found that smaller values of free swell and swelling potential were experienced for samples at lower water contents and dry density compared to those compacted at optimum, which was in contrast with Figure 2-5. This could be attributed to the fact that there is less dry clay material to cause swelling at low dry densities and the mineralogy of the clay. Thus, clay mineralogy also plays a major role in the extent of swell, with kaolinite swelling less than montmorillonite (Mishra et al., 2008).

At high water contents, clay soils have a well-developed DDL with the soil particles further away from each other due to increased repulsion hence they undergo higher shrinkage on drying and develop larger cracks. The cracks enable swelling as they function as inlets for water. However, the shrinkage volumetric strains are independent of the initial dry density

(Birle et al., 2008). Ashayeri and Yasrebi (2009) discovered that critical water content existed at 3 per cent dry of optimum at which the highest volume change was experienced.

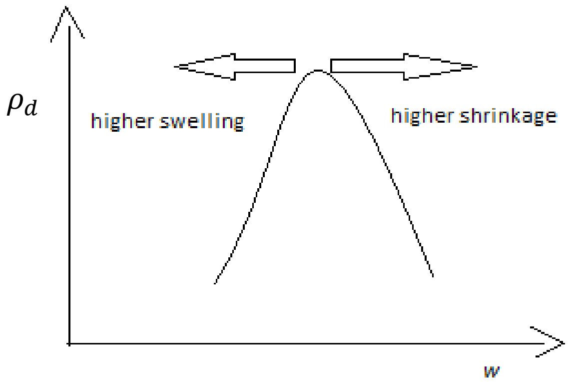


Figure 2-5: Effect of compaction on the volume change of compacted clay

Based on the effect of compaction on the engineering properties of soil, it is important that the water content of soil is controlled and that proper compaction is achieved. Soil compaction is carried out either in the laboratory or in the field.

2.3 Laboratory compaction

Laboratory compaction for determining the maximum dry density at optimum moisture content is categorised into Proctor tests for soils with more than 6 per cent fines and relative density tests for clean coarse soils (SP-GP) (Chen, 1999). Standard procedures detailing the compaction tests have been developed because of its importance in construction of earthworks.

2.3.1 Proctor tests

In 1933, R.R Proctor developed the standard Proctor test to assess compaction of fills (Coduto et al., 2011). However, due to the lower compaction effort in the standard Proctor test, the modified Proctor test was developed in the 1950's by the U.S Army Corps of Engineers in order to meet the compaction requirements for the heavier trucks and compaction equipment (Hveem, 1957). Figure 2-6 shows the Proctor mould and the hammers for the standard and the modified Proctor tests.

Figure 2-6: Proctor mould, standard and modified Proctor hammers

Proctor tests involve placing soil in layers and dropping a hammer of a given mass through a specified height a designated number of times, for each layer. The number of layers, height of hammer and number of drops differ depending on the Proctor test used and the standard followed. Table 2-1 shows the commonly used standards for the two Proctor tests.

Table 2-1: Comparison of different compaction standards

TEST	**STANDARD PROCTOR**		**MODIFIED PROCTOR**			
Standard followed	BS 1377 - 4	ASTM D-698 (A) /AASHTO T-99	BS 1377 - 4	ASTM D-1557(A) / AASHTO T-99	SANS 3001-GR30	TMH 1 – Method A7
Layer (no.)	3	3	5	5	5	5
Volume (cm^3)	1000	943	1000	943	943	943
Blows (no.)	27	25	27	25	25	25
Hammer weight (kg)	2.5	2.495	4.5	4.54	4.54	4.54
Drop height (mm)	300	304.8	450	457.2	457.2	457.2

From the tests, a Proctor curve such as Figure 2-7 for a particular soil at a given compactive effort is obtained, where $\gamma_{d\max}$ is the maximum dry density, w_o is the optimum moisture content and, S=100 % and S=80 % represent the zero air voids line and 20 % air voids line respectively. The modified Proctor test produces higher maximum dry density and lower optimum water content than the standard Proctor test due to the higher compaction effort exerted in the former test.

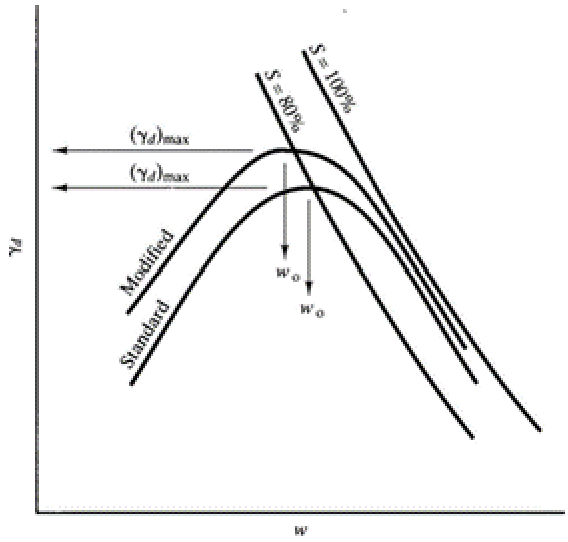


Figure 2-7: Typical Proctor curves showing the comparison between the standard and modified Proctor tests

The modified Proctor test therefore offers the advantage of reduced project costs because of the less volume of water required for optimum water content. The cost saving is even much more so for cohesive soils as compared to non-cohesive soils because the optimum moisture content for cohesive soils is greatly reduced by increasing the compactive effort (Connelly et al., 2008). The modified Proctor test is recommended for evaluating the compactness of non-cohesive soils (Selig, 1973) and is the preferred test for construction of highways because it offers high compaction effort while the standard Proctor test is the most commonly used test for compaction of fill (Chen, 1999).

2.3.2 Relative density

Relative density is used to describe the compactness of clean uniform sands and gravels. That is to say, free draining cohesionless soils with less than 15 % by dry mass passing the 75 μm sieve or those where 100 % by dry mass are passing the 75 mm sieve. Relative density, D_r is obtained using equation 2-1.

$$D_r = \left[\frac{\gamma_d - \gamma_{d\,\min}}{\gamma_{d\,\max} - \gamma_{d\,\min}}\right]\frac{\gamma_{d\,\max}}{\gamma_d} \qquad 2\text{-}1$$

where γ_d is the in situ dry unit weight, $\gamma_{d\min}$ is the dry unit weight in the soil's loosest state, and $\gamma_{d\max}$ is the dry unit weight in the soil's densest state.

Following ASTM D4254 -14, the dry unit weight in the loosest state is determined by loosely pouring oven dried soil through a funnel with a 25 mm spout for soils whose maximum particle size is greater than 9.5 mm or a 13 mm spout for those whose is less than 4.75 mm. The soil is poured through freefall at a height of 13 mm to fill a cylindrical metal mould of 2830 cm^3 volume. The weight of the dry soil, W_S and the volume of the mould, V are determined to calculate $\gamma_{d\min}$ as in equation 2-2.

$$\gamma_{d\min} = \frac{W_s}{V} \tag{2-2}$$

Other tests are used to obtain $\gamma_{d\max}$ and not the Proctor tests. The density index method has no direct relation with physical properties of the compacted soil and is erroneous as two index tests are required, and inaccuracies occur in both (Poulos and Hed, 1973). Therefore, it is not advisable to use relations between relative density and any of the Proctor tests because the relative density test has a lot of variability and the results are dependent on the operator of the test (Selig, 1973). In addition, the test is sensitive to particle distribution and shape such that increased angularity or eccentricity produces an increase in $\gamma_{d\max}$ and $\gamma_{d\min}$ (Cho et al., 2006). Hence, vibratory tests are used to compact granular soils (Drnevich et al., 2007). These include the vibrating table and vibrating hammer tests.

2.3.2.1 Vibrating table tests

Oven dried and/or saturated soil is filled in a mould of 2830 cm^3. A surcharge of 14 kPa is placed on the surface of the soil in the mould, and set up vibrated vertically using a vibrating table. A peak-to-peak amplitude of 0.33 ± 0.05 mm, at a frequency of 60 Hz is applied for 8 ± 0.25 minutes (ASTM D4253-14). The mould is weighed to obtain W_S. $\gamma_{d\max}$ is then calculated using equation 2-3.

$$\gamma_{d\max} = \frac{W_s}{V} \tag{2-3}$$

Vibrating table tests are time consuming, non-portable and expensive (Drnevich et al., 2007). As a result, the vibrating hammer test provides a portable alternative to the test.

2.3.2.2 Vibrating hammer tests

The vibrating hammer test provides results that are comparable to those of the vibrating table test and the modified Proctor test (Prochaska and Drnevich, 2005). They determined the maximum dry density using oven dried sand. However, Selig (1973) found that the maximum dry unit weight was obtained at saturated conditions. He thus recommended the use of saturated sand rather than oven dried sand. Therefore, according to ASTM D7382-07, oven dried and/or saturated soil is placed in three layers in a mould. The dimensions of the mould used are dependent on the particle size. Each layer of the soil is compacted using a vibrating hammer for a given duration. Table 2-2 shows the variations in the vibrating hammer test depending on particle size.

Table 2-2: Differences between Method A and Method B of the vibrating hammer test (ASTM D7382 -07)

SPECIFICATIONS	METHOD A	METHOD B
Mould diameter (mm)	152.4	279.4
Material passing sieve size (mm)	19	50
Layers (no.)	3	3
Time of compaction per layer (s)	60 ± 5	52 ± 5 at each of 8 locations

The dry density of the soil, γ_d is then calculated using equation 2-4. The range of water contents for effective compaction is then determined based on the zero air voids water content, w_{zAV} for the maximum water content and 80 % of w_{zAV} as the minimum value. Equation 2-5 is used to compute w_{zAV}. The maximum dry density is taken as the maximum of that obtained using either the oven dried or saturated soil.

$$\gamma_d = \frac{W_s}{V} \qquad \text{2-4}$$

$$w_{zAV} = \left(\frac{\gamma_w}{\gamma_{d\max}} - \frac{1}{G_s} \right) \times 100 \qquad \text{2-5}$$

where γ_w is the unit weight of water and G_s is the specific gravity of the soil solids.

Nonetheless, the vibrating hammer test is more efficient for granular soils because it excites individual particles (Sarsby, 2000), is applicable to a range of soils (Prochaska and Drnevich, 2005) and is a better representation of field compaction compared to the vibrating table (Drnevich et al., 2007).

2.4 Field compaction

Compaction in the field requires the application of greater energy unlike in the laboratory where low compactive energy is applied in multicycles and gravels (particles greater than 20 mm diameter) are excluded (Omotosho, 2004). Chinkulkijniwat et al. (2010) found gravel content greater than 20 % to affect the dry density and moisture content attained in the laboratory.

In the field, high loads from earth structures or heavy truck tyres are imparted onto the soil therefore denser states requiring more compactive effort are necessary to support the loads. This section discusses deep and surface methods of compacting soil in the field.

2.4.1 Deep compaction

Deep compaction is suitable for densifying thick layers of loose granular fills that may have been placed by hydraulic filling when reclaiming land (Bo et al., 2013). However, in the case of existing soils for foundations, several classification tests may be required to determine the soil classification. In addition, the soil profile may vary with the depth. Hence, it is convenient to determine the compactability of soil using cone penetration tests (CPT) that are taken over the soil profile (Massarsch, 1991). A method to classify soil compactability by deep compaction based on the cone resistance and friction ratio was proposed (Figure 2-8).

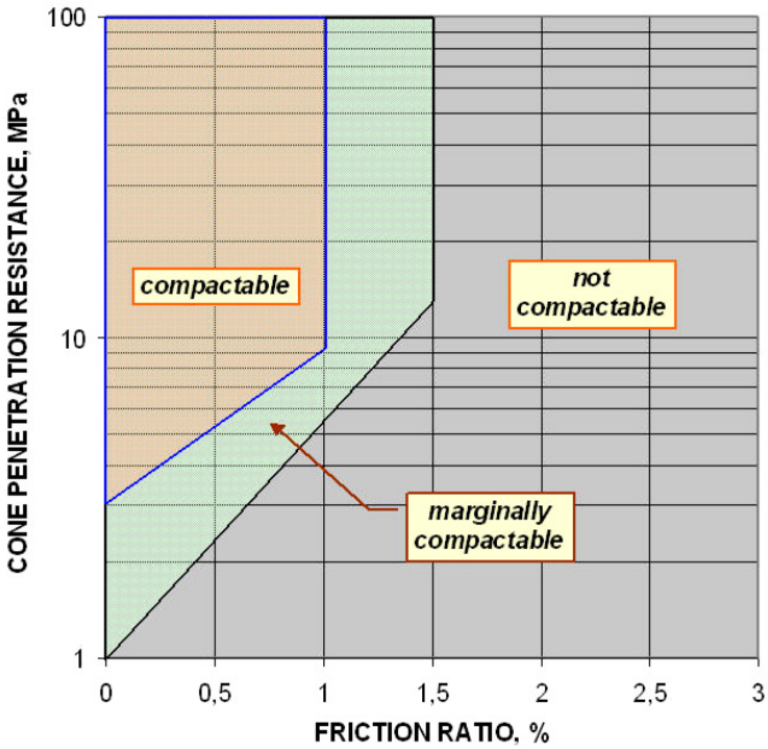


Figure 2-8: Soil classification for deep compaction based on CPT data (Massarsch, 1991)

Deep compaction is divided into dynamic compaction and vibrocompaction. Dynamic compaction has been improved into the rapid impact compaction method, while vibrocompaction is divided into vibroflotation and Muller resonance compaction. The details of the methods of compaction are given in the following sections.

2.4.1.1 Deep dynamic compaction

Deep dynamic compaction is widely used as a ground improvement method because it is cost effective, simple and improves soil properties to a considerable depth (Zou et al., 2005). The process (Figure 2-9) involves repeatedly tamping the soil with a heavy weight of 100 - 400 kN falling freely through a height of 10 - 40 m. The energy is applied to the soil in a grid pattern through either single or multiple passes (Figure 2-10). The craters created are either levelled or filled with soil.

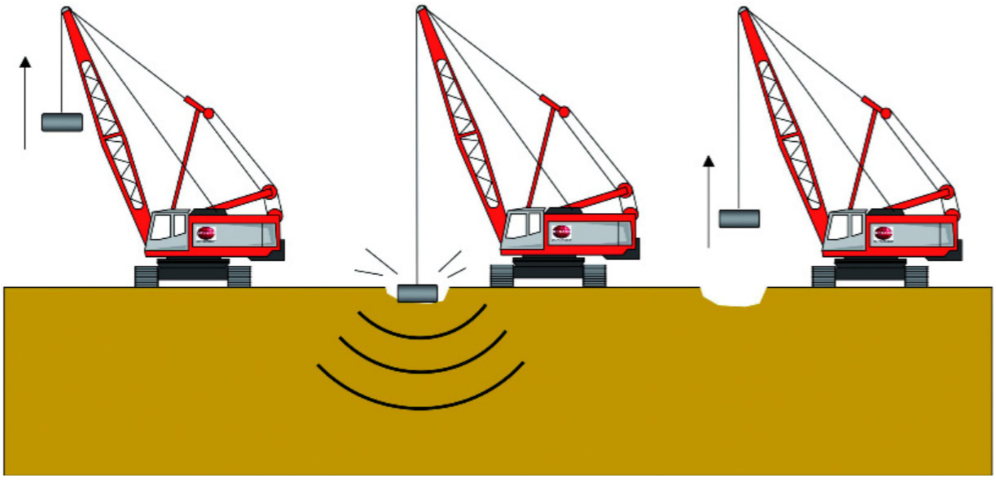


Figure 2-9: Dynamic compaction equipment and process (Source: vibromenard.co.uk)

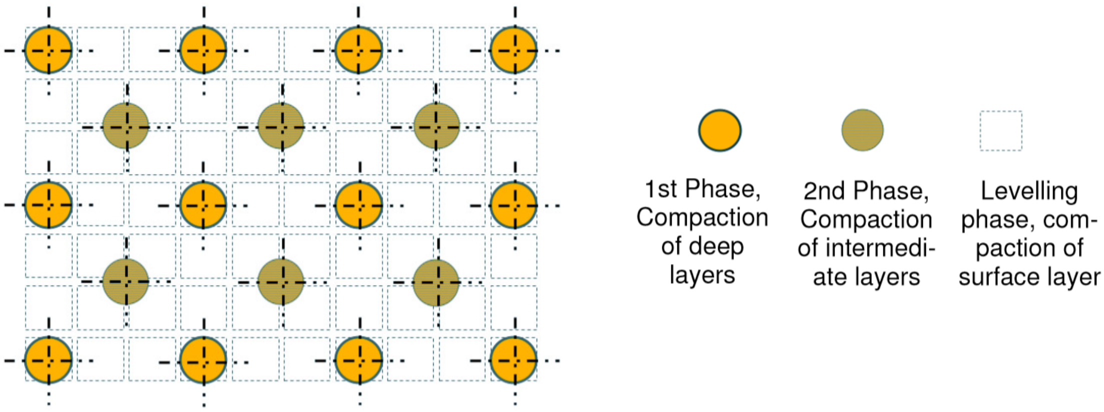


Figure 2-10: Dynamic compaction grid pattern and passes (Source: vibromenard.co.uk)

The impact force creates stress waves that push the soil particles into a tighter framework, reducing the void spaces and increasing the density of the soil (Pengelly et al., 1997). The force creates excess pore water pressures that are dissipated immediately in soils with high permeability (Miao et al., 2006). The method is therefore suitable for loose sand, gravel, silty sand and silt. In soft and liquefiable soil, the excess pore pressure is not dissipated immediately. As a result, cracks are formed in saturated fine-grained soils to enable drainage (Liu et al., 2008). However, lower tamping energies can be used to effectively compact fine-grained soils (Liu et al., 2008; Miao et al., 2006).

The practical application of dynamic compaction is empirical (Zou et al., 2005). It is dependent on the mass of tamper, height through which it falls and the sequence, the number of passes and the time delay between each pass, the grid spacing and the water content (Feng et al., 2010).

2.4.1.2 Rapid impact compaction

The rapid impact compaction (RIC) method was developed in the early 1990's as an improvement to deep dynamic compaction (Mohammed et al., 2013). It is also called controlled dynamic compaction. The process (Figure 2-11) involves dropping a weight of 30 to 90 kN at a fast rate (40 to 60 blows per minute) from a height of 1 to 2 m (Serridge and Synac, 2006). It is carried out at close spacing within an area of 6x6 m. RIC is suitable for compacting gravels, sands, silts, tailings material and landfills when near surface compaction is required (Ma et al., 2014). According to Mohammed et al. (2013), RIC is effective up to depths of 4-7 m. Depths up to 10 m have also been observed in Asia (Kristiansen and Davies, 2004). RIC results in reduced compressibility up to 50 %, increase in relative density of 25 % and increase in shear strength by 3^0 (Mohammed et al., 2013).

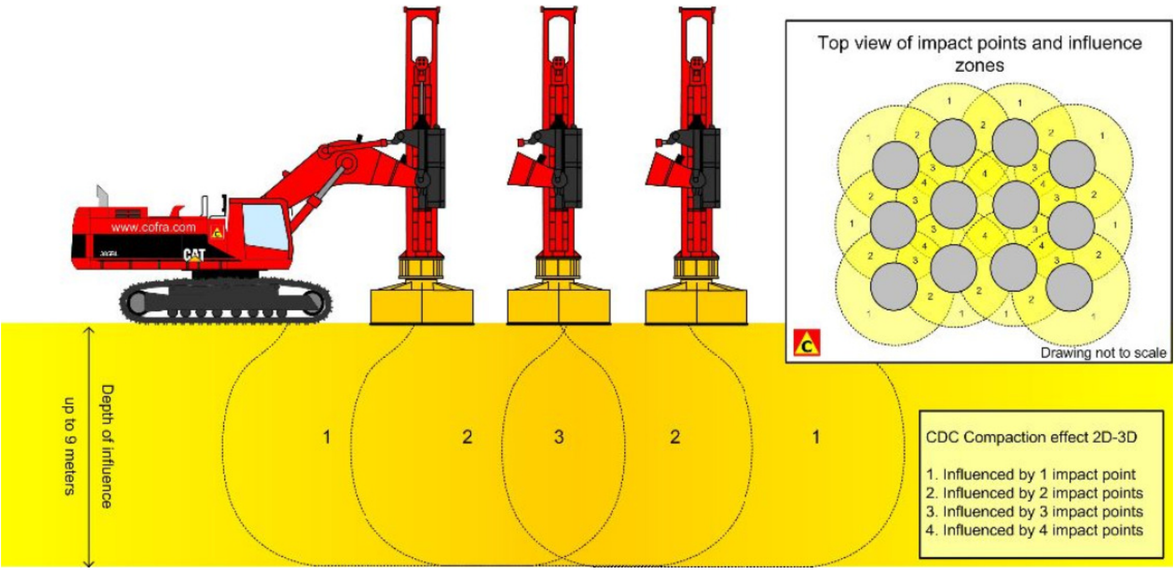


Figure 2-11: Rapid dynamic compaction equipment and process (Source: cofra.com)

2.4.1.3 Vibroflotation

Vibroflotation compaction was first used in Germany in the 1930s (Lopez-Querol et al., 2014). The process (Figure 2-12) involves penetrating a special probe, called a vibroflot to the desired depth, approximately 3-15 m (FHWA, 2001). The vibroflot produces horizontal vibrations at frequencies of up to 3000 cycles per minute and amplitudes of 10 to 23 mm (FHWA, 2001) and a jet of compressed air and water. The water saturates the soil around the probe and the soil liquefies due to the horizontal vibrations. At the desired depth, the jet of water is reduced or switched off. This induces horizontal forces around the probe causing the soil particles to rearrange into a denser state. The probe is withdrawn gradually and compacts the soil around it in steps. At the surface of the ground, a soil cone is formed which may be backfilled with in situ material or compacted granular fill. The procedure is done following a grid pattern. The surface is then levelled.

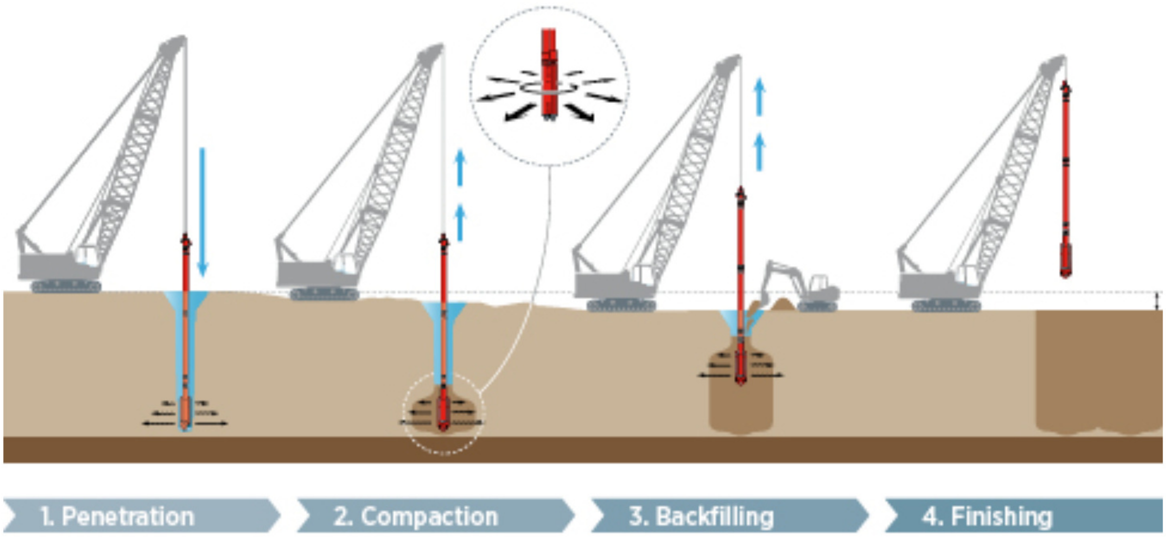


Figure 2-12: Process of vibro-compaction (Source: en.ptc.fayat.com)

The densities achieved with vibro-compaction decrease with increase in the probe withdrawal rate (Brown, 1977) and probe spacing (Brown, 1977; Bo, 2013). Brown (1977) observed that coarse granular soils were easier to compact than fine soils due to the generation of excess pore pressures in fine grained soils that impede volume change and prevent the soil particles from rearranging into a denser state (Rollins et al., 2003). As such, vibro-replacement is used for fine soils. It involves the construction of heavy weight bearing columns built from pebbles or crushed stones in cohesive soil (Shirazi et al, 2008). Figure 2-13 provides a guide to the choice of method to use depending on the soil particle size.

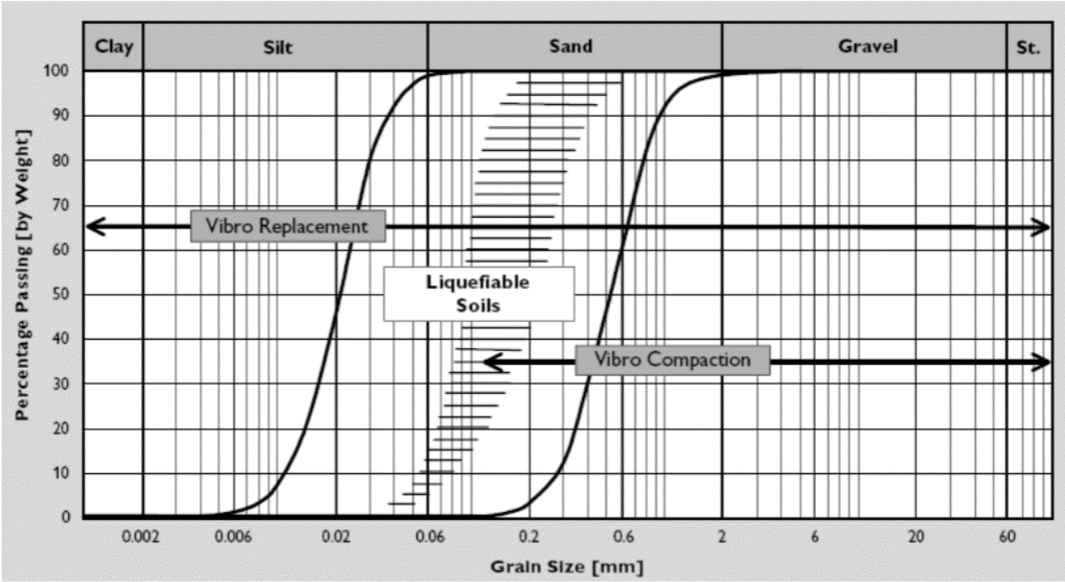


Figure 2-13: Particle size distribution for vibro compaction or vibro replacement (Keller, 2012)

2.4.1.4 Muller resonance compaction (MRC)

MRC shown in Figure 2-14 densifies sandy soils through the application of vertical vibrations to the whole soil profile causing rearrangement of particles. It does not require the saturation of soil using a jet of water but involves:

Using high frequencies of 23-25 Hz to push a vibrating probe into the ground to the desired depth (Bo et al., 2013). The high frequencies are required to overcome ground resistance to the penetration of the probe and reduce friction along the probe's shaft. In addition, at high frequencies the vibrations in the ground are low. The time required to penetrate the desired depth is recorded. At the desired depth, the frequency is adjusted to the resonance frequency of the ground for efficient transfer of vibration energy to the soil surrounding the probe, which amplifies the ground response. The probe is then vibrated vertically causing the whole mass of surrounding soil to rearrange and densify unlike the vibrocompaction method that densifies soil in steps. After the design compaction is attained, the probe is withdrawn at a high frequency to prevent decompression of the compacted soil. The advance of the probe is slowed at these frequencies, as well (Massarsch and Fellenius, 2005). Compaction is carried out in a grid pattern spaced at 3-5.5 m of two or more passes (Bo et al., 2013). At the second pass, a diagonal point of the grid is chosen and the probe driven to the desired depth, if the speed is similar or greater than that required in the first pass then the spacing is taken to be large. If the speed is less, a judgement call as to if it is too close or adequate is made.

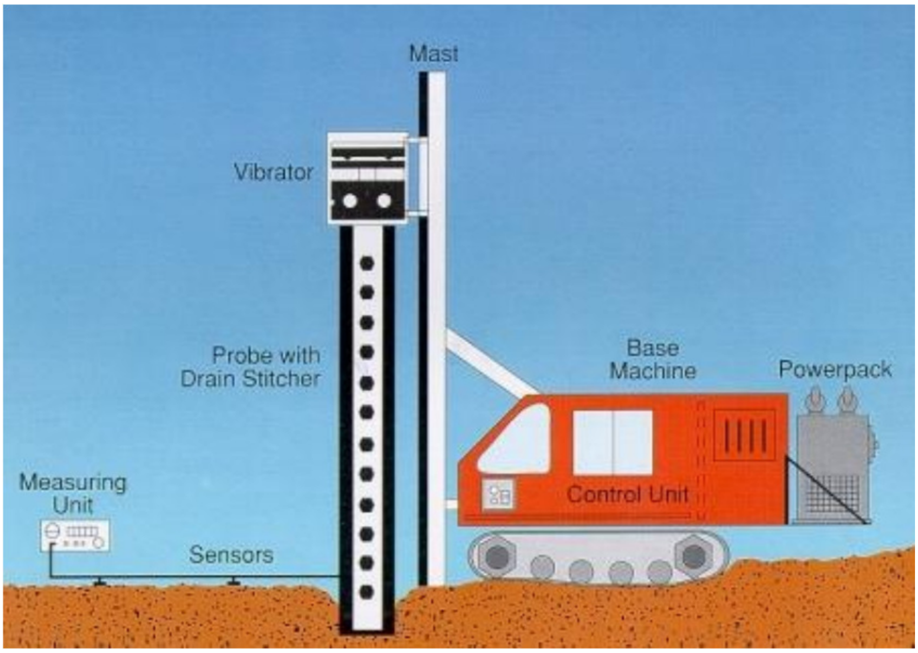


Figure 2-14: MRC electronic monitoring system for compaction control (Source: geoforum.com)

Bo et al. (2013) found the aging effect (increase in sand strength with time) to be more pronounced in top layers compacted using vibroflotation than MRC. This was attributed to dilatancy for soils compacted using MRC. However, the performance of vibratory methods is project specific and is dependent on several factors such as the type of sand fill and fines content (Bo et al., 2013).

2.4.2 Surface compaction

Surface compaction is applicable where soil is compacted in layers of up to 300 mm thick. The equipment used in compacting the soil are discussed in the following sections.

2.4.2.1 Smooth wheel rollers

Typically, smooth wheel rollers (Figure 2-15) have one large steel drum in front and two steel drums on the rear. Their gross weight is in the range of 8-10 tons and can be increased up to 20 tons by ballasting the inside space of the roller drums with either water or wet sand. Smooth wheel rollers exert less pressure, hence are usually used to finish the upper layers (Chen, 1999).

Figure 2-15: Smooth wheel roller (Source: mccpl.net)

2.4.2.2 Vibratory rollers

Vibratory rollers are similar to smooth wheel rollers with the modification that the drum or drums are made to vibrate by employing a rotating mass. However, the high dynamic frequency load induced by the vibrations is known to cause cracking in culverts where the soil above them is compacted using vibratory rollers. As a result, cushions consisting of expanded polystyrene are used to reduce the effect (Roh and Lee, 2007).

2.4.2.3 Pneumatic rollers

Pneumatic rollers (Figure 2-16) have a front and back axle with their wheels staggered so that they can compact soil layers with uniform pressure throughout the width. Pneumatic rollers provide a small compacting area with higher contact pressure, thus the exerted pressure is dependent on the number of wheels and the weight of the equipment (Kim et al., 2014). The rollers weigh 11 tons but their weight can be increased up to 25 tons or more through ballasting.

Figure 2-16: Pneumatic roller (Source: directindustry.com)

2.4.2.4 Sheepsfoot rollers

Sheepsfoot rollers consist of a steel drum on which many round or rectangular shaped protrusions are fixed. Sheepsfoot rollers (Figure 2-17a) compact the bottom of the lift first, followed by the middle and lastly the top. A modification to the sheepsfoot roller is the pad foot roller (Figure 2-17b), which is quickly replacing the sheepsfoot roller due to increased production and efficiency (RDSO, 2005). The weight of pad foot rollers ranges from 15 to 40 tons. They provide a higher degree of compaction and more uniform density. Pad foot rollers are suitable for compaction of subgrade soil (Kimmel, 2014).

a) 

b) 

Figure 2-17: a) Sheepsfoot drum (Source: purplewave.com) **and b) pad foot roller** (Source: imgarcade.com)

2.4.2.5 Rammer

The rammer (Figure 2-18) has a petrol or diesel engine that pushes the piston, and compacting plate into the air to drop back onto the soil. The jumping movement compacts the soil. They are capable of compacting soil layers 150 – 300 mm (Chen, 1999). Rammers are suitable for compacting both cohesive and non-cohesive soil in confined areas.

Figure 2-18: RT74 rammer (Source: iandickie.co.za)

2.4.2.6 Summary of the equipment

Table 2-3 shows the different types of rollers used and some of their corresponding properties.

Table 2-3: Types of rollers used in field compaction

PROPERTY	ROLLER TYPE			
	Smooth	Pneumatic	Sheepsfoot	Vibratory
Contact Pressure (kN/m^2)	310 - 380	600 - 700	1380 - 6900	2000 - 6000
Coverage (%)	100	70 - 80	8 - 12	
Soil type	Sand and Clay	Sand and Clay	Cohesive soils	Non-Cohesive soils
Mechanism of compaction	Pressure	Pressure and kneading	Kneading	Vibration

Thus, compaction in the laboratory is necessary to determine the maximum dry density and optimum moisture content at which the soil will be compacted in the field. Several instruments are available to choose from for compaction. However, the choice of compactor used will depend on the soil type, compactor energy and size of the working area. These will in effect also affect the degree of compaction attained.

2.5 Factors affecting the degree of compaction

The degree of compaction attained in the laboratory and the field is dependent on the moisture content, soil type, compaction energy; and compactor characteristics and the construction procedure in the case of field compaction. All of the aforementioned factors are interrelated and should each be considered in order to attain maximum dry density at optimal costs.

2.5.1 Water content

As the water content of soil is increased, its dry density increases up to the maximum dry density at optimum water content, for a particular compactive effort. Beyond the optimum water content, the dry density decreases. This is because, initially as more water is added to the soil, interparticle friction reduces enabling the particles to push closer to one another hence the air voids decrease and the density increases. As the soil state approaches the zero air voids line, the maximum dry density at optimum water content is attained. Thus beyond the optimum water content, any additional water results in reduction in the dry density because water starts to replace the soil particles.

2.5.2 Soil type and gradation

Soil is divided into two main categories namely non-cohesive and cohesive soils. Cohesive soils include silt and clay, and have the smallest particle size (< 0.075 mm). Non-Cohesive soils on the other hand, include gravel and sand, and their particle size ranges between 76.2 mm and 0.075 mm. The variation of moisture content and dry density for non-cohesive and cohesive soils is described in the next sections.

2.5.2.1 Non-cohesive soils

Clean sands and soils with liquid limit less than 30 have a Proctor curve of one-and-a-half peak. For example, the well graded gravel from Keesler in Figure 2-19. This is due to the phenomenon of bulking. Bulking is the increase in volume of sand when water is added; maximum volume is attained when all the sand particles are surrounded by water. Therefore, the desired density in sand is achieved at either fully dry or saturated water contents because at intermediate water contents capillary stresses in the voids resist compaction. A number of relations for determining the dry density of non-cohesive soil are found in Omar et al. (2003).

2.5.2.2 Cohesive soils

Cohesive soils are more sensitive to moisture content changes and cannot be compacted over a wide moisture range as compared to non-cohesive soils (Scott et al., 2012). However, they require more water to reach optimum. The optimum water content for cohesive soils can be calculated from the soil's plastic index. Several researchers have independently found that a relationship exists between dry unit weight, optimum water content, and the plastic index. A number of these relationships are given on page 157 of Das and Sobhan (2013).

Figure 2-19 shows the variation of optimum water content and dry density for different soil types. All soils were compacted using the modified compaction effort except for the clay of high plasticity, which was compacted using both the standard and modified Proctor test. Omar et al. (2003) observed that the most significant soil variables influencing dry density are the specific gravity, percentage retained on the 75 μm sieve and liquid limit. Hence, the maximum dry density obtained for a particular soil type will vary depending on the aforementioned variables.

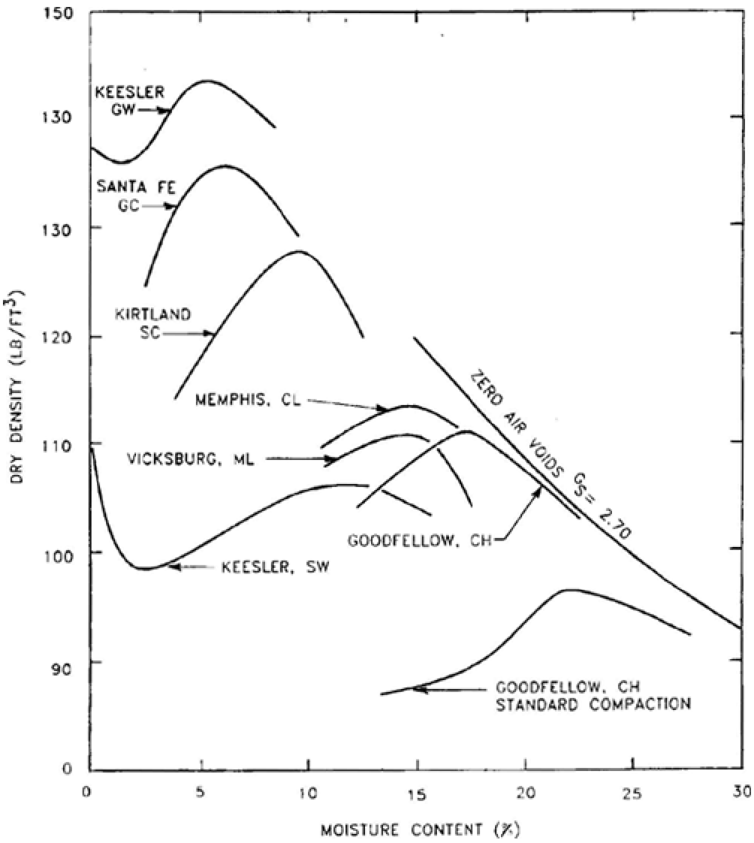


Figure 2-19: Variation of modified Proctor compaction characteristics for different soil types

(Christopher et al., 2006)

2.5.3 Compactor characteristics

Compactor characteristics such as mass, and operating frequency in the case of vibratory rollers affect the extent of compaction. Wong (1967) observed that heavy machinery with higher frequency exert higher compactive effort; therefore provide higher dry densities. Lewis (1959) obtained similar results (Figure 2-20). However, the effect of compactor mass reduces with increased water content due to reduction in the bearing capacity of the soil resulting in increased roller-soil contact area hence less contact stress (compaction energy) is applied (James and Shipton, 2012).

The number of wheels of pneumatic rollers also affects compaction. Pneumatic rollers attain compaction through exertion of point loads while smooth drum rollers exert a uniform force. Hence, pneumatic rollers require more passes to attain the same density as the smooth roller, which affects the construction procedure followed for a particular type of compactor (Kim et al., 2014). However, the kneading action of pneumatic rollers makes them suitable for compaction of clays.

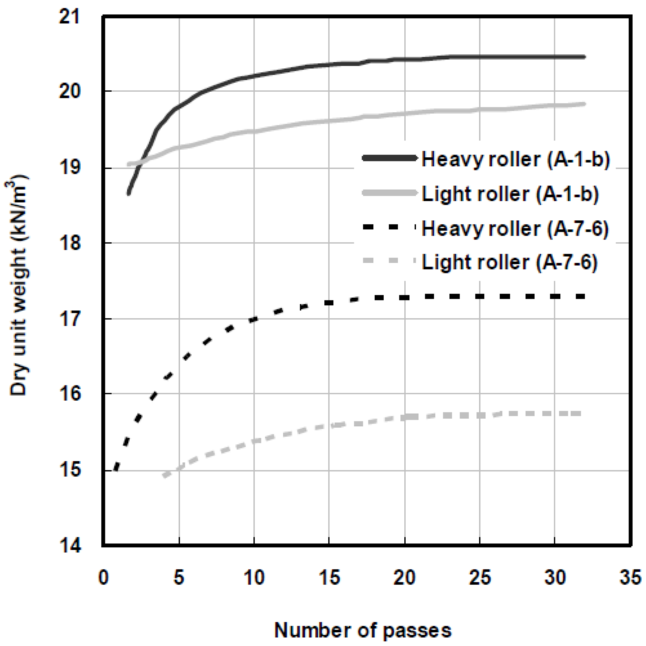


Figure 2-20: Typical growth curves for well-graded sand (A-1-b) and heavy clay (A-7-6) (Lewis, 1959)

2.5.4 Construction procedure

The following construction variables will affect the extent of compaction:-

- The layer thickness

  The layer thickness used will depend on compactor characteristics and the soil type. Soil type influences the distribution of contact stress on a surface (Kim et al., 2014). As a result of this, silty clays (cohesive soil) require lifts thinner than 300 mm as compared to uniform sand (non-cohesive soil) where good compaction is achieved in lifts 300 mm thick (Kim et al., 2014). The greater the layer thickness, the less the compaction efficiency because more compaction effort is required under each pass of the roller to achieve maximum dry density due to energy dissipation with depth (Liu and Kushwaha, 2012; Kim et al., 2014).

- Number of roller passes

  The dry density of soil increases with increase in the number of passes until an optimum number of passes is reached. Beyond this point, any increase in density is insignificant. The optimum number of passes is determined through trial tests. With reference to Figure 2-20, the optimum number of roller passes is five for the heavy compactor. Wong (1967) also observed that no significant statistical increase in density occurred after six passes. The principal compactive effect was achieved after the first pass and was smaller for each subsequent pass. However, Canillas and Salokhe (2001) determined that compaction could be accomplished during the first three passes of the tractor tire therefore, it is important that proper compaction be attained on the first pass. In addition, the number of passes necessary to attain maximum dry density will vary depending on the compactor and compactor weight used. Consequently, heavier compactors require fewer passes.

- Travel speed

  The lower the speed of the compactor, the greater the dry density attained. This is because the slower the compactor, the more the vibrations experienced at a point and the less the number of passes required to attain a particular dry density. However, the effect of compactor mass (Canillas and Salokhe, 2001; Liu and Kushwaha, 2012) and the number of passes (Canillas and Salokhe, 2001) are more significant. Figure 2-21 shows the effect of compactor travel speed with a wheel load of 75 kN on well graded sand.

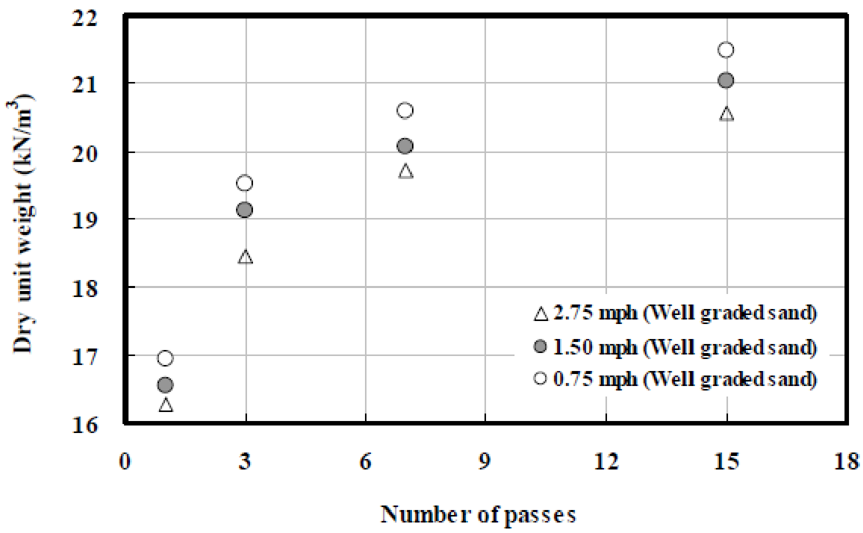


Figure 2-21: Effect of compactor speed (data from Selig and Yoo, 1977)

It is important therefore to determine the optimum rolling equipment variables, as well as soil specific variables such as soil type and water content. This way the rolling process is optimised and the compaction density can be achieved with minimum effort (James and Shipton, 2012). However, some of these variables such as the moisture content are given in the compaction specifications.

2.6 Specifications for compaction

Specifications are made to avoid variations in compaction and ensure uniformity and that the desired engineering properties are attained. The specifications are divided into three, namely: performance specifications, method specifications and end result specifications (TRB, 2009).

2.6.1 Performance based specifications

Performance based specifications define the performance characteristics (strength and stiffness) of the final product and link them to construction, materials, and other items under contractor control (FHWA, 2004). Performance is described as changes in the physical condition of the compacted subgrade and its response to the load (TRB 2009). Hence, performance based specifications determine the ability of the end product to meet performance requirements over time.

2.6.2 Method specifications

Method specifications, also known as work type specifications, involve instructing the contractor on what and how to compact. The contractor is given detailed instructions specifying the compactor type, lift thickness, number of passes, travel speed and moisture content. In this type of specification, the work procedure must be inspected to guarantee the quality of compaction. However, this specification tends to obligate the client to accept the completed work regardless of quality (TRB, 2009). Consequently, the end result specification is commonly used.

2.6.3 End result specifications

End result specifications require the contractor to achieve a certain degree of compaction based on the standard or modified Proctor test maximum dry density. Most specifications for earthworks specify that a relative compaction of 90 to 95% (Geotechnical Engineering Bureau, 2014) is achieved. Relative compaction index, RC given in equation 2-6, is the ratio of the compacted field dry density, γ_{d_field} to the maximum dry density, γ_d attained in the laboratory.

$$RC = \frac{\gamma_{d\_field}}{\gamma_d} \times 100 \qquad \text{2-6}$$

2.7 Summary

In this chapter, the effect of compaction on the structure of clay through the formation of the DDL or the aggregation of particles was discussed. This in turn affects its engineering properties. Hence, it is important that soil be compacted properly to attain the desired mechanical properties. Proctor and relative density tests in the laboratory, together with deep and surface compaction in the field were reviewed. The Proctor tests are used to obtain the maximum dry density and optimum moisture content at which soil is compacted in the field. However, the degree of compaction achieved may vary. Therefore, the various factors affecting the extent of compaction such as soil type were presented. Consequently, specifications are necessary to ensure that the compaction achieved is uniform and desirable. The different specifications were discussed at the end of the chapter. Thus, the compacted soil is tested to ensure that it meets the set control parameters in the specifications. Chapter 3 discusses the different density based tests used to measure compaction.

CHAPTER 3 DENSITY BASED TESTS FOR COMPACTION

3.1 Introduction

Density based tests measure the in-situ dry density of the soil directly thereby ensuring that end result specifications are met. This chapter reviews commonly used density based tests. They include volume replacement tests, the nuclear density gauge test and electrical density gauge test. The operating principles of the more complex tests; nuclear and electrical density gauges, are presented to provide an understanding of how they work. Finally, the different case studies relevant to this study are reviewed in order to identify what has been accomplished and the existing knowledge gaps.

3.2 Volume replacement tests

Volume replacement tests involve measuring the volume, *V* of a hole excavated to a depth of approximately 150 mm, obtaining the weight (*W)* of the excavated soil, and then determining the water content (*w*) of the soil in the laboratory. The bulk density (γ_m) and dry density of the compacted soil (γ_d) are then calculated as shown in equation 3-1 and equation 3-2 respectively. Volume replacement tests give accurate and repeatable results (Rathje et al., 2006). However, they are time consuming, as the contractor will not know if the compaction meets the standard until 24 hours later (Chen, 1999). They are also destructive since they necessitate excavating a hole. Volume replacement tests include the sand cone replacement, rubber balloon and the drive cylinder.

$$\gamma_m = W/V \quad \text{3-1}$$

$$\gamma_d = \gamma_m/(1+0.01w) \quad \text{3-2}$$

3.2.1 Sand cone replacement test

The apparatus (Figure 3-1) consists of a 100–150 mm diameter can, containing sand, a cone sloping at 60^0 to the horizontal and a base plate with a flanged hole in the centre (ASTM D1556). The unit weight of the sand is determined prior to testing. The test procedure is conducted according to ASTM D1556 for materials with particles smaller than 38 mm, otherwise ASTM D4914 is used. Equations 3-1 and 3-2 are used to compute the bulk density and the field dry density respectively.

Figure 3-1: Sand cone apparatus (Source: capco.co.uk)

The sand cone test provides acceptable density values in all soil types (Mejias-Santiago, Berney and Kyzar, 2013). According to Redus (1957) and Noorany et al. (2000), it provides the most accurate results for in situ density tests. However, sand cone densities are affected by material variation and particularly human error (Ishai and Livneh, 1983). In addition, it is hard to obtain accurate results using the SC test in stony soils (GTI, 2004). The test also requires an additional test such as the laboratory oven to measure the moisture content for calculating the dry density. Ishai and Livneh (1983) found the laboratory oven to have higher accuracy in granular material than that in fine-grained plastic materials. Furthermore, the sand cone test is sensitive to vibrations from construction machinery close to the test point hence any construction work close to the test point has to come to a standstill for the duration of the test.

3.2.2 Rubber balloon test

The rubber balloon apparatus (Figure 3-2), consists of a metal base plate with a 100 mm diameter hole in the centre, hand pump, graduated cylinder filled with water and a rubber membrane at the base. Even though the rubber balloon is accurate, the volume measured using this method is less when compared to the sand cone due to the presence of air voids (Redus, 1957). Furthermore, it is unsuitable for soils such as those with appreciable organic content or very soft clays, unbound granular soils (sand) and soils with significant amounts of rock or coarse material (ASTM D2167). These soils may deform when pressure is applied to the membrane during volume measurement, collapse during excavation or they may puncture the membrane, respectively.

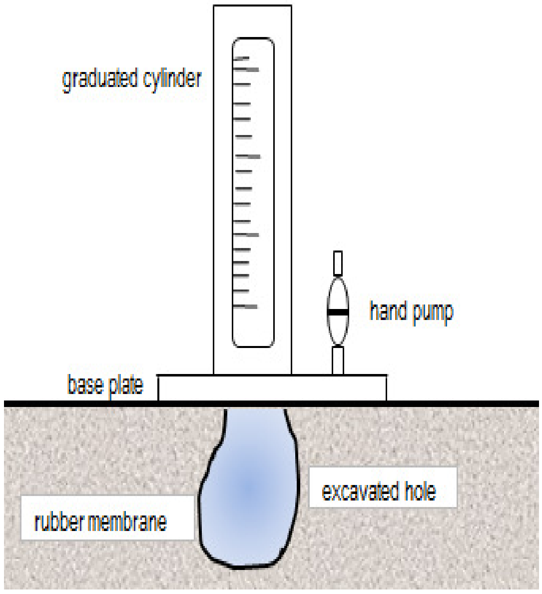


Figure 3-2: Test set up for the rubber balloon test

3.2.3 Drive cylinder test

The drive cylinder (Figure 3-3) consists of a thin walled cylinder open at both ends with outside diameter of approximately 102 to 152 mm. Noorany et al. (2000) recommended that the drive cylinder test is not used for soils that easily deform such as soft, highly plastic soils or non-cohesive soils. In addition, invalid results may be obtained for soils coarser than 4.75 mm due to the formation of voids along the cylinder wall during trimming (ASTM D2937). However, these can be reduced by using drive cylinders of volumes greater than 850 cm^3.

Figure 3-3: Drive cylinder apparatus (Source: hoskin.ca)

3.3 Nuclear density gauge

The nuclear density gauge (NDG) consists of a source of neutrons and gamma rays, Geiger Muller detector, and a device for recording the output pulses of the detector. Nuclear density gauges use low-level radiation to measure the bulk density, dry density, and moisture content of soil.

3.3.1 Background

Nuclear probes were developed due to the need to detect soil moisture variations in foundations without disturbing the equilibrium conditions (Ehlers et al., 1969). Similarly, the construction of highways, airport runways, and earth dams required a rapid yet accurate method to determine soil water content and density for field inspection and quality control (Lane et al., 1953). Nuclear probes developed from single density and moisture content probes, to surface gauges (Neville and Van Zelst, 1961) and then to the present day NDG (Figure 3-4), which functions as both a probe and surface gauge.

Figure 3-4: The Humboldt HS-5001SD moisture/density nuclear gauge (Source: humboldtscientific.com)

3.3.2 Operating principles

The NDG measures density and moisture content simultaneously. Moisture content measurements are based on the interaction between neutrons and hydrogen atoms in water (Pieper, 1949; Yates, 1950), while bulk density measurements are based on the scattering of gamma rays in soil (Krueger, 1950). The theory underlying moisture content and density measurement is explained.

3.3.2.1 Moisture content measurement

The NDG measures the water content of soil by slowing down neutrons through collisions with hydrogen such that further collisions have no impact on the neutrons: a process known as thermalisation. The number of collisions necessary to thermalize a fast neutron from its original energy of 2.5 MeV to 0.025 eV for various elements common in soil is shown in Table 3-1.

