University of Southern Queensland
Faculty of Health Engineering and Sciences

Redefining the Standard Compaction Test to Better Describe the Usage of Cotton Picking Machines on Australian Vertosols

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In fulfilment of the Requirements of:
Bachelor of Engineering

Abstract

The aim of this project is to investigate the applicability of the standard load used in the Uniaxial Compression Test to describe the impact of large harvesting machines, such as the John Deere 7760 cotton picker (JD7760), on the soil. In the past the Uniaxial Compression Test with a load of 200 kPa has been used to generate a reference maximum bulk density. This test has been used as the Proctor Test was seen to generate a load greater than that typically experienced under farm machinery.

However, due to a vast increase in the size and weight of farming machinery it is not uncommon to find soils that have experienced a loading of as much as 600 kPa (JD7760). As such, there is a need to either redefine the load used in the Uniaxial Compression Test or revert to the Proctor Test such that the reference compaction generated is representative of that experienced in the field.

In order to achieve the aforementioned aim a review of the pertinent literature has been undertaken. Following this samples were gathered from a variety of sites around South East Queensland.

SoilFlex was used to model the distribution of stresses within the soil during the application of a 600 kPa load. (600 kPa being taken as the standard load applied by a JD7760).The results from this analysis are then used to determine a range of applicable loading values (200-600 kPa). Using these values a series of Uniaxial Tests was conducted using a combination of principals derived from articles written by Häkansson (1990) and Suzuki (2013). In addition to this the Proctor Test was undertaken to provide further comparisons.

The results from these tests were then compared to the *in situ* bulk density for each location, allowing for the calculation of a degree of compaction for each loading. Some error was included in the testing that could be resolved through further testing. Despite this the correlations and trends shown within the data support the recommendation of the 1600 kPa proctor test as applicable for simulating the compaction caused by a JD7760.

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Acknowledgements

This research was carried out under the principal supervision of Dr. John Bennett. His input was invaluable in the construction of this research dissertation. In addition to this the input and support of Mr Stirling Roberton was highly appreciated. Many thanks must go to the farmers that were so welcoming in allowing the collection of samples from their farms: Mr Nigel Corish, Mr John Norman, Mr Glen Smith, Mr Jamie Grant, Mr Neil Nass and Mr Jake Hall from Auscott Limited. I would also like to thanks my Parents for proof reading countless drafts and Mr Kieran Richardson for his assistance during testing.

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Chapter 1 – Introduction

1.1 Background

The cotton industry is one of Australia’s largest rural exports, generating $2.5 billion (Cotton Australia 2012). The most costly and difficult to manage issue in modern agriculture is soil compaction (McGarry et al. 2003). This is can generally be attributed to a trend in farm machinery to becoming larger in order to be more efficient in the field. This has resulted in soil contact wheel-loads that far exceed the current upper limit load (200 kPa) of soil Uniaxial Compression Tests. With the increase in machine weight, the footprint of machines has also been increased to help spread the axel load over more wheels. Hence, even where machine traffic is guided using GPS systems, soil surface traffic can be more than 60% of the total soil surface, especially in cotton systems which harvest on a 6 row frontage. The resulting incidence of compaction is known to inhibit root growth, drastically reducing the ability of plants to extract water from the soil; thereby reducing the net yield of the crop (University of Minnesota 2001).

Currently the cotton industry does not consider the upper limits of soil compaction, but rather simply seeks to understand yield penalties, which is a reactive approach and not necessarily easily measureable. Agricultural scientists and engineers have suggested using the modified Proctor and/or the Uniaxial Compression Test to determine the potential compaction of a soil before operations begin. However, it is believed that the applied load used in the Uniaxial Compression Test is no longer an accurate representation of the load placed on the soil by the increasingly heavy machinery that has become standard within the Australian industry. As such it is necessary to investigate whether this applied load should be increased, and by how much, in order to better represent the reasonable level of maximum compaction.

Criticism of the modified Proctor Test from agricultural science is that the resulting compaction provided by the test is far greater than any agricultural machine would be capable of, and is instead representative of a sheep’s foot roller used in foundation construction. This has seen a preference for the Uniaxial Compression Test, which uses an upper limit load of 200 kPa. This load was considered to approximate the load applied by the mass of then current harvesters, primarily in European smaller farming systems. However, more modern machinery such as the John Deere 7760 have been calculated to have wheel-load at the soil surface of 400–600 kPa (three times current standards) depending on the stage of cotton module building it is undergoing. Hence, there is a need to redefine an upper reasonable load and to compare this to observed compaction using the modified Proctor Test. In doing this, in-field soil compaction can be referenced in terms of severity as a percentage of a reasonable upper load and subsequent compaction (i.e. percentage of maximum achievable compaction). This will provide means to compare compaction severity throughout the industry and could be used to provide motivation for adoption of permanent land controlled traffic, which currently requires an estimated $35K up-front conversion cost per machine (Neale 2011).

Cultivation to manage soil compaction is costly, and increasingly so, as depth of compaction increases. Conversion to true controlled traffic on permanent traffic lanes places soil compaction within the permanent lanes and these are not cultivated. Hence, undertaking this project will provide means to quantify the impact in dollar terms with the potential to calculate yield gains/losses, which will serve to aide a progression towards controlled traffic farming and provide important benchmarking capability for soil function Therefore, the project aims to compare the current reference compaction figures generated from a 200 kPa Uniaxial Test with those generated at higher loads and in different tests (Proctor Test).

1.2 Project Scope and Objectives

The scope of this project is limited to investigating the applicability of the reference compaction load in the Uniaxial Compression Test for Australian Vertosols under high stress in a cultivated and irrigated environment, however in order to conduct a thorough investigation some of the referenced literature is related to, but removed from the specific scope. Doing so allows an investigation of “best practice” within the field as a whole. To achieve the project aims within this scope, the following objectives must be met:

1. Review of best practice for measurement of agricultural compaction

2. Analysis of selected methods and modification of these to suit and assess increased weight of agricultural machinery

3. Experimental validation and evaluation of modified methods

Chapter 2 – Literature Review

2.1 Introduction

In order to ensure the experimental integrity of this project it is first necessary to conduct a review of the available literature to ensure that the theory and practices used are relevant within the field. In doing so a variety of areas relating to soil compaction will be investigated. These include the basics of soil compaction, the relationship between yield and compaction, the use of relative bulk density, surpassing the relative bulk density, existing alterations to the reference bulk density test and other methods of bulk density analysis.

This literature review will only cover vehicular compaction rather than considering other means (for example; compaction caused by grazing). This is because the levels of compaction under vehicles have been shown to be significantly greater than other means of compaction. (Lipiec & Hatano 2003), and as Australian farms having generally moved towards dedicated grazing and cropping zones in mixed farming systems (i.e. grazing no longer occurring on cropping zones).

2.2 Vertosol Soil Classification

This work is focussed on the Australian cotton industry, which is dominated by Vertosol soils (Isbell 2002). Therefore, before an in depth investigation of compaction and its effects can take place it is necessary to identify the most common properties of Vertosol soil to provide context to the discussion.

Vertosols are clay soils (>35% clay by definition, but often having >>50% clay) that exhibit shrink swell properties. The clay content is important as it defines the primary mechanisms affecting soil compaction (e.g. cohesion, or internal angle of friction). Vertosols exhibit strong cracking when dry, this cracking is typically >5mm wide and exists throughout the depth of a sample. These cracks swell shut as soil moisture approaches field capacity. The structure is generally composed of slickenside and/or lenticular structural aggregates although these properties are sometimes difficult to ascertain depending on the soil moisture content and climactic conditions. Lenticular peds result in slipping planes where soil peds move (heave) over one another during shrink-swell dynamics. Shrink-swell properties make direct measurement of soil bulk density difficult, meaning that many methodological approaches need specific calibration against these soils to determine their applicability.

2.3 Fundamentals of Soil Compaction

Soil compaction relates to the process of the reduction of pore space within a given sample (an increase in mass for a given volume). Generally this occurs as the result of an external load; whether it is a natural load (rain) or a mechanical load (vehicles). It can also occur under its own load over time and with depth, due to gravity (DAS 2010). This pore space can be occupied by air and/or water, but is more commonly sufficiently air filled to allow compaction to occur. Saturation of soil pores with water only occurs where water is allowed to pond upon the surface, thus saturation is infrequent for agricultural soils. On the other hand, even when drained under gravity (field capacity at -10 kPa) such conditions are less common than drier ones due to the influence of evapotranspiration and vegetative growth. However, very wet conditions are not necessarily optimal for soil compaction because water is a hydraulic fluid.

The key variables in soil compaction are soil properties, moisture content, mode of compaction and quantity of loading. In addition to this it is widely acknowledged that compaction will vary with depth in a soil sample (Etana et al. 1999), whereby under only natural conditions (soil mass and gravity) the density of soil increases with depth.

Thus the general composition of a soil sample is one that consists of soil water and air, as shown, below, in Figure 1.

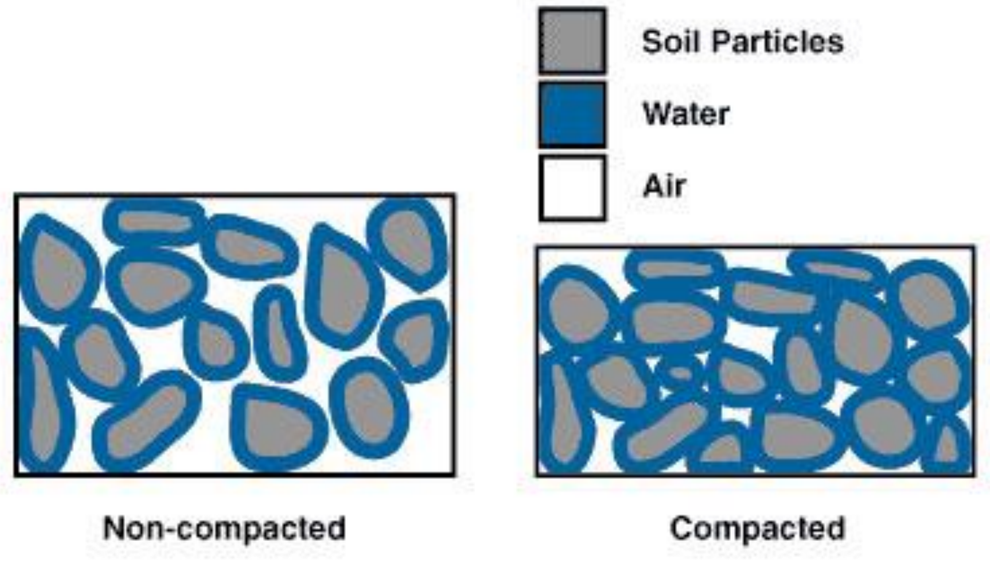
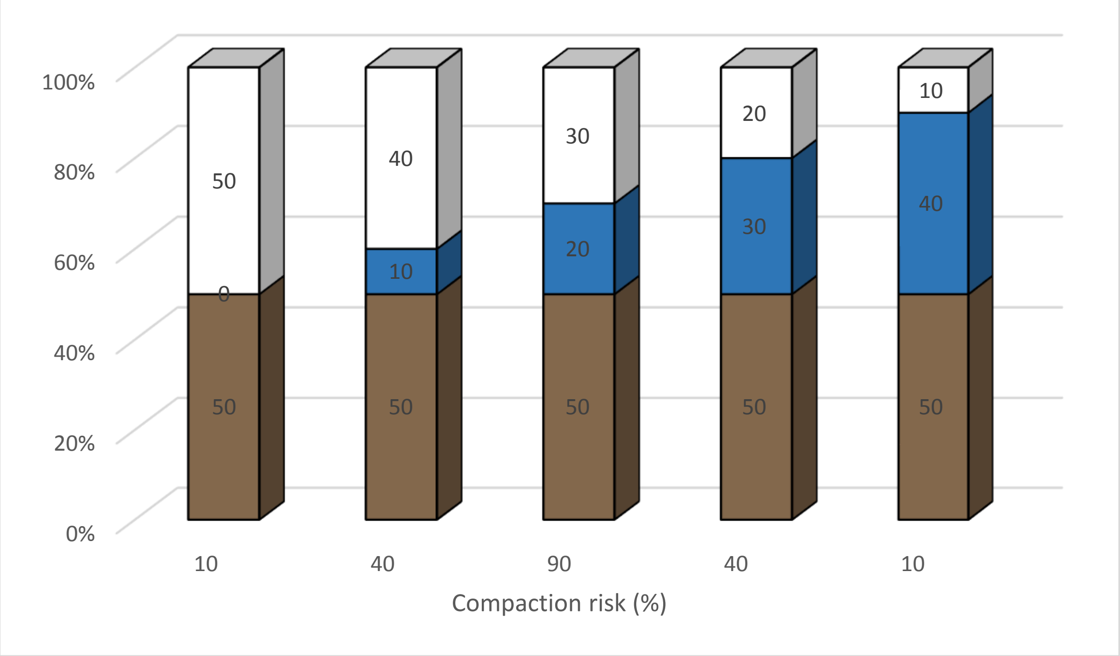


Figure 1: Effect of compaction on pore space showing the change in arrangement of the soil particles as compaction increases and the reduction of pore space (University of Minnesota 2001)

This can be simplified into the model presented, below, in Figure 2.

Figure 2: Idealised compaction model showing the components of soil in percent contribution and illustrating the risk of compaction with increasing water filled porosity; risk factors are generalised and would need to be determined specifically for individual soils, but are useful to illustrate compactive risk is not linearly related to moisture content



As can be seen in Figure 2 the composition of a soil sample can be split into its three parts, with the most dynamic variable being the change in water filled pores. As compaction occurs the relative quantity of these parts changes, but the reduction only occurs in air-filled soil space due to water being a hydraulic fluid. Thus, decreasing air-filled porosity results in an increase in volumetric moisture content (water per volume), but gravimetric moisture content has not changed (water per mass). Because of this one measure for soil compaction is total pore space as described by Kuipers and Van Ouwerkerk (1963). As a natural result of the reduction of pore space the density of the soil increases, thus the soil bulk density is also a measure of compaction (Håkansson 1990).

According to Kuipers and Van Ouwerkerk (1963) measuring and calculating total pore space in the field is difficult and time consuming and as such is not a practical measure of compaction. Therefore, this literature review will mainly focus on the use of bulk density of a sample as an indicator of compaction and the reasons for this choice. This is consistent with current industry practice, having been used by numerous authors (Håkansson 1990, L. E. A. S. Suzuki 2013, Lipiec & Hatano 2003, da Silva, Kay & Perfect 1997, Etana et al. 1999, Arvidsson 2014, Carter 1990).

2.3.1 Soil Texture

The texture of a soil profile has an integral effect on the maximum bulk density that can be generated at a given loading. This has been shown by Nhantumbo and Cambule (2006) in an investigation into the relationship between soil texture and compaction. This study has shown a parabolic influence of clay content on the maximum obtainable bulk density (using the Proctor Test). A similar, though less extreme, relationship was found between bulk density and silt plus clay content. In addition to this it was found that as the clay content increased the critical water content (water content at which the maximum bulk density is reached) increases. Again this trend holds true for silt plus clay, though less extreme. These relationships are found, below, in Figure 3 and 4 (Nhantumbo & Cambule 2006).

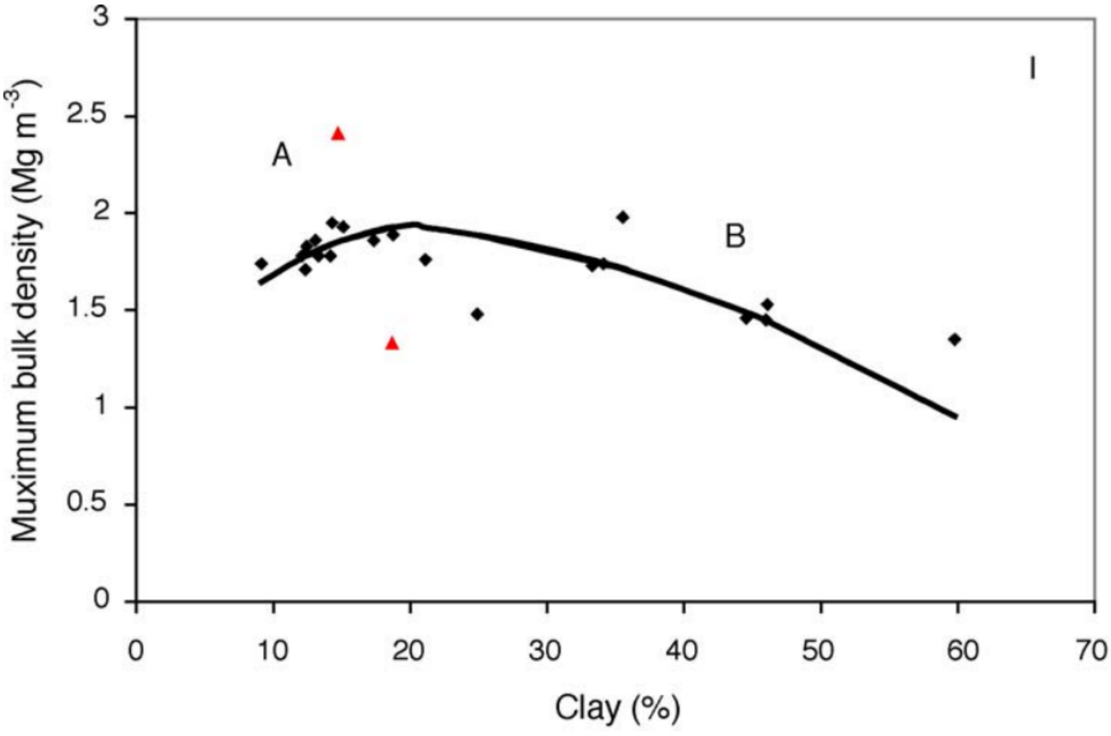


Figure 3: Relationship between Clay Content and Bulk Density reproduced from Nhantumbo and Cambule (2006) showing a parabolic trend between clay content and maximum bulk density. Included here to illustrate the relationship. Outliers are marked by A, B and the Triangles

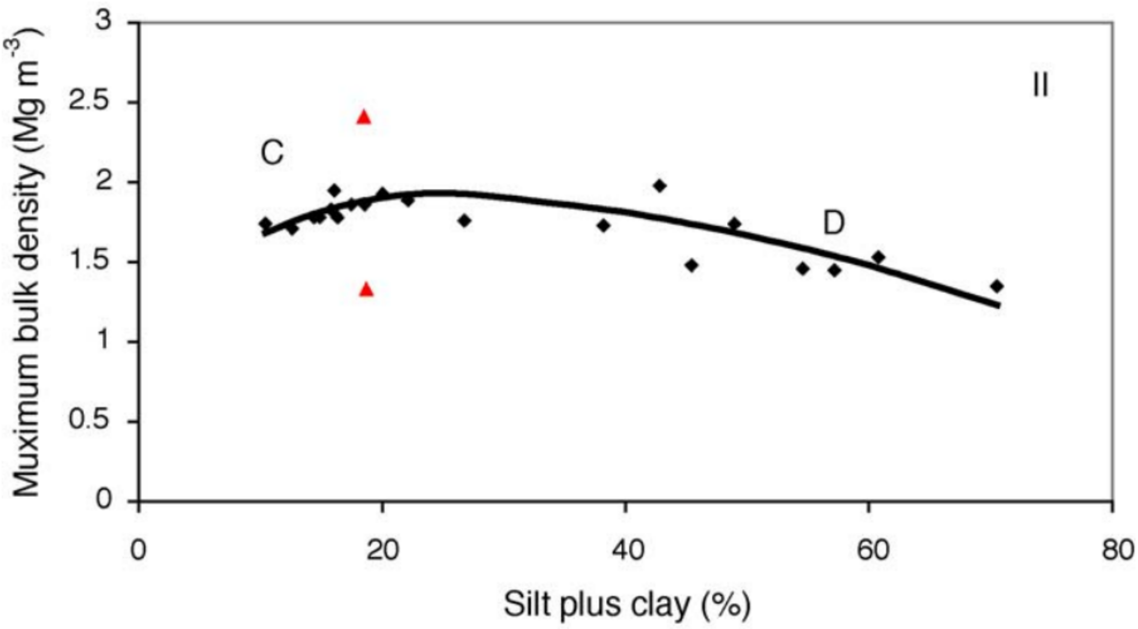


Figure 4: Relationship between Clay and Silt Content and Bulk Density reproduced from Nhantumbo and Cambule (2006) showing a parabolic trend between clay and silt content and maximum bulk density. Included here to illustrate the relationship. Outliers are marked by C, D and the Triangles

The governing forces of these effects are the internal angle of friction and the cohesion existing in the soil. These mainly pertain to the sand and clay contents respectively. The internal angles of friction is a measure of the resistance of soil particles to slide over each other, for example angular particles are less likely to slide over one another than rounded particles. The cohesiveness of a soil typically describes the bondage between individual particles (Hillel 1998). Both of these parameters are influenced by the moisture content and alter the strength of the soil. As such these areas are investigated in further detail below.

