Evaluating the Confinement Effect to Improve Gravel Runway Performance

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made available electronically to the public.

Abstract

This research was intended to adapt an existing strength testing method used only in Russia for conformance with Aircraft Flight Manuals typical of North America. Bearing strength requirements are typically listed by minimum California Bearing Ratio for gravel runway operations. The Boeing Cone Penetrometer is commonly used throughout North America to verify gravel runway bearing strength. Bombardier Inc. desired operational capacity in northern Russia at airports which lacked the necessary equipment for strength verification via Boeing Cone Penetrometer. The research objective was to investigate a correlation between results reported via Boeing Cone Penetrometer and the Udarnik U-1 used in Russia. A successfully documented correlation would allow for runway bearing strength verification via the Udarnik U-1, without alteration to Aircraft Flight Manuals.

Laboratory conditions allow for precise control of input parameters. Extrapolation to field conditions should be performed with caution. In controlling input parameters, such as pavement homogeneity, a trade-off ensues with other factors. In particular, the boundary conditions at field scale could be lost via the confinement effect of specimen mould walls experienced at bench scale. An investigation quantifying the confinement effect for each test method has therefore been deemed necessary, and formed the focus of this research.

Three soil types were studied (sand, clay, and organic), encompassing the broad range of pavement structures which could be encountered at remote runway locations. The Response Surface Method was adapted for use in the confinement effect investigation, considering mould diameter and soil unit weight as the independent variables. The same method was applied in the correlation investigation, considering moisture content and soil unit weight as the independent variables.

The method of investigation into the confinement effect shows promise. Modelling suggests that quadratic terms are significant, however further data points are required to estimate the parameter coefficients. It is recommended that axial treatment runs be performed which would allow completion of the confinement effect model. The complete confinement effect model could then be used to estimate field scale strengths based on the input parameters of bench scale testing, bridging the gap between field and lab testing.

The correlation investigation encountered challenges with respect to control of moisture content in combination with control of soil unit weight. In retrospect, these parameters are highly correlated. Since soil unit weight is inversely proportional to void space, variation of soil unit weight inherently restricts moisture content. To capture the effect of moisture on pavement strength, saturation level should be considered. Replacement of moisture content with saturation level as an independent variable could yield statistically significant models which capture the effects of both density and moisture; the experiment should be repeated using these independent variables.

Within limits, the correlation investigation was able to establish bearing strength models based solely on the soil unit weight as the independent variable. These models support the central region of the models developed in the confinement effect investigation.

This research provides new insight into overcoming the discrepancies between bench and field testing. First steps have been taken into defining the impact of confinement effect on bench scale Boeing Cone Penetrometer and Udarnik U-1 tests. Completion of the recommended next steps would yield correlation between the two test methods. This methodology could be further applied to review correlations between various bearing strength test methods. Other remote regions internationally which experience the same California Bearing Ratio reporting challenges could be accessed in this method. Future development along these lines would serve to increase consistency of aviation regulatory standards internationally.

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Dedication

To Drs. Dutton & Dutton;

You'll just have to address me as Master

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CHAPTER 1 Introduction

1.1. Introductory Statement

According to the United States Federal Aviation Administration, "airport pavements are constructed to provide adequate support for the loads imposed by airplanes and to produce a firm, stable, smooth, all-year, all-weather surface free of debris" (Federal Aviation Administration, 2009). The runway represents the interface between ground and air. The purpose of a runway is to safely and efficiently convey aircraft through departure and arrival at an airport (de Neufville, Reynolds, & Thoreson, 2003). A key component of fulfilling a runway's purpose is to adequately support an aircraft, both for safety purposes, and for repeated use requiring only reasonable maintenance costs. With respect to gravel runways, airport operators typically lack the same degree of control regarding bearing strength compared to hard surfaced runways. Accordingly, strength must be verified more often to ensure operational efficiency, without sacrificing safety.

1.2. Background

1.3. Research Objective

Aircraft Flight Manuals specify minimum runway strength requirements, among various other operational requirements. Bearing strength requirements are typically listed by minimum California Bearing Ratio for gravel runway operations. While the Boeing Cone Penetrometer is commonly used throughout North America to verify gravel runway bearing strength, Bombardier Inc. desired operational capacity in northern Russia at airports which lacked the necessary equipment for strength verification via Boeing Cone Penetrometer. Ground crews in Russia have familiarity with the Soviet era Udarnik U-1 drop hammer. The research objective was to investigate a correlation between results reported via Boeing Cone Penetrometer and Udarnik U-1. A successfully documented correlation would allow for runway bearing strength verification via the Udarnik U-1, without alteration to Aircraft operating manuals.

Research was conducted in a laboratory-controlled environment. Accordingly, laboratory specimens were prepared in moulds for testing with both methods. A challenge as a result of laboratory testing is that the mould walls impart a confining effect on the pavement specimens. Therefore, this effect must be quantified for the results to be meaningful at field scale. An investigation quantifying the confinement effect for each test method was therefore necessary, and forms a focus of this research.

Further, due to the often-remote locations of gravel runways, a wide variety of soil types may be used in gravel runway construction. A robust investigation is of importance for practical use of any correlation developed. To this end, the correlation and confinement effect investigations were conducted on a variety of specimen types.

1.4. Thesis Organization and Methodology

This thesis is organized into six chapters.

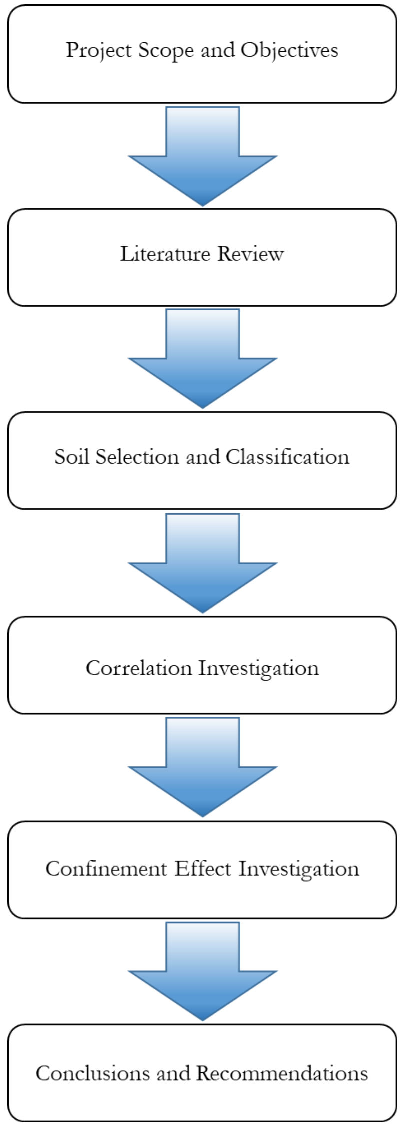

Figure 1.1: Overview of research methodology

Chapter 1 provides an introductory statement, identifies the research objective, and reviews the research methodology. Chapter 2 investigates existing literature on: gravel runway operations and challenges, existing methods to determine bearing strength, and the confinement effect. Chapter 3 reviews the results of soil classification, and outlines specimen preparation. Chapter 4 reviews and discusses the results of the correlation investigation between the Boeing Cone Penetrometer and the Udarnik U-1. Chapter 5 reviews and discusses the results of the confinement effect investigation for the Boeing Cone Penetrometer and the Udarnik U-1 respectively. Chapter 6 discusses application of the investigations, challenges and limitations in implementation, and recommendations for future work.

1.5. Methodology

Three soil types were selected for investigation: one each from the soil groups Type I, Type II, and Type III from which the Udarnik U-1 has been calibrated. Each soil type was then classified per the Unified Soil Classification System (ASTM D2487, 2006). Classification includes grain size analysis via sieving and hydrometer, and identification of plastic and liquid properties of the "fines" component.

Specimen preparation was conducted via a method adapted from ASTM D698 for the purposes of this investigation. The Udarnik U-1 penetrates 30 centimetres (cm) into the pavement structure, which required the fabrication of custom specimen moulds. Three moulds were fabricated, one each of diameter: 102 millimetre (mm), 154 mm, and 203 mm. Each mould consisted of a 13 mm steel base plate, three 133 mm deep sections of each respective diameter, and two threaded rods with which the sections could be secured. Prior to specimen preparation, each soil type was first classified per the Unified Soil Classification System and optimal moisture content was determined in accordance with ASTM D698. Each specimen was then prepared at optimal moisture content for compaction; the appropriate bearing strength test was performed; and the specimen was then removed from the mould and broken up for re-use. After testing, samples of at least 100 grams (g) of soil were taken to verify moisture content of each specimen. A sample was taken from each of 133 mm and 266 mm depth. De-ionized water was used to limit chemical changes within the soil over time and repeated use. This precaution was taken to allow repeated use of the soil for testing purposes. It is not anticipated to have any impact related to field results.

In total, twelve separate experiments were conducted: six confinement effect investigations, and six correlation investigations. Each group of six experiments was subdivided into three separate groups: Type I soil experiments, Type II soil experiments, and Type III soil experiments. Finally, each soil Type experiment was conducted twice: once with the Boeing Cone Penetrometer, and once with the Udarnik U-1. The modelling approach taken is further described in sections 1.5.3 and 1.5.4.

1.5.1. Soil Classification

The Federal Aviation Administration recommends classification of soils according to the Unified Soils Classification System (Federal Aviation Administration, 2009). Soil classification is performed through several analyses, including: soil particle size analysis, analysis of plastic and liquid behaviours, and moisture-density relationships (ASTM D2487, 2006). ASTM D2487 specifies methodology for the classification of soils.

The size and gradation of particles within a soil form the base means of classification. Soil particle gradation is determined in accordance with ASTM C136, whereby "a sample of dry aggregate of known mass is separated through a series of sieves of progressively smaller openings" (ASTM C136, 2014). A hydrometer analysis must be performed in accordance with ASTM D7928 to identify the gradation for the fines component of a soil. The apparatus relies on the principle that larger particles will settle in a column of liquid faster than smaller particles. Particles are assumed to approximate spherical objects, and Stokes' Law is relied upon to calculate the particle gradation based upon liquid density and time (ASTM D7982, 2018). The results of particle size gradation analysis place a soil within one of three parent groups of soils: coarse-grained soils, fine-grained soils, and organic soils. Soils are then further subdivided to classify specific traits of the soil.

In addition to particle size gradation, further analysis of the fines component of a soil is necessary. Fines may exhibit varying cohesive or expansive behaviour in the presence of water, which can affect the performance suitability of the soil as a pavement (Public Works & Government Services Canada, 1995). ASTM D4318 specifies the methodology for identifying and classifying soil fines according to three key values: Liquid Limit, Plastic Limit, and Plasticity Index (ASTM D4318, 2005). These key characteristics can be used to evaluate expected soil performance across a wide range of properties, however, of particular interest as it relates to pavement performance is the compactibility of a soil and the shear strength.

Having obtained the particle size gradation of both coarse and fine fractions, and after determining the Liquid Limit, Plastic Limit, and Plasticity Index, a soil can be classified in accordance with the Unified Soil Classification System. An important property for constructability and engineering performance is the moisture-density curve. Soil placed to serve as airfield pavement is compacted to achieve adequate density and shear strength (ASTM D698, 2007). ASTM D698 specifies a procedure for laboratory compaction of a soil to determine the optimal water content for maximum compaction.

1.5.2. Data Collection

Special laboratory adaptations, in excess of typical field data collection methods, were employed to improve the quality of data obtained. While traditional field methods are sufficient for strength verification, further precision is necessary to better identify correlation between the two devices.

The hydraulic pump powering the Boeing Cone Penetrometer was equipped and calibrated with a pressure transducer. As will be discussed in Chapter 2, the Boeing Cone Penetrometer readings are typically taken via gauge pressure reading. In laboratory, the pressure transducer readings were taken in addition to gauge pressure readings. The pressure transducer values were used for the purposes of CBR determination. For the purposes of field testing, gauge pressure is adequate for determining bearing strength. Gauge pressure readings were typically similar to pressure transducer readings, within 10 percent of the pressure transducer readings. Larger variability was exhibited at low pressure readings, however the effect on results was minimal from a practical standpoint (very low CBR results reported via either pressure reading).

Additionally, a string pot was equipped in parallel to the cylinder piston. Thus, the vertical displacement of the cylinder could be measured in real-time to better control the depth of penetration into the soil specimen. An operator in field would typically rely on experience to ensure the appropriate depth of penetration has been achieved.

A HOBO data logger (Onset Computer Corp., Bourne MA, USA) was used to collect the results electronically from both the pressure transducer and the string pot.

By nature of the Udarnik U-1, as discussed in Chapter 2, the data collection method could not be modified.

A balance precise to the tenth of a kilogram was used to measure soil and water masses.

1.5.3. Correlation Investigation

The correlation investigation was designed to follow the Response Surface Method experimental design (Montgomery, 2012). The design made use of a 2^2 factorial design considering soil unit weight and moisture content as the independent variables. Bearing strength was selected as the dependent variable. A total of nine treatment combinations were measured per experiment, including centre-points. The test order of each combination of factors was randomly assigned, with the exception of center-point replication. Five centre-point replications were performed to provide an estimate of error while simultaneously providing insight into any lurking variables during the experimentation. The test order of centre-points was deliberately scheduled: two to start the experiment, two to end the experiment, and one in the middle of the experiment. Unfortunately, moisture content proved difficult to control during the experiment and could not yield results. The Response Surface Method is further discussed in section 1.5.4.

As such, a simple linear regression was used taking the soil unit weight as the independent variable, with the respective strength reading from each device as the dependent variable. A total of nine treatments were assessed per experiment.

For application of correlations to field scale, the strength response values must first be corrected to account for any confinement effect. Figure 1.2 provides an overview of the correlation investigation process.

A total of six experiments were conducted: three each using the Boeing Cone Penetrometer and the Udarnik U-1. With each test apparatus, three different soil types were tested. Upon successful completion of the experimentation and analysis, correct factors could be identified for each apparatus on each soil.

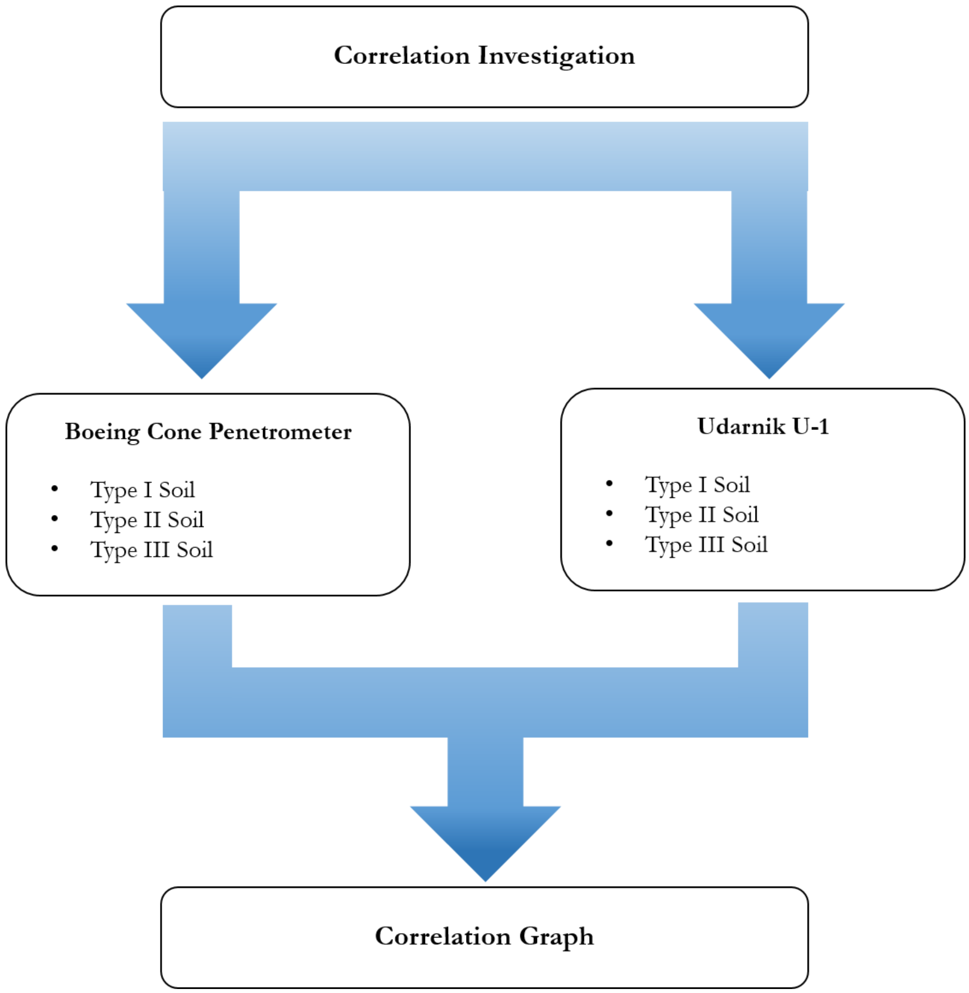

Figure 1.2: Overview of correlation investigation methodology

1.5.4. Confinement Effect Investigation

An investigation was conducted to quantify any confinement effect that could affect bearing strength readings. The investigation was based off of the Response Surface Method experimental design (Montgomery, 2012). The design made use of a 2^2 factorial design considering mould diameter and soil unit weight as the independent variables, with the respective strength reading from each device as the dependent variable. A total of nine treatments were performed per experiment, including centre-points. Test order of each combination of factors was randomly assigned. Five centre-point replications were performed to provide an estimate of error while simultaneously providing insight into any lurking variables during the experimentation (Khuri & Mukhopadhyay, 2010). The test order of centre-points was deliberately scheduled: two to start the experiment, two to end the experiment, and one in the middle of the experiment. Minimal bias is introduced, since the centre points are equally normalized to the midpoint of each independent variable (Baş & Boyacı, 2007). The base nine-point experiment could be augmented with axial runs had higher-order terms been identified in the model after initial analysis. Upon completion of the confinement effect investigation, the reported strength results could then be corrected in the correlation investigation to allow for application of the laboratory results for use in-field. The Response Surface Method is an efficient means of identifying a model, however further testing via traditional factorial design should be pursued once a satisfactory operating range and experimental method have been identified (Collins, 2009).

Figure 1.3 provides an example of the Response Surface Method.

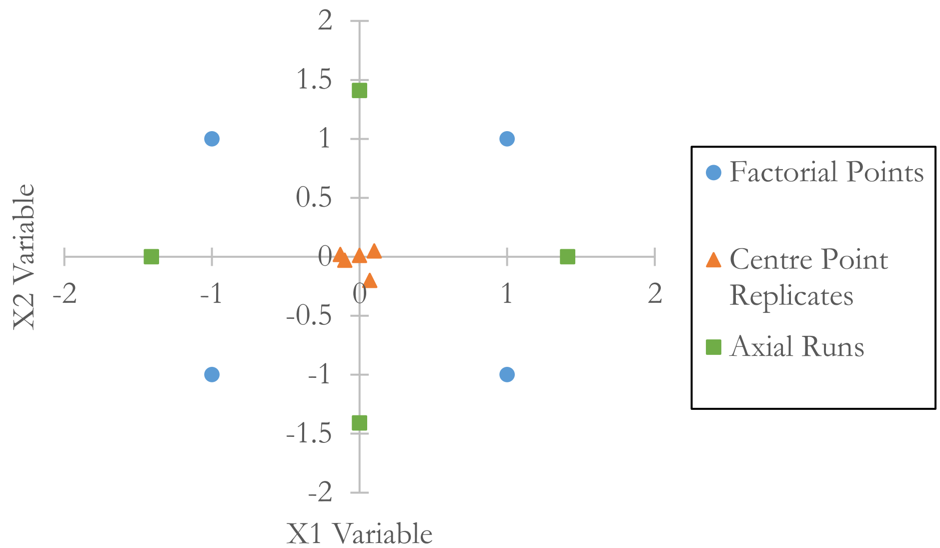

Figure 1.3: Example of the Response Surface Method

A total of six experiments were conducted: three each using the Boeing Cone Penetrometer and the Udarnik U-1. With each test apparatus, three different soil types were tested. Upon successful completion of the experimentation and analysis, correct factors could be identified for each apparatus on each soil. Figure 1.4 provides an overview of the confinement effect experimental process.

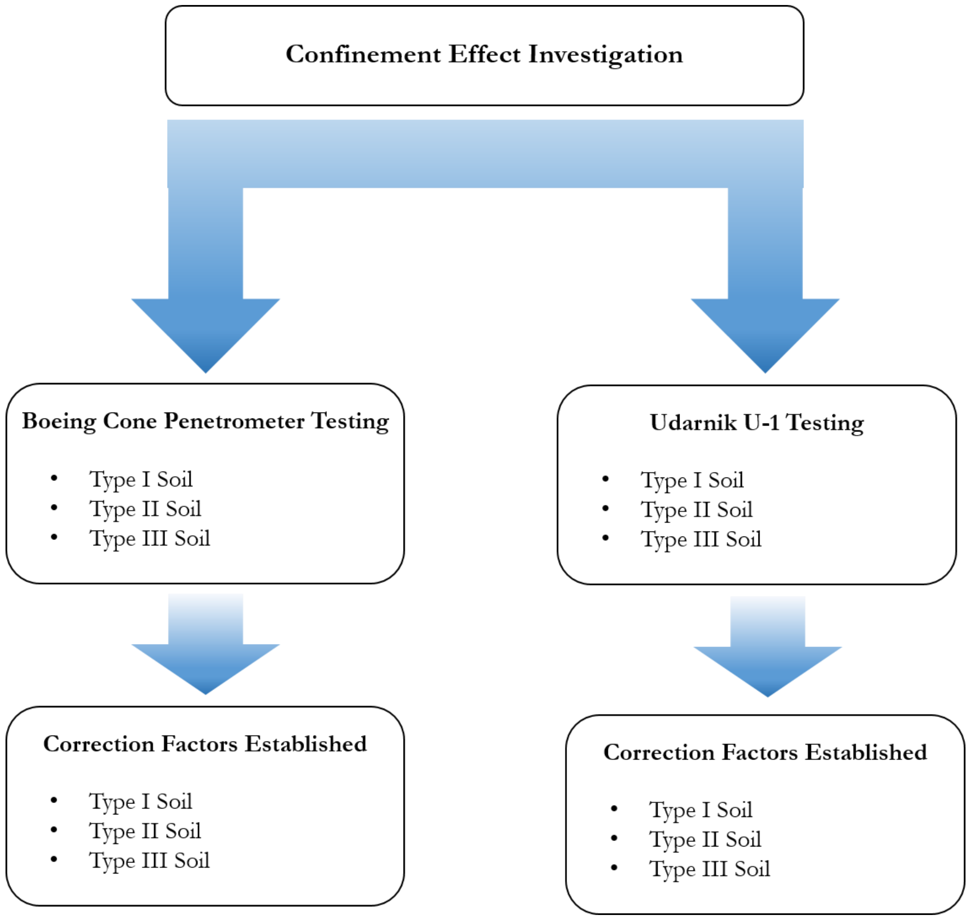

Figure 1.4: Overview of confinement effect investigation methodology

CHAPTER 2 Literature Review

2.1. Overview of Gravel Runway Operations

Transport Canada defines gravel runways as "manually constructed pavements with the surface composed of unbound granular material" (Transport Canada, 2012). The term gravel in "gravel runway" therefore refers to unbound granular material, as opposed to the strict definition of gravel from a soil classification perspective. Gravel runways are a subset of unpaved runways. Sometimes referred to as unimproved runways, an unpaved runway is generally described as any runway which does not provide an asphaltic or Portland cement concrete surface (Transport Canada, 2012). In omitting placement of traditional hard pavements, the capital cost of gravel runways can be significantly reduced. Accordingly, gravel runways are often located in areas servicing low passenger volumes or in remote locations where the cost of obtaining materials would prove exorbitant. As of 2013, a total of 944 unpaved runways are listed in Canada, including 75 runways exceeding 1,524 m in length (Central Intelligence Agency, 2018). Figure 2.1 illustrates the number of unpaved runways by country.