Table 3-1: Values of n, ξ and σ_s for principal soil elements (Adair, 1950)

Element	Atomic number, Z	Relative energy lost in a collision, ξ	Cross section for fast neutrons 2.5 MeV, σ_s in Barns	Cross section for slow neutrons 0.025 eV, σ_s in Barns	Number of collisions required for thermalisation
Hydrogen	1	1.000	2.55	47.5	18.0
Carbon	12	0.162	1.60	4.6	113.0
Nitrogen	14	0.145	1.00	13.0	131.0
Oxygen	16	0.128	1.50	4.2	149.0
Chlorine	17	0.113	2.70	40.0	322.0
Sodium	23	0.086	2.60	3.6	214.0
Magnesium	24	0.082	2.00	3.5	225.0
Aluminium	27	0.075	2.50	1.6	246.0
Silicon	28	0.071	3.20	2.5	257.0
Phosphorus	31	0.063	3.00	4.0	286.0
Sulphur	32	0.061	2.60	1.3	295.0
Potassium	39	0.050	3.80	3.0	360.0
Calcium	40	0.049	4.90	1.5	368.0
Cadmium	48	0.041	4.40	6.0	444.0
Manganese	55	0.037	3.00	12.0	487.0
Iron	56	0.035	13.00	3.0	515.0

With reference to Table 3-1, hydrogen requires the least collisions (18) for thermalisation. This makes hydrogen effective for slowing down neutrons. Water in construction soil contains the most hydrogen (11 %) compared to clay minerals (Adair, 1950). Hence, it is assumed that the hydrogen content of soil, particularly sub soil, is almost entirely due to its water content. Therefore, the water content of soil is proportional to the amount of thermalised neutrons reflected to the detector (helium-3). However, the water content measured is affected by:

1) The depth of measurement, which is the depth at which 98 % of the neutrons pass before they are reflected to the detector is a function of the moisture content. The higher the moisture content the lower the depth of measurement. Figure 3-5 shows that at depths greater than 100 mm, the moisture content reading is almost constant.

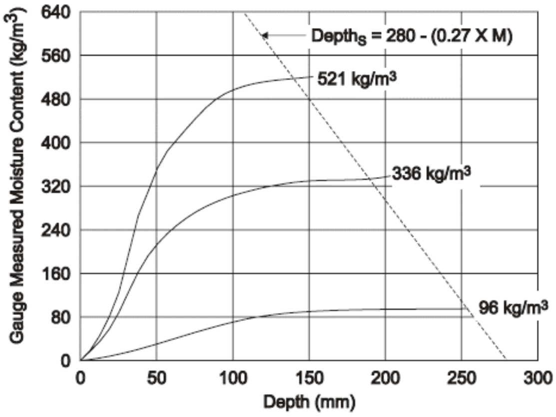


Figure 3-5: Effect of moisture on depth of measurement (Source: Troxler 3440 Manual, 2006)

2) Presence of significantly large quantities of strong neutron absorbers (Troxler, 1963). Table 3-2 shows the relative absorption coefficient of some elements whose relative absorption coefficient is greater than hydrogen. The presence of these elements with high cross sections in sufficient amounts in the soil may result in neutron moderation predominating through interaction with these elements rather than with hydrogen (Friedenwald, 1963). Therefore, the reading obtained is not representative of the soil moisture content.

Table 3-2: Relative absorption capability of some elements for thermal neutrons (0.025 eV) (Troxler, 1963)

STRONG ABSORBERS	CROSS SECTIONAL AREA (Barns)	COMMONLY ENCOUNTERED ELEMENTS	CROSS SECTIONAL AREA (Barns)
Cadmium	2450	Iron	2.53
Boron	755	Potassium	2.07
Indium	196	Nitrogen	1.88
Gold	98.8	Sodium	0.505
Lithium	71.0	Calcium	0.44
Silver	63.0	Hydrogen	0.332
Chlorine	33.6		

3.3.2.2 Density measurement

The NDG measures the density of soil based on the scattering and absorption properties of gamma radiation with matter. Gamma rays interact with the orbital electrons in the test material through either the photoelectric effect, or pair production or Compton scattering illustrated in Figure 3-6.

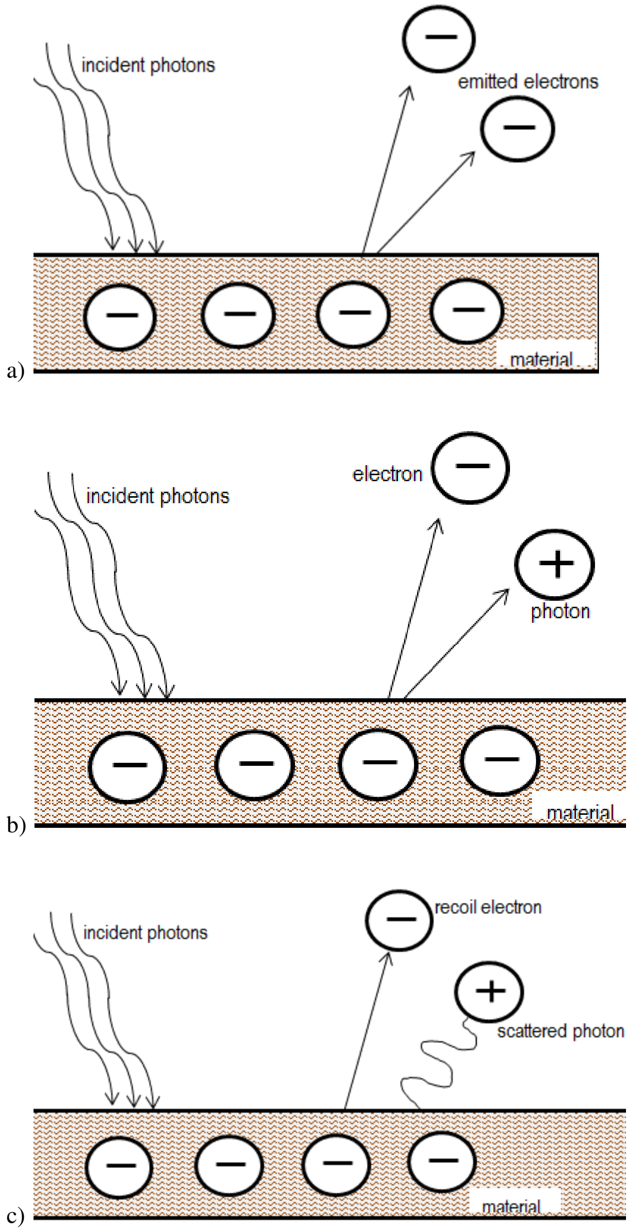


Figure 3-6: Gamma ray photon interaction with matter

The NDG uses Cesium-137 as the gamma source (Troxler 3440 Manual, 2002). Cesium emits a monoenergetic gamma ray of 0.66 MeV (Friedenwald, 1963). Photons in the energy range of 0.35 MeV to 2.5 MeV are absorbed almost exclusively through Compton scattering (Roy and Winterkorn, 1957). Compton scattering is dependent upon the electron density of the absorber (test material).

In the NDG, the scattered photons are measured by the Geiger Muller detector at the base of the gauge and are then converted into density readings by a microprocessor using calibrated empirical algorithms. The detector count is inversely proportional to the measured density for radiation sources in the ground because a dense soil has more electrons and therefore a higher probability of interaction with the emitted photons. As a result, dense media absorb most of the gamma rays as illustrated in equation 3-3 developed by Davisson and Evans (1952). Equation 3-3 gives the relationship between the linear absorption coefficient, μ and the total cross section e^{μ}, for ideal geometry.

$$\mu = \rho N \frac{Z}{A} e^{\mu} \left(cm^{-1}\right) \qquad 3\text{-}3$$

where

ρ = density of the absorbing medium

N = Avogadro's number = 6.02 x 10^{23}

Z = atomic number of absorber element (number of electrons)

A = atomic weight of absorber element

In a fixed geometry e^{μ} is constant, *Z/A* is approximately 0.5 for all light elements ($Z \leq 30$) or their compounds and *N* is constant. Hence, the linear absorption coefficient,μ is proportional to the density, ρ of the absorber such as soil.

For radiation sources at the surface of the ground, the absorption coefficient is inversely proportional to the density of the material. The detector count of scattered photons is therefore proportional to the density of the soil because the emitted photons penetrate the material and have to be scattered at least once before they are detected. Therefore the denser the material, the more gamma rays are redirected. Placing the nuclear source at the surface relates to backscattering in the NDG, while the placement of the nuclear source in the ground relates to direct transmission. Consequently, the density of the soil in the NDG is measured in either the direct transmission mode or backscatter mode as shown in Figure 3-7.

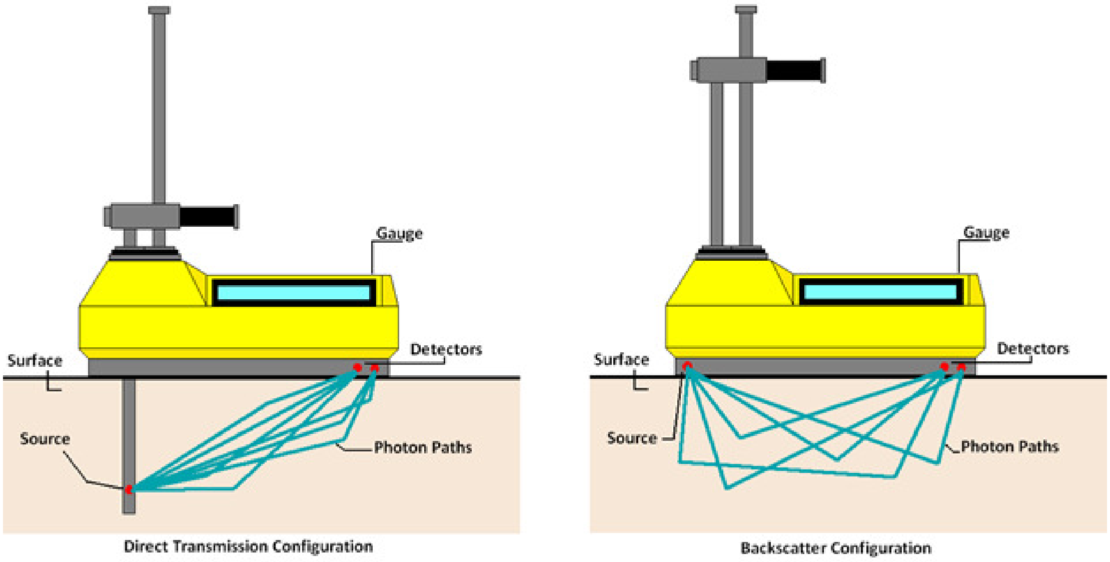


Figure 3-7: Configuration of the nuclear density gauge in direct transmission mode and backscatter mode

(Meehan and Hertz, 2011)

Winter and Clarke (2002) recommended the use of direct transmission mode for measuring density because measurements made in backscatter mode represent only the top 135 mm of material. U.S. Army Engineer Waterways Experiment Station (1969) also noted that densities determined in the backscatter mode were not accurate and that the use of the direct transmission mode with the factory calibration curve produced accurate densities when compared to volume replacement tests. The NDG has high repeatability characteristics with the standard deviation for bulk density not exceeding 0.20 kN/m^3 (Ishai and Livneh, 1983). However, NDG dry densities and bulk densities were consistently less than those of the sand cone test, while the moisture content was higher than that of the laboratory oven (Kaderabek and Ferris, 1979). Noorany et al. (2000) also observed that the significant variation of NDG moisture content measurements from those of the laboratory oven is a serious source of error.

3.4 Electrical density gauge

The electrical density gauge (Figure 3-8) is a relatively new instrument patented in April 2002 (Anderson et al., 2005). It was invented to provide a non-nuclear, portable, low cost field use device for measuring dry density of soil. The density and moisture content of the soil is inferred from the measured dielectric properties (capacitance, C_s and resistance, R_s) of the compacted soil.

Figure 3-8: The Humboldt electrical density gauge model H-4114SD.3F (Source: geneq.com)

3.4.1 Operating principles

Current is applied to the soil through probes pushed into the soil. The measurement circuit of the EDG (Figure 3-9) consists of a 3 MHz alternating current source (1), a current sensing resistor (2) and spike type probes (3a and 3b).

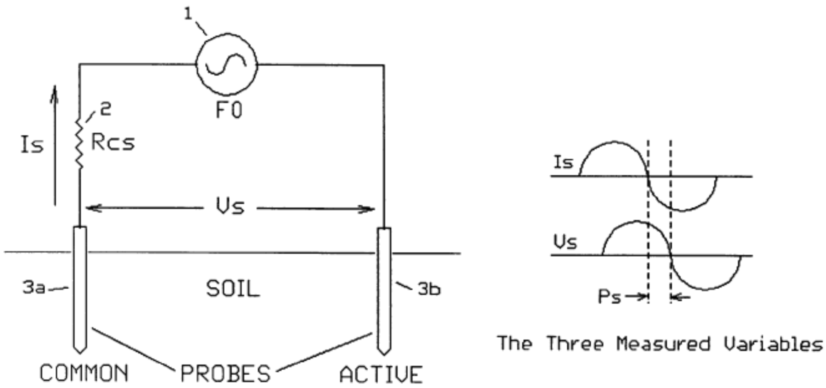


Figure 3-9: Schematic of the EDG electric circuit and the phase relationship between I_s and V_s

(Source: Anderson et al., 2005)

The soil current, I_s and probe-to-probe voltage, V_s between the soil and probes, as well as the phase difference, P_s are measured simultaneously. The temperature, T at the temperature probe location is also measured. Values for I_s, V_s, P_s *and* T are obtained at each test location. The soil dielectric properties are calculated using equation 3-4 and equation 3-5 respectively. The soil test volume is represented as a resistor and capacitor in an equivalent parallel circuit.

$$C_s = \frac{-I_s}{\omega V_s}\left(\frac{\tan\theta}{\sqrt{1+\tan^2\theta}}\right) \qquad 3\text{-}4$$

$$R_s = \frac{V_s}{I_s}\sqrt{1+\tan^2\theta} \qquad 3\text{-}5$$

where ω is the natural frequency, $\omega = 2\pi f$

f is the frequency for the EDG i.e. f= 3 MHz

θ is the phase difference, P_s in degrees

The measured dielectric properties are specific to a soil type. Therefore, a soil model is developed for each soil by relating the measured dielectric properties to the corresponding bulk density, γ_m and the weight of water per unit volume, W_w measured using other tests such as the sand cone replacement and the laboratory oven method respectively. Mejias-Santiago et al. (2013a) recommended the use of laboratory tests for moisture content calibration and that the data for each device is collected in the same location to eliminate spatial variances in soil density. Two equations are generated during modelling, one (equation 3-6) relating the bulk density and soil electrical impedance, Z_s (equation 3-7), and the other (equation 3-8) relating the weight of water per unit volume to the quotient of C_s/R_s.

$$\gamma_m = b_1 + Z_s m_1 \qquad 3\text{-}6$$

$$Z_s = \frac{V_s}{I_s} \; or \; Z_s = \frac{R_s}{\sqrt{1+\omega^2 C_s^2 R_s^2}} \qquad 3\text{-}7$$

$$W_w = b_2 + (C_s/R_s)m_2 \qquad 3\text{-}8$$

where b_1 and b_2 is the intercept and m_1 and m_2 is the slope of equation 3-6 and 3-8 respectively.

ASTM D7698-11 recommends the use of temperature compensated values for Z_s and C_s/R_s when building the soil model. However, Meehan and Hertz (2011) observed that inclusion of the EDG temperature correction algorithm lowered the R^2 values for the calibration curves, thus not improving the results. Consequently, the soil model developed is used to calculate the soil bulk density (equation 3-9) and weight of water per unit volume (equation 3-10) for subsequent EDG tests conducted in the same type of soil.

$$\gamma_d = \gamma_m - W_w \qquad 3\text{-}9$$

$$w = \frac{\gamma_m}{\gamma_d} - 1 \qquad 3\text{-}10$$

3.4.2 Electrical properties of compacted soil

The process of compaction results in a reduction in air voids in the soil, which affects the capacitance of the soil and its resistance (Hertz and Meehan, 2013). Hence, the electrical properties measured by the EDG are the capacitance and resistance of the soil, from which the impedance of the soil is computed.

Capacitance is a function of the area of the conducting electrodes, separation distance, permittivity of space and the relative permittivity of the dielectric material between the plates. In the EDG, all these properties are constant save for the relative permittivity of the material. As such, the soil capacitance is dependent on the permittivity of the soil, which is affected by the frequency. The EDG operates at a frequency of 3 MHz. At low frequencies (30 kHz to 50MHz), the permittivity of soil is dominated by the water content of the soil (Pluta and Hewitt, 2009). The permittivity of compacted soil increases with increased dry density and water content because air has a low dielectric constant (1) compared to water (42.5). However, at moisture contents near saturation permittivity stabilises and is constant (Wu et al., 2011)

The relationship between resistivity and moisture content, bulk density and dry density is different. Various researchers (Higgs, 1930; McCollum and Logan, 1930; Kalinski and Kelly, 1993; Yoon and Park, 2001; Ozcep et al. 2009, 2010) have shown resistivity to have a non-linear (exponential) relationship with moisture content Figure 3-10. At low moisture content, resistivity decreases rapidly with increasing moisture content and then stabilises (McCarter, 1984). As a result electrical resistivity is more influenced by low moisture contents (Beck et al., 2011). Abu Hassanein et al. (1996) and Beck et al. (2011) found a critical moisture content to exist close to the optimum moisture content below which resistivity decreases rapidly with increasing moisture content and above which resistivity is almost constant. Hence, resistivity is more sensitive to changes in compaction at low moisture contents than high moisture contents (Osman et al. 2012).

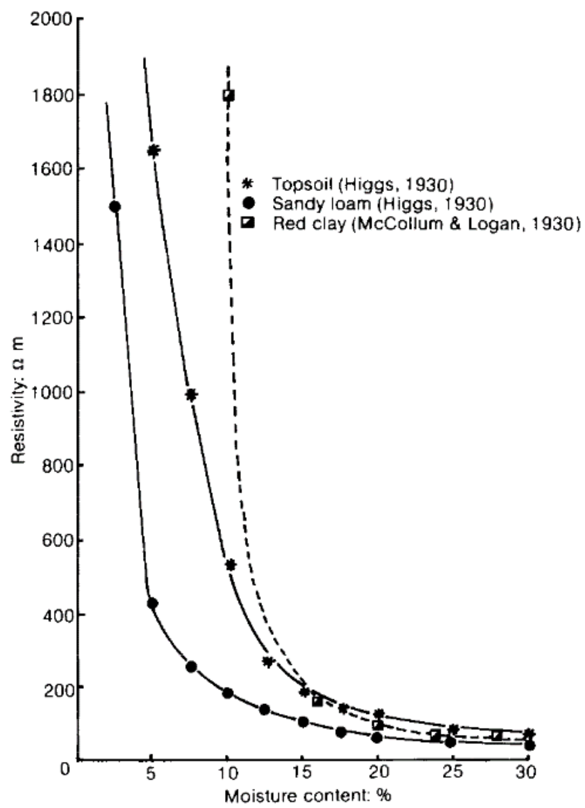


Figure 3-10: Variation of soil resistivity with moisture content (McCarter, 1984)

Bai et al. (2013) and Toll and Hassan (2015) found resistivity to decrease with increase in dry density up to the maximum dry density beyond which it stabilises. Toll and Hassan (2015) measured the resistivity of compacted clay and found the resistivity of clay compacted wet of optimum to be independent of compaction and compaction effort due to the reduction in micropores and increase in the moisture content of the soil. Beck et al. (2011) noted the importance to distinguish between the effect of water content and dry density on resistivity. They noted a linear decrease between electrical resistivity and dry density for each water content within a particular density range Figure 3-11. Their results were similar to those observed by McCarter (1984) though he examined the effect of resistivity on the air voids ratio. Toll and Hassan (2015) investigated the relationship between resistivity and both the void ratio and dry density. Their findings shown in Figure 3-12 were similar to those of McCarter (1984) and Beck et al (2011).

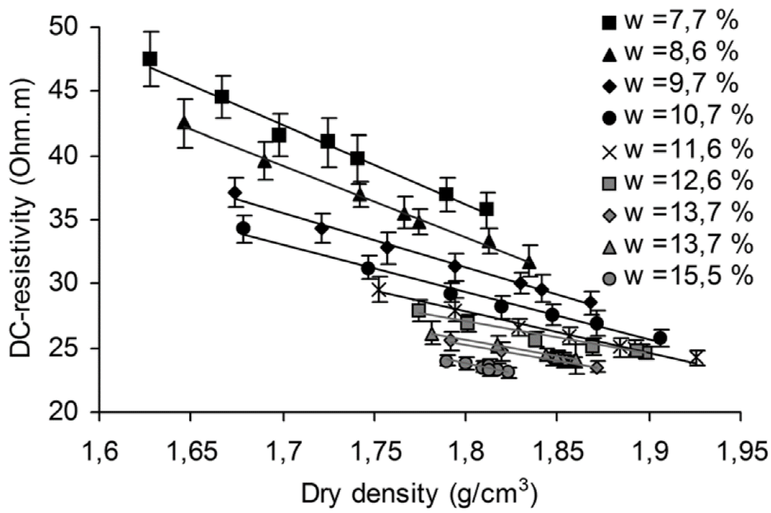


Figure 3-11: Influence of dry density on electrical resistivity at various water content values, w for silt
(Beck et al., 2011)

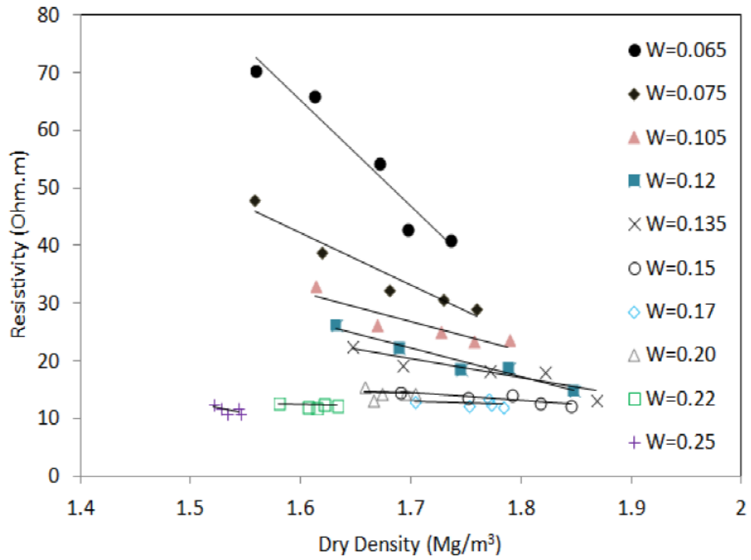


Figure 3-12: Electrical resistivity-density relationship for compacted clay at various moisture contents
(Toll and Hassan, 2015)

Beck et al. (2011) found the effect of water content on resistivity to be more significant than dry density. Kibria (2011) also determined resistivity to be more sensitive to changes in moisture content than bulk density. Siddiqui and Osman (2013) found a poor relationship between resistivity and bulk density and concluded that there was no definite relationship between the two. This was attributed to the fact that the bulk density of soil is largely dependent on the solid constituents of soil than the liquid phase as opposed to resistivity. As such, the poor relationship between resistivity and bulk density could have contributed to the less significant effect of dry density.

Consequently, research has shown the moisture content of soil to have a greater effect on resistivity than its bulk density. However, this is especially so at lower moisture contents than higher moisture contents.

3.5 Case studies

In this section, a review of previous studies is presented. The review was performed to obtain a better understanding of the findings of previous researchers. It also helped identify the gaps in the research.

3.5.1 Framework of non-nuclear methods evaluation for soil QC and QA in highway pavement construction (Cho et al., 2012)

Cho et al. (2012) evaluated the efficiency of the electrical density gauge (EDG) in terms of cost and accuracy of density and moisture content measurements relative to the NDG. The tests were carried out at two sites composed of brown dirt and peorian loess soils.

The cost effectiveness of each test was determined using a lifecycle cost analysis considering all the costs associated with owning, operating and maintaining the equipment for the duration of their useful life. The results showed that the EDG is cheaper with a net present worth of 9,000 dollars compared to the NDG with a net present worth of 27,264 dollars. Hence, the high annual cost of the NDG related to its maintenance and operation made the EDG three times a cheaper investment.

The accuracy of the tests was evaluated by taking density and moisture content measurements using both the NDG and EDG at the same test spot. The EDG was calibrated using the NDG (Troxler 3440). The measured values were compared to reference tests i.e. the laboratory oven method for moisture content and the drive cylinder for field dry unit weight. The drive cylinder was preferred over the sand cone or rubber balloon due to inconsistency of results by the latter tests. Cho et al. (2012) developed a framework (Figure 3-13) for evaluating different types of non-nuclear tests relative to the NDG for quality control (QC) of compaction.

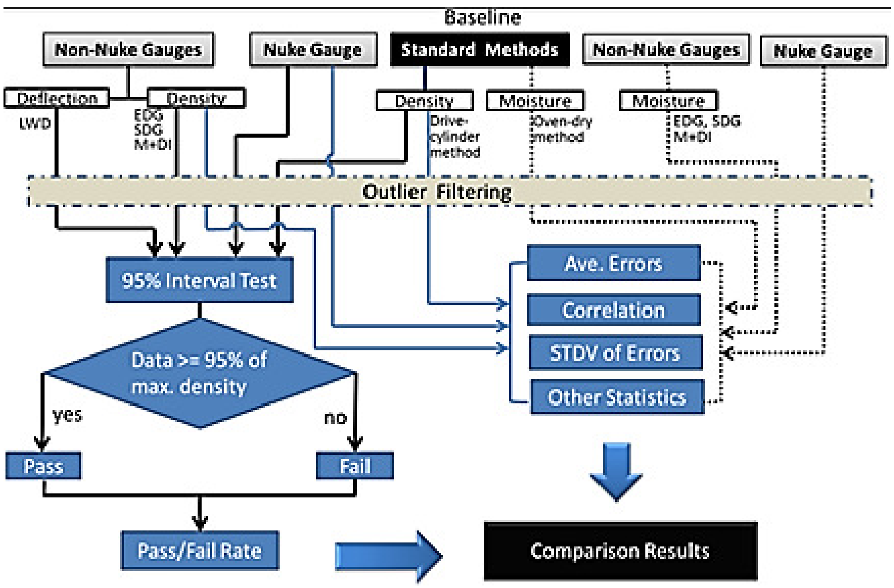


Figure 3-13: Framework for evaluating the performance of non-nuclear tests (Cho et al., 2012)

Following the framework in Figure 3-13 for analysis, the correlation results between the density and moisture content measurements of the NDG, EDG and the standard tests are shown in Figure 3-14 and Figure 3-15 respectively.

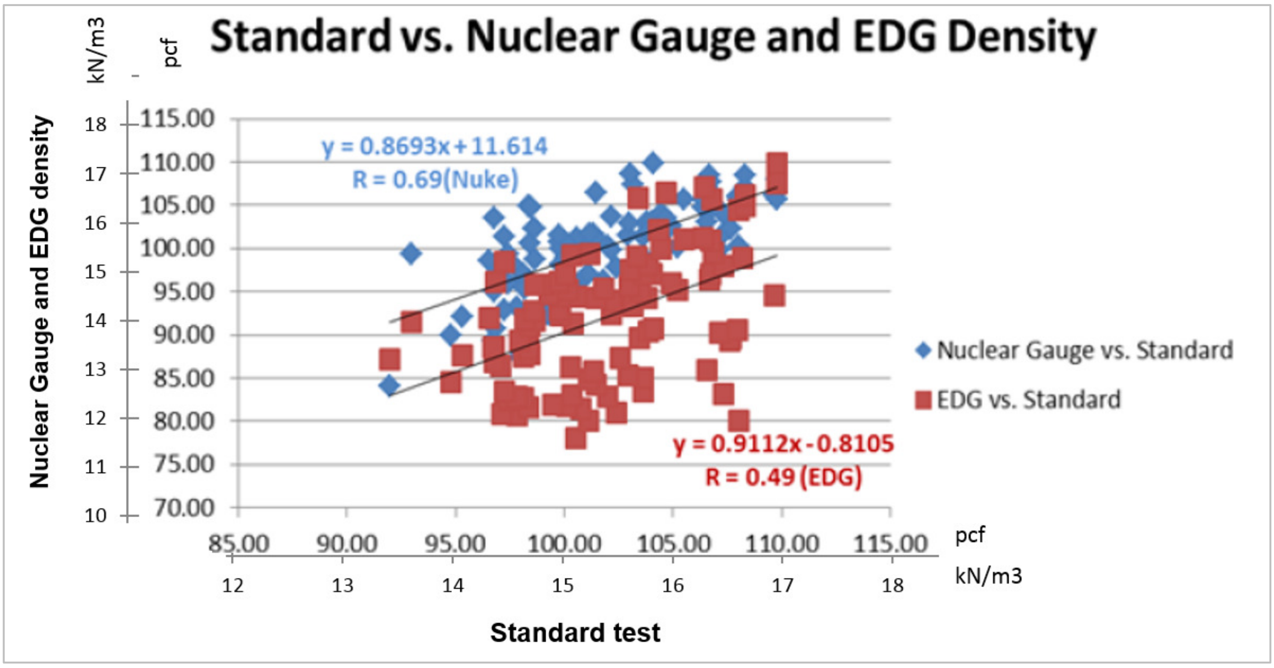


Figure 3-14: Comparison of NDG and EDG density measurements to the standard (Cho et al., 2012)

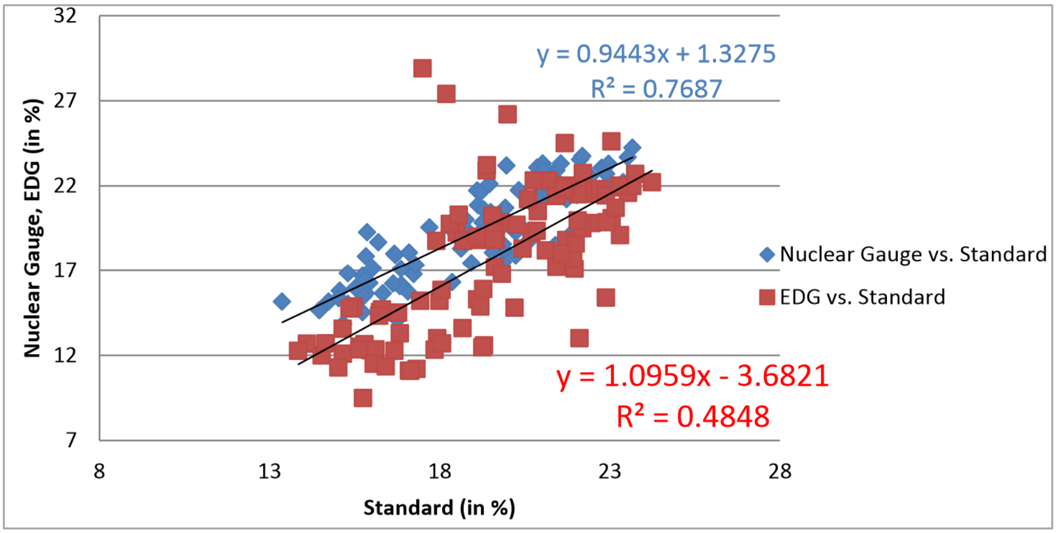


Figure 3-15: Comparison of NDG and EDG moisture measurements to the standard (Cho et al., 2012)

The NDG correlated better with the standard tests. The EDG showed reliable accuracy in moisture content measurement. However, it had lower correlation for density measurements. Furthermore, the correlation between the sites varied. The high variations among the EDG data for the two soil types were attributed to the fact that the soil model built was based on a wide range. Cho et al. (2012) recommended that in order to improve EDG's density reading accuracy, the manufacturer should consider redesigning the soil modelling process.

3.5.2 Using electrical density gauges for field compaction control (Meehan and Hertz, 2011)

Meehan and Hertz (2011) evaluated three calibration methods i.e. two field calibration methods and a "large mould" Proctor-type calibration method. The effect of temperature correction on EDG calibration relationships was also investigated by developing soil models with and without using the EDG temperature correction algorithm. The soil models developed using the different calibration methods were tested and compared to other density tests (NDG, sand cone and the drive cylinder).

The study was carried out in two phases. The first phase comprised of field calibration at two sites: 1) the Dover site with light grey to light brown silty clayey sand having trace amounts of fine gravel and 2) the Middletown site with brown silty sand having trace amounts of fine gravel. The average of three NDG tests corresponding to one EDG test were taken at each in situ test location for calibrating the EDG on both sites. The calibration procedure recommended by the manufacturer was followed.

The second phase used brown silty sand with trace amounts of fine gravel and involved the evaluation of the Proctor type calibration method and a field box method. The Proctor type calibration method involved compacting soil at varying moisture contents and densities in a mould with an inside diameter of 378 mm and a depth of 254 mm (Figure 3-16). A tamper falling through a height of 450 mm was used to compact the soil. The dry density of the compacted soil was calculated and used in building the EDG model.

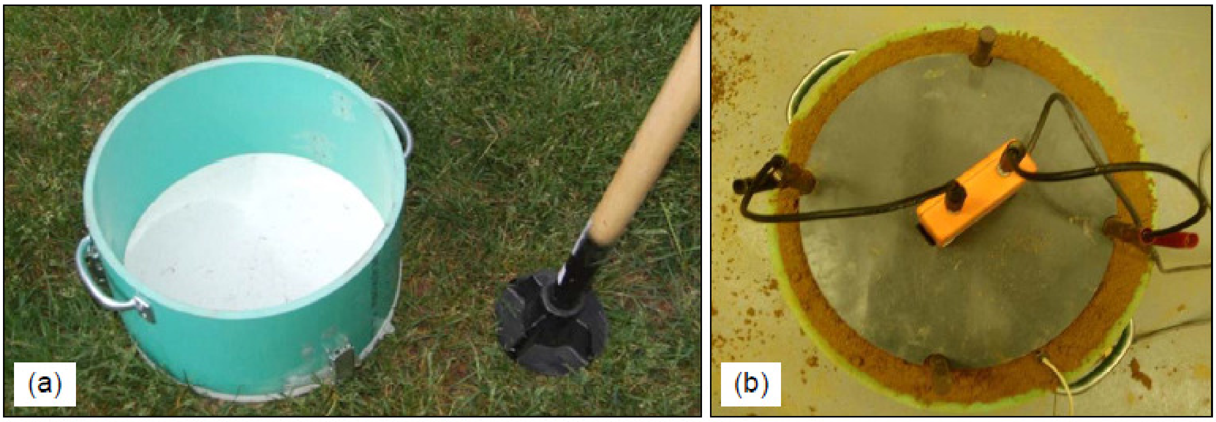


Figure 3-16: Large "Proctor type" mould calibration approach: a) plastic mould with tamper; b) EDG calibration process in mould (Meehan and Hertz, 2011)

The field box method involved simulating field compaction conditions in a box with inside dimensions of 1520x910x300 mm. The calibration procedure discussed in the first phase was followed. Figure 3-17 shows the soil models developed using the three calibration methods, with and without applying the EDG temperature correction.

Tests were conducted using the different models and their results compared to the other density tests. Little agreement was observed between the EDG and the tests, irrespective of the calibration procedure used. This was attributed to difficulty in creating a soil model that is truly representative of the range of moisture contents and densities likely to be encountered, and soil variability.

Meehan and Hertz (2011) recommended that a good soil model be used in order to get results comparable to the NDG. In addition, the EDG temperature correction algorithm tended not to produce a significantly marked improvement in EDG test results. They suggested that in order to evaluate the accuracy and effectiveness of the EDG further, extra field studies were needed on a variety of commonly used soils and other construction materials.

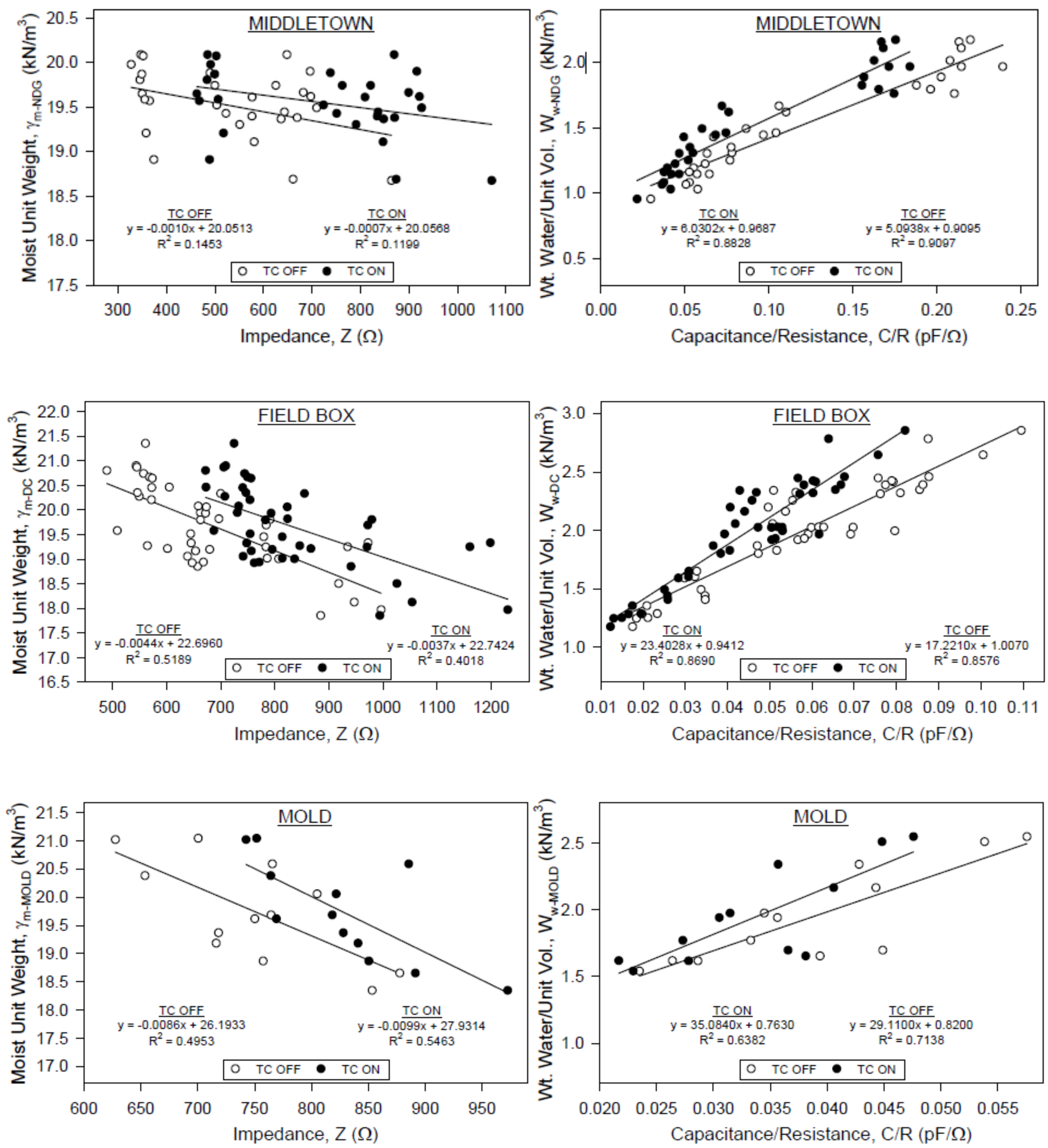


Figure 3-17: EDG calibration for the field, field box and mould calibration of the Middleton soil
(Meehan and Hertz, 2011)

3.5.3 Device comparison for determining field soil moisture content (Mejias-Santiago et al., 2013a)

Mejias-Santiago et al. (2013a) sought to identify a technology that could effectively measure soil moisture content in the field without the use of a nuclear source or a laboratory oven due to the time delays associated with using the oven. The effect of soil grain size distribution on seven soils namely: fine grained high plasticity clay, loess, silty-sand, concrete sand, clay-gravel, silty-gravel, and crushed limestone was also determined.

Mejias-Santiago et al. (2013a) measured the moisture content of the different soil types using each of the tests (NDG, EDG and the laboratory oven). The tests were conducted in the field during a large-scale density study (Mejias-Santiago et al., 2013b) where the EDG was calibrated using the NDG. The moisture content obtained from the EDG and NDG tests was compared with that of the laboratory oven. Figure 3-18 shows the correlation between the EDG and NDG measured values to the laboratory oven method for all soils tested.

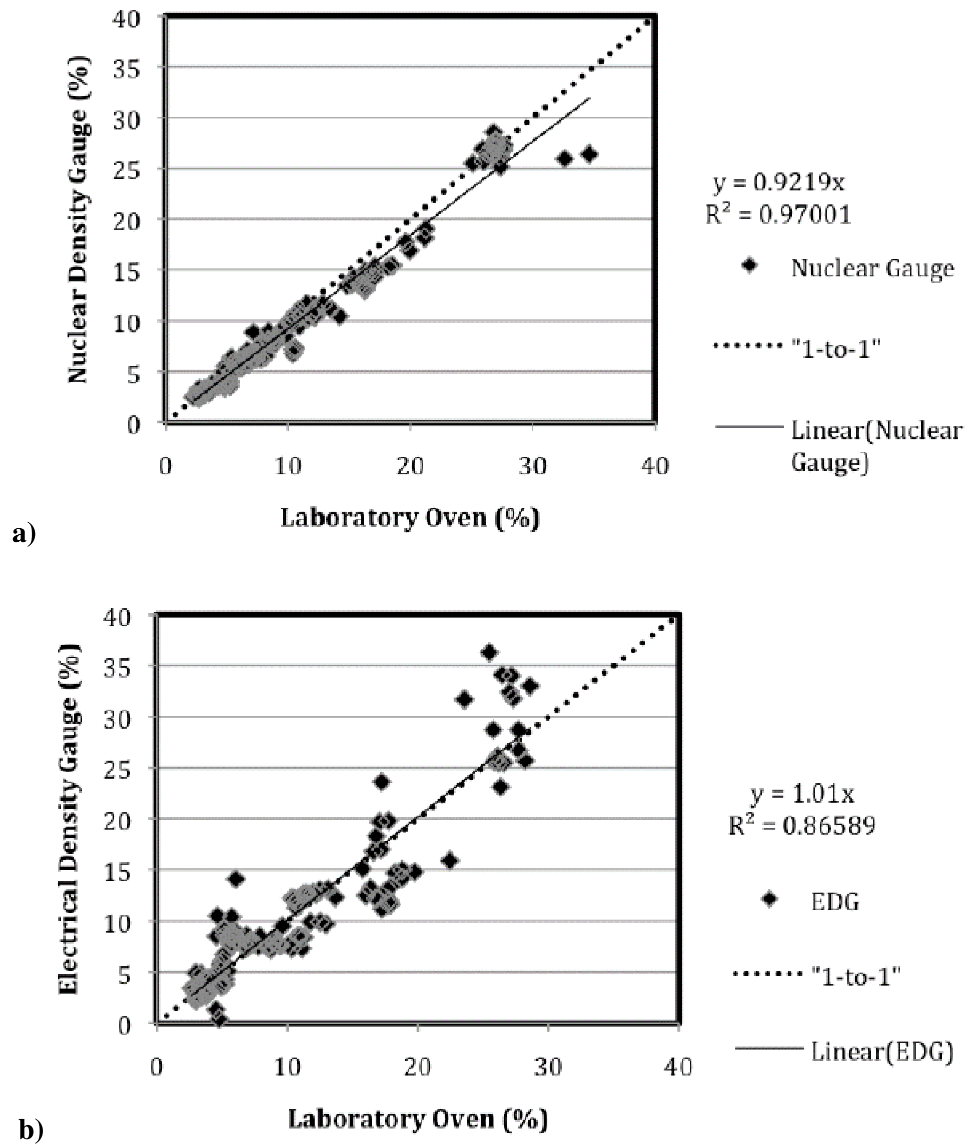


Figure 3-18: Correlation of all field measured moisture contents between a) nuclear density gauge and the laboratory oven; and b) electrical density gauge and the laboratory oven (Mejias-Santiago et al., 2013)**.**

The accuracy and precision of the tests was also determined where, accuracy determined the ability of the device to capture moisture content compared to the laboratory oven, while precision determined the deviation of the measured value from the laboratory oven value. The combination of accuracy and precision was determined using the total analytical error. The

EDG was more accurate than the NDG. However, a lot of scatter was observed for the soils and the precision of the EDG was less than that of the NDG. A summary of the accuracy and precision of the three tests is shown in Table 3-3.

Table 3-3: Summary of accuracy and precision for the laboratory oven, EDG and NDG

(Data from Mejias-Santiago et al., 2013a)

DEVICE	SLOPE	ACCURACY	PRECISION	RATIO OF AVERAGE	TOTAL ANALYTICAL ERROR
Laboratory oven	1.000	0	0.089	1.000	0.089
Nuclear density gauge	0.922	-0.078	0.108	0.916	0.196
Electrical density gauge	1.010	0.010	0.318	1.040	0.316

Mejias-Santiago et al. (2013a) concluded that the EDG is accurate. However, its accuracy and precision is highly dependent upon proper calibration of points. They also found that cohesive soils with high moisture contents usually provided erroneous results while non-cohesive soils such as sands and gravels tended to yield accurate measurements. Rathje et al. (2006) also noted that the EDG would not operate on highly plastic clays. However, they also found the EDG to report consistently the same dry unit weight when tested on poorly graded sand samples even when the sand cone reading was different.

3.5.4 Evaluation of non-nuclear density gauges for determining in-place density of unbound materials (Rose, 2013)

The study aimed to determine the accuracy and reproducibility of the EDG compared to the sand cone, nuclear density gauge and laboratory oven method through analysis of data from field tests. The experiments were conducted at 18 sites in the state of Idaho. The soils at the sites comprised of fine-grained gravel, coarse fills, sands, silts and clays.

Two EDG models were built using the sand cone (SC) method following ASTM D1556-07 (EDG (SC) model) and the NDG following AASHTO T310-11 (EDG (NDG) model). Three test spots, which were the minimum required to build the soil model were used for either of the reference tests (NDG and SC). The NDG was used first at the test spots according to ASTM T310-11 in the direct transmission mode at a depth of 150 mm. This was followed by the EDG using 150 mm tapered metal darts at a point near the NDG test point. The test procedure followed ASTM D7698-11. The SC test was then conducted at a point less than 300 mm away from the test spots but in line with the roller pass. The moisture content for the model points was determined by drying a portion of the excavated soil from the SC test in the microwave following ASTM D4643-10. The obtained moisture contents and bulk densities were entered in to the EDG and the soil model calibration completed.

The dry density and moisture content at seven other tests spots was measured following the same sequence i.e. NDG, followed by EDG nearby and SC less than 300 mm away. The moisture content of the soil was measured using the laboratory oven following ASTM D2216-10. A series of NDG models (Troxler 3440, 3430, and 3411-B models and Instrotek Explorer 3500, CPN MC-3, and CPN MC-1 models) were used when conducting the tests.

Based on statistical results from the t-test at the 5 % level of significance (Table 3-4), EDG measurements did not vary significantly from the reference tests except for the bulk density measurements made using the EDG (NDG) model which varied from those of the SC test.

Table 3-4: *p*-value summary for t-tests (Rose, 2013)

PROPERTY	TEST	EDG (SC) MODEL	EDG (NDG) MODEL
Bulk density	SC	0.09	**0.028**
	NDG	0.13	0.16
Dry density	SC	0.13	0.051
	NDG	0.91	0.20
Moisture content	Oven (SC)	0.57	0.65
	NDG	0.29	0.51

Using both models EDG moisture content and dry density results were correlated with the laboratory oven moisture content (Figure 3-19) and sand cone test (Figure 3-20).

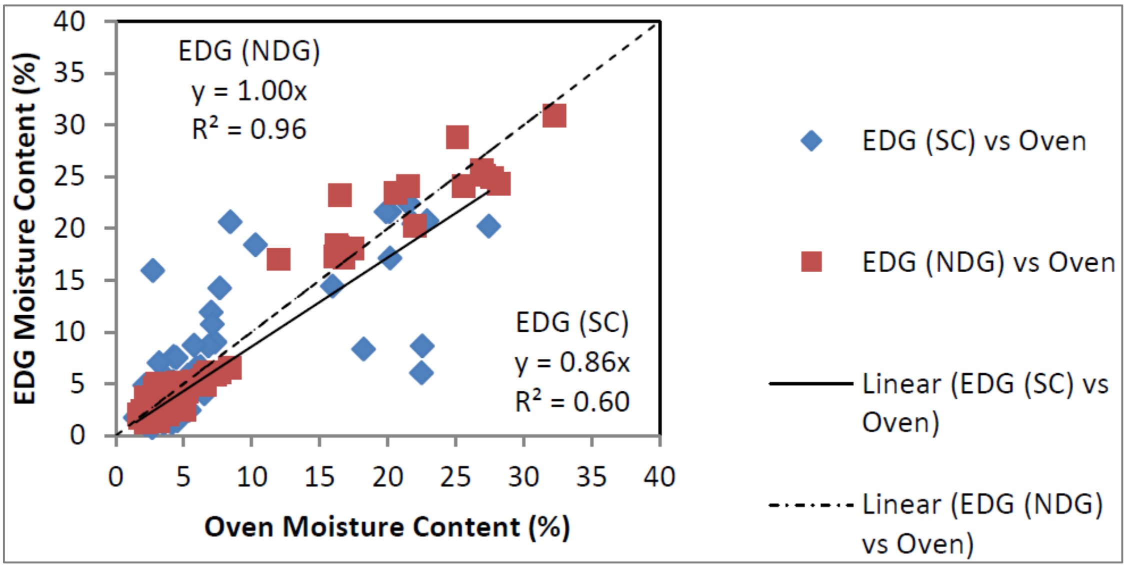


Figure 3-19: Moisture content correlation for EDG models to the oven (Rose, 2013)

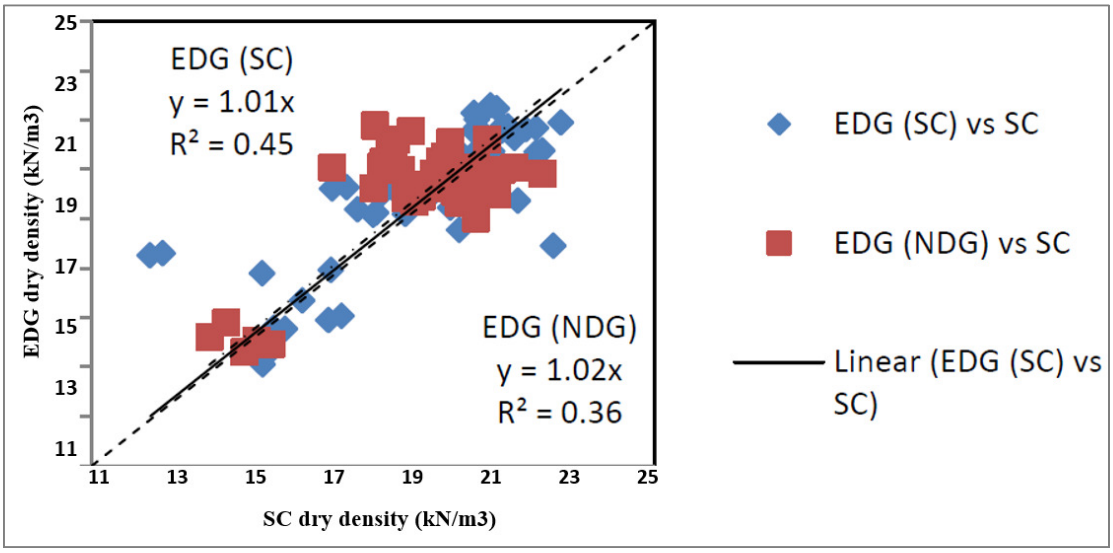


Figure 3-20: Dry density correlation for EDG models to the SC (Rose, 2013)

Correlation results revealed the EDG (NDG) model to have higher correlation for moisture content than the EDG (SC) model. However, the EDG (SC) model had higher correlation for dry density than the EDG (NDG) model.

The effect of increasing the number of points on model accuracy was also investigated using a 3-point, 5-point and a 10-point soil model. Rose (2013) observed that there was little change in the accuracy of EDG measurements and hence the number of points used was insignificant. However, he recommended calibrating the EDG following ASTM D7698-11 in order to cover the range of expected moisture content and density.

It was concluded that EDG (SC) model results were unreliable compared to those of the EDG (NDG) model. In addition, the EDG was not accurate or precise enough for use in compaction QC or QA. However, this could be attributed to the fact that the tests were conducted at different spots and the EDG is sensitive to variations in soil properties. Also based on the obtained t-test results, dry density and moisture content measurements obtained using the EDG (SC) model have high p-values (underlined in red) when compared to the NDG dry density and laboratory oven moisture content obtained for the sand cone test despite not being taken in the same spot. Therefore, the EDG (SC) model could be used to produce reliable EDG measurements when taken in the same spot.

3.6 Chapter summary

Different density-based tests were covered in this chapter. Among these were volume replacement tests, the NDG and EDG. A review of previous studies evaluating the EDG as a suitable replacement for the NDG was presented. The NDG uses radioactive emissions to operate therefore requires adherence to strict regulations.