2.3.2 Soil Strength

Soil strength has been described as the ability of the soil to withstand stress without experiencing a structural failure (Defossez & Richard 2002). Lipiec and Hatano (2003) conducted experiments into the effects of compaction on a wide array of soil properties. This covered areas such as moisture content (discussed further below), soil strength, aeration, heat flow and structural arrangement. Soil strength, as a parameter, is most commonly assessed as cone resistance or shear strength, especially in relation to crop growth. Soil strength is shown to increase with an increase in compaction whilst the deformable volume decreases. This occurs due to a reorganisation of the structural arrangement of the soil particles.

This structural rearrangement results in a reduction in macropore space as evidenced by Lipiec and Hatano (2003) where a morphological study of compactive zones using an ellipse showed that the percentage of macropores decreased with the trafficking of the soil, even at the lowest machinery loads, this was associated with an decrease in soil structure towards an apedal massive structural arrangement. This analysis was furthered supported through the use of resin impregnated soil imaging, revealing that pore spaced is reduced even by a single tractor pass. This reduction mainly occurs in the elongated and continuous pores. This is significant as these pores account for a large portion of soil water infiltration (Awedat et al. 2012) and are used by plants for both root growth and allowing a reliable flow of water and nutrients through the water.

2.3.3 Moisture Content

It has been reported and commonly accepted that moisture content has a large impact on the “compactability” of a soil sample; indeed, moisture content has been called the most important factor affecting soil compaction processes (Hamza & Anderson 2005). This occurs because it reduces the cohesive forces between clay particles, allowing clay particles to slide over one another with greater ease (DAS 2010).

However, as moisture content becomes greater than the plastic limit, approaches and then overcomes the liquid limit, water begins to reduce the levels of compaction reached as the available pore space is filled and then over filled by water, preventing a reduction in volume; this explains the non-linear risk of compaction with increasing soil moisture depicted in Figure 2. Water is an incompressible fluid, thus soil pores cannot compress any further once filled. However, as the liquid limit is approached, the soil behaves as a liquid as the cohesive forces within the soil are almost eliminated. This has the effect of severely limiting the strength of the soil (DAS 2010). This means ruts are formed in the field and soil pores are shut through a process of smearing. Whilst this is not compaction, it is also detrimental to agricultural production systems.

Plastic and liquid limits come from the three “Atterberg Limits” used in engineering to describe the behaviour of the soil at various moisture contents, as shown, below, in Figure 5. These limits represent a change in the state of the soil.

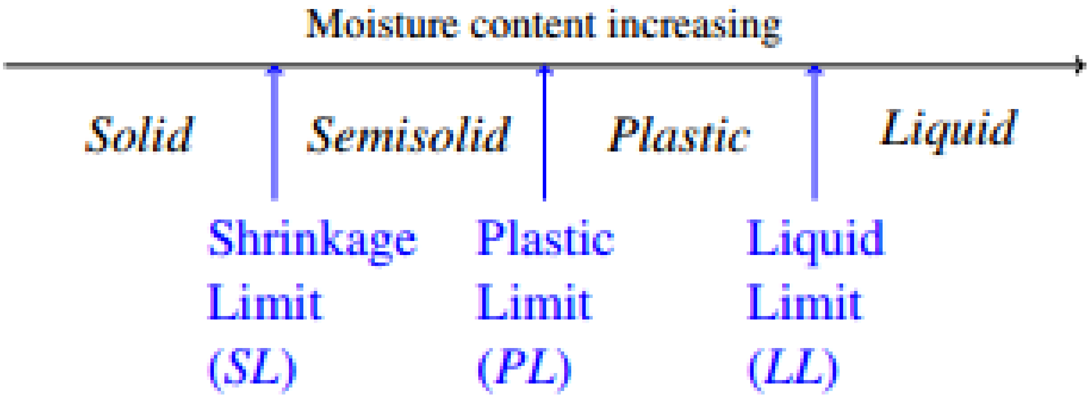


Figure 5: Illustration of the Atterberg Limits in relation to increasing moisture content (University of Southern Queensland 2013)

Hamza and Anderson (2005) support the aforementioned notion of the load-bearing capacity of the soil being reduced, regardless of compaction level, as the moisture content is increased past the liquid limit. This can occur to such a level that soils with high compaction exhibit the same or similar penetration resistance regardless of compactive force. Meaning the maximum permissible ground pressure of agricultural machinery that permitted satisfactory crop production decreases as moisture content increases. Stated differently; the strength of a soil (and thus its bearing capacity) increases with increasing compaction but has an inverse relationship with moisture content. Stress and displacement (and thus compaction) can then be said to be highly dependent on water content and soil type.

For these reasons the moisture content in the field has a great effect on the levels of compaction reached, thus the moisture content used during testing will have a great impact on the applicability of the results.

2.3.4 Depth

Depth is of great importance when considering compaction because of considerable variation between depth and soil profile. Making it important to compare soils of the same depths when testing compaction (Radford et al. 2000, Hamza & Anderson 2005, Bennett, Antille & Jenson 2015).

Typically conventional tillage will produce compaction varying from 10-60cm according to Hamza and Anderson however it is most common in the upper 10cm of the sample. Notwithstanding, the influence of heavier machines has been recorded at 80 cm depths in recent work with the JD7760 (Bennett, Antille & Jensen 2015). It is noted that these figures are for a range of soils and the effect of compaction on an individual soil will be dependent on its specific properties.

Radford et al. (2002) conducted experiments that examined the impact of compaction over a depth of 0.6m in an Australian Vertosol. Data was gathered using soil cores and a gamma probe. Each method produced varying results however the general trend of these remained reasonably constant. For the most part a compacted sample had an increased bulk density to a depth of 0.35m after which there was little difference in the bulk densities. Similar results were found for penetration resistance and torsional shear strength.

2.3.5 Mode of Compaction

The mode of compaction can significantly influence the level of compaction experienced. This is best highlighted in a study by (Raghavan & Ohu 1985) on the equivalent static loading of the Proctor Test. This study and others have shown that the mode of compaction has a substantial effect on the type of compaction.

It is commonly accepted that two modes of compaction exist: static and impact. Each has a unique effect on the level and nature of compaction. Typically, a static loading will require more effort to produce the same bulk density as that produced by an impact load (Raghavan & Ohu 1985).

Vehicular loading is assumed to be of a static nature as rate of loading is quite slow (Håkansson 1990). Whilst this assumption holds true in the majority of the literature, Häkansson goes on to state that other forms of compaction are present, especially in at the surface of the soil where longitudinal stresses due to the rotation of the wheel are found.

In an agricultural setting it can be said that vehicular loading represents the greatest compaction that the average sample of soil will experience (Hamza & Anderson 2005). This is confirmed by Lipiec and Hatano (2003), stating that vehicular compaction is found to produce the largest compaction and cause the greatest deterioration of soil structure.

The degree of compaction generated by the agricultural machinery is dependent on a number of factors, as noted above: soil mechanical strength, structure of the soil, loading and water content. The loading generated by the tyre is then dependent on axle load, tyre dimensions, velocity and the soil tyre interaction. This compaction is noted in up to 100% of the ground area in farms that use conventional tillage, and even up to 30% in those that experience no tillage. The impact of this is vastly increased by the fact that most models of tractors and harvesters have a load that exceeds the recommended maximum load to avoid unacceptable soil compaction (Hamza & Anderson 2005).

The loading generated by the vehicle can be described in two different ways: force or pressure (kN or kPa). Force will remain relatively constant for a vehicle (that is not taking on more load) however the pressure that is placed on the soil is highly dependent on the tyre type, configuration and pressure (Keller et al. 2007). Whilst all tyres may produce a dramatic increase in compaction underneath the wheel path, some also increase the compaction beside the wheel path, although compaction will greatly decrease the further from the centre of the wheel path. The pressure exerted by a vehicle can be altered by increasing or decreasing the tyre pressure. In doing so the contact area of the vehicle force is changed, whereby decrease in pressure increases contact area and can decrease depth of compaction. In addition to this there are efforts to reduce compactive pressure at the tyre by using tracks or low pressure radial tyres. Despite these measures some evidence has been shown to suggest that these measures will only reduce compaction in the top layers of the soil as well as increasing the total compacted area of the farm (Hamza & Anderson 2005) .

Gassman et al. (1989) conducted modelling using ANSYS to analyse the impact of tracked and wheeled compaction in an effort to determine the differences in compaction each method produces. The generated model was constructed such that it represented a non-homogenous soil profile, this is because soil profiles are rarely uniform in the field. Unlike other attempts to model the soil tyre interaction this model assumes an elastic plastic behaviour for the soil, as the mass of machinery is known to permanently deform the soil, but depending on moisture content and the precompression stress, can rebound elastically to some extent. The model was limited in that, as a cost saving measure, a two dimensional analysis was used. This means that longitudinal stressors were not considered in the analysis. The results generated from this model further supported the evidence presented by Hamza and Anderson (2005) above that the use of tracks only slightly reduces compaction in the top 30cm of the soil, below this the bulk density is found to be very similar regardless of the treatment.

The results of this model should be treated with a degree of caution. As comparison against actual field values highlighted that the model significantly underestimated the bulk density in the top 15cm of soil (although it was within 2.5% accuracy as the depth increased). The author also expressed a need for more accurate simulation of the vehicular loading and more accurate measurement of soil stress strain relationships to increase the accuracy of the model (Gassman, Erbach & Melvin 1989).

Vehicular compaction can have such a devastating impact on cropping production systems that authors (Hamza & Anderson 2005, Bennett et al. 2015) have suggested lessening the mass of farm machinery and increasing the contact area in an effort to reduce the impact.

In addition to the individualistic effect of the load the number of passes a particular vehicle makes also has a significant impact on the compaction generated in the field. Whilst 90% of the compaction occurs in the first pass, as the number of passes increase so too does the compaction experienced, especially in layers greater than 30cm below the surface (Hamza & Anderson 2005).

The effect the size of a vehicle and the number of passes undertaken has on soil compaction was investigated by Jorajuria et al. (1997). The experimental procedure applied involved the varying use of light and heavy tractors on different plots compared to a control plot. On the experimental plots soil moisture content, dry bulk density and cone penetrometer data were gathered and compared to grassland yield. From this series of experiments a number of conclusions were drawn: the relationship between tractor weight and subsoil compaction was independent of the average applied pressure; as the number of passes increased, the depth to which compaction from the difference in tractor weight was measured decreased; and the same compaction generated by one pass of a heavy tractor can be readily achieved through several passes of a lighter one (Jorajuria, Draghi & Aragon 1997).

This suggests that unless the load at a wheel is vastly lowered the use of smaller equipment the increased number of required passes could produce the same compaction as a single pass whilst vastly increasing the man hours required to adequately service the field.

2.4 The Relationship between Crop Yield and Compaction

As previously stated compaction will alter the physical properties (such as bulk density and total pore space) of the soil. In addition to this a number of other changes in the soils composition and structure occur as compaction is increased. These changes can be experienced in not only the soils physical properties but also in the chemical and biological properties.

It has been repeatedly shown that these effects have a significant impact on crop growth, (Suzuki, Reichert & Reinert 2013, B.J. Radford 2001). Investigations generally show a crop experiencing an adverse response to compaction, conversely some evidence exists to suggest that compaction can be beneficial in suitably low amounts (University of Minnesota 2001). As such the following section will investigate both the positive and negative impacts of compaction on the ability of a soil to support a crop.

For desirable crop production the moisture content should be less than that of the plastic limit, with the optimum production at 0.95 of the Plastic Limit. (Hamza & Anderson 2005).

2.4.1 Positive Effects of Compaction

Whilst it is widely accepted that soil compaction is detrimental to crop health a number of authors have found that compaction can be beneficial, provided it is not in excess. This benefit is caused by an increased contact area between plant roots or seeds and the soil promoting greater access to nutrition (University of Minnesota 2001, Carter 1990). The relationship between bulk density and yield has been shown to be curvilinear by several authors (Reichert, Susuki & Reinert 2009, Arvidsson 2014, Inge Håkansson 2000).

However it has been found that for Australian Vertosol soils, the level of compaction that is seen to produce an optimum yield is easily surpassed by vehicular traffic. This is because of the high clay content in Vertosols, compared to the soils investigated by Reichert, Susuki & Reinert (2009), Arvidsson (2014), Inge Håkansson (2000). As shown by Figures 3 and 4 clay content has a huge effect on the achievable degree of compactness.

It is worth stating that the impact this relationship will have on yield is dependent on the specific soil and crop from which the data was gathered. However the general nature of the trend has been shown to hold true for a number of crop and soil types by Arvidsson (2014).

2.4.2 Negative Effects of Compaction

A negative crop response to compaction is well documented in academic literature (Reichert, Susuki & Reinert 2009, Arvidsson 2014, Inge Håkansson 2000) as well as industry best practice (NSW Agriculture 1998). It has been found that compaction will adversely affect physical fertility of the soil, especially in relation to the supply of water and nutrients (Hamza & Anderson 2005). This occurs as a result of the increase of bulk density, decrease in porosity, and increase in soil strength, decreasing soil water infiltration and decreasing water holding capacity, resulting in a reduction of crop yield (Hamza & Anderson 2005, Lipiec & Hatano 2003).

Recently Arvidsson and Häkansson (2014) conducted research into the response of different crops to compaction. While this was conducted over a relatively short term it provides valuable insight into the effect of compaction on the growth of a supported crop. In this set of experiments a number of different crop types were used and the yield of each was analysed in four instances; no compaction, minimal compaction, moderate compaction and heavy compaction. Since a number of different crops were used a relative yield is required to ensure that the response is comparable between samples. In this case a reference yield was taken as the yield of an un-trafficked (no compaction) site. A similar method has been used for compaction and this will be discussed in depth in the following section. In this study the relationship found between the degree of compactness and the relative yield of the crop was curvilinear. This has been shown by numerous authors to be constant regardless of crop type or soil type. However, the exact relationship will vary with soil and crop type. This makes it pertinent to consider studies that focus on Australian conditions or cotton crops.

The dominant soil type in the Australian cotton producing region is the Vertosol, comprising of 75% of the cropped area (Isbell 2002). Generally speaking cotton is well suited to Australian Vertosols due to the soil's water holding capacity and shrink-swell attributes. Cotton root systems are not damaged by soil shrinkage, however due to the high retention of water and the relative high water content at permanent wilting point (–1500 kPa) there is a narrow traffic operating window when considering water content against the applied stresses (Virmani, Sahrawat & Burford 1982, Daniells, Larson & Anthony 1996). Therefore, compaction in Australian Vertosols is a highly important consideration.

The negative connotations of Vertosols susceptibility to compaction are exacerbated by the fact that cotton is a tillage intensive crop, due to current commercial seed requirements of Bollgard II® cotton (Monsanto 2012), and the impact of low hydraulic conductivity in high clay content soils where traffic has historically been uncontrolled (McConnell, Frizzell & Wilkerson 1989, Spoor, Tijink & Weisskopf 2003). Because of this compaction has resulted in an estimated loss of AUD 850 million a year (Walsh 2002).

This is due to a reduction in yield that has been shown to be as high as 30% in central Queensland (when compared to fields experiencing no compaction) (Neale 2011).

McGarry (1990) conducted research into the growth of cotton plants on Australian Vertosols. The experimental design involved differing compaction of two adjacent fields on the Darling Downs, Queensland. The dramatic effect of soil compaction on a commercial cotton farm was shown and is demonstrated, below, in Figure 6.

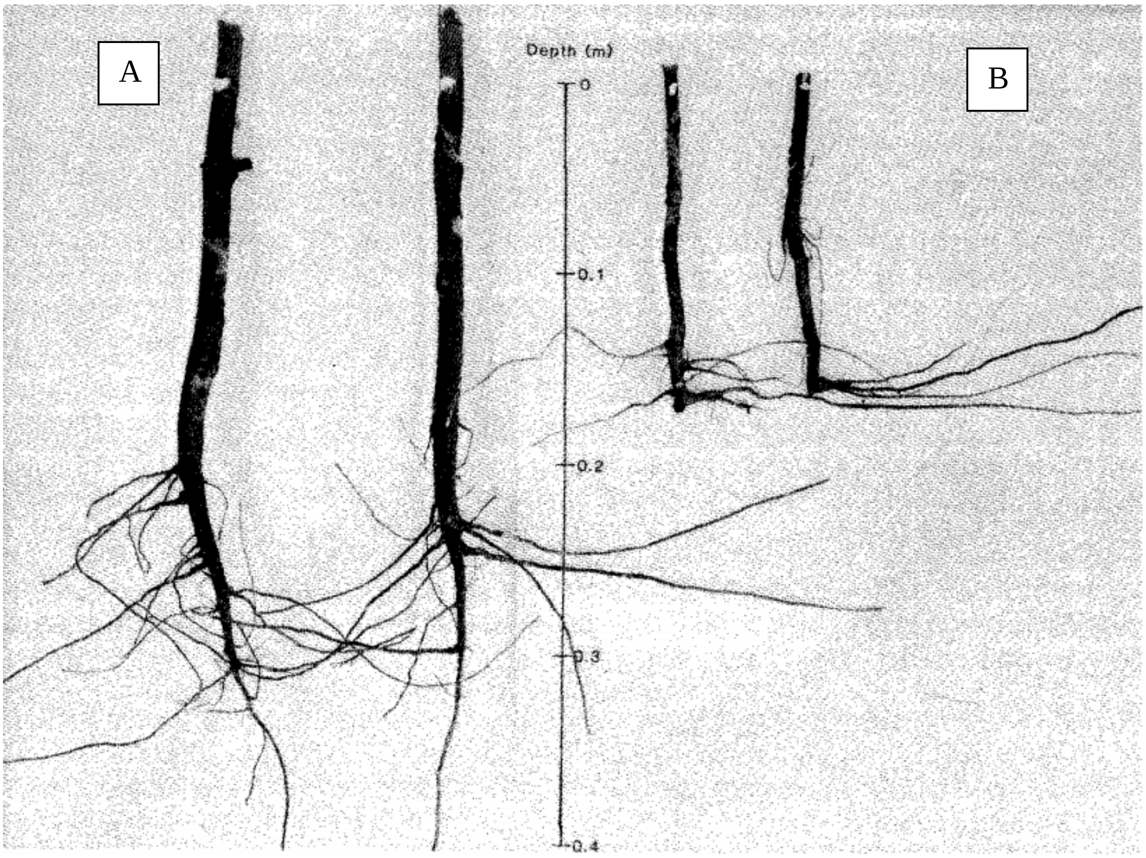


Figure 6: Impact of compaction on root growth showing greater growth in the less compacted field (A) whilst growth is severely restricted in field B (Carter 1990)

Here the root structure is visibly unable to grow past the compacted soil at a depth of 0.145 m in field A. This is supported by numerical data, showing that the bulk density (measured by soil porosity) is the causal factor limiting cotton root growth in field A (McGarry 1990). However the presence of this compaction severely limits the window of suitable conditions for crop growth making it more difficult for a land manager to optimise production (Hamza & Anderson 2005).