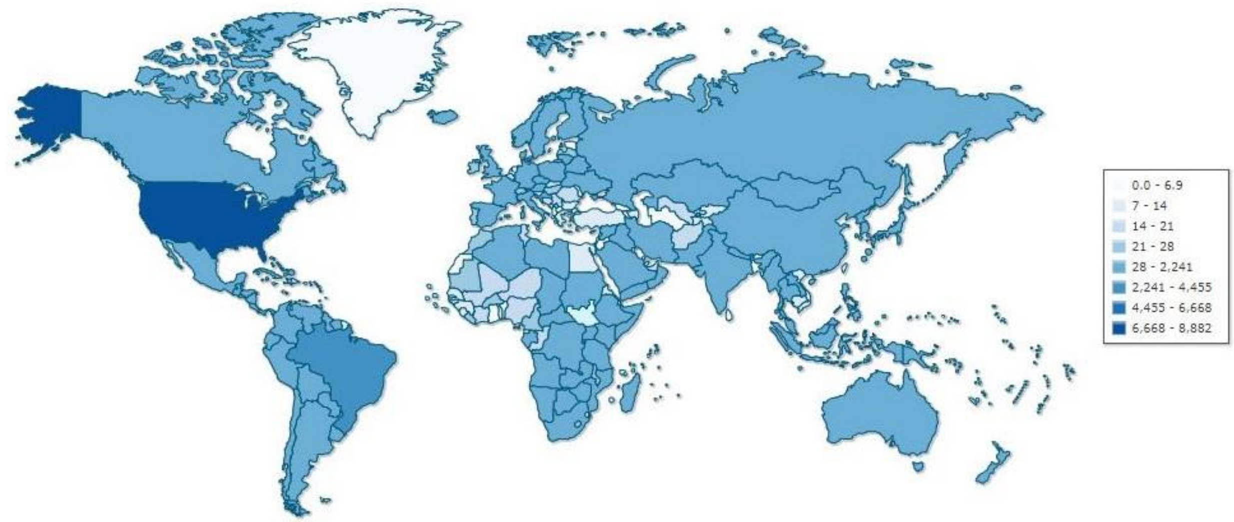

Figure 2.1: Number of unpaved runways by country (Central Intelligence Agency, 2018)

Gravel runways are particularly suited for use in Canada, due to the vast tracts of remote land and permafrost regions. In frost-susceptible regions, gravel runways have the advantage of being easily graded should pavement distresses occur as a result of frost heave (Whiteley, 2006). Furthermore, when frozen through, gravel runways can exhibit strength characteristics similar to that have hard surfaced runways, however extended periods of at least -20 °C are typically required to achieve this level of performance (Transport Canada, 2012). Frozen runways may occur in conjunction with other operational challenges such as reduced friction performance (Huang, 2003).

Unfortunately, gravel runways do present several operational challenges. First and foremost, by nature of its unbound material, gravel runways are more susceptible to foreign object debris. Propeller and turbine wash can dislodge loose gravel from the runway surface, which can pose a risk to aircraft safety. For larger aircraft operating on gravel runways, special kits are typically installed to provide additional protection (Transport Canada, 2012). Furthermore, jet and propeller blast can dislodge large volumes of gravel from the runway due to routine use, imposing additional routine maintenance costs. Gravel runways are susceptible to strength fluctuations in the presence of water. Spring thaws are of particular concern, especially when the full depth of the pavement structure has been frozen (Transport Canada, 2012). Proper crown on the runway is essential to direct water away, and adequate drainage can alleviate moisture related concerns. Rutting, settlement, localized soft spots, dust, and debris are common challenges related to the operation of gravel runways (National Project Team, 1997).

The most common cause of operational challenges with gravel runways is surface layer failure as a result of shear stresses imposed by aircraft tires (Transport Canada, 2016). Aircraft operating on gravel runways often operate with reduced tire pressure, in an attempt to mitigate this challenge. Aircraft performance is a direct trade-off when operating with reduced tire pressures, and maximum take-off weight may suffer as a result (Transport Canada, 2012). Shear strength is derived from aggregate interlock, friction, and cohesion. For gravel runways, California Bearing Ratio is typically the measurement of choice (Transport Canada, 2016). California Bearing Ratio compares the unit load required to penetrate a standard piston 2.5 mm and 5.1 mm of the soil of interest to unit load required to penetrate crushed limestone (ASTM D1883, 2016). It is expressed as a ratio of penetration. For example, a California Bearing Ratio of 50 represents half the strength of pure crushed limestone.

2.2. Bearing Strength Reporting

Interpretation of field reported test results can only provide a partial understanding of bearing strength. To adequately assess the strength characteristics for a given airport pavement, an understanding of pavement thickness and its constituents is required. At a minimum, the bearing strength of a pavement should be reviewed once every 10 years, however Transport Canada has suggested pavement strength should be reviewed whenever the structural properties of the pavement have changed (Transport Canada, 2016). In practice, the structural properties of gravel runways can vary frequently due to moisture-related seasonal weather changes. At times, spring and fall seasons can introduce structural changes on a daily basis. Increased frequency of testing is desirable to increase operational capacity, without sacrificing safety.

2.3. Field Testing Methods

An accurate, resource-efficient means of measuring runway bearing strength in field is desirable. In the pursuit of accuracy and resource efficiency, several different methods have been developed over the years and across the globe. For all methods, variation in water content can significantly impact the results of the test. As yet, no method has been developed that is insensitive to the presence of large stones; operator knowledge and experience is relied upon.

2.3.1. California Bearing Ratio

With the adoption of the California Bearing Ratio as the standard measure of gravel runway surface strength, ASTM D4429 – *Standard Test Method for CBR (California Bearing Ratio) of Soils in Place* has become the definitive measure against which other methods are compared (Danyluk, Shoop, Affleck, & Wieder, 2008). Regrettably, the method can be resource intensive and time-consuming. Consequently, the method is poorly suited for frequent testing of runway surface course strength (Transport Canada, 2016).

To perform the test *in situ*, a suitable area of the runway must first be cleared of loose debris. Since results are sensitive to moisture content, dried materials should also be cleared from the test area to expose representative pavement conditions. A resistive load is required to perform the test accurately. The device can be placed beneath a large truck axle as in Figure 2.2 (note: a pick-up truck provides inadequate resistance). Since gravel runways by necessity require frequent regrading, a grader serves as an ideal candidate to provide the resistive load. The apparatus can be placed directly beneath the grader blade.

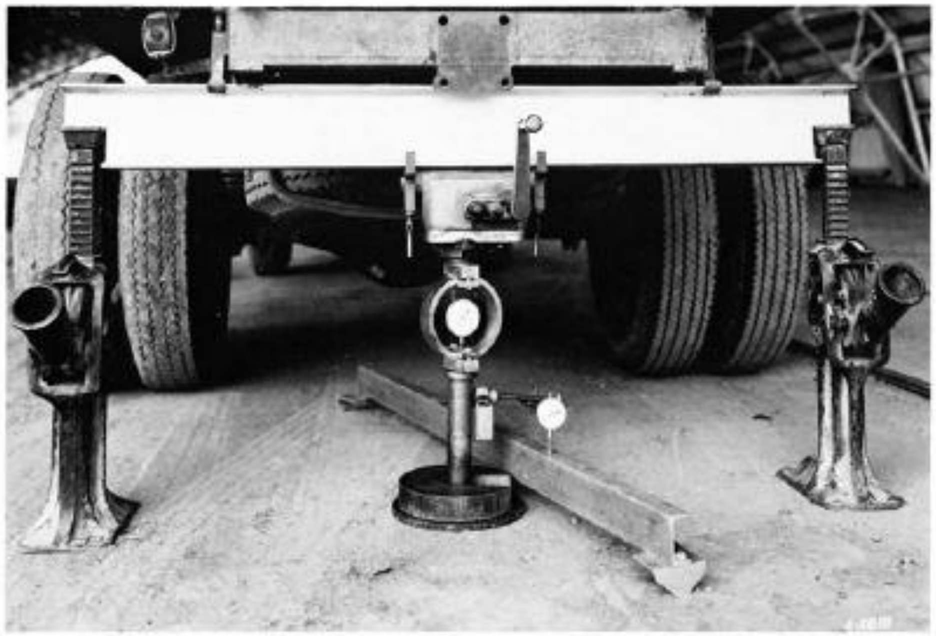

Figure 2.2: Example of field in place testing setup (ASTM D4429, 2009)

Surcharge plates are used in conjunction with a screw-jack to apply a uniform rate of loading to the penetration piston. A rate of 1.3 mm/minute should be targeted. Load cell readings are taken at every 0.64 mm of penetration, until the piston has penetrated to a depth of 12.7 mm. Upon completion of the test, a sample at the test site is taken for moisture content analysis, and the density should be determined from a sample point nearby. The California Bearing Ratio is determined from a stress penetration curve published within ASTM D4429. (ASTM D4429, 2009)

2.3.2. Boeing Cone Penetrometer

In 1969, Hammond, Marshall, and Lund developed the High Load Penetrometer for Boeing (hereafter referred to as the Boeing Cone Penetrometer). The procedure was developed as a faster method to obtain runway bearing strength values. The device consists of a 51 mm diameter steel cone that is driven into the pavement by a hydraulic piston. Site preparation is very similar to that of the field in place California Bearing Ratio: the site should be cleared of loose debris, dry material, and relatively level. A resistive load is required to perform the test accurately. The device can be placed beneath a large truck axle as in Figure 2.3 (note: a pick-up truck provides inadequate resistance). Since gravel runways by necessity require frequent regrading, a grader serves as an ideal candidate to provide the resistive load. The apparatus can be placed directly beneath the grader blade.

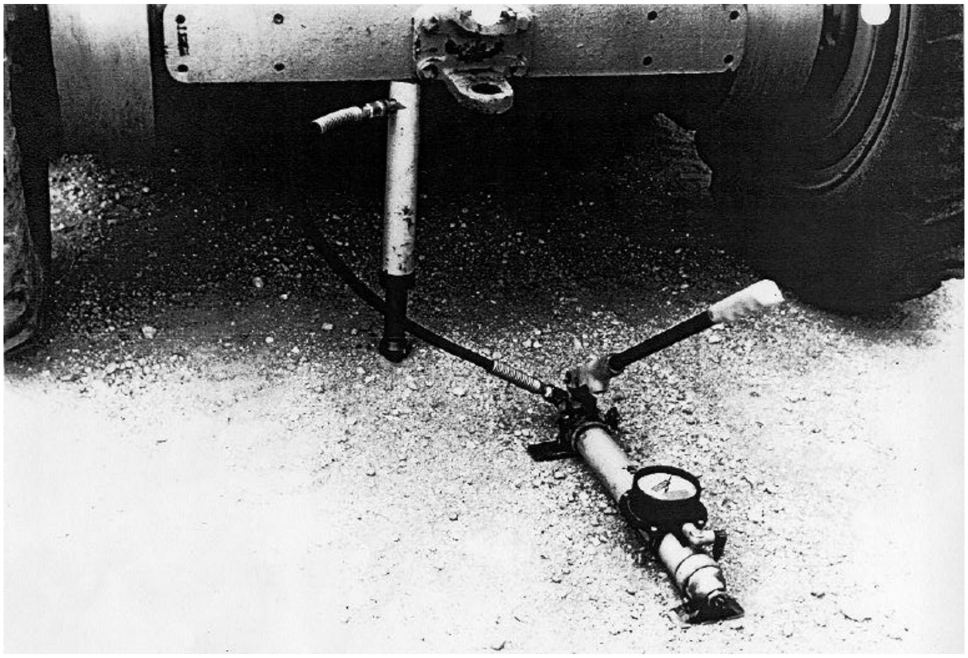

Figure 2.3: Typical Boeing Cone Penetrometer setup (Hammond, 1969)

The cone reference point is driven approximately 102 mm below the runway surface by the hydraulic cylinder. A pressure reading is taken from the cylinder gauge within 30 seconds of when the cylinder penetration has reached equilibrium at the prescribed depth. Boeing has developed a curve which transforms the gauge pressure reading into a California Bearing Ratio. (Hammond, 1969)

2.3.3. Udarnik U-1 Drop Hammer

Relatively little published documentation could be found on the Udarnik U-1 Drop Hammer. The Udarnik U-1 is a Soviet era drop hammer developed to verify soil bearing pressures. The device is hand operated, and features a 2.5 kilogram (kg) weight that is dropped repeatedly from a height of 50 cm. The repeated impacts drive a 13 mm steel cylinder into the pavement, and the number of strikes required to drive the cylinder to a depth of 10 cm and 30 cm are recorded. Curves relate soil bearing strength to the number of strikes required to penetrate to each depth. Separate curves have been developed for three main soil types: sands, clays, and organic soils. The average strength between each penetration depth is reported as the soil strength. The soil strength determination graphs are available in Appendix A, as found in the Manual on the Operation of Civilian Aerodromes of the Russian Federation. Figure 2.4 illustrates a schematic of the apparatus, while Figure 2.5 portrays the device in use (in laboratory conditions). The advantages of the Udarnik U-1 include speed of testing, reduced operator training, portability, and the depth of penetration can provide insight on pavement performance beyond the surface layer. Disadvantages include restriction to testing of relatively softer pavements, and skewed results could be reported for any pavements whose surface course does not extend beyond 30 cm in depth. The Udarnik U-1 reports a bearing strength in kilopascals and has not been correlated to California Bearing Ratio. Furthermore, Transport Canada has identified that such impact test methods may not correlate well to California Bearing Ratio (Transport Canada, 2016).

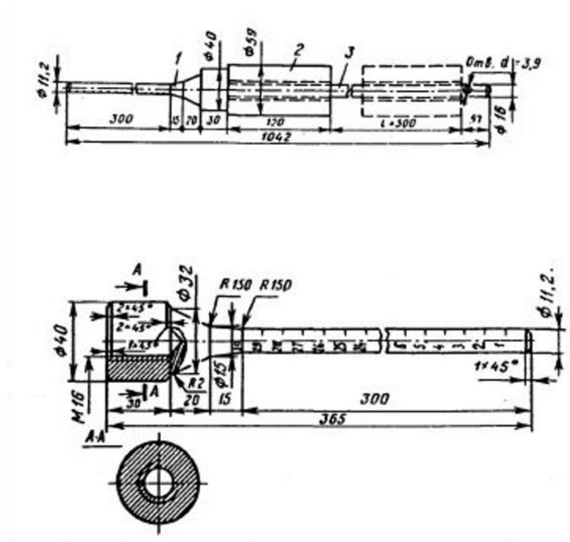

Figure 2.4: Schematic of the Udarnik U-1 (Russian Aerodrome Standards, 1994)

Figure 2.5: Laboratory testing with the Udarnik U-1

2.3.4. Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer is a drop hammer similar in use to the Udarnik U-1. It consists of a standard 8 kg weight that is dropped through a height of 575 mm to drive a conical tipped rod into the granular pavement. The conical point is 20 mm in diameter at its base, and it can be used to penetrate to a depth of 1,000 mm or beyond when rod extensions are installed. ASTM D6951 –

Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications outlines the use, procedure, and significance of the test method. The penetration depth is recorded after each strike, and standard curves transforming the penetration depth to California Bearing Ratio have been developed for different soils (ASTM D6951, 2009). The Dynamic Cone Penetrometer is less commonly used in civil aviation applications, however it is frequently used for military aircraft operations (Transport Canada, 2016). Figure 2.6 portrays a schematic of the Dynamic Cone Penetrometer.

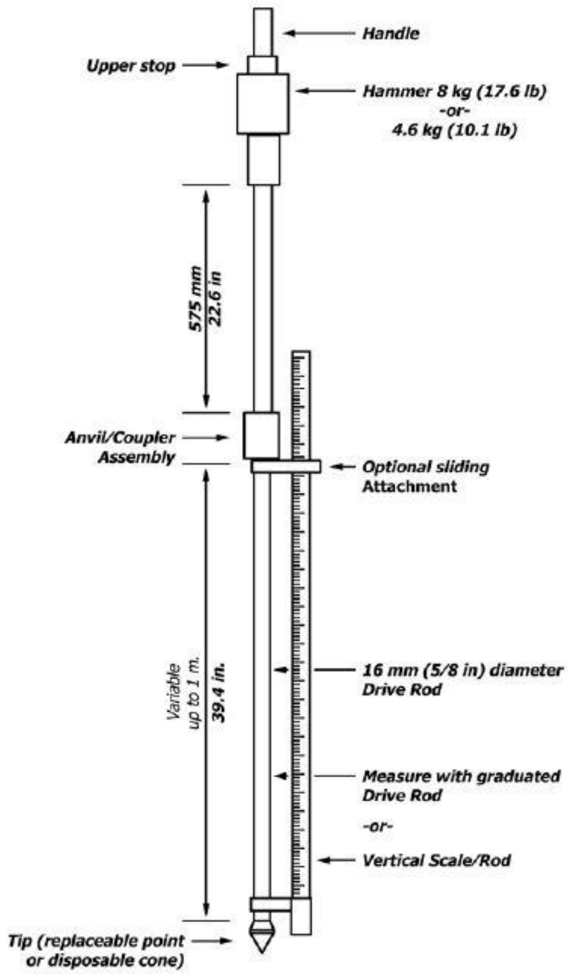

Figure 2.6: Schematic of the Dynamic Cone Penetrometer (ASTM D6951, 2009)

The advantages of the Dynamic Cone Penetrometer include speed of testing, reduced operator training, portability, and the depth of penetration can provide insight on pavement performance beyond the surface layer (Lee, Kim, Woo, & Lee, 2014; Misra, Upadhyaya, Horn, Kondagari, & Gustin, 2005; Mohammadi, Nikoudel, Rahimi, & Khamehchiyan, 2008; Taylor, Nguyen, & Mohajerani, 2015). Disadvantages include labour intensity, and misleading results could be reported for any pavements whose structure is unknown. Knowledge of the pavement structure could allow interpretation of various pavement courses through a single test procedure however. Transport

Canada has identified that such impact test methods may not correlate well to California Bearing Ratio (Transport Canada, 2016).

2.4. Confinement Effect

When performing field testing of gravel runway bearing strength, test locations are typically selected far from pavement boundary condition areas such as the runway shoulders. With respect to the precise test location, the pavement boundaries can be said to extend infinitely. As the test device interacts with the pavement, the stresses imparted are extended to the particles bordering the test location and decrease in intensity as distance increases radially from the test location. This behaviour approximates that of load dissipation beneath aircraft tires.

While laboratory conditions allow for increased control of the pavement uniformity and moisture conditions, the underlying challenge is accounting for reduced stress dissipation as a result of the specimen mould. The lack of displacement at the mould boundaries is referred to as the confinement or confining effect. Field testing can be thought of as using a mould of infinite diameter. Of course, practical limitations restrict specimen mould diameter in lab. Accordingly, any test performed in laboratory on a given soil, at a specific water content and compaction level may report strength values exceeding those that would otherwise exist in field under the same conditions. (Ampadu, Ackah, Nimo, & Boadu, 2017) have begun the process of developing confinement effect corrections for use with lateritic soils and the Dynamic Cone Penetrometer. They determined that at a mould diameter to cone diameter ratio of 25 to 1, the confinement effect became negligible for laboratory testing. Applicability of this ratio for use with other soils remains unconfirmed.

CHAPTER 3 Specimen Preparation

Chapter 3 will first discuss the results of soil classification. Specimen preparation will then be discussed, with a focus on the control of soil density.

3.1. Soil Classification Results

Three soils were selected and classified for experimental use, per the Unified Soil Classification System. For each of soils Type I, Type II, and Type III, the results are presented including: soil type, optimal moisture content, and plasticity index as appropriate.

3.1.1. Type I Soil

Type I soil was determined to be a well-graded sand with silt (SW-SM) soil. SW-SM soils are characterized as coarse-grained soils, with greater than 50 % of sample mass retained on the No. 200 sieve, and 50 % or more passing the No. 4 sieve. The fines content is between 5 % and 12 %. The results of the particle size gradation are found in Table 3.1 below.

Table 3.1: Type I soil sieve analysis results

Sieve Number	Mass Retained (g)	Percent Passing	Total Percent Retained
4	0.3	99.9	0.1
10	28.4	94.1	5.9
20	146.3	63.7	36.3
40	118	39.3	60.7
60	55.9	27.7	72.3
100	42.8	18.8	81.2
200	55.9	7.2	92.8
Fines	34.8	0.0	100.0

Via the standard Proctor test (ASTM D698, 2007), the optimal moisture content was determined to be 10.4 % by mass. Accordingly, for the purposes of consistent specimen compaction, a moisture content of 10.4 % was targeted. Actual moisture content was taken upon completion of each test. The relationship between the dry unit weight and moisture content is shown in Figure 3.1. The blue points depict results from the standard Proctor test, while the orange line depicts the theoretical values at 100 % compaction (no air voids present). The relationship has been reasonably depicted, since the 0 % air void line remains to the right of the moisture-density curve.

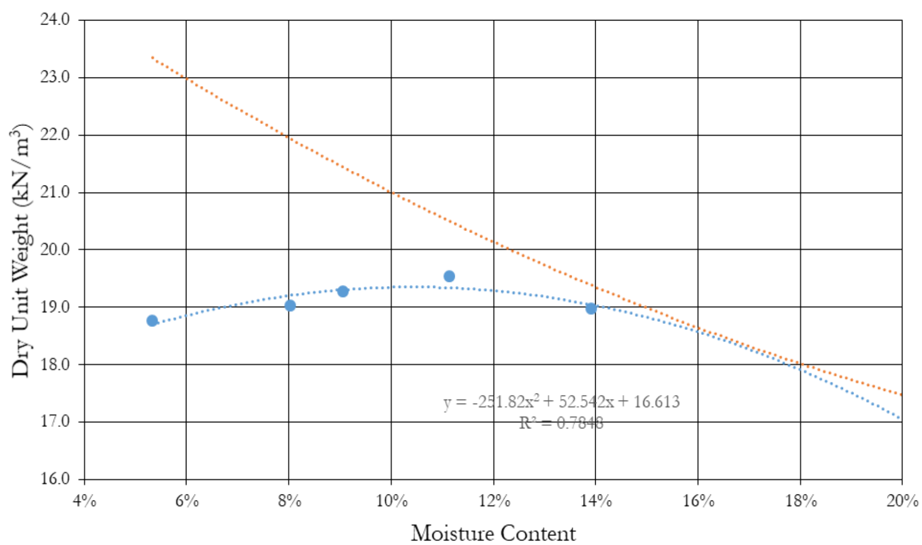

Figure 3.1: Type I soil moisture-density plot

The fines were determined to have no plastic properties, and accordingly a plasticity index could not be determined.

3.1.2. Type II Soil

Type II soil was determined to be a lean clay (CL) soil. Lean clays are characterized as fine-grained soils with 50 % or more passing the No. 200 sieve. They are inorganic in nature, with a plasticity index greater than 7 while plotting on or above the A line. The results of the particle size gradation are found in Table 3.2 below.

Table 3.2: Type II soil sieve analysis results

Sieve Number	Mass Retained (g)	Percent Passing	Total Percent Retained
4	---	100.0	0.0
10	---	100.0	0.0
20	19.0	89.5	10.5
40	24.8	75.7	24.3
60	13.0	68.5	31.5
100	10.5	62.6	37.4
200	13.9	54.9	45.1
Fines	98.9	0.0	100.0

Via the standard Proctor test (ASTM D698, 2007), the optimal moisture content was determined to be 15.4 % by mass. However, a moisture content of 13 % was selected for the purposes of specimen compaction. A reduction in moisture content resulted in less soil sticking to equipment. The reduction in compactibility was overcome by increased compactive effort. The relationship between the dry unit weight and moisture content is shown in Figure 3.2.