The EDG was found to have reliable accuracy especially when measuring moisture content. However, its accuracy was highly dependent on the model developed for testing the particular soil type. EDG results were found to vary from one soil type to another such that results that are more accurate were obtained in non-cohesive soils than in cohesive soils with high moisture contents. Generally, the EDG was less accurate than the NDG. However, the EDG was calibrated using the NDG in all these studies. The NDG in itself lacks a 1:1 plot with the reference tests. Hence, the NDG is not recommended for calibrating the EDG. This study hypothesised that the sand cone was a better method for calibrating the EDG because it is accurate. It also hypothesised that EDG measurements for density and moisture content are equal to those of the sand cone and laboratory oven respectively. Following the stated hypotheses, the accuracy of the EDG for measuring compaction was evaluated using sites in South Africa.

CHAPTER 4 METHODOLOGY

4.1 Testing Apparatus and Equipment

The test equipment used in the study included an electrical density gauge, sand cone, laboratory oven, laboratory model and tamper.

4.1.1 Sand cone

The sand cone equipment shown in Figure 4-1 was used to determine the in-place density of the soil. The equipment comprised the sand cone apparatus, a metal base plate and a metallic mould. The sand cone apparatus consisted of a metallic cylindrical container of diameter 112 mm capable of holding more than 4 kg of calibrated sand (0.03 m^3). The container had a conical valve controlled outlet at the bottom of diameter 112 mm through which sand flowed at a constant rate when opened.

The metal plate (400 x 400 mm) was made of stainless steel and provided a stable base with a centre flanged 112 mm diameter hole on which the sand cone apparatus was placed. The plate also functioned as a guide template for the hole diameter during excavation. The flanged edges of the plate prevented the loss of excavated material.

The mould had an internal diameter of 101.4 mm and a height of 126.8 mm. It was used to calibrate the sand used in the test. The flanged edges of the mould assisted in placing the sand cone apparatus properly.

Figure 4-1: Sand cone apparatus

4.1.2 Electric density gauge

The electrical density gauge used in the study was obtained from the manufacturers, Humboldt Mfg. Co, and supplied by Protsurv Geo centre (pty) limited. The Humboldt H-4114SD.3F electrical density gauge, serial number 1513 was used to carry out the tests (Figure 4-2). The test components included a case into which the EDG was built on the right side, a grey circular dart template, four 150 mm steel tapered darts, a hammer, soil sensor, two sensor cables and a temperature probe, which were stored on the left side of the case.

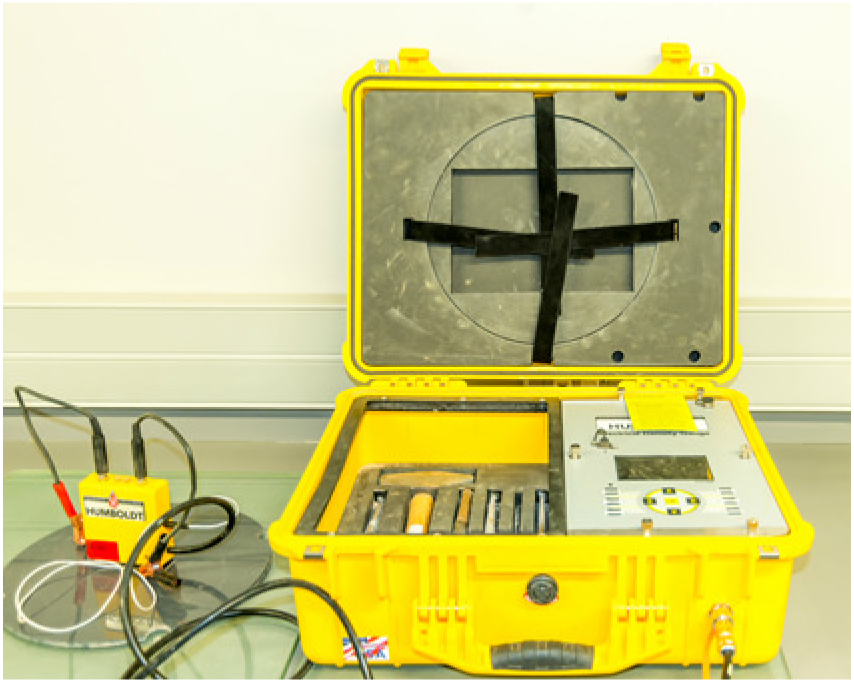


Figure 4-2: The Humboldt H-4114SD.3F electrical density gauge

The case provided storage for all the gauge parts and facilitated their transportation. The four detents on the dart template guided the pushing of the four darts into the test material using the hammer. The soil sensor was an orange box with two pins on top and a long black cable. The cable gathered electrical information about the soil and transferred it to the EDG computer to which it was connected from the front. The soil sensor was attached to the dart template using velcro. Each of the two soil sensor cables had a plug opening approximately 6.35 mm on one end and alligator clips on the other end. These were connected to two opposite darts. The plug openings were attached to the sensor to complete the connection through the darts. The temperature probe was white in colour and was inserted in to a port on the side of the sensor. It measured the temperature of the soil during the test.

4.1.3 Laboratory oven

A thermostatically controlled oven (Figure 4-3) capable of maintaining a temperature of 110 ± 5^0C was used for drying the samples.

Figure 4-3: Thermostatically controlled oven.

4.1.4 Laboratory Compaction model

The compaction tests in the laboratory were conducted in a bench scale model (Figure 4-4). The model was composed of a circular tank made of high-density polyethylene (HDPE) because it has no electrical conductivity and therefore, would not interfere with EDG electrical measurements in the tank. The inside diameter and height of the model were 1500 mm and 1300 mm respectively in order to provide adequate working space and the use of a tamping rammer. Steel bracings prefabricated in the laboratory were provided to prevent bulking of the tank sides under the weight of the soil which enabled proper compaction of the soil. Marks were made inside the tank in 200 mm intervals around the sides of the tank to determine whether the required lift thickness was attained. Schematics showing the front and top elevation of the model are shown in Figure 4-5 and Figure 4-6 respectively.

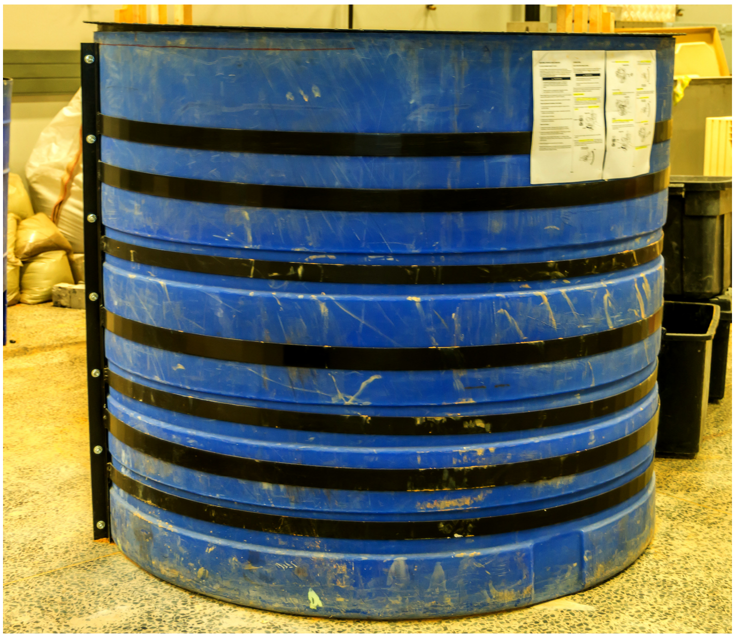


Figure 4-4: Pictorial representation of the laboratory model

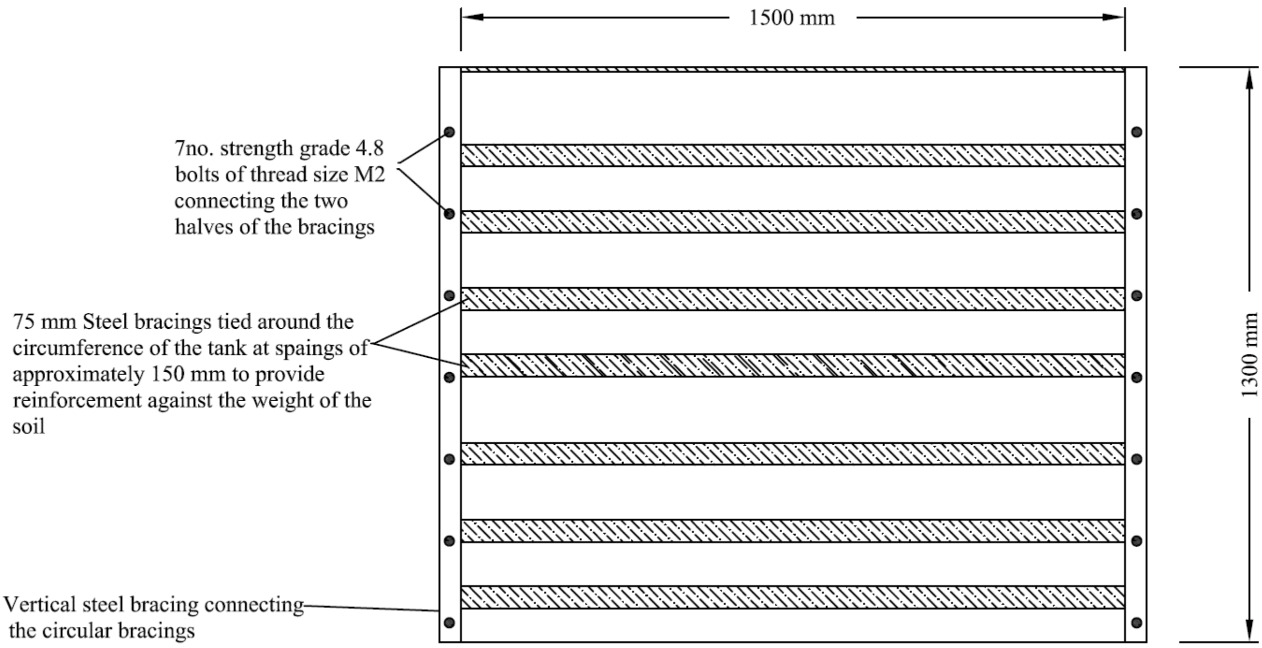


Figure 4-5: Front elevation of the laboratory model

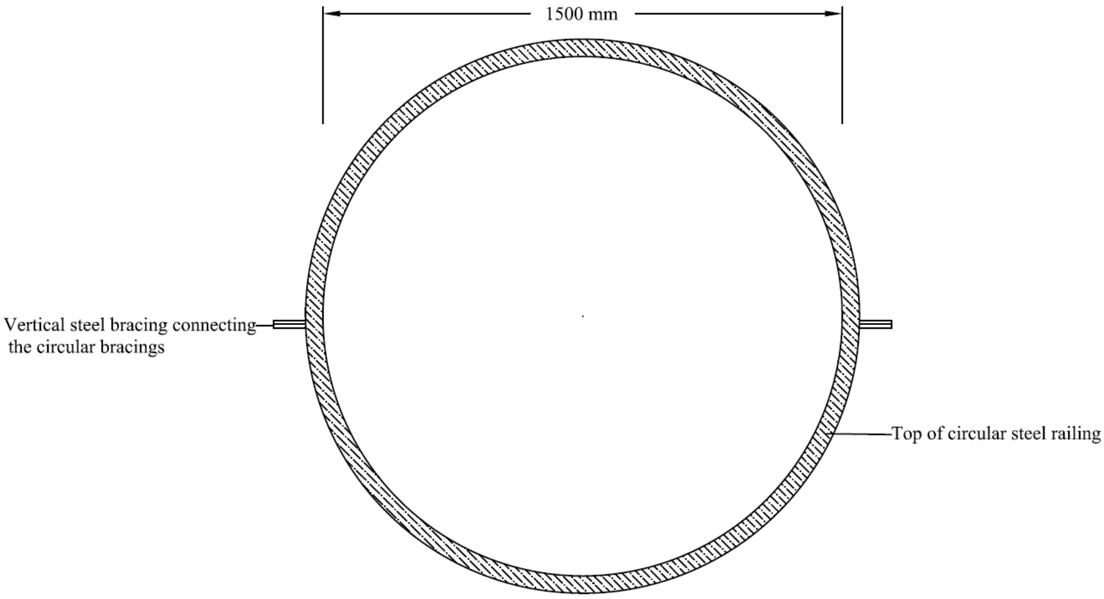


Figure 4-6: Top elevation of the laboratory model

4.1.5 Rammer

The RT74 rammer (Figure 4-7) used in the laboratory had shoe dimensions of 285x335 mm and an operating weight of 70 kg. It applied an impact force of approximately 16 kN at 650 to 700 blows per minute. The rammer was used because it is suitable for compacting all soil types and can be used in confined spaces.

Figure 4-7: RT74 rammer

4.2 Test methods

4.2.1 Sand cone test

4.2.1.1 Sand properties

Cape Flats sand, used for the sand cone test, was sourced from Philippi Quarry in the Cape Flats region of Cape Town, South Africa. The sand was clean uniformly graded, uncemented, durable and free flowing as required by ASTM D1556 to avoid segregation during handling, storage and use. It is a light grey sand with round particles (Kalumba, 1998). The particle sizes ranged from 1.18 mm to 0.075 mm with a coefficient of uniformity of 2.9, which was greater than 2, the value recommended by ASTM D1556. The grading curve for the sand used is shown in Figure 4-8.

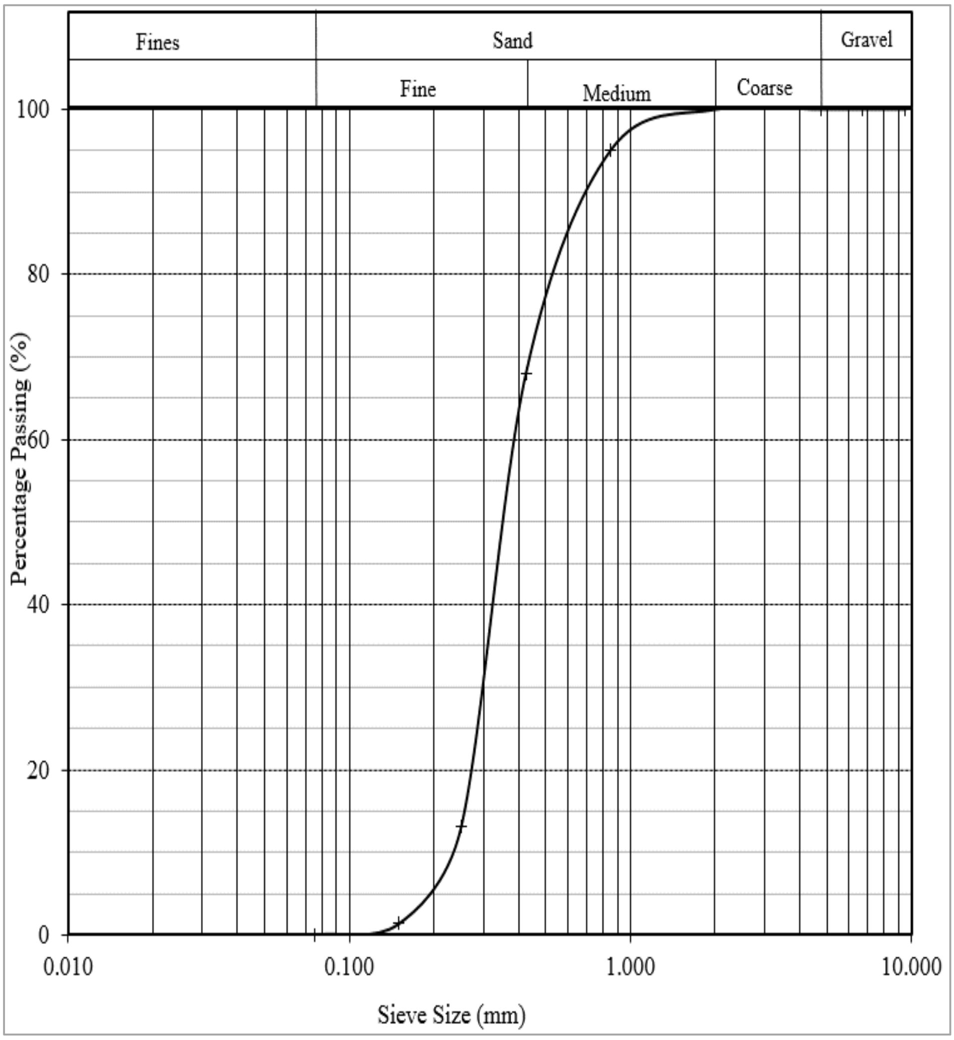


Figure 4-8: Particle size grading for sand used in the sand cone test

4.2.1.2 Calibration of the sand

The sand was calibrated to determine its bulk density following ASTM D1556 – "Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method." The process involved the determination of two factors, namely the cone correction factor and the calibration factor.

The cone correction factor was determined as follows:

The apparatus was filled with the sand, leaving an allowance of at least 30 mm to avoid spill. The weight, W_1 of the apparatus was recorded to the nearest gram. The base plate was then placed on a level surface and the sand cone placed on the plate. The valve was opened to allow sand to flow through until it stopped flowing, at which point the valve was closed. The apparatus and retained sand were weighed, W_2. The cone correction factor, W_3 was obtained as the difference between W_1 and W_2.

The procedure for determining the calibration factor was:

The volume, V of the mould was determined. The sand cone was then filled with the sand and its weight, W_6 recorded to the nearest gram. The plate was then placed on the mould and the SC placed on the plate. The valve was opened, and then closed when the sand stopped flowing. The apparatus was then weighed, W_5. The weight of the sand, W_4 required to fill the mould was calculated as the difference between W_6 and W_5. The calibration factor, which is the bulk density of the sand, ρ_b was calculated to 3 significant figures in g/cm^3 using equation 4-1.

$$\rho_b = \frac{W_4}{V} \qquad 4\text{-}1$$

It was required that the sand is recalibrated whenever there was a change in supply. However, the same supply was used for the duration of the study. Nonetheless, the sand was recalibrated at the start of each day as a check. Sample results for calibration of the sand are presented in Appendix B.1.

4.2.1.3 Soil tests procedure

The sand cone test was carried out according to ASTM D1556 – "Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method". The SC was filled with the calibrated sand and the weight recorded. An area representative of the compacted soil was chosen to conduct the test. Any loose and uncompacted material was removed and the area cleared and levelled before the base plate was placed. A hole was then excavated using the plate as a guide to a depth greater than 130 mm. The excavated soil was carefully and quickly put in a labelled plastic bag and the bag sealed immediately afterwards to prevent loss of moisture. The sand cone was then placed onto the base plate. Using the circle marked on the template, it was aligned with the excavated hole. The valve was opened and the sand allowed to flow into the hole. When the sand stopped flowing, the valve was shut and the apparatus weighed to the nearest gram.

The moisture content of the soil was measured according to ASTM D2216-10 - "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass." In the laboratory, clean empty pans were weighed to the nearest 0.1 g. The excavated soil in the sealed plastic bags was transferred to empty pans and weighed immediately. The pans were then placed overnight (12 to 16 hours) in the oven maintained at 110 ± 5^0C. After which the dried samples were removed from the oven and the pans allowed to cool until they could be comfortably handled with bare hands and the balance would not be affected by heat transmission or convection or both, before the sample was weighed. The change in mass after drying was the mass of water. The same weighing balances were used for the duration of the study, one weighing to the nearest gram for the sand cone test and another weighing to the nearest 0.1 g for measuring moisture content.

4.2.2 Electrical density gauge test

4.2.2.1 Soil model calibration of the EDG

A soil model is the result of the calibration procedure that establishes a correlating linear function between EDG measured electrical properties (Figure 3-9) and the measured physical properties (bulk density and moisture content) (ASTM D7698-11). The EDG was calibrated following ASTM D7698-11 – "Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method."

Before developing the EDG soil model, 20 kg of the soil passing the 4.75 mm sieve representative of the soil at the site where testing was to be conducted were obtained. The soil was used to determine the maximum dry density and optimum moisture content of the soil according to ASTM D698 - "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort"

At the site, the EDG (Figure 4-2) was switched on and the soil model for the site named before it was developed. The data obtained from the Proctor tests and the USCS of the soil were entered into the EDG. At least six test spots consisting of two different soil densities and three water contents over the expected range of measurements were chosen. The test spots were chosen such that the soil was as consistent as possible. The model had a fit of 0.000 at the start that increased as more points were added. The following was the procedure for the first test spot:

> The test spot was cleared to remove any loose and uncompacted material and then levelled. The grey circular dart template was removed from the lid of the case, and placed on the ground at the test spot. The four darts were positioned at the detents (holes on the side of the template preventing its movement) on the template. Using the hammer, the darts were driven in perpendicular to the ground until the shoulder of the darts was level and in contact with the ground surface. The cable of the sensor was connected to the EDG unit via the sensor port at the front of the EDG. The sensor was then attached to the template using the velcro fastening system. The two sensor cables

were then attached to the two pins on the sensor via the plug on each. Their other end with the alligator clips was each clamped to two opposing darts. Care was taken to ensure that the cables were straight and not crossing. The thermistor was then plugged into the port on the side of the sensor. A T-handle probe was used to create a hole greater than 50 mm deep away from the dart into which the thermistor was inserted. The first electrical test was then taken, after which the EDG made a beeping sound signalling the transfer of the alligator clips to the other two opposing darts. The alligator clips were transferred and the second electrical test measured. The measurements were saved to the EDG. The darts were then removed with minimal disturbance to the ground and the sand cone template placed at the spot. The sand cone test was then immediately carried out at the centre of the EDG test spot to avoid any variations in moisture content and soil. The test point number on the EDG and the corresponding SC measurements were recorded. The EDG was then moved to the next test spot and the procedure repeated. This was done for all subsequent tests.

12 to 16 hours later when the moisture content was determined, the SC bulk density and moisture content were entered into the EDG computer, and matched to the corresponding electrical measurement at each test spot. The electrical readings were correlated to the actual compaction and moisture content. The model developed was saved. During the soil modelling process, two graphs were developed; one relating impedance and bulk density and the other relating the weight of water per unit volume to the C/R ratio. Each point on the graphs was evaluated to refine the graphs and adjust the fit. Outlier points in the graphs were turned off to achieve a higher fit for more accuracy. The manufacturer recommended a fit greater than 0.6 for accurate and reliable readings. The adjusted model with higher fit was saved to complete the model calibration process.

4.2.2.2 Soil test procedure

EDG density and moisture content tests were carried out according to the ASTM D7698-11 – “Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method.” The EDG was switched on and a jobsite added and selected. The corresponding model for the soil at the site was assigned to the jobsite. The same procedure as in the calibration process was followed at each test spot. The test results were displayed on the EDG screen at the end of each test and saved to the EDG. They comprised of the dry density, bulk density, moisture content, weight of moisture per unit volume, relative compaction and the maximum dry density.

4.3 Laboratory tests

To determine the performance of the EDG under a controlled environment, the tests were first conducted in the Geotechnical Laboratory at the University of Cape Town.

4.3.1 Material description

Two soils, classified as uniformly graded sand and a clayey sand were tested in the laboratory. Figure 4-9 shows the materials used, described as Klipheuwel sand and Cape Town clayey sand.

4.3.1.1 Klipheuwel sand

The sand was excavated from a borrow pit at the Kersfontein Quarry–Malmesbury area in Cape Town. It was a clean reddish brown sand with some fines and the particles were angular as observed under a microscope by Kalumba (1998).

4.3.1.2 Cape Town clayey sand

The clayey sand was sourced from the construction site for a new lecture theatre on the south side of the upper campus at the University of Cape Town. The soil, excavated from the site during the construction of the foundation, was yellowish brown, with soft weathered rock gravel.

a) b)

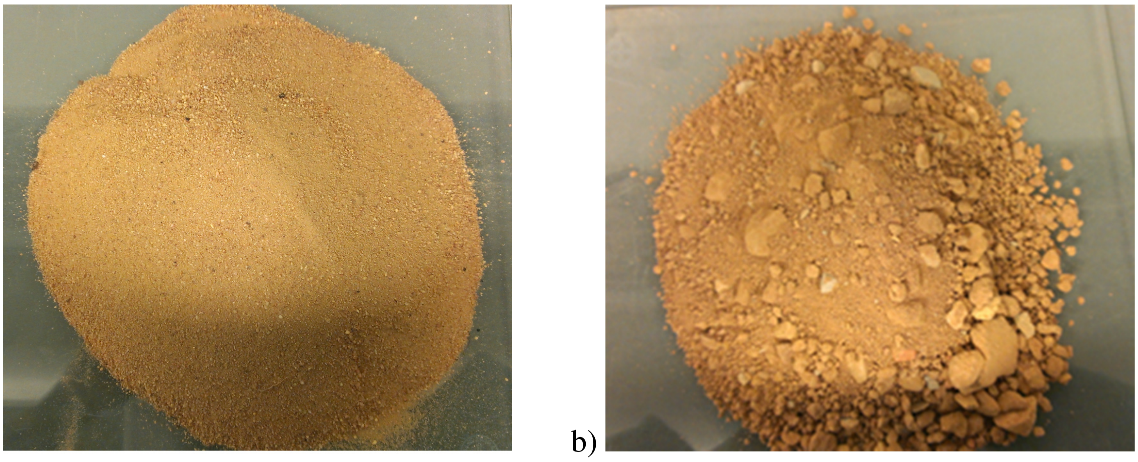


Figure 4-9: Laboratory materials a) Klipheuwel sand and b) Cape Town clayey sand

To determine the mechanical properties of the soils, the classification tests listed in Table 4-1 were conducted. The test standards that were followed and the purpose of the tests were also included in the table. The plastic limit test was only carried out for Cape Town clayey sand because it was cohesive.

Table 4-1: Experiments for laboratory soil classification

PROPERTY	METHOD	TEST STANDARD	REASON FOR THE OBTAINING PROPERTY
Liquid limit	Casagrande	ASTM D4318 - 10	Used to determine the maximum moisture content beyond which the soil flows when compacted
Plastic limit	Plastic limit	ASTM D4318 - 10	Used to determine the range of moisture contents for testing
Natural moisture content	Oven drying	ASTM D2216 - 10	Used to determine the additional volume of water when mixing
Specific gravity	Small pycnometer	ASTM D854 - 10	Used in the Proctor curve for calculating the zero air voids line
Maximum dry density	Proctor Test	ASTM D698 -12	Used in the analysis of results
Optimum moisture content	Proctor Test	ASTM D698 -12	Used in the variations of the moisture content
Particle size distribution	Particle size analysis	ASTM D6913 - 04	Used to determine the distribution of the soil particles

Sieve analysis results for the soils are shown in Figure 4-10. From the grading curves, the soils were classified according the USCS. Klipheuwel sand comprised of 96.6 % sand and 3.4 % fines (passing the 0.075 mm sieve). Its coefficient of uniformity was 1.87 and the coefficient of curvature was 0.86. It was classified as a uniformly graded sand (SP). Cape Town clayey sand had 43.45 % sand, 52.45 % fines, the remaining 4.1 % was gravel. The fines had a plasticity index of 6 % and a liquid limit of 20 %. Therefore, it was classified as a clay of low plasticity. According to the USCS, Cape Town clayey sand was classified as a clayey sand (SC-CL).

Figure 4-11 shows the Proctor curves obtained in the laboratory using standard effort from which the maximum dry density and optimum moisture content for each of the soils was determined.

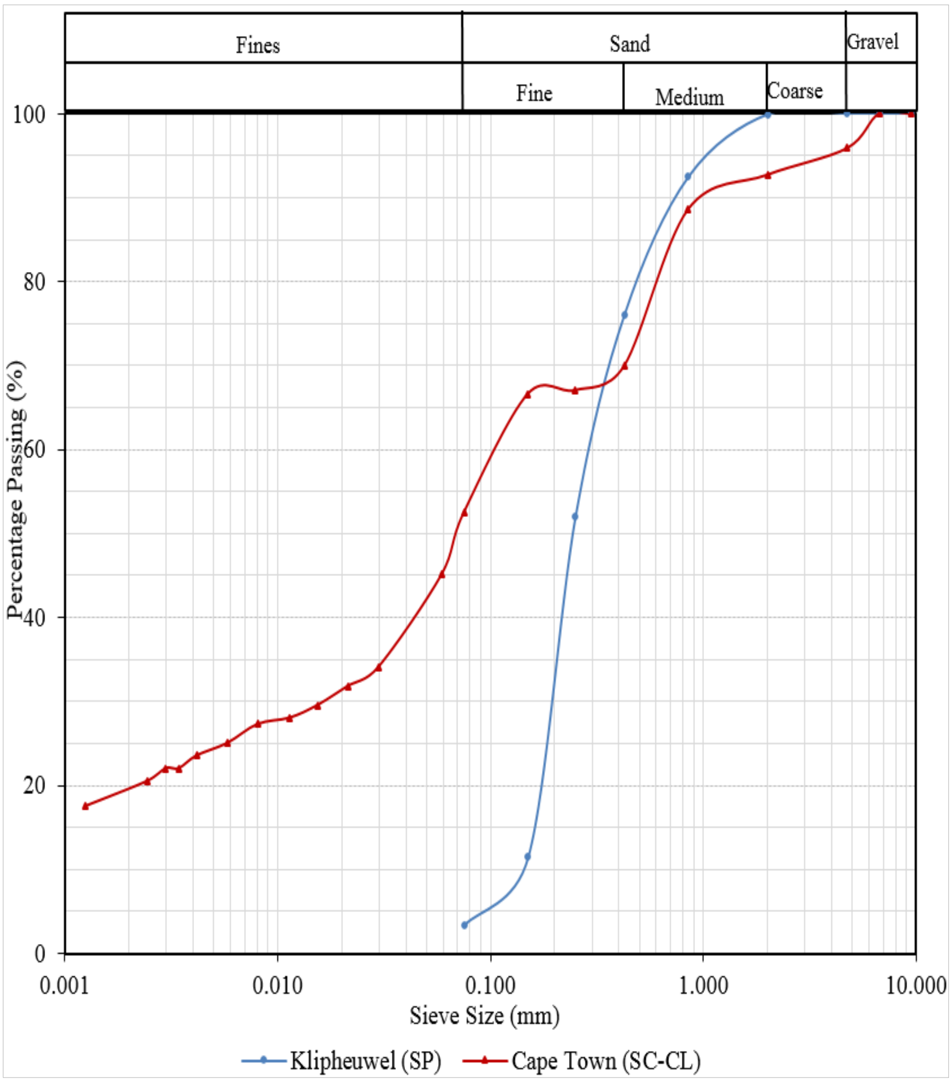


Figure 4-10: Grading curves for Klipheuwel sand and Cape Town clayey sand

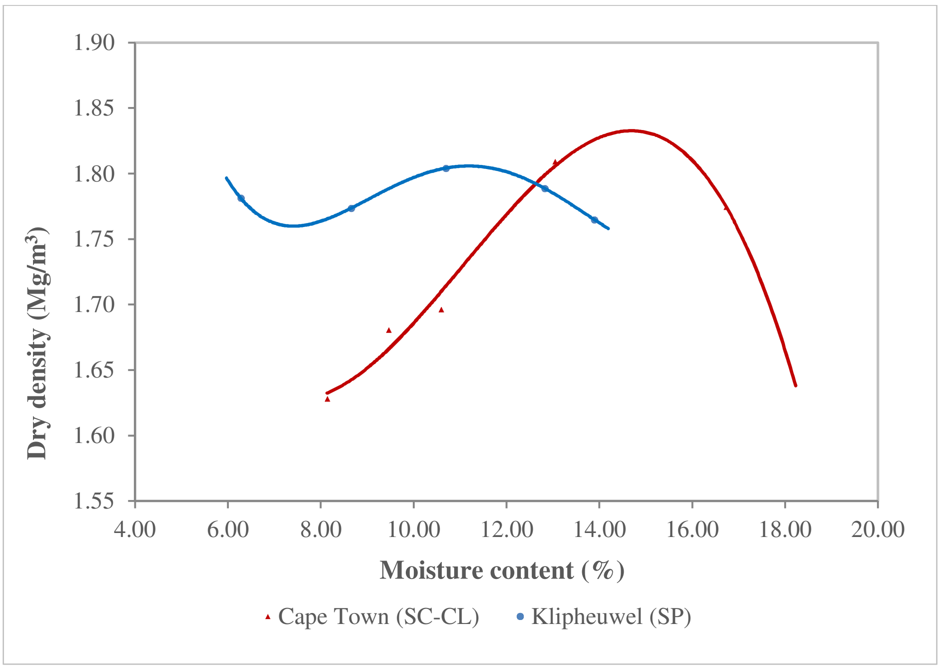


Figure 4-11: Standard effort Proctor curves for Klipheuwel sand and Cape Town clayey sand

Table 4-2 provides a summary of the mechanical properties of the two soils. The detailed data is presented in Appendix B.2 and Appendix B.3 for Klipheuwel sand and Cape Town clayey sand respectively.

Table 4-2: Summary of laboratory soil mechanical properties

PROPERTY	UNIT	KLIPHEUWEL SAND	CAPE TOWN CLAYEY SAND
Specific gravity, G_s	_	2.66	2.61
Particle size range	mm	0.075-1.18	0.001-4.75
Mean grain size, D_{50}	mm	0.25	0.07
Natural moisture content	%	2.2	varied (14.63-16.40)
Optimum moisture content	%	11	15
Maximum dry density	kN/m^3	18.15	17.95

4.3.2 Testing procedure

4.3.2.1 Material preparation

To prepare the soil, the natural moisture content of three representative samples of the soil was measured using the laboratory oven following ASTM D2216. From this, the amount of water required for the three moisture levels i.e. +/- 3% of the optimum moisture content and at optimum moisture content was determined. The three moisture contents also aided in developing the EDG soil model. The moisture content of Cape Town clayey sand varied as the samples were collected after it had rained and was higher than the required moisture content on the dry side of optimum (-3 % of OMC). To ensure uniform moisture content, all the soil tested in the laboratory was oven dried. The soil was loaded onto trays and put in the oven at 110 ± 5^0C for 12 to 16 hours, after which the oven was switched off and the soil allowed to cool. The dried soil was transferred to plastic bags and sealed. Another batch of soil was loaded on the trays and the process repeated until an amount sufficient for conducting the tests was available. It took 3 days to get the required quantity of soil. The dry soil was carried to the mixer using a crane. The volume of soil required for a 200 mm compacted lift was calculated based on the area of the laboratory model. Using the volume obtained and the desired bulk density, the weight of soil required for the lift was calculated. Since the mixer could not contain all the soil required, the soil was weighed in 75 kg batches and poured into the mixer. The amount of water required for each moisture content was calculated for each batch, starting with dry of optimum. Sample calculations are presented in Appendix C.1.

The mixer was switched on and the dry soil in the mixer mixed for 10 minutes to disintegrate any cemented soil. The required water was then poured around the soil and the mixing process continued until a uniform mix was attained. The amount of time required to achieve uniform mixing was determined during the process and used for subsequent mixes. After obtaining a homogeneous mix, the blended material was quickly transferred from the mixer to a sealable plastic bag, which was kept tightly closed to maintain the moisture content. The bags also enabled the carrying of soil using a crane from the mixer to the model. The process of mixing was repeated to ensure that a sufficient quantity of blended soil was available for the preparation of the compacted lift. The blended soil was transferred into the model, covered and stored for at least 16 hours to allow for moisture stabilisation. For subsequent moisture contents (optimum and wet of optimum), the soil was excavated and the additional amount of water required computed and the mixing process repeated.

4.3.2.2 Test program

After 16 hours, the cover was removed and the soil levelled using a hand trowel to facilitate workability. The loosely placed lift was then compacted using the rammer to 200 mm thick. The thickness of the lift was chosen to avoid contact between the 150 mm probes and the base of the laboratory model. The soil was compacted to provide a minimum level of compaction so that tests would be conducted within typical limits. No strict compaction standards were followed.

After compaction, a test spot was chosen, cleared out to remove any loose uncompacted material and flattened. EDG soil calibration and test measurements were done concurrently for each moisture content tested. However, the EDG was calibrated first following ASTM D7698-11 – "Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method." The measurements of the first four test spots were used for calibration. After, the density and moisture content of the compacted soil were measured using the calibrated EDG following ASTM D7698-11. The EDG was used first because it is less destructive. The four tapered metal darts, each 150 mm long, were driven into the soil. The average of two electrical measurements was taken for each set of opposite dart pairs. Because no data for bulk density and moisture content had been entered into the EDG computer prior to the tests, no EDG measurements for bulk density, dry density or moisture content were displayed on the screen. However, the points were saved so that they could be correlated later on when the data from the physical properties had been entered.

Bulk density measurements were then taken at the same spot using the SC according to ASTM D1556 – "Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method." The samples collected from the SC test were used for moisture content determination using the oven following ASTM D2216-10 - "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass." Figure 4-12 shows the schematics of the test sequence.

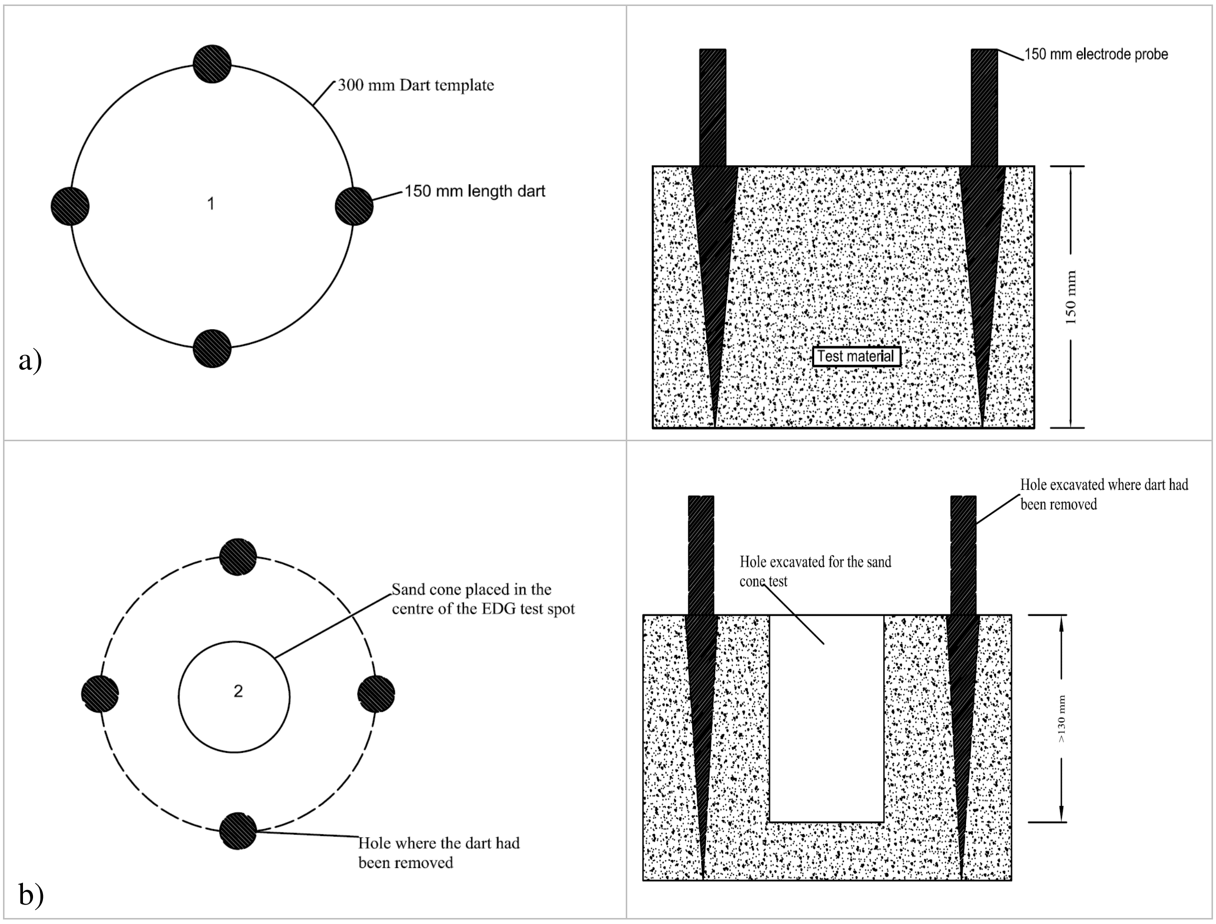


Figure 4-12: a) represents the first step in testing involving the use of the EDG; b) represents the second step involving the use of the SC at the centre of the EDG test spot

At least ten test spots (including the four for calibration) were measured using the both the EDG and SC in the same spot. EDG test measurements for Klipheuwel sand were taken twice at a spot to measure the repeatability of the EDG. 16 hours later, the bulk density and moisture content values from the SC and LO respectively, for the EDG soil model were input into the EDG. The electrical measurements were paired with the corresponding moisture and density value at each spot. The graphs plotted were then refined to adjust the fit. The process was repeated for the remaining two moisture contents. When all the points for the model had been collected, the soil model was adjusted to obtain the final fit. The EDG bulk density, dry density and moisture content were correlated to the adjusted model with the higher fit and the final measurements obtained. Table 4-3 shows the value of fit for soil models developed during laboratory calibration of the EDG. The detailed soil models are presented in Appendix C.2.

Table 4-3: Values of model fit for laboratory soil calibration of the EDG

MATERIAL	MODEL FIT
Klipheuwel sand	0.888
Cape Town clayey sand	0.823

4.4 Field testing

The field tests were conducted after the laboratory experiments were completed. The tests were done at three sites spread out in Cape Town, namely Khayelitsha, Pinelands and Burgundy Estate. In situ density and moisture content tests were carried out at the sites. The location of the sites is shown in Figure 4-13, the individual site locations are shown in APPENDIX A. The soils tested represent typical soils encountered on construction sites in Cape Town.

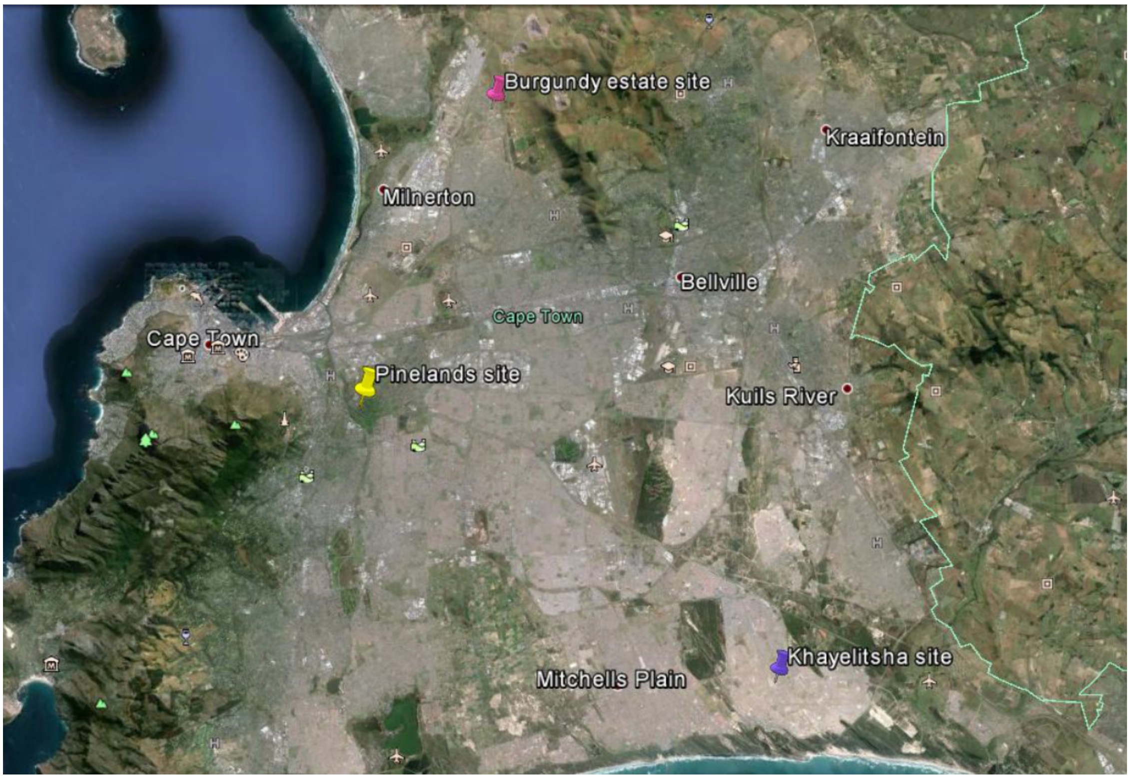


Figure 4-13: Overview of the site locations represented by the place marks (Google maps, 2015)

4.4.1 Material description

Four soil materials, shown in Figure 4-14 were tested in the field. All the soils tested in the field were non-cohesive. Three of them were poorly graded sands and the fourth was a gravelly sand. The detailed description of the soils is given below.

4.4.1.1 Khayelitsha sand

Khayelitsha is located in the southern suburbs of Cape Town has a geology comprised of slightly metamorphosed sedimentary rocks, which were overlain by numerous layers of sand sediments some of which were cemented into sandy limestone (City of Cape Town, 2011a).

The soil at the site was a light brown uncemented sand with some gravel and was variable from one point to another.

4.4.1.2 Pinelands

Pinelands is located in the central business area of Cape Town and was underlain by Table mountain sandstone that was overlain by loam and sandy loam soils (City of Cape Town, 2011b). The site had a high water table at approximately 1 m below ground level and piling was ongoing. The existing soil was not suitable for transferring loads from the planned structures therefore a G5 material was compacted over the soil. The G5 material, a greyish brown gravelly sand was tested during the study.

4.4.1.3 Burgundy sand

Burgundy site is located in the northern part of Cape Town. The geology was made up of Malmesbury group rock, which consisted of dark grey mudstones and lighter coloured sandstones. The Sandveld Group that is mainly represented by the Springfontyn Formation overlied the Malmesbury rock. It consisted of reddish to grey, unconsolidated quartz sand deposited by wind (City of Cape Town, 2011c). The top layer of the soil profile consisted of light grey fine sand with rootlets, which was underlain by light brown to light orange, medium dense sand. This was exposed on one part of the site and was named Burgundy sand (SP1) for the purpose of the study and the other light grey sand was called Burgundy sand (SP2).

a)

b)

c)  d) 

Figure 4-14: Soil materials for the field a) Khayelitsha sand, b) Pinelands gravelly sand, c) Burgundy sand (SP1) and d) Burgundy sand (SP2)

Classification tests were conducted on each of the soils tested. Table 4-4 lists the tests that were carried out, the standard followed and the reason for the test. All the soils at the sites were non-cohesive therefore, no Atterberg limits were determined. In addition, the tests were done in situ so the natural moisture content of the soils was similar to the moisture content obtained for the density tests. Therefore, the natural moisture content of the soil was not listed among the tests.

Table 4-4: Experimental tests for field soil classification

PROPERTY	METHOD	TEST STANDARD	REASON FOR THE OBTAINING PROPERTY
Specific gravity	Small pycnometer	ASTM D854 - 10	Used in the Proctor curve for calculating the zero air voids line
Maximum dry density	Proctor Test	ASTM D698 -12	Used in the analysis of results
Optimum moisture content	Proctor Test	ASTM D698 -12	Used in the variations of the moisture content
Particle size distribution	Particle size analysis	ASTM D6913 - 04	Used to determine the distribution of the soil particles

The grading curves for the soils as was obtained from the sieve analysis test are shown in Figure 4-15. From these, the percentage grain sizes for gravel, sand and fines were obtained as well as the mean diameter, D_{50}. The coefficient of curvature, C_c and coefficient of uniformity, C_u were calculated.

The Proctor curves for the soils obtained using the standard compaction effort are shown in Figure 4-16. The curves were used to determine the maximum dry density and optimum moisture content of each soil. Table 4-5 below presents a summary of the results obtained from the classification tests for the soils used in the field. For detailed classification results, see Appendix B.4 to Appendix B.7.

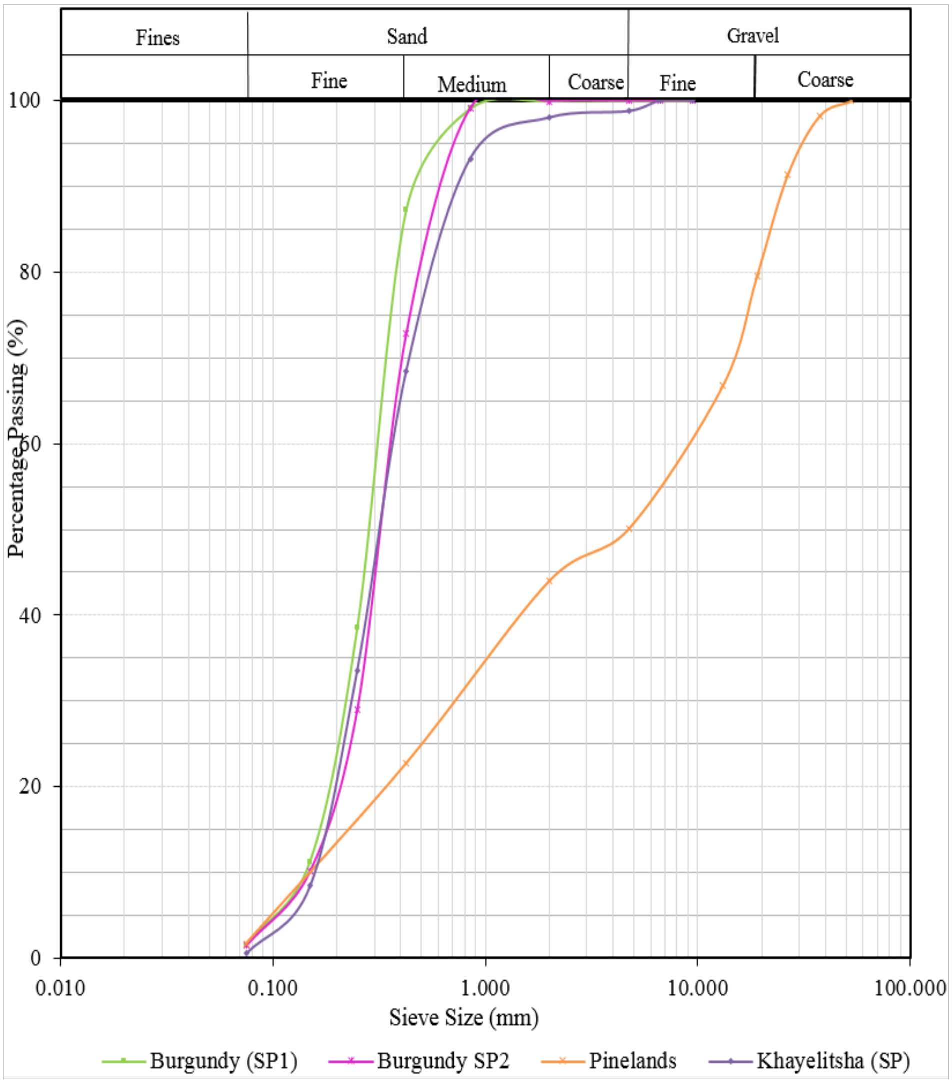


Figure 4-15: Grading curves for the field soils

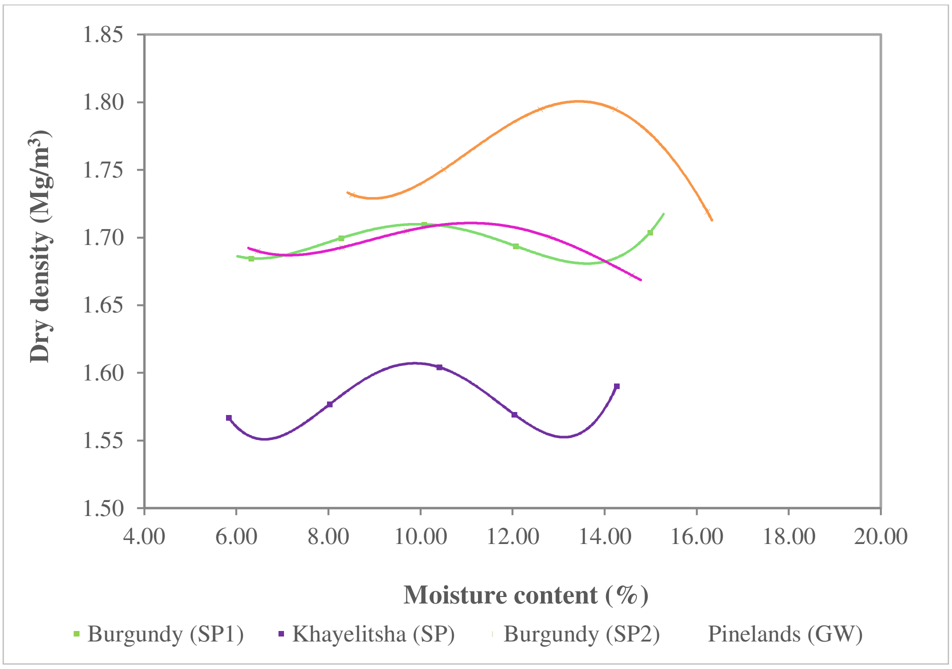


Figure 4-16: Proctor curves for soils tested in the field

Table 4-5: Index properties for the field soils

SOIL IDENTITY	USCS class	C_c	C_u	D_{50} mm	Grain size by weight (%)			G_s	MDD kN/m^3	OMC %
					Gravel	Sand	Fines			
Khayelitsha sand	SP	0.87	2.38	0.32	1.24	98.19	0.57	2.67	15.75	9.8
Pinelands	GW-SW	0.36	60	4.75	49.9	48.4	1.7	2.59	17.67	13.5
Burgundy sand, SP1	SP	1.18	2.28	0.28	0	98.43	1.57	2.58	16.78	10
Burgundy sand, SP2	SP	1.25	2.4	0.32	0	98.55	1.45	2.64	16.78	11

4.4.2 Testing procedure

The materials in the field were tested in situ therefore material preparation was not required. A test area was chosen, cleared out to remove any loose uncompacted material and flattened. The test area was then divided into several test spots. Like in the laboratory, EDG soil calibration and test measurements were done concurrently. The EDG was calibrated first following ASTM D7698-11 – "Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method." The measurements of the first four test spots were used for calibration. These were randomly chosen and distributed around the test area to obtain representative densities and moisture contents. After, the in situ density and moisture content of the soil were measured using the calibrated EDG following ASTM D7698-11. The EDG was used first because it is less destructive. The four tapered metal darts, each 150 mm long, were driven into the soil. The average of two electrical measurements was taken for each set of opposite dart pairs. Because no data for bulk density and moisture content had been entered into the EDG computer prior to the tests, no EDG measurements for bulk density, dry density or moisture content were displayed on the screen. However, the points were saved so that they could be correlated later on when the sand cone and oven method measurements had been entered.