Empirical support is provided by Radford et al. (2000) where the emergence of wheat on an Australian Vertosol was analysed showing a drop from 93% to 72% emergence between a plot experiencing uniform compaction and a control. It is noted however that this data was collected under optimum conditions for growth and that the difference in emergence would have been greater considering what could, perhaps, be a more realistic scenario. Furthermore Kulkarni and Bajwa (2005) showed that soil compaction has been shown to increase the stress in cotton plants when compared to those growing in uncompacted soil. Hence, it is clear that compaction impact needs to be considered in aiding agricultural traffic management strategy design, particularly as machines become larger to increase the in-field efficiency of harvest.

2.5 Use of Relative Bulk Density

During studies into compaction and its effects on crop yield and other soil parameters it has been found that bulk density data alone cannot be used to generate trend lines that are valid across soil types or geographical location. This has prompted research into a parameter that can allow comparison between different soils with the aim of identifying trends to shape best practice in the field. To satisfy this the concept of a reference bulk density was conceived, allowing for comparisons between bulk density and a litany of other soil parameters. The process of using the reference bulk density achieved at a standardised loading almost totally eliminates soil properties (such as clay and silt content, organic matter). This allows for simplified comparison between soils of different types or location (Håkansson 1990, Carter 1990, Reichert, Susuki & Reinert 2009, da Silva, Kay & Perfect 1997, Hamza & Anderson 2005).

The most popular method of generating the reference bulk density for agriculture is the Uniaxial Compression Test described by Häkansson (1990). This is heavily supported within the literature, used in an overwhelming number of experiments (Lipiec & Hatano 2003, da Silva, Kay & Perfect 1997, Etana et al. 1999, Arvidsson 2014, Carter 1990). Although some authors have used the Proctor Test (Twerdoff et al. 1999, Nhantumbo & Cambule 2006), with reservations from the agricultural community that this is only relevant to engineering applications. However, as the load applied to the soil increases, the relevance of this test should also increase (i.e. agricultural traffic becomes equivalent to road foundation preparation traffic).

Conversely, Twerdoff et al. suggested that the Proctor Test provided similar values to that of the Uniaxial Compression Test at 200 kPa. However, this seems to be highly disputed in the literature by Häkansson, Suzuki and numerous others. Suzuki has suggested that the actual value may be closer to 1600 kPa (Suzuki, Reichert & Reinert 2013, Håkansson 1990, Twerdoff et al. 1999).

Whilst both the Proctor and Uniaxial Tests are used throughout the literature there is significant evidence available to suggest why the Uniaxial Test is more popular when considering vehicular compaction in an agricultural setting. This evidence is included in the paper Häkansson (1990) used to present the method and is examined in more detail in “Research Design and Methodology” (Chapter 3).

Irrespective of conflicting discussion around the method used to determine a reference bulk density, it has been found by numerous sources that a reference bulk density allows reliable comparison between soil types, provide the means used to obtain it is kept constant (Arvidsson 2014, Håkansson & Lipiec 2000, Hamza & Anderson 2005).

Possibly the most poignant of these is the review article by Häkansson and Lipiec (2000) where an appraisal of the usefulness of this method was conducted. This review paper covers a large snapshot (64 unique articles) of the literature available at the time of its writing in 2000. In analysing the applicability of the reference bulk density Häkansson and Lipiec (2000) state that it is “well known that crop response versus porosity (or bulk density) is different for soils of different texture or organic content”. This also holds true for the optimum values of these parameters. This makes it difficult to compare one soil to another in terms of distance to the optimum crop growing conditions as the values generated for one soil will not be applicable for another. To test the applicability of using the reference bulk density to eliminate this variability the data from 100 field experiments (in Sweden) was compiled and compared. These experiments tested the relationship between clay and organic matter, and the degree of compaction. This was then used to generate an equation for the optimum degree of compaction based on these variables, one such example of this can be seen, below, in Equation 2.1:

$$D_{opt} = 90.3 - 0.216C + 0.0038C^2 - 0.214H \qquad \text{Eqn 2.1}$$

Where

$D_{opt} = Optimum\ Degree\ of\ Compactness$

$C = Clay\ Content$

$H = Organic\ Matter$

By comparing the results generated in these equations it was found that the optimum degree of compactness was very similar irrespective of clay or organic carbon content. The variations that were present were explained to be due to factors other than soil characteristics such as weather or extreme variances in crop type, although these differences are somewhat limited.

This information is then compared with and supported by other experiments conducted in Norway, Poland and Australia. This allows the conclusion that the use of a reference bulk density can eliminate most of the variables in crop response between soils. Following this conclusion Häkansson and Lipiec state that “since the degree of compactness affects crop growth similarly in most [cases], it can be assumed that it also influences the most significant compaction dependant growth factors similarly”, with these factors being aeration and penetration resistance. A number of articles are referenced, setting critical limits of 10% (v/v) (air-filled porosity) and 3 MPa (penetration). In doing so a series of tests comparing the use of the degree of compactness, bulk density and the porosity showing that applying the use of the degree of compactness results in a higher degree of similarity between soils. This further supports the notion that the reference bulk density provides greater means for comparison between soils, despite the fact that in these comparisons the group of soils tested had very small differences in parameters, meaning that the advantages gained were small yet still statistically relevant. (Håkansson & Lipiec 2000)

Häkansson and Lipiec (2000) further investigated the applicability of the reference bulk density in modelling vehicular loading experienced in the field. In investigating this the reference bulk density test (200 kPa Uniaxial; Häkansson 1990) is said to generate a compaction that is slightly higher than the infield compaction that a soil should experience. This comparison is altered somewhat by the moisture content of the soil although this can be accounted for given the required information as the magnitude of the differences are similar between textural groups. The testing can become even more accurate when using matric tension in place of the moisture content (Håkansson & Lipiec 2000).

These findings have been used and supported recently, where the relative bulk density has been used to simplify comparison between soils in a collaborative article by Arvidsson and Häkansson (2014). The response of different crops to soil compaction was investigated and compaction was measured using Häkansson’s (1990) method of relative compaction. Five different crops on different plots were compared without consideration for other soil properties (although other soil properties were examined for the purposes of sound experimental procedure).

This is further supported by da Silva et. al. (1997) where a comparison between use of the reference bulk density and actual bulk density was undertaken. In doing so it was concluded that whilst it was possible to use bulk density to measure the effects of management and inherent soil properties through multiple regression analyses the parameters were more easily compared when using a reference bulk density. In addition to this it was found that the use of the reference made comparisons easier when advising land managers (da Silva, Kay & Perfect 1997).

Nhantambo and Cambule (2006) conducted a series of experiments to correlate bulk density provided by the Proctor Test and the texture of the soil (clay and silt content). Equations were generated using soil constituents (silt and clay content) to generate a bulk density value with some success although the relationship was found to be specific to the soil type. They concluded that this may be avoided by applying the relative compaction concepts (Nhantumbo & Cambule 2006). Furthermore, Carter (1990) has shown that the use of the relative bulk density is valid on fine sandy loams. A four year study was conducted on two sites under mouldboard ploughing with samples selected randomly from each site (three from one and four from the other). Several cores were taken over the course of a year and compared with a reference density generated through the use of the standard Proctor Test (Australian Standards 2003). In calculating the reference bulk density a close relationship between macroporosity and the reference bulk density was determined. This is useful as the macro porosity is not an easily measurable in-field, so by knowing the relationship between it and the relative bulk density an understanding of the current state of a compacted soil can become more easily determined. It was further shown that this process was also applicable when considering yield or equilibrium bulk density.

As demonstrated, relative bulk density is used widely throughout the agricultural industry, and with good reason; it effectively eliminates variable interference of most other soil related parameters, thus allowing for direct comparisons between soils. This is especially the case when considering optimum levels of compaction with a large subsample of soils and crops having the same or very similar peak degree of compactness. Whilst there is evidence to suggest that bulk density can be used for comparison it requires multiple regression analyses with several variables making it a relatively more time consuming and unclear process.

However, Arvidsson and Häkansson (2014) state that one of the limitations of using a reference bulk density to prescribe optimum compaction for maximising yield is that there is no indication of the nature of the curve. As shown the nature of curvilinear relationship between reference bulk density and yield often vary wildly, despite similarities in the optimum density. Consequently using the reference bulk density as a target does not provide insight into the consequence of exceeding or falling short of the targeted compaction, thus relative bulk density is not a good indicator of sensitivity to compaction. (Arvidsson 2014)

Despite the widespread use of relative bulk density as a measure of compaction there is some contention as to the most applicable method to determine the reference bulk density, with some authors utilising the Uniaxial Compression Test while others use the Proctor Test. In addition to the differing use of each method, the specific load applied in each test differs as well. Considering the increase in the use of large and heavy machinery, it is prudent to reconsider if current reference loadings are appropriate.

2.6 Surpassing the Reference Bulk Density

Whilst it has largely been confirmed that the reference bulk density is a highly advantageous parameter for comparing the levels of compaction between soils or for identifying an optimum compaction, evidence exists that shows that it is common for the reference compaction generated by the 200 kPa Uniaxial Test to be exceeded. This has been demonstrated for a number of levels of compaction (Lipiec & Hatano 2003, Suzuki, Reichert & Reinert 2013). It is suggested that this occurs because the reference load of 200 kPa was selected 25 years ago (Håkansson 1990) and is no longer valid when considering modern farming machinery and techniques (Suzuki, Reichert & Reinert 2013) where the loadings generated have been known to reach 300-650 kPa (Lipiec & Hatano 2003, Bennett et al. 2015).

Etana (1999) conducted a series of experiments and incorporated data from other experiments in the region relating effects of tillage depth on the physical properties of the soil. The soil was found to have a high clay content (as high as 52.1%), which is similar to the clay content in Australian Vertosols (CSIRO 2015). Häkansson’s method for both field and reference sampling was used to determine the bulk densities of the samples (Håkansson 1990). In doing so it was found that relative compaction reached levels as high as 110.2% during tilling operations. The peak of 110% was said to be unrealistic and that it was probably affected by textural variations, although no evidence was shown to support this. It was further suggested that near or greater than 100% compaction was above optimum for plant growth but was common in mechanized agriculture (Etana et al. 1999). Additionally, it has been shown that in no tillage systems the reference bulk density of 200 kPa is often exceeded giving a degree of compaction greater than 100%. Furthermore, it has been suggested that crop growth was unaffected by compactions of greater than 100% in no tillage fields (Suzuki, Reichert & Reinert 2013), but this requires further investigation given the breadth of information opposing these findings.

No tillage farms exhibit a number of different characteristics when compared with regular tillage processes. Thus, before information gathered from non-tillage system can be incorporated an understanding of its nature is required. Huang et al (2015) conducted experiments into the effects of no-tillage operations on soil physical properties, suggesting that no tillage operations have a differing effect to regular tillage. This investigation involved the comparison of three different tillage techniques (conventional tillage, no tillage with straw cover and no tillage with no straw cover) and their effect on common soil parameters such as: bulk density, water infiltration and organic matter (Huang et al. 2015). It was found that there were no significant differences in bulk density (and thus relative compaction) below the top layers of soil, between the analysed treatments, disagreeing with the hypothesis presented at the beginning of the journal article. It was found that the infiltration rate was significantly higher in the no-tillage plots (Huang et al. 2015).

Literature has demonstrated that reference bulk density has been surpassed, so it is necessary to investigate the possibility of increasing the reference such that values remain less than 100%, or understanding what a comparative compaction of >100% means for agricultural systems. This former process was investigated by Suzuki et al. (2013) for plots experiencing no tillage, but tilled systems need to be considered also.

2.7 Alteration to the Reference Bulk Density

Given the increase in machinery size and weight, particularly in the Australian cotton industry, it is pertinent to consider the relevance of current reference density loadings against modification of the loading. The reference bulk density has been previously altered by Suzuki et al. (2013) for no-till systems, and thus this section discusses the merits of this work in informing a way forward for Australian tilled soils. Whilst there might be expected differences in the systems due to presence or absence of cultivation, the work serves to provide insight useful to tilled systems also.

In justifying the increase in relative bulk density Suzuki et al. (2013) have cited a number attributing factors. The first of which is the difference in soils under no tillage to support a crop at higher compaction levels due to an increase in water infiltration (when compared to tilled soils). It was also noted that the compression given by 200 kPa is less than that which restricts root growth (Suzuki, Reichert & Reinert 2013).

Suzuki et al. (2013) aimed to identify the best stress to obtain reference bulk density with undisturbed samples, quantify the impact of particle size distribution on the degree of compactness and evaluate the correlation between degree of compactness and yield. This is very similar to the aim of this project with the key difference that this project uses tilled soils.

In addition, they undertook numerous undisturbed compression tests at an increasing range of application loads (200, 400, 800, 1600, 3200 kPa). The Proctor Test was also included for comparison. Once these tests were compared to the field compaction and yield information, Suzuki et al. (2013) selected >800 kPa and up to 1600 kPa as a reference load (Suzuki, Reichert & Reinert 2013). However, the presentation of a choice of references appears to be confounding in that it defeats the purpose of a universal reference. Based on the discussion provided in previous sections, the reference load should be based on the range of loads a soil is likely to receive (i.e. based on the machinery in the current farming system). This raises further questions around the applicability of changing the reference load in terms of comparison back to crop yield potential. It would be advantageous to consider if the reference load for the 100% degree of compactness should remain as current (200 kPa) and further loading be considered as achieving >100% of that loading. From here yield potential would need to be further compared against >100% degree of compactness data.

In performing this series of experiments Suzuki et al. (2013) used two methods of load applications: static and sequential loading. Static loading has a fairly intuitive process and involves the constant application of a load to a sample over a period of time. Sequential loading involved loading the soil with progressively increasing loads for five minutes each. In doing so it was found that the resulting bulk densities were comparable to those generated through the use of the static loading (Suzuki, Reichert & Reinert 2013). Furthermore it was discovered that, in order to reach the “true” maximum bulk density a load greater than 3200 kPa would be necessary. This was suggested because even between loadings of 1600 kPa and 3200 kPa there was a change in bulk density (Suzuki, Reichert

& Reinert 2013). Whilst "true" maximum bulk density provides a more uniform point of reference, it may not necessarily provide a realistic indication of density in the field based on current machinery and potential crop yield. It will be important that any reference density used is based on consideration of the agricultural production system, as this should serve as a "production success" threshold for the viability of a farming system.

The selection of >800 kPa and up to 1600 kPa was informed using the infield compaction data to determine the degree of compactness at each different loading, generating the results in Table 1. This is achieved by taking the ratio of the field bulk density to the bulk density that is generated at each different reference loading.

Table 1: Suzuki et al. Degree of Compaction Results taking the ratio of infield compaction to the compaction generated by the listed reference load (Suzuki, Reichert & Reinert 2013)

Reference Load	***Degree of Compactness Experienced in Field***
200 kPa	65-100%
400 kPa	63-98%
800 kPa	61-93%
1600 kPa	57-90%

As can be seen in Table 1, the 1600 kPa value was selected as it provides the degree of compactness that is unlikely to be exceeded in the field. Whilst values for loading at 400 kPa and 800 kPa give values that could be used they still produce results that may conceivably be exceeded on a regular basis. These results also leave little room for future increases in harvester sizes, which could be significant given current trend.

It is also suggested that results approximately equal to 100% cannot be explained because, at this level of compactness, the yield of the plant should be stopped, which was not observed (Suzuki, Reichert & Reinert 2013). This is confirmed by Reichart (2009).

2.8 Other Methods of Bulk Density Calculation

The literature presents alternate methods of bulk density determination. These however don't appear to have been used to generate a degree of compactness and their use in the literature is limited.

Da Silva et al. (1997) used a method created by Rowe and Barden (1966) to calculate a reference bulk density in which a Rowe consolidation cell is used in a porous condition to allow sufficient water dispersion. To this a load of 200 kPa was applied for one hour or until drainage had ceased. After which the sample was unloaded and any expansion was allowed to occur. From this the volume of the specimen was determined and thus a reference bulk density was calculated. This method is notably similar to Häkansson's method and does not appear to provide any further advantages.

Another method for determining compaction that has been used is the estimation of pore space as per Kuipers and Van Ouwerkerk (1963) although this was found to be very involved relative to other forms of compaction measurement and required many man hours to complete (Kuipers & Van Ouwerkerk 1963). Given that these methods do not provide any further advantages, or are overly laborious, it is suggested that Uniaxial Compression and the Proctor Tests are adequate for consideration and potential modification.

2.9 Conclusion

In this literature review a number of areas have been investigated including the basics of compaction, the relationship between yield and compaction, the current uses of the relative bulk density, evidence of the surpassing of the bulk density and other methods that have been used to describe bulk density. The literature has highlighted that current machine loadings far exceed current reference loadings, and suggest that further consideration is required to relate changes in bulk density to a universal degree of compactness.

When compaction occurs it has been shown that a variety of changes occur within the soil including a decrease in pore space and increase in the soil strength. The moisture content effects these parameters with a parabolic nature, affecting the ability to compare soils of differing moisture contents. This suggests that moisture content must be considered in any compaction comparative measure.

Whilst, typically a static loading will produce a lessor bulk density than the impact load, static loading has been shown in the literature as representative of agricultural machinery. Hence, when considering an agricultural machine and investigating increased reference loading, it is expected that static loading will be the most representative.

Of utmost importance, this review has demonstrated a significant knowledge gap in our ability to compare universally the impact of large, heavy machinery on the degree of compactness. Reference bulk density is widely used throughout the literature, but has been shown to underestimate current agricultural loads. While attempts have been made to alter the reference density to better suit conditions in the field there is a paucity of literature contributing to this dialogue and to tilled soils in the Australian cotton context.