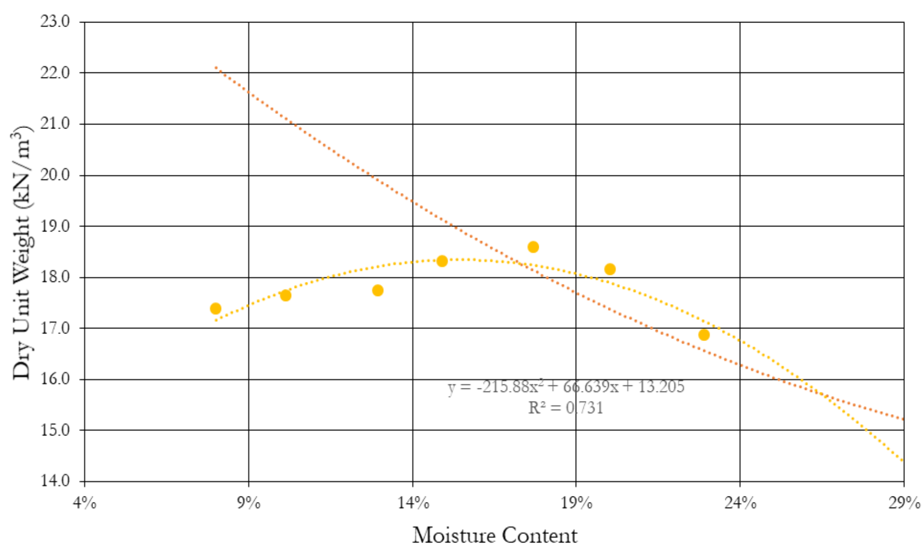

Figure 3.2: Type II soil moisture-density plot

The yellow points depict results from the standard Proctor test, while the orange line depicts the theoretical values at 100 % compaction (no air voids present). Since the 0 % air void line intersects with the moisture-density curve, it is not an ideal representation of the moisture-density relationship. It is not possible to have density greater than that which lies upon the 0 % air void line, since it represents the case where a unit volume is occupied in its entirety by solid soil particles. However, for the purposes of this investigation, the objective is merely to select a moisture content with which to compact and prepare the specimens. As such, the results were deemed satisfactory.

The fines were determined to have a liquid limit of 35, a plastic limit of 18, and a plasticity index of 17.

3.1.3. Type III Soil

Type III soil was determined to be an organic clay (OL) soil. Organic clays are fine grained soils with 50 % or more passing the No. 200 sieve. They are typically rich brown or black earths in colour, and a ratio of oven dried liquid limit to non-dried liquid limit should be less than 0.75. The results of the particle size gradation are found in Table 3.3 below.

Table 3.3: Type III soil sieve analysis results

Sieve Number	Mass Retained (g)	Percent Passing	Total Percent Retained
4	---	100.0	0.0
10	---	100.0	0.0
20	9.2	93.3	6.7
40	8.7	86.9	13.1
60	8.2	80.9	19.1
100	7.4	75.4	24.6
200	10.6	67.6	32.4
Fines	92.2	0.0	100.0

Via the standard Proctor test (ASTM D698, 2007), the optimal moisture content was determined to be 11 %. The soil exhibited expansive properties, which resulted in challenges in conducting the Proctor test. The true optimal moisture content may have been slightly higher, however the soil remained adequately workable. Accordingly, 11 % moisture content was deemed suitable for compaction. The relationship between the dry unit weight and moisture content is shown in Figure 3.3. The green points depict results from the standard Proctor test, while the orange line depicts the theoretical values at 100 % compaction (no air voids present). Since the 0 % air void line intersects with the moisture-density curve, it is not an ideal representation of the moisture-density relationship. It is not possible to have density greater than that which lies upon the 0 % air void line, since it represents the case where a unit volume is occupied in its entirety by solid soil particles. However, for the purposes of this investigation, the objective is merely to select a moisture content with which to compact and prepare the specimens. As such, the results were deemed satisfactory.

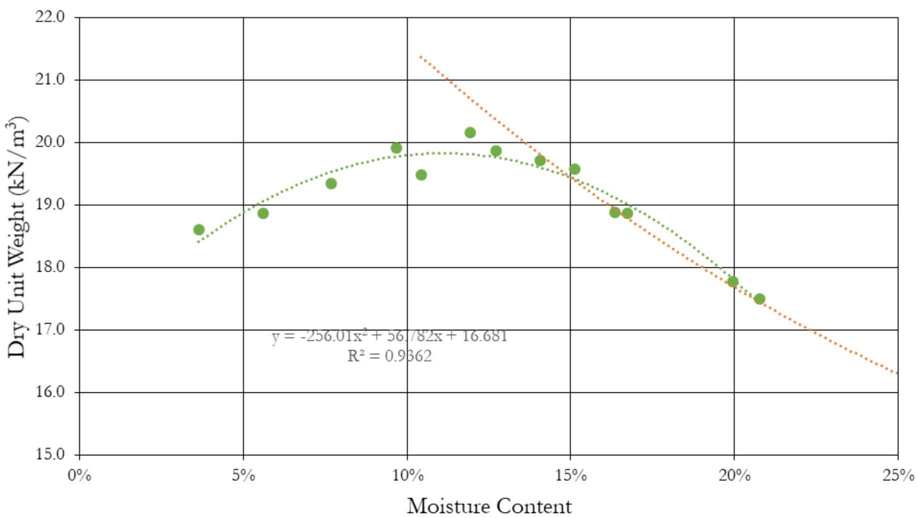

Figure 3.3: Type III soil moisture-density plot

The fines were determined to have a liquid limit of 25, a plastic limit of 16, and a plasticity index of 9.

3.2. Soil Density

Laboratory testing allowed for controlled compaction of specimens, as well as a means of verifying the actual density achieved. After soil classification, compactive effort was calibrated to determine three distinct compaction levels for each soil type. The number of blows and number of compaction layers were varied until compactive efforts yielded soil densities which could be coded to even intervals at -1, 0, and 1. Since the confinement effect investigation utilized three different mould diameters, compactive effort method improved the ability to achieve consistent soil densities for testing. Each mould prepared specimens to a height of 400 mm. Compactive effort is characterized as:

$$(compactive\ effort) = \frac{(drop\ height)\ x\ (mass)\ x\ (\#\ of\ layers)\ x\ (\#of\ drops\ per\ layer)}{(mould\ volume)}$$

The compactive effort used for each experiment is discussed in chapters 4 and 5.

CHAPTER 4 Correlation Investigation Results and Discussion

Chapter 4 will first consider experimentation results from each soil Type investigation tested with the Boeing Cone Penetrometer. Subsequently, experimentation results for each soil Type investigation tested with the Udarnik U-1 will be presented. The correlation between results for each soil Type will then be investigated, and a summary of chapter results will be given in conclusion.

4.1. Boeing Cone Penetrometer Investigation

4.1.1. Type I Soil

The Type I soil investigation was performed using exclusively the 154 mm diameter mould. Three levels of compaction were used during specimen preparation: a low level compaction of four hammer blows per layer, in three separate layers, for a compactive effort of approximately 2,969 kg/m^2; a high level compaction of 25 hammer blows per layer, in nine separate layers, for a compactive effort of approximately 55,676 kg/m^2; and a mid-level compaction of 12 hammer blows per layer, in three separate layers, for a compactive effort of approximately 8,908 kg/m^2. Specimen unit weight ranged from 19.71 kN/m^3 to 21.66 kN/m^3. Specimen moisture content ranged from 9.9 % to 11.1 %. Table 4.1 below illustrates the input variables and piston adjusted California Bearing Ratio derived from the data logger.

Table 4.1: Type I soil correlation investigation Boeing Cone Penetrometer data

Trial	Compactive Effort (kg/m2)	Unit Weight (kN/m3)	Moisture Content	Piston Pressure (PSI)	CBR
2018071401	8908	20.68	10.9%	1251	67
2018071402	8908	20.58	10.3%	1170	63
2018071403	55676	21.66	9.9%	3665	147
2018071501	2969	19.73	11.1%	433	25
2018071601	8908	20.81	11.0%	1233	66
2018071602	2969	19.71	10.2%	648	37
2018071701	55676	21.44	10.3%	3329	140
2018071702	8908	20.79	10.8%	1235	66
2018071703	8908	20.71	10.4%	1182	63

A linear regression was performed through MS Excel, where the unit weight was taken as the independent variable and the California Bearing Ratio was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 16.113 and an adjusted R square of 0.851. The regression can be viewed in Figure 4.1 below.

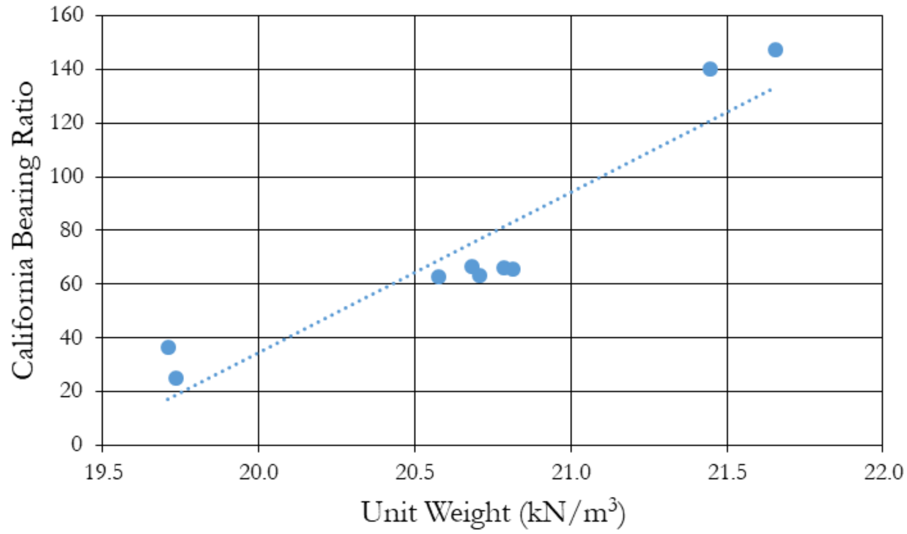

Figure 4.1: Type I soil correlation investigation: unit weight vs. California Bearing Ratio plot and linear regression

The model equation is given by:

$$CBR = 75.057 + 58.066\frac{(\gamma - 20.68)}{0.97} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Table 4.2 displays the regression statistics, Table 4.3 displays the ANOVA results, and Table 4.4 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable X1.

Table 4.2: Regression statistics

Multiple R	0.933
R Square	0.870
Adjusted R Square	0.851
Standard Error	16.113
Observations	9

Table 4.3: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	12148.900	12148.900	46.793	<0.001
Residual	7	1817.412	259.630		
Total	8	13966.312			

Table 4.4: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	75.057	5.371	13.974	<0.001	62.357	87.758	yes
X1	58.066	8.488	6.841	<0.001	37.994	78.138	yes

The regression statistics and ANOVA results indicate very strong evidence that the model fits the data, and that the parameters account for the fit. However, further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 4.2 displays a linear "thick pen line" which validates the analytical method.

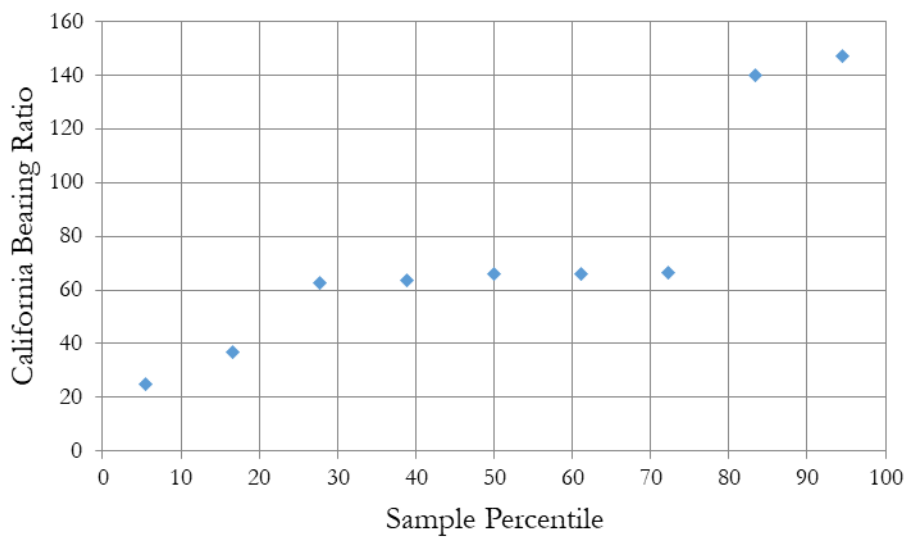

Figure 4.2: Type I soil correlation investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 4.3 depicts the residual plot for the Type I soil correlation investigation.

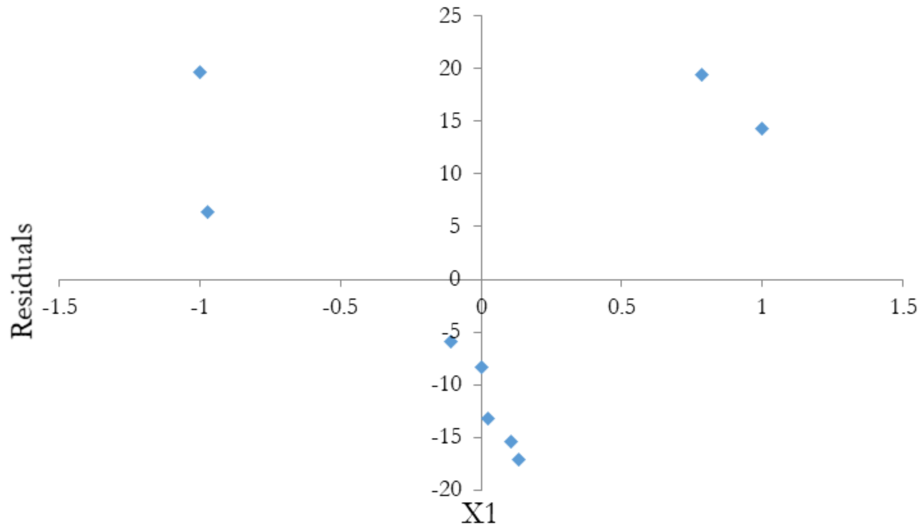

Figure 4.3: Type I soil correlation investigation unit weight (X1) vs. residuals

The results of the residual plot cannot definitively indicate a lack of pattern. A case could be made that the plot suggests a quadratic relationship. Further repetition of the experiment could confirm or reject such a conclusion. With the data available, and supported by the results from the diagnostic checks, it has been deemed that the investigation yielded data that can accurately model California Bearing Ratio response based on the unit weight of the Type I, SW-SM soil. It is nevertheless recommended that further testing be conducted, such as a factorial experiment with percent saturation and unit weight as the independent variables.

4.1.2. Type II Soil

The Type II soil investigation was performed exclusively with the 154 mm diameter mould. Three levels of compaction were used during specimen preparation: a low level compaction of four hammer blows per layer, in three separate layers, for a compactive effort of approximately 2,969 kg/m^2; a high level compaction of 29 hammer blows per layer, in nine separate layers, for a compactive effort of approximately 64,584 kg/m^2; and a mid-level compaction of 17 hammer blows per layer, in three separate layers, for a compactive effort of approximately 25,240 kg/m^2. Specimen unit weight ranged from 13.92 kN/m^3 to 18.45 kN/m^3. Specimen moisture content ranged from 12.6 % to 20.6 %. Table 4.5 below illustrates the input variables and piston-adjusted California Bearing Ratio derived from the data logger.

Table 4.5: Type II soil correlation investigation Boeing Cone Penetrometer data

Trial	Compactive Effort (kg/m2)	Unit Weight (kN/m3)	Moisture Content	Piston Pressure (PSI)	CBR
2018081401	25240	16.68	12.6%	796	44
2018081402	25240	16.52	12.9%	847	47
2018081403	64584	17.87	13.3%	1402	74
2018082001	2969	13.92	20.6%	206	12
2018082101	25240	17.21	12.9%	809	45
2018082102	2969	14.37	12.9%	337	20
2018082201	64584	18.45	19.0%	587	33
2018082501	25240	17.10	16.5%	870	48
2018082502	25240	16.76	13.1%	897	50

A linear regression was performed through MS Excel, where the unit weight was taken as the independent variable and the California Bearing Ratio was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 12.882 and an adjusted R square of 0.488. The regression can be viewed in Figure 4.4 below.

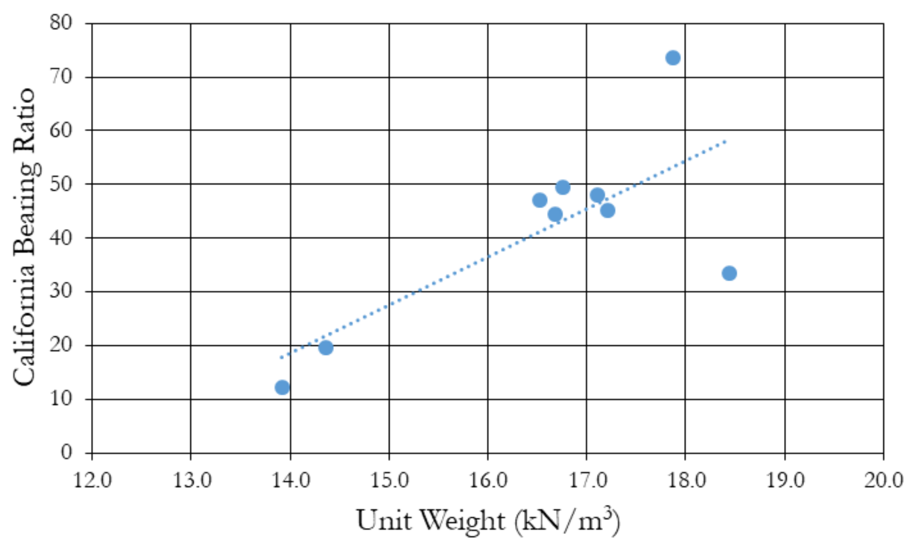

Figure 4.4: Type II soil correlation investigation: unit weight vs. California Bearing Ratio plot and linear regression

The model equation is given by:

$$CBR = 38.213 + 20.297\frac{(\gamma - 16.18)}{2.26} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Table 4.6 displays the regression statistics, Table 4.7 displays the ANOVA results, and Table 4.8 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable X1.

Table 4.6: Regression statistics

Multiple R	0.743
R Square	0.552
Adjusted R Square	0.488
Standard Error	12.882
Observations	9

Table 4.7: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1433.122	1433.122	8.636	0.022
Residual	7	1161.625	165.946		
Total	8	2594.748			

Table 4.8: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	38.213	4.432	8.622	<0.001	27.733	48.693	yes
X1	20.297	6.907	2.939	0.022	3.965	36.629	yes

The ANOVA results indicate very strong evidence that the parameters account for the model. However, the regression statistics suggest that the model provides only marginal fit to the data. Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a “thick pen line” they can be said to be normally distributed. Figure 4.5 displays a linear “thick pen line” which validates the analytical method.

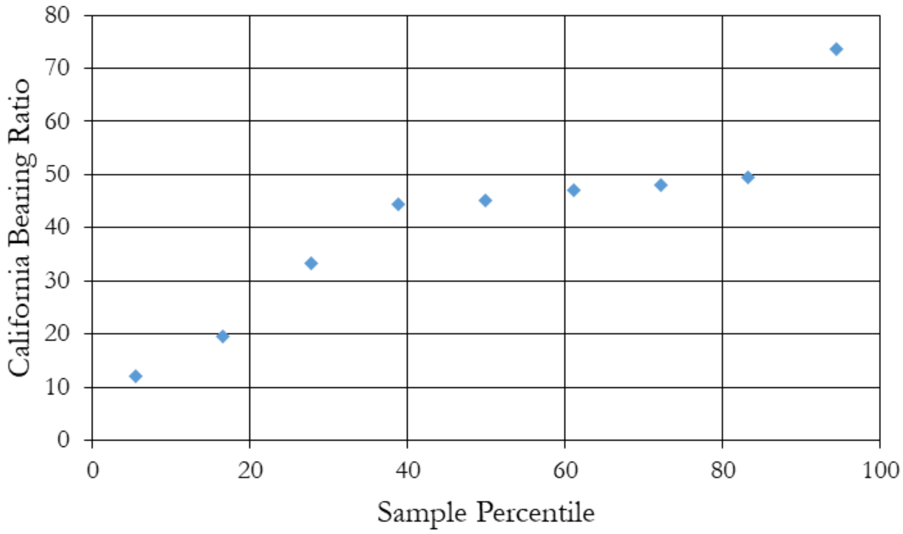

Figure 4.5: Type II soil correlation investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centering about a mean of zero (Montgomery, 2012). Figure 4.6 depicts the residual plot for the Type I soil correlation investigation.

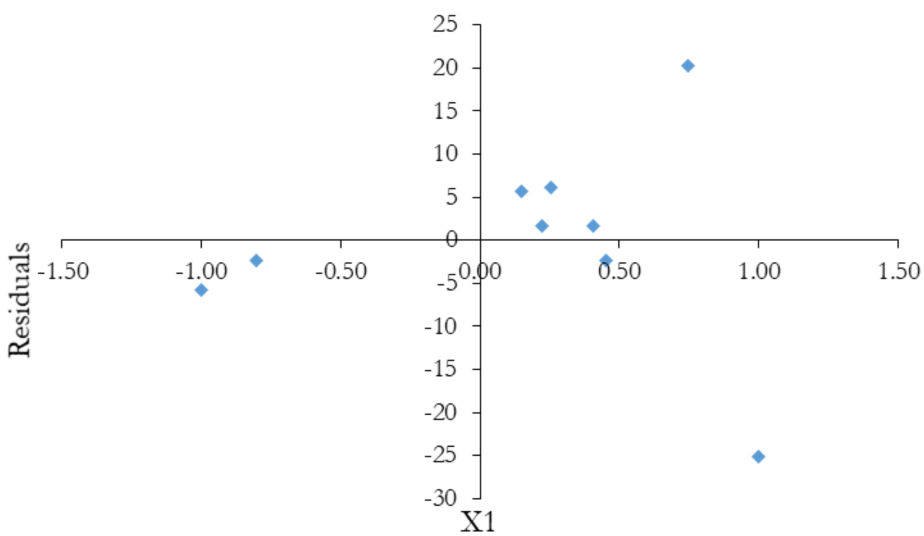

Figure 4.6: Type I soil correlation investigation unit weight (X1) vs. residuals

The results of the residual plot did not exhibit any particular pattern. It can be concluded that the investigation yielded data that can be used to model California Bearing Ratio response based on the unit weight of the Type II, CL soil. However, the model does not provide a high degree of accuracy. While analysis including moisture content could not provide a statistically significant model, it could still be possible that moisture content affected results. It is therefore recommended that further testing be conducted via a traditional factorial method, with percent saturation and soil unit weight as the independent variables.

4.1.3. Type III Soil

The Type III soil investigation was performed using exclusively the 154 mm diameter mould. Three levels of compaction were used during specimen preparation: a low level compaction of four hammer blows per layer, in three separate layers, for a compactive effort of approximately 2,969 kg/m^2; a high level compaction of 29 hammer blows per layer, in nine separate layers, for a compactive effort of approximately 64,584 kg/m^2; and a mid-level compaction of 12 hammer blows per layer, in three separate layers, for a compactive effort of approximately 17,816 kg/m^2. Specimen unit weight ranged from 15.60 kN/m^3 to 21.71 kN/m^3. Specimen moisture content ranged from 10.7 % to 17.1 %. Table 4.9 below illustrates the input variables and piston adjusted California Bearing Ratio derived from the data logger.

Table 4.9: Type III soil correlation investigation Boeing Cone Penetrometer data

Trial	Compactive Effort (kg/m2)	Unit Weight (kN/m3)	Moisture Content	Piston Pressure (PSI)	CBR
2018072301	17816	18.63	11.0%	711	40
2018072302	17816	18.50	10.8%	554	32
2018072303	2969	15.60	10.7%	161	10
2018072401	64584	21.71	12.0%	1356	72
2018072501	17816	20.10	14.2%	251	15
2018072502	2969	16.97	17.1%	55	3
2018072601	64584	21.66	13.8%	529	30
2018072701	17816	19.42	11.7%	509	29
2018072702	17816	19.23	11.6%	476	27

A linear regression was performed through MS Excel, where the unit weight was taken as the independent variable and the California Bearing Ratio was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 15.669 and an adjusted R square of 0.383. The regression can be viewed in Figure 4.7 below.