Bulk density measurements were then taken at the same spot using the SC according to ASTM D1556 – "Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method." The samples collected from the SC test were used for moisture content determination using the oven following ASTM D2216-10 - "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass." The same test sequence as in the laboratory was followed.

At least ten test spots (including the four for calibration) were measured using both the EDG and SC in the same spot. Two EDG measurements for the tests were taken at a spot to measure the repeatability of the EDG. 16 hours later, the bulk density and moisture content values from the SC and LO respectively, for the EDG soil model were input into the EDG. The electrical measurements were paired with the corresponding moisture and density value at each spot. The graphs plotted were then refined to adjust the fit. Another site visit was made to obtain points with a different moisture content, and the process repeated. The site visits were arranged such that they were made after it had rained and on a dry day. This was so that a range of moisture contents could be used in developing the soil model. However, the soils at Burgundy drained easily therefore their moisture content varied within a small range. When all the points for the model had been collected, the soil model was adjusted to obtain the final fit. The EDG bulk density, dry density and moisture content were correlated to the adjusted model with the higher fit. Table 4-6 shows values of fit for the soil models developed during calibration. The details pertaining to the soil model data are shown in Appendix C.2.

Table 4-6: Values of model fit for field soil calibration of the EDG

MATERIAL	MODEL FIT
Khayelitsha sand	0.516
Pinelands gravely sand	0.864
Burgundy sand, SP1	0.163
Burgundy sand, SP2	0.232

4.5 Data processing

4.5.1 EDG data

For the EDG, the dry density was calculated by the EDG as the difference between the EDG measured bulk density and weight of water per unit volume. At the end of all the tests for every soil, the soil model data and job site data were transferred from the EDG using a universal serial bus (USB). The data was then processed using gauge report and exported to excel where it was converted to metric units using a multiple of 0.15709 kN/m^3 to 1 pcf. The converted data collected from the EDG measurements is shown in Appendix D.1. The average of the repeated EDG measurements was used in the analysis of the results.

4.5.2 Sand cone data

Using equation 4-2, the volume, V of the test hole was calculated from the weight of the sand required to fill the hole only and the bulk density of the calibrated sand.

$$V = \frac{W_1 - W_2 - W_3}{\rho_{b1}} \qquad 4\text{-}2$$

where W_1 was the weight of the sand cone before pouring sand into the hole

W_2 was the weight of the sand cone after pouring the sand into the hole

W_3 was the weight of the sand required to fill the cone only (cone correction factor)

ρ_{b1} was the bulk density of the calibrated sand

Using the calculated volume, V the bulk density of the soil, ρ_{b2} was determined (equation 4-3) where *M* was the mass of the excavated soil.

$$\rho_{b2} = \frac{M}{V} \qquad 4\text{-}3$$

The dry density of the soil was calculated using equation 3-2, where the moisture content, *w* was calculated using equation 4-4, and M_s was the mass of dry soil.

$$w = \frac{M - M_s}{M_s} \qquad 4\text{-}4$$

The detailed data showing the bulk density, moisture content and dry density of the soil obtained using the sand cone test is in Appendix D.2.

CHAPTER 5 RESULTS AND ANALYSIS

The results obtained in both the laboratory and field are presented. Scatter plots comparing EDG repeated measurements (moisture content, bulk and dry density) and those comparing EDG and reference tests (sand cone and the oven) are presented first. Lastly, the precision and accuracy of EDG measurements is analysed using statistical tests. The detailed explanations for the observed trends in the results are discussed in the next chapter.

5.1 Scatter plots for repeated measurements

Repeatability tests were conducted to determine the extent of variations in the results from the different measurement methods. The tests involved obtaining independent test results for identical test items using the same method, laboratory, operator and equipment within short intervals of time (ASTM E177-14). Therefore, test and retest measurements were only done for the EDG because the sand cone (SC) test is destructive and identical test items could not be used.

The repeated measurements for EDG moisture content, bulk density and dry density were plotted against the corresponding measurements to obtain the slope and coefficient of determination *(R^2)*. Ideally, if the EDG repeated measurements were equal, the slope and R^2 would be equal to one. However, a slope greater than 1 indicated overestimation of the measurement while a slope less than 1 indicated underestimation of the measurement. On the other hand, a R^2 greater than 0.8 indicated strong linear correlation between the measurements.

5.1.1 Repeatability in the laboratory

In the laboratory, Klipheuwel sand was used to conduct the repeatability tests. Figure 5-1, Figure 5-2 and Figure 5-3 show scatter plots of EDG repeated measurements for moisture content, bulk and dry density respectively. Table 5-1 shows the coefficient of determination, slope and deviation of the slope from 1 for the repeated tests in the laboratory.

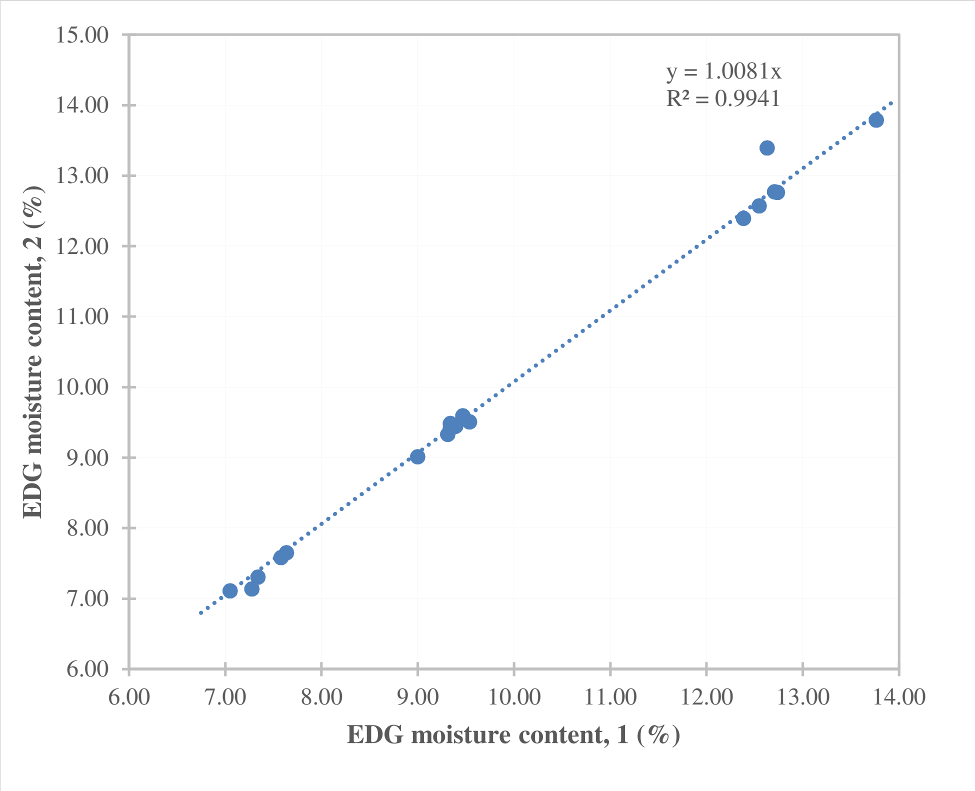


Figure 5-1: Plot of EDG repeated measurements for moisture content in Klipheuwel (SP)

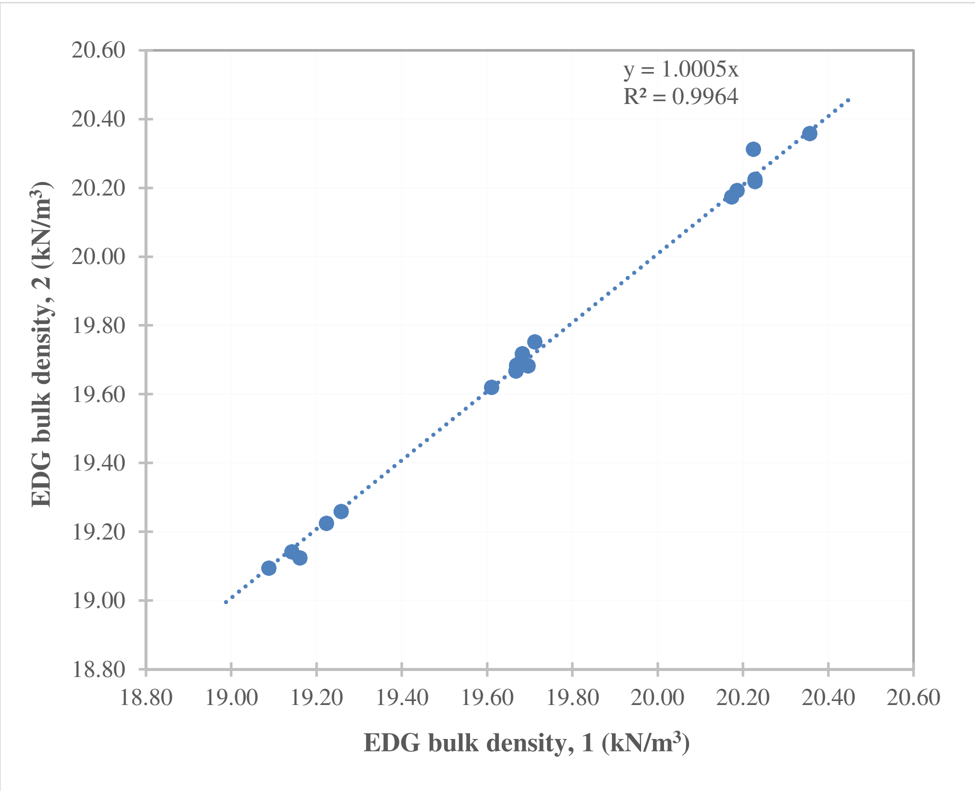


Figure 5-2: Plot of EDG repeated measurements for bulk density in Klipheuwel (SP)

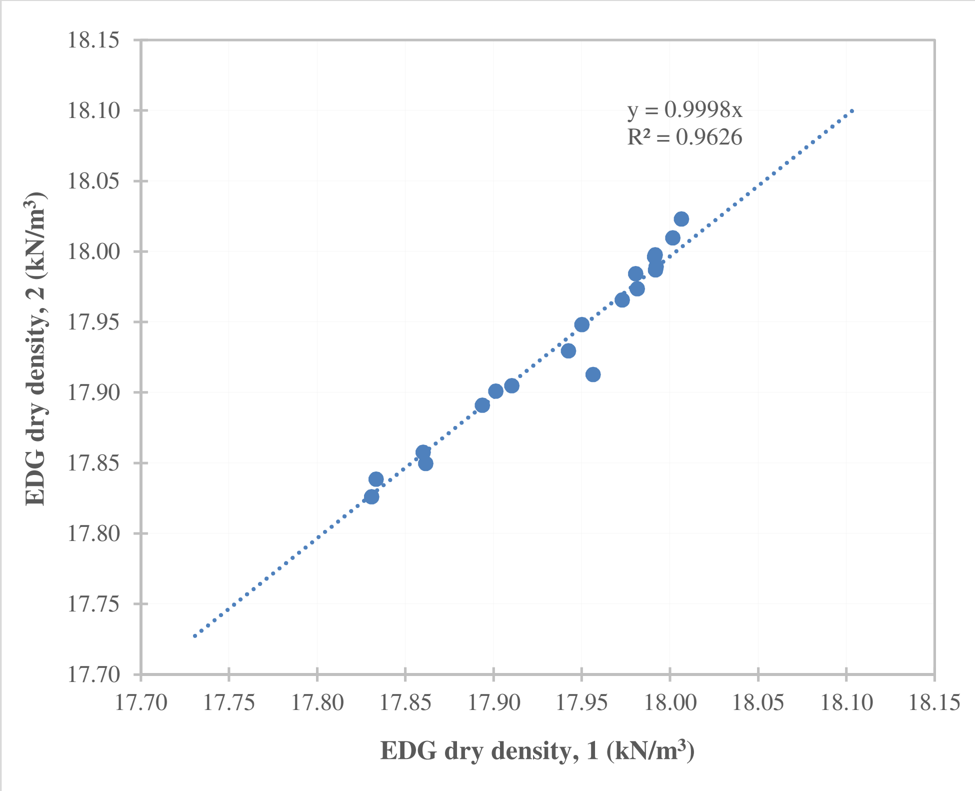


Figure 5-3: Plot of EDG repeated measurements for dry density in Klipheuwel (SP)

Table 5-1: Coefficient of determination and slope of repeated laboratory tests

PROPERTY	R^2	SLOPE (m)	DEVIATION OF SLOPE FROM 1
Moisture content	0.9941	1.0081	0.0081
Bulk density	0.9964	1.0005	0.0005
Dry density	0.9626	0.9998	- 0.0002

From the coefficient of determination (R^2) in Table 5-1, the EDG had strong linear correlation (R^2 greater than 0.8) for repeated moisture content, bulk and dry density measurements. The R^2 value *(0.9626)* for the equation relating the repeated dry density measurements ***(y=0.9998x)*** could only account for ***96.26 %*** of the variation and was less than the R^2 for the other parameters because dry density was calculated from both the moisture content and bulk density. Therefore, errors were carried over from both moisture content and bulk density measurements.

The slope of the lines was close to one for the repeated measurements. However, repeated moisture and bulk density measurements were overestimated (slope greater than 1) compared to the ones before, while dry density measurements were underestimated.

5.1.2 Repeatability in the field

It was necessary to determine repeatability in the field as well, because the repeatability tests in the laboratory were conducted under a controlled environment. Repeatability tests in the field were conducted for all the soils tested due to different ambient conditions at each site, which are known to affect EDG measurements. Figure 5-4, Figure 5-5 and Figure 5-6 show scatter plots of EDG repeated measurements for moisture content, bulk and dry density respectively. Table 5-2 shows the coefficient of determination, slope and its deviation from one for each of the line of each of the soils in the plots.

Table 5-2: Coefficient of determination and slope of repeated field tests

SOIL	MOISTURE CONTENT			BULK DENSITY			DRY DENSITY		
	R^2	slope	slope-1	R^2	slope	slope-1	R^2	slope	slope-1
Khayelitsha	0.979	0.9985	-0.0015	0.9521	1.0002	0.0002	0.9655	1.0003	0.0003
Pinelands	0.9983	1.0011	0.0011	0.9991	1.0007	0.0007	0.999	1.0005	0.0005
Burgundy (SP1)	0.8975	0.9983	-0.0017	0.913	1.001	0.001	0.912	1.0011	0.0011
Burgundy (SP2)	0.8476	1.0007	0.0007	0.9583	1.0003	0.0003	0.9502	1.0004	0.0004

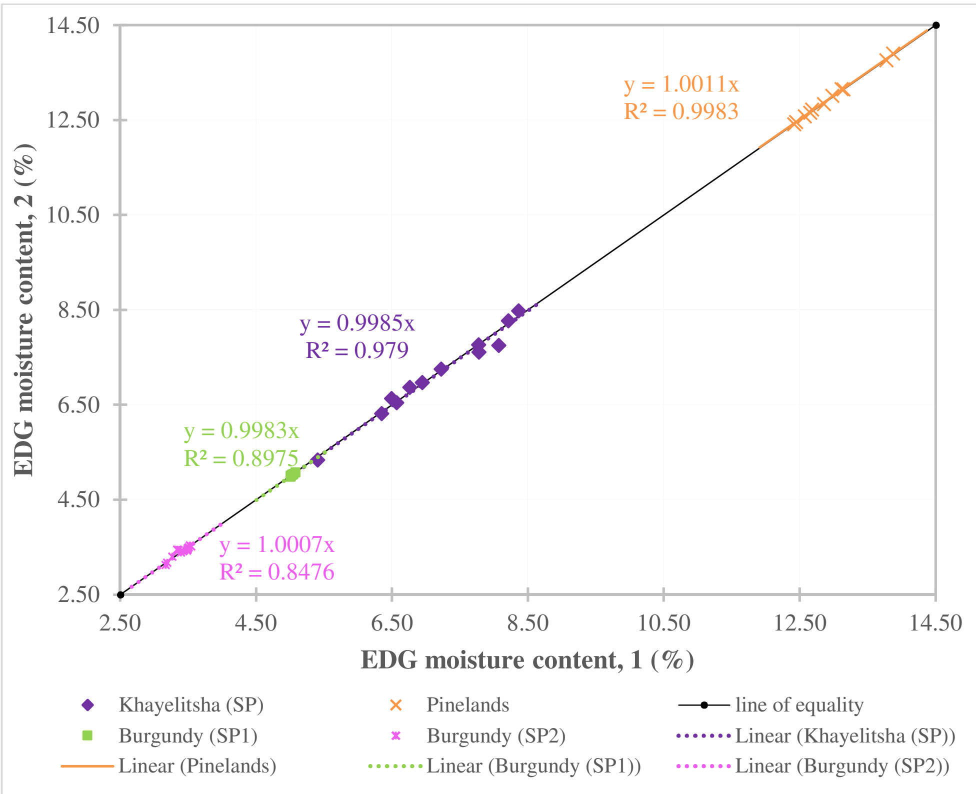


Figure 5-4: Plot of EDG repeated moisture contents for the soil in the field

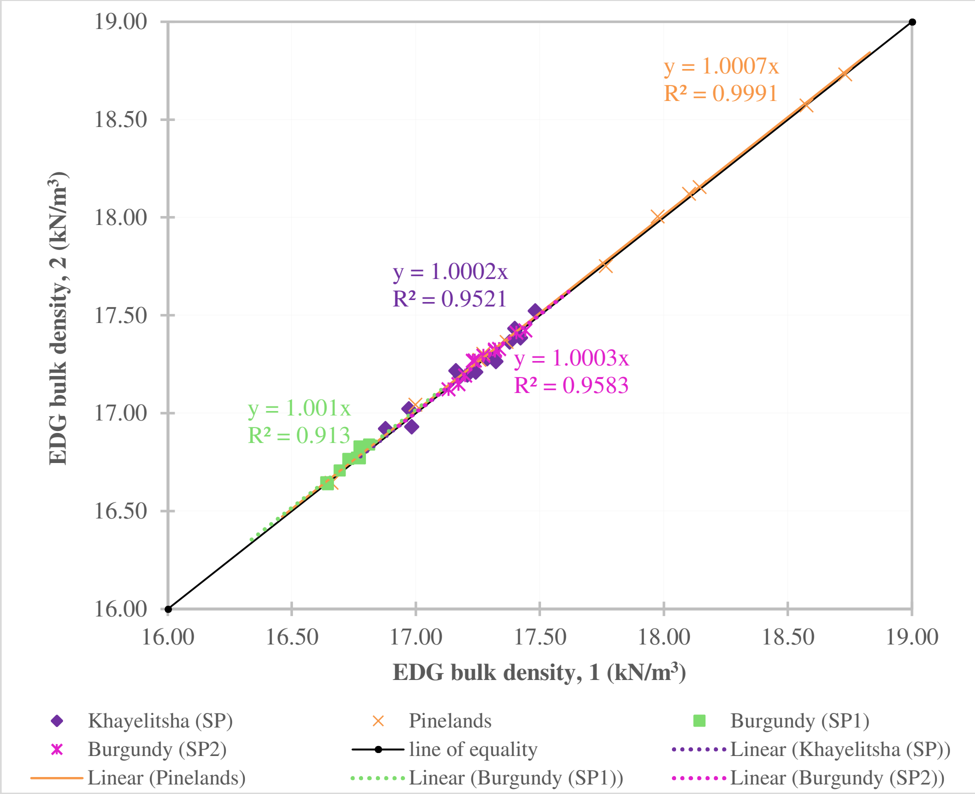


Figure 5-5: Plot of repeated EDG bulk density for the soil in the field

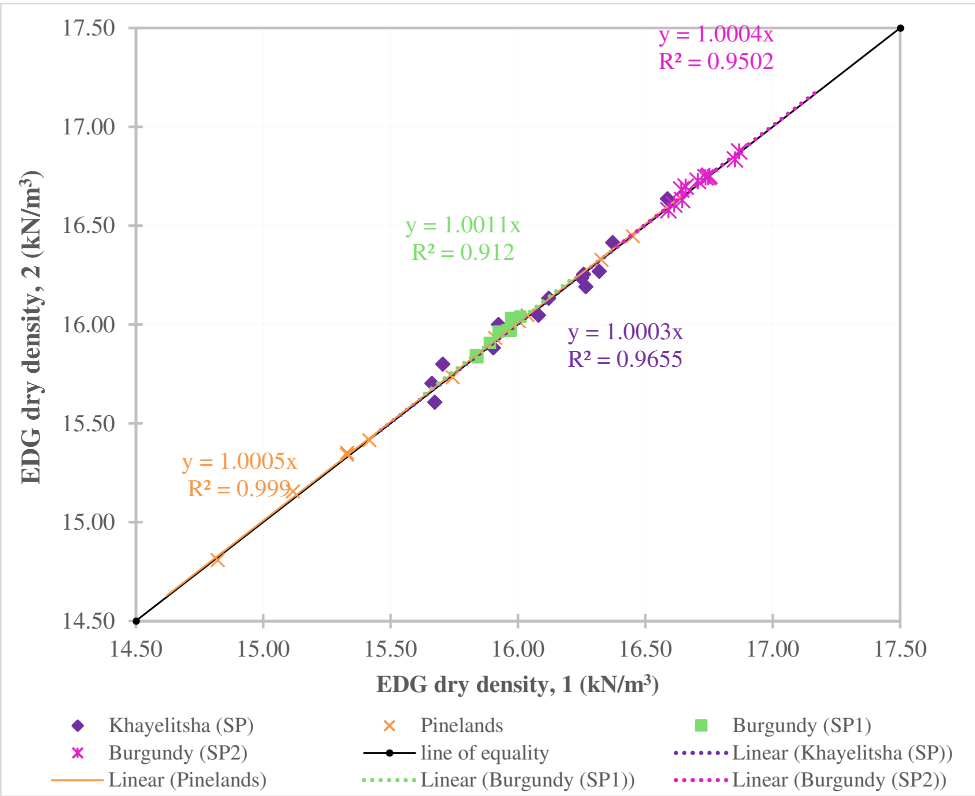


Figure 5-6: Plot of repeated EDG dry density for soil in the field

From Table 5-2, the coefficients of determination, R^2 for EDG repeated measurements in the field were greater than 0.8 therefore the measurements had strong linear correlation. The repeatability of moisture content was affected by the fit of the soil model such that the R^2 was slightly lower for soils whose model fit developed during calibration was less than 0.5 (Burgundy sands SP1 and SP2) and increased with increasing model fit.

All the slopes of the lines were close to one. Based on the slopes, moisture content repeated measurements in Burgundy sand (SP2) and Pinelands gravelly sand were overestimated (slope greater than 1) while those for Burgundy sand (SP1) and Khayelitsha sand were underestimated (slope less than 1). Repeated bulk density and dry density were overestimated for all the soils tested.

5.2 Scatter plots for laboratory and field results

The results were presented based on the measurements (moisture content, bulk and dry density in APPENDIX D) obtained from the laboratory and field. Scatter plots showing EDG measurements on the *y-axis* and the reference test (sand cone and oven drying) measurements on the *x-axis* were plotted to determine if EDG measured compaction equalled that of the reference tests hence a least squares regression line with the intercept equal to zero was fit to the data. Ideally, if EDG results were equal to the reference test results, all the points would plot on the line of equality at 45^0. In addition, the coefficient of determination, R^2 and the slope of the regression line would be one. However, a slope less than 1 was indicative of the EDG underestimating compaction while a slope greater than 1 indicated overestimation by the EDG.

5.2.1 Moisture content measurement

Figure 5-7 and Figure 5-8 show the comparison of EDG moisture content *(y-axis)* to oven moisture content *(x-axis)* in the laboratory and field respectively. The solid line represents the line of equality at 45^0 while the dotted lines represent the fitted regression lines for the Klipheuwel sand and Cape Town clayey sand in the laboratory and Khayelitsha sand, Pinelands gravelly sand, Burgundy sand SP1 and SP2 in the field. The vertical lines in the plots represent the optimum moisture content (OMC) of the soil to the nearest 0.5 %. Table 5-3 shows the coefficient of determination *(R^2),* slope and deviation of the slope from one for the regression lines.

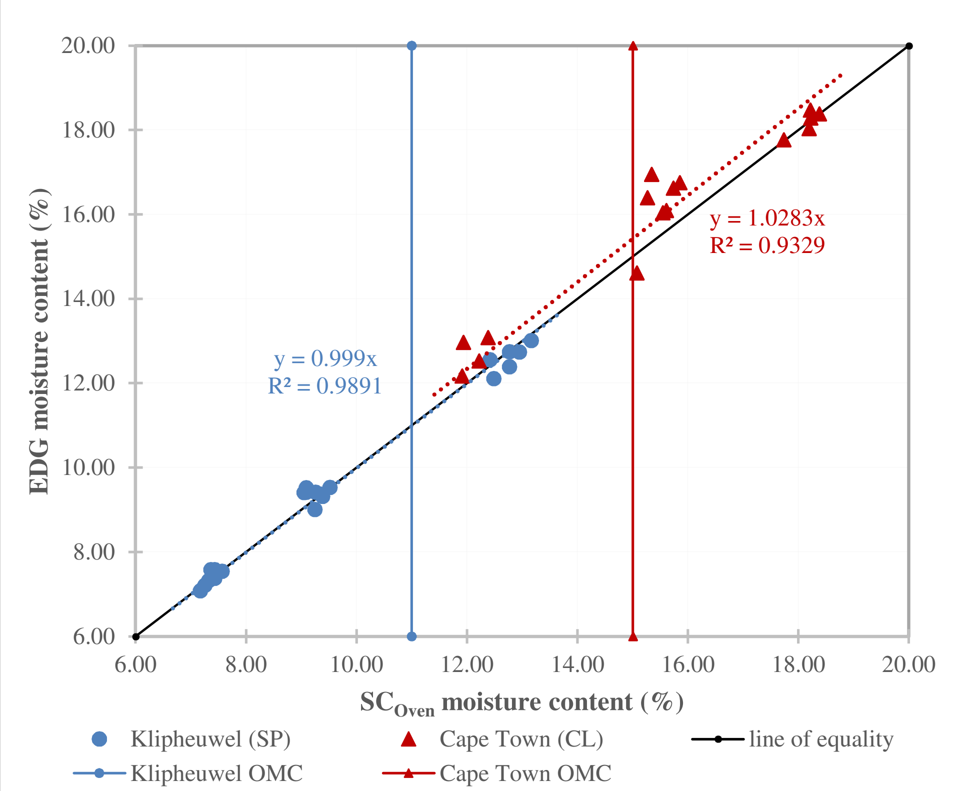


Figure 5-7: Comparison of laboratory measured moisture contents for the EDG to the LO

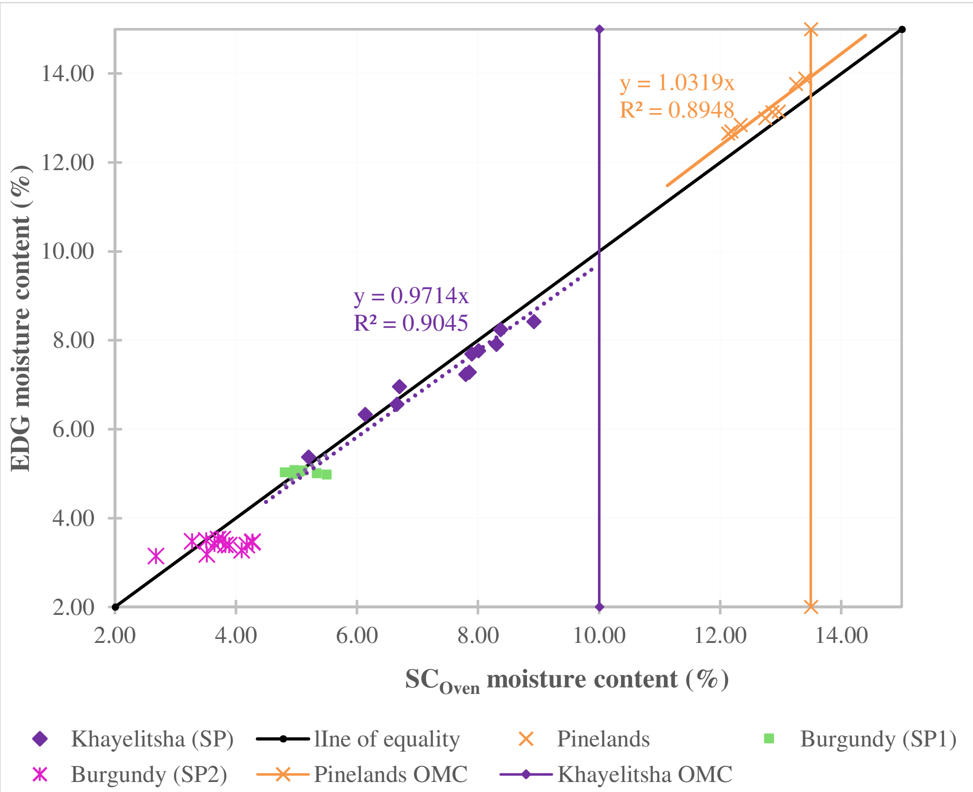


Figure 5-8: Comparison of field measured moisture contentment for the EDG to the LO

Table 5-3: Coefficient of determination and slopes for moisture content measurements

SOIL	R^2	SLOPE (m)	DEVIATION OF SLOPE FROM 1
Klipheuwel sand	0.9891	0.999	-0.001
Cape Town (CL)	0.9329	1.0283	0.0283
Khayelitsha sand	0.9045	0.9714	-0.0286
Pinelands gravelly sand	0.8948	1.0319	0.0319

From Table 5-3, strong linear correlation ($R^2 > 0.8$) and slopes close to one were observed for EDG measured moisture content and oven moisture content for soils with model fit greater than 0.5. EDG measured moisture contents for Burgundy sands SP1 and SP2 were independent of those of the oven due to the lower model fit of 0.163 and 0.232 respectively. However, the linear correlation for Khayelitsha was slightly stronger than that at Pinelands despite having a lower model fit (0.516) than Pinelands (0.864). This was attributed to the fact that higher moisture contents (>12 %) were measured for Pinelands compared to Khayelitsha hence the EDG performed better at low moisture contents (<12 %). In addition, the EDG underestimated low moisture contents (slope < 1) while those greater than 12 % were overestimated as shown by the slope greater than 1.

For individual soils, the EDG overestimated moisture contents lower than the optimum moisture content (represented by the vertical lines), and underestimated moisture contents higher than this point. Figure 5-7 and Figure 5-8 showed that EDG moisture contents less than the optimum moisture content (OMC) plotted above the line of equality and EDG moisture contents greater OMC plotted below the line of equality. The OMC for Burgundy sands SP1 and SP2 were not shown in Figure 5-8 because the EDG measured moisture contents were independent of those of the oven and no clear pattern was visible. However, this trend was hard to observe for soils tested in the field as the tests were conducted at natural moisture content, which was less than their OMC.

5.2.2 Bulk density measurement

Figure 5-9 and Figure 5-10 show scatter plots comparing EDG measured bulk density on the *y-axis* to that of the sand cone (SC) on the *x-axis* in the laboratory and field respectively. The solid black line is the line of equality at 45^0 along which all EDG bulk densities would plot if they were equal to those of the SC. The dashed yellow lines represent references for deviations of $\pm$ 0.1 kN/m^3 of EDG bulk density measurements from the SC. According to ASTM D1556, bulk density should be reported to 3 significant figures therefore EDG bulk densities differing by greater than $\pm$ 0.1 kN/m^3 were considered unacceptable for use in place of the SC measurements.

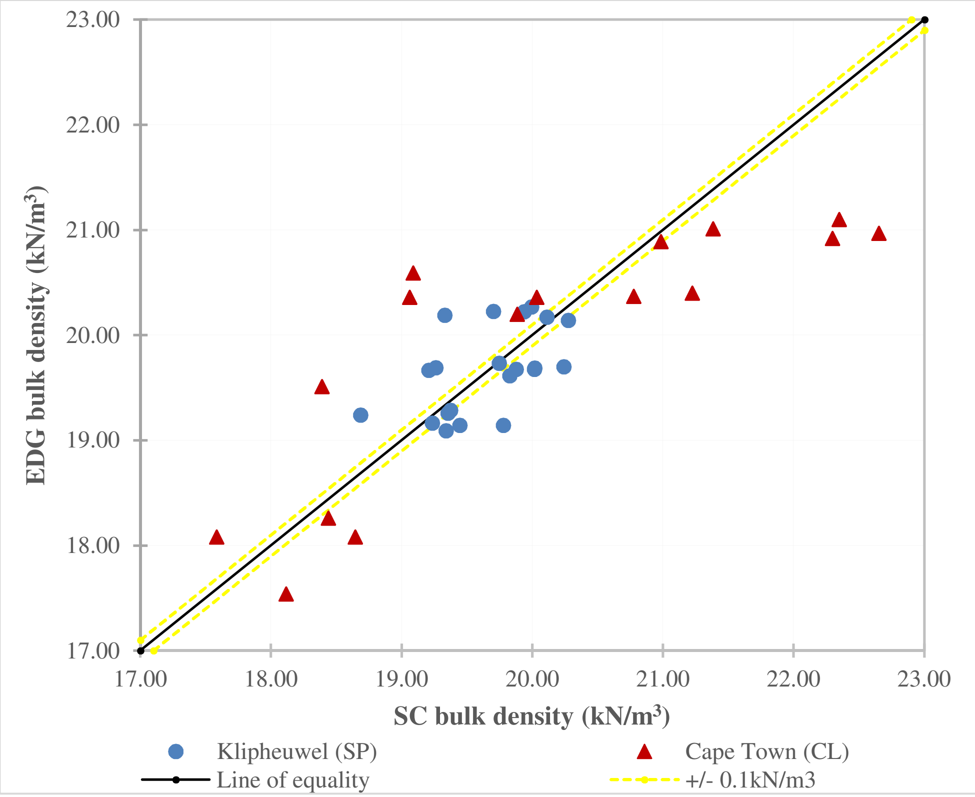


Figure 5-9: Comparison of laboratory measured bulk density of the EDG to the SC

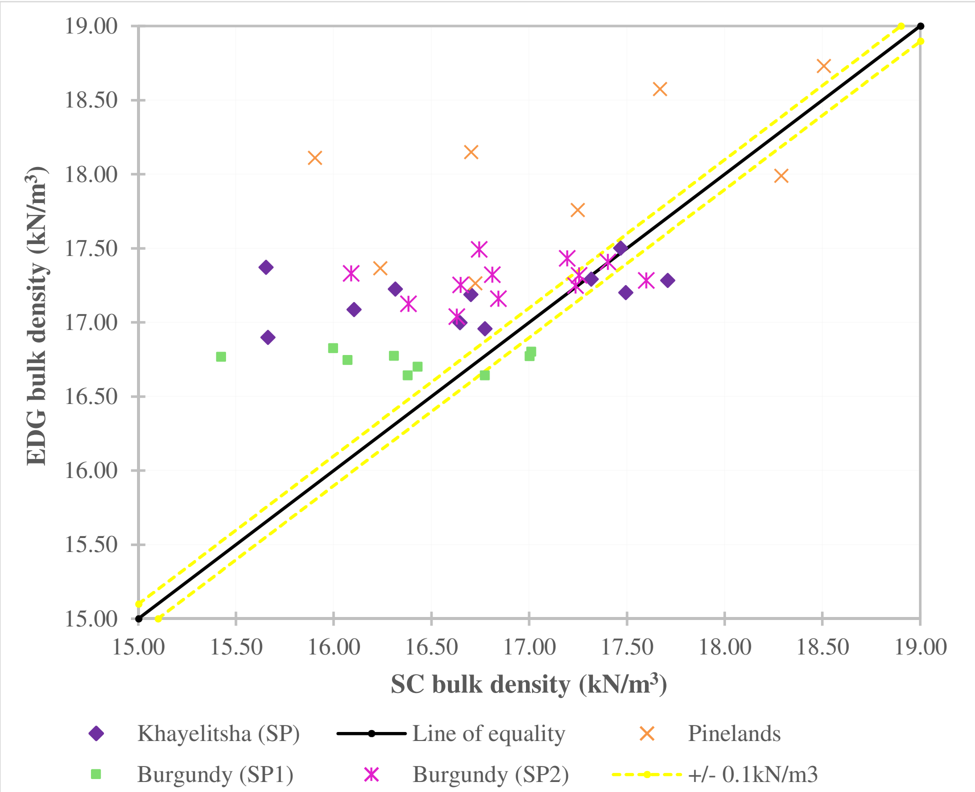


Figure 5-10: Comparison of field measured bulk density of the EDG to the SC

EDG bulk density measurements deviated from the line of equality especially in the field therefore varied from those of the SC test and were unreliable. The higher variations in the Pinelands gravelly sand were attributed to inaccuracy of sand cone results when used in gravelly soils and the presence of vibrations from piling at the site. Additionally, EDG measurements for bulk density in the field were consistent much as those measured by the SC test were changing hence its measurements were independent of those of the sand cone (SC). Table 5-4 shows the percentage of EDG bulk density measurements for each soil within the acceptable band of ± 0.1 kN/m^3.

Table 5-4: Percentage of EDG bulk densities within ± 0.1 kN/m^3

SOIL TYPE	NO. OF POINTS WITHIN ± 0.1 kN/m^3	PERCENTAGE (%)
Klipheuwel (SP)	6	30
Cape Town (SC-CL)	1	6.3
Khayelitsha (SP)	2	18.2
Pinelands	0	0
Burgundy sand (SP1)	1	11.1
Burgundy sand (SP2)	3	23.1

The EDG performed better in the uniformly graded sands and the performance increased with increasing model fit, from 0.888 for Klipheuwel sand to 0.163 for Burgundy sand SP1. The percentage of acceptable points for Pinelands and Cape Town clayey sand were lower than the other soils despite the high model fit (greater than 0.8). This was attributed to the high moisture content (>12 %) of the soils at which the measurements were made.

5.2.3 Dry density measurement

The sand cone (SC) dry density was calculated using equation 3-2 and substituting the SC measured bulk density and oven moisture content. Figure 5-11 and Figure 5-12 show scatter plots of EDG measured dry density against the calculated SC dry density for the laboratory and field data respectively. The solid line and dashed line are as defined in section 5.2.2. The vertical lines represent the maximum dry density (MDD) for the respective soil to the nearest 0.05 kN/m^3.

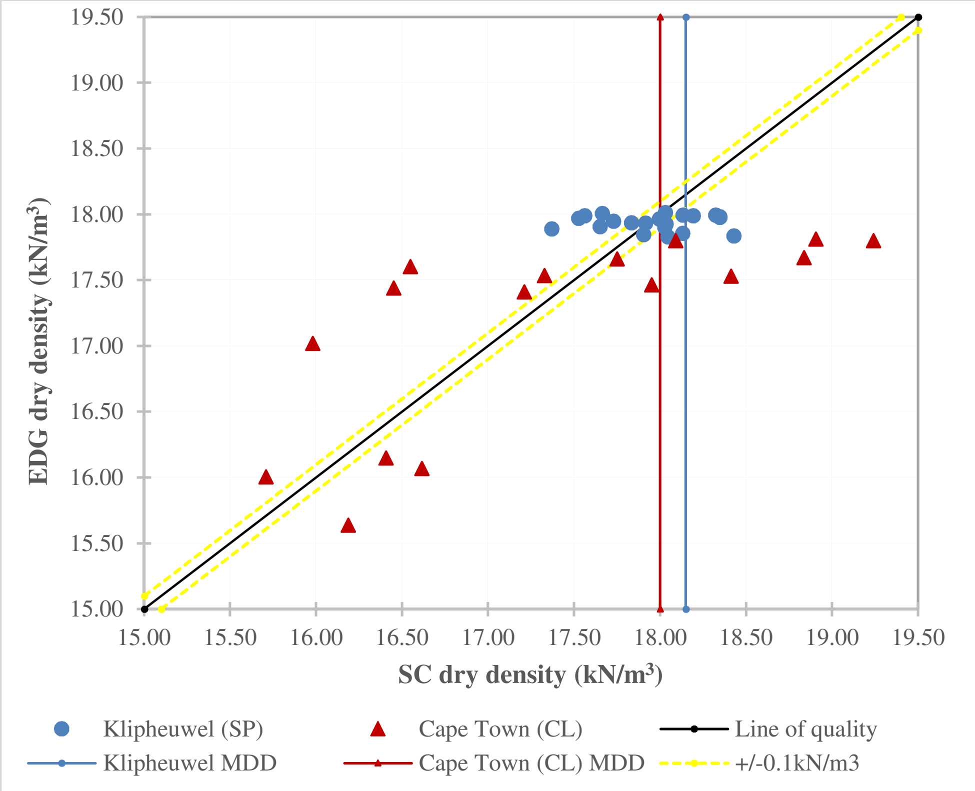


Figure 5-11: Comparison of laboratory measured dry density of the EDG to the SC

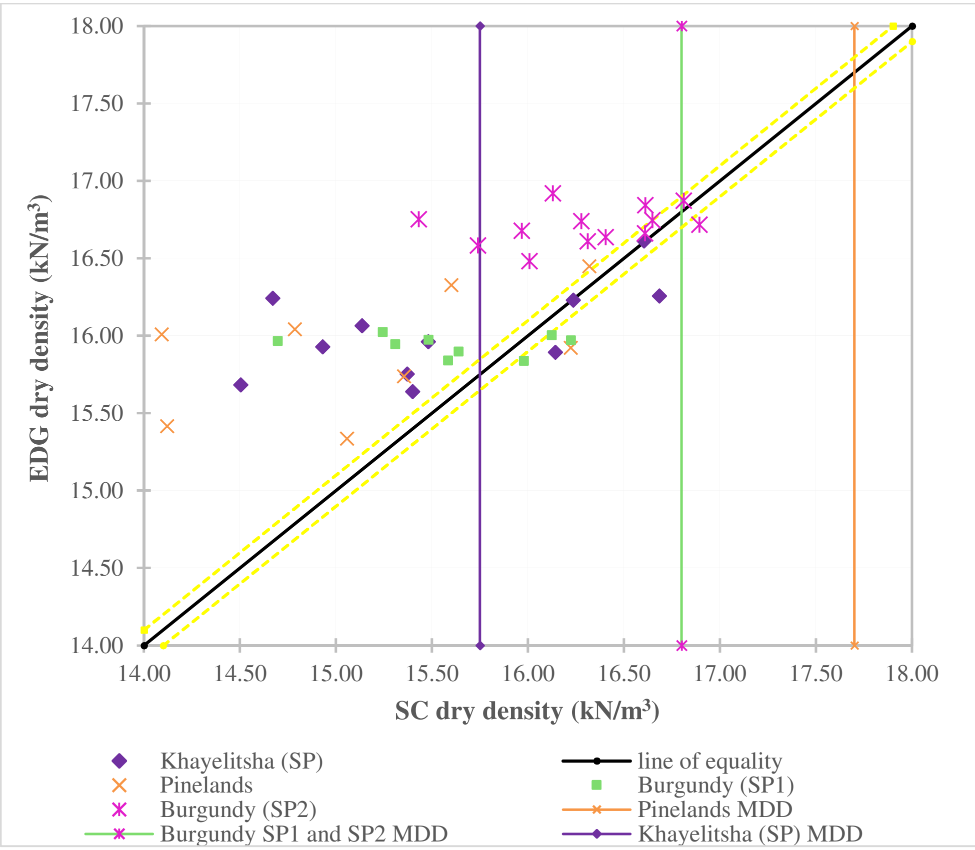


Figure 5-12: Comparison of field measured dry density of the EDG to the SC

Like the EDG bulk density measurements, the dry density measurements were spread from the line of equality especially in the field. In addition, EDG measured dry densities for Klipheuwel sand, Khayelitsha sand, Pinelands gravelly sand, Burgundy sand SP1 and SP2 were independent of those of the SC test considering that the EDG gave consistent dry densities much as the dry densities measured by the SC test varied. These results were similar to those observed by Rathje et al. (2006) for EDG dry density measurements in poorly graded sands. For the Cape Town clayey sand, EDG measured dry densities greater than the MDD were independent of the SC test.

Figure 5-11 and Figure 5-12 showed that EDG dry densities less than the MDD plotted above the line of equality hence were overestimated while dry densities above this point were underestimated. The observed trend was attributed to resistivity being more sensitive to dry density less than the MDD and is stable above MDD (Bai et al. 2013).

Table 5-5 shows the percentage of EDG dry density measurements for each soil within the acceptable band of ± 0.1 kN/m^3.

Table 5-5: Percentage of EDG dry densities within ± 0.1 kN/m^3

SOIIL TYPE	NO. OF POINTS WITHIN ± 0.1 kN/m^3	PERCENTAGE (%)
Klipheuwel (SP)	8	40
Cape Town (SC-CL)	1	6.3
Khayelitsha (SP)	2	18.2
Pinelands	1	12.5
Burgundy sand (SP1)	2	11.1
Burgundy sand (SP2)	3	23.1

From Table 5-5, Klipheuwel sand had the highest percentage (40 %) of points within the acceptable band, followed by Burgundy sand SP2. Cape Town clayey sand had the lowest percentage of acceptable points compared to other soils. Hence, the EDG performed better in the non-cohesive soils than the Cape Town clayey sand.

5.3 Precision of the EDG

Precision is defined as "the closeness of agreement between independent test results under stipulated test conditions" (ASTM E177). EDG precision was determined based on the repeatability limits and t-tests.

5.3.1 Repeatability limits

The repeatability limit, *r* is the value less than which the absolute difference between two test results obtained under repeatability conditions would lie with a probability of approximately

95 % (ASTM E177). The *r* determines both systematic and random error therefore it is a useful statistic when dealing with test-retest reliability for the same method (Bland and Altman, 1986 and 1999). Two measurements were taken for a test spot using the EDG and the *r* calculated using equation 5-1 (ASTM E177). The detailed differences and their standard deviation under repeatability conditions is shown in Appendix E.1.

$$r = 1.96\sqrt{2} \times SD \qquad 5\text{-}1$$

where SD is the standard deviation of the differences between repeated measurements.

Ideally, the *r* should be zero therefore, the closer it is to zero the higher the repeatability of the EDG test with respect to that soil. Table 5-6 shows the SD and *r* of the EDG for moisture content, bulk and dry density measurements.

Table 5-6: Standard deviation and repeatability limits for EDG measurements

	MOISTURE CONTENT (%)		BULK DENSITY (kN/m^3)		DRY DENSITY (kN/m^3)	
Soil type	SD	*r*	SD	*r*	SD	*r*
Klipheuwel (SP)	***0.179***	***0.496***	0.017	0.046	0.012	0.033
Khayelitsha (SP)	***0.120***	***0.332***	***0.039***	***0.107***	***0.052***	***0.144***
Pinelands (G5)	0.020	0.055	0.019	0.053	0.015	0.042
Burgundy (SP1)	0.010	0.028	0.020	0.055	0.020	0.057
Burgundy (SP2)	0.025	0.069	0.019	0.052	0.019	0.054

For moisture content measurements, Burgundy sand (SP1) had the smallest *r* of all the soils tested while Klipheuwel sand had the largest *r*. Therefore, the EDG required a change in moisture content of at least 0.028 % in Burgundy sand SP1 to detect a change in moisture content at the 95 % confidence interval. Any change less than 0.028 % could have been due to inherent test inaccuracy because the EDG could not detect moisture content changes less than 0.028 % in Burgundy sand SP1. Klipheuwel sand required a change of at least 0.496 % for the EDG to detect a change in moisture content reliably at the 95 % confidence level. For both bulk and dry density measurements, the smallest *r* (0.046 and 0.033) was observed in Klipheuwel sand and the largest *r* (0.107 and 0.144) was observed in Khayelitsha sand. Overall, the site at Khayelitsha had the lowest repeatability due to variations in the soil.

In addition, EDG repeatability for moisture content measurement had engineering acceptability as all the *r* were less than 1 % ; moisture content differences between repeated measurements greater than 1 % were taken to be unreliable and therefore engineeringly unacceptable. For bulk and dry density measurements, the repeatability of the EDG was satisfactory for engineering use except for Khayelitsha sand where *r* was greater than 0.1 kN/m^3. Density measurements with differences between repeated measurements greater than 0.1 kN/m^3 were taken to be unreliable and not suitable for replacing sand cone density measurements.

5.3.2 Paired t –test

The two-tailed paired t-test was used to test for statistically significant differences between the average of the reference test measurements (oven moisture content, sand cone bulk and dry density measurements) and the EDG measurements for each soil. The t-test hypothesises that the mean measurements of either test are equal. A *p* value less than 0.05 indicated that the null hypothesis was false and the means of the tests were different at the 5 % level of significance. The t-test provides sound analysis for differences (Romero, 2000); it however does not give any indication of the direction or size of the difference. Therefore, the confidence interval (CI) giving the range of values within which the difference between the test measurements is expected to lie 95 % of the time was calculated using equation 5-2. Nonetheless, it is affected by the sample size and the extent to which data is spread.

$$CI = \bar{d} \pm t_{\alpha/2} \times \sqrt{\frac{SD^2}{n}} \qquad 5\text{-}2$$

where $\bar{d}$ is the mean difference of the two tests with sample size n and standard deviation, SD. $t_{\alpha/2}$ is the t value corresponding to the 5 % level of significance for a two tailed test with $n-1$ degrees of freedom.

5.3.2.1 t-test for moisture content measurements

The average of the difference between oven and EDG moisture content was determined and used to calculate the *p* value, which was used to assess the significance of the differences between the tests. Minitab® 17 a statistical software was used in the analysis of data for the paired t-test. Table 5-7 shows the results obtained from the t-test for the differences. Soils with $p < 0.05$ are bold and italicised in the table. These denoted statistically significant differences between the tests. There was a need to differentiate between statistical significance and engineering relevance. For this study, differences between the oven moisture content and that of the EDG greater than $|1|$ % were unreliable and considered unacceptable for engineering use because ASTM D2216 requires that moisture content is reported to the nearest whole number when using scales weighing to the nearest 0.1 g.

Table 5-7: t-test results for moisture content

SOIL TYPE	*p*-VALUE	NO. OF TESTS	CONFIDENCE INTERVAL (%)	t-TEST	ENGINEERING RELEVANCE
Klipheuwel (SP)	0.831	21	-0.111,0.090	Accept	Accept
Cape Town (SC-CL)	***0.003***	16	-0.764,-0.186	***Reject***	Accept
Khayelitsha (SP)	0.070	11	-0.018,0.388	Accept	Accept
Pinelands (GW-SW)	***0.0001***	8	-0.529,-0.287	***Reject***	Accept
Burgundy (SP1)	0.617	9	-0.139,0.220	Accept	Accept
Burgundy (SP2)	***0.011***	13	0.091,0.586	***Reject***	Accept

From Table 5-7, p values less than 0.05 (in italics and bold) indicated that there was a difference between the average oven measured moisture content and that of the EDG for Cape Town clayey sand, Pinelands gravelly sand and Burgundy sand (SP2). Relative to oven moisture content, EDG moisture content for Cape Town and Pinelands soil were overestimated as shown by the negative confidence interval (CI), while EDG moisture contents for Burgundy sand (SP1) were underestimated as implied by the positive CI for the differences. Hence, the EDG overestimated moisture contents greater than 12 % and underestimated moisture contents lower than 12 % as was observed in the scatter plots. Much as the observed differences for the three soils were statistically significant, they were engineeringly acceptable because the confidence interval for the likely differences did not include 1 %. Hence, EDG moisture content measurement were suitable for use in place of the oven-measured values.

5.3.2.2 t-test for bulk and dry density measurements

Paired t-tests for the difference between sand cone measurements and EDG measurements for bulk density and dry density were computed using Minitab 17® statistical software. Table 5-8 and Table 5-9 show the t-test results for bulk density and dry density mean differences respectively. The p values for the two-tailed paired t-test at the 5 % level of significance were calculated and the values of $p < 0.05$ are bold and italicised in Table 5-8 and Table 5-9. These values were indicative of soils whose EDG average bulk density or dry density was statistically different from that of the sand cone test. To differentiate between statistical significance and engineering relevance, differences greater than 0.1 kN/m^3 were taken to be unacceptable for engineering use and were therefore unreliable because ASTM D1556 requires that the density is reported to three significant figures.