Chapter 3 – Stress Analysis and Applicability of the Uniaxial and Proctor Tests

3.1 Introduction

This chapter directly addresses the second objective of this work: Analysis of selected methods and modification of these to suit and assess increased weight of agricultural machinery. In assessing the research design and methodology a number assistive measures were used to determine the most applicable and effective testing methods and loads. This includes the literature review in terms of compaction assessment methods best practice (Objective 1) and soil stress analysis (from the JD7760) using the SoilFlex model generated by Keller et al. 2007. Keller et al.'s (2007) model will be used here to validate the loading scenarios, ensuring tested loads are applicable to the JD7760.

As discussed in the literature review (Chapter 2) a number of testing techniques exist for the determination of a reference bulk density. The two most common of these are the Uniaxial Compression Test and the standard Proctor Test. As such these two methods will be critically analysed with the aim of generating a reference bulk density approach that is applicable to Australian Vertosols. Whilst the standard forms of these tests will be considered, modified methods will also be examined to further allow selection. Loading will primarily be considered based on the current cotton picker, the JD7760, but a range of loading will be further considered as it is acknowledged that machine weight may still increase with future innovations.

The principal methodology for this work will be to determine loading throughout the soil profile based on the JD7760 wheel load. Hence, in order to achieve this, stress analysis of the machine impact via SoilFlex will be undertaken; it is noted that throughout the analysis and experimental process, this dataset will also act as validation towards use of the SoilFlex analytical model to fingerprint additional in-field machinery impact. SoilFlex stress analysis will then be used to inform critical analysis, and modification, of Uniaxial and Proctor methods for determination of the degree of compactness and increased loading effect for numerous Australian Vertosols (primary cotton industry soil). Results from this objective will inform the modifications required for each test in incorporating increased machine loading, allowing an experimental validation dataset to be collected and evaluation of an appropriate approach for the JD7760 to be made.

3.2 SoilFlex Model

Before modelling can begin it is first necessary to gain an understanding of the SoilFlex model. A description, uses and limitations of the model is provided by Keller et. al. (2007) and explains the models uses and limitations. In addition Keller (Unpublished) provides detail of the models workings. These will be used as the main references when analysing the model. It is outside the scope of this dissertation to conduct in depth analysis of the published model.

However; it is noted that the model has been utilised throughout the world, is based on classical soil mechanics theory and application, and is currently being assessed for direct validity to Vertosols by Bennett et al. (Unpublished). Therefore, information will be presented to provide the reader with an understanding of the models advantages and limitations in respect to this projects aim.

SoilFlex is a model that works in two dimensions to calculate soil stresses and compaction resulting from agricultural field traffic (Keller et al. 2007). The model has been created such that it follows an analytical approach first conceived by Boussinesq (1885).

The SoilFlex model calculates the following parameters: stress state, changes in bulk density and vertical displacement. These are calculated as a result of three distinct stages: surface stresses, stress propagation and finally soil deformation as a function of stress. A flow chart of these stages can be found in Appendix B (Keller et al. 2007)

In defining the contact stresses Keller et al. (2007) have separated the components of each stress to provide the vertical and horizontal values in separate matrices. The contact area of the wheel is assumed to be equal to the tyre width and the contact area is found by dividing the load by the inflation pressure. The distribution of stress under the wheel is then calculated as uniform, linear or generated by a power function. More options exist for these parameters and are provided in detail in Appendix C. The availability of these options allows the input of either single or dual tyred wheels or to simulate multiple passes of tyres.

The determination of stress propagation through the soil is based on the work of Boussinesq (1885), Cerruti (1888), Fröhlich (1934) and Söhne (1953) and involves splitting the contact area into a series of smaller point loads (Keller et al. 2007). These points have an area and a normal stress which provides a load calculated, below, as per the approach of Söhne (1953):

$$P_i = \sigma_i A_i \qquad \text{Eqn 3.1}$$

Where:

$P_i = Equivelent\ point\ loading\ in\ element\ i$
$\sigma_i = Stress\ in\ element\ i$
$A_i = Area\ of\ element\ i$

In addition to this a shear point load is related to a radial stress by using Equation 3.2 (Keller et al. 2007):

$$\sigma_{r,i} = \frac{\varepsilon P_i}{2\pi r_i^2} cos^{\varepsilon-2}(\theta_i) + \frac{\varepsilon H_i}{2\pi r_i^2} sin^{\varepsilon-2}(\theta_i)\cos(\delta_i) \qquad \text{Eqn 3.2}$$

$\sigma_{r,i} = Radial\ Stress$
$r_i = distance\ from\ point\ load\ to\ desired\ point$
$\varepsilon = Concentration\ factor\ (Frolich, 1934)$
$\theta_i = angle\ between\ normal\ load\ and\ poition\ of\ desired\ point$
$\delta_i = \ Angle\ between\ shear\ load\ and\ verticel\ plane$

Having obtained these parameters soil compaction can be determined through stress-strain relationships. This investigation will exclusively consider the application of O'Sullivan and Robertson's (1996) method to describe the compressive behaviour of agricultural soils. This is because it provides the most complete data in the model. All the models discussed above are classified as strain hardening models, meaning that an increase in strain is coupled with an increase in the strength of the soil.

The basis of O'Sullivan and Robertson's model is displayed, below, in Figure 7 (Keller et al. 2007). The Virgin Compression Line (VCL) is the behaviour in the initial compressive cycle, the recompression lines (RCL, RCL dash) are the compression lines for the following compressive cycles. The equations describing these lines follow (Equations 3.3, 3.4, 3.5)

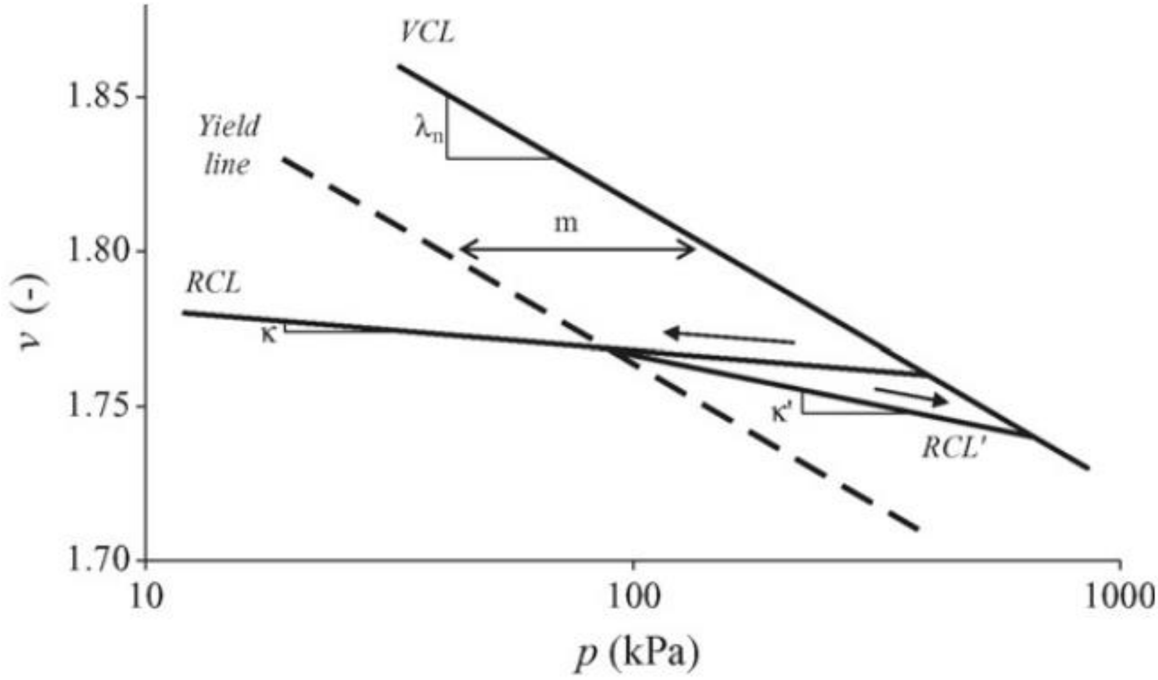


Figure 7: O'Sullivan and Robertson's model used in SoilFlex showing the different stages of compaction: virgin compression and two types of re-compression (Keller et al. 2007)

$$VCL: v = N - \lambda_n \ln(p) \qquad \text{Eqn 3.3}$$

$$RCL: v = v_{init} - k\ln(p) \qquad \text{Eqn 3.4}$$

$$RCL': v = v_{YL} - k'\ln(p) \qquad \text{Eqn 3.5}$$

Where:

$v = specific\ volume$

$p = mean\ normal\ stress$

$N = the\ mean\ specific\ volume\ when\ p = 1kPa$

$\lambda_n = compression\ index$

$v_{init} = initial\ specific\ volume$

$v_{YL} = specific\ voluem\ when\ the\ yeild\ line\ intersects\ the\ recompression\ line$

$k' = slope\ of\ the\ steep\ recompression\ line = \sqrt{\lambda_n k}$

After this the bulk density figures are calculated by the Equation 3.6:

$$\rho = \frac{\rho_s}{v} \qquad \text{Eqn 3.6}$$

Where:

$\rho_s = density\ of\ solids$

The final output that SoilFlex provides that is relevant in this dissertation is the vertical soil displacement and stress distribution. In SoilFlex this is achieved through either a uniaxial analysis or a more complicated multiaxial analysis. The Uniaxial Test is used for this dissertation. The uniaxial approximation has been ratified in the literature as an acceptable model; noting that some sources have suggested that it could result in under prediction. For a full justification see Keller (2007, p399). The uniaxial analysis uses the methods presented by Koolen and Kuipers (1983).

3.2.1 Limitations and Validation

Whilst this model is applicable to this dissertation it is unreasonable to expect that it would be without limitations. These limitations will be investigated and their impact on this project assessed to ensure that the use of this model is justified, and to assist future soil specific validation.

One limitation of the model is its inability to consider separate layers of soil (i.e. non-uniform soils such as Chromosols). This is because introducing layers conflicts with the analytical equations of Boussinesq (1885) and Cerruti (1888). These equations were developed for a semi-finite, elastic, homogeneous and isotropic medium, though some work has been done to account for the inelasticity of the soil. In the context of this dissertation this shouldn’t present as an issue as Vertosols are considered homogenous with depth in terms of textural characteristics, which would be the major soil based property affecting simulations.

When compared to field experiments Keller et al. (2007) found that SoilFlex agrees very well with the measured stress. However the vertical displacement was underestimated in the topsoil and overestimated in the subsoil; this occurred in both the uniaxial and multi-axial approaches. The cause of this was assumed to be related to the uncertainty in the required parameters prompting the sensitivity analysis found in Keller et al. (2007).

Comparisons between SoilFlex and a finite element approach have been conducted in the past. It was found that these models were comparable in their results. Keller et al. (2007) state that this suggest that the analytical approach for the calculation of stress distribution is justified.

3.3 John Deere JD7760

One cotton harvester that is currently used on Australian soils is the John Deere JD7760. This is a 4 wheel drive, on board module building harvester with the option of running either single (aftermarket modification) or dual wheel operations (standard configuration). With some modification the harvester can be set up to harvest cotton from a 4 – 12 m frontage. It has been described as having a loading of approximately 500-600 kPa (Bennett et al. 2015, Braunack & Johnston 2014).

For this analysis the standard configuration JD7760 will be modelled as per Table 2 (Bennett et al. 2015, John Deere & Company 2015, Good Year 2015).

Table 2: Parameters listed used for modelling of the JD7760 in a standard configuration within the SoilFlex model taken from (Bennett et al. 2015, John Deere & Company 2015, Good Year 2015)

Parameter	***Dimension***
Tyre Configuration	Dual
Starting Weight	32 Mg
Average Front Wheel Load	5.43 Mg
Front Wheel Spacing	0.4 m
Front Tyre	520/85R42-R1
Front Tyre Inflation Pressure	0.25 MPa
Average Rear Wheel Load	8.25 Mg
Rear Tyres	520/85R34-R1
Rear Tyre Inflation Pressure	0.38 MPa

3.4 SoilFlex Modelling

Modelling of the expected load case (Table 2) is presented below. This has occurred with the purpose of informing a reasonable selection of trial loads. Whilst it is tempting to merely select the application load of 600 kPa that is generated by the JD7760 it is more applicable to consider the influence of the loading over the depth of the soil to generate a range of loadings that is applicable for testing and comparison of future innovations that could be heavier.

The SoilFlex model was set up to run two different scenarios. One describing the dual front wheel trafficking and the other describing single rear wheel trafficking. This in conjunction with the soil parameters listed, below, in Table 3 allows for modelling to be undertaken using O’Sullivan and Robertson’s deformation model.

Table 3: Soil Parameters used to model compaction within SoilFlex. These are standard numbers in the model used to indicate a trend and are not intended to be indicative of a Vertosol

Parameter	***Layer 1***	***Layer 2***
Lower boundary (cm)	**150**	**150**
Soil mechanical parameters:		
Specific volume v (-) at p = 1 kPa - **N**	**1.811**	**1.777**
Slope of the VCL ($[\ln(p)]^{-1}$) - λ_n	**0.068**	**0.070**
Slope of the RCL ($[\ln(p)]^{-1}$) - **κ**	**0.0194**	**0.0137**
Slope of the "steeper" RCL ($[\ln(p)]^{-1}$) - **κ***	**0.0363**	**0.0310**
Separation between yield line and VCL ([ln(p)]) - **m**	**0.8**	**0.9**
Soil cohesion (kPa) - **c**	**60**	**100**
Angle of internal friction (deg) - **φ**	**30**	**30**

The data tables for the figures presented in the upcoming sections are reproduced in Appendix D.

3.4.1 Front Wheel Loading (Duals)

When running the SoilFlex model for the front wheels the following outputs are generated, presented, below in Figures 8 through 13.

In Figure 8 the vertical stress under each wheel is visible as well as the interaction between the stress under each wheel at depth. Note that the model had limited output regarding the width of the sample thus cutting of the output at 70cm from the centreline, this does not have a large impact on this investigation since the peak stressors are found in the centreline of the wheel.

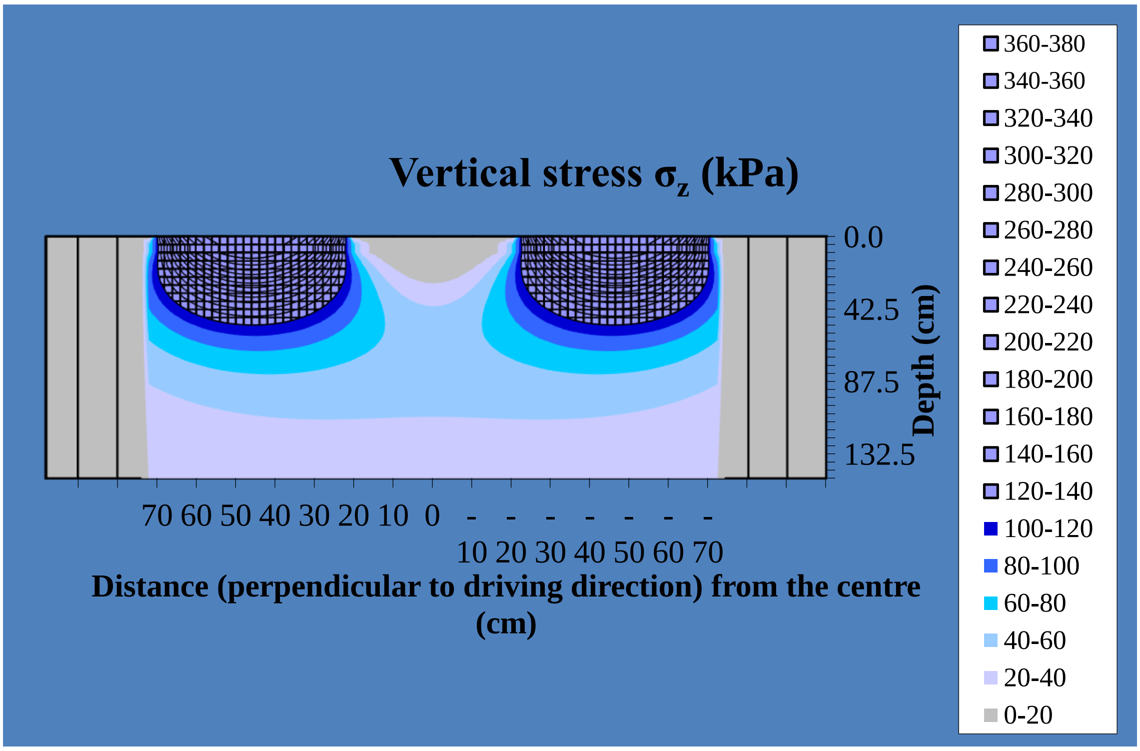


Figure 8: SoilFlex output representing vertical stress distribution under the front wheels of a JD7760. Note that the output has been cut off at 70 cm from the centreline, this has no effect on the use of the results as the peak stresses are under the centreline of the wheel

In Figure 9, below, it is shown that the peak surface loading is generated at the centre of the wheel, the value of this loading is 375 kPa and this value decreases radially from the centre.

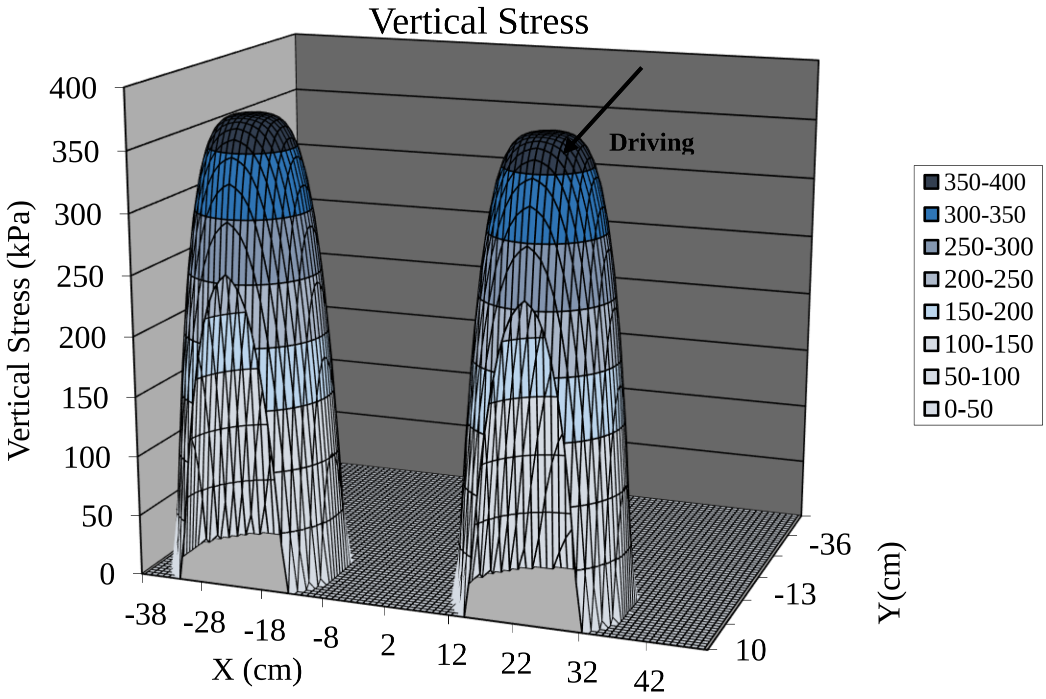


Figure 9: SoilFlex output representing the vertical contact stress as a result of the JD7760's front wheels

In Figure 10, below, the vertical stress over the considered depth (1.5m) is shown in the centreline of the wheel path. This location is equidistant from either wheel. This output shows an increase in stress at a depth of 65 cm, producing a peak of 52 kPa. This suggests that the stresses of each wheel only interact at the aforementioned depth, confirmed in Figure 9, above, and although this is a small stress it could be considered to have some impact on bulk density. This means that the surface between the wheels experiences minimal stress according to SoilFlex, although in-field measurement documented by Bennett et al. (2015) suggests that a compaction pan, similar to a plough pan, can be seen to develop between dual wheel configurations at a depth of 20–40 cm.