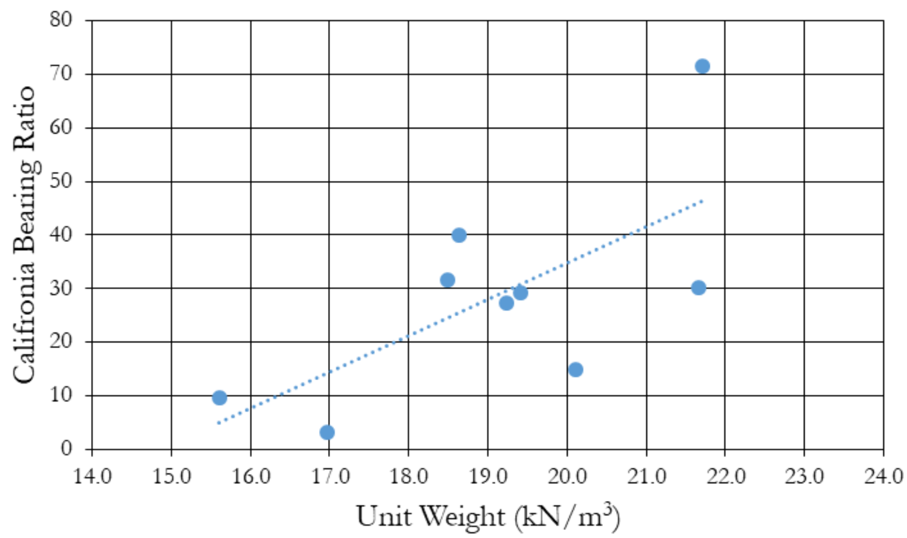

Figure 4.7: Type III soil correlation investigation: unit weight vs. California Bearing Ratio plot and linear regression

The model equation is given by:

$$CBR = 25.649 + 20.722\frac{(\gamma - 18.66)}{3.05} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Table 4.10 displays the regression statistics, Table 4.11 displays the ANOVA results, and Table 4.12 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable X1.

Table 4.10: Regression Statistics

Multiple R	0.678
R Square	0.460
Adjusted R Square	0.383
Standard Error	15.669
Observations	9

Table 4.11: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1465.572	1465.572	5.969	0.045
Residual	7	1718.687	245.527		
Total	8	3184.259			

Table 4.12: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	25.650	5.362	4.784	0.002	12.972	38.328	yes
X1	20.722	8.482	2.443	0.045	0.666	40.779	yes

The ANOVA results indicate some evidence that the parameters account for the model. However, the regression statistics suggest that the model provides poor fit to the data. Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 4.8 displays a linear "thick pen line" which validates the analytical method.

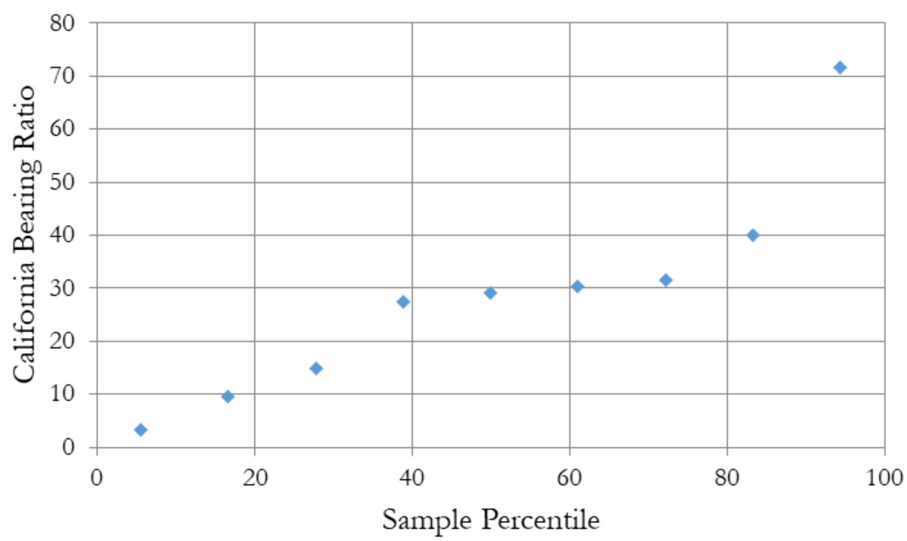

Figure 4.8: Type III soil correlation investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 4.9 depicts the residual plot for the Type I soil correlation investigation.

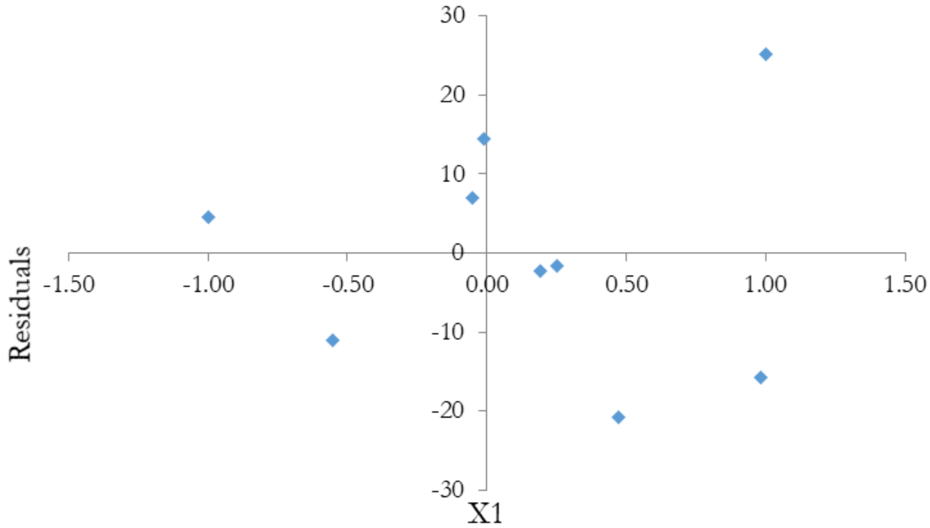

Figure 4.9: Type III soil correlation investigation unit weight (X1) vs. residuals

The results of the residual plot did not exhibit any particular pattern, which does not suggest the presence of variables uncaptured from the process. It was concluded that the investigation did not yield data that can be used to reliably model California Bearing Ratio response based on the unit weight of the Type III, OL soil. While analysis including moisture content could not provide a statistically significant model, it could still be possible that moisture content affected results. It is therefore recommended that further testing be conducted via a traditional factorial method, with percent saturation and soil unit weight as the independent variables. Further experimentation should be conducted to provide further insight into response behaviour.

4.2. Udarnik U-1 Investigation

4.2.1. Type I Soil

The Type I soil investigation was performed using exclusively the 154 mm diameter mould. Three levels of compaction were used during specimen preparation: a low level compaction of four hammer blows per layer, in three separate layers, for a compactive effort of approximately 2,969 kg/m^2; a high level compaction of 25 hammer blows per layer, in nine separate layers, for a compactive effort of approximately 55,676 kg/m^2; and a mid-level compaction of 12 hammer blows per layer, in three separate layers, for a compactive effort of approximately 8,908 kg/m^2. Specimen unit weight ranged from 19.63 kN/m^3 to 21.79 kN/m^3. Specimen moisture content ranged from 9.7 % to 12.9 %. Table 4.13 below illustrates the input variables, strike count to depths of 10 cm and 30 cm, and the resulting soil strength as determined from the Udarnik U-1 graphs.

Table 4.13: Type I correlation investigation Udarnik U-1 data

Trial	Compactive Effort (kg/m2)	Unit Weight (kN/m3)	Moisture Content	σ10 Strikes	σ30 Strikes	σ (kPa)
2018071801	8908	20.63	10.0%	2	9	550
2018071802	8908	20.52	10.2%	2	9	550
2018071803	55676	21.79	9.7%	4	15	900
2018071804	2969	20.60	12.9%	1	3	400
2018071901	8908	20.89	10.4%	2	7	500
2018071902	2969	19.63	9.8%	1	4	400
2018072001	55676	21.71	11.7%	3	13	775
2018072002	8908	20.94	10.9%	1	6	400
2018072003	8908	20.71	10.6%	2	8	450

A linear regression was performed through MS Excel, where the unit weight was taken as the independent variable and the soil strength was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 113.454 and an adjusted R square of 0.593. The regression can be viewed in Figure 4.10 below.

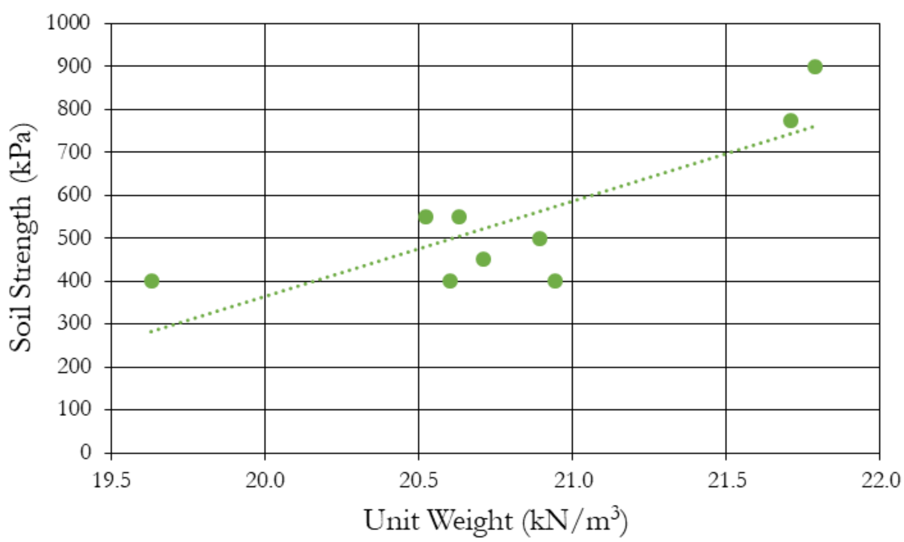

Figure 4.10: Type I soil correlation investigation: unit weight vs. soil strength plot and linear regression

The model equation is given by:

$$\sigma = 521.413 + 238.090\frac{(\gamma - 20.71)}{1.08} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Table 4.14 displays the regression statistics, Table 4.15 displays the ANOVA results, and Table 4.16 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable Z1.

Table 4.14: Regression statistics

Multiple R	0.802
R Square	0.644
Adjusted R Square	0.593
Standard Error	113.454
Observations	9

Table 4.15: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	162953.176	162953.176	12.660	0.009
Residual	7	90102.380	12871.769		
Total	8	253055.556			

Table 4.16: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	521.413	38.507	13.541	<0.001	430.358	612.468	yes
Z1	238.090	66.916	3.558	0.009	79.859	396.321	yes

The ANOVA results indicate strong evidence that the parameters account for the model. The regression statistics suggest that the model provides good fit to the data. Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 4.11 displays a linear "thick pen line" which validates the analytical method.

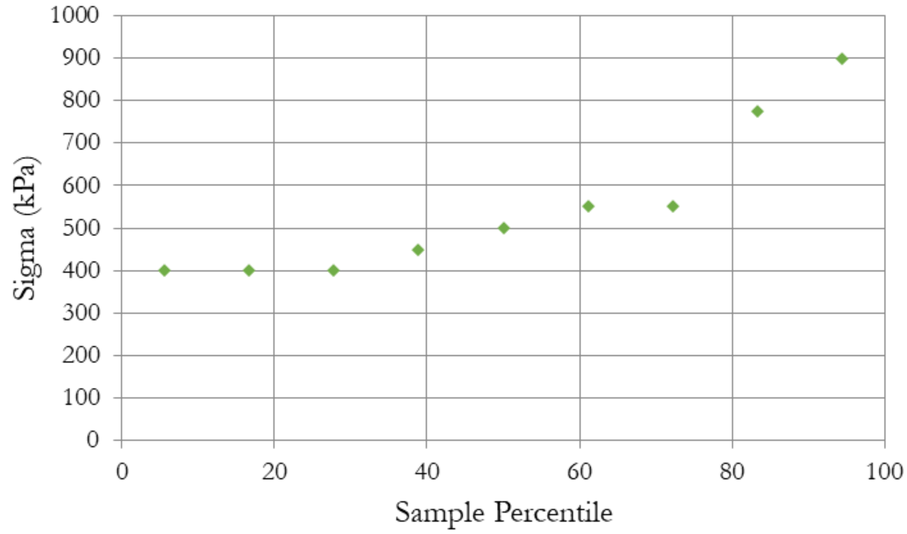

Figure 4.11: Type I soil correlation investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 4.12 depicts the residual plot for the Type I soil correlation investigation.

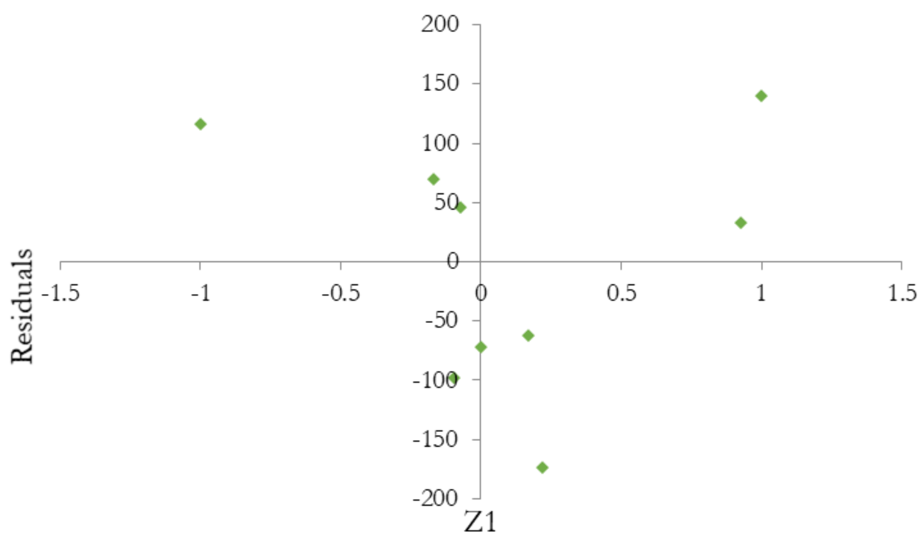

Figure 4.12: Type I soil correlation investigation unit weight (Z1) parameter vs. residuals

The results of the residual plot do not exhibit a pattern. With the data available, and supported by the results from other diagnostic checks, it has been deemed that the investigation yielded data that can model sigma soil strength response, with a low to moderate degree of accuracy, based on the unit weight of the Type I, SW-SM soil. While analysis including moisture content could not provide a statistically significant model, it could still be possible that moisture content affected results. It is recommended that further testing be conducted via a traditional factorial experiment with percent saturation and soil unit weight as the independent variables.

4.2.2. Type II Soil

The Type II soil investigation was performed using exclusively the 154 mm diameter mould. Three levels of compaction were used during specimen preparation: a low level compaction of four hammer blows per layer, in three separate layers, for a compactive effort of approximately 2,969 kg/m^2; a high level compaction of 29 hammer blows per layer, in nine separate layers, for a compactive effort of approximately 64,584 kg/m^2; and a mid-level compaction of 17 hammer blows per layer, in three separate layers, for a compactive effort of approximately 25,240 kg/m^2. Specimen unit weight ranged from 14.31 kN/m^3 to 19.08 kN/m^3. Specimen moisture content ranged from 12.5 % to 21.1 %. Table 4.17 below illustrates the input variables, strike count to depths of 10 cm and 30 cm, and the resulting soil strength as determined from the Udarnik U-1 graphs.

Table 4.17: Type II soil correlation investigation Udarnik U-1 data

Trial	Compactive Effort (kg/m2)	Unit Weight (kN/m3)	Moisture Content	σ10 Strikes	σ30 Strikes	σ (kPa)
2018082503	25240	17.00	12.8%	7	36	1175
2018082504	25240	17.26	13.1%	8	44	1275
2018082505	64584	18.52	12.7%	13	79	1275
2018082701	2969	14.31	21.1%	1	7	250
2018082702	25240	17.42	13.9%	5	28	1050
2018082703	2969	14.45	13.4%	2	8	375
2018082910	64584	19.08	19.3%	2	47	850
2018083101	25240	17.21	12.5%	6	29	1125
2018083102	25240	17.08	14.5%	7	31	1175

A linear regression was performed through MS Excel, where the unit weight was taken as the independent variable and the soil strength was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 261.095 and an adjusted R square of 0.539. The regression can be viewed in Figure 4.13 below.

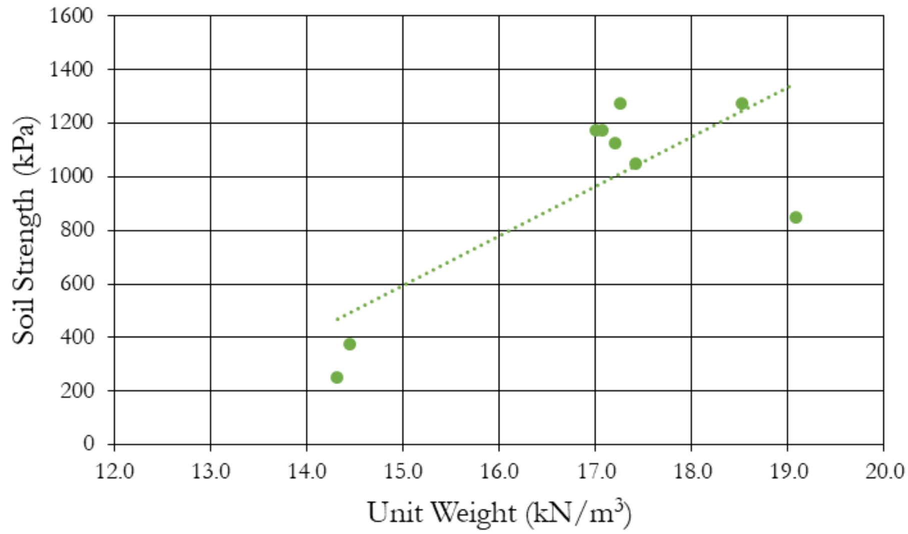

Figure 4.13: Type II soil correlation investigation: unit weight vs. soil strength plot and linear regression

The model equation is given by:

$$\sigma = 907.513 + 440.836\frac{(\gamma - 16.70)}{2.38} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Table 4.18 displays the regression statistics, Table 4.19 displays the ANOVA results, and Table 4.20 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable Z1.

Table 4.18: Regression statistics

Multiple R	0.773
R Square	0.597
Adjusted R Square	0.539
Standard Error	261.095
Observations	9

Table 4.19: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	706555.730	706555.730	10.365	0.015
Residual	7	477194.270	68170.610		
Total	8	1183750.000			

Table 4.20: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	907.513	88.027	10.310	<0.001	699.363	1115.663	yes
Z1	440.836	136.931	3.219	0.015	117.045	764.627	yes

The ANOVA results indicate strong evidence that the parameters account for the model. The regression statistics suggest that the model provides good fit to the data. Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 4.14 displays a linear "thick pen line" which validates the analytical method.

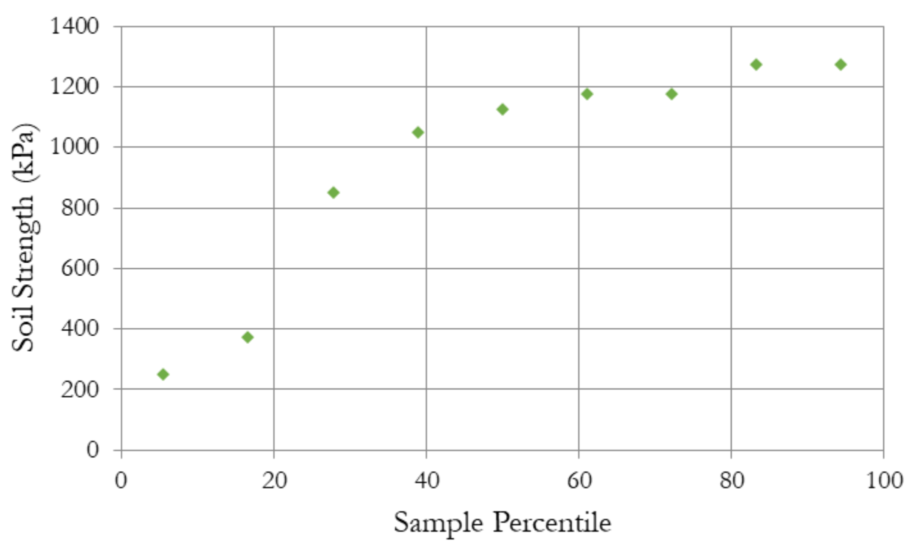

Figure 4.14: Type II soil correlation investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 4.15 depicts the residual plot for the Type II soil correlation investigation.

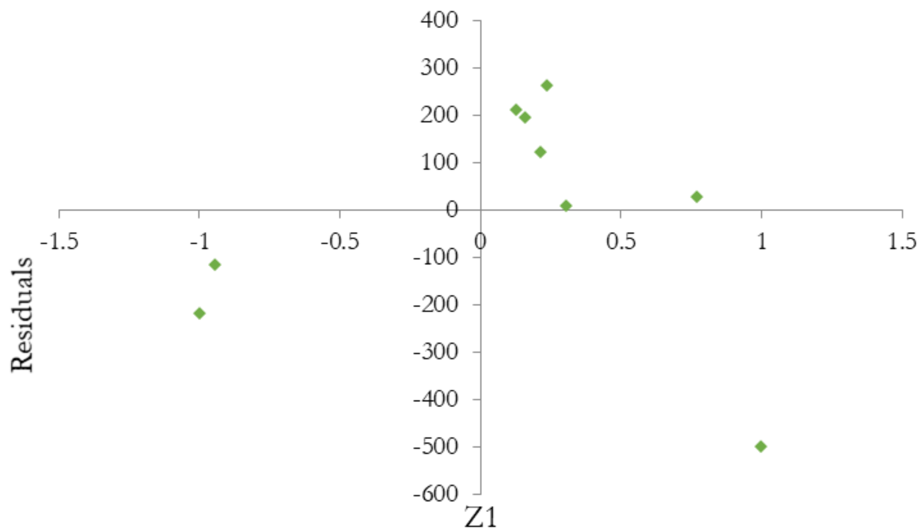

Figure 4.15: Type II soil correlation investigation unit weight (Z1) parameter vs. residuals

The results of the residual plot do not exhibit a pattern. With the data available, and supported by the results from other diagnostic checks, it has been deemed that the investigation yielded data that can model sigma soil strength response, with a low to moderate degree of accuracy, based on the unit weight of the Type II, CL soil. While analysis including moisture content could not provide a statistically significant model, it could still be possible that moisture content affected results. It is recommended that further experimentation be conducted via a traditional factorial design taking percent saturation and soil unit weight as the independent variables.

4.2.3. Type III Soil

The Type III soil investigation was performed using exclusively the 154 mm diameter mould. Three levels of compaction were used during specimen preparation: a low level compaction of four hammer blows per layer, in three separate layers, for a compactive effort of approximately 2,969 kg/m^2; a high level compaction of 29 hammer blows per layer, in nine separate layers, for a compactive effort of approximately 64,584 kg/m^2; and a mid-level compaction of 12 hammer blows per layer, in three separate layers, for a compactive effort of approximately 17,816 kg/m^2. Specimen unit weight ranged from 16.18 kN/m^3 to 21.66 kN/m^3. Specimen moisture content ranged from 10.7 % to 13.0 %. Table 4.21 below illustrates the input variables, strike count to depths of 10 cm and 30 cm, and the resulting soil strength as determined from the Udarnik U-1 graphs.

Table 4.21: Type III soil correlation investigation Udarnik U-1 data

Trial	Compactive Effort (kg/m2)	Unit Weight (kN/m3)	Moisture Content	σ10 Strikes	σ30 Strikes	σ (kPa)
2018072703	17816	19.23	11.2%	4	19	650
2018072704	17816	19.29	11.4%	4	18	600
2018072705	2969	16.18	11.1%	2	7	275
2018072801	64584	20.97	10.7%	12	47	1125
2018072901	17816	19.55	11.2%	4	19	650
2018072902	2969	16.45	13.0%	1	4	175
2018072903	64584	21.66	11.8%	3	31	775
2018073101	17816	19.63	11.2%	4	20	675
2018073101	17816	19.42	11.2%	5	20	725

A linear regression was performed through MS Excel, where the unit weight was taken as the independent variable and the soil strength was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 129.157 and an adjusted R square of 0.782. The regression can be viewed in Figure 4.16 below.