Table 5-8: t-test results for bulk density

SOIL TYPE	*p*-VALUE	NO. OF TESTS	CONFIDENCE INTERVAL (kN/m^3)	t-TEST	ENGINEERING RELEVANCE
Klipheuwel (SP)	0.891	21	-0.190 ,0.167	Accept	***Reject***
Cape Town (SC-CL)	0.562	16	-0.362 ,0.641	Accept	***Reject***
Khayelitsha (SP)	***0.042***	11	-0.922 ,-0.020	***Reject***	***Reject***
Pinelands (G5)	***0.019***	8	-1.482 ,-0.187	***Reject***	***Reject***
Burgundy (SP1)	0.072	9	-0.770 ,0.041	Accept	***Reject***
Burgundy (SP2)	***0.006***	13	-0.621 ,-0.131	***Reject***	***Reject***

Table 5-9: t-test results for dry density

SOIL TYPE	*p*-VALUE	NO. OF TESTS	CONFIDENCE INTERVAL (kN/m^3)	t-TEST	ENGINEERING RELEVANCE
Klipheuwel (SP)	0.730	21	-0.115 ,0.161	Accept	***Reject***
Cape Town (SC-CL)	0.353	16	-0.229 ;0.605	Accept	***Reject***
Khayelitsha (SP)	***0.036***	11	-0.891 ,-0.038	***Reject***	***Reject***
Pinelands (G5)	***0.029***	8	-1.323 ;-0.099	***Reject***	***Reject***
Burgundy (SP1)	0.066	9	-0.735 ;0.029	Accept	***Reject***
Burgundy (SP2)	***0.003***	13	-0.664 ;-0.168	***Reject***	***Reject***

From Table 5-8 and Table 5-9, Khayelitsha, Pinelands and Burgundy sand (SP2) had *p* values less than 0.05 hence EDG bulk and dry density measurements in these soils were statistically different from those of the sand cone test. The negative confidence interval for the mean bulk and dry density differences in these soils showed that the EDG overestimated their densities relative to the sand cone test. EDG measured bulk and dry density measured in Klipheuwel (SP), Cape Town (SC-CL) and Burgundy (SP1) were not statistically different from those of the sand cone test. However, the confidence interval of the differences was greater than the maximum allowable difference ($|0.1|$ kN/m^3) for all the soils. Therefore, the observed differences were engineeringly unacceptable and EDG bulk and dry density measurements were not suitable for use as a replacement for sand cone measurements.

5.4 Accuracy of the EDG

Accuracy is defined as the "closeness of agreement between a test result and the accepted reference value" (ASTM E177). The sand cone bulk and dry density and laboratory oven method moisture content measurements were the reference values for EDG test results. The accuracy of the EDG was determined based on the variation of its values from the reference values. Passing and Bablok regression together with Bland and Altman plots were used to determine the existence of bias between the EDG measurements for moisture content, bulk density, dry density and those of the oven and sand cone. Lastly, the extreme spread of variation of the measurements was calculated and the performance of the EDG ranked for the soils tested. Each of these methods is discussed in detail in the following sections.

5.4.1 Passing and Bablok regression

The Passing and Bablok regression method determines the ability of two measurement methods to measure the same parameter or the presence of a systematic difference (Passing and Bablok, 1983 and 1984). Unlike ordinary regression that assumes an error-free independent variable and normally distributed error terms, the Passing and Bablok regression method does not. The sand cone test is prone to human errors (Ishai and Livneh, 1983) and inaccurate results are obtained when the SC test is used in gravelly soils (GTI, 2004). Hence, the Passing and Bablok regression method was deemed suitable for the analysis.

Two tests X and Y whose structural linear relationship is defined by $y_i^* = b + mx_i^*$ are considered, where y_i^* and x_i^* are the expected values for the sample, b is the intercept and m is the slope of the line. The Passing and Bablok regression method estimates the slope and intercept of the line and uses the Cusum linearity test to assess the hypothesis of a linear relationship between X and Y at the 5 % level of significance such that a p value less than 0.05 is indicative of it being non-linear. The regression method also checks for the hypothesis that the linear relationship is defined by $y = x$.

Using the calculated confidence intervals for m and b, the hypothesis that $m = 1$ and $b = 0$ is verified. If the confidence interval includes one for the slope and zero for the intercept, then the hypothesis that $y = x$ is accepted and the measurements of the two methods are equal. Otherwise, the methods would be biased relative to each other. The slope of the line indicates the amount of proportional bias, while the intercept of the line indicates the amount of constant bias. XLSTAT-Life (2015) a Microsoft EXCEL-add in was used to analyse the data.

5.4.1.1 Moisture content analysis

EDG measured moisture content was plotted against oven measured moisture content and tested for linearity. Figure 5-13 shows the Passing and Bablok plots for moisture content measured during the study. The dashed black line represents the line of equality on which all the points would plot if the EDG measured moisture content was equal to that of the oven. The solid red line is the Passing and Bablok hypothesised model regression line based on the collected data. Table 5-10 shows the values for the slope and intercept of the regression line, together with the upper and lower boundaries for the 95 % confidence interval (CI).

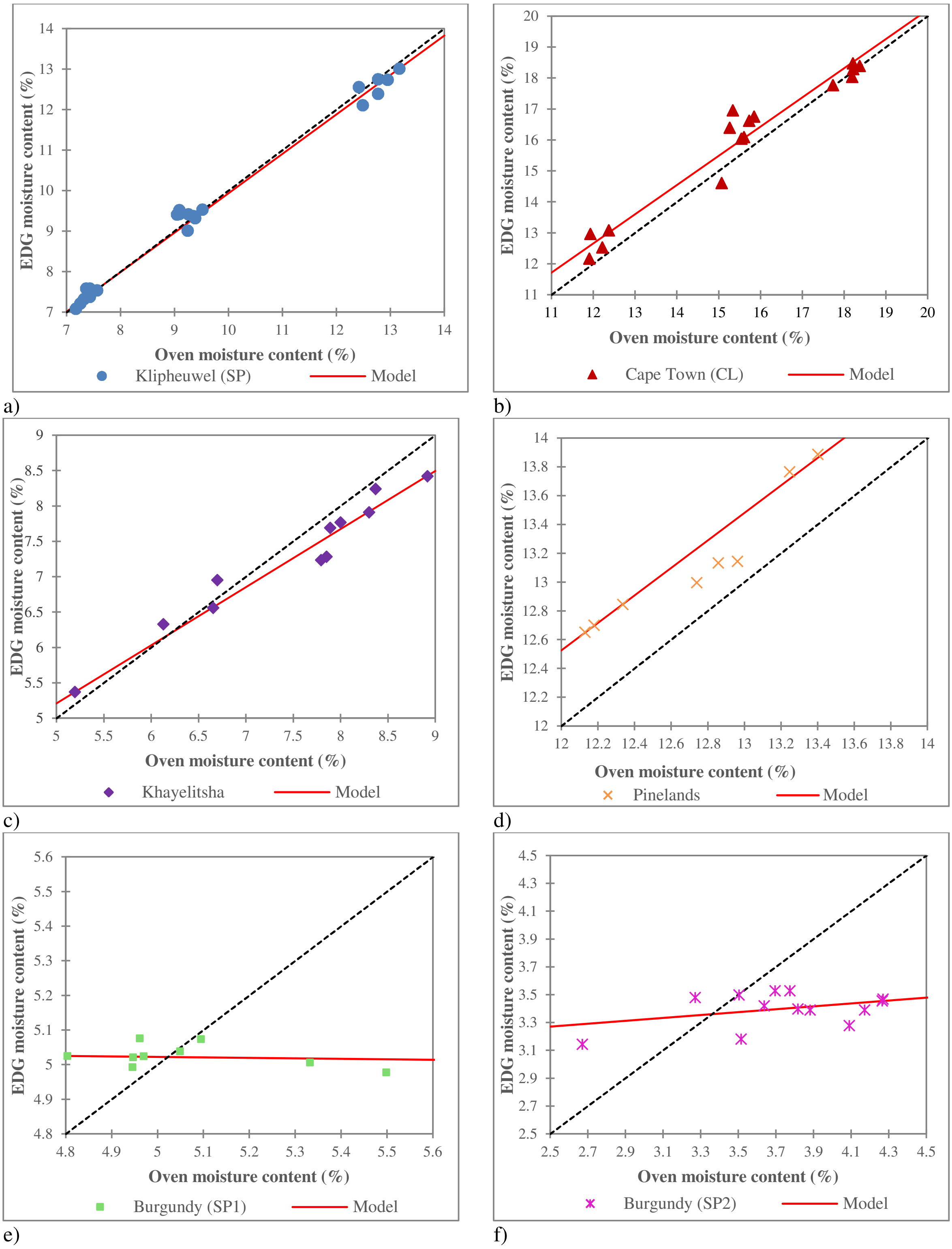


Figure 5-13: Passing and Bablok regression models for moisture content measurements

Table 5-10: Model coefficients and confidence intervals for EDG measured moisture content

SOIL TYPE	*P*-VALUE FOR LINEARITY	MODEL COEFFICIENTS				SIGNIFICANCE (y=x)
			Value	Lower bound (95 %)	Upper bound (95 %)	
Klipheuwel (SP)	0.587	Intercept	0.197	-0.282	0.668	Accept
		Slope	0.974	0.931	1.033	Accept
Cape Town (SC-CL)	0.088	Intercept	1.358	-1.634	3.443	Accept
		Slope	0.942	0.810	1.147	Accept
Khayelitsha (SP)	1.00	Intercept	1.104	-0.645	2.104	Accept
		Slope	0.821	0.700	1.056	Accept
Pinelands	0.699	Intercept	1.069	-4.127	5.844	Accept
		Slope	0.955	0.565	1.347	Accept
Burgundy (SP,1)	0.699	Intercept	*5.090*	***3.052***	***5.604***	**Reject**
		Slope	*-0.013*	***-0.114***	***0.397***	**Reject**
Burgundy (SP,2)	0.441	Intercept	*3.011*	***2.004***	***3.844***	**Reject**
		Slope	*0.104*	***-0.111***	***0.365***	**Reject**

The p values (p >0.05) in second column of Table 5-10, showed that a linear relationship between EDG and oven measured moisture content was detected by the Cusum linearity test for all the soils tested. The confidence intervals for the intercept and slope of the line defining the relationship between EDG and oven moisture content measurements for Klipheuwel (SP), Cape Town (SC-CL), Khayelitsha (SP) and Pinelands included a value of zero for the intercept and one for the slope, therefore $y = x$ and EDG measurements for moisture in these soils were equal to those of the oven.

The EDG moisture contents for Burgundy, SP1 and SP2 were not equal to those of the oven because neither of the confidence interval for their slopes ((-0.114, 0.397) and (-0.111, 0.365)) included one nor did that of their intercepts ((3.052, 5.604) and (2.004, 3.844)) include zero, hence $y \neq x$. The Passing and Bablok regression for EDG measured moisture content in Burgundy sand SP1 $(n = 9)$ showed a proportional bias of -0.013 and a constant bias of 5.090 while Burgundy sand SP2 $(n = 13)$ had a proportional bias of 0.104 and a constant bias of 3.011 as determined from the slope and intercept of the regression line. Therefore, EDG moisture content measurements for soils whose calibration soil model fit was less than 0.5 were unreliable for replacing oven measurements. This was in agreement with the results observed in section 5.2.1.

5.4.1.2 Bulk density analysis

EDG measured bulk density was plotted against sand cone (SC) measured bulk density. Figure 5-14 shows the Passing and Bablok plots for bulk density measurements of the soils tested. The solid red line represents the Passing and Bablok regression model line and the dashed black line represents the line of equality along which all EDG bulk densities would plot if they were equal to those of the SC. Table 5-11 shows the values for the intercept and slope of the regression line, and their upper and lower boundaries at the 95 % confidence interval.

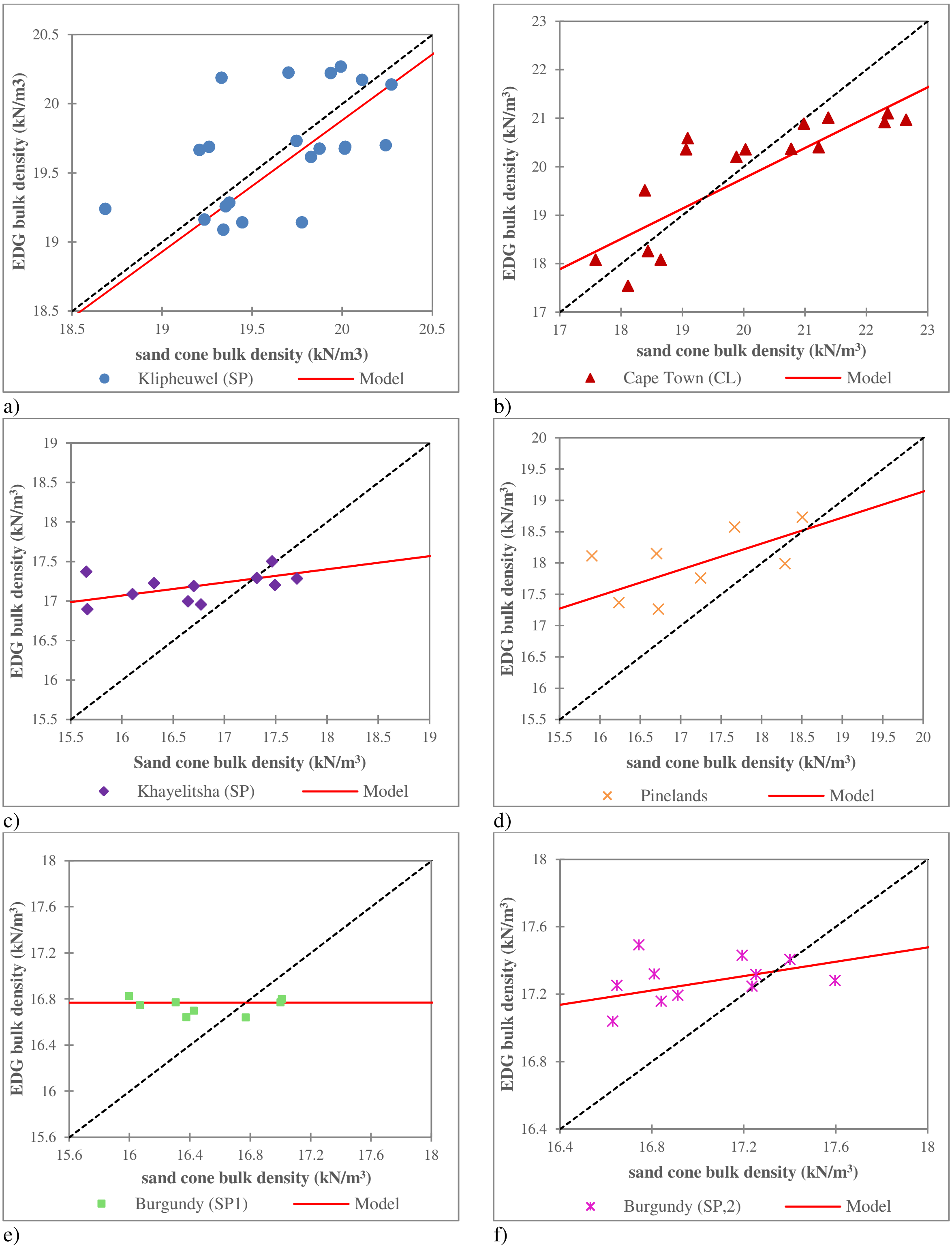


Figure 5-14: Passing and Bablok regression models for bulk density measurements

Table 5-11: Model coefficients and their confidence intervals for EDG measured bulk density

SOIL TYPE	*P*-VALUE FOR LINEARITY	MODEL COEFFICIENTS				SIGNIFICANCE (y=x)
			Value	Lower bound (95 %)	Upper bound (95 %)	
Klipheuwel (SP)	0.988	Intercept	0.859	-13.127	8.368	Accept
		Slope	0.951	0.569	1.666	Accept
Cape Town (CL)	0.270	Intercept	7.257	-0.607	14.190	Accept
		Slope	0.625	0.301	1.017	Accept
Khayelitsha (SP)	1.000	Intercept	**14.425**	***11.345***	***17.991***	***Reject***
		Slope	**0.165**	**-0.047**	**0.350**	**Reject**
Pinelands	1.000	Intercept	10.843	-11.059	18.924	Accept
		Slope	0.415	-0.051	1.685	Accept
Burgundy (SP,1)	0.699	Intercept	**16.760**	***13.825***	***19.152***	***Reject***
		Slope	**0.000**	**-0.149**	**0.175**	**Reject**
Burgundy (SP,2)	1.000	Intercept	**13.655**	***9.144***	***17.491***	***Reject***
		Slope	**0.212**	**-0.012**	**0.476**	**Reject**

The p values (p >0.05) in the second column of Table 5-11 for the Cusum linearity test, showed that all EDG bulk density measurements varied linearly with those of the sand cone. The confidence interval (CI) for the slopes and intercept of Klipheuwel, Cape Town clayey sand and Pinelands all included values of 1 for the slope and 0 for the intercept at the 5 % level of significance. Therefore, $y = x$ and EDG bulk density measurements in these soils were equal to those of the sand cone.

The 95 % CI for the slope and intercept of the linear relationship between EDG bulk density measurements and those of the sand cone for Khayelitsha (SP) and Burgundy, SP1 and SP2 did not include one and zero respectively. Table 5-11 shows the 95 % CI for the slope in bold and the intercept in bold and italics for Khayelitsha, Burgundy sand SP1 and SP2. The EDG measurements for these soils were biased relative to those of the sand cone. The amount of proportional bias was equal to the slope of the regression line, while the amount of constant bias was equal to the intercept of the line. Therefore, EDG bulk density measurements in Khayelitsha had constant bias of 14.425 and proportional bias of 0.165, while those in Burgundy sand SP1 had constant bias of 16.76 and no proportional bias and those for Burgundy sand SP2 had constant bias of 13.655 and proportional bias of 0.212.

5.4.1.3 Dry density analysis

EDG measured dry density was plotted against sand cone dry density that was calculated by substituting the bulk density measured using the sand cone and oven measured moisture content in equation 3-2. Figure 5-15 shows the Passing and Bablok plots for dry density of the soils tested. The solid red line represents the Passing and Bablok model regression line and the dashed black line represents the line of equality. Table 5-12 shows the values for the model coefficients and the confidence interval for the intercept and slope of the model.

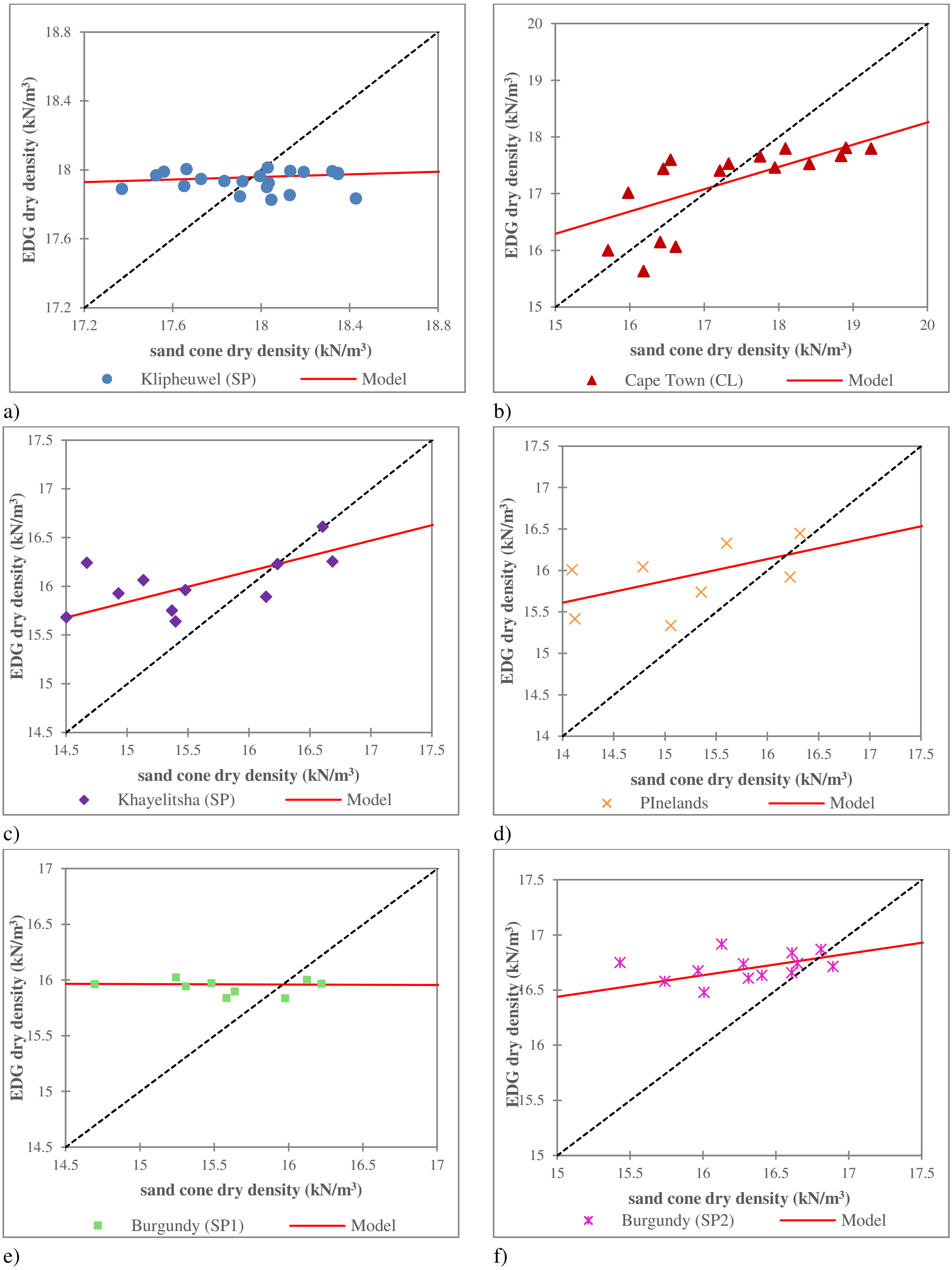


Figure 5-15: Passing and Bablok regression models for dry density measurements

Table 5-12: Model coefficients and their confidence intervals for EDG measured dry density

SOIL TYPE	*P*-VALUE FOR LINEARITY	MODEL COEFFICIENTS				SIGNIFICANCE (y=x)
			Value	Lower bound (95 %)	Upper bound (95 %)	
Klipheuwel (SP)	0.400	Intercept	17.280	15.330	19.261	**Reject**
		Slope	0.038	-0.074	0.146	**Reject**
Cape Town (CL)	0.270	Intercept	10.392	2.322	14.471	**Reject**
		Slope	0.393	0.170	0.850	**Reject**
Khayelitsha (SP)	0.164	Intercept	11.097	5.503	15.044	**Reject**
		Slope	0.316	0.059	0.669	**Reject**
Pinelands	1.000	Intercept	11.923	-4.987	17.241	**Reject**
		Slope	0.263	-0.084	1.358	**Reject**
Burgundy (SP,1)	0.699	Intercept	16.033	13.243	18.672	**Reject**
		Slope	-0.005	-0.177	0.171	**Reject**
Burgundy (SP,2)	0.441	Intercept	13.493	9.771	16.794	**Reject**
		Slope	0.196	-0.005	0.422	**Reject**

The relationship between EDG measured dry density and that of the sand cone (SC) was linear as shown by the *p* values for the Cusum linearity test which are greater than 0.05 (second column of Table 5-12). The Passing and Bablok regression method showed that EDG dry density measurements were not equal to those of the SC based on the confidence interval (CI) for the slope and intercept of the model line. All the slope CIs did not include one and the intercept CIs did not include zero, therefore the EDG dry densities had both constant bias (equal to the intercept value of the line) and proportional bias (equal to the slope of the line).

EDG dry density measurements for all the soils were found to vary significantly from those of the SC based on the Passing and Bablok regression method. Therefore, the measurements were rejected even though both the EDG measured moisture content and bulk density for some of the soils, such as Klipheuwel sand, were found to be acceptable. The Passing and Bablok model for EDG measured moisture content and bulk density in Klipheuwel were found to lie closer to the line of equality as compared to the EDG dry density Passing and Bablok model. This could be attributed to the high spread of bulk density measurements observed in the model.

5.4.2 Variation of EDG measurements

To determine the variation of EDG measurements the absolute difference between the reference measurements (sand one and oven) and EDG measurements was determined (see APPENDIX E for the detailed results). The standard deviation of the soils was plotted against the absolute difference. Standard deviation (SD) is a measure of the extent to which points deviate from the centre. If the majority of values are close to the mean, the SD is smaller and vice versa.

5.4.2.1 Moisture content variation

The standard deviation of EDG moisture content measurements and the absolute difference between oven measured moisture content and that of the EDG was calculated for each soil tested to determine the variation of EDG measurements. Figure 5-16 shows a plot of the absolute moisture content differential variation for the EDG from the laboratory oven method.

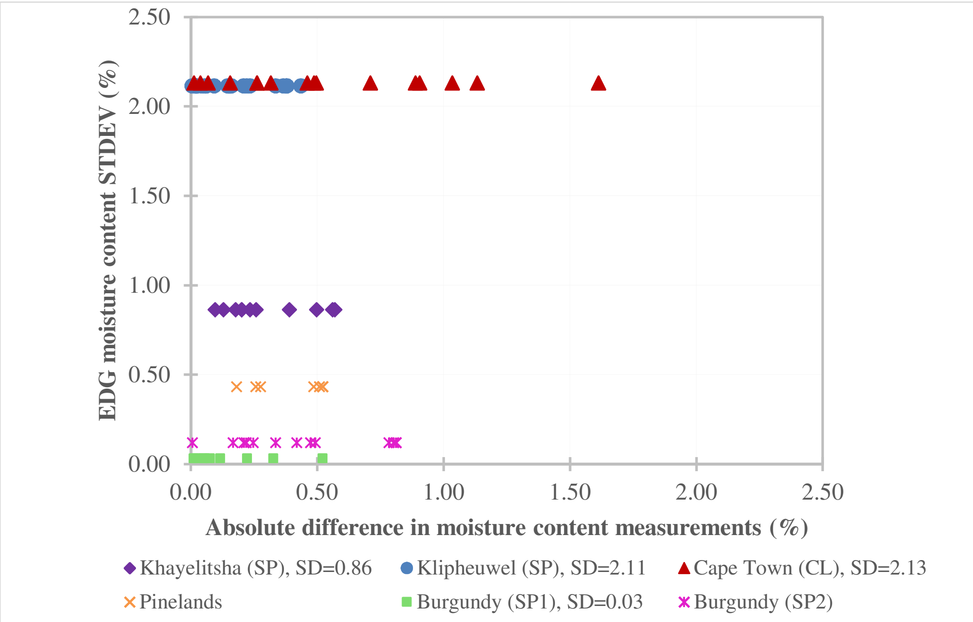


Figure 5-16: Absolute moisture content differential variation for the EDG

From Figure 5-16, higher standard deviations were observed in the laboratory as compared to the field. This was because a wider range of moisture contents (approximately 6 %) was measured in the laboratory compared to the field. Accordingly, Burgundy sands, SP1 with a moisture content range of 0.1 % and Burgundy sand SP2 with a moisture content range of 0.3 % had the lowest standard deviation. The detailed results showing the range for the measurements are shown in APPENDIX D.

EDG measured moisture content in Cape Town (CL) varied the most from that of the oven with differences greater than 1 % when compared to the other soils. These results are similar to those observed by Rathje et al. (2006). They observed that the EDG performed poorly in highly plastic soils. Taking difference less than 1 % to be engineeringly acceptable, EDG measured moisture content in Klipheuwel sand, Pinelands, Khayelitsha sand, Burgundy sand SP1 and SP2 were acceptable and suitable for compaction measurement. Therefore, the EDG performed well for moisture content measured in non-cohesive soils. However, only one non-cohesive soil was tested in the study so the results are inconclusive for cohesive soils.

5.4.2.2 Bulk and dry density variation

The standard deviation of EDG densities for the study materials was plotted against the absolute difference between the SC measured density and that of the EDG. Figure 5-17 and Figure 5-18 show the absolute bulk density and dry density differentials between the sand cone and EDG.

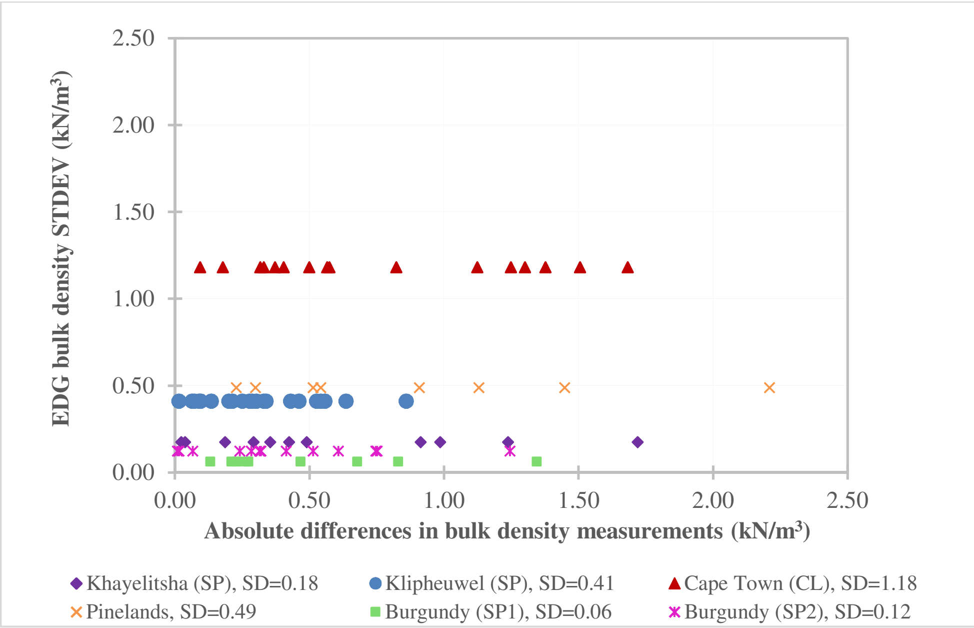


Figure 5-17: Absolute bulk density differential variation for the EDG

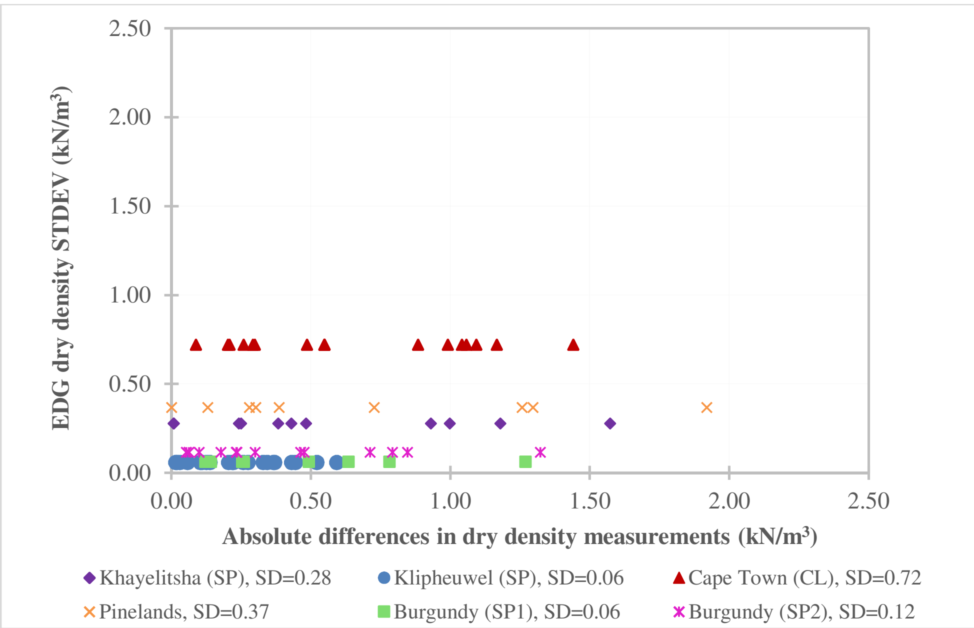


Figure 5-18: Absolute dry density differential variation for the EDG

For density measurements, there was no clear distinction between tests conducted in the laboratory and those in the field. Cape Town (CL) had the highest standard deviation because its densities deviated the most from the mean. The non-cohesive soils had lower standard deviations because the EDG measured density was consistent and therefore independent of that measured by the sand cone. Hence, EDG bulk densities in the non-cohesive soils did not vary greatly from the mean.

Figure 5-17 and Figure 5-18 showed that the highest spread of differences for EDG bulk density and dry density from the sand cone was observed at Pinelands, followed by Khayelitsha and Cape Town (CL) and the lowest differences were found in Klipheuwel (SP).

5.4.3 Error analysis using the Bland and Altman analysis

The Bland and Altman (*B and A*) analysis computes the agreement between two quantitative measurements based on the average difference between the methods and the limits of agreement (Bland and Altman, 1986). The method comprises a *B and A* scatter plot in which the y-axis shows the difference between the paired measurements for the tests and the x-axis represents the average of the paired measurements. However, for this study the reference test measurements (sand cone bulk and dry density and oven moisture content) were taken as the reference measurements, and the average of the EDG and reference tests (sand cone and oven) was not used.

The average bias between the two tests is estimated from the mean of the differences between the tests provided the differences are not related to the magnitude of the measurements. On the scatter plot, lines for the 95 % confidence interval (CI) for the bias and the limits of agreement (*LoA*) are also shown. Equation 5-2 was used to determine the CI for the bias, and equation 5-3 was used to determine the *LoA* that were used to estimate the interval within which 95 % of the differences for the EDG relative to the reference tests fell. Based, on the expected range of differences inference was made as to the suitability of the EDG for replacement of the reference tests. XLSTAT 2015, a Microsoft EXCEL add-in was used in the analysis and plotting of the data.

$$LoA = \bar{d} \pm (1.96 \times SD) \qquad 5\text{-}3$$

where LoA - limits of agreement, $\bar{d}$ is the mean difference, and SD is the standard deviation.

5.4.3.1 Moisture content analysis

The difference between oven moisture content and that of the EDG was calculated. From this, the average difference and its 95 % CI as well as the *LoA* for the EDG moisture content were determined and used to draw the Bland and Altman plots shown in Figure 5-19 for all the soils. In the plot, the solid blue line represents the average difference (bias), the dashed blue lines represent the 95 % CI for the bias, and lastly the dotted red lines represent the 95 % CI for the *LoA*. Table 5-13 provides a summary of these values for each soil tested.

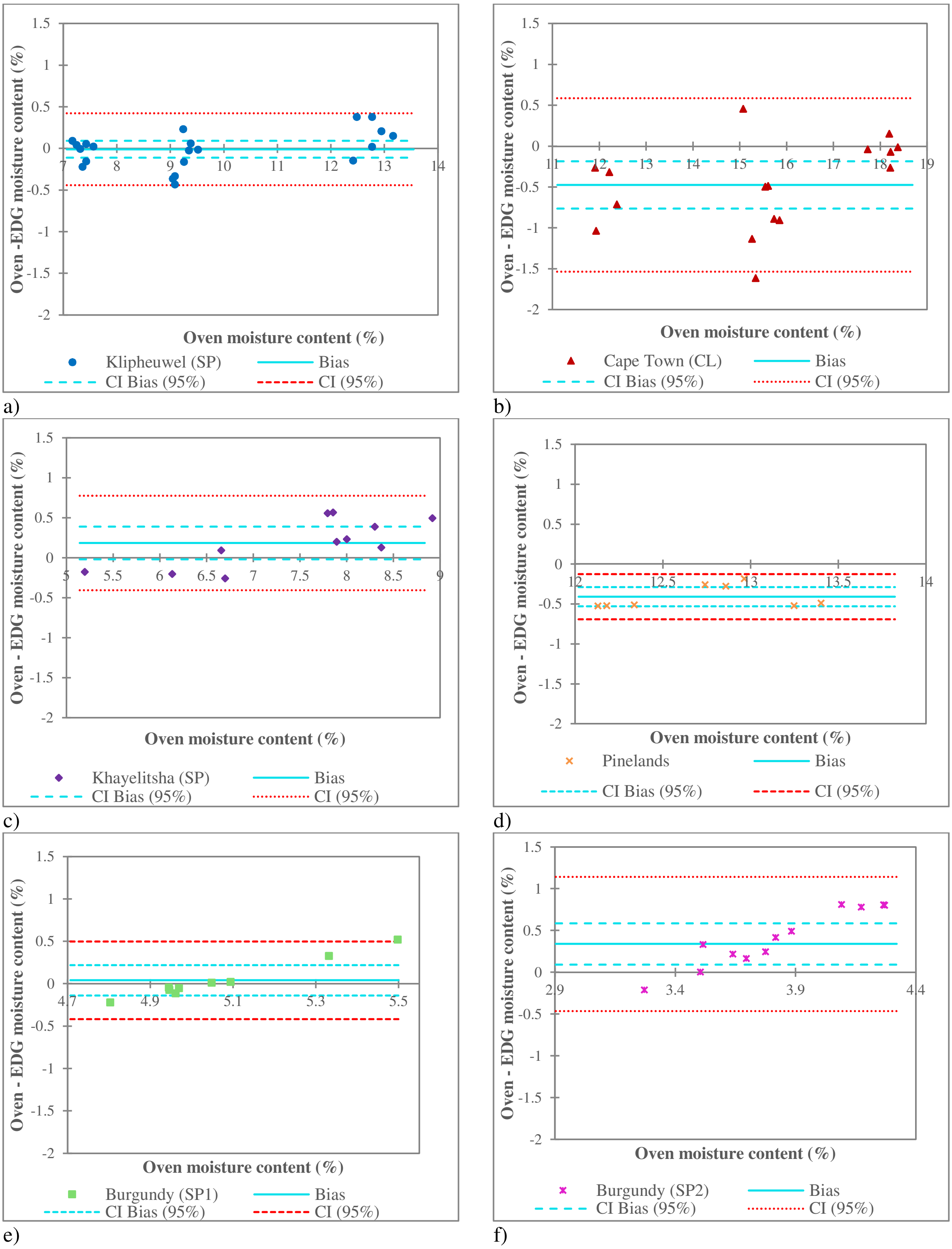


Figure 5-19: Bland and Altman plots for EDG moisture content measurements

The Bland and Altman plots in Figure 5-19 showed the difference between oven moisture content and that of the EDG to increase positively with increasing moisture content for the poorly graded sands. However, the trend was less pronounced for Pinelands and Cape Town CL.

Table 5-13: Bias, confidence interval of the bias and the confidence interval of the moisture content differences for the Bland and Altman plots shown in Figure 5-19

SOIL TYPE	BIAS (%)	CONFIDENCE INTERVAL OF BIAS (%)	LIMITS OF AGREEMENT (%)
Klipheuwel (SP)	-0.010	-0.111 ,0.090	-0.443 ,0.422
Cape Town (CL)	-0.475	-0.764 ,-0.186	-1.537 ,0.587
Khayelitsha (SP)	0.185	-0.018, 0.388	-0.407, 0.778
Pinelands	-0.408	-0.529 ,-0.287	-0.692 ,-0.124
Burgundy (SP1)	0.040	-0.139 ,0.220	-0.417 , 0.498
Burgundy (SP2)	0.339	0.091,0.586	-0.463 ,1.141

From Table 5-13, the largest bias was observed in Cape Town clayey sand (-0.475) followed by Pinelands gravelly sand (-0.408) which meant that on average the EDG overestimated the moisture content in these soils. Therefore, 95 % of the time the EDG measured moisture content would be 1.537 greater and 0.587 less than that of the oven for Cape Town (CL), and at most 0.692 or at least 0.124 greater than that of the oven for Pinelands. From Figure 5-19, 6.25 % (1/16) of the measurements for Cape Town CL were outside the limits of agreement (*LoA)*.

The lowest bias was observed in Klipheuwel SP (-0.010) followed by Burgundy sand SP1 (0.040) which implied that the EDG overestimated the moisture content for Klipheuwel and underestimated that for Burgundy sand SP1. The *CIs* for the *LOA* were less than the maximum allowable difference for moisture content (1 %) except for Cape Town CL hence moisture content measurements in Cape Town CL would require caution in using them as they could differ by more than 1 %.

5.4.3.2 Bulk density analysis

The difference between SC bulk density and EDG bulk density was determined. From this, the average difference, its confidence interval and limits of agreement for the EDG bulk density was determined and used to plot the Bland and Altman plots shown in Figure 5-20 for all the soils. The solid blue line represents the average difference (bias), the dashed blue lines represent the 95 % confidence interval (CI) of the bias and the dotted red lines represent the limits of agreement in which the differences were expected to fall 95 % of the time. Table 5-14 provides a summary of the corresponding values for the study materials.

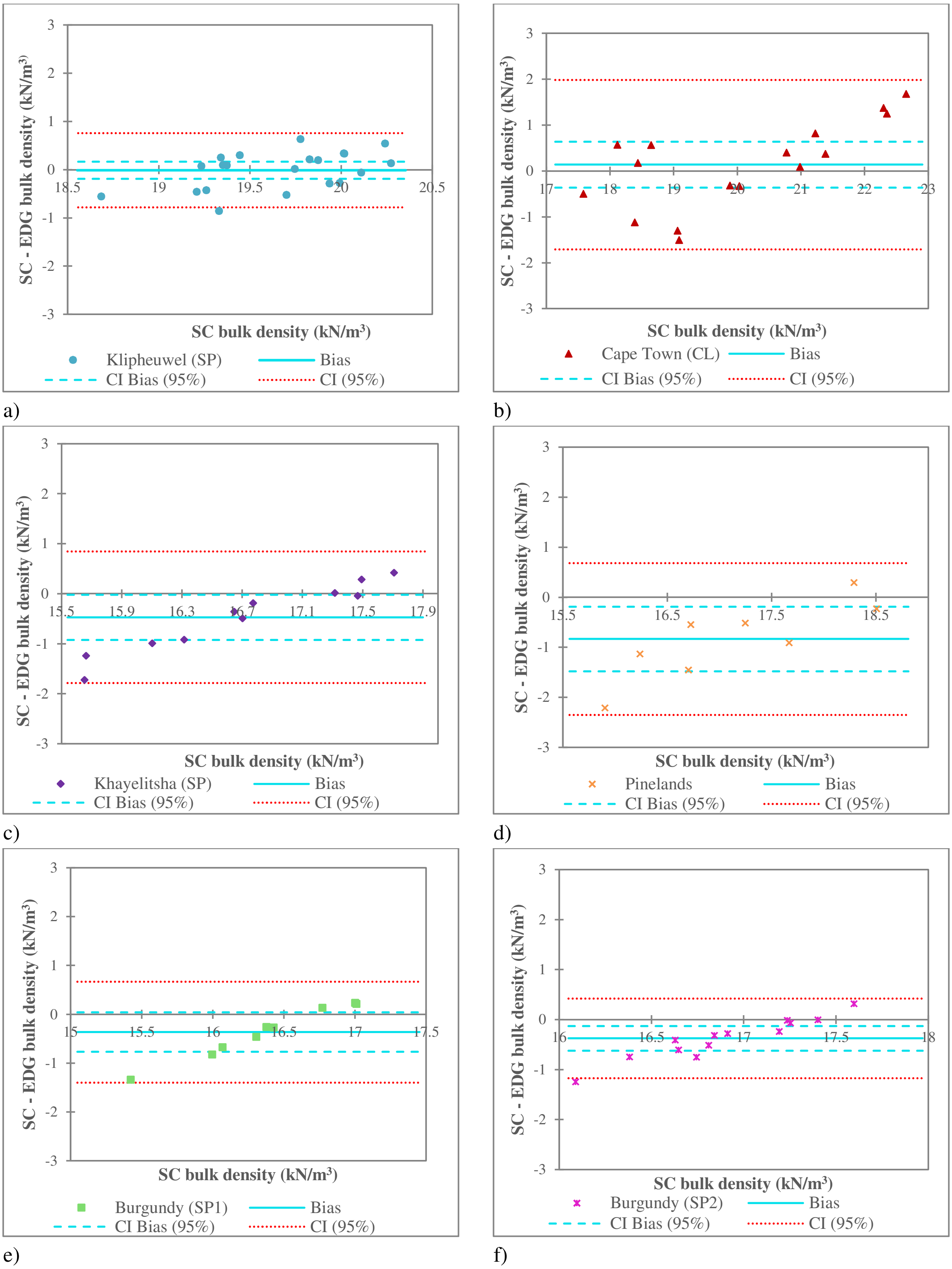


Figure 5-20: Bland and Altman plots for bulk density measurements for the soils tested

Table 5-14: Bias, confidence interval of the bias and the confidence interval of the bulk density differences for the Bland and Altman plots shown in Figure 5-20

SOIL TYPE	BIAS (kN/m^3)	CONFIDENCE INTERVAL OF BIAS (kN/m^3)	CONFIDENCE INTERVAL OF DIFFERENCES (kN/m^3)
Klipheuwel (SP)	-0.012	-0.190 ,0.167	-0.780, 0.756
Cape Town (CL)	0.140	-0.362 ,0.641	-1.706, 1.985
Khayelitsha (SP)	-0.471	-0.922 ,-0.020	-1.787,-0.845
Pinelands	-0.834	-1.482 ,-0.187	-2.353,0.684
Burgundy (SP1)	-0.365	-0.770 ,0.041	-1.399, 0.670
Burgundy (SP2)	-0.376	-0.621 ,-0.131	-1.170, 0.419

From second column of Table 5-14, the lowest bias was observed in Klipheuwel (-0.012) and the highest bias was observed in Pinelands (-0.834). Overall, the EDG overestimated the bulk density in the non-cohesive soils as shown by the negative bias and underestimated that of Cape Town (CL). The largest limits of agreement were observed for Cape Town CL (-1.706, 1.985) and Pinelands (-2.353, 0.684). Hence 95 % of the time, EDG bulk density measurements for Cape Town CL were likely to be underestimated by 1.985 kN/m^3 and overestimated by 1.706 kN/m^3, and those for Pinelands were likely to be overestimated by 2.353 kN/m^3 and underestimated by 0.684 kN/m^3. Based, on the calculated limits of agreement, EDG bulk density was not suitable for use in place of the sand cone bulk density.

The Bland and Altman plots in Figure 5-20 showed the difference between the SC and EDG bulk density to increase positively with increasing bulk density. The clusters in the plots for Klipheuwel sand (a) and Cape Town CL (b) showed that the increase in bulk density was also a function of the moisture content of the soil. Figure 5-21 and Figure 5-22 show the relation between the difference of SC and EDG bulk density and the moisture content of the soil for Klipheuwel sand and Cape Town CL for the three moisture contents at which the soils were tested. The plots showed that the difference between SC bulk density and that of the EDG increased positively with increasing bulk density but was also affected by the moisture content of the soil. Beck et al (2013) and Toll and Hassan (2015) found resistivity to decrease with increasing dry density for a particular moisture content therefore the relationship is dependent on the moisture content at which it is measured.

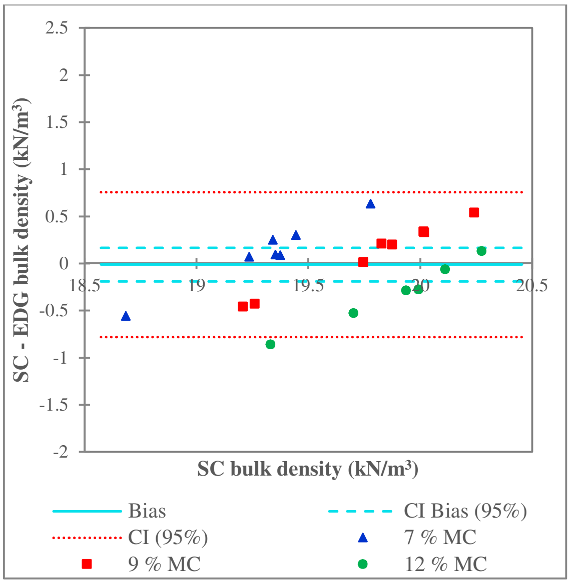


Figure 5-21: Bland and Altman plot showing variation of bulk density differences with moisture content for Klipheuwel

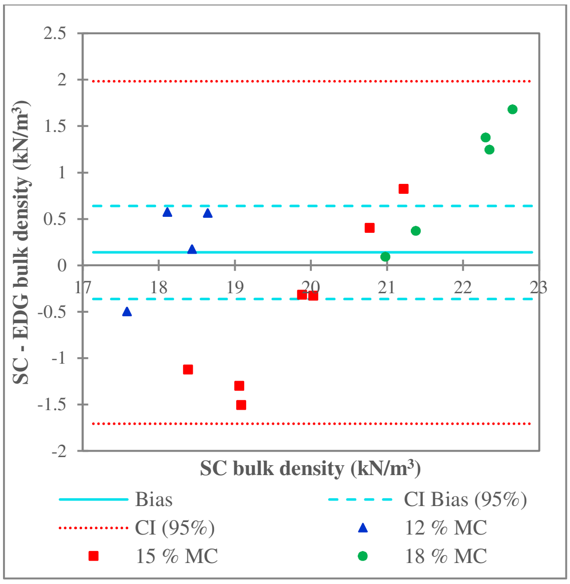


Figure 5-22: Bland and Altman plot showing variation of bulk density differences with moisture content for Cape Town (CL)

5.4.3.3 Dry density

The difference between SC dry density and EDG dry density was computed. From this, the average difference and limits of agreement for the EDG dry density were determined and used to plot the Bland and Altman plots shown in Figure 5-23 for all the soils. The solid blue line represents the average difference (bias), the dashed blue lines represent the 95 % confidence interval (CI) of the bias and the dotted red lines represent the limits of agreement in which the differences were expected to lie 95 % of the time. Table 5-15 provides a summary of the corresponding values for the study materials.

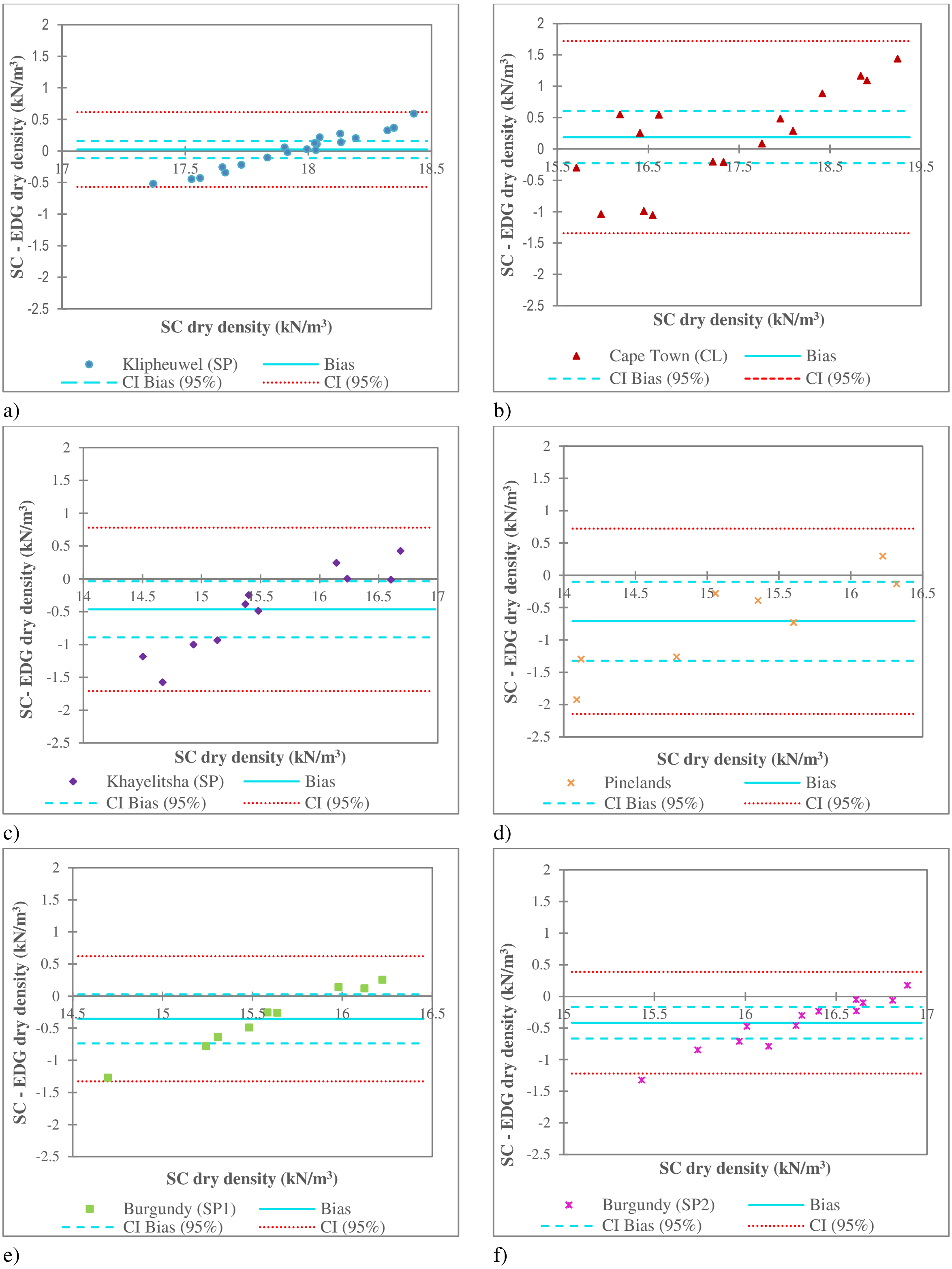


Figure 5-23: Bland and Altman plots for dry density measurements for the soils tested

Table 5-15: Bias, confidence interval of the bias and the confidence interval of the bulk density differences for the Bland and Altman plots shown in Figure 5-23

SOIL TYPE	BIAS	CONFIDENCE INTERVAL OF BIAS	CONFIDENCE INTERVAL OF DIFFERENCES
Klipheuwel (SP)	0.023	-0.115 ,0.161	-0.569,0.615
Cape Town (CL)	0.188	-0.229 ;0.605	-1.346, 1.721
Khayelitsha (SP)	-0.464	-0.891 ,-0.038	-1.708,0.780
Pinelands	-0.711	-1.323 ;-0.099	-2.146, 0.724
Burgundy (SP1)	-0.353	-0.735 ;0.029	-1.327, 0.621
Burgundy (SP2)	-0.416	-0.664 ;-0.168	-1.222, 0.390

From Table 5-15, the largest bias (-0.711) and limits of agreement (-2.146, 0.724) were observed at Pinelands, and the lowest bias (0.023) and limits of agreement (-0.569, 0.615) were observed in Klipheuwel sand. The Bland and Altman plots (Figure 5-23) showed the difference between the SC and EDG dry density to increase positively as the dry density increased. For all the soils tested, the limits of agreement indicated that the expected difference between sand cone dry density and that of the EDG was likely to be more than the maximum allowable difference (0.1 kN/m^3) for density 95 % of the time. Hence, EDG dry density measurements were not suitable for replacing the sand cone results.