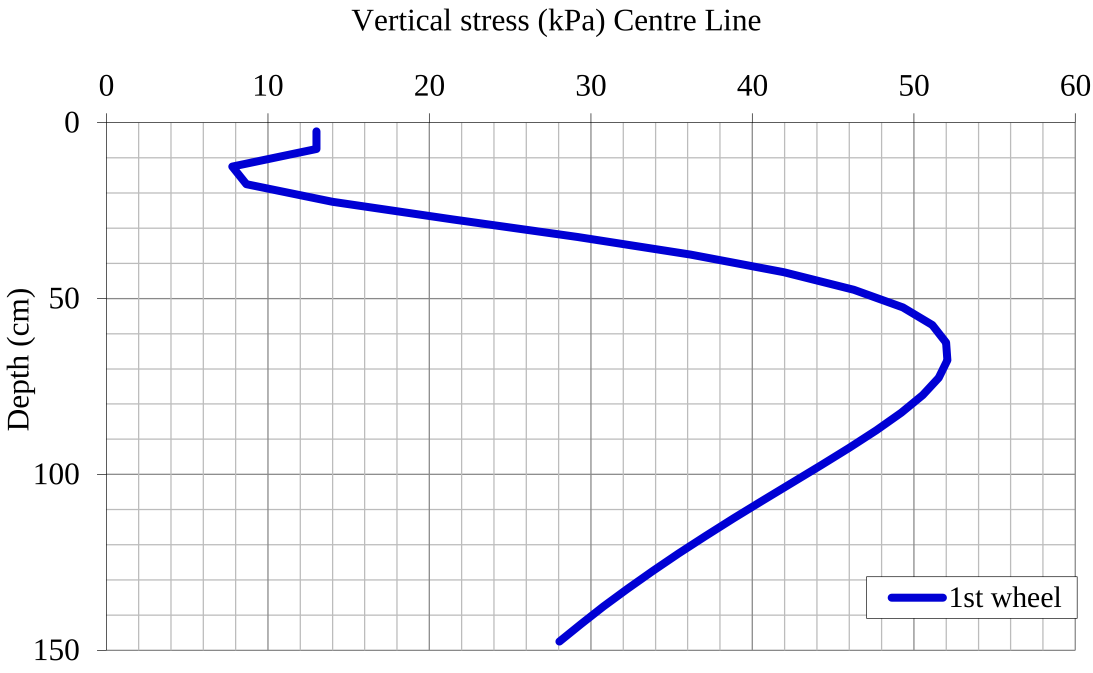


Figure 10: SoilFlex output under the centre line of the sample showing the distribution of stress with depth as a result of traffic by the front wheels of the JD7760. Note that the centreline of the sample is equidistant from either wheel

The result of this stress distribution is depicted in Figure 11. This has assumed an initial bulk density of 1.67 g/cm^3. In Figure 10 it can be seen that the peak bulk density (in between the two wheels) is at a depth that is lower than the peak stress. The bulk density increase is very small. This suggests that the 52 kPa peak is only just sufficient to cause compaction.

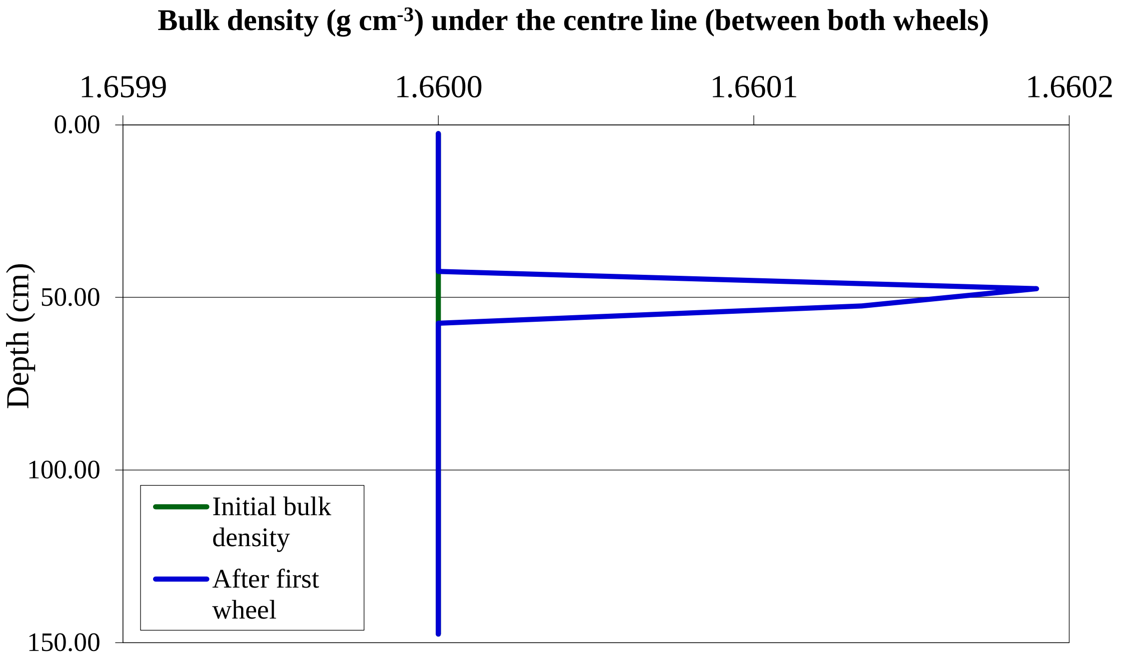


Figure 11: SoilFlex output under the centre line of the sample showing the change in bulk density with depth. Note that the centreline of the sample is equidistant from either wheel. The green line represents the initial bulk density whilst the blue lien represents the bulk density after one pass of the wheel

The vertical stress under the wheel is shown in Figure 12, below, (each wheel produces an identical distribution). In Figure 12 shows an exponential decrease in the vertical stress from the peak loading at the surface. This results in the stress being negligible after a depth of 1m where the stress has been reduced to 40 kPa.

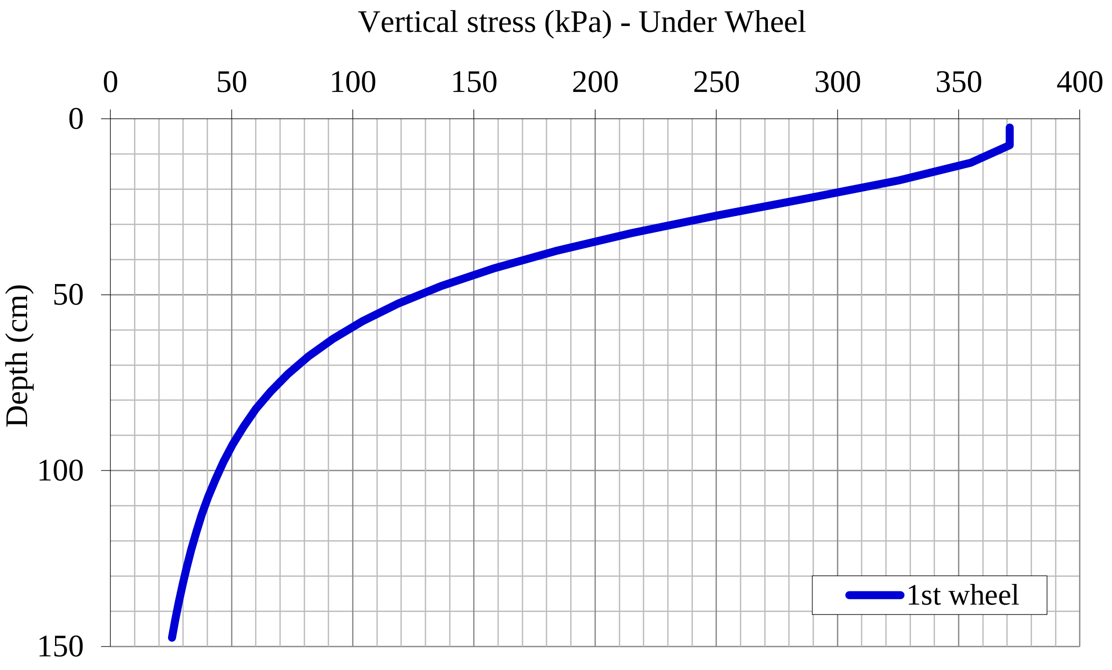


Figure 12: SoilFlex output showing the distribution of vertical stresses under one of the front wheels

Supporting the findings shown above, Figure 13, below, shows that, as the stress falls below approximately 50-60 kPa the increase in bulk density falls to zero.

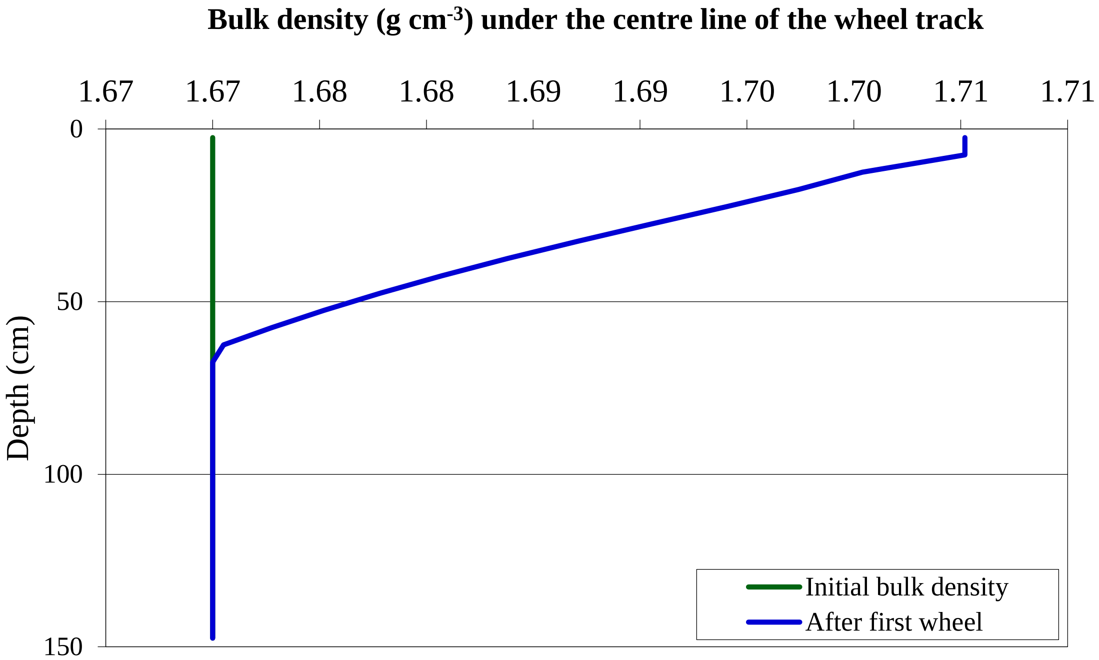


Figure 13: SoilFlex output showing the change in bulk density under one of the front wheels. The green line represents the initial bulk density whilst the blue line represents compaction after trafficking

3.4.2 Rear Wheel Loading

Similar to the front wheels when running the SoilFlex model for the outputs for the rear wheel are presented below.

Figure 14, below, shows the vertical stress distribution under the rear wheel, with a peak of approximately 570 kPa under the centre of the wheel.

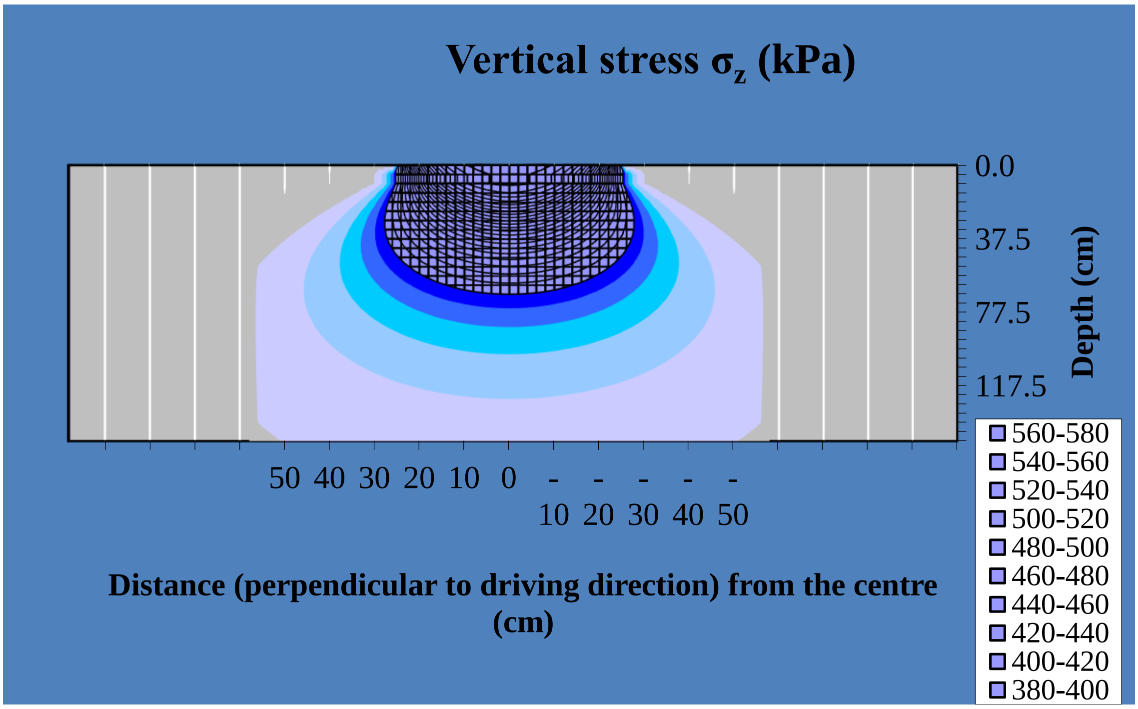


Figure 14: SoilFlex output representing vertical stress distribution under the rear wheel of a JD7760.

The contact stress provided by the tyre is shown in Figure 15. Again the stress peaks in the centre and decreases radially outward, however in this case the peak contact stress of 570 kPa.

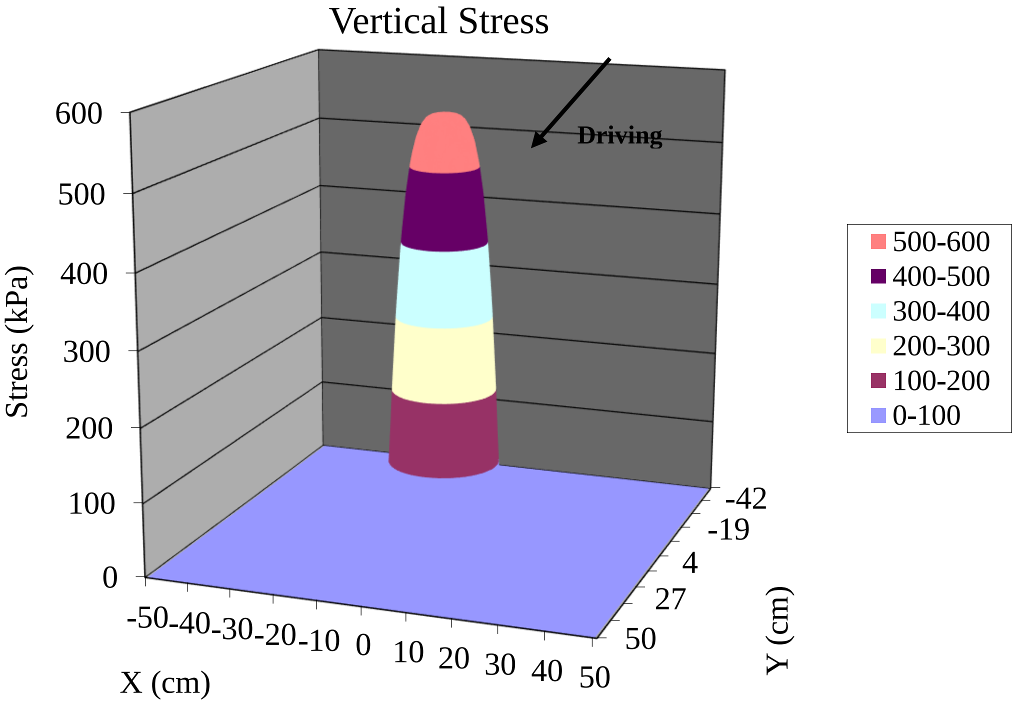


Figure 15: SoilFlex output representing the vertical contact stress as a result of the JD7760's rear wheel

The vertical stress distribution follows a similar trend to the front wheels (Figure 16) however with a higher starting value. The change in bulk density is shown, below, in Figure 17, where it can again be seen that the change in bulk density falls to zero when the stress falls to a value less than approximately 50 kPa.