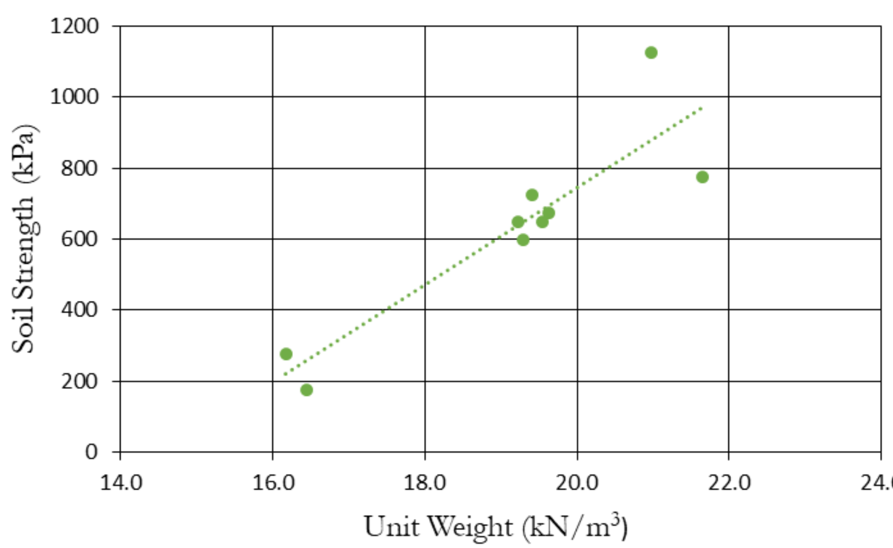

Figure 4.16: Type III soil correlation investigation: unit weight vs. soil strength plot and linear regression

The model equation is given by:

$$\sigma = 595.630 + 376.128\frac{(\gamma - 18.92)}{2.74} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Table 4.22 displays the regression statistics, Table 4.23 displays the ANOVA results, and Table 4.24 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable Z1.

Table 4.22: Regression Statistics

Multiple R	0.900
R Square	0.809
Adjusted R Square	0.782
Standard Error	129.157
Observations	9

Table 4.23: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	495034.773	495034.773	29.676	<0.001
Residual	7	116770.783	16681.540		
Total	8	611805.556			

Table 4.24: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	595.630	43.455	13.707	<0.001	492.875	698.385	yes
Z1	376.128	69.046	5.448	0.001	212.861	539.395	yes

The ANOVA results indicate very strong evidence that the parameters account for the model. The regression statistics suggest that the model provides strong fit to the data. Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a “thick pen line” they can be said to be normally distributed. Figure 4.17 displays a linear “thick pen line” which validates the analytical method.

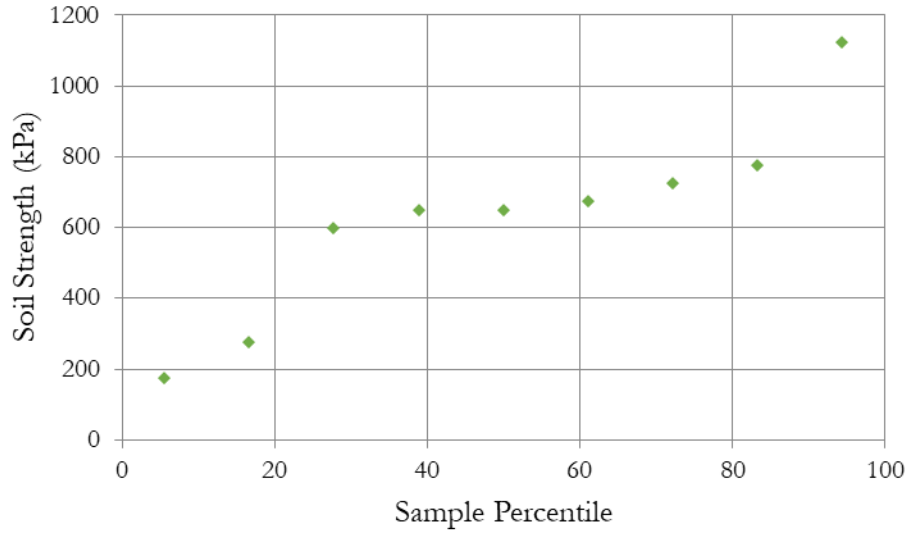

Figure 4.17: Type III soil correlation investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 4.18 depicts the residual plot for the Type III soil correlation investigation.

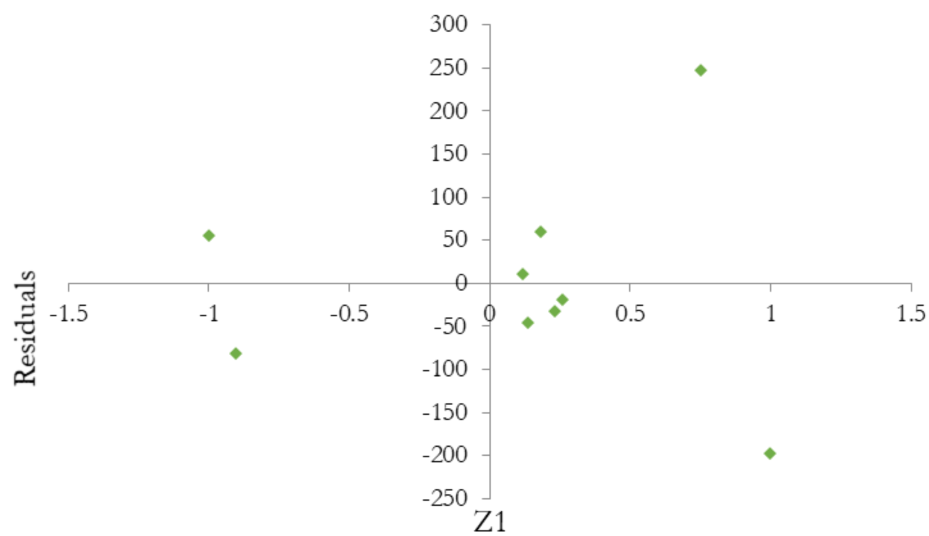

Figure 4.18: Type III soil correlation investigation Z1 parameter vs. residuals

The results of the residual plot do not exhibit a pattern. With the data available, and supported by the results from other diagnostic checks, it has been deemed that the investigation yielded data that can accurately model sigma soil strength response based on the unit weight of the Type III, OL soil. While analysis including moisture content could not provide a statistically significant model, it could still be possible that moisture content affected results. It is recommended that further experimentation be conducted via a traditional factorial design taking percent saturation and soil unit weight as the independent variables.

4.3. Results Correlation

In the absence of confinement effect correction factors, any correlation based on the preceding results would provide unreliable results for in-field application. Chapter 5 will summarize the results from the confinement effect investigation, in an effort to provide the necessary correction factor to allow for in-field correlation of the Chapter 4 results. Unfortunately, the research has proven incapable of correlating the strength readings between the Boeing Cone Penetrometer and the Udarnik U-1. However, these preliminary findings have provided promising insight into the impact of confinement effect on laboratory testing results.

4.4. Chapter 4 Summary

Six experiments were conducted to investigate the relationship between soil strength and soil unit weight: three experiments were conducted using the Boeing Cone Penetrometer, and three experiments were conducted using the Udarnik U-1. Three different soils were tested: a Type I (SW-SM) soil; a Type II (CL) soil; and a Type III (OL) soil. A linear regression was performed for each experimental set of data, and diagnostic checks were performed to consider model validity. Table 4.25 summarizes the regression equations for each soil type and test method.

Table 4.25: Summary of Chapter 4 linear regression models

Soil Type	Boeing Cone Penetrometer	Udarnik U-1
Type I (SW-SM)	$CBR = 75.057 + 58.066\frac{(\gamma - 20.68)}{0.97} + E_i$	$\sigma = 521.413 + 238.090\frac{(\gamma - 20.71)}{1.08} + E_i$
Type II (CL)	$CBR = 38.213 + 20.297\frac{(\gamma - 16.18)}{2.26} + E_i$	$\sigma = 907.513 + 440.836\frac{(\gamma - 16.70)}{2.38} + E_i$
Type III (OL)	$CBR = 25.649 + 20.722\frac{(\gamma - 18.66)}{3.05} + E_i$	$\sigma = 595.630 + 376.128\frac{(\gamma - 18.92)}{2.74} + E_i$

The results from Chapter 4 cannot be directly compared between test methods for correlation in the absence of confinement effect corrections. The confinement effect investigation is discussed in Chapter 5. Ultimately, this experimentation could not establish correlations without further data collection.

CHAPTER 5 Confinement Effect Investigation Results and Discussion

Chapter 5 will first consider confinement effect experimentation results from each soil Type investigation tested with the Boeing Cone Penetrometer. Subsequently, experimentation results for each soil Type investigation tested with the Udarnik U-1 will be presented. The confinement effect exhibited by each mould diameter on each test apparatus will be discussed, and a summary of chapter results will be given in conclusion.

5.1. Boeing Cone Penetrometer Investigation

5.1.1. Type I Soil

The Type I soil investigation was performed with the objective of identifying what effect, if any, confinement had on specimen bearing strength. Specimen mould diameter served as the first independent variable, having three distinct levels: the small diameter of 102 mm, the large diameter of 203 mm, and the medium diameter of 154 mm. Soil unit weight served as the second independent variable. Specimen unit weight ranged from 19.59 kN/m^3 to 21.50 kN/m^3. A hammer of weight 5.84 kg that fell through a height of 316 mm was used for compaction of specimens within the 154 mm and 203 mm moulds, while a standard proctor hammer of weight 2.5 kg which fell through a height of 300 mm was used for the 102 mm mould.

In the small (102 mm) mould, low unit weight was achieved via five hammer blows per layer, in six separate layers for a compactive effort of 6,848 kg/m^2, while high unit weight was achieved via 27 hammer blows per layer in nine separate layers for a compactive effort of 55,469 kg/m^2. In the large (203 mm) mould, low unit weight was achieved via 16 hammer blows per layer in three separate layers for a compactive effort of 6,859 kg/m^2, while high unit weight was achieved via 44 hammer blows per layer in nine separate layers for a compactive effort of 56,588 kg/m^2. Specimens prepared in the 154 mm mould received 15 hammer blows per layer in three separate layers for a compactive effort of 11,135 kg/m^2. Specimen moisture content ranged from 9.7 % to 10.9 %. Table 5.1: below illustrates the input variables and piston adjusted California Bearing Ratio derived from the data logger.

Table 5.1: Type I soil confinement effect investigation Boeing Cone Penetrometer data

Trial	Compactive Effort (kg/m2)	Mould Diameter (mm)	Unit Weight (kN/m3)	Moisture Content	Piston Pressure (PSI)	CBR
2018071102	11135	154	20.37	10.4%	1394	73
2018071103	11135	154	20.31	9.7%	1372	72
2018071104	6848	102	19.59	9.8%	4452	160
2018071105	56588	203	21.35	10.1%	1556	80
2018071201	11135	154	20.79	10.9%	1407	74
2018071202	6859	203	20.32	10.1%	675	38
2018071203	55469	102	21.50	9.7%	4308	158
2018071204	11135	154	20.55	10.0%	1460	76
2018071205	11135	154	20.63	9.7%	1215	65

A model was developed through use of ANOVA in MS Excel, based on the Response Surface Method. While the method is traditionally used to navigate a process towards an optimal set of process parameters, in this case the objective was to efficiently identify the possibility of quadratic parameters. Two independent variables were used: soil unit weight and mould diameter. The California Bearing Ratio was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 2.108 and an adjusted R square of 0.738. The model can be viewed in Figure 5.1 below, as generated in Matlab.

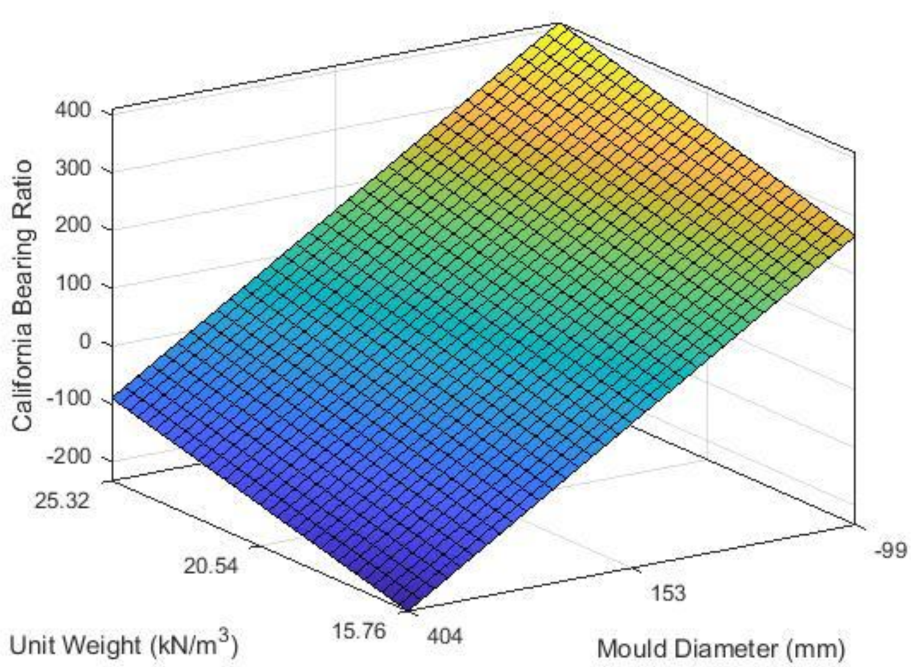

Figure 5.1: Type I soil confinement effect investigation: unit weight and mould diameter vs. California Bearing Ratio

The model equation is given by:

$$CBR = 88.608 + 14.284\frac{(\gamma - 20.54)}{0.96} - 50.012\frac{(D - 153)}{50.23} + E_i$$

where:

γ is the soil unit weight in kN/m^3;

D is the mould diameter in mm; and

E_i is the residual

Table 5.2 displays the regression statistics, Table 5.3 displays the ANOVA results, and Table 5.4 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable X1. Mould diameter is represented by the variable X2. The interaction effect between unit weight and mould diameter is represented by X1X2.

Table 5.2: Regression statistics

Multiple R	0.915
R Square	0.837
Adjusted R Square	0.782
Standard Error	2.108
Observations	9

Table 5.3: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**3**	**11744.316**	**3914.772**	**220.212**	**<0.001**
X1	1	816.174	816.174	45.911	0.002
X2	1	10004.769	10004.769	562.784	<0.001
X1X2	1	923.372	923.372	51.941	0.002
Residual	**5**	**3138.111**	**784.528**		
Lack of Fit	1	3067.002	3067.002	172.524	<0.001
Pure Error	4	71.109	17.777		
Total	**8**	**14037.829**			

Table 5.4: Parameter Statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	88.608	6.698	13.230	0.000	71.391	105.825	yes
X1	14.284	13.414	1.065	0.336	-20.196	48.765	no
X2	-50.012	10.416	4.802	0.005	-76.786	-23.237	yes
X1X2	15.194	13.870	1.095	0.323	-20.460	50.847	no

It is important to note that a lack of fit has also been identified which is statistically significant in the model. Insufficient degrees of freedom exist to estimate parameters for quadratic terms. Completion of axial runs would allow an estimate of the parameters for the quadratic terms of soil unit weight squared and mould diameter squared. With respect to the confinement effect, this does not come as a surprise. It should be expected that as specimen mould diameter increases, the effect on California Bearing Ratio would decrease in a nonlinear manner. As the mould diameter is increased to a particular size, it would be large enough to accurately reflect *in situ* conditions. An increase of mould diameter beyond this threshold size would yield no tangible difference in California Bearing Ratio compared to the results obtained from soil compacted to the same unit weight in field.

While the regression statistics and ANOVA results indicate very strong evidence that the model fits the data, the significance check on individual parameters failed to reject the scenario that a zero value could represent the coefficients for soil density and the interaction effect. It is possible that the mould diameter, and thus the confinement effect, has dominated the response. Soil density has nevertheless been included in the model, since it is commonly accepted as a factor in bearing strength. Furthermore, the results from Chapter 4 suggest that soil density can provide predictive capacity as it relates to bearing strength. Further testing would be needed to validate the results. Updated regression statistics and ANOVA results are provided in Table 5.5 and Table 5.6 respectively.

Table 5.5: Revised regression statistics

Multiple R	0.878
R Square	0.771
Adjusted R Square	0.738
Standard Error	2.108
Observations	9

Table 5.6: Revised ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**2**	**10820.943**	**5410.472**	**304.347**	**<0.001**
X1	1	816.174	816.174	45.911	0.002
X2	1	10004.769	10004.769	562.784	<0.001
Residual	**5**	**3138.111**	**784.528**		
Lack of Fit	1	3067.002	3067.002	172.524	<0.001
Pure Error	4	71.109	17.777		
Total	**8**	**14037.829**			

Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 5.2 displays a linear "thick pen line" which validates the analytical method.

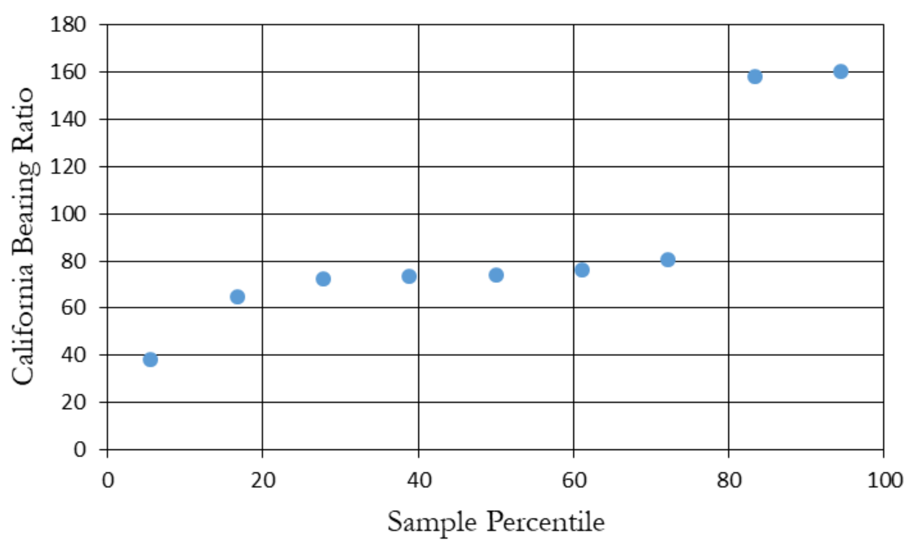

Figure 5.2: Type I soil confinement effect investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 5.3 and Figure 5.4 depict the residual plots for the Type I soil confinement effect investigation. For diagnostic purposes, coded variables were used to investigate residual plots. The plots could be interpreted as exhibiting quadratic tendencies, which further supports the notion that quadratic terms are missing from the model. With higher order terms missing from the model, an accurate correction to laboratory-generated strength values could not be established.

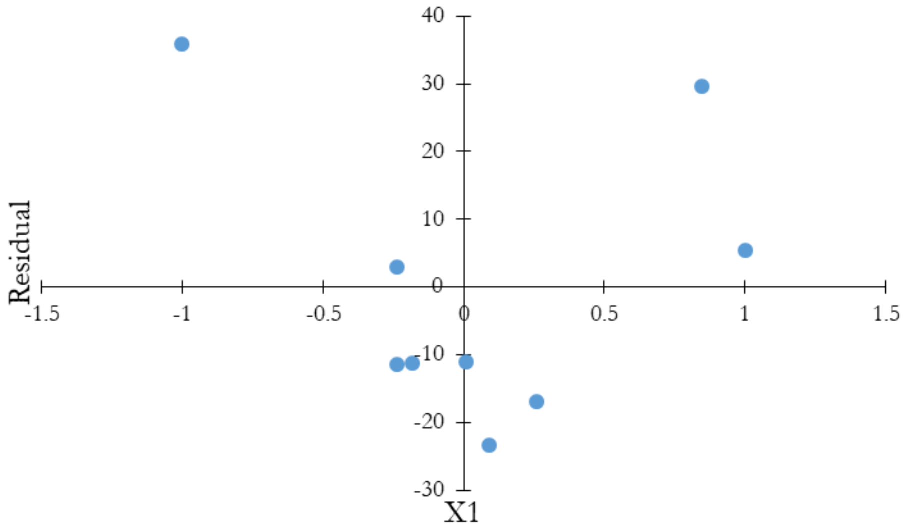

Figure 5.3: Type I soil confinement effect investigation unit weight (X1) vs. residuals

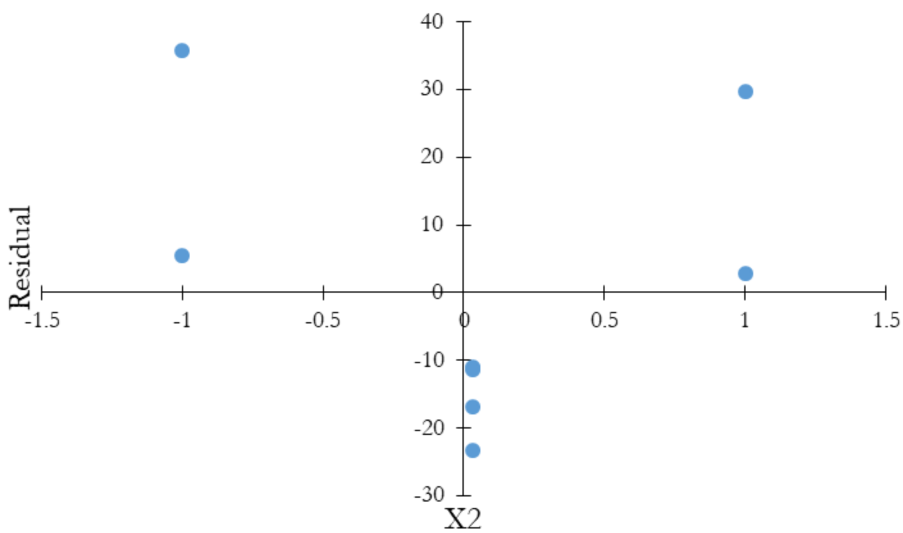

Figure 5.4: Type I soil confinement effect investigation mould diameter (X2) vs. residuals

5.1.2. Type II Soil

The Type II soil investigation was performed with the objective of identifying what effect, if any, confinement had on specimen bearing strength. Specimen mould diameter served as the first independent variable, having three distinct levels: the small diameter of 102 mm, the large diameter of

203 mm, and the medium diameter of 154 mm. Unit weight served as the second independent variable. Specimen unit weight ranged from 14.87 kN/m^3 to 19.83 kN/m^3. A hammer of weight 5.84 kg that fell through a height of 316 mm was used for compaction of specimens within the 154 mm and 203 mm moulds, while a standard proctor hammer of weight 2.5 kg which fell through a height of 300 mm was used for the 102 mm mould.

In the small (102 mm) mould, low unit weight was achieved via five hammer blows per layer, in three separate layers for a compactive effort of 3,424 kg/m^2, while high unit weight was achieved via 30 hammer blows per layer in nine separate layers for a compactive effort of 61,632 kg/m^2. In the large (203 mm) mould, low unit weight was achieved via seven hammer blows per layer in three separate layers for a compactive effort of 3,001 kg/m^2, while high unit weight was achieved via 50 hammer blows per layer in nine separate layers for a compactive effort of 64,305 kg/m^2. Specimens prepared in the 154 mm mould received 15 hammer blows per layer in six separate layers for a compactive effort of 22,270 kg/m^2. Specimen moisture content ranged from 13.9 % to 14.8 %. Table 5.7 below illustrates the input variables and piston adjusted California Bearing Ratio derived from the data logger.

Table 5.7: Type II soil confinement effect investigation Boeing Cone Penetrometer data

Trial	Compactive Effort (kg/m2)	Mould Diameter (mm)	Unit Weight (kN/m3)	Moisture Content	Piston Pressure (PSI)	CBR
2018083103	22270	154	16.92	14.0%	771	43
2018083104	22270	154	17.18	14.4%	796	44
2018083105	3001	203	14.88	14.8%	246	14
2018083106	64305	203	18.84	14.6%	1031	56
2018083107	22270	154	17.55	14.0%	726	41
2018083108	61632	102	19.83	14.5%	1881	94
2018083109	3424	102	14.87	14.1%	355	21
2018083110	22270	154	17.42	14.0%	690	39
2018083111	22270	154	17.31	13.9%	701	39

A model was developed through use of ANOVA in MS Excel, based on the Response Surface Method. While the method is traditionally used to navigate a process towards an optimal set of process parameters, in this case the objective was to efficiently identify the possibility of quadratic parameters. Two independent variables were used: soil unit weight and mould diameter. The California Bearing Ratio was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 1.186 and an adjusted R square of 0.754. The model can be viewed in Figure 5.5 below, as generated in Matlab.