5.4.4 Extreme spread of variation

The deviation of EDG measured values from those of the reference tests is an indicator of the test's performance (Mejias-Santiago et al., 2013a). Mejias-Santiago et al. (2013b) determined the accuracy of devices from the extreme spread of variation. This involved determining the percent deviation of reference test measurements from those of the EDG using equation 5-4.

$$\%\, deviation = (Reference\ test_{measurement} - EDG_{measurement})/Reference\ test_{measurement} \qquad 5\text{-}4$$

Next, the average of the percentage deviation greater than zero (AVG_{HI}) and that less than zero (AVG_{LO}) was determined and the absolute difference between the two determined. This gave an indication of the spread of variability. Equations 5-5 to 5-7 were used to calculate the average percentage deviation and their absolute difference (AVGSpread).

$$AVG_{HI} = \sum(\%\, deviation > 0)/number\_of\_samples \qquad 5\text{-}5$$

$$AVG_{LO} = \sum(\%deviation < 0)/number\_of\_samples \qquad 5\text{-}6$$

$$AVGSpread = |AVG_{HI} - AVG_{LO}| \qquad 5\text{-}7$$

After the absolute difference was determined, the range of the extreme positive and negative deviation was determined to obtain a measure of accuracy. The lower the value the more accurate the EDG was for that soil. Table 5-16, Table 5-17 and Table 5-18 show the percentage average spread and the range of percentage deviation for moisture content, bulk density and dry density respectively for the soils tested.

Table 5-16: Percentage average spread and the range of percentage deviation for moisture content

SOIL TYPE	AVG_{HI} (%)	AVG_{LO} (%)	AVGSpread (%)	Max-Min DEVIATION (%)
Klipheuwel (SP)	1.36	-2.09	3.45	7.80
Cape Town (CL)	1.95	-4.06	6.01	13.56
Khayelitsha (SP)	4.14	-3.50	7.64	11.08
Pinelands (G5)	0	-3.22	3.22	4.30
Burgundy (SP1)	4.04	-2.10	6.14	14.07
Burgundy (SP2)	11.51	-12.04	23.55	37.54

Table 5-17: Percentage average spread and the range of percentage deviation for bulk density

SOIL TYPE	AVG_{HI} (%)	AVG_{LO} (%)	AVGSpread (%)	Max-Min DEVIATION (%)
Klipheuwel (SP)	1.24	-2.23	3.47	7.65
Cape Town (CL)	3.43	-4.48	7.91	15.31
Khayelitsha (SP)	1.39	-4.62	6.01	13.37
Pinelands (G5)	1.63	-6.01	7.64	15.53
Burgundy (SP1)	1.12	-4.04	5.16	10.07
Burgundy (SP2)	1.78	-2.62	4.40	9.51

Table 5-18: Percentage average spread and the range of percentage deviation for dry density

SOIL TYPE	AVG_{HI} (%)	AVG_{LO} (%)	AVGSpread (%)	Max-Min DEVIATION (%)
Klipheuwel (SP)	1.19	-1.66	2.85	6.21
Cape Town (CL)	3.73	-3.86	7.59	14.00
Khayelitsha (SP)	1.38	-4.86	6.24	13.28
Pinelands (G5)	1.86	-5.87	7.73	15.47
Burgundy (SP1)	1.07	-4.06	5.13	10.20
Burgundy (SP2)	1.04	-2.92	3.96	9.61

Using the calculated percentage average spread and the range of deviation the performance of the EDG for moisture content, bulk and dry density measurement was ranked for the soils tested. The average spread and the range of deviation increased in the same order for the soils. Hence, the performance was ranked from 1 having the minimum value for average spread and range of deviation to 6 having the maximum value for average spread and range of deviation. The rankings for the soils are shown in Table 5-19.

Table 5-19: Ranking of EDG measurements for the soils tested

SOIL TYPE	MOISTURE CONTENT	BULK DENSITY	DRY DENSITY	SUMMATION OF THE RANKS	PERFORMANCE RANKING
Klipheuwel (SP)	2	1	1	**4**	**1**
Cape Town (CL)	4	6	5	**15**	**6**
Khayelitsha (SP)	3	4	4	**11**	**3**
Pinelands (G5)	1	5	6	**12**	**5**
Burgundy (SP1)	5	3	3	**11**	**3**
Burgundy (SP2)	6	2	2	**10**	**2**

Table 5-19 showed that fine-grained non-cohesive soils had low scores for deviation and therefore ranked highly in terms of performance. Hence, the EDG had high accuracy in the fine-grained non-cohesive soils (Klipheuwel, Burgundy (SP1), Khayelitsha and Burgundy (SP2)). The EDG performed poorly for Pinelands gravelly sand despite the high model fit (>0.8). The lowest accuracy overall was observed in the Cape Town (CL). Hence, the EDG performed poorly in the cohesive soil.

5.5 Summary of analyses

The results obtained from the laboratory and field to determine the suitability of the EDG as a compaction test. Statistical tests were used to determine the ability of the EDG to measure moisture content, bulk density and dry density equal to those of the reference tests (oven and sand cone)

The results showed that:

1. The EDG had high repeatability in both the laboratory and field and therefore showed good precision. The repeatability increased with increasing EDG soil model fit for moisture content, bulk density and dry density measurements. The lowest repeatability overall was observed for Khayelitsha sand due to inconsistencies in the soil at the site.
2. The EDG moisture contents for soils with model fits greater than 0.5 were reliable when compared to the oven moisture content. The EDG performed better at moisture contents less than 12 % than those above this value. EDG moisture contents less than 12 % were underestimated and those greater than 12 % were overestimated. For individual soils, a relationship existed between EDG measured moisture content and, the optimum moisture content (OMC) of the soil such that moisture contents slightly greater than the OMC were underestimated, and those less than the OMC were overestimated.
3. Wide spread was observed for EDG bulk density measurements. They were also independent of the sand cone densities. The measurements were affected by the fit of

the soil model and moisture content. Better performance was observed in the laboratory and for soils at lower moisture contents and having higher model fit.

4. Likewise high spread was observed for EDG dry densities especially those in the field due to inhomogeneity of materials in the field. A relationship existed between EDG measured dry densities and MDD such that dry densities slightly less than MDD were overestimated and those above this point were underestimated. In addition, EDG dry density in the poorly graded sands was independent of that of the sand cone.

CHAPTER 6 DISCUSSION OF RESULTS

6.1 Introduction

This study evaluated the efficiency of the EDG in measuring compaction. The repeatability of the EDG was examined. In addition, the accuracy of EDG measurements for moisture content, bulk density and dry density was determined through comparison of the EDG test measurements with the reference tests (oven for moisture content and the sand cone for bulk density and dry density). This was done to determine if the measurements of the tests were equal or if a systematic difference existed between them. This section discusses the results as shown in the preceding chapter. The applicability of the EDG based on the research findings is presented at the end of the chapter.

6.2 Repeatability

The findings of this study indicated the EDG to have high repeatability in both the laboratory and the field. These results were similar to the findings of Wells and Bryson (2014). For this study, the maximum repeatability limit ($r = 0.406$) was observed for Klipheuwel sand. Test and retest experiments revealed that the range over which measurements were made and variations in the soil affected EDG repeatability. The EDG assumes a linear relationship when building the soil model therefore, the large range (approximately 6 %) over which the moisture content for Klipheuwel was measured could have contributed to the higher value for the repeatability limit. This might have been because the resistivity of soil varies non-linearly with moisture content as explained by Ozcep et al. (2009, 2010) hence the relationship is linear over narrow ranges of moisture content. In addition, Cho et al. (2012) attributed variations in EDG measurements to developing the soil models over a wide range. Khayelitsha had the highest repeatability limits overall for bulk density, dry density and the second largest for moisture content. This may have been due to inconsistencies in the soil at site as the EDG is sensitive to changes in soil composition. However, the repeatability limits were within acceptable ranges (< 1 % for moisture content and < 0.1 kN/m^3 for bulk and dry density) for engineering use except for density measurements at Khayelitsha where the difference was greater than 0.1 kN/m^3.

The repeatability limits obtained during this study showed that the EDG provided valid measurements and any differences in measurements arose from changes in moisture content and density and not errors from the EDG. However, for EDG measurements taken over a large range and in soils of variable consistency, multiple EDG measurements at the same spot would be required and the average taken as a representative value in order to reduce the effect of variations.

6.3 Accuracy of EDG measurements

The EDG measures moisture content, bulk density and dry density simultaneously. The accuracy of the EDG for each of the aforementioned parameters is discussed in the following sections.

6.3.1 Moisture content measurement

The EDG measured moisture content accurately as was shown by the confidence interval (CI) from the paired t-test for the expected difference between The oven measured moisture content and that of the EDG. The CI for the expected range of differences did not include any values greater than 1 % and therefore EDG measurements for moisture content were engineeringly acceptable 95 % of the time. Similarly, Cho et al. (2012) and Mejias-Santiago et al. (2013a) found the EDG to provide accurate moisture content measurements. The Bland and Altman plots also showed the difference between oven moisture content and that of the EDG to increase linearly with increase in moisture content indicating the existence of proportional bias for EDG moisture content measurements.

The findings of this research showed that the accuracy of EDG moisture content was dependent on the soil model calibration. This was such that a model fit greater than 0.5 was required for accurate and reliable moisture content measurements. The Passing and Bablok regression method proved that the EDG moisture content was equal to that of the oven for soils with a model fit greater than 0.5 at the 5 % level of significance. This was in agreement with Mejias-Santiago et al. (2013a) who found that the accuracy of EDG moisture content was highly dependent on proper calibration of the points.

Statistical analyses in this study also showed the EDG to perform better at low moisture contents (<12 %). *P* values less than 0.05 were obtained from the paired t-test for Cape Town clayey sand and Pinelands that had high moisture contents (> 12%). This indicated that their EDG average moisture content was statistically different from that of the oven at the 5 % level of significance. This could have been attributed to resistivity being more sensitive to changes at lower moisture content and stabilising at high moisture contents as stated by Abu Hassanein et al. (1996), Beck et al. (2011) and Osman et al. (2012). However, Burgundy sand (SP2) also had a *p* value less than 0.05 despite having a low moisture content (approximately 3 %). The significant *p* value may have been due to the soil model fit less than 0.5 developed during calibration.

This study also showed that for individual soils, a relationship existed between EDG measured moisture content and, the optimum moisture content (OMC) of the soil. EDG moisture contents slightly greater than the OMC plotted under the line of equality hence were underestimated relative to the oven, while those less than this point plotted above the line of equality, and were therefore overestimated. This could have been attributed to the fact that a turning point exists between resistivity and moisture at around optimum moisture content such that resistivity decreases rapidly for moisture contents less than the OMC and then stabilises after OMC as stated by Abu Hassanein et al. (1996) and Beck et al. (2011).

In the field therefore, the EDG would require that model fits greater than 0.5 are developed during calibration to obtain accurate and reliable moisture content measurements. In addition, in cases where offsets were to be used to correct the EDG moisture content two different values would be required; one for moisture contents less than OMC and the other for moisture contents greater than OMC. However, the observed differences bore no engineering significance and no offset for correction would be required to use them.

6.3.2 Bulk density measurement

EDG bulk density measurements were inaccurate as shown by the statistical tests and the observed range of differences between the sand cone (SC) and EDG bulk density. *P* values less than 0.05 were obtained for EDG bulk density measurements in Khayelitsha sand, Pinelands gravelly sand and Burgundy sand SP1 indicating that their average EDG bulk density was different from that of the SC at the 5 % level of significance. A previous study by Cho et al. (2012) also found the EDG to have lower correlation for density measurements. Osman et al. (2012) observed a poor relationship between resistivity and bulk density, which might have contributed to the inaccuracy of EDG bulk density measurements. They also concluded that there was no definite relationship between resistivity and bulk density.

Scatter plots for EDG bulk density measurements especially those in the field, showed wide spread because it was hard to ensure uniformity of soil in the field. Pinelands gravelly sand had the widest spread caused by inaccurate results from the SC for gravelly soils (GTI, 2004) and the presence of vibrations at the site due to piling. Bland and Altman plots showed the difference between SC bulk density measurements and those of the EDG to increase linearly with increasing density hence the EDG had proportional bias with the SC. The plots also showed that the linear increase was dependent on the moisture content at which the soil was tested. This might have been because resistivity has an independent relationship with each moisture content and dry density, which is a function of the bulk density as indicated by McCarter (1984), Beck et al. (2013) and Toll and Hassan (2015).

Furthermore, the results of this study showed that the EDG required soil model fits greater than 0.8 to provide reasonable estimates for the bulk density of the soil. Passing and Bablok regression methods indicated that EDG bulk density measurements were equal to those of the sand cone for soils whose model fit for calibration was greater than 0.8. Thus, the EDG required soil calibration fits greater than 0.8 to provide an estimate of the soil's bulk density. However, a soil model fit greater than 0.8 is hard to achieve in the field due to soil variations. Also, based on the observed differences between EDG bulk density and that of the sand cone (SC), differences as big as 2 kN/m^3 were expected and these were engineeringly unacceptable for accurate bulk density measurements. Therefore, the EDG is not a feasible test for measuring bulk density in compaction.

6.3.3 Dry density measurement

EDG dry density measurements were also found to be inaccurate because they were statistically different from those of the SC. The Passing and Bablok regression method rejected all EDG dry density measurements for the soils tested implying that they were not equal to those of the SC at the 5 % level of significance. In addition, high spread was observed for EDG dry densities especially those in the field. The Bland and Altman plots showed the difference between EDG dry density and that of the sand cone to increase linearly with increasing dry density.

EDG dry densities were independent of those from the SC for Klipheuwel sand, Khayelitsha sand, Pinelands gravelly sand, Burgundy sand SP1 and SP2 i.e. the EDG returned consistent dry densities for these soils in as much as those of the sand cone were changing. This was evidenced by the scatter plots for EDG dry density against SC dry density that were almost horizontal. Rathje et al. (2006) obtained similar results when using the EDG in poorly graded sands. However, the EDG dry density measurements for Cape Town clayey sand were only consistent for dry densities greater than the maximum dry density (MDD). This was attributed to the difference in fabric between clay compacted dry of optimum and that compacted wet of optimum. Toll and Hassan (2015) explained that clay compacted wet of optimum is easily moulded and has reduced pore sizes thus the resistivity is low and independent of any increase in compaction. This could have resulted in the consistent dry density EDG measurements at densities greater than MDD.

The findings of this research revealed that a relationship existed between EDG measured dry densities and the soil's MDD. Dry densities slightly less than MDD plotted above the line of equality in the scatter plots and were overestimated, while those above this point plotted below the line of equality and were underestimated. The observed trend was probably due to resistivity being more sensitive to dry density less than the MDD and stabilising at dry densities greater than MDD as stated by Bai et al. (2013). However, the trend was more observable for soils tested in the laboratory because the dry density of the soils tested in the field was less than their MDD for most of the data collected.

The EDG was observed to perform well for moisture content measurement and poorly for bulk density and dry density measurement hence EDG density measurements were unreliable. Cho et al. (2012) and Rose (2013) also found the EDG to provide inaccurate density measurements making it unsuitable for use in compaction quality control or quality assurance. Accordingly, EDG dry density measurements were unreliable irrespective of the soil model fit. This could have been because resistivity is more sensitive to moisture content than bulk density and dry density as shown by Kibria (2011) and Beck et al. (2011). Therefore, the EDG is only suitable for measuring moisture content and not bulk density or dry density of compacted soil.

6.4 Effect of soil type

The EDG performed better in the non-cohesive soils than cohesive soils based on the ranking of EDG performance for this study. The EDG performance was ranked according to the observed deviation of EDG measurements from the reference tests (sand cone for bulk density and dry density, and oven for moisture content). Results for ranking showed that the EDG performed better in the non-cohesive soils particularly Klipheuwel sand, followed by Burgundy sand SP2 and then Burgundy sand SP1 and Khayelitsha sand. Cape Town clayey sand and Pinelands gravelly sand had the highest variation, thus the EDG performed poorly in these soils. However, the variations for Pinelands could be explained by the fact that the sand cone provides inaccurate measurements in gravelly soils and the presence of vibrations from piling at the site. It follows therefore, that variations at Pinelands arose from inaccuracies in the sand cone test, while those for Cape Town clayey sand arose from the performance of the EDG. Consequently, the EDG performed poorly in cohesive soils. These results are similar to those obtained by Rathje et al (2006). They observed that the EDG would not operate properly in highly plastic clay soils. Nonetheless, the poor performance of the EDG in Cape Town clayey sand and Pinelands gravelly sand could also have been due to the high moisture contents at which the measurements were made.

6.5 Practical relevance of this research

Earthworks comprise a large percentage of project costs (Sthapit and Mori 1994; Wells and Bryson 2014) therefore, it is important to ensure proper compaction of the soil to avoid failure of infrastructure such as earth dams and embankments. The most important parameters in the measurement of compaction are the dry density and the moisture content. Therefore, compaction specifications clearly state the required dry density and moisture content. The dry density is calculated using equation 3-2 and is dependent on both the bulk density and moisture content of the soil. As a result, it is important that the accurate values for both bulk density and moisture content be measured in the field. It is also necessary that the measurement process is quick in order to save time and reduce project duration.

Volume replacement tests such as the sand cone test are used for accurate dry density determination. However, they require a waiting period of 24 hours to determine the moisture content, which is time consuming. Hence, the NDG that measures dry density and moisture content instantaneously is used as a quicker alternative. While the NDG was observed to have high repeatability for bulk density, it had lower repeatability for moisture content determination (Ishai and Livneh, 1983). Several researchers (Kaderabek and Ferris 1979; Gabr et al. 1995; Viyanant et al. 2004; Sagario and Ooi 2011) have reported that NDG measured moisture contents were higher and differed from those of the oven. The difference was attributed to the NDG misinterpreting other hydrogen sources in soil such as organic matter, and the presence of other neutron absorbers like Boron, Cadmium, and Chlorine. The moisture content measured by the NDG is also affected by loss of neutrons to the atmosphere at depths less than 0.3 m and variable clay content (Veenstra et al., 2005). Figure 6-1 shows the NDG measured dry density of clay to vary significantly from that of the drive cylinder due to inaccuracies in NDG measured moisture content. NDG moisture content measurements are therefore a significant source of error in NDG measurements (Noorany et al., 2000).

The accuracy of the NDG can be improved by adjusting NDG densities using laboratory oven measured moisture content, which requires 24 hours before any results are obtained. Under such circumstances, the EDG would provide a quicker and accurate alternative to the oven method for moisture content determination.

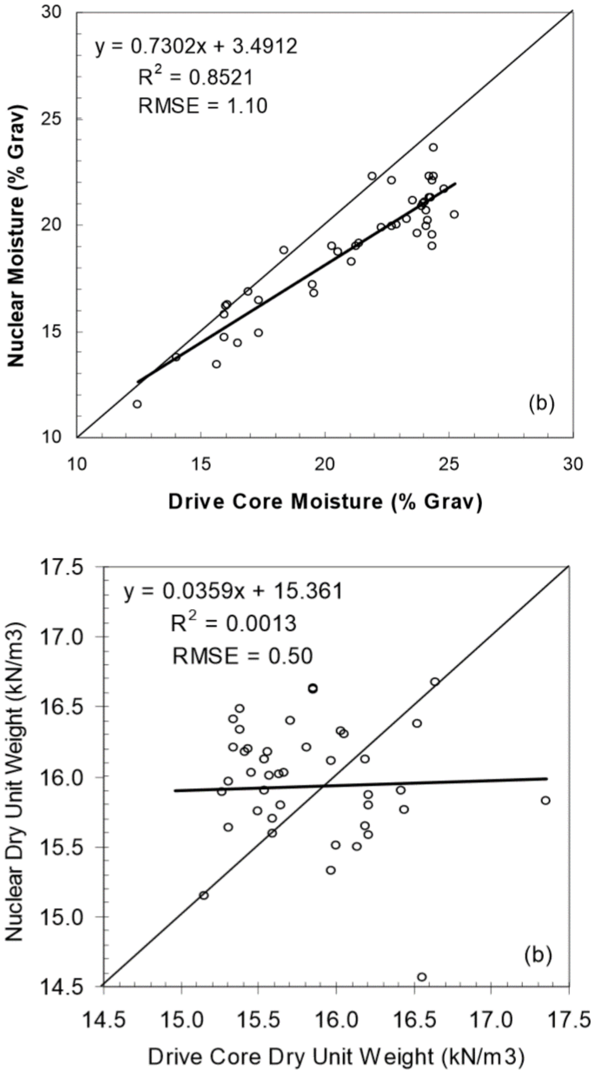


Figure 6-1: Effect of NDG measured moisture content in clay on the dry unit weight (Veenstra et al., 2005)

6.5.1 Field use of the EDG

The study results showed that EDG moisture content values have suitable reliability for measurement of the compaction characteristics unlike those for bulk density and dry density. Therefore, the dry density of the study materials was calculated using equation 3-2. The EDG measured moisture content and the bulk density obtained from the sand cone test were substituted into the equation, and the dry density calculated (see APPENDIX F for detailed values of the calculated dry densities).

Figure 6-2 shows a scatter plot comparing the calculated dry density to the dry density measured by the sand cone test for all the soils (Klipheuwel, Cape Town clayey sand, Khayelitsha sand, Pinelands gravelly sand, Burgundy sand SP1 and SP2) tested in the study. From the graph, the points were found to lie close to the line of equality for all soils except for a few outliers observed in Klipheuwel sand and Pinelands gravelly sand. Hence, the EDG moisture content could be used to accurately determine the dry density of compacted soil and the use of the oven, which is time consuming avoided.

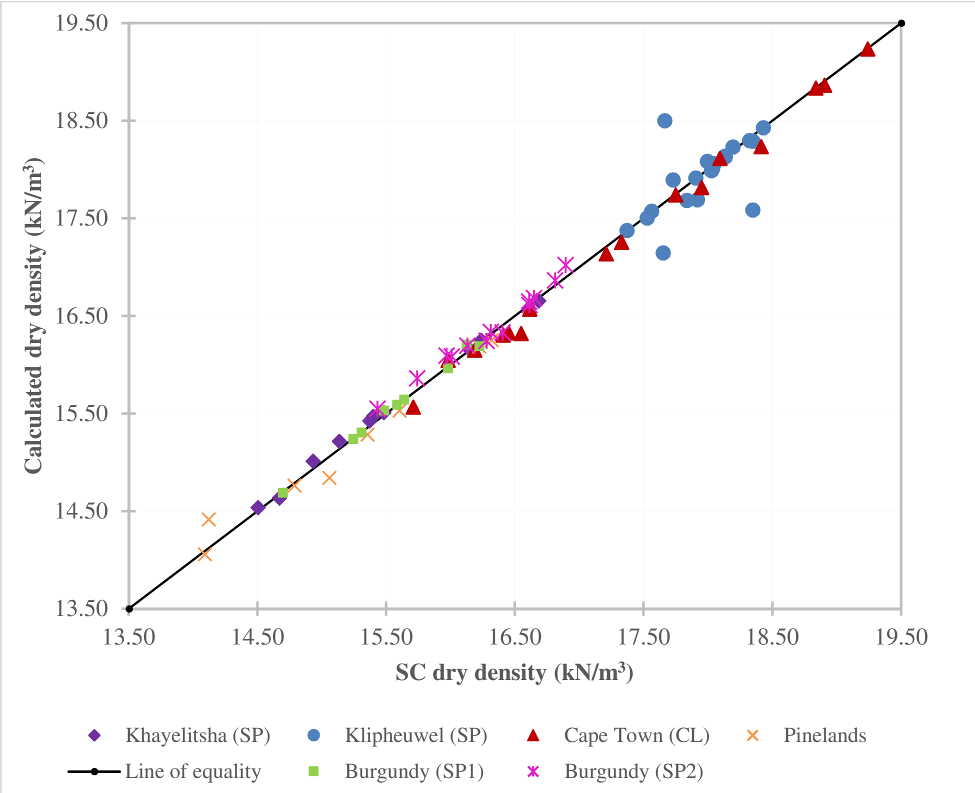


Figure 6-2: Comparison of calculated dry density to SC dry density

6.5.2 Framework for compaction tests

Figure 6-2 showed that the EDG could be used to measure moisture content and the quantity used to determine the dry density of compacted soil accurately. In the field, it is important that the density and moisture content of the soil is measured accurately and that the tests used are fast. It is suggested therefore, that the EDG be used for determining moisture content and that other tests such as the NDG are used for determining the bulk density of the soil. Hence, the EDG would be calibrated over the expected range of moisture contents and then used to measure moisture content instantaneously while the NDG is used for bulk density measurements. Using the EDG measured moisture content and NDG measured bulk density, the dry density of the compacted soil could be calculated from equation 3-2. Consequently, the compaction quality control process is expedited and accurate measurements are obtained. Figure 6-3 shows a framework that could be used as a guide for choosing a suitable test method for assessing soil compaction characteristics. The choice of test would be dependent on the degree of accuracy required and urgency of the test measurements.

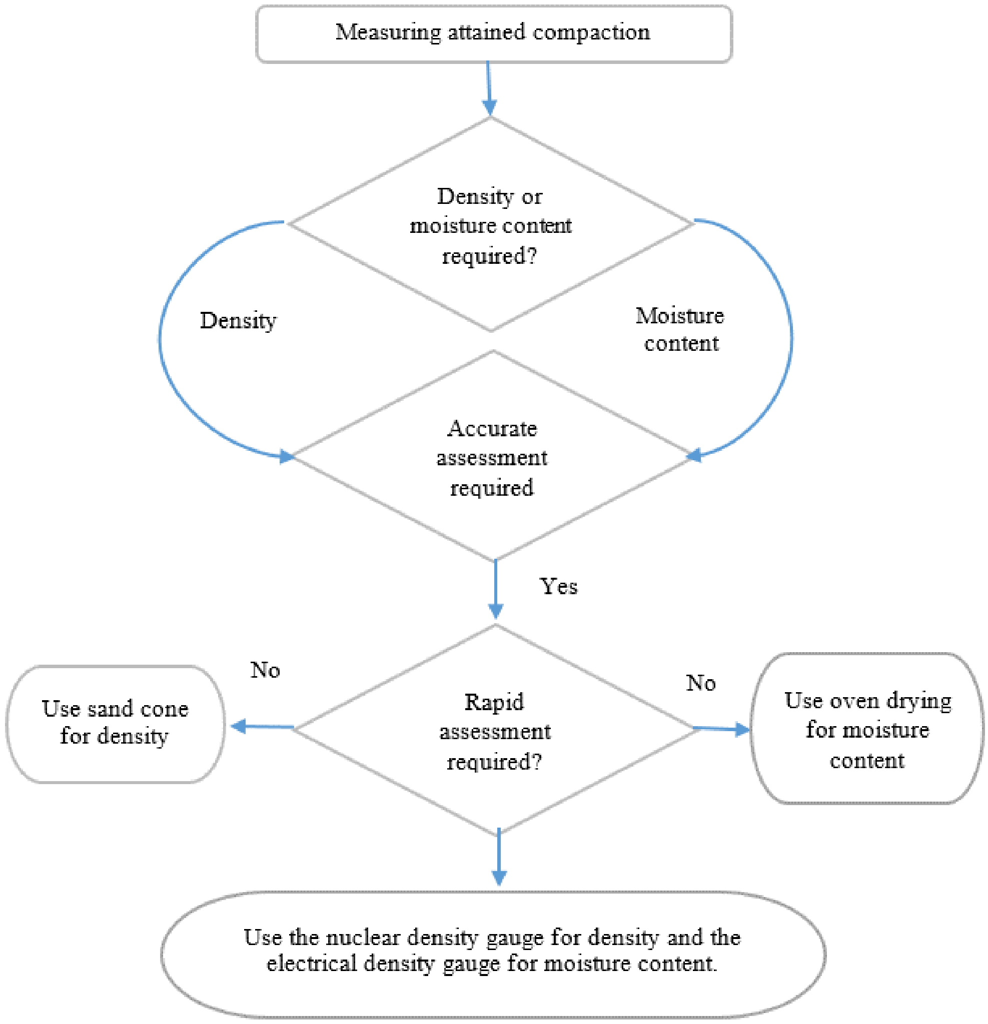
<table>
<tr><th colspan="2">COMPACTION PROCESS</th></tr>
<tr><td>Laboratory tests</td><td>Conduct standard or modified proctor tests to determine the maximum dry density and optimum moisture content</td></tr>
<tr><td>Field compaction</td><td>Surface compaction
• Sheepsfoot roller for clay soils
• Vibratory roller for granular soils
• Smooth drum rollers for both granular and clay soils</td></tr>
<tr><td>In-place tests for density and moisture content</td><td>
</td></tr>
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Figure 6-3: Framework for rapid and accurate assessment of compaction

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

This study evaluated the efficiency of the EDG for measurement of compaction characteristics using South African soils as a basis of the tests. The compaction process requires that the parameters of the compacted soil, which include the moisture content, bulk density and dry density, be assessed quickly and accurately. The compaction parameters of six soils comprising of four uniformly graded sands, a gravelly sand and a clayey sand was measured using the EDG, followed by the sand cone test and oven at the same location as the EDG. The sand cone provided reference measurements for bulk density and dry density while the oven provided reference measurements for moisture content. EDG measurements were compared to the reference measurements to determine its accuracy. The major findings of this study are summarised herein. Recommendations for future research and possible improvements that could be made to the EDG are also presented.

7.2 Conclusions

The following conclusions were drawn from the study;

1. The EDG had good repeatability hence few errors if any would arise from the use of the EDG for measuring compaction. In cases, where the EDG is to be used to measure compaction over a wide range or in soils of variable consistency, it is required that the average of a multiple of measurements in the same spot is used to reduce variations in measurements.
2. The EDG provided accurate moisture content measurements hence it was suitable for measuring moisture content in compaction. A soil model fit greater than 0.5 was required for accurate moisture content measurement. However, model fits less than 0.5 provided good estimates for moisture content. EDG measured moisture was related to the optimum moisture content of the soil, such that moisture content dry of optimum was overestimated and that wet of optimum was underestimated.
3. The EDG provided inaccurate bulk density and dry density measurements hence could not accurately measure the density of compacted soil.
4. EDG measured dry density was related to the maximum dry density (MDD) of the soil, such that dry densities less than the MDD were overestimated while those less than the MDD were underestimated.
5. The EDG performed better in non-cohesive soils than cohesive soils.

7.3 Recommendations

The study revealed that the EDG does not offer accurate soil density measurements; however, it provides quick reliable values for moisture content. Therefore, it can be used alongside other density measurement tests such as the sand cone test or the NDG. Nonetheless, the EDG requires that some adjustments are made before it can be used for compaction measurement as an independent test. The following are the recommendations pertaining to future research:

1. There is a need to investigate the performance of the EDG in cohesive soils. Only one cohesive soil was tested during this study; the geology of the area made it hard to find an available site with cohesive soil. Hence, the results obtained from the study in cohesive soils maybe inconclusive.
2. There is a need for further research into the relationship for bulk density and the electrical properties of soil in order to improve the accuracy. EDG bulk density measurements. Further investigations into the relationship between bulk density, capacitance and electrical resistivity are required. There is also a need to improve the calibration relationship for bulk density in the EDG soil model for more accurate results of dry density to be obtained.
3. Research has shown the relationship between electrical resistivity and moisture content to vary exponentially. The relationship is linear within a narrow range of moisture contents and therefore it is necessary to specify the range of moisture content within which soil models are developed.

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APPENDIX

EVALUATION OF THE ELECTRICAL DENSITY GAUGE FOR IN-SITU MOISTURE AND DENSITY DETERMINATION

BY

ANGELLA LEKEA

SUPERVISED BY DR DENIS KALUMBA

CO-SUPERVISED BY FARIDAH CHEBET

REPORT OF REVISIONS

University of Cape Town

Department of Civil Engineering

November 2015

TABLE OF CONTENTS

1. General

1.1 Minor Typographical Errors and Minor Changes

Section/Chapter	Page	Paragraph	Line/ Eqn.	Corrected to…
Whole document				'proctor' was changed to 'Proctor'
Chapter 1	2	2	1	Reference changed to …Cho et al. (2012)…
	3	Last paragraph	1	… presentation of …
Chapter 2	6	Last paragraph	2	Compressibility is…application of a static load.
	10	1	1	…a hammer of a given mass…
	12	1	5	Space removed W_s
		3	4	W_s; spaces were also inserted before and after all the symbols used.
	13	Table 2-2		Method A and Method B
		2	3	…field compaction…
	14			Reference spelling corrected to 'Massarsch'
		1	1	…or heavy truck tyres are imparted…
	16	2	last	Changed to 'Mohammed et al., 2013'
	18	2	9	...high frequency to prevent decompression...
	19	1	1	…be more pronounced in top…
	21	1	last	Revised to (Kimmel, 2014)
	23	2	1	…of one-and-a-half peak.
	27	2	1	Method specifications, also known as…
		3	last	density, γ_{d_field} to the maximum dry density, γ_d attained
Chapter 3	30	2	5	GRI (2004) edited to GTI (2004) for the reference Gas Technology Institute (GTI). 2004. "Evaluation of Soil Compaction Measuring Devices," GTI-04/0067, Gas Technology Institute, Des Plaines, IL.
	34	Table 3-2		Barns is the unit for the cross section area of elements
	39	Equation 3-7		$Z_s = \frac{V_s}{I_s} \ or \ Z_s = \frac{R_s}{\sqrt{1+\omega^2 C_s^2 R_s^2}}$
	40	3	2	Corrected to McCollum and Logan (1930)…

Section/Chapter	Page	Paragraph	Line/ Eqn.	Corrected to…
			7	Abu Hassanein et al. (1996)
Chapter 3	50	Table 3-4		p-value summary for t-tests (Rose, 2013)
		Figure 3-19		Moisture content correlation for EDG models to the oven (Rose, 2013)
	51	Figure 3-20		Dry density correlation for EDG models to the SC (Rose, 2013)
	52	1	4	…results that are more accurate were obtained in non-cohesive soils than in cohesive soils…
		1	5	…the EDG was less accurate than the NDG.
Chapter 4	59	3	7	…immediately afterwards to prevent…
	60	Heading section 4.2.2.1		Soil model calibration of the EDG
	62	4	3	…with soft weathered rock gravel.
	63	Table 4-1		…calculating the zero air voids line.
	68	2	2	…and the fourth was a gravelly sand.
	70	Table 4-4		…calculating the zero air voids line.
	72	3	1	…using both the EDG…
	73	1	4	…the soils at Burgundy drained…
Chapter 5	80	3	6	…to the reference test results…
	91	2 and 3		Font size of the equations was corrected.
		3	4	The slope of the line indicates…
	104	2	9	Toll and Hassan (2015)
	108	1	1	…show the percentage average spread…
Chapter 7	120	1	2	The compaction process…
		2	1	The EDG had good repeatability…

1.2 Review of Specific Chapters/Sections

1.2.1 Chapter 2

The comment on the effect of the diffuse double layer (DDL) on structure of compacted clay (page 4) was noted and the sentences have been amended to read as;

> *Lambe (1958a) attributed the structure of clay at the different water contents to the effect of the diffuse double layer (DDL). The DDL is well-developed at high moisture contents and there is greater repulsion between the particles forming a dispersed structure. Therefore, the density of the soil increases as more particles can fit in a given volume.*

Regarding the effect of dry density and moisture content on swelling potential of compacted clays in paragraph 3 *(p.8)* has been reviewed to read as below and comparison made to Figure 2-5 in the text.

> *The swell potential of clays increases with reduction in water content (Mishra et al., 2008). At low water contents, soil has a high affinity for water due to matric suction (Chen, 1988) thus swells more. However, Ashayeri and Yasrebi (2009) found that smaller values of free swell and swelling potential were experienced for samples at lower water contents and dry density compared to those compacted at optimum, which was in contrast with Figure 2-5. This could be attributed to the fact that there is less dry clay material to cause swelling at low dry densities and the mineralogy of the clay. Thus, clay mineralogy also plays a major role in the extent of swell, with kaolinite swelling less than montmorillonite (Mishra et al., 2008).*

The statement about the change in the shrinkage limit and shrinkage volume at high moisture contents in paragraph 4 (last paragraph, p.8) has been revised because the shrinkage limit is constant. The explanation has been amended as:

> *At high water contents, clay soils have a well-developed DDL with the soil particles further away from each other due to increased repulsion hence they undergo higher shrinkage on drying and develop larger cracks. The cracks enable swelling as they function as inlets for water.*

The values in Table 2-1 have been revised and modifications made to the table with respect to the relevant standards as shown below.

TEST	**STANDARD PROCTOR**		**MODIFIED PROCTOR**			
Standard followed	BS 1377 - 4	ASTM D-698 (A) /AASHTO T-99	BS 1377 - 4	ASTM D-1557(A) / AASHTO T-99	SANS 3001-GR30	TMH 1 – Method A7
Layer (no.)	3	3	5	5	5	5
Volume (cm^3)	1000	943	1000	943	943	943
Blows (no.)	27	25	27	25	25	25
Hammer weight (kg)	2.5	2.495	4.5	4.54	4.54	4.54
Drop height (mm)	300	304.8	450	457.2	457.2	457.2

The dependency of the relative density test results on the operator conducting the tests (p. 12, paragraph 2, line 5) has been explained as follows to remove any ambiguity.

> *Therefore, it is not advisable to use relations between relative density and any of the Proctor tests because the relative density test has a lot of variability and the results are dependent on the operator of the test (Selig, 1973).*

The line 2 of heading 2.4.13 of the vibroflotation method of deep compaction was rephrased to read:

The process (Figure 2-12) involves penetrating a special probe, called a vibroflot to the desired depth, approximately 3-15 m (FHWA, 2001). The vibroflot produces horizontal vibrations…

The backfilling process of the cone in question describes the cone formed at the top of the excavated hole as shown in Figure 2-12. The hole formed is compacted while gradually withdrawing the vibroflot and a cone is formed at the surface of the ground which requires backfilling since the soil has been compacted into a smaller volume and extra soil (backfill) is required to fill the cone. Therefore, the procedure is described as:

The process (Figure 2-12) involves penetrating a special probe, called a vibroflot to the desired depth, approximately 3-15 m (FHWA, 2001). The vibroflot produces horizontal vibrations at frequencies of up to 3000 cycles per minute and amplitudes of 10 to 23 mm (FHWA, 2001) and a jet of compressed air and water. The water saturates the soil around the probe and the soil liquefies due to the horizontal vibrations. At the desired depth, the jet of water is reduced or switched off. This induces horizontal forces around the probe causing the soil particles to rearrange into a denser state. The probe is withdrawn gradually and compacts the soil around it in steps. At the surface of the ground, a soil cone is formed which may be backfilled with in situ material or compacted granular fill.

The depth described in the Muller resonance frequency method has been defined to provide clarity such that the sentence reads as:

The time required to penetrate the desired depth is recorded. At the desired depth, the frequency is adjusted…

The word tamping roller, in section 2.4.2.4, has been removed and replaced with pad foot roller which is a modification to the sheepsfoot roller. Tamping roller and pad foot roller are used interchangeably, however to maintain consistency this has been changed to pad foot roller, such that it reads;

A modification to the sheepsfoot roller is the pad foot roller…The weight of pad foot rollers ranges from 15 to 40 tons.

The last sentence of section 2.5.1 has been deleted so that the paragraph ends as:

… As the soil state approaches the zero air voids line, the maximum dry density at optimum water content is attained. Thus beyond the optimum water content, any additional water results in reduction in the dry density because water starts to replace the soil particles.

The sentence in line 2 p. 24 leading up to Figure 2-20 by Lewis (1959) has been rephrased to provide clarity between the authors. The sentence now reads as;

Wong (1967) observed that heavy machinery with higher frequency exert higher compactive effort; therefore provide higher dry densities. Lewis (1959) obtained similar results (Figure 2-20).

The explanation for the reduction in compactor effectiveness with increased water content and compactor mass has been re-examined and clarification has been provided as follows on page 24:

> *However, the effect of compactor mass reduces with increased water content due to reduction in the bearing capacity of the soil resulting in increased roller-soil contact area hence less contact stress (compaction energy) is applied (James and Shipton, 2012).*

A statement on the kneading action of pneumatic rollers and their applicability for different soils has been added to paragraph 2 line 3 on page 24.

> *Hence, pneumatic rollers require more passes to attain the same density as the smooth roller, which affects the construction procedure followed for a particular type of compactor (Kim et al., 2014). However, the kneading action of pneumatic rollers makes them suitable for compaction of clays.*

1.2.2 Chapter 3

The inconsistency of results in section 3.2.3 (p.43) with those of Cho et al. (2012) could have been brought about by the differences in the soil types tested. Such that the drive cylinder would appear to perform better in some soils relative to the sand cone, and then poorly in some other soils such as collapsible soils.

The concluding sentence to the summary in section 3.6 has been revised so that it is in line with the objectives of the study, as follows;

> *Following the stated hypotheses, the accuracy of the EDG for measuring compaction was evaluated using sites in South Africa.*

1.2.3 Chapter 4

In section 4.2.2.1 reference has been made to the Figure 3-9 for the electrical density gauge (EDG) circuit and Figure 4-2 for the EDG used in the study to aid in understanding the text description. In addition, the detents have been clearly described.

> *A soil model is the result of the calibration procedure that establishes a correlating linear function between EDG measured electrical properties (Figure 3-9) …*
>
> *At the site, the EDG (Figure 4-2) was switched on and the soil model for the site named before it was developed. …*
>
> *The four darts were positioned at the detents (holes on the side of the template preventing its movement) on the template.*

A question on the ability to attain uniform density for the compacted soil and the effect of the laboratory model boundary on EDG measurements were raised with reference to page 66.

It was hard to achieve a uniform density given the cylindrical shape of the laboratory moel and the rectangular shape of the compactor's foot. However, since the moisture content of the soil was controlled and the volume of the soil required was known, densities varying within a narrow range were obtainable.

The EDG uses current to measure the density of the soil, while the nuclear density gauge (NDG) use nuclear radiation. Unlike, radiation which is scattered, current moves in a straight line so that EDG measurements would not be affected by boundary conditions. Furthermore, for measurements that would be taken close to the edge, no interference would have been incurred as the tank was made from high density polyethylene which is an insulator.

1.2.4 Chapter 5

A paragraph has been added at the end of section 5.4.1.3 to discuss the rejection of all EDG dry density measurements by the Passing and Bablok model as opposed to its acceptance of both the bulk density and moisture content measurements of some soils. It reads as;

EDG dry density measurements for all the soils were found to vary significantly from those of the SC based on the Passing and Bablok regression method. Therefore, the measurements were rejected even though both the EDG measured moisture content and bulk density for some of the soils, such as Klipheuwel sand, were found to be acceptable. The Passing and Bablok model for EDG measured moisture content and bulk density in Klipheuwel were found to lie closer to the line of equality as compared to the EDG dry density Passing and Bablok model. This could be attributed to the high spread of bulk density measurements observed in the model.

1.2.5 Chapter 7

The conclusion has been re-written in past tense to provide for easy reading. The recommendations on page 121 have been edited according to the recommendations of the external examiner as follows.

4. *There is a need to investigate the performance of the EDG in cohesive soils. <u>Only one cohesive soil was tested during this study; the geology of the area made it hard to find an available site with cohesive soil.</u> Hence, the results obtained from the study in cohesive soils maybe inconclusive.*
5. *There is a need for further research into the relationship for bulk density and the electrical properties of soil in order to <u>improve the accuracy</u>. EDG bulk density measurements. Further investigations into the relationship between bulk density, capacitance and electrical resistivity are required. There is also a need to improve the calibration relationship for bulk density in the EDG soil model for more accurate results of dry density to be obtained.*

1.3 Remarks

The external examiners suggested the following recommendations for further research:

- The external examiners recommended that a further study be done to determine a parameter that might tie-up the results of the tests to enhance the findings of the thesis.
- It was also recommended that correlation between density and moisture content measurements of the EDG and the nuclear density gauge (NDG) be determined as the NDG is the most widely used test in South Africa.
- It was suggested that the EDG be used on a real project as the testing method and laboratory checks conducted during construction to determine any interferences.

1.4 References

All references were updated as follows:

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2. Final Comments

I am grateful for the insightful and helpful comments made by the external examiners. The attainment of high densities in compaction at the stipulated moisture contents is important for the sustainability of engineering structures. Therefore, accurate and reliable tests are required to measure the density and moisture content achieved in the field. The evaluation of the electrical density gauge for measuring density and moisture content is an interesting topic that needs further dedicated studies. Nevertheless, I hope that the information availed herein will be of help to researchers and any practicing engineer.

Signed: ……………………………………..

Date: ……………………………………….