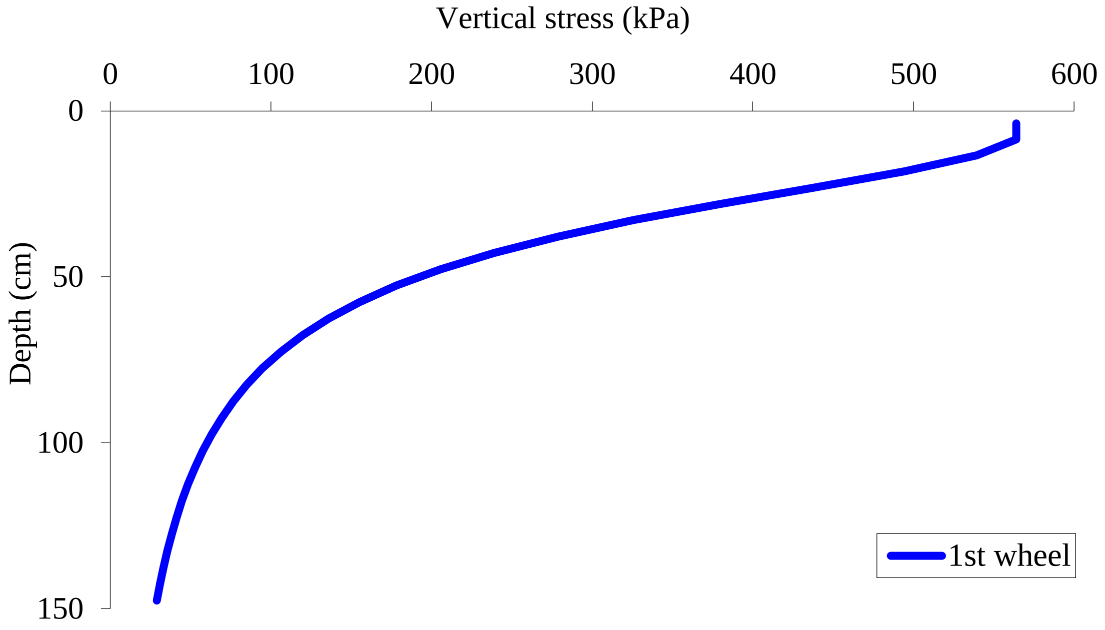


Figure 16: SoilFlex output under the centre line of the sample showing the distribution of stress with depth as a result of trafficking by the rear wheel of a JD7760

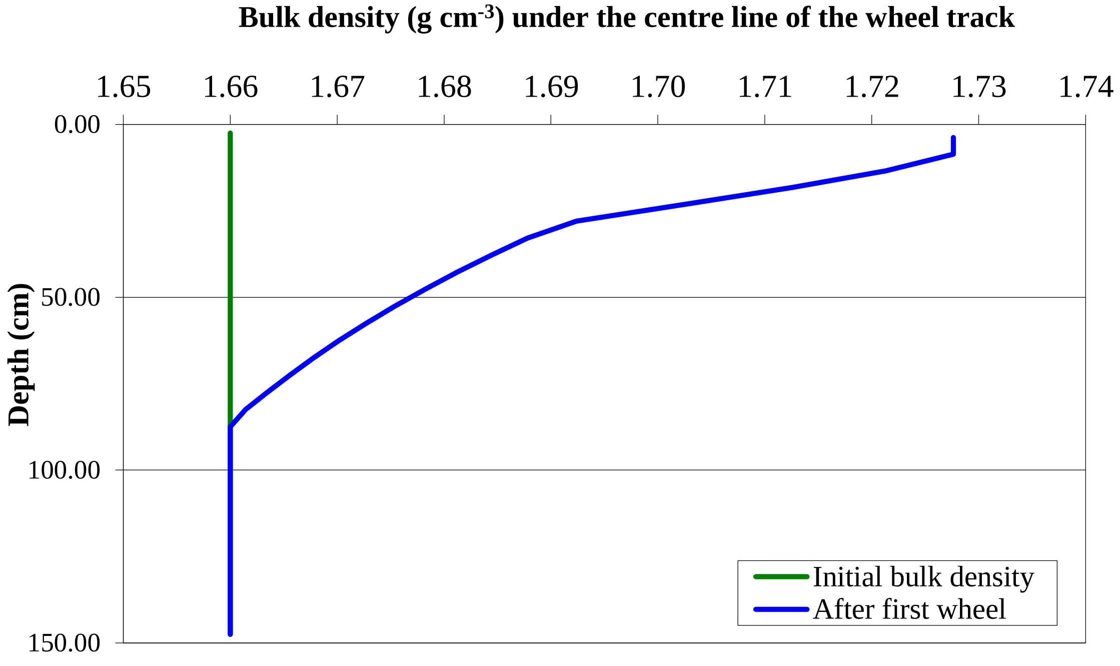


Figure 17: SoilFlex output showing the change in bulk density with depth as a result of trafficking by the rear wheel of a JD7760. The green line represents initial bulk density whilst the blue line represents to bulk density after a single pass

3.5 SoilFlex Analysis and Comparison

From the model outputs a number of conclusions can be drawn in relation to the loading and its nature. These conclusions will allow informed selection of loadings to test when replicating the loading of the JD7760.

In order to analyse the front wheel loading of the JD7760 two key aspects of the outputs should be considered: the influence of a single wheel and the effect of the two wheels interacting.

As seen in Figures 8 and 9 the peak contact stress of the wheels is generated from a single wheel, in isolation of the effects of the other wheel. This is very obvious in Figure 9 where the green "unchanged" bulk density is shown between each wheel. As the depth increases the stress generated by the wheels begin to interact elongating the area of stress influence. This is supported in Figures 10 and 12 where the stress under one wheel can be compared to the stress under the centreline of the trafficked area (i.e. centred between the wheels). This comparison shows that the wheels do interact although the interaction is negligible when compared to the peak loadings generated under the single wheel. Thus the loadings underneath the centre of the wheel will be considered for comparison between the front and rear wheels.

Upon comparison between the front and rear wheel loading cases similarities are immediately visible: the nature of the decrease of stress in exponential with the bulk density influenced by the wheel compaction up to a depth of approximately 70-90 cm, despite the differences in additional loading. Suggesting that considering data to a depth of 1m is a conservative approach. In addition to this the peak loadings of both the front and rear wheels occurs under the centre of the tyre.

In addition to this the change in vertical stress is considerably lower after depth of 1m when compared to the change from 0-1m. Using this as a boundary it is now possible to compare the raw data with the aim of identifying a range of applicable stresses for testing. This has been achieved through the use of Table 4 below.

Table 4: Tabulated SoilFlex output listing the stresses experienced at each depth and the average stresses over a range of depth with an aim to simplify the selection of applicable loads to test

	Rear			***Front***		
Depth (cm)	***Bulk Density (g/cm3)***	***Vertical Stress (kPa)***	***Average Vertical Stress (kPa)***	***Bulk Density (g/cm3)***	***Vertical Stress (kPa)***	***Average Vertical Stress (kPa)***
0.00	■	570	570	■	375	375
2.50	1.73	564	556	1.71	371	365.67
7.50	1.73	564		1.71	371	
12.50	1.72	539		1.70	355	
17.50	1.71	494	437	1.70	325	287.67
22.50	1.70	438		1.69	288	
27.50	1.69	380		1.69	250	
32.50	1.69	326	281	1.69	215	185.67
37.50	1.68	279		1.68	184	
42.50	1.68	239		1.68	158	
47.50	1.68	206	180	1.68	137	120.00
52.50	1.68	178		1.68	119	
57.50	1.67	155		1.67	104	
62.50	1.67	136	121	1.67	92	82.33
67.50	1.67	120		1.67	82	
72.50	1.67	106		1.67	73	
77.50	1.66	95	86	1.67	66	60.33
82.50	1.66	85		1.67	60	
87.50	1.66	77		1.67	55	
92.50	1.66	69	63	1.67	50	46.67
97.50	1.66	63		1.67	47	
102.50	1.66	57		1.67	43	

From Table 4 it can be seen that despite different loadings the change in bulk density is similar at 27.5 cm depth. Additionally the rear wheel is shown to have a larger influence on the compaction at a depth, in spite of a lower contact stress. This notion is supported in the literature.

This model suggests that the stress values less than 100 kPa do not have a noticeable impact on soil compaction, suggesting that it would provide a good lower bound to the considered stresses.

The peak loading that is generated by the harvester is approximately 600 kPa under the rear wheel and, in both cases, decreases logarithmically with depth. This loading pattern is used to plausibly suggest that testing loads of 600, 400, 200 and 100 kPa will generate a bulk density that will give results that are indicative of compaction that has been experienced in the field. This is because the loads are representative of the stresses that are experienced over the applicable depth of soil. However as has been described in the literature review, similar testing has been undertaken by Suzuki et al. (2013) finding that the stresses of 800 kPa and 1600 kPa were of good use for an indicative test, thus these loadings will also be considered to provide direct comparison to their work.

3.6 Critical Analysis and Modification of Assessment Methods

As previously stated; the literature suggests that the most common methods of determining the reference bulk density are the Uniaxial and the Proctor Tests. Both of these tests use a standard compactive force to produce a compaction. For this dissertation both the standard tests and variations to these tests will be analysed.

3.6.1 Standard Uniaxial Test

The standard Uniaxial Test most referenced in the literature has been described by Häkansson (1990). In selecting the Uniaxial Compression Test as the preferred method for reference testing Häkansson considered a variety of factors that would best describe the conditions experienced in the field. In addition to this a preference was stated for testing that could be easily reproduced without a large expenditure of man hours. This reasoning and its applicability are investigated below.

The chief conditions that were examined by Häkansson included the size and inclusions of foreign matter in the samples, the moisture content and the manner and intensity of loading (Håkansson 1990). Furthermore this suggests that, whilst the exact size of the specimen is not critical, it should be as large as possible and include the same stones, plant residues etc. that is included in the field; easily achieved in bulk sampling.

Perhaps the most important key parameter that Häkansson considered in his experimental design is the mode and intensity of the loading stating that the “reference test should have a mode and intensity of loading similar to that in the applications concerned” (Håkansson 1990). Suggested that the loading of agricultural soils is generally of the static type and is supported in the literature review (Chapter 2). As such this dissertation utilised a static loading in the Uniaxial Compression Test.

The chosen loading intensity (200 kPa) was selected by Häkansson due to its location in the upper range of the loading the soil experiences, at the time of method development (prior to the 1990s). This lends strong merit to the necessity of increasing the reference loading considering the current loading of more modern machinery. A load in the higher regions of what is experienced by the soil was selected to avoid the soil being pre-compressed by a load greater than the testing load. It is also stated that the load should not be so high as to detract from the relevance of the test.

The moisture content in Häkansson’s tests was managed through the use of an exceptionally long loading time and a porous base, allowing for equalisation of the moisture content of the samples. This process took one week (Håkansson 1990).

3.6.2 Modifications to the Uniaxial Test

In order to suit the requirements and time limitations of this dissertations some changes to the methodology of the standard Uniaxial Test presented by Häkansson (1990) are required. The modifications will either reduce the time of testing, match the available materials for testing or to include variable loading.

The introduction of variable loading will follow the methods presented by Suzuki et al. (2013). Not all of the method presented by Suzuki et al. will be applicable since the paper considers no tillage plots however the methods of alteration considered are still applicable.

The first alteration to the Uniaxial Test presented by Häkansson (1990) is a change to the applied loading; as described in Suzuki et al. (2013). This is achieved by altering the load applied to the sample and comparing the resultant bulk density to values gathered in the field (and generated within the SoilFlex model). Differing from Suzuki et al., the actual values of loading will be altered to suit the values produced in SoilFlex: 100, 200, 400, 600, 800 and 1600 kPa. These values should give an indication of the soil over its depth and the utilisation of the higher stresses may be used to allow for future growth as may be necessary.

Further alteration to the test will is required to combat major hindrances to the timeline. This includes consideration of the moisture content and time of loading (noting these are somewhat interrelated). Häkansson's (1990) original method utilises a drained test to equalise the moisture content between samples, however this requires approximately one week per test. As such a different method of accounting for water content is required. This can be achieved in two ways: test a range of moisture contents as per the Proctor Test or test a single moisture content taken as a standard.

Ideally a range of moisture contents would be used as a means for calculating the maximum bulk density under each load. This, however, would require significantly more testing than required by a standard moisture content. The main drawback in using a standard moisture content is the variability between soils. For example, the moisture content that produces maximum compaction in one soil may produce significantly more or less compaction in another. However this could be negated since the compaction recorded will be used as an arbitrary reference to the soil itself and would only be an issue if the compaction generated was lower than that experienced in the field.

It is suggested that using a range of moisture contents to produce a maximum compaction would be most applicable to determine the reference compaction. This however will dramatically increase the time required for testing. A way around this issue within this project could be to conduct the Proctor Test before the Uniaxial Compression Testing. This will allow accurate determination of the ideal moisture content for compaction for use within the Uniaxial Testing. This moisture content will be the same between tests.

Since the moisture content is no longer a factor it is possible to reduce the time of loading to a more reasonable level. Since most of the compaction occurs during the first pass of a vehicle in the field relatively low loading times can be used. Suzuki et al. (2013) has used 5 minutes, which represents the current experimental process also.

3.6.3 Standard Proctor Test

The Proctor Test uses a number of sub-replicates of the same soil sample and volume compacted at a constant load with moisture varying for each sub-replicate. This allows the optimum moisture content for soil compaction to be determined for the given load. At the optimum moisture content, the maximum dry density occurs for that same given load, which is then used to provide the reference density for the given load. Testing refers to AS1289.5.1.1.

3.6.4 Modifications to the Proctor Test

Given the availability of the Proctor Test equipment it is postulated that the simplest manner in which to alter the loading generated in the test is through altering the number of blows to each layer. Two hammer types are available: the standard and modified hammer. The standard hammer has been used in this situation to provide a higher resolution in the number of blows provided to each layer for the smaller stresses, allowing more uniform compaction (i.e. more blows are required to reach a stress value, thus when considering lower values the hammer is more likely to compact the entire surface of the soil sample) and closer adherence to the required loads.

The compactive effect of the Proctor blows on the soil sample can be calculated following the equations stated by Raghaven and Ohu (1985) (Equations 3.7, 3.8):

$$Compactive\ Effort\ (C) = \frac{M * g * h * L\ * N_B}{V} \qquad \text{Eqn 3.7}$$

Where:

$$M = mass\ of\ the\ hammer\ (kg)$$

$$g = acceleration\ due\ to\ gravity\ \left(\frac{m}{s^2}\right)$$

$$\text{L} = \text{number of layers}$$

$$h = height\ of\ fall\ (m)$$

$$N_B = Number\ of\ blows\ per\ layer$$

$$V = Volume\ of\ sample\ (m^3)$$

Using the standard conditions described in AS1289.5.1.1 a compactive effort is produced:

$$C = \frac{2.7 \times 9.81 \times 0.3 \times 3 \times\ 25}{0.001}$$

$$C = 595.95\ kPa$$

This matches the compactive effort stated in AS1289.5.1.1 of 596 kPa, thus the equation is assumed to be reasonable.

Furthermore Raghavan and Ohu (1985) suggest an equation to link static loading with the Proctor loading, (R^2 value= 0.998 @ 0.0001). This relationship is critical as it allows the comparison of the impact load of the Proctor Test to be expressed in terms of a static load. The differences in these loading types have been discussed in the literature review.

$$Statp = 66.70 + 22.10ProcB \qquad \text{Eqn 3.8}$$

Where:

$$Statp = static\ pressure\ equivalence$$

$$ProcB = Number\ of\ Proctor\ Blows$$

This relationship is true for the standard Proctor Test.

This set of equations has been graphed in Figure 18 to provide a visual indication of the relationships with the data tables included in Appendix E for reference.

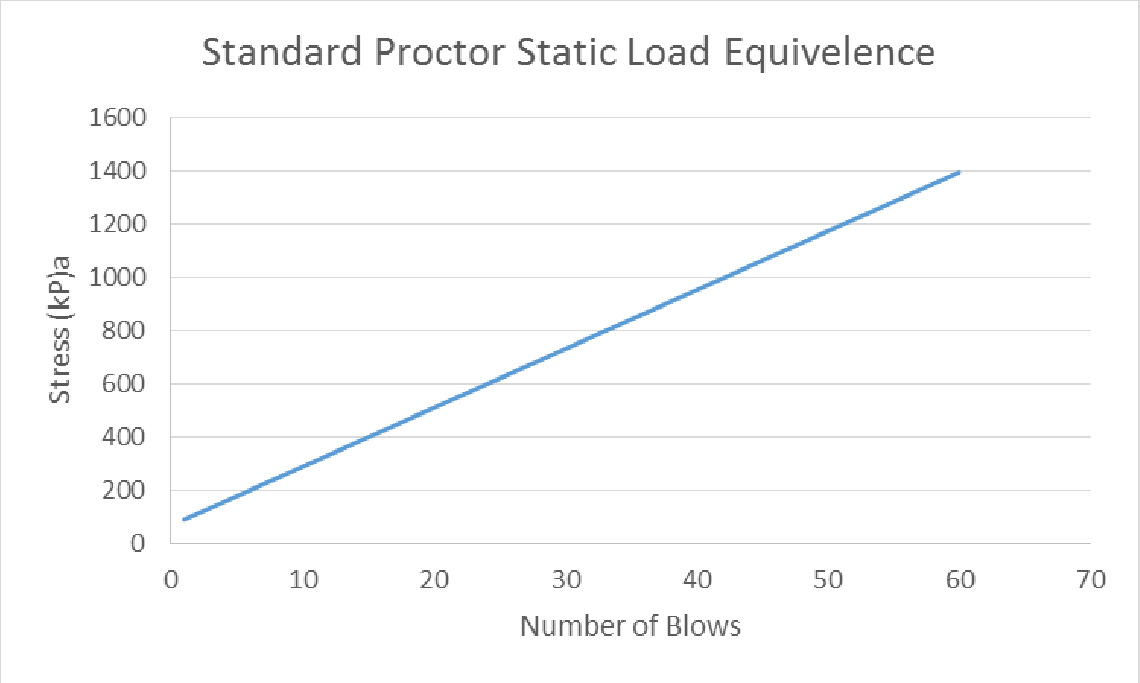


Figure 18: Standard Proctor Test static load equivalence showing a linear increase in equivalent static load provided by a number of compactive blows provided by the standard Proctor Test

As can be seen, the equivalent static load is typically greater than the actual compactive effort although as the number of blows increases the difference in actual and equivalent loading decreases. This indicates that the sharp impact of the hammer fall has a greater effect than a static load, which is discussed within the literature review (Chapter 2).

The above relationship has been used to generate the required number of blows, presented, below, in Table 5. This table also displays the actual equivalent static pressure. As previously discussed, in order for the Proctor Test to be reliable some degree of uniform compaction must be applied to the soil, as the Proctor Test uses a soil column of greater diameter than the diameter of the hammer. Hence, multiple blows represent multiple impacts as might occur in the passing of a sheep's foot roller. Thusly, the static loading requirement of 100 kPa has been eliminated from assessment with the Proctor Test variant as one blow is not sufficient for uniform compaction.

Table 5: Standard Proctor Test static load equivalence at the required loadings for testing

Static Load Required (kPa)	***Number of Proctor Blows***	***Equivalent Static Load (kPa)***
100	1 (not to be included)	88.8
200	6	199.3
400	15	398.2
600	24 (use standard of 25)	597.1
800	33	796.0
1600	69	1591.6

These loadings will occur at the optimum moisture content provided by the unmodified Proctor Tests.

3.6.5 Experimental Factor Summary

In summary, based on the critical analysis of methods and modification of these, the experimental factors for this study are identified as:

1. The Uniaxial Compression Test modified to suit a single pass of a heavy machine with the loads 200, 400, 600, 800 and 1600 kPa
2. The Proctor Test conducted as per the standard and modified variants of the test to suit a range of static load synonymous with large machinery and literature thresholds using 6, 15, 25, 33 and 69 blows (representing static loadings of 200, 400, 600, 800 and 1600 kPa)

The bulk density gathered from these tests will be compared to those gathered in the field as part of an interrelated project.

Chapter 4 - Experimental Procedure

Given the stress analysis conducted for the JD7760 using SoilFlex, and the ensuing methodological analysis and modification (Chapter 3), the detailed experimental procedure is set out below for each test:

4.1 Soil Sampling and Preparation

This project has utilised bulk disturbed samples collected from a variety of locations listed in Table 6. These samples have then been assigned an alphabetic handle to simplify discussion.