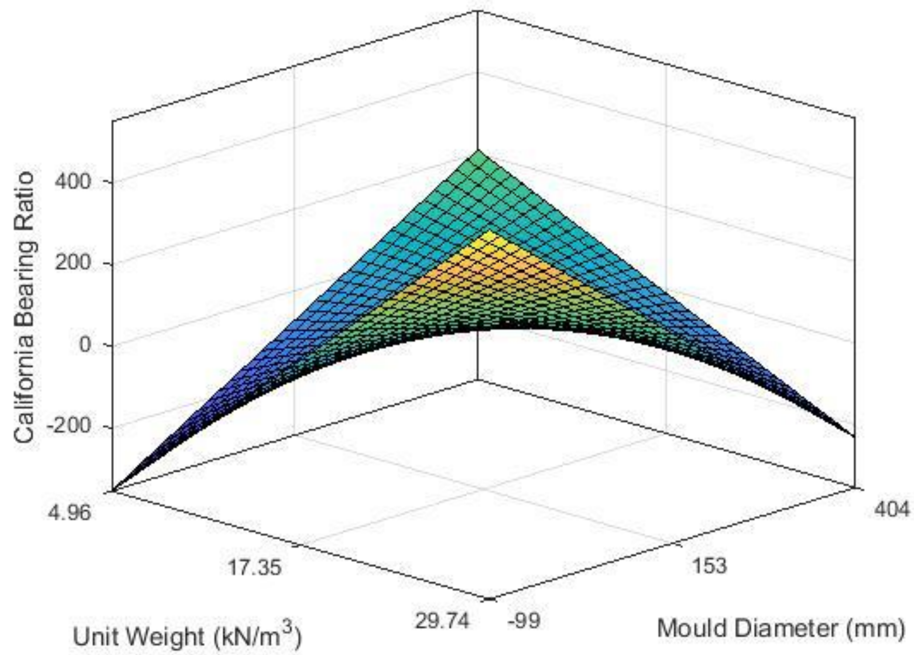

Figure 5.5: Type II soil confinement effect investigation: unit weight and mould diameter vs. California Bearing Ratio

The model equation is given by:

$$CBR = 43.531 + 23.177\frac{(\gamma - 17.35)}{2.48} - 10.961\frac{(D - 153)}{50.23} - 13.439\frac{(\gamma - 17.35)}{2.48}\frac{(D - 153)}{50.23} + E_i$$

where:

γ is the soil unit weight in kN/m^3;

D is the mould diameter in mm; and

E_i is the residual

Table 5.8 displays the regression statistics, Table 5.9 displays the ANOVA results, and Table 5.10 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable X1. Mould diameter is represented by the variable X2. The interaction effect between unit weight and mould diameter is represented by X1X2.

Table 5.8: Regression statistics

Multiple R	0.903
R Square	0.816
Adjusted R Square	0.754
Standard Error	1.186
Observations	9

Table 5.9: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**3**	**3351.711**	**1117.237**	**198.567**	**<0.001**
X1	1	2148.777	2148.777	381.902	<0.001
X2	1	480.549	480.549	85.408	<0.001
X1X2	1	722.386	722.386	128.390	<0.001
Residual	**5**	**77.391**	**15.478**		
Lack of Fit	1	54.885	54.885	9.755	<0.001
Pure Error	4	22.506	5.627		
Total	**8**	**4109.757**			

Table 5.10: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	43.531	2.039	21.347	0.000	38.289	48.773	yes
X1	23.177	3.399	6.819	0.001	14.440	31.915	yes
X2	-10.961	3.074	3.565	0.016	-18.863	-3.058	yes
X1X2	-13.439	3.413	3.938	0.011	-22.211	-4.666	yes

The regression statistics and ANOVA results indicate very strong evidence that the model fits the data, and that the parameters account for the fit. However, it is important to note that a lack of fit has been identified which is statistically significant in the model. Insufficient degrees of freedom exist to estimate parameters for the quadratic terms. Completion of axial runs would allow an estimate of the parameters for the quadratic terms of soil unit weight squared and mould diameter squared. With respect to the confinement effect, this does not come as a surprise. It should be expected that as specimen mould diameter increases, the effect on California Bearing Ratio would decrease in a nonlinear manner. As the mould diameter is increased to a particular size, it would be large enough to accurately reflect in-situ conditions. An increase of mould diameter beyond this threshold size would yield no tangible difference in California Bearing Ratio compared to the results obtained from soil compacted to the same unit weight in field.

Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 5.6 displays a linear "thick pen line" which validates the analytical method.

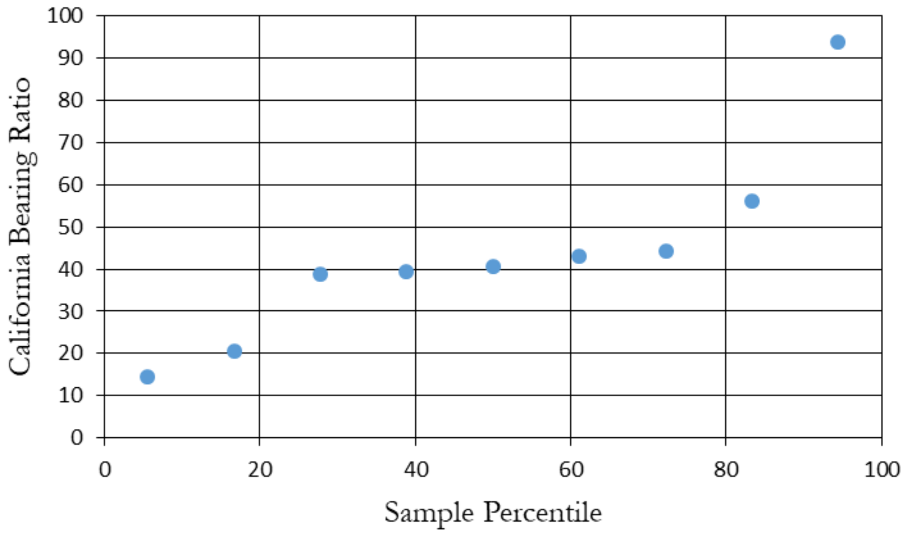

Figure 5.6: Type II soil confinement effect investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012).Figure 5.7, Figure 5.8, and Figure 5.9 depict the residual plots for the Type II soil confinement effect investigation. For diagnostic purposes, coded variables were used to investigate residual plots. The plots do not exhibit any pattern, which does support the validity of the model. However, with higher order terms missing from the model, as suggested by the ANOVA, an accurate correction to laboratory generated strength values could not be established.

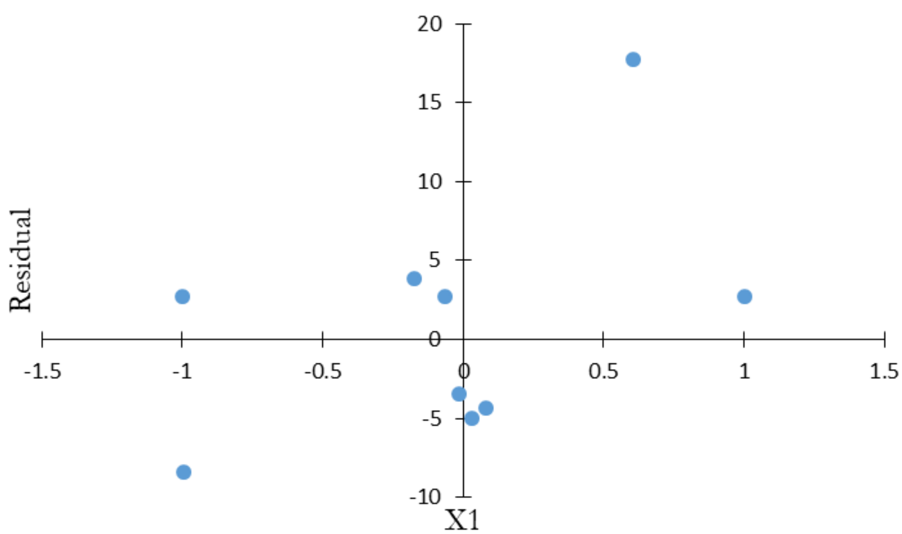

Figure 5.7: Type II soil confinement effect investigation unit weight (X1) vs. residuals

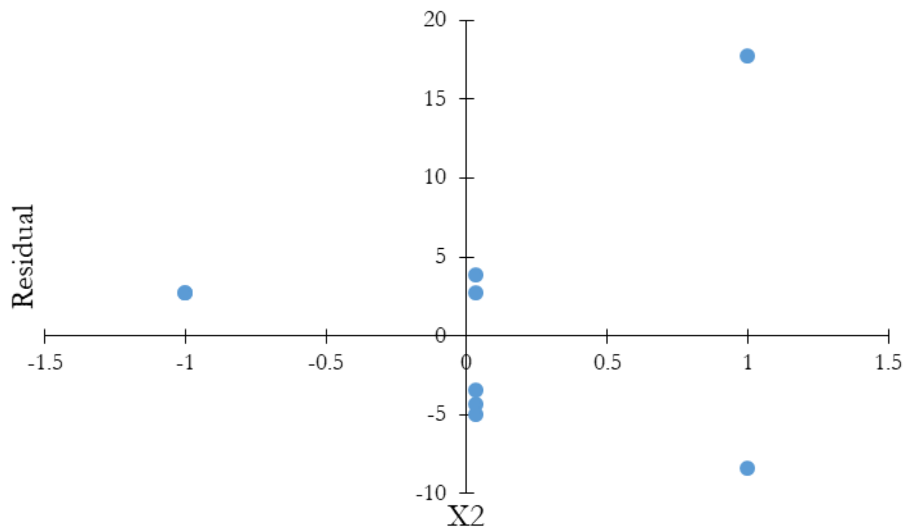

Figure 5.8: Type II soil confinement effect investigation mould diameter (X2) vs. residuals

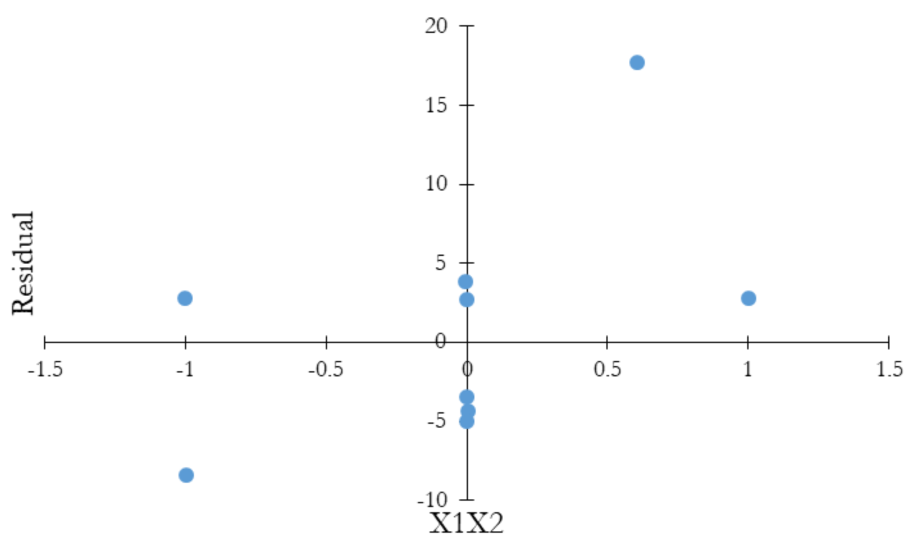

Figure 5.9: Type II soil confinement effect investigation X1X2 parameter vs. residuals

5.1.3. Type III Soil

The Type III soil investigation was performed with the objective of identifying what effect, if any, confinement had on specimen bearing strength. Specimen mould diameter served as the first independent variable, having three distinct levels: the small diameter of 102 mm, the large diameter of 203 mm, and the medium diameter of 154 mm. Unit weight served as the second independent variable.

Specimen unit weight ranged from 15.70 kN/m^3 to 21.86 kN/m^3. A hammer of weight 5.84 kg that fell through a height of 316 mm was used for compaction of specimens within the 154 mm and 203 mm moulds, while a standard proctor hammer of weight 2.5 kg which fell through a height of 300 mm was used for the 102 mm mould.

In the small (102 mm) mould, low unit weight was achieved via four hammer blows per layer, in three separate layers for a compactive effort of 2,739 kg/m^2, while high unit weight was achieved via 31 hammer blows per layer in nine separate layers for a compactive effort of 63,686 kg/m^2. In the large (203 mm) mould, low unit weight was achieved via seven hammer blows per layer in three separate layers for a compactive effort of 3,001 kg/m^2, while high unit weight was achieved via 49 hammer blows per layer in nine separate layers for a compactive effort of 63,019 kg/m^2. Specimens prepared in the 154 mm mould received 12 hammer blows per layer in six separate layers for a compactive effort of 17,816 kg/m^2. Specimen moisture content ranged from 10.3 % to 11.0 %. Table 5.11 below illustrates the input variables and piston adjusted California Bearing Ratio derived from the data logger.

Table 5.11: Type III soil confinement effect investigation Boeing Cone Penetrometer data

Trial	Compactive Effort (kg/m2)	Mould Diameter (mm)	Unit Weight (kN/m3)	Moisture Content	Piston Pressure (PSI)	CBR
2018080201	17816	154	19.58	11.0%	484	28
2018080202	17816	154	19.58	10.7%	504	29
2018080203	63686	102	21.86	10.6%	2096	102
2018080204	2739	102	15.70	10.3%	188	11
2018080205	17816	154	19.26	10.3%	574	33
2018080206	63019	203	21.24	10.6%	837	46
2018080207	3001	203	16.27	10.3%	118	7
2018080401	17816	154	19.89	10.9%	501	29
2018080402	17816	154	19.66	10.8%	471	27

A model was developed through use of ANOVA in MS Excel, based on the Response Surface Method. While the method is traditionally used to navigate a process towards an optimal set of process parameters, in this case the objective was to efficiently identify the possibility of quadratic parameters. Two independent variables were used: soil unit weight and mould diameter. The California Bearing Ratio was taken as the dependent variable. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 1.090 and an adjusted R square of 0.859. The model can be viewed in Figure 5.10 below, as generated in Matlab.

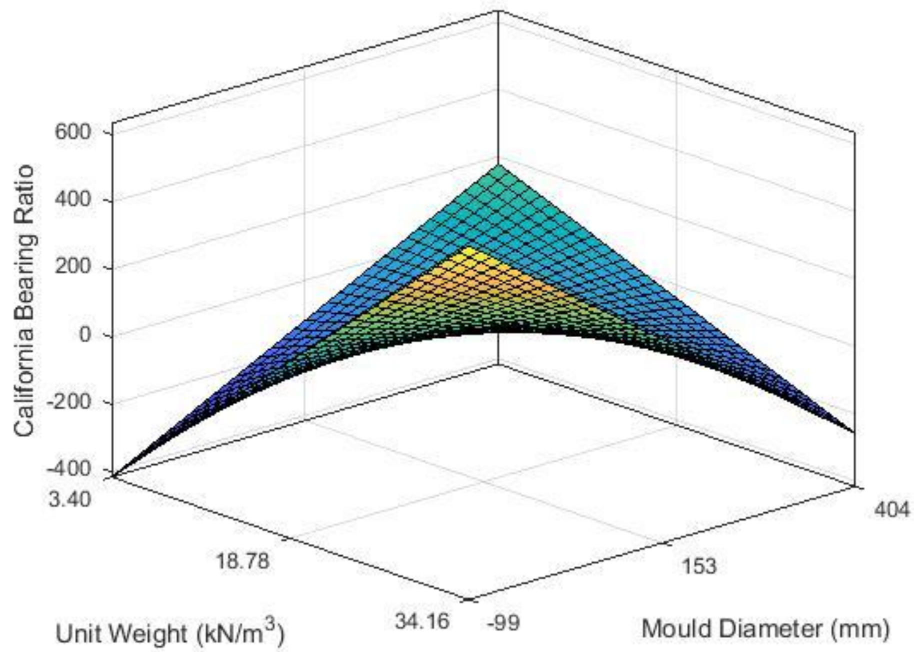

Figure 5.10: Type III soil confinement effect investigation: unit weight and mould diameter vs. California Bearing Ratio

The model equation is given by:

$$CBR = 34.664 + 30.634\frac{(\gamma - 18.78)}{3.08} - 14.944\frac{(D - 153)}{50.23} - 14.871\frac{(\gamma - 18.78)}{3.08}\frac{(D - 153)}{50.23} + E_i$$

where:

γ is the soil unit weight in kN/m^3;

D is the mould diameter in mm; and

E_i is the residual

Table 5.12 displays the regression statistics, Table 5.13 displays the ANOVA results, and Table 5.14 displays parameter statistics. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable X1. Mould diameter is represented by the variable X2. The interaction effect between unit weight and mould diameter is represented by X1X2.

Table 5.12: Regression statistics

Multiple R	0.945
R Square	0.894
Adjusted R Square	0.859
Standard Error	1.090
Observations	9

Table 5.13: ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**3**	**5531.829**	**1843.943**	**387.794**	**<0.001**
X1	1	3753.890	3753.890	789.470	<0.001
X2	1	893.303	893.303	187.868	<0.001
X1X2	1	884.636	884.636	186.045	<0.001
Residual	**5**	**373.828**	**74.766**		
Lack of Fit	1	354.808	354.808	74.619	0.001
Pure Error	4	19.020	4.755		
Total	**8**	**6188.266**			

Table 5.14: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	34.664	4.857	7.137	0.001	22.178	47.150	yes
X1	30.634	7.748	3.954	0.011	10.718	50.551	yes
X2	-14.944	7.082	2.110	0.089	-33.148	3.260	no
X1X2	-14.871	7.957	1.869	0.121	-35.324	5.582	no

It is important to note that a lack of fit has been identified which is statistically significant in the model. Insufficient degrees of freedom exist to estimate parameters for the quadratic terms. Completion of axial runs would allow an estimate of the parameters for the quadratic terms of soil unit weight squared and mould diameter squared. With respect to the confinement effect, this does not come as a surprise. It should be expected that as specimen mould diameter increases, the effect on California Bearing Ratio would decrease in a nonlinear manner. As the mould diameter is increased to a particular size, it would be large enough to accurately reflect in-situ conditions. An increase of mould diameter beyond this threshold size would yield no tangible difference in California Bearing Ratio compared to the results obtained from soil compacted to the same unit weight in field.

While the regression statistics and ANOVA results indicate very strong evidence that the model fits the data, the significance check on individual parameters failed to reject the scenarios, at a 5% significance level, that a zero value could represent the coefficients for mould diameter and the interaction effect between unit weight and mould diameter. However, at a 10% significance level, the hypothesis would be rejected and mould diameter would be included in the model. The interaction effect between unit weight and mould diameter would require a significance level of at least 13% to be included in the model. Since the Type II and Type III soils are similar in nature, it was deemed acceptable to include both mould diameter and the interaction effect in the model. Further testing is required to validate results.

Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 5.11 displays a linear "thick pen line" which validates the analytical method.

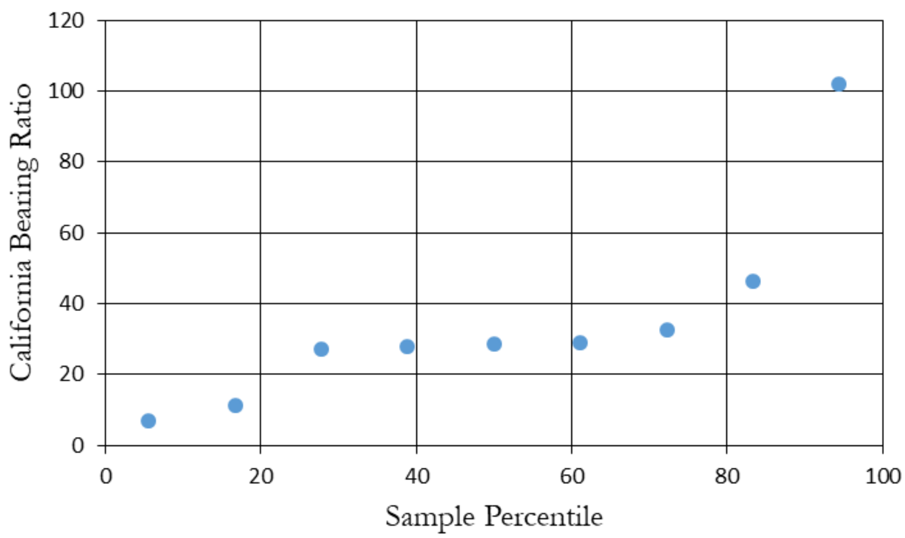

Figure 5.11: Type III soil confinement effect investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 5.12, Figure 5.13, and Figure 5.14 depict the residual plots for the Type III soil confinement effect investigation. For diagnostic purposes, coded variables were used to investigate residual plots. The plots may exhibit some quadratic tendencies, but they generally do not exhibit any pattern. The plots could therefore support both the validity of the model, and the possibility of quadratic terms which were not captured. With the higher order terms missing from the model, as suggested by the ANOVA, an accurate correction to laboratory generated strength values could not be established.

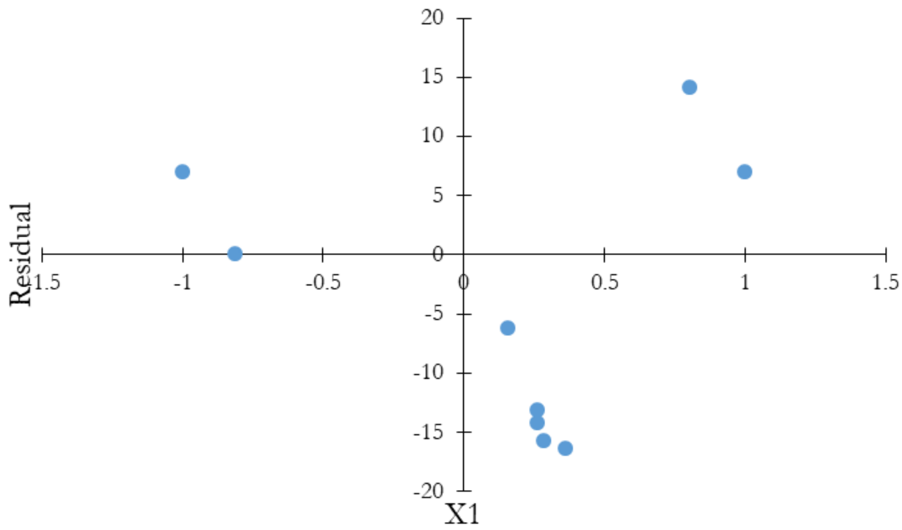

Figure 5.12: Type III soil confinement effect investigation unit weight (X1) vs. residuals

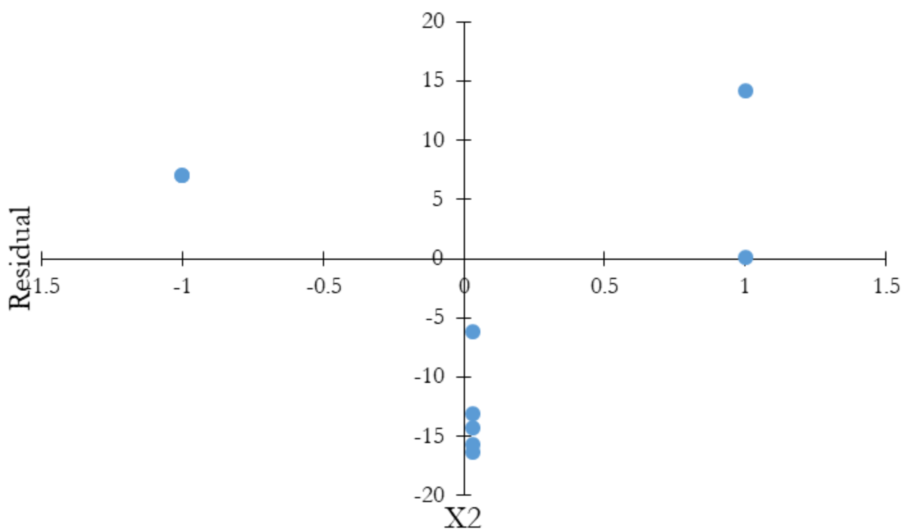

Figure 5.13: Type III soil confinement effect investigation mould diameter (X2) vs. residuals

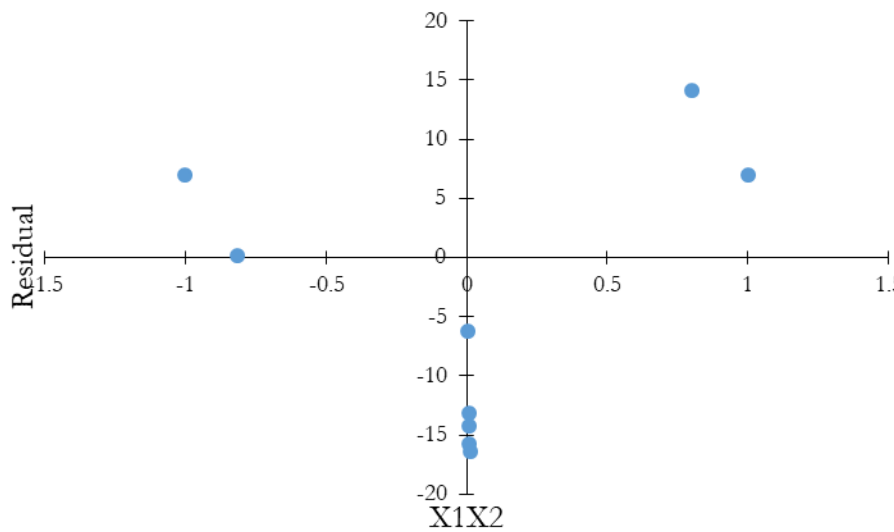

Figure 5.14: Type III soil confinement effect investigation interaction effect (X1X2) vs. residuals

5.2. Udarnik U-1 Investigation

5.2.1. Type I Soil

The Type I soil investigation was performed with the objective of identifying what effect, if any, confinement had on specimen bearing strength. Specimen mould diameter served as the first independent variable, having three distinct levels: the small diameter of 102 mm, the large diameter of 203 mm, and the medium diameter of 154 mm. Unit weight served as the second independent variable. Specimen unit weight ranged from 19.72 kN/m^3 to 21.33 kN/m^3. A hammer of weight 5.84 kg that fell through a height of 316 mm was used for compaction of specimens within the 154 mm and 203 mm moulds, while a standard proctor hammer of weight 2.5 kg which fell through a height of 300 mm was used for the 102 mm mould.