LIST OF APPENDICES

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LIST OF TABLES

APPENDIX A SITE LOCATIONS

Appendix A.1 **Khayelitsha**

Figure A-1: Site in Khayelitsha (Google maps, 2015)

Appendix A.2 **Pinelands**

Figure A-2: Site in Pinelands (Google maps, 2015)

Appendix A.3 **Burgundy Estate**

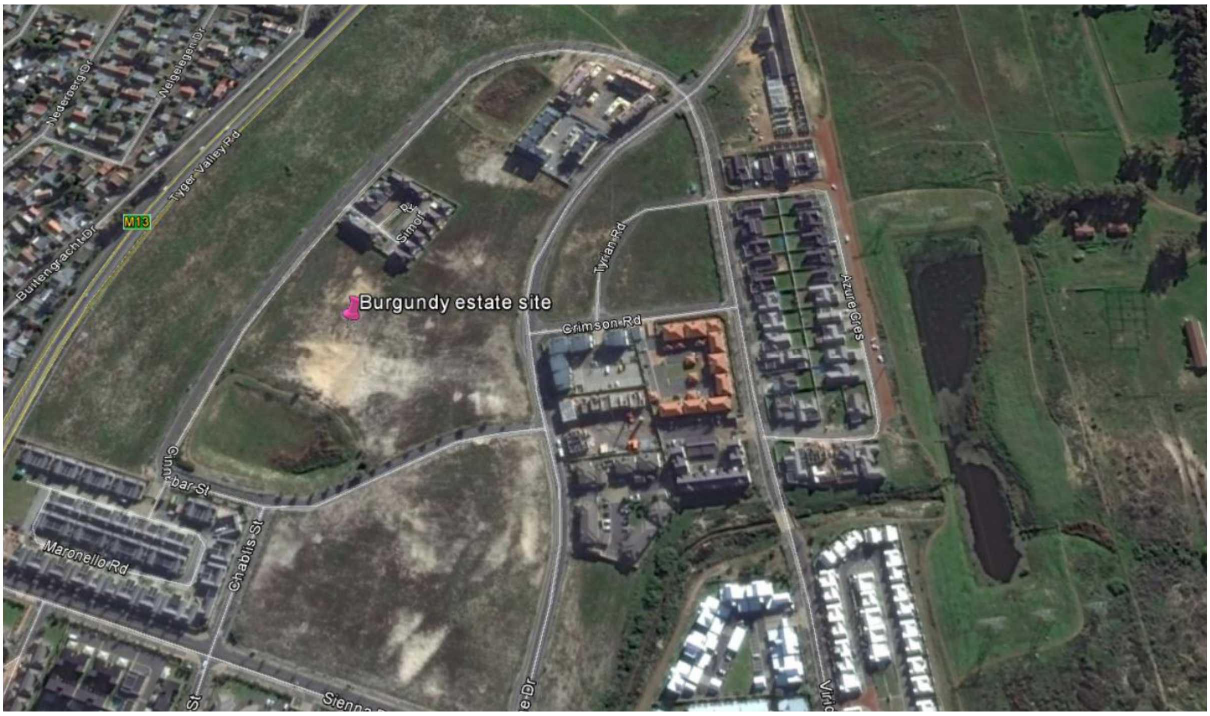


Figure A-3: Site in Burgundy Estate (Google maps, 2015)

APPENDIX B   CLASSIFICATION TESTS

Appendix B.1 Cape Flats sand

Table B-1: Sample calculations for calibrating the sand cone

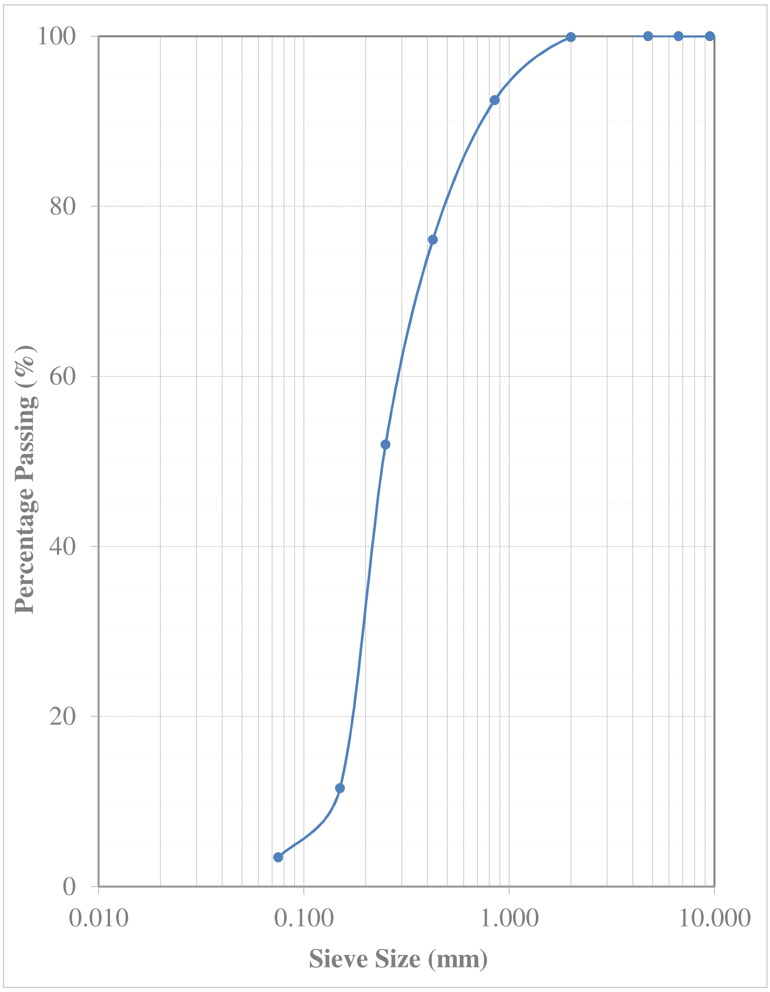
	CALIBRATION OF SAND CONE APPARATUS											
1	Volume of Calibrating container, V cm^3	1024126 mm^3		1024 cm^3								
2	Weight of cylinder + sand (before pouring) W_1 (g)	6333	6434	6573	6435	6540	6385	6487	6294	6557	6562	6257
3	Weight of cylinder + sand (after pouring) W_2 (g)	4405	4505	4646	4503	4605	4443	4554	4343	4607	4611	4309
4	Mean weight of sand in cone of pouring cylinder, W_3 (g)	414	418	419	419	419	420	417	418	420	423	434
5	Weight of sand to fill calibrating container, W_4 (g)	1514	1511	1508	1513	1516	1522	1516	1533	1530	1528	1514
6	Bulk density of sand (g/cm^3)	1.48	1.48	1.47	1.48	1.48	1.49	1.48	1.50	1.49	1.49	1.48

Appendix B.2 Klipheuwel (SP)

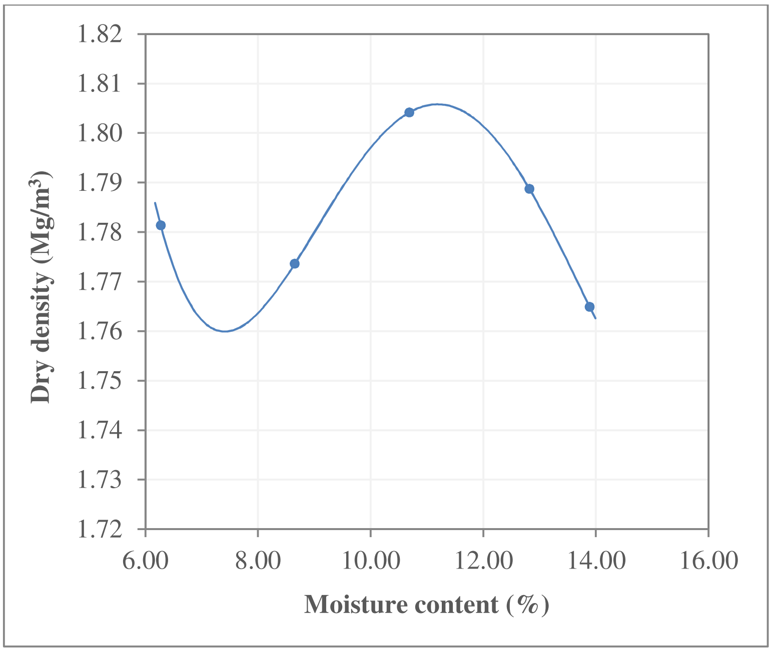
Table B-2: Calculations for specific gravity for Klipheuwel sand

SPECIFIC GRAVITY		
Pycnometer bottle no.	25	39
W_P= Wt. empty clean pycnometer (g)	34.718	36.93
W_{PS}=Wt. of empty pycnometer + dry soil (g)	44.896	47.06
W_B= Wt. of pycnometer +dry soil+ water (g)	91.100	94.59
W_A=Wt. of pycnometer +water (g)	84.731	88.28
$W_{PS}-W_P$	10.178	10.13
W_A-W_B	6.369	6.31
Specific gravity (G_s)	2.67	2.65
Average specific gravity	2.66	

Graph B-1: Particle size distribution for Klipheuwel sand



Graph B-2: Plot of dry density against moisture content for Klipheuwel sand



Appendix B.3 Cape Town (CL)

Table B-3: Calculations of liquid limit for Cape Town (CL)

LIQUID LIMIT (%)				
Can no.	A3	A4	A1	A2
Mass of can (g)	9.5	9.5	9.5	9.6
Mass of wet soil + can (g)	22.7	26.2	26.5	26.9
Mass of dry soil + can (g)	20.4	23.5	23.7	23.98
Mass of dry soil (g)	10.9	14	14.2	14.38
Mass of water	2.3	2.7	2.8	2.92
Water content (%)	21.10	19.29	19.72	20.31
No. of drops	15	29	23	20
Liquid limit = 19.7% = 20%				

Graph B-3: Plot of moisture content against blows for liquid limit for Cape Town (CL)

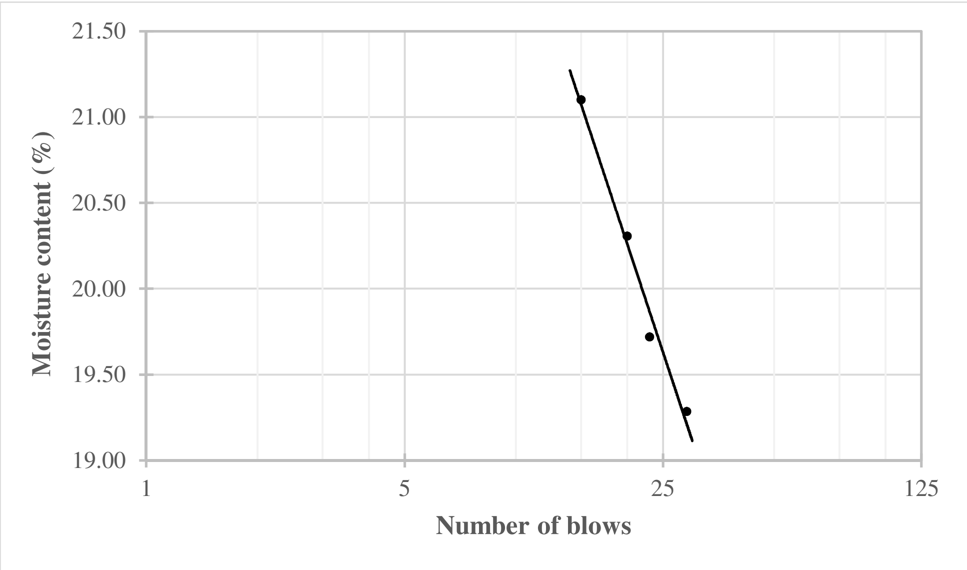


Table B-4: Calculations for plastic limit for Cape Town (CL)

PLASTIC LIMIT (%)			
Can no.	APL3	APL2	APL1
Mass of can (g)	9.6	9.5	9.7
Mass of wet soil + can (g)	11.8	11.7	12.1
Mass of dry soil +can (g)	11.5	11.5	11.8
Mass of dry soil (g)	1.9	2	2.1
Mass of water (g)	0.3	0.2	0.3
Water content (%)	15.79	10.00	14.29
Plastic Limit (%)	**13.36**		
Plasticity index = 19.7-13.4 = 6.3 %			
Clay of low plasticity, CL			

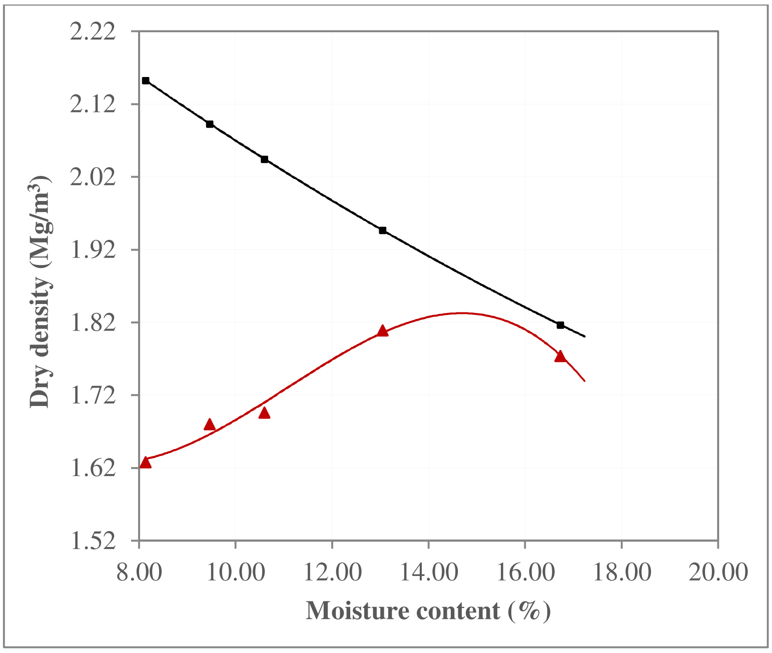
Table B-5: Calculations for natural moisture content for Cape Town (CL)

NATURAL MOISTURE CONTENT (%)			
Pan number	ANM1	ANM1	ANM1
Wt. pan + wet soil (g)	2751.6	2112.3	2568.9
Wt. pan+dry soil (g)	2415.4	1878.5	2246.4
Wt. pan (g)	280.3	280.3	280.3
Wt. dry soil (g)	2135.1	1598.2	1966.1
Wt. moisture (g)	336.2	233.8	322.5
Natural moisture content (%)	15.75	14.63	16.40

Table B-6: Calculations for specific gravity for Cape Town (CL)

SPECIFIC GRAVITY			
Pycnometer bottle no.	39	6	26
W_P= Wt. empty clean pycnometer (g)	37.000	35.358	34.393
W_{PS}=Wt. of empty pycnometer + dry soil (g)	47.402	45.816	44.393
W_B= Wt. of pycnometer +dry soil+ water (g)	94.687	90.323	90.35
W_A=Wt. of pycnometer +water (g)	88.278	83.88	84.032
W_{PS}-W_P	10.402	10.458	10.248
W_A-W_B	6.409	6.443	6.318
Specific gravity (G_s)	2.61	2.60	2.61
Average specific gravity		**2.61**	

Graph B-4: Plot of dry density against moisture content for Cape Town (CL)

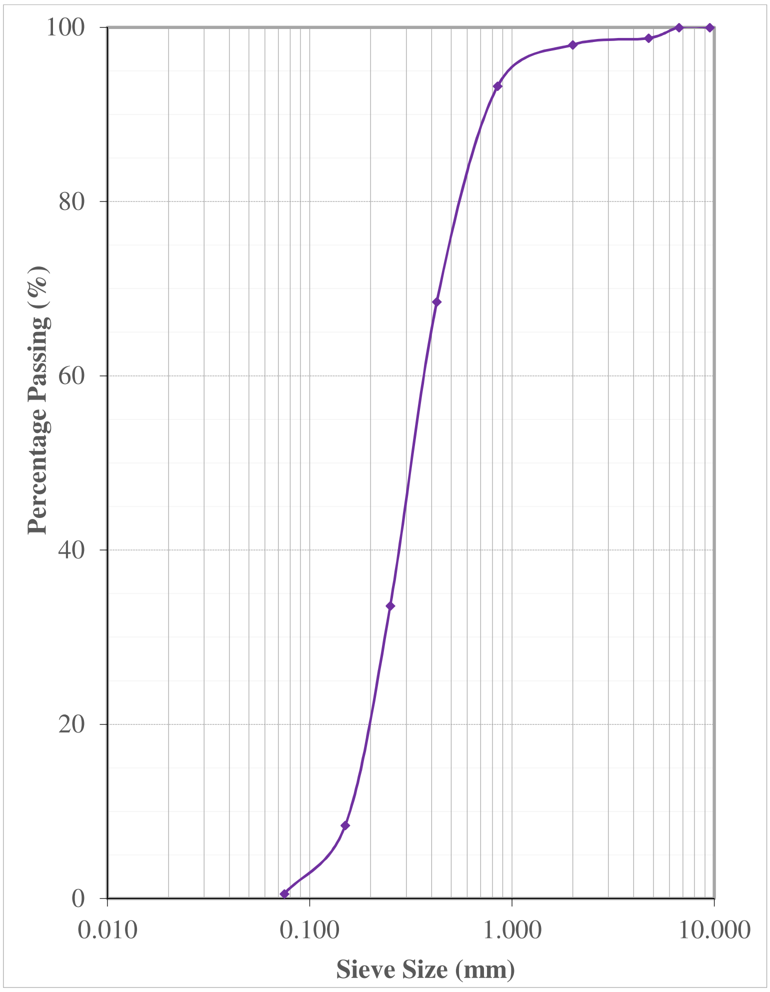


Appendix B.4 Khayelitsha sand

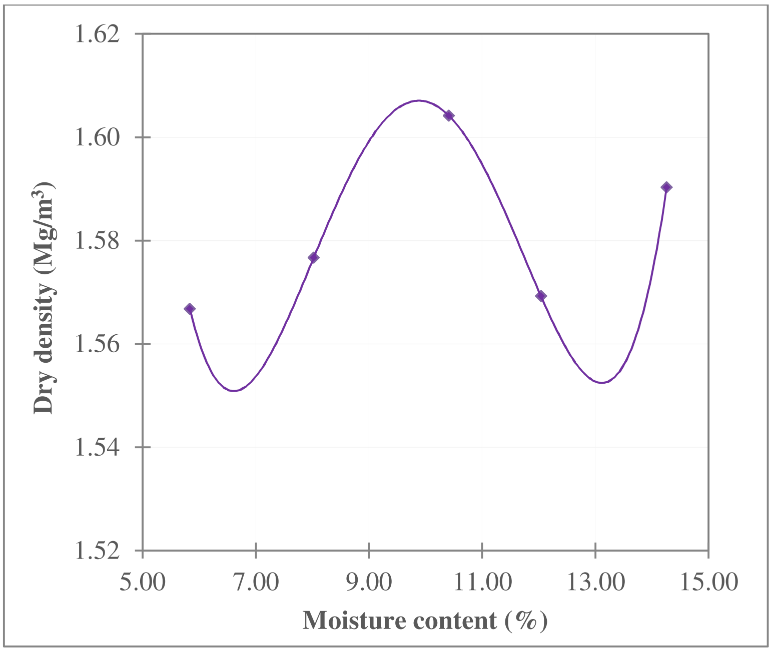
Table B-7: Calculations for specific gravity for Khayelitsha sand

SPECIFIC GRAVITY		
Pycnometer bottle no.	26	4
W_P= Wt. empty clean pycnometer (g)	34.251	35.355
W_{PS}=Wt. of empty pycnometer + dry soil (g)	44.343	45.372
W_B= Wt. of pycnometer +dry soil+ water (g)	90.361	93.557
W_A=Wt. of pycnometer +water (g)	84.027	87.319
W_{PS}-W_P	10.092	10.017
W_A-W_B	6.334	6.238
Specific gravity (G_s)	2.69	2.65
Average specific gravity	**2.67**	

Graph B-5: Particle size distribution for Khayelitsha



Graph B-6: Plot of moisture content against dry density for Khayelitsha

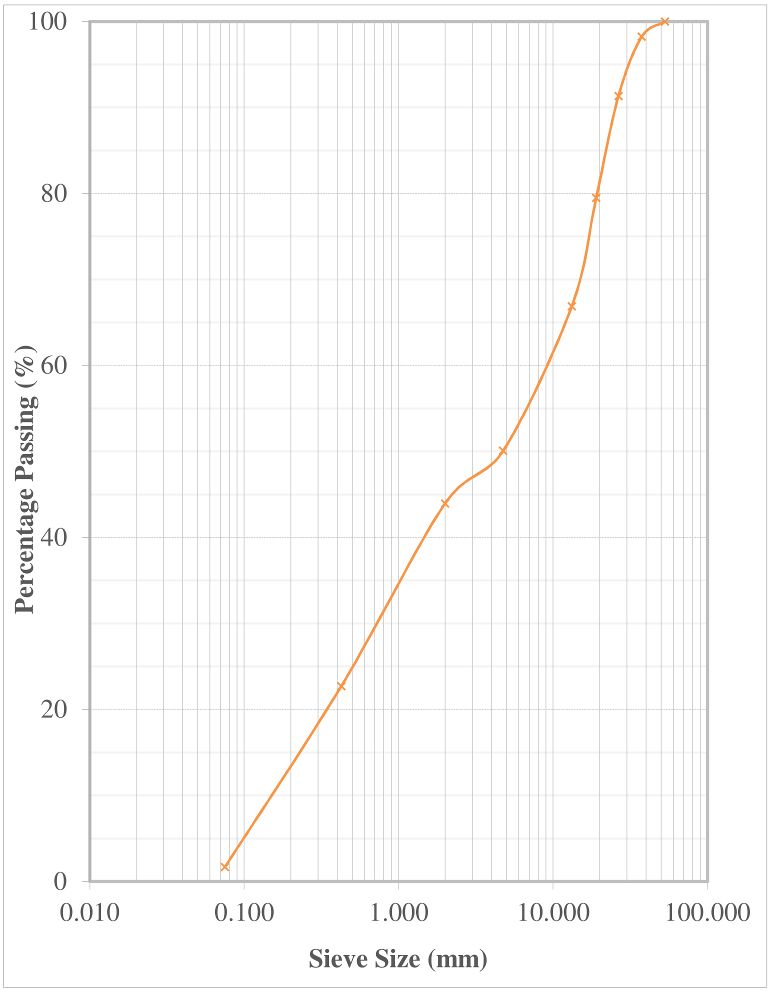


Appendix B.5 Pinelands

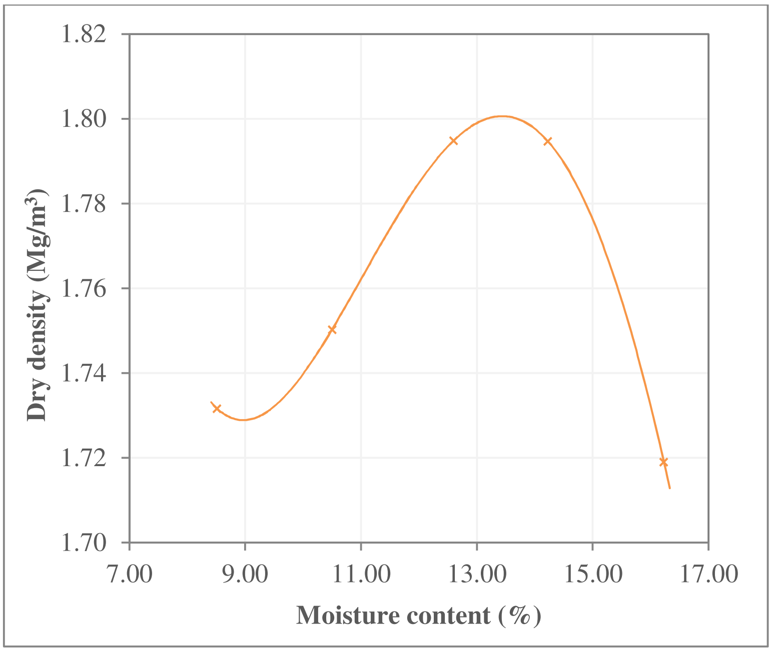
Table B-8: Calculations for specific gravity for Pinelands

SPECIFIC GRAVITY		
Pycnometer bottle no.	25	2
W_P= Wt. empty clean pycnometer (g)	35.048	37.377
W_{PS}=Wt. of empty pycnometer + dry soil (g)	45.073	47.426
W_B= Wt. of pycnometer +dry soil+ water (g)	91.043	94.802
W_A=Wt. of pycnometer +water (g)	84.957	88.565
W_{PS}-W_P	10.025	10.049
W_A-W_B	6.086	6.237
Specific gravity (G_s)	2.55	2.64
Average specific gravity	**2.59**	

Graph B-7: Particle size distribution for Pinelands



Graph B-8: Plot of moisture content against dry density for Pinelands

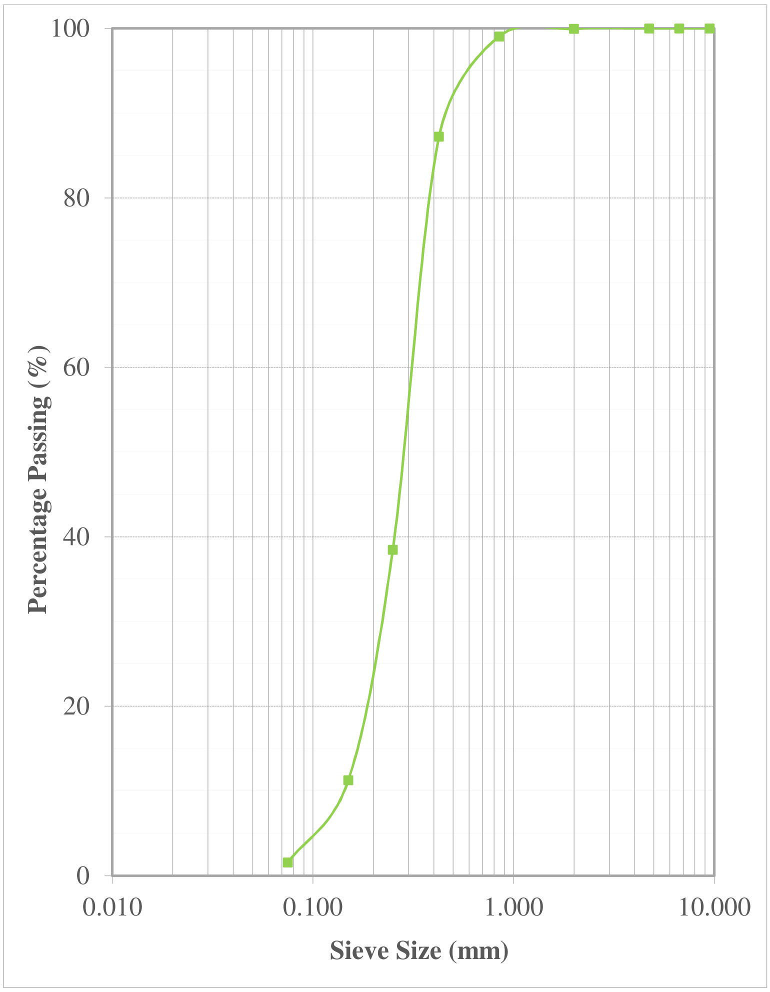


Appendix B.6 Burgundy sand (SP1)

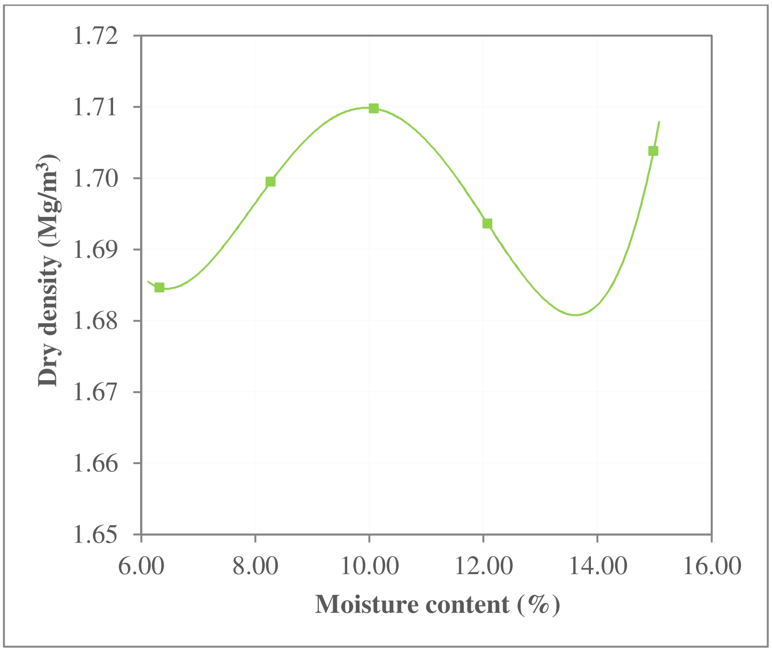
Table B-9: Calculations for specific gravity of Burgundy sand (SP1)

SPECIFIC GRAVITY		
Pycnometer bottle no.	58	21
W_P= Wt. empty clean pycnometer (g)	33.807	34.718
W_{PS}=Wt. of empty pycnometer + dry soil (g)	43.902	44.79
W_B= Wt. of pycnometer +dry soil+ water (g)	90.761	90.88
W_A=Wt. of pycnometer +water (g)	84.534	84.751
W_{PS}-W_P	10.095	10.072
W_A-W_B	6.227	6.129
Specific gravity (G_s)	2.61	2.55
Average specific gravity	**2.58**	

Graph B-9: Plot of particle size distribution for Burgundy sand (SP1)



Graph B-10: Plot of moisture content against dry density for Burgundy sand (SP1)

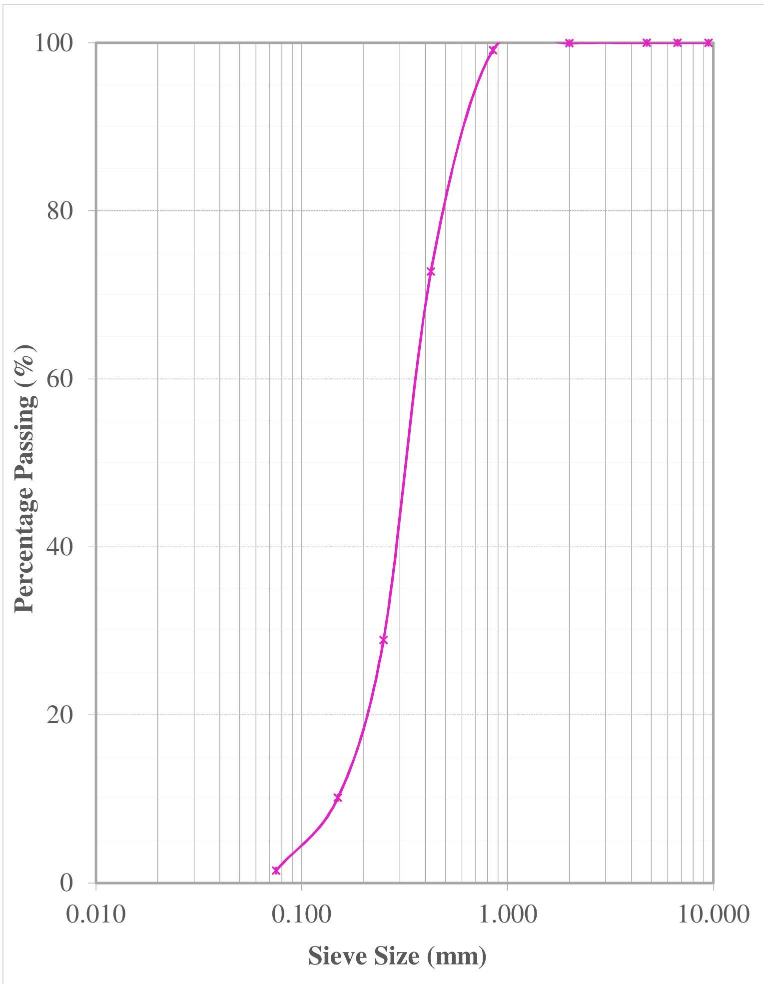


Appendix B.7 Burgundy sand (SP2)

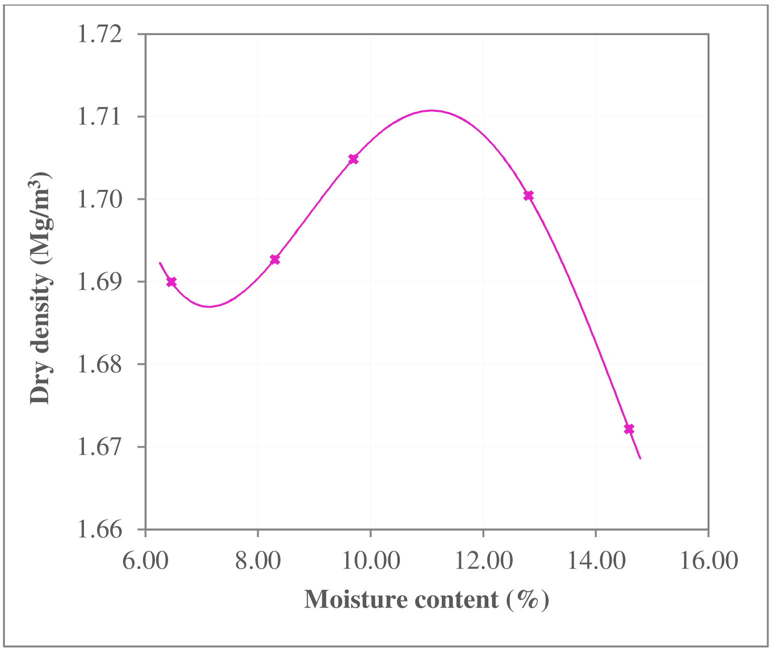
Table B-10: Calculations of specific gravity for Burgundy sand (SP2)

SPECIFIC GRAVITY		
Pycnometer bottle no.	24	1
W_P= Wt. empty clean pycnometer (g)	33.87	34.995
W_{PS}=Wt. of empty pycnometer + dry soil (g)	43.877	45.005
W_B= Wt. of pycnometer +dry soil+ water (g)	89.674	93.646
W_A=Wt. of pycnometer +water (g)	83.407	87.484
W_{PS}-W_P	10.007	10.01
W_A-W_B	6.267	6.162
Specific gravity (G_s)	2.68	2.60
Average specific gravity	**2.64**	

Graph B-11: Plot of particle size distribution for Burgundy sand (SP2)



Graph B-12: Plot of moisture content against dry density for Burgundy sand (SP2)



APPENDIX C MATERIAL PREPARATION

Appendix C.1 Sample calculations for quantity of soil for each lift

- Area of the tank, $A = \pi \times \frac{1.5^2}{4} = 1.767 m^2$
- Volume of soil required for a 200 mm lift, $V = 1.767 \times 0.2 = 0.353 m^3$
- Considering Klipheuwel soil as the soil used. The soil was oven dried prior to mixing hence the moisture content is zero. The dry density for Klipheuwel sand was determined as 18.15 kN/m^3 at an optimum moisture content of 11% from the Proctor test.
- For moisture contents dry of optimum say 7%, the bulk density is calculated as $\gamma_b = \gamma_d (1 + m)$
- Hence for Klipheuwel the bulk density was $= 18.15(1 + 0.07) = 19.42 kN / m^3$
- The mass of the soil required was determined as $M = \rho_b \times V = 19.42 \times 100 \times 0.353 = 690 kg$
- The soil was mixed in 75 kg batches, hence the amount of water added to each 75 kg batch was calculated as
- $= 75 \times 0.07 = 5.25 kg$ of water, which were weighed out and added to the soil in the mixer shown in Figure C-1.

Figure C-1: Mixer used for mixing the soil in the laboratory

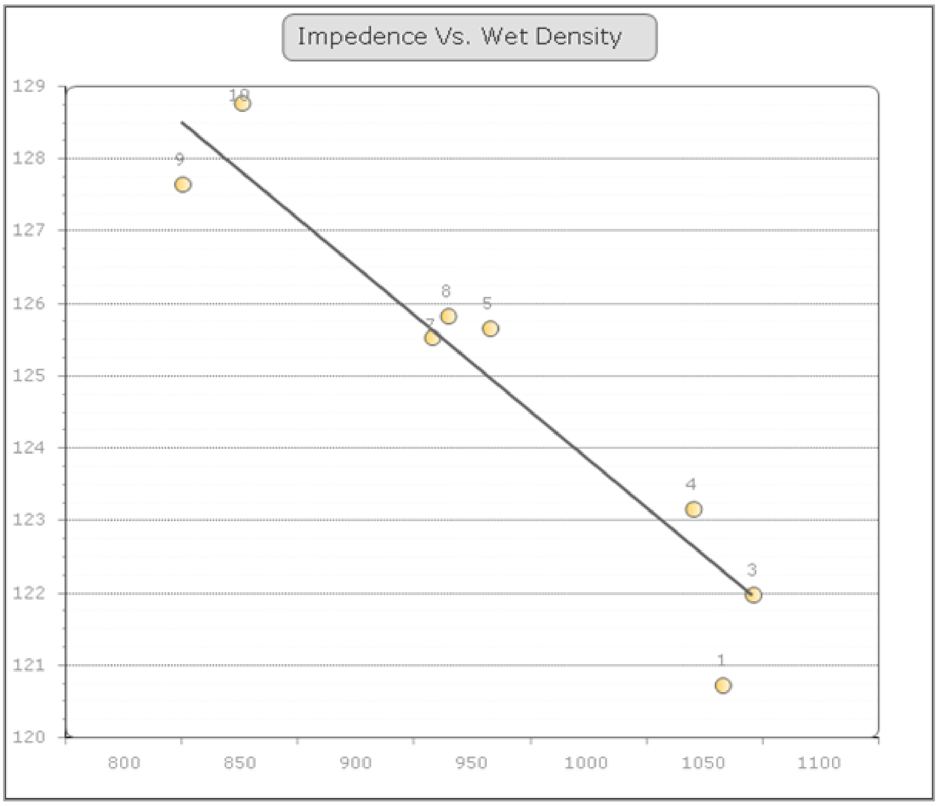
Appendix C.2 Soil models

Klipheuwel sand

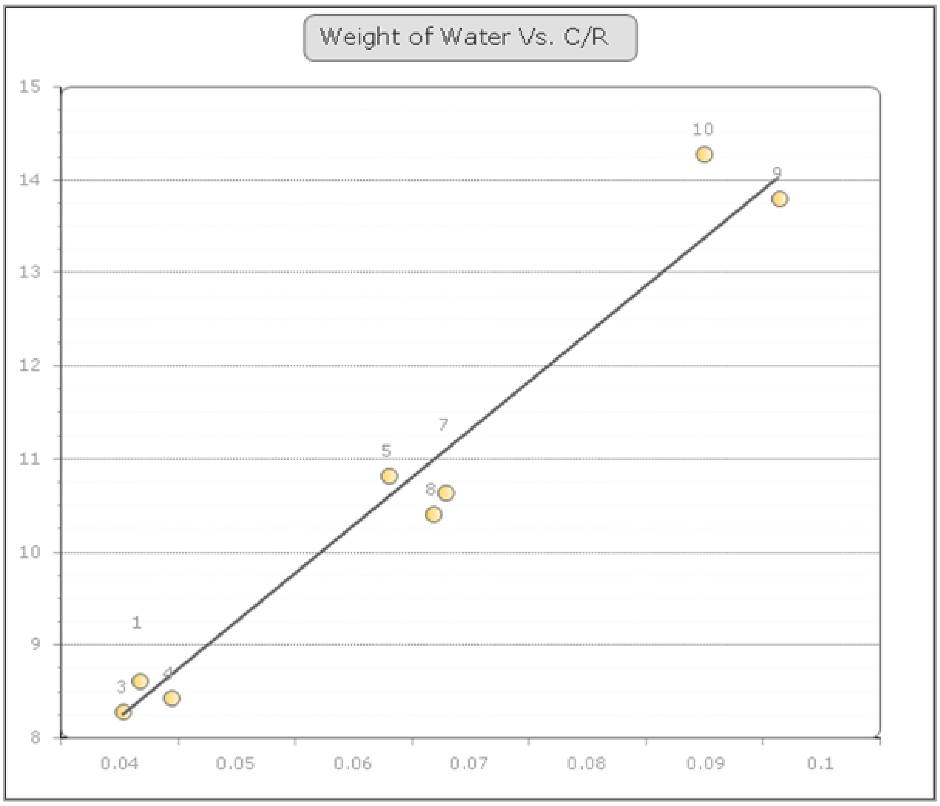
Table C-1: Data used in developing the EDG model for Klipheuwel

FIT	0.888	NO TEMPERATURE COMPENSATION		
KLIPHEWEUL SOIL MODEL DATA				
Field test	Wet density (kN/m^3)	Dry density (kN/m^3)	Weight of moisture (kN/m^3)	Moisture content (%)
1	18.97	17.61	1.36	7.70
2	18.52	17.22	1.29	7.49
3	19.16	17.86	1.30	7.30
4	19.35	18.02	1.33	7.36
5	19.74	18.04	1.70	9.44
6	19.20	17.56	1.65	9.38
7	19.72	18.05	1.67	9.27
8	19.77	18.13	1.64	9.03
9	20.05	17.89	2.17	12.13
10	20.23	17.99	2.25	12.48
11	19.61	17.46	2.16	12.35
12	20.13	17.91	2.22	12.40

Graph C-1: Plot of EDG measured impedance against the sand cone measured bulk density for Klipheuwel



Graph C-2: Plot of weight of water per unit volume against the capacitance to resistance ratio for Klipheuwel

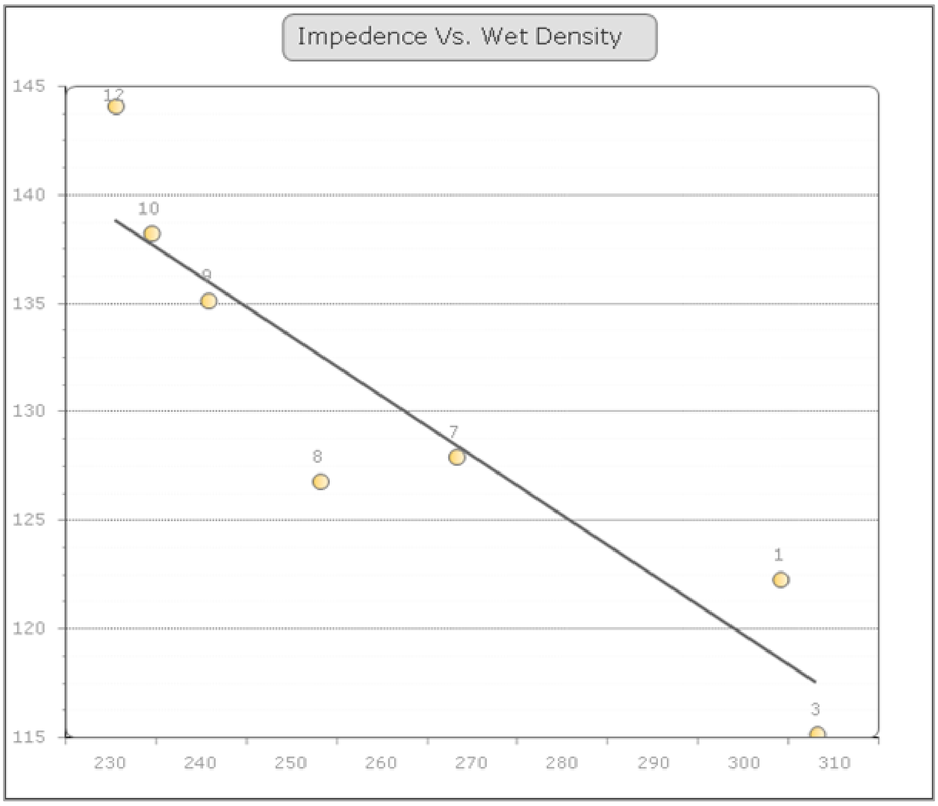


Cape Town (CL)

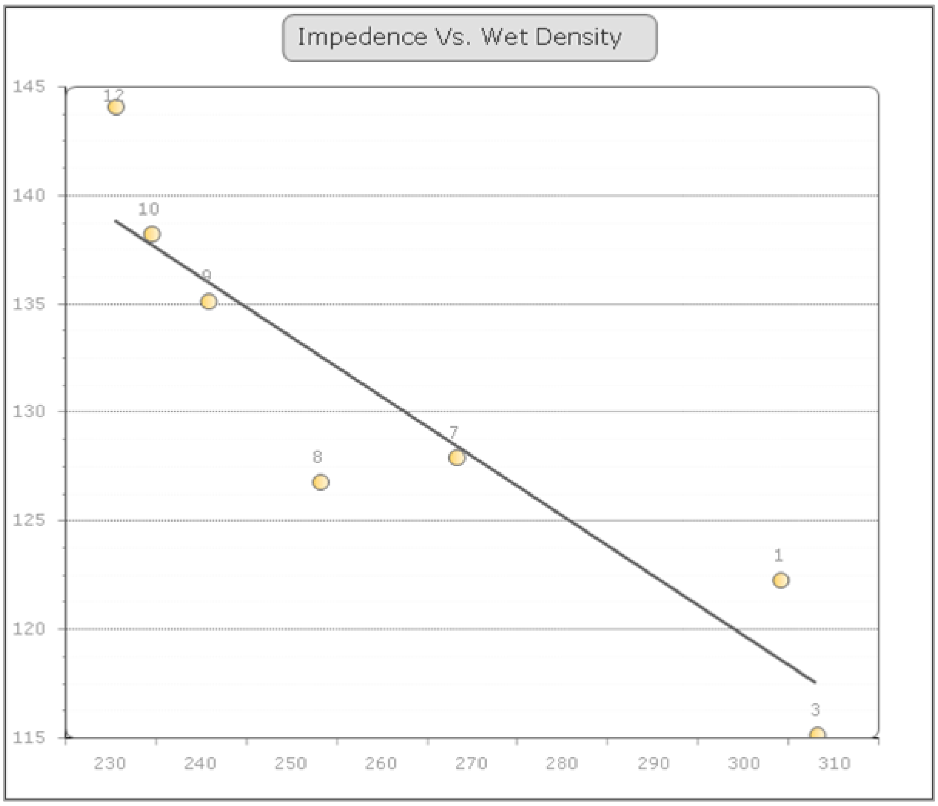
Table C-2: Data used in developing the EDG model for Cape Town (CL)

FIT	0.823	NO TEMPERATURE COMPENSATION		
CAPE TOWN (CL) SOIL MODEL DATA				
Field test	Wet density (kN/m^3)	Dry density (kN/m^3)	Weight of moisture (kN/m^3)	Moisture content (%)
1	19.22	17.11	2.11	12.32
2	19.10	17.04	2.07	12.14
3	18.10	16.18	1.93	11.91
4	17.57	15.70	1.87	11.93
5	19.38	16.71	2.67	15.95
6	18.38	15.97	2.41	15.07
7	20.10	17.47	2.63	15.06
8	19.93	17.30	2.63	15.21
9	21.23	17.95	3.28	18.27
10	21.72	18.34	3.38	18.43
11	22.15	18.73	3.43	18.29
12	22.64	19.23	3.41	17.73

Graph C-3: Plot of EDG measured impedance against the sand cone measured bulk density for Cape Town (CL)



Graph C-4: Plot of weight of water per unit volume against the capacitance to resistance ratio for Cape Town (CL)

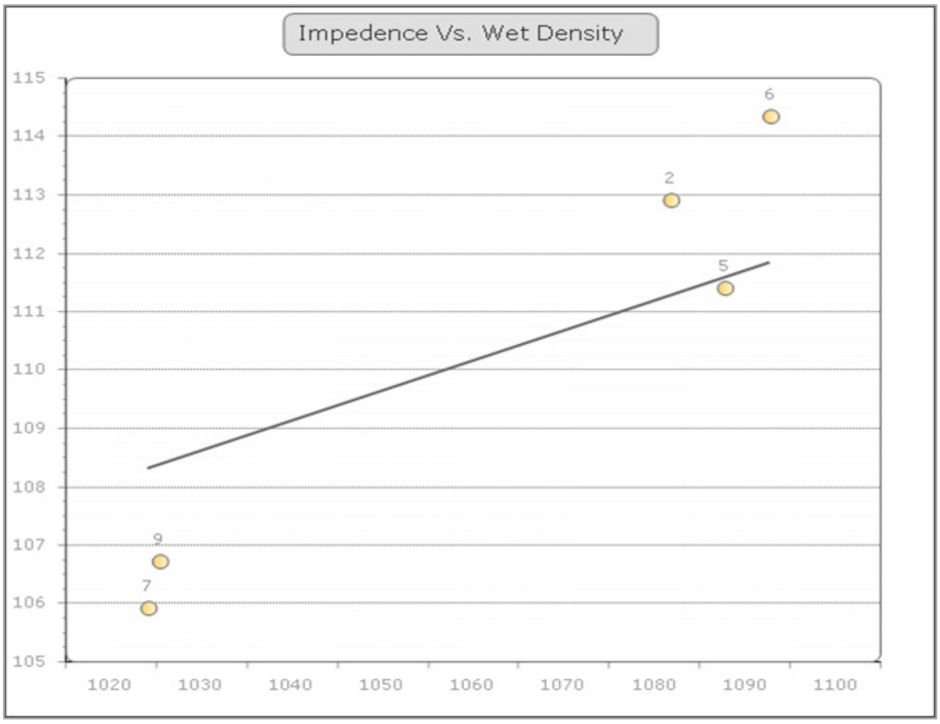


Khayelitsha sand

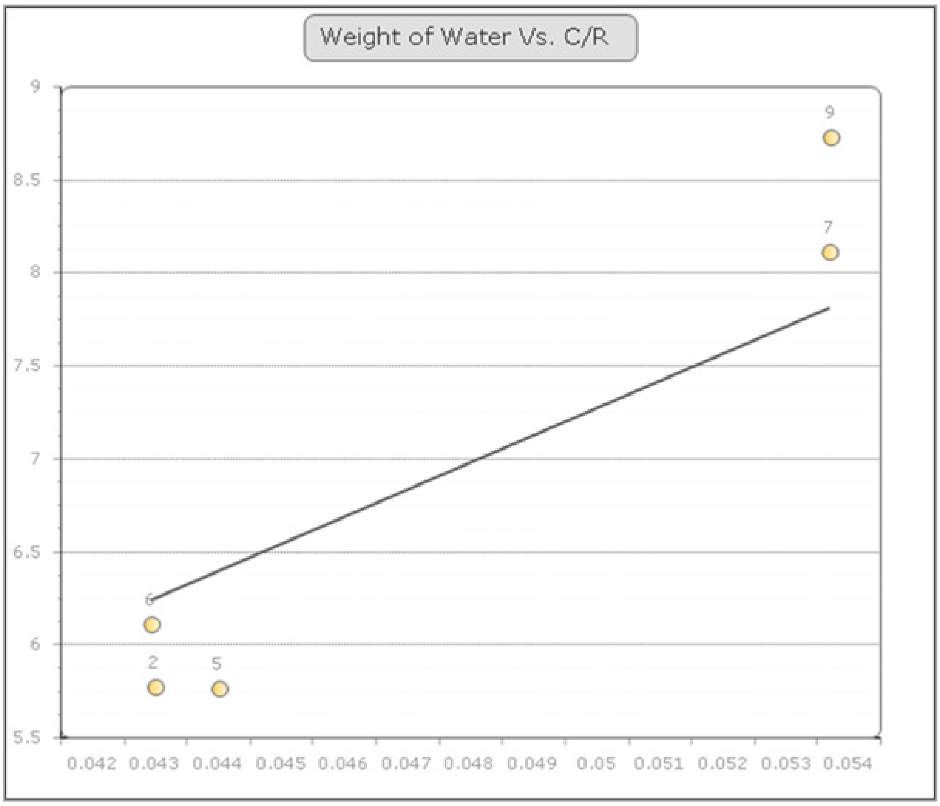
Table C-3: Data used in developing the EDG model for Khayelitsha

FIT	0.516	NO TEMPERATURE COMPENSATION		
KHAYELITSHA SOIL MODEL DATA				
Field test	Wet density (kN/m^3)	Dry density (kN/m^3)	Weight of moisture (kN/m^3)	Weight of Moisture (kN/m^3)
1	17.24	16.13	1.11	1.09
2	17.74	16.83	0.91	0.85
3	17.87	16.95	0.92	0.85
4	17.72	16.65	1.07	1.01
5	17.51	16.60	0.91	0.86
6	17.97	17.00	0.96	0.89
7	16.64	15.37	1.28	1.30
8	17.18	15.94	1.24	1.23
9	16.77	15.40	1.37	1.40
10	17.41	15.98	1.42	1.40
11	16.56	15.39	1.17	1.20

Graph C-5: Plot of EDG measured impedance against the sand cone measured bulk density for Khayelitsha



Graph C-6: Plot of weight of water per unit volume against the capacitance to resistance ratio for Khayelitsha

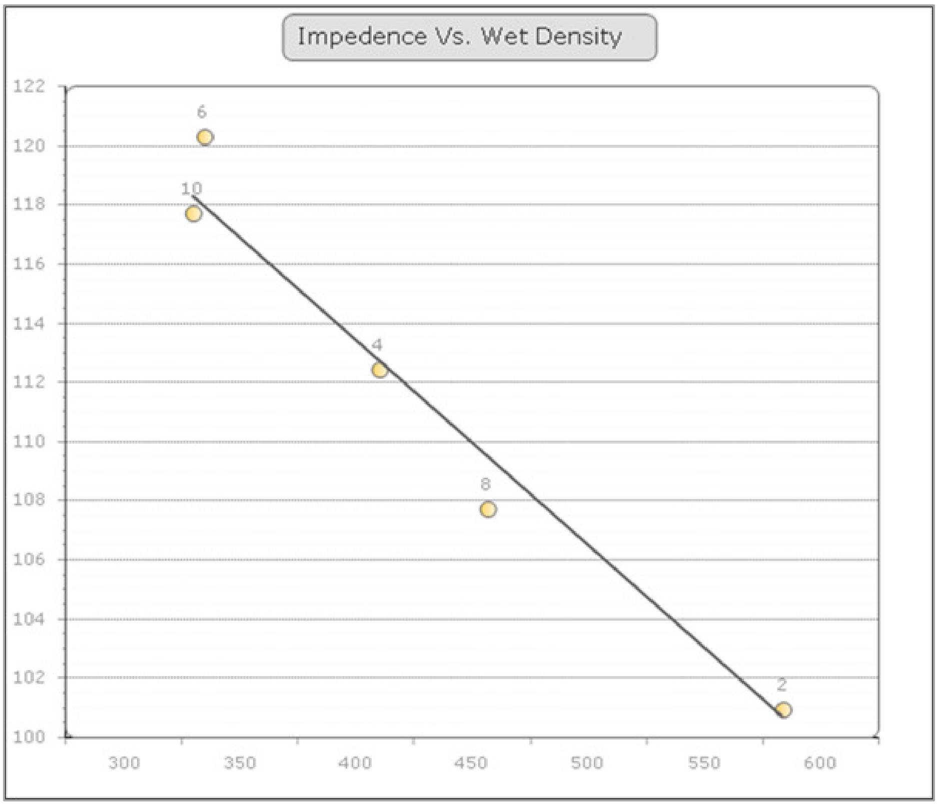


Pinelands

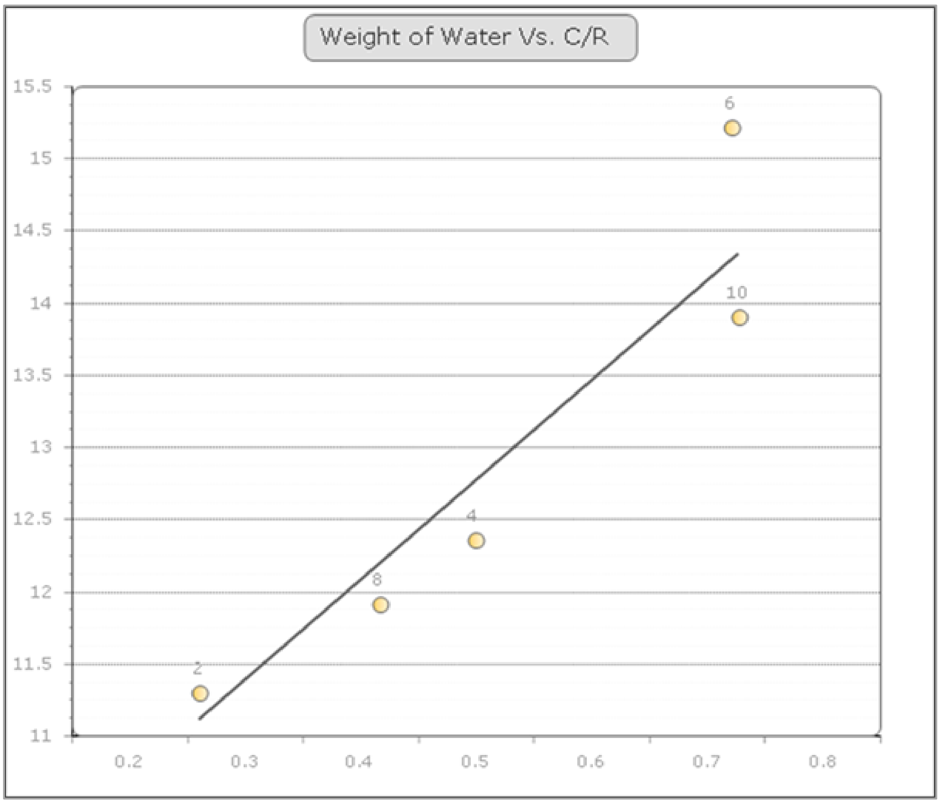
Table C-4: Data used in developing the EDG model for Pinelands

FIT	0.864	NO TEMPERATURE COMPENSATION		
PINELANDS SOIL MODEL DATA				
Field test	Bulk density (kN/m^3)	Dry density (kN/m^3)	Weight of moisture (kN/m^3)	Moisture content (%)
1	18.64	16.64	2.00	12.01
2	15.87	14.09	1.78	12.60
3	18.53	16.59	1.94	11.70
4	17.67	15.73	1.94	12.35
5	17.97	15.61	2.35	15.06
6	18.91	16.52	2.39	14.48
7	18.43	16.43	1.99	12.13
8	16.93	15.05	1.87	12.44
9	19.93	18.37	1.56	8.47
10	18.50	16.31	2.19	13.40
11	22.61	20.16	2.46	12.18

Graph C-7: Plot of EDG measured impedance against the sand cone measured bulk density for Pinelands



Graph C-8: Plot of weight of water per unit volume against the capacitance to resistance ratio for Pinelands

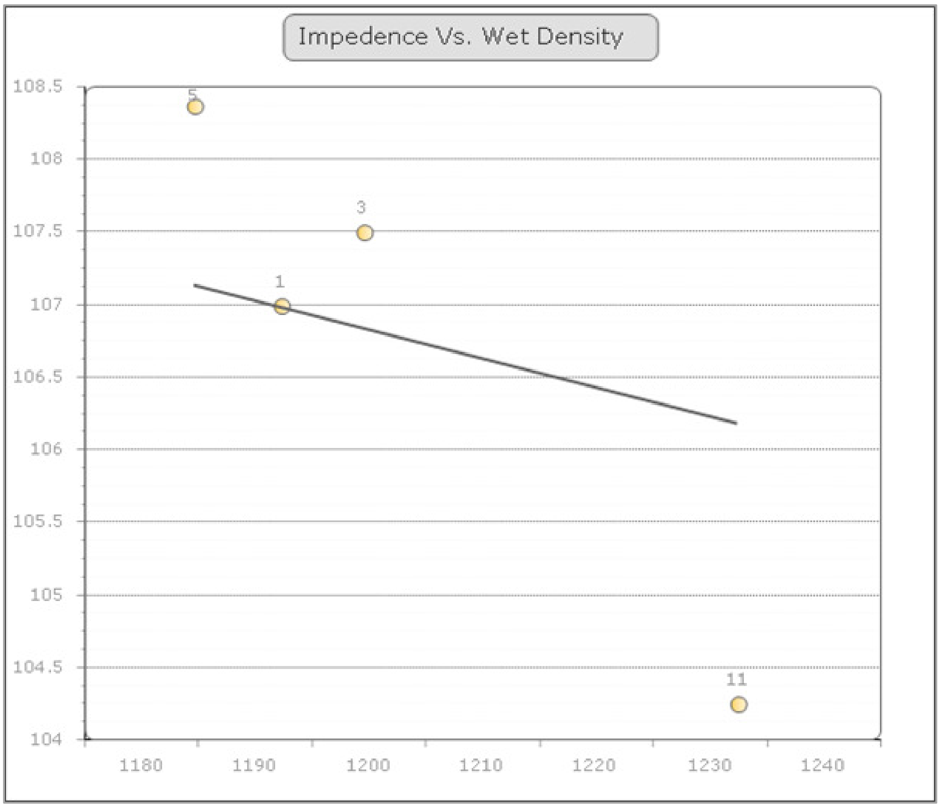


Burgundy sand (SP1)