Table 6: Sample Locations and Handle

Location	***Handle***
Toobeah, QLD	A
Goondiwindi, QLD	B
Yelarbon, QLD	C
Aubigny, QLD	D
Jimbour, QLD	E
Warren, NSW	F

Sampling was conducted over a depth of 0-20 cm below the surface using handheld shovels. The samples were then placed in containers and protected from drying.

Once the samples were collected the soil was dried in an oven at 105°C for 4-7 hours to allow soil to be dry enough for subsequent handling without smearing of soil structure prior to the experiment. Following this the sample was carefully made to pass through a 19mm sieve by breaking down the larger peds. The soil was then allowed to air dry.

A smaller air-dried sub-sample was placed in the oven at 105°C for 72hrs to determine the oven dry moisture content allowing the calculation of true moisture content during the tests.

4.2 Standard Proctor Test

The Proctor Tests were conducted with reference to AS1289.5.1.1.

4.2.1 Equipment

The equipment used was as follows:

1. Standard Proctor mould A: Ø D=105mm, H=115mm with a baseplate and collar that can be firmly attached
2. 2.7kg steel rammer/hammer
3. Level rigid foundation for testing
4. Scales (±0.005kg)
5. Strong spatula
6. Steel straightedge
7. Mixing apparatus
8. Shovel
9. Sealable containers
10. Screw driver (for removing sample from mould and for attaching the mould to the base plate)

Photos of the equipment are available in Appendix F. AS1289.5.1.1 shows schematics and tolerances for the mould and hammer.

4.2.2 Procedure

The testing procedure was as follows (AS1289.5.1.1):

1. Soil samples were prepared according to the procedure in Section 4.1
2. Soil was moistened to a gravimetric moisture content that was approximated to be lower than the optimum moisture content and was allowed to cure for 20-30min
3. Soil was placed in the Proctor mould such that it was filled approximately 50%
4. The Proctor hammer was then used to compact the soil over 25 blows. These blows were spaced evenly over the surface
5. An approximately equivalent volume of soil was again added to the mould to create the second lift
6. The Proctor hammer was then used to compact the soil over 25 blows. These blows were spaced evenly over the surface
7. An approximately equivalent volume of soil was again added to the mould to create the third lift
8. The Proctor hammer was then used to compact the soil over 25 blows. These blows were spaced evenly over the surface

9. The collar was then removed and the soil surface trimmed such that it was level with the edge of the collar
10. The mass of the mould and the soil was then taken and used to calculate the wet as in Equation 4.1 below:

$$\rho_{wet} = \frac{Mass}{Volume} \qquad \text{Eqn 4.1}$$

Where:

$$Mass = mass\ of\ mould\ and\ soil - mass\ of\ the\ mould$$

11. The dry bulk density was then calculated accounting for the moisture content
12. The soil was then removed from the mould and the equipment was cleaned
13. Steps 2 through 11 are then repeated for moisture contents such that the optimum moisture content has been adequately straddled i.e. two points either side of the optimum moisture content were found
14. The removed soil was re-prepared as per chapter 4.1 for use in later tests

4.3 Standard Proctor Test with Modified Load

The modified loading of the Proctor Test was achieved by altering the number of blows per layer as discussed in Chapter 3, otherwise the procedure was as per AS1289.5.1.1.

4.3.1 Equipment

The equipment used was as per that in Sub-section 4.2.1.

4.3.2 Procedure

The testing procedure was again in accordance with AS1289.5.1.1 and as per Sub-section 4.2.2. However, where 25 blows were used, the number of blows was changed to match the static loads as detailed in Table 5. The test was repeated three times for each level of compactive effort (Static load equivalent).

4.4 Uniaxial Test

The procedure developed for the Uniaxial Test was determined as per Häkansson (1990) but was modified procedurally to suit a single pass of heavy machinery and to provide comparison to Suzuki et al. (2013).

4.4.1 Equipment

The equipment used during this testing is included below:

1. Standard Proctor mould B: Ø D=152mm, H=132.5mm with a baseplate and collar that can be firmly attached
2. Shop press – rated to 6,000kg
3. Load cell calibrated and rated to 10,000kg
4. Level rigid foundation for testing
5. Scales (±0.005kg)
6. Strong spatula
7. Steel straightedge
8. Ruler
9. Mixing apparatus
10. Shovel
11. Sealable containers
12. Screw driver (for removing sample from mould and for attaching the base plate to the mould)

4.4.2 Procedure

1. Soil samples were prepared according to the procedure in Section 4.1.
2. Soil was moistened to the optimum gravimetric moisture content that was determined in 4.2.2 and was allowed to cure for 20-30 minutes
3. Soil was added to the mould
4. A load plate was placed on the soil (assuming that the mass of the load plate has negligible effects of the compaction of the soil)
5. The mould and soil were placed in the shop press and the load cell was placed on top of the load plate
6. A load of 200 kPa was applied using the shop press for five minutes (some adjustment was required during the first minute of loading to ensure the correct load was maintained.
7. The deformation of the sample was then measured at four points on the surface of the sample and the average was taken (unless there was significant variation in the height)
8. The average deformation was then used to calculate the volume of the soil
9. The soil and mould was then weighed and used to calculate the dry and weight bulk densities as per steps 10 and 11 in Section 4.2.2.
10. The soil was then removed from the mould and the equipment was cleaned

11. Steps 2 through 11 were then repeated using the following loads: 400, 600, 800 and 1600 kPa as determined in chapter 3. The test was repeated three times for each compactive effort
12. The soil was then re-prepared as per 4.1

4.5 Safety

Safety was paramount in conducting the experimentation. A full copy of the USQ safety forms are included in Appendix G however the key points and safety features will be briefly discussed here.

4.5.1 General

The general safety issues that were encountered in the process of experimentation mainly pertained to air quality and physical safety issues.

Since the soils were moved in a dried condition any pouring or violent disruption to the soil resulted in clouds of dust particles that could possibly cause harm if inhaled. This was mitigated by ensuring that the work space was open and well ventilated, allowing cross breezes to disperse the particles quickly. When this was not possible the task was undertaken outdoors or with the operator wearing a dust mask.

The physical safety issues that were presented in the testing related to the movement and lifting of the heavy containers of soil and the repetitive movements required when performing the Proctor Test, particularly in the cases where >25 blows were required. Mitigation of these issues was in the form of previously received training and the use of correct technique.

4.5.2 Proctor Tests

In the Proctor Test the main hazard that was presented relates to the use of a falling hammer. This constituted a minor pinching/crushing hazard to the operator. The operator’s familiarity with the hammer and its correct operation mitigated the risk to an acceptable level. To operate the hammer as intended the user only interacts with the non-moving parts.

4.5.3 Uniaxial Tests

The Uniaxial Test presents a greater risk than the Proctor Test however the hazards are not likely to occur in such a small number of uses. This was because the hazards associated with using the equipment relate to its catastrophic failure which was unlikely to occur given that anticipated loadings were well below the safe operating limits.

If failure were to occur the operator was separated from the equipment by a physical barrier which all but completely alleviates the hazard from the user.

Chapter 5 – Results

5.1 Introduction

This section presents the major results with in-depth and integrated explanation occurring in Chapter 6 (Discussion). Results are presented on the basis of the individual measurements. This chapter will also present the *in situ* bulk density data taken in-field allowing comparisons of the laboratory results to in-field observed results from a load directly applied by a JDD7760 cotton picker. The raw data from the below tests has been included in Appendices H and I.

5.2 Proctor Test

The presentation of the results from the proctor tests will be undertaken in two parts, one investigating the standard compactive effort at multiple moisture contents as described in Section 4.2, the other describing the modified compactive efforts at an un-changing moisture content (Section 4.3).

5.2.1 Standard Compactive Effort

In undertaking the testing described in Section 4.2 the following results have been generated (Figures 19 to 23). In the generation of these results an optimum moisture content (OMC) has been selected to allow the progression of testing (manipulation to static load applicable to likely imposed agricultural traffic loading).

Sample A

The proctor testing of Sample A experienced difficulties that resulted in inconclusive results that could not be used to generate the OMC. Whilst the data presented in Table and Figure 19 below appears to show a parabolic trend the data gathered is not seen to be representative of the soil. This is because the apparatus was not able to function as intended; with each strike significant volume of sample was removed as clay stuck to the hammer. This prevented the un-obstructed fall of the hammer, reducing the energy input into the soil voiding the results shown below.

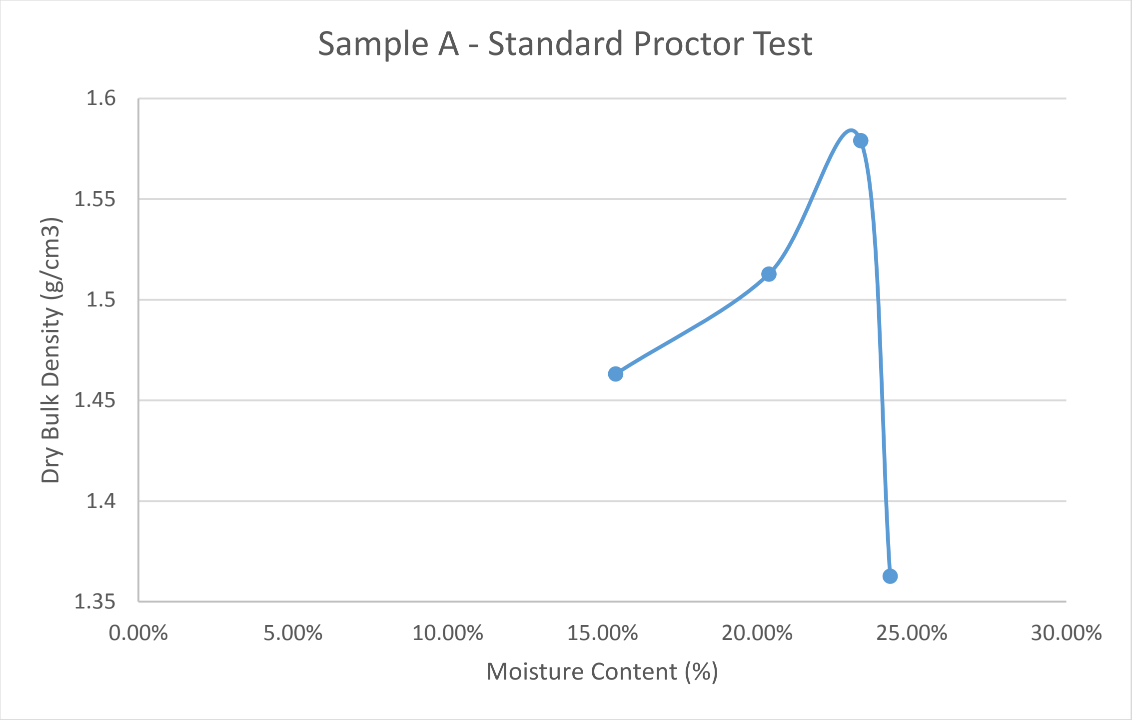


Figure 19: Proctor graph showing the change in bulk density with moisture content, note the values are seen to be an inaccurate representation of the soils behaviour

Sample B

Sample B followed the expected trend. Four moisture contents were tested as per AS1289.5.1.1 and were deemed to adequately straddle the optimum moisture content. This is shown below in Figure 20.

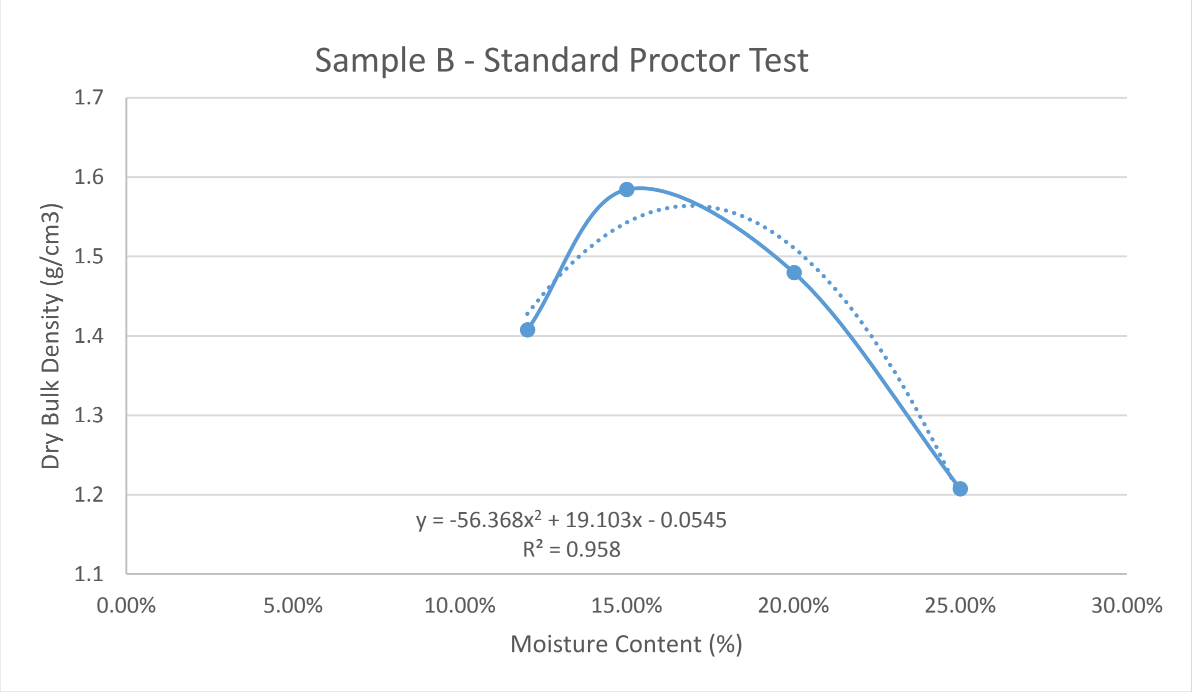


Figure 20: Proctor graph for Sample B showing a parabolic nature with an optimum moisture content of 17% and a corresponding peak bulk density of 1.56 g/cm^3

A visual examination of Figure 20 shows that the optimum moisture content exists between 15% and 20%, this however is insufficiently accurate for this project. As such a trend line was overlaid on the data, supplying a strong relationship with the data (R^2=0.958). Through derivation and manipulation of this equation the optimum moisture content can be given with confidence as 17%. The use of this equation can also allow the determination of the peak density that could be achieved at the optimum moisture content. This gives the peak bulk density of 1.56 g/cm^3.

Sample C

Testing on Sample C occurred largely without issue, however after testing four moisture contents a peak was not straddled. This resulted in the testing of a greater number of moisture contents as shown in Appendix H. As a result of this, the testing of a higher number of moisture contents gives an understanding of the increase of the moisture content over a wider range. The data resulting from the test is presented below in Figure 21.

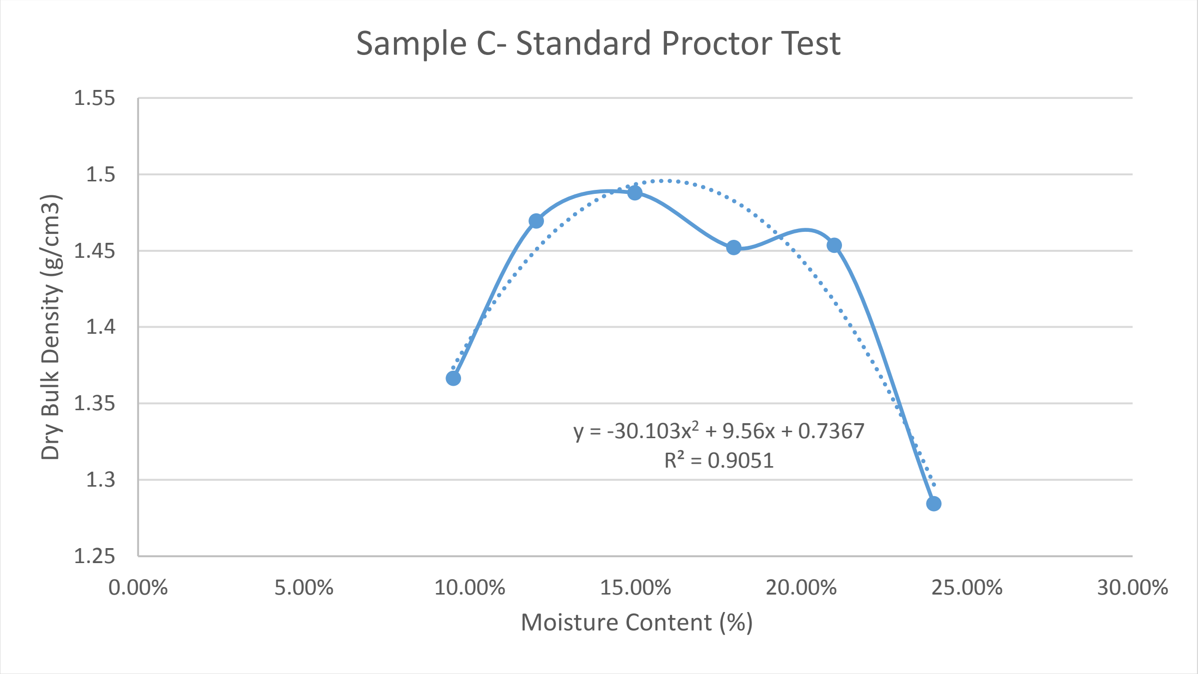


Figure 21 Proctor graph for Sample C showing a parabolic nature with an optimum moisture content of 16% and a corresponding peak bulk density of 1.5 g/cm^3

As can be seen the data generally follows a parabolic curve, described by a quadratic equation with an R^2 value of 0.9051 representing a good fit. Despite the data generally following the trend, one point at approximately 18% moisture content is lower than expected. Using the same calculative process as described for Sample B the optimum moisture content was found to be 16% and the peak bulk density was found to be approximately 1.5 g/cm^3.

Sample D

Again, during testing for Sample D the optimum moisture content was not identified after 4 iterations, as such, a greater number of tests were undertaken. This has resulted in data that follows a quadratic trend with an extremely strong R^2 value of 0.9993. The optimum moisture content was derived as 28.1% with a corresponding peak bulk density of 1.21 g/cm^3 is produced, shown below in Figure 22.