In the small (102 mm) mould, low unit weight was achieved via five hammer blows per layer, in six separate layers for a compactive effort of 6,848 kg/m^2, while high unit weight was achieved via 27 hammer blows per layer in nine separate layers for a compactive effort of 55,469 kg/m^2. In the large (203 mm) mould, low unit weight was achieved via 16 hammer blows per layer in three separate layers for a compactive effort of 6,859 kg/m^2, while high unit weight was achieved via 44 hammer blows per layer in nine separate layers for a compactive effort of 56,588 kg/m^2. Specimens prepared in the 154 mm mould received 15 hammer blows per layer in three separate layers for a compactive effort of 11,135 kg/m^2. Specimen moisture content ranged from 9.9 % to 10.1 %. Table 5.15 below illustrates the input variables, strike count to depths of 10 cm and 30 cm, and the resulting soil strength as determined from the Udarnik U-1 graphs.

Table 5.15: Type II soil confinement effect investigation Udarnik U-1 data

Trial	Compactive Effort (kg/m2)	Mould Diameter (mm)	Unit Weight (kN/m3)	Moisture Content	σ10 Strikes	σ30 Strikes	σ (kPa)
2018061304	11135	154	20.34	10.1%	2	9	550
2018061305	11135	154	20.34	10.1%	2	11	650
2018061306	6848	102	19.72	10.1%	2	8	450
2018061307	56588	203	21.26	10.0%	2	9	550
2018061308	11135	154	20.18	9.9%	2	10	600
2018061501	6859	203	19.99	10.1%	2	9	550
2018061502	55469	102	21.33	10.1%	2	10	600
2018061503	11135	154	20.26	10.0%	2	10	600
2018061504	11135	154	20.25	9.9%	2	9	550

A model was developed through use of ANOVA in MS Excel, based on the Response Surface Method. While the method is traditionally used to navigate a process towards an optimal set of process parameters, in this case the objective was to efficiently identify the possibility of quadratic parameters. Two independent variables were used: soil unit weight and mould diameter. Soil strength was taken as the dependent variable.

The null hypothesis was not rejected at the 5% significance level, however it was evident that the soil unit weight was significant. Table 5.16 displays the preliminary ANOVA results. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable Z1. Mould diameter is represented by the variable Z2. The interaction effect between unit weight and mould diameter is represented by Z1Z2.

Table 5.16: Preliminary ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**3**	**20302.067**	**6767.356**	**3.867**	**0.112**
Z1	1	20302.067	20302.067	11.601	0.027
Z2	1	625.000	625.000	0.357	0.582
Z1Z2	1	56.470	56.470	0.032	0.866
Residual	**5**	**13125.000**	**3281.250**		
Lack of Fit	1	6125.000	6125.000	3.500	0.135
Pure Error	4	7000.000	1750.000		
Total	**8**	**25000.000**			

The analysis of variance was repeated without consideration of mould diameter and the interaction effect, and the regression then proved significant. The regression was found to be statistically significant at a 5 % significance level, with a standard error of 20.917 and an adjusted R square of 0.812. The model can be viewed in Figure 5.15 below.

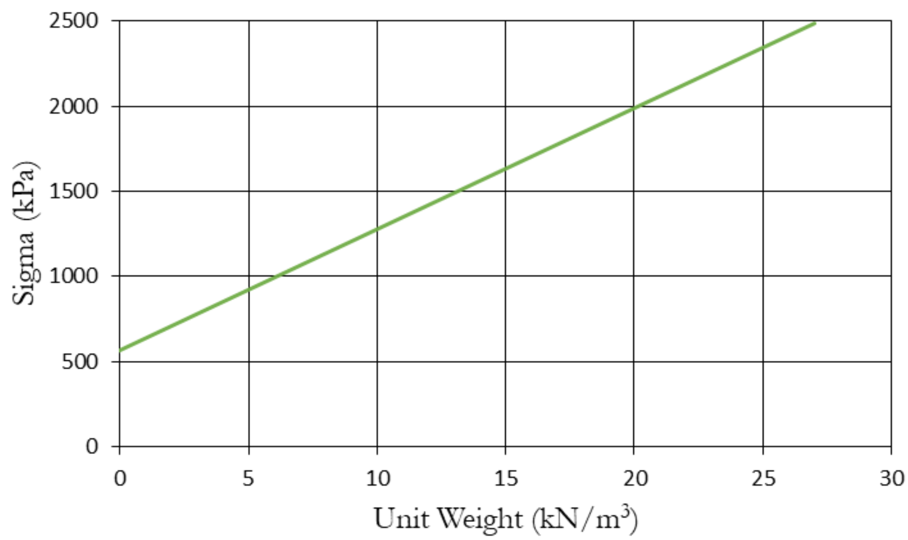

Figure 5.15: Type I soil confinement effect investigation: unit weight vs. soil strength

The model equation is given by:

$$\sigma = 566.667 + 71.243\frac{(\gamma - 20.53)}{0.81} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Table 5.17 displays the regression statistics, Table 5.18 displays the revised ANOVA results, and Table 5.19 displays parameter statistics.

Table 5.17: Regression statistics

Multiple R	0.901
R Square	0.812
Adjusted R Square	0.812
Standard Error	20.917
Observations	9

Table 5.18: Revised ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**1**	**20302.067**	**20302.067**	**11.601**	**0.027**
Z1	1	20302.067	20302.067	11.601	0.027
Residual	**5**	**13125.000**	**3281.250**		
Lack of Fit	3	6125.000	6125.000	3.500	0.135
Pure Error	7	7000.000	1750.000		
Total	**8**	**25000.000**			

Table 5.19: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	566.667	18.977	29.861	<0.001	521.794	611.539	yes
Z1	71.243	29.300	2.432	0.045	1.960	140.525	yes

Only soil unit weight exhibited significance. It was of interest to note that a lack of fit was not identified as statistically significant in the model. Accordingly, strength results as determined in laboratory do not require correction for direct comparison to field results.

Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 5.16 displays a linear "thick pen line" which validates the analytical method.

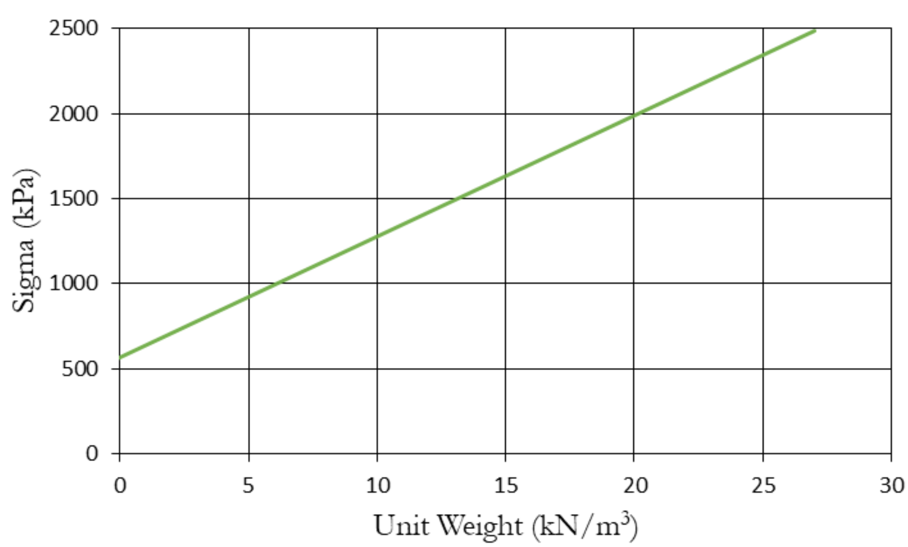

Figure 5.16: Type I soil confinement effect investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 5.17 depicts the residual plot for the Type I soil confinement effect investigation. For diagnostic purposes, coded variables were used to investigate residual plots. No pattern was evident in the residual plot, and therefore the validity of the model was supported. The investigation yielded an accurate model, and it suggested that the mould diameters used have no impact on soil strength results compared to what would be expected under the same conditions in field. No correction factor is required to estimate the response for the Type I soil tested via the Udarnik U-1.

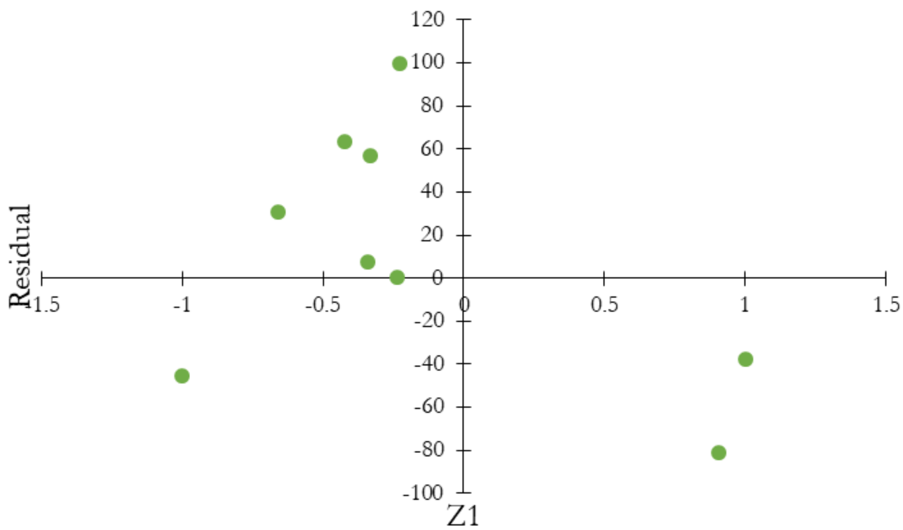

Figure 5.17: Type I soil confinement effect investigation Z1 parameter vs. residuals

5.2.2. Type II Soil

The Type II soil investigation was performed with the objective of identifying what effect, if any, confinement had on specimen bearing strength. Specimen mould diameter served as the first independent variable, having three distinct levels: the small diameter of 102 mm, the large diameter of 203 mm, and the medium diameter of 154 mm. Unit weight served as the second independent variable. Specimen unit weight ranged from 14.30 kN/m^3 to 19.47 kN/m^3. A hammer of weight 5.84 kg that fell through a height of 316 mm was used for compaction of specimens within the 154 mm and 203 mm moulds, while a standard proctor hammer of weight 2.5 kg which fell through a height of 300 mm was used for the 102 mm mould.

In the small (102 mm) mould, low unit weight was achieved via five hammer blows per layer, in three separate layers for a compactive effort of 3,424 kg/m^2, while high unit weight was achieved via 30 hammer blows per layer in nine separate layers for a compactive effort of 61,632 kg/m^2. In the large (203 mm) mould, low unit weight was achieved via seven hammer blows per layer in three separate layers for a compactive effort of 3,001 kg/m^2, while high unit weight was achieved via 50 hammer blows per layer in nine separate layers for a compactive effort of 64,305 kg/m^2. Specimens prepared in the 154 mm mould received 15 hammer blows per layer in six separate layers for a compactive effort of 22,270 kg/m^2. Specimen moisture content ranged from 13.2 % to 14.7 %. Table 5.20 below illustrates the input variables, strike count to depths of 10 cm and 30 cm, and the resulting soil strength as determined from the Udarnik U-1 graphs.

Table 5.20: Type II soil confinement effect investigation Udarnik U-1 data

Trial	Compactive Effort (kg/m2)	Mould Diameter (mm)	Unit Weight (kN/m3)	Moisture Content	σ10 Strikes	σ30 Strikes	σ (kPa)
2018082901	22270	154	17.21	14.0%	4	24	975
2018082902	22270	154	17.05	14.2%	5	27	1063
2018082903	3001	203	14.30	14.7%	2	9	400
2018082904	64305	203	18.42	13.7%	12	69	1275
2018082905	22270	154	17.29	13.7%	7	38	1175
2018082906	61632	102	19.47	14.0%	18	93	1275
2018082907	3424	102	14.75	13.6%	2	9	400
2018082908	22270	154	17.26	13.3%	6	37	1150
2018082909	22270	154	17.34	13.2%	6	35	1150

A model was developed through use of ANOVA in MS Excel, based on the Response Surface Method. While the method is traditionally used to navigate a process towards an optimal set of process parameters, in this case the objective was to efficiently identify the possibility of quadratic parameters. Two independent variables were used: soil unit weight and mould diameter. Soil strength was taken as the dependent variable.

The regression was found to be statistically significant at a 5 % significance level, with a standard error of 41.552 and an adjusted R square of 0.471. Table 5.21 displays the preliminary ANOVA results. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable Z1. Mould diameter is represented by the variable Z2. The interaction effect between unit weight and mould diameter is represented by Z1Z2.

Table 5.21: Preliminary ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**3**	**509955.962**	**169985.321**	**24.613**	**0.005**
Z1	1	423556.088	423556.088	61.329	0.001
Z2	1	<0.001	<0.001	<0.001	1.000
Z1Z2	1	86399.874	86399.874	12.510	0.024
Residual	**5**	**183680.556**	**45920.139**		
Lack of Fit	1	156055.556	156055.556	22.596	0.009
Pure Error	4	27625.000	6906.250		
Total	**8**	**949305.556**			

It was evident that the mould diameter was not significant in the model. The regression was repeated without consideration of mould diameter. Table 5.22 displays the regression statistics, Table 5.23 displays the revised ANOVA results, and Table 5.24 displays parameter statistics.

Table 5.22: Regression statistics

Multiple R	0.733
R Square	0.537
Adjusted R Square	0.471
Standard Error	41.552
Observations	9

Table 5.23: Revised ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**2**	**509955.962**	**169985.321**	**24.613**	**0.006**
Z1	1	423556.088	423556.088	61.329	0.001
Z1Z2	1	86399.874	86399.874	12.510	0.024
Residual	**5**	**183680.556**	**45920.139**		
Lack of Fit	2	156055.556	78027.778	11.298	0.023
Pure Error	4	27625.000	6906.250		
Total	**8**	**949305.556**			

Table 5.24: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	984.722	43.748	22.509	<0.001	877.674	1091.771	yes
Z1	325.406	74.158	4.388	0.005	143.949	506.863	yes
Z1Z2	-146.969	75.513	1.946	0.100	-331.744	37.805	no

While the regression statistics and ANOVA results indicate evidence that the model fits the data, the significance check on individual parameters failed to reject the scenario that a zero value could represent the coefficients for the interaction effect. Accordingly, the interaction effect should not be considered in the model, and it can thus be concluded that the soil strength reported from lab testing was not affected by the confinement effect. Figure 5.18 displays the model.

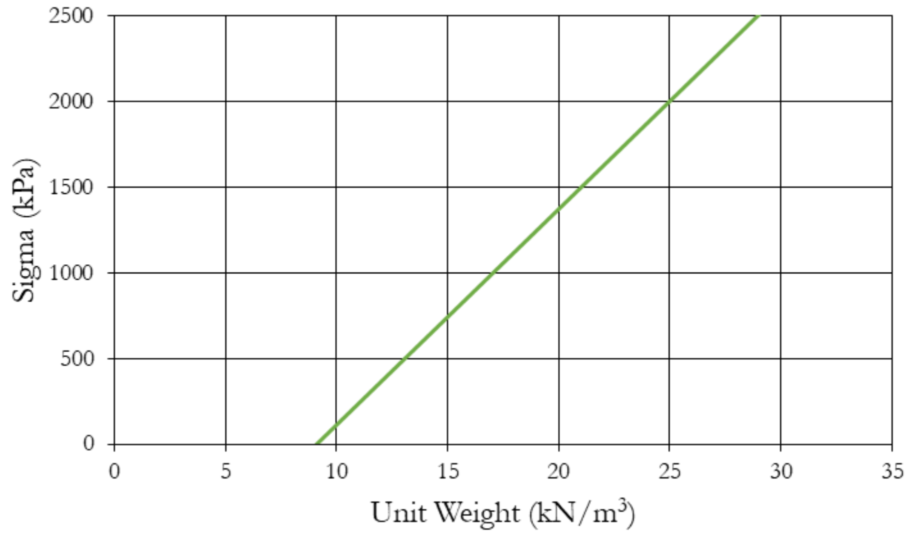

Figure 5.18: Type I soil confinement effect investigation: unit weight vs. soil strength

The model is given by the equation:

$$\sigma = 984.722 + 325.406\frac{(\gamma - 16.88)}{2.58} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

While soil unit weight exhibited significance, a lack of fit was also determined to be statistically significant in the model. Further data points are required to provide sufficient degrees of freedom to estimate the higher order terms missing from the model. A correction factor could therefore not be estimated on the response for the Type II soil tested via the Udarnik U-1 in lab, for the purposes of representing field conditions.

Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 5.19 displays a linear "thick pen line" which validates the analytical method.

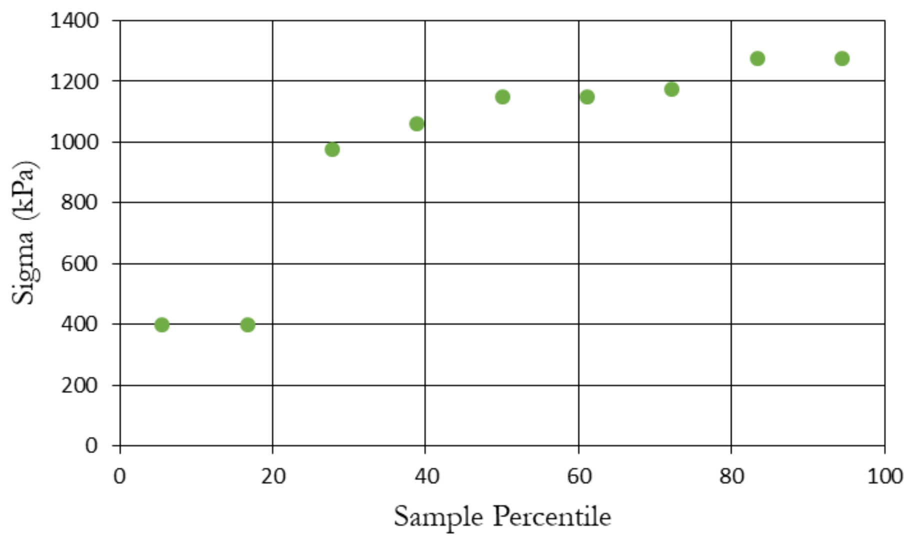

Figure 5.19: Type II soil confinement effect investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 5.20 depicts the residual plot for the Type II soil confinement effect investigation.

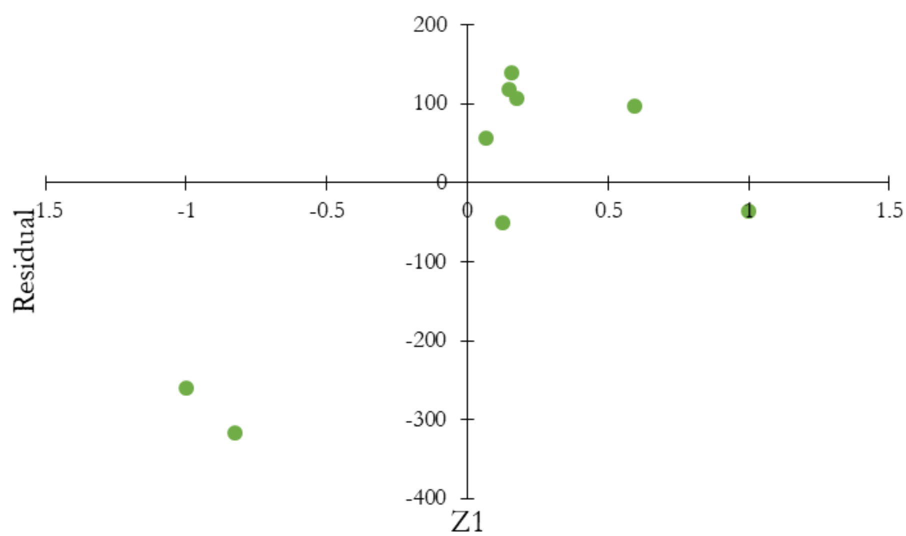

Figure 5.20: Type II soil confinement effect investigation Z1 parameter vs. residuals

5.2.3. Type III Soil

The Type III soil investigation was performed with the objective of identifying what effect, if any, confinement had on specimen bearing strength. Specimen mould diameter served as the first independent variable, having three distinct levels: the small diameter of 102 mm, the large diameter of 203 mm, and the medium diameter of 154 mm. Unit weight served as the second independent variable. Specimen unit weight ranged from 15.59 kN/m^3 to 21.97 kN/m^3. A hammer of weight 5.84 kg that fell through a height of 316 mm was used for compaction of specimens within the 154 mm and 203 mm moulds, while a standard proctor hammer of weight 2.5 kg which fell through a height of 300 mm was used for the 102 mm mould.

In the small (102 mm) mould, low unit weight was achieved via four hammer blows per layer, in three separate layers for a compactive effort of 2,739 kg/m^2, while high unit weight was achieved via 31 hammer blows per layer in nine separate layers for a compactive effort of 63,686 kg/m^2. In the large (203 mm) mould, low unit weight was achieved via seven hammer blows per layer in three separate layers for a compactive effort of 3,001 kg/m^2, while high unit weight was achieved via 49 hammer blows per layer in nine separate layers for a compactive effort of 63,019 kg/m^2. Specimens prepared in the 154 mm mould received 12 hammer blows per layer in six separate layers for a compactive effort of 17,816 kg/m^2. Specimen moisture content ranged from 9.5 % to 10.70 %. Table 5.25 below illustrates the input variables, strike count to depths of 10 cm and 30 cm, and the resulting soil strength as determined from the Udarnik U-1 graphs.

Table 5.25: Type III soil confinement effect investigation Udarnik U-1 data

Trial	Compactive Effort (kg/m2)	Mould Diameter (mm)	Unit Weight (kN/m3)	Moisture Content	σ10 Strikes	σ30 Strikes	σ (kPa)
2018080403	17816	154	19.84	10.6%	5	20	725
2018080404	17816	154	19.66	10.6%	4	19	650
2018080405	63686	102	21.97	10.7%	10	52	1125
2018080406	2739	102	15.59	10.5%	1	4	175
2018080501	17816	154	19.23	10.3%	5	22	750
2018080502	63019	203	21.06	9.8%	10	47	1125
2018080503	3001	203	16.35	9.5%	2	7	275
2018080504	17816	154	19.18	9.6%	5	22	750
2018080505	17816	154	19.02	9.5%	5	22	750

A model was developed through use of ANOVA in MS Excel, based on the Response Surface Method. While the method is traditionally used to navigate a process towards an optimal set of process parameters, in this case the objective was to efficiently identify the possibility of quadratic parameters. Two independent variables were used: soil unit weight and mould diameter. Soil strength was taken as the dependent variable.