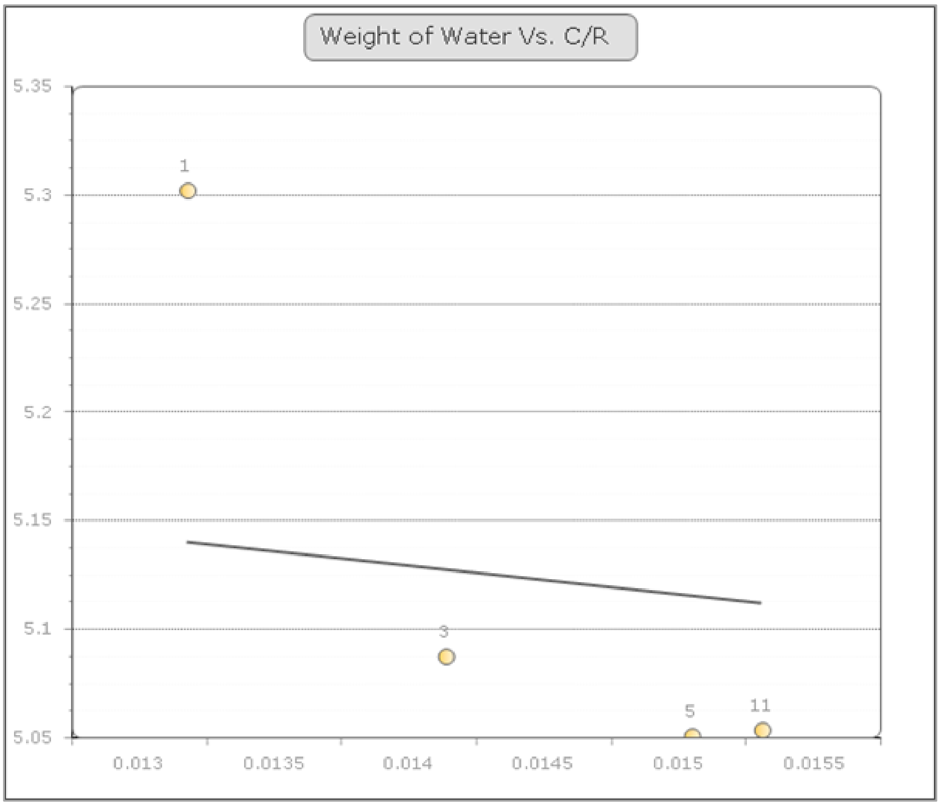
Table C-5: Data used in developing the EDG model for Burgundy sand (SP1)

FIT	0.163	NO TEMPERATURE COMPENSATION		
BURGUNDY SAND (SP1) SOIL MODEL DATA				
Field test	Wet density (kN/m³)	Dry density (kN/m³)	Weight of moisture (kN/m³)	Moisture content (%)
1	16.81	15.98	0.82	5.21
2	16.96	16.14	0.80	5.07
3	16.89	16.09	0.78	4.97
4	17.07	16.12	0.93	5.94
5	17.02	16.23	0.77	4.89
6	17.02	16.23	0.77	4.91
7	16.88	16.09	0.76	4.86
8	16.35	15.60	0.76	4.83
9	15.42	14.69	0.78	4.95
10	16.06	15.30	0.78	4.97
11	16.38	15.58	0.80	5.09

Graph C-9: Plot of EDG measured impedance against the sand cone measured bulk density for Burgundy sand (SP1)



Graph C-10: Plot of weight of water per unit volume against the capacitance to resistance ratio for Burgundy sand (SP1)

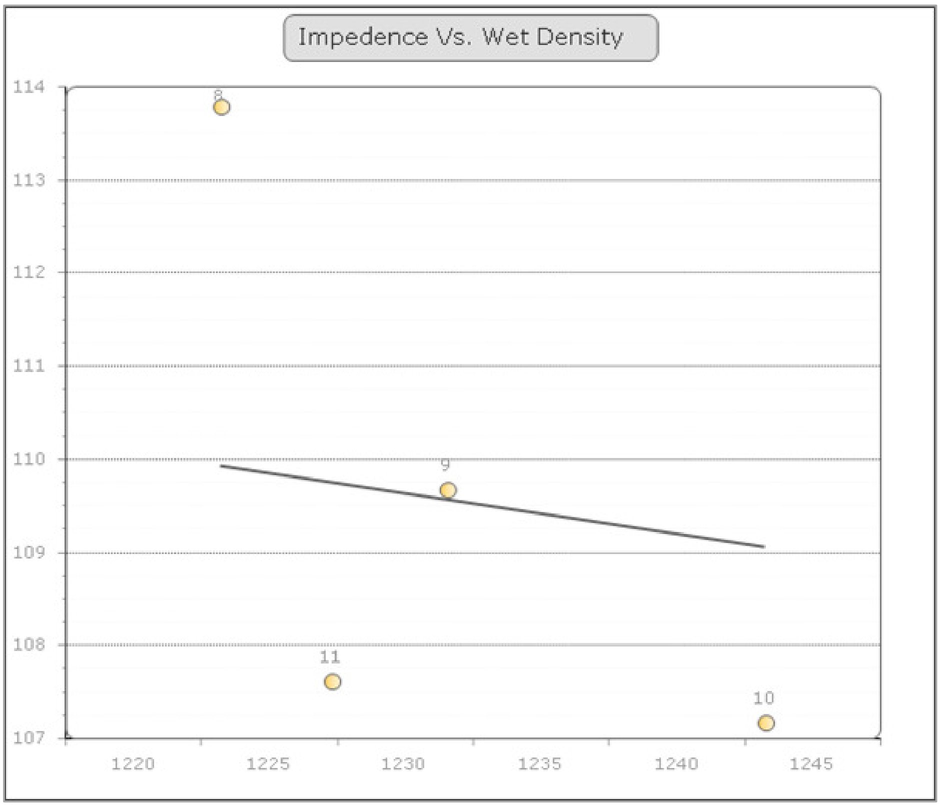


Burgundy sand (SP2)

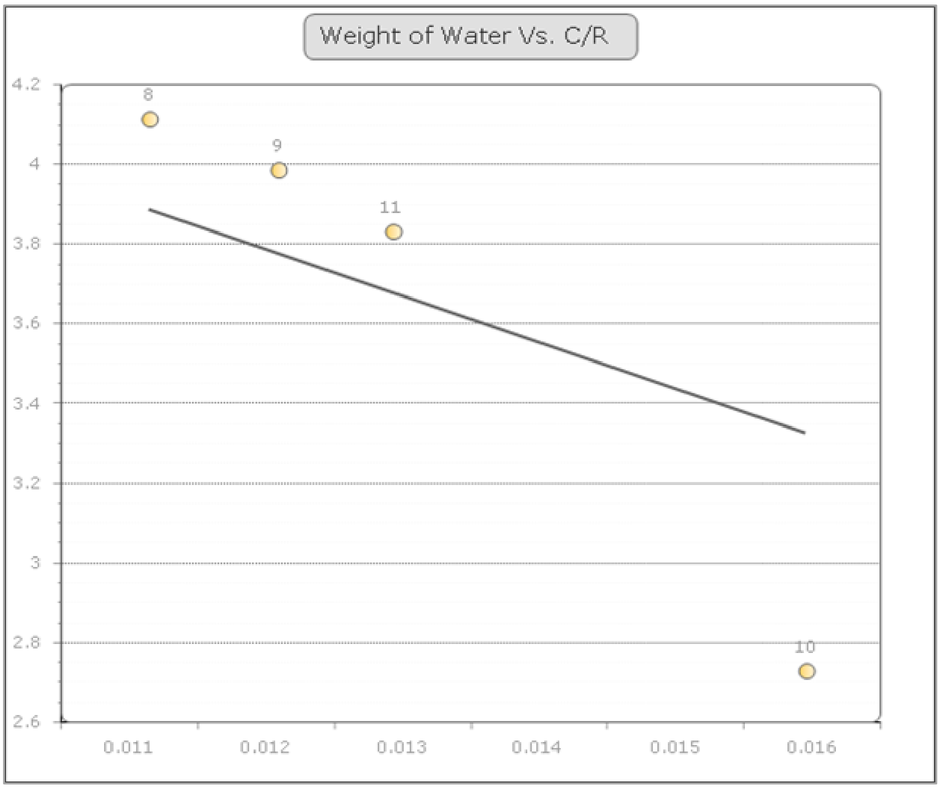
Table C-6: Data used in developing the EDG model for Burgundy sand (SP2)

FIT	0.232	NO TEMPERATURE COMPENSATION		
BURGUNDY SAND (SP2) SOIL MODEL DATA				
Field test	Wet density (kN/m^3)	Dry density (kN/m^3)	Weight of water (kN/m^3)	Moisture content (%)
1	17.04	16.47	0.54	3.46
2	16.85	16.17	0.66	4.22
3	17.11	16.49	0.59	3.79
4	16.75	16.12	0.61	3.89
5	17.60	16.90	0.66	4.17
6	17.42	16.81	0.57	3.62
7	17.48	16.88	0.56	3.53
8	17.88	17.23	0.59	3.75
9	17.23	16.60	0.59	3.77
10	16.84	16.41	0.41	2.67
11	16.91	16.30	0.58	3.70

Graph C-11: Plot of EDG measured impedance against the sand cone measured bulk density for Burgundy sand (SP2)



Graph C-12: Plot of weight of water per unit volume against the capacitance to resistance ratio for Burgundy sand (SP2)



APPENDIX D DATA COLLECTED

Appendix D.1 Electrical density gauge data

LABORATORY DATA

Klipheuwel sand

Table D-1: Electrical density gauge measurements for Klipheuwel sand

Test no.	Bulk Density (kN/m^3)		Moisture content (%)		Dry density (kN/m^3)	
1	19.26	19.26	7.58	7.58	17.90	17.90
2	19.16	19.12	7.27	7.14	17.86	17.85
3	19.22	19.22	7.63	7.65	17.86	17.86
4	19.09	19.09	7.05	7.11	17.83	17.83
5	19.14	19.14	7.34	7.31	17.83	17.84
6	19.67	19.67	9.31	9.33	17.99	17.99
7	19.71	19.75	9.47	9.59	18.01	18.02
8	19.68	19.70	9.39	9.45	17.99	18.00
9	19.61	19.62	9.00	9.01	17.99	18.00
10	19.67	19.68	9.34	9.41	17.99	17.99
11	19.67	19.68	9.39	9.45	17.98	17.98
12	19.70	19.68	9.53	9.51	17.98	17.97
13	19.68	19.72	9.34	9.48	18.00	18.01
14	20.22	20.31	12.63	13.40	17.96	17.91
15	20.17	20.17	12.38	12.40	17.95	17.95
16	20.23	20.22	12.74	12.76	17.94	17.93
17	20.19	20.19	12.71	12.77	17.91	17.90
18	20.36	20.36	13.76	13.79	17.89	17.89
19	20.23	20.22	12.54	12.57	17.97	17.97
Range	**1.270**	**1.270**	**6.710**	**6.680**	**0.180**	**0.190**
Mean	**19.719**	**19.726**	**9.916**	**9.985**	**19.938**	**17.936**
SE of mean	**0.0957**	**0.0975**	**0.502**	**0.518**	**0.0138**	**0.0143**
SD	**0.417**	**0.425**	**2.188**	**2.258**	**0.060**	**0.062**

Cape Town (SC-CL)

Table D-2: Electrical density gauge measurements for Cape Town (CL)

Test no.	Bulk Density (kN/m³)	Moisture content (%)	Dry density (kN/m³)
1	18.26	13.08	16.15
2	18.08	12.53	16.07
3	17.54	12.17	15.64
4	18.08	12.96	16.01
5	19.51	14.61	17.02
6	20.36	16.75	17.44
7	20.37	16.62	17.46
8	20.20	16.04	17.41
9	20.36	16.09	17.53
10	20.40	16.39	17.53
11	20.59	16.95	17.60
12	20.89	18.29	17.66
13	21.10	18.47	17.81
14	21.01	18.04	17.80
15	20.97	17.77	17.80
16	20.92	18.39	17.67
Range	**3.560**	**6.300**	**2.170**
Mean	**19.915**	**15.947**	**17.163**
SE of mean	**0.305**	**0.550**	**0.186**
SD	**1.220**	**2.202**	**0.744**

FIELD DATA

Khayelitsha sand

Table D-3: Electrical density gauge measurements for Khayelitsha sand

Test no.	Bulk Density (kN/m³)		Moisture content (%)		Dry density (kN/m³)	
1	17.38	17.37	6.94	6.97	16.25	16.23
2	17.21	17.20	8.21	8.27	15.90	15.88
3	17.16	17.22	7.77	7.61	15.92	16.00
4	16.98	16.93	8.36	8.48	15.67	15.61
5	16.88	16.92	7.77	7.76	15.66	15.70
6	17.32	17.26	6.49	6.63	16.27	16.19
7	17.18	17.19	6.57	6.54	16.12	16.13
8	17.24	17.21	7.22	7.25	16.08	16.05
9	17.48	17.52	5.40	5.33	16.59	16.64
10	16.97	17.02	8.07	7.75	15.70	15.80
11	17.29	17.28	6.34	6.31	16.26	16.25
12	17.42	17.39	6.76	6.87	16.32	16.27
13	17.40	17.43	6.28	6.21	16.37	16.41

Test no.	Bulk Density (kN/m^3)		Moisture content (%)		Dry density (kN/m^3)	
Range	**0.600**	**0.600**	**2.960**	**3.150**	**0.930**	**1.030**
Mean	**17.224**	**17.226**	**7.091**	**7.075**	**16.085**	**16.089**
SE of mean	**0.0520**	**0.0510**	**0.248**	**0.248**	**0.0819**	**0.0806**
SD	**0.187**	**0.184**	**0.895**	**0.893**	**0.295**	**0.291**

Pinelands

Table D-4: Electrical density gauge measurements for Pinelands

Test no.	Bulk Density (kN/m^3)		Moisture content (%)		Dry density (kN/m^3)	
1	17.27	17.30	12.68	12.72	15.33	15.35
2	17.26	17.27	12.57	12.58	15.33	15.34
3	17.00	17.04	12.44	12.46	15.12	15.16
4	16.66	16.64	12.41	12.41	14.82	14.81
5	18.73	18.73	13.87	13.90	16.45	16.45
6	17.37	17.37	12.65	12.65	15.42	15.41
7	18.10	18.12	13.11	13.15	16.00	16.02
8	18.58	18.57	13.77	13.76	16.33	16.33
9	18.14	18.16	13.14	13.15	16.04	16.05
10	17.77	17.75	12.85	12.84	15.74	15.73
11	17.97	18.01	12.98	13.01	15.91	15.93
Range	**2.070**	**2.090**	**1.460**	**1.490**	**1.630**	**1.640**
Mean	**17.714**	**17.724**	**12.952**	**12.966**	**15.681**	**15.684**
SE of mean	**0.198**	**0.198**	**0.149**	**0.150**	**0.156**	**0.155**
SD	**0.658**	**0.657**	**0.495**	**0.496**	**0.517**	**0.515**

Burgundy sand (SP1)

Table D-5: Electrical density gauge measurements for Burgundy sand (SP1)

Test no.	Bulk Density (kN/m^3)		Moisture content (%)		Dry density (kN/m^3)	
1	16.76	16.77	5.03	5.02	15.96	15.97
2	16.81	16.84	5.01	4.99	16.01	16.04
3	16.77	16.77	5.02	5.03	15.97	15.97
4	16.73	16.77	5.04	5.02	15.92	15.96
5	16.77	16.83	5.01	4.98	15.97	16.03
6	16.65	16.64	5.08	5.08	15.84	15.83
7	16.69	16.71	5.05	5.04	15.89	15.91
8	16.64	16.65	5.08	5.07	15.83	15.84
9	16.77	16.77	5.00	5.01	15.97	15.97
Range	**0.170**	**0.200**	**0.080**	**0.100**	**0.180**	**0.210**
Mean	**16.732**	**16.750**	**5.0356**	**5.0267**	**15.929**	**15.947**
SE of mean	**0.0198**	**0.0235**	**0.0099**	**0.0111**	**0.0210**	**0.0247**
SD	**0.0593**	**0.0705**	**0.0296**	**0.0332**	**0.0631**	**0.0740**

Burgundy sand (SP2)

Table D-6: Electrical density gauge measurements for Burgundy sand (SP2)

Test no.	**Bulk Density (kN/m³)**		**Moisture content (%)**		**Dry density (kN/m³)**	
1	17.13	17.12	3.26	3.30	16.59	16.58
2	17.24	17.27	3.35	3.44	16.66	16.70
3	17.33	17.33	3.34	3.45	16.75	16.75
4	17.27	17.29	3.48	3.43	16.71	16.73
5	17.23	17.27	3.49	3.44	16.64	16.68
6	17.32	17.32	3.39	3.39	16.74	16.75
7	17.44	17.42	3.54	3.52	16.85	16.83
8	17.40	17.41	3.42	3.42	16.87	16.88
9	17.17	17.15	3.50	3.49	16.64	16.63
10	17.32	17.33	3.19	3.17	16.73	16.74
11	17.20	17.19	3.17	3.12	16.61	16.61
Range	**0.310**	**0.300**	**0.370**	**0.400**	**0.280**	**0.300**
Mean	**17.277**	**17.282**	**3.3755**	**3.3791**	**16.708**	**16.716**
SE of mean	**0.0287**	**0.0292**	**0.0382**	**0.0389**	**0.0278**	**0.0272**
SD	**0.0953**	**0.0969**	**0.1268**	**0.1289**	**0.0921**	**0.0904**

Appendix D.2 Sand cone data

LABORATORY DATA

Klipheuwel sand

Table D-7: Reference test measurements for Klipheuwel sand

Test no.	Bulk Density (kN/m^3)	Moisture content (%)	Dry density (kN/m^3)
1	18.68	7.56	17.37
2	19.23	7.43	17.90
3	19.37	7.43	18.03
4	19.35	7.36	18.03
5	19.44	7.25	18.13
6	19.34	7.17	18.05
7	19.78	7.32	18.43
8	19.21	9.38	17.56
9	19.75	9.52	18.03
10	20.02	9.26	18.32
11	19.83	9.35	18.13
12	19.87	9.24	18.19
13	20.01	9.09	18.35
14	19.26	9.09	18.35
15	20.24	9.04	17.66
16	20.27	12.48	17.99
17	19.99	13.16	17.92
18	20.11	12.77	17.73
19	19.94	12.77	17.83
20	19.33	12.95	17.65
21	19.70	12.41	17.53
Range	**1.590**	**5.990**	**1.060**
Mean	**19.653**	**9.620**	**17.961**
SE of mean	**0.0899**	**0.480**	**0.0644**
SD	**0.412**	**2.198**	**0.295**

Cape Town (CL)

Table D-8: Reference test measurements for Cape Town (CL) sand

Test no.	Bulk Density (kN/m^3)	Moisture content (%)	Dry density (kN/m^3)
1	18.44	12.37	16.41
2	18.64	12.21	16.61
3	18.11	11.91	16.19
4	17.58	11.93	15.71
5	18.39	15.07	15.98
6	19.06	15.85	16.45
7	20.77	15.73	17.95
8	19.88	15.54	17.21
9	20.03	15.60	17.33
10	21.22	15.26	18.41
11	19.09	15.34	16.55
12	20.98	18.22	17.75
13	22.35	18.21	18.90
14	21.38	18.19	18.09
15	22.65	17.73	19.24
16	22.30	18.37	18.84
Range	**5.070**	**6.460**	**3.530**
Mean	**20.054**	**15.471**	**17.351**
SE of mean	**0.412**	**0.584**	**0.283**
SD	**1.649**	**2.336**	**1.131**

FIELD DATA

Khayelitsha sand

Table D-9: Reference test measurements for Khayelitsha sand

Test no.	Bulk Density (kN/m^3)	Moisture content (%)	Dry density (kN/m^3)
1	15.65	6.70	14.67
2	17.47	5.19	16.60
3	17.71	6.13	16.68
4	17.32	6.66	16.23
5	15.66	8.00	14.50
6	17.49	8.37	16.14
7	16.70	7.89	15.48
8	16.31	7.79	15.13
9	16.10	7.85	14.93
10	16.65	8.30	15.37
11	16.77	8.92	15.40
Range	**2.060**	**3.730**	**2.180**
Mean	**16.712**	**7.436**	**15.557**

Test no.	Bulk Density (kN/m³)	Moisture content (%)	Dry density (kN/m³)
SE of mean	**0.220**	**0.338**	**0.227**
SD	**0.730**	**1.120**	**0.754**

Pinelands

Table D-10: Reference test measurements for Pinelands

Test no.	Bulk Density (kN/m³)	Moisture content (%)	Dry density (kN/m³)
1	16.24	12.13	14.12
2	17.25	12.34	15.35
3	15.90	12.86	14.09
4	16.70	12.96	14.79
5	17.67	13.25	15.60
6	18.51	13.40	16.32
7	18.29	12.74	16.22
8	16.72	12.18	15.06
Range	**2.610**	**1.270**	**2.230**
Mean	**17.160**	**12.732**	**15.194**
SE of mean	**0.333**	**0.169**	**0.301**
SD	**0.942**	**0.479**	**0.850**

Burgundy sand (SP1)

Table D-11: Reference test measurements for Burgundy sand (SP1)

Test no.	Bulk Density (kN/m³)	Moisture content (%)	Dry density (kN/m³)
1	15.42	4.95	14.70
2	16.00	4.95	15.24
3	17.00	4.80	16.22
4	16.07	4.97	15.31
5	17.01	5.50	16.12
6	16.77	4.96	15.98
7	16.43	5.05	15.64
8	16.38	5.09	15.58
9	16.31	5.33	15.48
Range	**1.590**	**0.700**	**1.520**
Mean	**16.377**	**5.0667**	**15.586**
SE of mean	**0.171**	**0.0724**	**0.160**
SD	**0.513**	**0.2171**	**0.479**

Burgundy sand (SP2)

Table D-12: Reference test measurements for Burgundy sand (SP2)

Test no.	Bulk Density (kN/m^3)	Moisture content (%)	Dry density (kN/m^3)
1	16.38	4.09	15.74
2	16.74	3.82	16.13
3	16.63	3.88	16.01
4	16.65	4.26	15.97
5	16.09	4.27	15.43
6	17.60	4.17	16.89
7	17.24	3.77	16.61
8	17.25	3.64	16.65
9	17.19	3.50	16.61
10	17.40	3.52	16.81
11	16.84	2.67	16.40
12	16.81	3.27	16.28
13	16.91	3.70	16.31
Range	**1.510**	**1.600**	**1.460**
Mean	**16.902**	**3.735**	**16.295**
SE of mean	**0.118**	**0.123**	**0.119**
SD	**0.424**	**0.444**	**0.431**

APPENDIX E   VARIATION OF EDG MEASUREMENTS

Appendix E.1   Repeated measurements differences

Klipheuwel sand

Table E-1: Repeated measurement differences for Klipheuwel sand

Moisture content (%)		Difference	Bulk Density (kN/m^3)		Difference	Dry density (kN/m^3)		Difference
7.58	7.58	-0.01	19.26	19.26	0.00	17.90	17.90	0.00
7.27	7.14	0.13	19.16	19.12	0.04	17.86	17.85	0.01
7.63	7.65	-0.02	19.22	19.22	0.00	17.86	17.86	0.00
7.05	7.11	-0.06	19.09	19.09	-0.01	17.83	17.83	0.00
7.34	7.31	0.03	19.14	19.14	0.00	17.83	17.84	-0.01
9.31	9.33	-0.02	19.67	19.67	0.00	17.99	17.99	0.00
9.47	9.59	-0.13	19.71	19.75	-0.04	18.01	18.02	-0.02
9.39	9.45	-0.06	19.68	19.70	-0.02	17.99	18.00	-0.01
9.00	9.01	-0.02	19.61	19.62	-0.01	17.99	18.00	-0.01
9.34	9.41	-0.08	19.67	19.68	-0.01	17.99	17.99	0.00
9.39	9.45	-0.06	19.67	19.68	-0.02	17.98	17.98	0.00
9.53	9.51	0.03	19.70	19.68	0.01	17.98	17.97	0.01
9.34	9.48	-0.15	19.68	19.72	-0.04	18.00	18.01	-0.01
12.63	13.40	-0.77	20.17	20.17	0.00	17.96	17.91	0.04
12.38	12.40	-0.02	20.23	20.22	0.01	17.95	17.95	0.00
12.74	12.76	-0.03	20.19	20.19	-0.01	17.94	17.93	0.01
12.71	12.77	-0.07	20.36	20.36	0.00	17.91	17.90	0.01
13.76	13.79	-0.03	20.23	20.22	0.00	17.89	17.89	0.00
SD		0.179	SD		0.017	SD		0.012

Khayelitsha sand

Table E-2: Repeated measurement differences for Khayelitsha sand

Moisture content (%)		Difference	Bulk Density (kN/m^3)		Difference	Dry density (kN/m^3)		Difference
6.94	6.97	-0.03	17.38	17.37	0.01	16.25	16.23	0.02
8.21	8.27	-0.06	17.21	17.20	0.01	15.90	15.88	0.02
7.77	7.61	0.17	17.16	17.22	-0.06	15.92	16.00	-0.08
8.36	8.48	-0.12	16.98	16.93	0.05	15.67	15.61	0.07
7.77	7.76	0.01	16.88	16.92	-0.04	15.66	15.70	-0.04
6.49	6.63	-0.14	17.32	17.26	0.06	16.27	16.19	0.07
6.57	6.54	0.02	17.18	17.19	-0.01	16.12	16.13	-0.01
7.22	7.25	-0.03	17.24	17.21	0.03	16.08	16.05	0.03
5.40	5.33	0.07	17.48	17.52	-0.04	16.59	16.64	-0.05
8.07	7.75	0.32	16.97	17.02	-0.05	15.70	15.80	-0.09
6.34	6.31	0.03	17.29	17.28	0.01	16.26	16.25	0.00
6.76	6.87	-0.11	17.42	17.39	0.04	16.32	16.27	0.05

6.28	6.21	0.07	17.40	17.43	-0.04	16.37	16.41	-0.04
SD		0.120	SD		0.039	SD		0.052

Pinelands

Table E-3: Repeated measurement differences for Pinelands

Moisture content (%)		Difference	Bulk Density (kN/m^3)		Difference	Dry density (kN/m^3)		Difference
12.68	12.72	-0.04	17.27	17.30	-0.03	15.33	15.35	-0.02
12.57	12.58	-0.01	17.26	17.27	-0.02	15.33	15.34	-0.01
12.44	12.46	-0.01	17.00	17.04	-0.05	15.12	15.16	-0.04
12.41	12.41	0.00	16.66	16.64	0.02	14.82	14.81	0.01
13.87	13.90	-0.03	18.73	18.73	0.00	16.45	16.45	0.00
12.65	12.65	0.00	17.37	17.37	0.00	15.42	15.41	0.00
13.11	13.15	-0.04	18.10	18.12	-0.02	16.00	16.02	-0.01
13.77	13.76	0.01	18.58	18.57	0.00	16.33	16.33	0.00
13.14	13.15	-0.01	18.14	18.16	-0.01	16.04	16.05	-0.01
12.85	12.84	0.02	17.77	17.75	0.01	15.74	15.73	0.01
12.98	13.01	-0.04	17.97	18.01	-0.03	15.91	15.93	-0.02
SD		0.020	SD		0.019	SD		0.015

Burgundy sand (SP1)

Table E-4: Repeated measurement differences for Burgundy sand (SP1)

Moisture content (%)		Difference	Bulk Density (kN/m^3)		Difference	Dry density (kN/m^3)		Difference
5.03	5.02	0.01	16.76	16.77	-0.01	15.96	15.97	-0.01
5.01	4.99	0.02	16.81	16.84	-0.03	16.01	16.04	-0.03
5.02	5.03	0.00	16.77	16.77	0.00	15.97	15.97	0.00
5.04	5.02	0.02	16.73	16.77	-0.04	15.92	15.96	-0.04
5.01	4.98	0.03	16.77	16.83	-0.06	15.97	16.03	-0.06
5.08	5.08	0.00	16.65	16.64	0.01	15.84	15.83	0.01
5.05	5.04	0.01	16.69	16.71	-0.02	15.89	15.91	-0.02
5.08	5.07	0.00	16.64	16.65	-0.01	15.83	15.84	-0.01
5.00	5.01	0.00	16.77	16.77	0.00	15.97	15.97	0.00
SD		0.010	SD		0.020	SD		0.020

Burgundy sand (SP2)

Table E-5: Repeated measurement differences for Burgundy sand (SP2)

Moisture content (%)		Difference	Bulk Density (kN/m^3)		Difference	Dry density (kN/m^3)		Difference
3.26	3.30	-0.03	17.13	17.12	0.01	16.59	16.58	0.01
3.48	3.43	0.05	17.24	17.27	-0.03	16.66	16.70	-0.04
3.49	3.44	0.05	17.33	17.33	0.01	16.75	16.75	0.00
3.39	3.39	0.00	17.27	17.29	-0.02	16.71	16.73	-0.02
3.54	3.52	0.03	17.23	17.27	-0.04	16.64	16.68	-0.04
3.42	3.42	0.01	17.32	17.32	0.00	16.74	16.75	0.00
3.50	3.49	0.01	17.44	17.42	0.02	16.85	16.83	0.02
3.19	3.17	0.01	17.40	17.41	-0.01	16.87	16.88	-0.01
3.17	3.12	0.05	17.17	17.15	0.02	16.64	16.63	0.01
3.49	3.47	0.01	17.32	17.33	-0.01	16.73	16.74	-0.01
3.52	3.53	-0.01	17.20	17.19	0.00	16.61	16.61	0.01
SD		0.025	SD		0.019	SD		0.019

Appendix E.2 Absolute differences

Klipheuwel

Table E-6: Absolute differences for moisture content, bulk density and dry density measurements in Klipheuwel sand

Test no.	LO moisture content (%)	EDG moisture content (%)	Absolute Difference	SC bulk density (kN/m^3)	EDG bulk density (kN/m^3)	Absolute Difference	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	Absolute Difference
1	7.56	7.54	0.02	18.68	19.24	0.56	17.37	17.89	0.52
2	7.43	7.37	0.05	19.23	19.16	0.07	17.90	17.85	0.06
3	7.43	7.58	0.16	19.37	19.28	0.09	18.03	17.93	0.11
4	7.36	7.58	0.22	19.35	19.26	0.09	18.03	17.90	0.12
5	7.25	7.21	0.04	19.44	19.14	0.30	18.13	17.86	0.27
6	7.17	7.08	0.09	19.34	19.09	0.25	18.05	17.83	0.22
7	7.32	7.32	0.00	19.78	19.14	0.63	18.43	17.84	0.59
8	9.38	9.32	0.06	19.21	19.67	0.46	17.56	17.99	0.43
9	9.52	9.53	0.01	19.75	19.73	0.01	18.03	18.01	0.01
10	9.26	9.42	0.16	20.02	19.69	0.33	18.32	17.99	0.33
11	9.35	9.37	0.02	19.83	19.62	0.21	18.13	17.99	0.14
12	9.24	9.01	0.23	19.87	19.68	0.20	18.19	17.99	0.20
13	9.09	9.42	0.33	20.01	19.68	0.34	18.35	17.98	0.36
14	9.09	9.52	0.43	19.26	19.69	0.43	18.35	17.98	0.37
15	9.04	9.41	0.36	20.24	19.70	0.54	17.66	18.01	0.34
16	12.48	12.11	0.38	20.27	20.14	0.13	17.99	17.97	0.03
17	13.16	13.01	0.15	19.99	20.27	0.28	17.92	17.93	0.02
18	12.77	12.39	0.38	20.11	20.17	0.06	17.73	17.95	0.22
19	12.77	12.75	0.02	19.94	20.22	0.29	17.83	17.94	0.10

20	12.95	12.74	0.21	19.33	20.19	0.86	17.65	17.91	0.26
21	12.41	12.56	0.14	19.70	20.23	0.52	17.53	17.97	0.44

Cape Town (CL)

Table E-7: Absolute differences for moisture content, bulk density and dry density measurements in Cape Town (CL)

Test no.	LO moisture content (%)	EDG moisture content (%)	Absolute Difference	SC bulk density (kN/m^3)	EDG bulk density (kN/m^3)	Absolute Difference	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	Absolute Difference
1	12.37	13.08	0.71	18.44	18.26	0.18	16.41	16.15	0.26
2	12.21	12.53	0.32	18.64	18.08	0.56	16.61	16.07	0.55
3	11.91	12.17	0.26	18.11	17.54	0.57	16.19	15.64	0.55
4	11.93	12.96	1.03	17.58	18.08	0.50	15.71	16.01	0.30
5	15.07	14.61	0.46	18.39	19.51	1.12	15.98	17.02	1.04
6	15.85	16.75	0.90	19.06	20.36	1.30	16.45	17.44	0.99
7	15.73	16.62	0.89	20.77	20.37	0.40	17.95	17.46	0.48
8	15.54	16.04	0.50	19.88	20.20	0.32	17.21	17.41	0.20
9	15.60	16.09	0.49	20.03	20.36	0.33	17.33	17.53	0.21
10	15.26	16.39	1.13	21.22	20.40	0.82	18.41	17.53	0.88
11	15.34	16.95	1.61	19.09	20.59	1.50	16.55	17.60	1.06
12	18.22	18.29	0.07	20.98	20.89	0.09	17.75	17.66	0.09
13	18.21	18.47	0.26	22.35	21.10	1.25	18.90	17.81	1.09
14	18.19	18.04	0.15	21.38	21.01	0.37	18.09	17.80	0.29
15	17.73	17.77	0.04	22.65	20.97	1.68	19.24	17.80	1.44
16	18.37	18.39	0.01	22.30	20.92	1.38	18.84	17.67	1.17

Khayelitsha

Table E-8: Absolute differences for moisture content, bulk density and dry density measurements in Khayelitsha sand

Test no.	LO moisture content (%)	EDG moisture content (%)	Absolute Difference	SC bulk density (kN/m^3)	EDG bulk density (kN/m^3)	Absolute Difference	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	Absolute Difference
1	6.70	6.95	0.26	15.65	17.37	1.72	14.67	16.24	1.57
2	5.19	5.37	0.18	17.47	17.50	0.04	16.60	16.61	0.01
3	6.13	6.33	0.20	17.71	17.28	0.42	16.68	16.26	0.43
4	6.66	6.56	0.10	17.32	17.29	0.02	16.23	16.23	0.01
5	8.00	7.77	0.23	15.66	16.90	1.24	14.50	15.68	1.18
6	8.37	8.24	0.13	17.49	17.20	0.29	16.14	15.89	0.25
7	7.89	7.69	0.20	16.70	17.19	0.49	15.48	15.96	0.48
8	7.79	7.23	0.56	16.31	17.23	0.91	15.13	16.06	0.93
9	7.85	7.28	0.57	16.10	17.09	0.98	14.93	15.93	1.00
10	8.30	7.91	0.39	16.65	17.00	0.35	15.37	15.75	0.38
11	8.92	8.42	0.50	16.77	16.96	0.18	15.40	15.64	0.24

Pinelands

Table E-9: Absolute differences for moisture content, bulk density and dry density measurements in Pinelands

Test no.	LO moisture content (%)	EDG moisture content (%)	Absolute Difference	SC bulk density (kN/m^3)	EDG bulk density (kN/m^3)	Absolute Difference	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	Absolute Difference
1	12.13	12.65	0.52	16.24	17.37	1.13	14.12	15.42	1.29
2	12.34	12.85	0.51	17.25	17.76	0.51	15.35	15.74	0.39
3	12.86	13.13	0.28	15.90	18.11	2.21	14.09	16.01	1.92
5	12.96	13.14	0.18	16.70	18.15	1.45	14.79	16.04	1.26
7	13.25	13.77	0.52	17.67	18.57	0.91	15.60	16.33	0.73
8	13.40	13.89	0.49	18.51	18.73	0.23	16.32	16.45	0.13
9	12.74	13.00	0.26	18.29	17.99	0.30	16.22	15.92	0.30
10	12.18	12.70	0.52	16.72	17.26	0.54	15.06	15.34	0.28

Burgundy sand (SP1)

Table E-10: Absolute differences for moisture content, bulk density and dry density measurements in Burgundy sand (SP1)

Test no.	LO moisture content (%)	EDG moisture content (%)	Absolute Difference	SC bulk density (kN/m^3)	EDG bulk density (kN/m^3)	Absolute Difference	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	Absolute Difference
1	4.95	5.02	0.07	15.42	16.77	1.34	14.70	15.97	1.27
2	4.95	4.99	0.05	16.00	16.82	0.83	15.24	16.02	0.78
3	4.80	5.03	0.22	17.00	16.77	0.23	16.22	15.97	0.25
4	4.97	5.02	0.05	16.07	16.75	0.68	15.31	15.94	0.63
5	5.50	4.98	0.52	17.01	16.80	0.21	16.12	16.00	0.12
6	4.96	5.08	0.12	16.77	16.64	0.13	15.98	15.84	0.14
7	5.05	5.04	0.01	16.43	16.70	0.27	15.64	15.90	0.26
8	5.09	5.07	0.02	16.38	16.64	0.26	15.58	15.84	0.25
9	5.33	5.01	0.33	16.31	16.77	0.47	15.48	15.97	0.49

Burgundy sand (SP2)

Table E-11: Absolute differences for moisture content, bulk density and dry density measurements in Burgundy sand (SP2)

Test no.	LO moisture content (%)	EDG moisture content (%)	Absolute Difference	SC bulk density (kN/m^3)	EDG bulk density (kN/m^3)	Absolute Difference	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	Absolute Difference
1	4.09	3.28	0.81	16.38	17.13	0.75	15.74	16.58	0.85
2	3.82	3.40	0.42	16.74	17.49	0.75	16.13	16.92	0.79
3	3.88	3.39	0.49	16.63	17.04	0.41	16.01	16.48	0.47
4	4.26	3.46	0.81	16.65	17.25	0.61	15.97	16.68	0.71
5	4.27	3.47	0.80	16.09	17.33	1.24	15.43	16.75	1.32
6	4.17	3.39	0.78	17.60	17.28	0.31	16.89	16.72	0.18
7	3.77	3.53	0.25	17.24	17.25	0.01	16.61	16.66	0.05
8	3.64	3.42	0.22	17.25	17.32	0.07	16.65	16.75	0.10
9	3.50	3.50	0.00	17.19	17.43	0.24	16.61	16.84	0.23
10	3.52	3.18	0.33	17.40	17.41	0.01	16.81	16.87	0.06
11	2.67	3.14	0.47	16.84	17.16	0.32	16.40	16.64	0.23
12	3.27	3.48	0.21	16.81	17.32	0.51	16.28	16.74	0.46
13	3.70	3.53	0.17	16.91	17.20	0.28	16.31	16.61	0.30

Appendix E.3 Percentage deviation of the measurements

Klipheuwel sand

Table E-12: Percentage deviation for moisture content, bulk density and dry density measurements in Klipheuwel sand

LO moisture content (%)	EDG moisture content (%)	% deviation	sand cone bulk density (kN/m^3)	EDG bulk density (kN/m^3)	%deviation	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	% deviation
7.56	7.54	0.30	18.68	19.24	-2.97	17.37	17.89	-3.00
7.43	7.37	0.71	19.23	19.16	0.37	17.90	17.85	0.32
7.43	7.58	-2.09	19.37	19.28	0.46	18.03	17.93	0.60
7.36	7.58	-3.00	19.35	19.26	0.49	18.03	17.90	0.69
7.25	7.21	0.58	19.44	19.14	1.55	18.13	17.86	1.51
7.17	7.08	1.28	19.34	19.09	1.29	18.05	17.83	1.20
7.32	7.32	-0.06	19.78	19.14	3.21	18.43	17.84	3.21
9.38	9.32	0.65	19.21	19.67	-2.39	17.56	17.99	-2.45
9.52	9.53	-0.16	19.75	19.73	0.07	18.03	18.01	0.08
9.26	9.42	-1.73	20.02	19.69	1.64	18.32	17.99	1.79
9.35	9.37	-0.24	19.83	19.62	1.07	18.13	17.99	0.76
9.24	9.01	2.52	19.87	19.68	1.00	18.19	17.99	1.12
9.09	9.42	-3.67	20.01	19.68	1.69	18.35	17.98	1.99

9.09	9.52	-4.78	19.26	19.69	-2.23	18.35	17.98	2.01
9.04	9.41	-4.03	20.24	19.70	2.67	17.66	18.01	-1.94
12.48	12.11	3.02	20.27	20.14	0.66	17.99	17.97	0.16
13.16	13.01	1.14	19.99	20.27	-1.38	17.92	17.93	-0.11
12.77	12.39	2.97	20.11	20.17	-0.31	17.73	17.95	-1.25
12.77	12.75	0.15	19.94	20.22	-1.44	17.83	17.94	-0.58
12.95	12.74	1.61	19.33	20.19	-4.44	17.65	17.91	-1.45
12.41	12.56	-1.16	19.70	20.23	-2.66	17.53	17.97	-2.53

Cape Town (CL)

Table E-13: Percentage deviation for moisture content, bulk density and dry density measurements in Cape Town (CL)

Oven moisture content (%)	EDG moisture content (%)	% deviation	sand cone bulk density (kN/m^3)	EDG bulk density (kN/m^3)	% deviation	sand cone dry density (kN/m^3)	EDG dry density (kN/m^3)	% deviation
12.37	13.08	-5.73	18.44	18.26	0.96	16.41	16.15	1.57
12.21	12.53	-2.58	18.64	18.08	3.03	16.61	16.07	3.29
11.91	12.17	-2.19	18.11	17.54	3.16	16.19	15.64	3.39
11.93	12.96	-8.66	17.58	18.08	-2.83	15.71	16.01	-1.89
15.07	14.61	3.05	18.39	19.51	-6.11	15.98	17.02	-6.51
15.85	16.75	-5.70	19.06	20.36	-6.82	16.45	17.44	-6.02
15.73	16.62	-5.65	20.77	20.37	1.94	17.95	17.46	2.70
15.54	16.04	-3.19	19.88	20.20	-1.59	17.21	17.41	-1.17
15.60	16.09	-3.11	20.03	20.36	-1.64	17.33	17.53	-1.20
15.26	16.39	-7.42	21.22	20.40	3.87	18.41	17.53	4.80
15.34	16.95	-10.50	19.09	20.59	-7.88	16.55	17.60	-6.38
18.22	18.29	-0.37	20.98	20.89	0.44	17.75	17.66	0.49
18.21	18.47	-1.43	22.35	21.10	5.58	18.90	17.81	5.78
18.19	18.04	0.85	21.38	21.01	1.73	18.09	17.80	1.61
17.73	17.77	-0.21	22.65	20.97	7.42	19.24	17.80	7.48
18.37	18.39	-0.06	22.30	20.92	6.17	18.84	17.67	6.19

Khayelitsha sand

Table E-14: Percentage deviation for moisture content, bulk density and dry density measurements in Khayelitsha sand

LO moisture content (%)	EDG moisture content (%)	% deviation	SC bulk density (kN/m^3)	EDG bulk density (kN/m^3)	% deviation	SC dry density (kN/m^3)	EDG dry density (kN/m^3)	% deviation
6.70	6.95	-3.84	15.65	17.37	-10.98	14.67	16.24	-10.71
5.19	5.37	-3.39	17.47	17.50	-0.21	16.60	16.61	-0.05
6.13	6.33	-3.27	17.71	17.28	2.39	16.68	16.26	2.57

6.66	6.56	1.43	17.32	17.29	0.13	16.23	16.23	0.04
8.00	7.77	2.92	15.66	16.90	-7.89	14.50	15.68	-8.13
8.37	8.24	1.53	17.49	17.20	1.66	16.14	15.89	1.54
7.89	7.69	2.54	16.70	17.19	-2.92	15.48	15.96	-3.11
7.79	7.23	7.18	16.31	17.23	-5.59	15.13	16.06	-6.14
7.85	7.28	7.24	16.10	17.09	-6.12	14.93	15.93	-6.68
8.30	7.91	4.69	16.65	17.00	-2.12	15.37	15.75	-2.49
8.92	8.42	5.56	16.77	16.96	-1.10	15.40	15.64	-1.56

Pinelands

Table E-15: Percentage deviation for moisture content, bulk density and dry density measurements in Pinelands

Oven moisture content (%)	EDG moisture content (%)	% deviation	sand cone bulk density (kN/m^3)	EDG bulk density (kN/m^3)	% deviation	sand cone dry density (kN/m^3)	EDG dry density (kN/m^3)	% deviation
12.13	12.65	-4.30	16.24	17.37	-6.95	14.12	15.42	-9.17
12.34	12.85	-4.12	17.25	17.76	-2.97	15.35	15.74	-2.51
12.86	13.13	-2.14	15.90	18.11	-13.89	14.09	16.01	-13.62
12.96	13.14	-1.39	16.70	18.15	-8.67	14.79	16.04	-8.50
13.25	13.77	-3.93	17.67	18.57	-5.14	15.60	16.33	-4.65
13.40	13.89	-3.62	18.51	18.73	-1.23	16.32	16.45	-0.79
12.74	13.00	-2.01	18.29	17.99	1.63	16.22	15.92	1.86
12.18	12.70	-4.27	16.72	17.26	-3.23	15.06	15.34	-1.85

Burgundy sand (SP1)

Table E-16: Percentage deviation for moisture content, bulk density and dry density measurements in Burgundy sand (SP1)

Oven moisture content (%)	EDG moisture content (%)	% deviation	sand cone bulk density (kN/m^3)	EDG bulk density (kN/m^3)	% deviation	sand cone dry density (kN/m^3)	EDG dry density (kN/m^3)	% deviation
4.95	5.02	-1.51	15.42	16.77	-8.71	14.70	15.97	-8.63
4.95	4.99	-0.95	16.00	16.82	-5.18	15.24	16.02	-5.12
4.80	5.03	-4.61	17.00	16.77	1.36	16.22	15.97	1.56
4.97	5.02	-1.10	16.07	16.75	-4.21	15.31	15.94	-4.15
5.50	4.98	9.46	17.01	16.80	1.23	16.12	16.00	0.75
4.96	5.08	-2.32	16.77	16.64	0.78	15.98	15.84	0.88
5.05	5.04	0.20	16.43	16.70	-1.65	15.64	15.90	-1.66
5.09	5.07	0.41	16.38	16.64	-1.62	15.58	15.84	-1.64
5.33	5.01	6.10	16.31	16.77	-2.86	15.48	15.97	-3.18

Burgundy sand (SP2)

Table E-17: Percentage deviation for moisture content, bulk density and dry density measurements in Burgundy sand (SP2)

Oven moisture content (%)	EDG moisture content (%)	% deviation	sand cone bulk density (kN/m^3)	EDG bulk density (kN/m^3)	% deviation	sand cone dry density (kN/m^3)	EDG dry density (kN/m^3)	% deviation
4.09	3.28	19.85	16.38	17.13	-4.55	15.74	16.58	-5.37
3.82	3.40	10.97	16.74	17.49	-4.48	16.13	16.92	-4.90
3.88	3.39	12.66	16.63	17.04	-2.48	16.01	16.48	-2.96
4.26	3.46	18.99	16.65	17.25	-3.64	15.97	16.68	-4.45
4.27	3.47	18.77	16.09	17.33	-7.73	15.43	16.75	-8.56
4.17	3.39	18.75	17.60	17.28	1.78	16.89	16.72	1.04
3.77	3.53	6.51	17.24	17.25	-0.08	16.61	16.66	-0.32
3.64	3.42	5.99	17.25	17.32	-0.38	16.65	16.75	-0.59
3.50	3.50	0.14	17.19	17.43	-1.39	16.61	16.84	-1.40
3.52	3.18	9.50	17.40	17.41	-0.04	16.81	16.87	-0.37
2.67	3.14	-17.69	16.84	17.16	-1.89	16.40	16.64	-1.43
3.27	3.48	-6.39	16.81	17.32	-3.04	16.28	16.74	-2.84
3.70	3.53	4.50	16.91	17.20	-1.67	16.31	16.61	-1.84

APPENDIX F DRY DENSITY CALCULATIONS USING EDG MOISTURE CONTENT AND SC BULK DENSITY

Appendix F.1 Klipheuwel

Table F-1: Calculated dry density for Klipheuwel using EDG measured moisture content

EDG moisture content (%)	sand cone bulk density (kN/m^3)	Calculated dry density (kN/m^3)	sand cone dry density (kN/m^3)
7.54	18.68	17.37	17.37
7.37	19.23	17.91	17.90
7.58	19.37	18.01	18.03
7.58	19.35	17.99	18.03
7.21	19.44	18.14	18.13
7.08	19.34	18.06	18.05
7.32	19.78	18.43	18.43
9.32	19.21	17.57	17.56
9.53	19.75	18.03	18.03
9.42	20.02	18.29	18.32
9.37	19.83	18.13	18.13
9.01	19.87	18.23	18.19
9.42	20.01	18.29	18.35
9.52	19.26	17.59	18.35
9.41	20.24	18.50	17.66
12.11	20.27	18.08	17.99
13.01	19.99	17.69	17.92
12.39	20.11	17.89	17.73
12.75	19.94	17.68	17.83
12.74	19.33	17.15	17.65
12.56	19.70	17.50	17.53

Appendix F.2 Cape Town (CL)

Table F-2: Calculated dry density for Cape Town (CL) using EDG measured moisture content

EDG moisture content (%)	sand cone bulk density (kN/m^3)	Calculated dry density (kN/m^3)	sand cone dry density (kN/m^3)
13.08	18.44	16.30	16.41
12.53	18.64	16.57	16.61
12.17	18.11	16.15	16.19
12.96	17.58	15.56	15.71
14.61	18.39	16.04	15.98
16.75	19.06	16.33	16.45
16.62	20.77	17.81	17.95
16.04	19.88	17.14	17.21
16.09	20.03	17.25	17.33
16.39	21.22	18.23	18.41
16.95	19.09	16.32	16.55
18.29	20.98	17.74	17.75
18.47	22.35	18.86	18.90
18.04	21.38	18.11	18.09
17.77	22.65	19.23	19.24
18.39	22.30	18.83	18.84

Appendix F.3 Khayelitsha sand

Table F-3: Calculated dry density for Khayelitsha sand using EDG measured moisture content

EDG moisture content (%)	sand cone bulk density (kN/m^3)	Calculated dry density (kN/m^3)	sand cone dry density (kN/m^3)
6.95	15.65	14.63	14.67
5.37	17.47	16.58	16.60
6.33	17.71	16.65	16.68
6.56	17.32	16.25	16.23
7.77	15.66	14.53	14.50
8.24	17.49	16.16	16.14
7.69	16.70	15.51	15.48
7.23	16.31	15.21	15.13
7.28	16.10	15.01	14.93
7.91	16.65	15.42	15.37
8.42	16.77	15.47	15.40

Appendix F.4 Pinelands

Table F-4: Calculated dry density for Pinelands using EDG measured moisture content

EDG moisture content (%)	sand cone bulk density (kN/m^3)	Calculated dry density (kN/m^3)	sand cone dry density (kN/m^3)
12.65	16.24	14.41	14.12
12.85	17.25	15.28	15.35
13.13	15.90	14.06	14.09
13.14	16.70	14.76	14.79
13.77	17.67	15.53	15.60
13.89	18.51	16.25	16.32
13.00	18.29	16.19	16.22
12.70	16.72	14.84	15.06

Appendix F.5 Burgundy sand (SP1)

Table F-5: Calculated dry density for Burgundy sand (SP1) using EDG measured moisture content

EDG moisture content (%)	sand cone bulk density (kN/m^3)	Calculated dry density (kN/m^3)	sand cone dry density (kN/m^3)
5.02	15.42	14.69	14.70
4.99	16.00	15.24	15.24
5.03	17.00	16.19	16.22
5.02	16.07	15.30	15.31
4.98	17.01	16.20	16.12
5.08	16.77	15.96	15.98
5.04	16.43	15.64	15.64
5.07	16.38	15.59	15.58
5.01	16.31	15.53	15.48

Appendix F.6 Burgundy sand (SP2)

Table F-6: Calculated dry density for Burgundy sand (SP2) using EDG measured moisture content

EDG moisture content (%)	sand cone bulk density (kN/m^3)	Calculated dry density (kN/m^3)	sand cone dry density (kN/m^3)
3.28	16.38	15.86	15.74
3.40	16.74	16.19	16.13
3.39	16.63	16.08	16.01
3.46	16.65	16.09	15.97
3.47	16.09	15.55	15.43
3.39	17.60	17.02	16.89
3.53	17.24	16.65	16.61
3.42	17.25	16.68	16.65
3.50	17.19	16.61	16.61
3.18	17.40	16.86	16.81
3.14	16.84	16.33	16.40
3.48	16.81	16.24	16.28
3.53	16.91	16.34	16.31