The regression was found to be statistically significant at a 5 % significance level, with a standard error of 21.651 and an adjusted R square of 0.723. Table 5.26 displays the preliminary ANOVA results. Coded variables were used during statistical analysis to preserve orthogonality. Accordingly, unit weight is represented by the variable Z1. Mould diameter is represented by the variable Z2. The interaction effect between unit weight and mould diameter is represented by Z1Z2.

Table 5.26: Preliminary ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**3**	**630135.036**	**210045.012**	**112.024**	**<0.001**
Z1	1	595941.156	595941.156	317.835	<0.001
Z2	1	2500.000	2500.000	1.333	0.313
Z1Z2	1	31693.879	31693.879	16.903	0.015
Residual	**5**	**13055.556**	**3263.889**		
Lack of Fit	1	5555.556	5555.556	2.963	0.160
Pure Error	4	7500.000	1875.000		
Total	**8**	**828055.556**			

It was evident that the mould diameter was not significant in the model. The regression was repeated without consideration of mould diameter. Table 5.27 displays the regression statistics, Table 5.28 displays the revised ANOVA results, and Table 5.29 displays parameter statistics.

Table 5.27: Regression statistics

Multiple R	0.871
R Square	0.758
Adjusted R Square	0.723
Standard Error	21.651
Observations	9

Table 5.28: Revised ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**2**	**627635.036**	**313817.518**	**167.369**	**<0.001**
X1	1	595941.156	595941.156	317.835	<0.001
X1X2	1	31693.879	31693.879	16.903	0.015
Residual	**5**	**13055.556**	**3263.889**		
Lack of Fit	2	5555.556	2777.778	1.481	0.330
Pure Error	4	7500.000	1875.000		
Total	**8**	**828055.556**			

Table 5.29: Parameter statistics

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*H0 (5 %) Rejected?*
Intercept	702.778	28.581	24.589	<0.001	632.843	772.712	yes
Z1	385.986	49.095	7.862	<0.001	265.854	506.118	yes
Z1Z2	-89.014	50.166	1.774	0.126	-211.765	33.737	no

While the regression statistics and ANOVA results indicate strong evidence that the model fits the data, the significance check on individual parameters failed to reject the scenario that a zero value could represent the coefficients for the interaction effect. Accordingly, the interaction effect should not be considered in the model, and it can thus be concluded that the soil strength reported from lab testing was not affected by the confinement effect. Figure 5.21 displays the model.

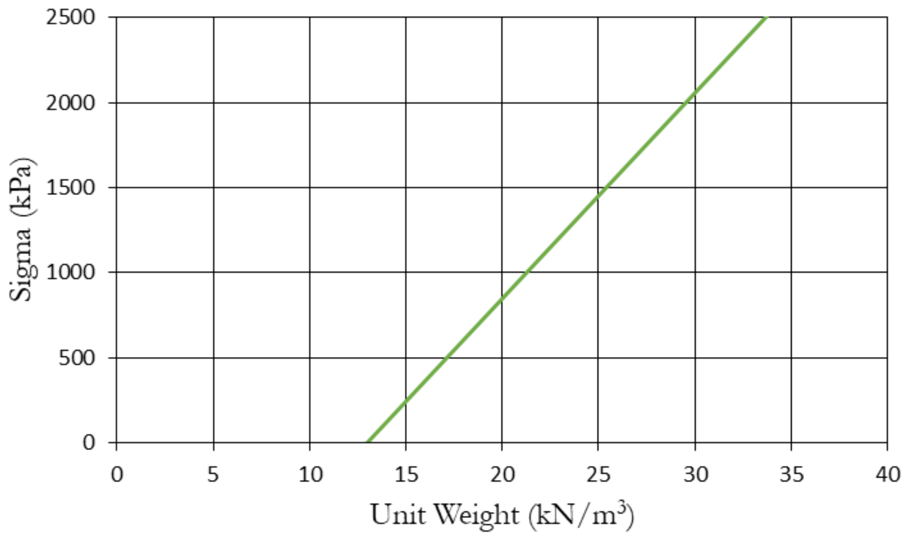

Figure 5.21: Type III soil confinement effect investigation: unit weight vs. soil strength

The model is given by the equation:

$$\sigma = 702.778 + 385.986\frac{(\gamma - 18.78)}{3.19} + E_i$$

where:

γ is the soil unit weight in kN/m^3; and

E_i is the residual

Further diagnostic checks are required to confirm the assumption of normality and to identify the possibility of lurking variables unaccounted for in the model. Normality can be verified through means of a normal probability plot (Montgomery, 2012). Where the points fall within a "thick pen line" they can be said to be normally distributed. Figure 5.22 displays a linear "thick pen line" which validates the analytical method.

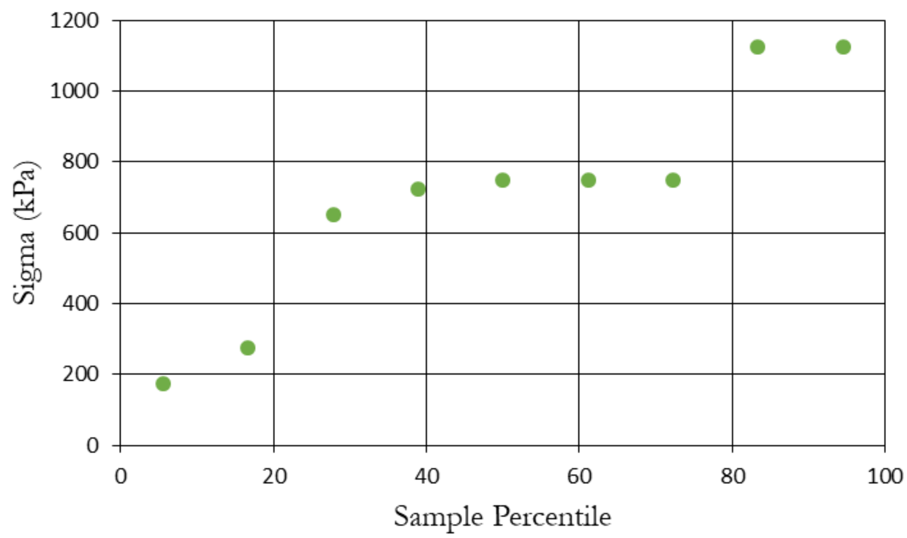

Figure 5.22: Type III soil confinement effect investigation normal probability plot

To identify lurking variables, a plot of residuals should exhibit no visible pattern while centring about a mean of zero (Montgomery, 2012). Figure 5.23 depict the residual plots for the Type III soil confinement effect investigation.

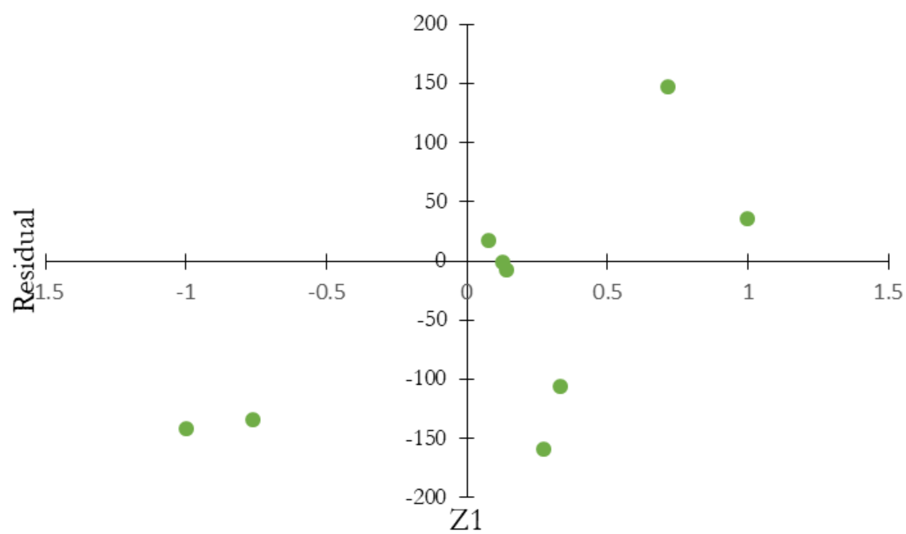

Figure 5.23: Type III soil confinement effect investigation Z1 parameter vs. residuals

The investigation yielded an accurate model, and it suggested that the mould diameters used do not directly impact soil strength results reported compared to what would be expected under the same conditions in field. A correction factor is not required to estimate the response for the Type III soil tested via the Udarnik U-1 in lab to represent field conditions.

5.3. Confinement Effect Correction Factors

5.3.1. Calculation of Correction Factors

In theory, as mould diameter continues to increase, there should come a point where mould diameter is large enough to approximate the field conditions. That is, field conditions can be thought of as a mould of infinite diameter. Bearing strength results beyond a certain threshold diameter will be approximately equal to the results obtained in any mould of larger diameter. Bearing strength results cannot be less than the results obtained from a mould of infinite diameter. Bearing strength therefore converges on an asymptote which represents the true bearing strength of the soil. The purpose of performing the confinement effect study was to select a mould diameter which adequately approximates the infinite boundary condition.

Through the model developed for a soil and test apparatus combination, a correction factor could be obtained as follows:

1. For any given soil unit weight *i*, the bearing strength response is calculated at a mould diameter of interest, 154 mm in the algebraic example below.
2. For the same soil unit weight *i*, the bearing strength response is calculated at a mould diameter that approximates an infinite diameter (such as was attempted to be determined in this Chapter).
3. For the soil unit weight *i*, the difference in bearing strength response represents the correction factor. The generalized formula is that field response is equal to lab response, less the correction factor.

$$Y_{154} = \beta_0 + \beta_1 X_i + \beta_2 X_{154} + \beta_{12} X_i X_{154} + E_i$$

$$Y_\infty = \beta_0 + \beta_1 X_i + \beta_2 X_\infty + \beta_{12} X_i X_\infty + E_i$$

$$\Delta = Y_{154} - Y_\infty$$

$$Y_{Lab} = Y_{Field} + \Delta$$

$$\therefore Y_{Field} = Y_{Lab} - \Delta$$

5.3.2. Boeing Cone Penetrometer Correction Factors

For the Type I, SW-SM soil, mould diameter was determined to have a strong effect on CBR response. Lack of fit was found to be significant, which suggests the presence of higher order terms. Further data must be acquired to provide sufficient degrees of freedom to model these terms. Four axial run treatments should be conducted, using coded variable combinations of: (-1.41 , 0); (1.41 , 0); (0 , -

1.41); and (0 , 1.41) (Figure 1.3). As such, a correction factor could not be obtained. For SW and SM soils, an asymptote could be expected to exist about the range of 20 – 40 CBR (Yoder & Witczak, 1975).

For the Type II, CL soil, mould diameter was determined to have a strong effect on CBR response. Lack of fit was found to be significant, which suggests the presence of higher order terms. Further data must be acquired to provide sufficient degrees of freedom to model these terms. Four axial run treatments should be conducted, using coded variable combinations of: (-1.41 , 0); (1.41 , 0); (0 , -1.41); and (0 , 1.41) (Figure 1.3). As such, a correction factor could not be obtained. For CL soils, an asymptote could be expected to exist about the range of 5 – 15 CBR (Yoder & Witczak, 1975).

For the Type III, OL soil, mould diameter was determined to have a strong effect on CBR response. Lack of fit was found to be significant, which suggests the presence of higher order terms. Further data must be acquired to provide sufficient degrees of freedom to model these terms. Four axial run treatments should be conducted, using coded variable combinations of: (-1.41 , 0); (1.41 , 0); (0 , -1.41); and (0 , 1.41) (Figure 1.3). As such, a correction factor could not be obtained. For OL soils, an asymptote could be expected to exist about the range of 4 – 8 CBR (Yoder & Witczak, 1975).

5.3.3. Udarnik U-1 Correction Factors

For the Type I, SW-SM soil, mould diameter in the study range did not affect bearing strength results as reported. As a result, laboratory testing could be performed without correction, and would represent in-field results.

For the Type II, CL soil, mould diameter did not affect bearing strength results as reported. Lack of fit was found to be significant, which suggests the presence of higher order terms. Further data must be acquired to provide sufficient degrees of freedom to model these terms. Four axial run treatments should be conducted, using coded variable combinations of: (-1.41 , 0); (1.41 , 0); (0 , -1.41); and (0 , 1.41) (Figure 1.3). As such, a correction factor could not be obtained.

For the Type III, OL soil, mould diameter did not affect bearing strength results as reported. Lack of fit was not found to be significant, however given the significance of a negative interaction effect, and the fact that the soil does have cohesive properties, one would reasonably expect some behavioural similarity to that of the Type II soil. Accordingly, it is suspected that the experimental data failed to detect a lack of fit that may exist. It is recommended that four axial run treatments be conducted as with the Type II soil. Findings suggest no correction factor is required, however prudence dictates further experimentation to confirm results.

5.4. Chapter 5 Summary

Six experiments were conducted to identify soil strength correction factors based on soil unit weight, and mould diameter as inputs: three experiments were conducted using the Boeing Cone Penetrometer, and three experiments were conducted using the Udarnik U-1. Three different soils were tested: a Type I (SW-SM) soil; a Type II (CL) soil; and a Type III (OL) soil. Response Surface Method regression was performed for each experimental set of data, and diagnostic checks were performed to consider model validity.

Without correction factors, comparing the results obtained from the Boeing Cone Penetrometer and Udarnik U-1 would result in an apples-to-oranges scenario. Since the confinement effect may impact results from each test apparatus in varied amounts, the in-field pavements represented may vary. Thus, real world application of any correlation requires correction factors.

In the case of the Boeing Cone Penetrometer, each experiment suggested the presence of higher order terms in the model. Further data points are required to determine reliable correction factors.

Regarding the Udarnik U-1, experimentation on the Type I soil determined that no correction factor is required for laboratory testing to represent field conditions. Type II soil experimentation revealed the presence of higher order terms in the model, which would require further testing to estimate. Accordingly, a correction factor could not be determined. The Type III soil results indicated that a correction factor is not required, however given the similarity between Type II and Type III soils, it is recommended further testing be conducted to validate the results.

Soil strength models for both the Boeing Cone Penetrometer and Udarnik U-1 are within the range of the models developed in Chapter 4.

CHAPTER 6 Conclusions and Recommendations

The purpose of this research was to adapt an existing strength testing method used only in Russia for conformance with Aircraft Flight Manuals typical of North America. Bearing strength requirements are typically listed by minimum California Bearing Ratio for gravel runway operations. The Boeing Cone Penetrometer is commonly used throughout North America to verify gravel runway bearing strength. Bombardier Inc. desired operational capacity in northern Russia at airports which lacked the necessary equipment for strength verification via Boeing Cone Penetrometer. The research objective was to investigate a correlation between results reported via Boeing Cone Penetrometer and the Udarnik U-1 used in Russia. A successfully documented correlation would allow for runway bearing strength verification via the Udarnik U-1, without alteration to Aircraft Flight Manuals.

Laboratory conditions allow for precise control of input parameters. Field conditions introduce a higher degree of uncertainty, which may require additional resources to compensate. Extrapolation of laboratory results for use in field conditions should be performed with caution. In controlling laboratory input parameters, such as pavement homogeneity, a trade-off ensues with other factors. In particular, the boundary conditions at field scale could be lost via the confinement effect of specimen mould walls experienced at bench scale. An investigation quantifying the confinement effect for each test method was therefore necessary, and forms the focus of this research.

Three soil types were studied (sand, clay, and organic), encompassing the broad range of pavement structures which could be encountered at remote runway locations. The Response Surface Method was adapted for use in the confinement effect investigation, considering mould diameter and soil unit weight as the independent variables. The same method was applied in the correlation investigation, considering moisture content and soil unit weight as the independent variables.

The correlation investigation encountered challenges with respect to control of moisture content in combination with control of soil unit weight. In retrospect, these parameters are highly correlated. Since soil unit weight is inversely proportional to void space, variation of soil unit weight inherently restricts moisture content. To capture the effect of moisture on pavement strength, saturation level should be considered. Replacement of moisture content with saturation level as an independent variable could yield statistically significant models which capture the effects of both density and moisture; the experiment should be repeated using these independent variables.

Several models were successfully developed for each apparatus. For the Boeing Cone Penetrometer, adjusted R-squared values of 0.851, 0.488, and 0.383 were obtained for the sand, clay, and organic soils, respectively. For the Udarnik U-1, adjusted R-squared values of 0.593, 0.539, and 0.782 were obtained for the sand, clay, and organic soils, respectively.

Within limits, the correlation investigation was able to establish bearing strength models based solely on the soil unit weight as the independent variable. These models support the central region of the models developed in the confinement effect investigation.

The method of investigation into the confinement effect shows promise. Modelling suggests that quadratic terms probably exist, however further data points are required to estimate the parameter coefficients. It is recommended that axial treatment runs be performed which would allow completion of the confinement effect model. The complete confinement effect model could then be used to estimate field-scale strengths based on the input parameters of bench scale testing, bridging the gap between field and lab testing.

Several models were successfully developed for each apparatus. For the Boeing Cone Penetrometer, adjusted R-squared values of 0.738, 0.754, and 0.859 were obtained for the sand, clay, and organic soils, respectively. Statistically significant lack of fit suggested that higher order terms were missing in the case of each Boeing Cone Penetrometer confinement effect model. For the Udarnik U-1, adjusted R-squared values of 0.812, 0.471, and 0.723 were obtained for the sand, clay, and organic soils, respectively. For the sand, confinement effect was not exhibited for the Udarnik U-1. For the clay, a statistically significant lack of fit suggested that higher order terms were missing from the model. While a lack of fit was not determined to be statistically significant for the organic soil, similarities in properties between the clay and organic soils suggests further testing would be prudent.

This research provides new insight into overcoming the discrepancies between bench and field testing. First steps have been taken into defining the impact of confinement effect on bench scale Boeing Cone Penetrometer and Udarnik U-1 tests. Completion of the recommended next steps would enhance our understanding of the correlation between the two test methods, should any exist. This methodology could be further applied to review correlation between various bearing strength test methods. Other remote regions internationally which experience the same California Bearing Ratio reporting challenges could be accessed in this method. Future development along these lines would serve to increase consistency of aviation regulatory standards internationally.

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APPENDIX A – Udarnik U-1 Strength Determination

Soil strength in measuring point is calculated using the below formula:

$$\sigma_M = \frac{\sigma_{10} + \sigma_{30}}{2},$$

where σ_M - soil strength in measuring point, kPa (kg*sec/cm^2);

σ_{10} - soil strength at the depth of 10 cm;

σ_{30} - soil strength at the depth of 30 cm.

Soil strength factor is determined as arithmetic mean value of soil strength factors in measuring points divided by their amount. The weight mass should be verified periodically by weighing. The maximum tolerance ± 10 g is allowed.

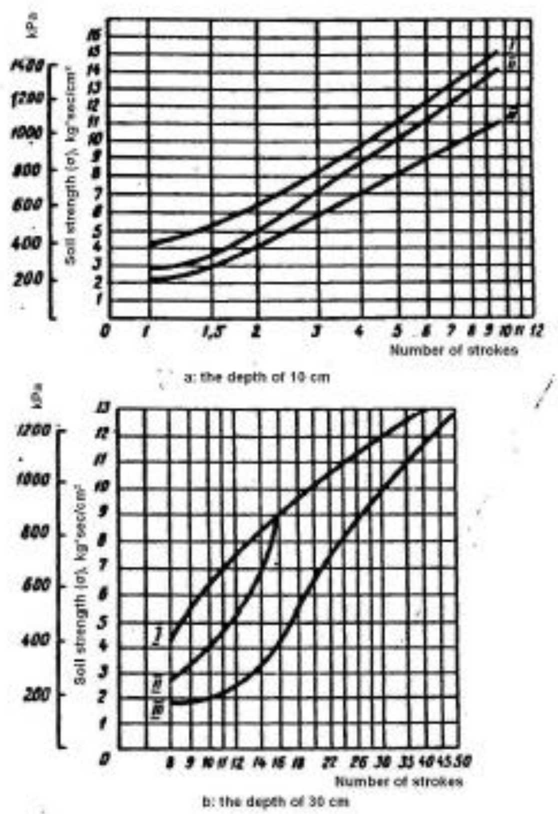

Fig. 5. Graphs to determine soil strength with U-1 striker:
I - for sandy, sandy silt, sandy-loam and fine sandy-loam soils; *II* - for silt, loamy, heavy loam, loam-silt and heavy soils; *III* - for black earth, brown earth and other salted soils.

Note. The soil type mentioned on graphs is determined based on laboratory test, or in the field environment approximately from the Table 1.

Table 1

I						II						III					
Sandy and fine soils		Sandy, sandy-loam		Silt, sandy-loam, ashen-gray soils		Silt, loamy, heavy loam, loam-silt and heavy soils						Black earth, brown earth and fulvous salted soils					
N_{10}	σ_{10}	N_{30}	σ_{30}	N_{30}	σ_{30}	N_{10}	σ_{10}	N_{30}	σ_{30}	N_{30}	σ_{30}	N_{10}	σ_{10}	N_{30}	σ_{30}	N_{30}	σ_{30}
1.0	3,9	7,0	3,0	29	11.9	1.0	2.2	7	2.0	29	11.9	1,0	1.9	7	1,4	29	9,5
1.5	4,8	8	4,5	30	12,0	1.5	3,4	8	2,2	30	12.0	1.5	2,8	8	1.5	30	9.7
2.0	6,0	9	5,3	31	12,1	2.0	4.7	9	3,0	31	12,1	2.0	4.0	9	1.5	31	9,8
2.5	7.3	10	6.2	32	12.2	2,5	5,8	10	3.6	32	122	2,5	5.0	10	1.8	32	10,0
3.0	8.2 .	11	6,8	33	12,3	3,0	7,0	11	4.3	33	12.3	3,0	5,7	11	1.9	33	10,3
3,5	9.0	12	7.3	34	12,4	3,5	8.0	12	5,0	34	12,4	3.5	6,3	12	2.2	34	10,6
4,0	9,7	13	7,8	35	12,5	4,0	8.7	13	6.0	35	12,5	4.0	6,8	13	2.8	35	10,7
4,5	10.5	14	8.4	36	12,6	4,5	9,5	14	7.2	36	12,6	4.5	7,2	14	3,2	36	10,8
5,0	11.2	15	8.7	37	12.7	5,0	10.2	15	8.1	37	12,7	5,0	7.8'	15	3,8	371	4,0
6,0	12.0	16	9.0	38	12,8	6,0	11.2	16	9,0	38	12,8	6,0	8,5	16	4,3	38	11.1
7.0	13.0	17	9.4	39	12,9	7.0	12,0	17	9.4	39	12,9	7,0	9.2	17	5.0	39	11,3
8,0	13,7	18	9,8	40	13,0	8,0	13,0	18	9,8	40	13,0	8,0	9.9	18	5,5	40	11.5
9,0	14,3	19	10,0	41	13,1	9.0	13,8	19	10.0	41	13,1	9.0	10,5	19	6,0	41	11.7
10,0	15,0	20	10.3	42	13,2	10,0	14,5	20	10,3	42	13,2	10,0	11,1	20	6.4	42	11.9
11,0	15,5	21	10,5	43	13,3	11,0	15.0	21	10,5	43	13,3	11,0	11,6	21	6,7	43	12.1
12,0	16,0	22	10,7	44	13,4	12,0	-	22	10,8	44	13.4	12,0	12.1	22	7,3	44	12,2
-	-	23	10,9	45	13,5	-	-	23	10,9	45	13.5	-	-	23	7,6	45	12,3
-	-	24	11,0	46	13,6	-	-	24	11.0	46	13,6	-	-	24	7,9	46	12.5
-	-	25	11,2	47	13,7	-	-	25	11.2	47	13,7	-	-	25	8,3	47	12,6
-	-	26	11,4	48	13,8	-	-	26	11.4	48	13,8	-	-	26	8,5	48	12,8
-	-	27	11,5	49	13,9	-	-	27	11,6	49	13,9	-	-	27	8,9	49	12.9
-	-	28	11.7	50	14.0	-	-	28	11.7	50	14,0	-	-	28	9,2	50	13.0