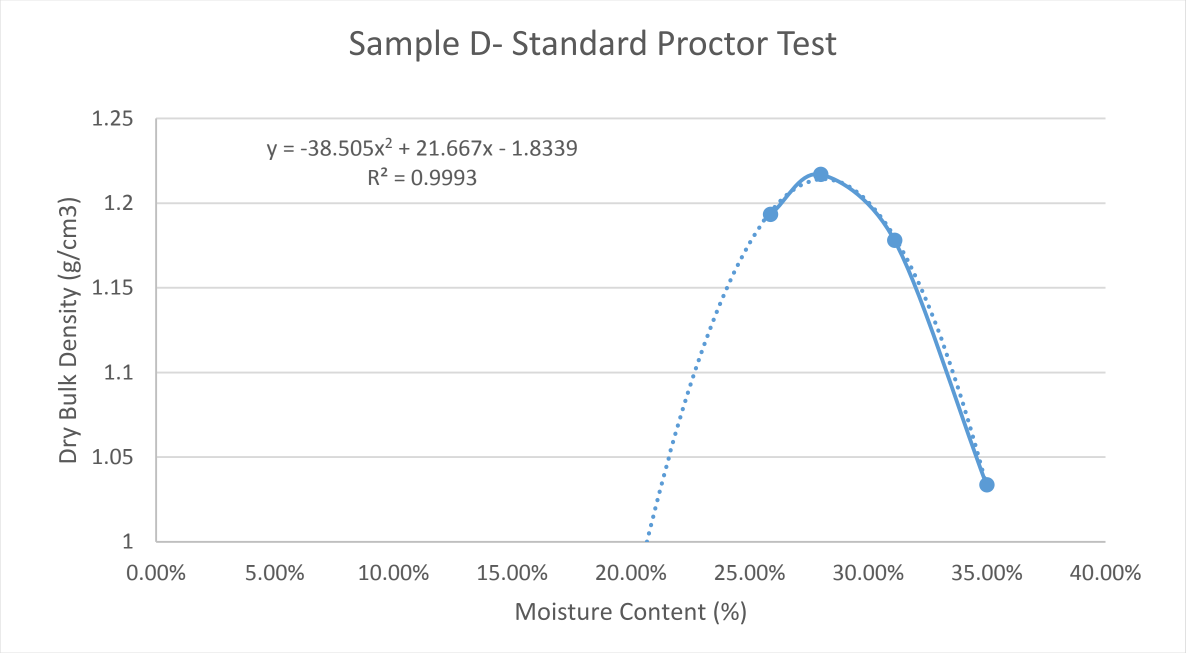


Figure 22 Proctor graph for Sample D showing a parabolic nature with an optimum moisture content of 28.1% and a corresponding peak bulk density of 1.21 g/cm^3

Sample E

Sample E suggests that the maxima has just been exceeded by the first moisture content tested, although fitting a trend line to this moves the OMC to a lower moisture content. Whilst, the quadratic equation fitted has an R^2 value of 0.9783 indicating a good fit, the OMC value for this soil should have lower confidence placed in it than for previous successful proctor tests. However, for the sake of comparing modified compression methods, the relative differences will still be applicable. For this sample the optimum moisture content was found to be 22% generating a bulk density of 1.27 g/cm^3, visualised below in Figure 23.

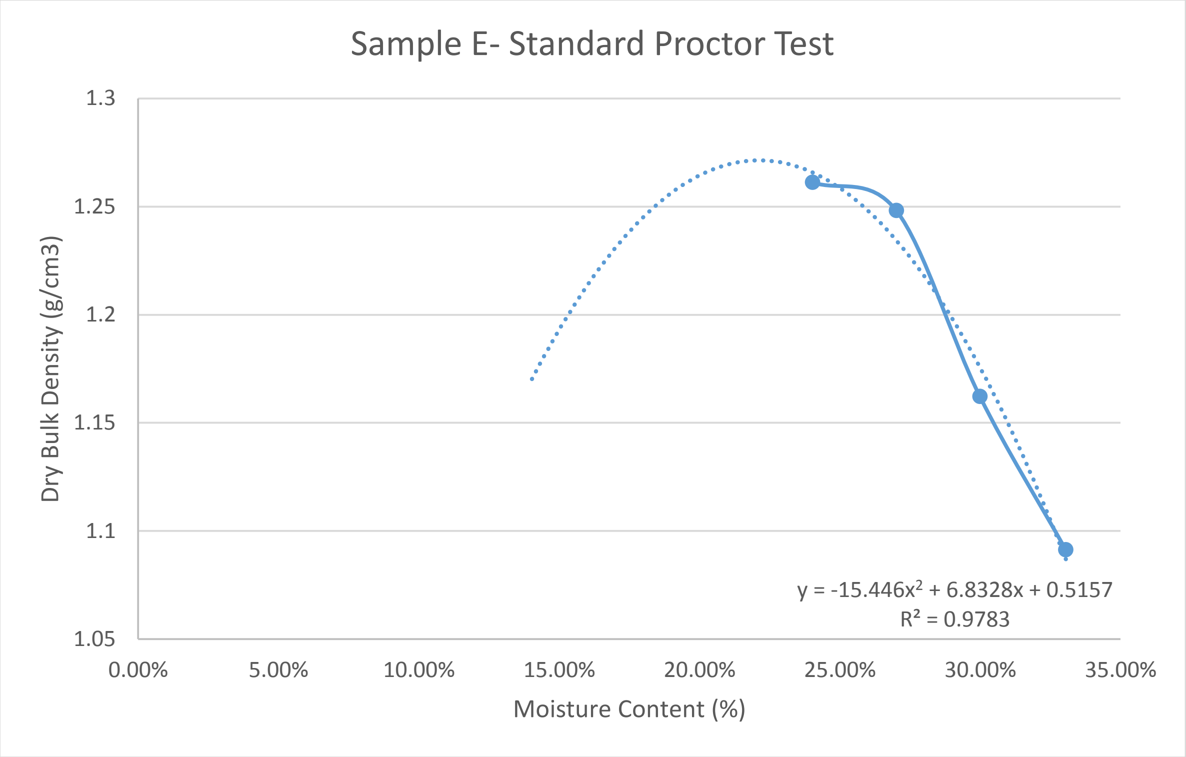


Figure 23 Proctor graph for Sample E showing a parabolic nature with an optimum moisture content of 22% and a corresponding peak bulk density of 1.27 g/cm^3

Sample F

The proctor testing of Sample F experienced abnormalities that resulted in inconclusive results. From Figure 24 the optimum moisture content might be assumed to be approximately 20%, however, similar to Sample A, testing was not possible as the apparatus no longer functioned as intended as, with each strike, a significant volume of sample was remove with the hammer. This prevented the un-obstructed fall of the hammer, reducing the energy input into the soil. This is shown below in Figure 24 where the data is exceptionally erratic. Repeated iterations of the test resulted in similarly inconclusive results across all moisture ranges. It is suggested that this soil may have OMC of ~22%, demonstrated by a strongly correlated regression, but the inconclusive nature of the results (highly variable even in repetition) suggest it would be unwise to proceed with comparison at these values.

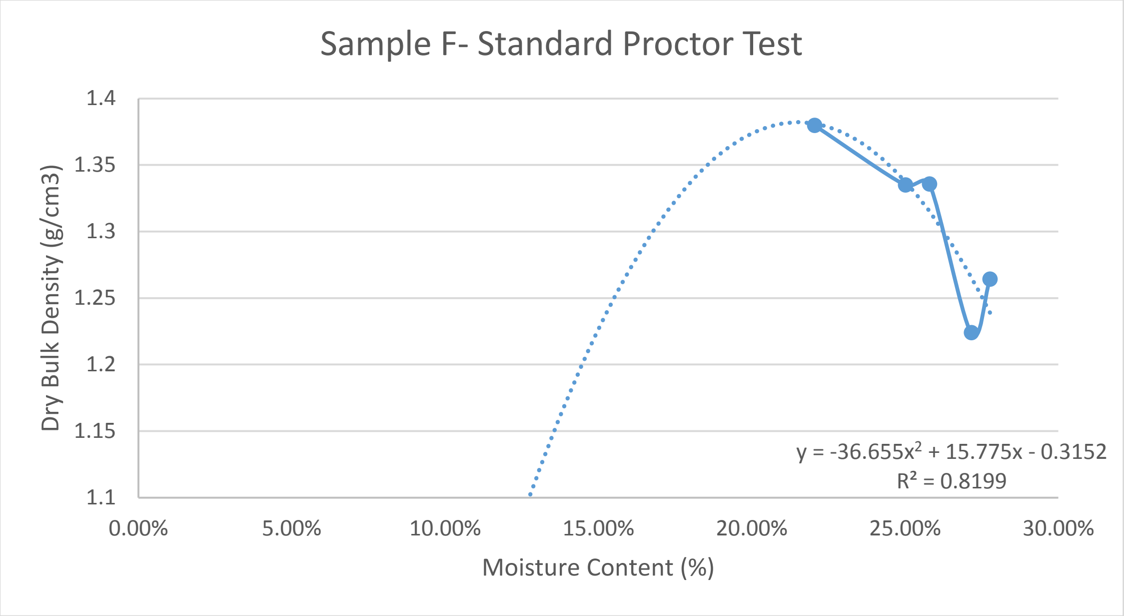


Figure 24: Proctor graph showing the change in bulk density with moisture content, note the values are seen to be an inaccurate representation of the soils behaviour

Summary

Testing for the optimum moisture content was carried out on the six soils, generating conclusive results for four samples (Sample B through Sample E). The remaining two samples (Samples A and F) experienced difficulties in testing, the full implications and reasoning for this has been discussed in Chapter 6 (Evaluation of Modified Methods). Future work would be required to determine mechanisms controlling behaviour for Samples A and F.

The four soils that generated usable results exhibited tendencies towards a parabolic trend for which an equation was generated. Resolving this equation for the optimum position allowed the determination of the optimum moisture content and peak bulk densities as summarised in Table 7 below.

Table 7: Summary of the optimum moisture contents and peak bulk densities determined for Samples A through F

Sample	*Optimum Moisture Content (%)*	*Bulk Density (g/cm3)*
A	Not Identified	Not Identified
B	17	1.56
C	16	1.5
D	28	1.21
E	22	1.27
F	Not Identified	Not Identified

5.2.2 Modified Compactive Effort

As discussed in Chapter 4 (Experimental Procedure) the use of the proctor test with a modified compactive effort was carried out. Due to an undetected calculative error in Microsoft EXCEL the moisture contents for some samples are higher than the optimum values calculated in the initial proctor test. The implications of this will be discussed in Chapter 6 (Evaluation of Modified Methods). Whilst tests were not carried out at the exact OMC, the error was consistent between tests meaning that relative comparisons are valid and thus useful in assessing the methodologies.

The modified proctor test resulted in data sets comparing an increasing compactive effort (number of blows) with dry bulk density. This includes the bulk density values gathered for 25 blows as per the standard test.

Generally speaking, the data tended to exhibit a logarithmic trend with the change in bulk density becoming smaller as the compactive effort increases. This follows a steep increase in the bulk density at the lower compaction levels.

For ease of reference, the equivalent static loading of the proctor test blows has been presented in Table 8 for reference when considering the modified proctor test results. The loading values in the below graphs (Figures 25 through 28) are listed in terms of number of blows.

Table 8: Number of blows in the Proctor Test and equivalent static loads

Number of Blows	***Equivalent Static Load (kPa)***
6	200
15	400
25	600
33	800
69	16,000

Sample B

Shown in Appendix H is the data gathered in the proctor test with modified compactive efforts when testing Sample B. This shows that generally the bulk density followed a logarithmic trend approaching a plateau towards 69 blows. This is furthered below in Figure 25 where the average bulk density at each compactive effort is shown. This figure includes a trend line of logarithmic nature with an R^2 value of 0.9234 representing a reliable fit.

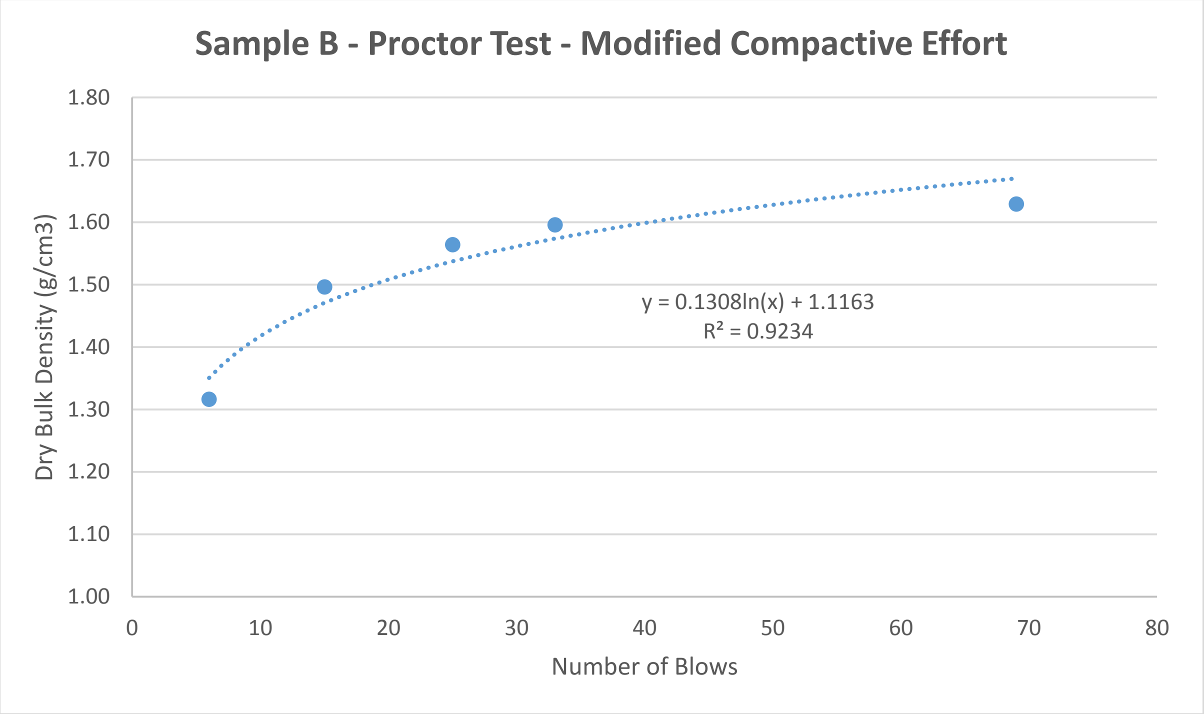


Figure 25: Proctor Test graph for Sample B showing a logarithmic relationship between the number of blows and bulk density. Displayed points are the average of values presented in Appendix H

Sample C

The data gathered from sample C again shows a logarithmic trend, with the trend line fitted to the average bulk densities showing an R^2 value of 0.8817. This sample again shows the bulk density having reduced change in bulk density between 33 and 69 blows than between the earlier loading, visible in Figure 26.

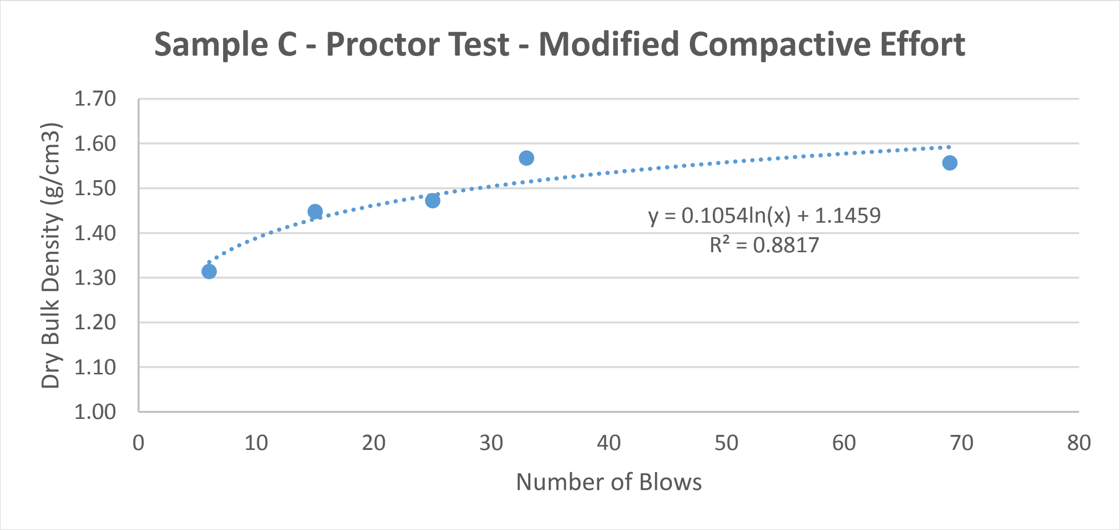


Figure 26 Proctor Test graph for Sample C showing a logarithmic relationship between the number of blows and bulk density. Displayed points are the average of values presented in Appendix H

Sample D

Sample D experienced the highest degree of variability of all the samples in this test, showing a moderate R^2 relationship of 0.467 when the average values are fitted to a logarithmic trend. This is a better fit than provided before the exclusion of outliers. The dataset is shown below in Figure 27. Given the clear trend displayed by other Samples (B, C and E), the logarithmic trend is considered reliable, but further testing would be required to confirm this.

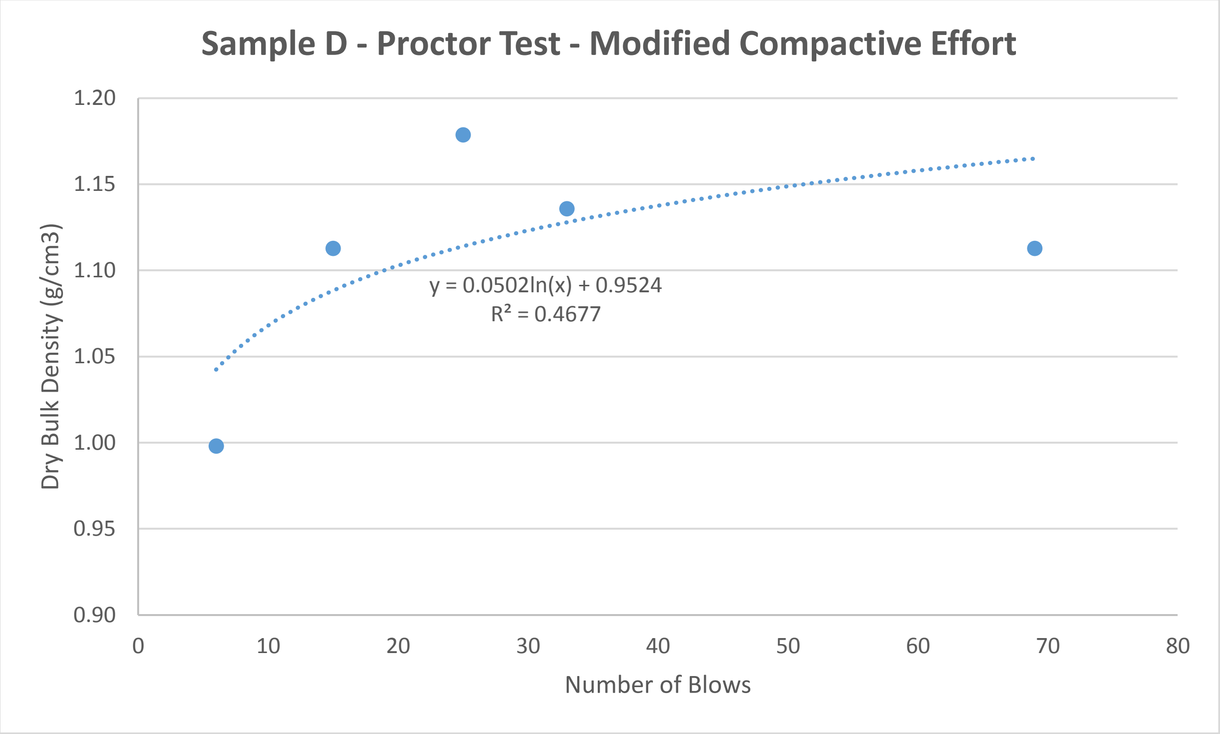


Figure 27: Proctor Test graph for Sample C showing a logarithmic relationship between the number of blows and bulk density. Displayed points are the average of values presented in Appendix H.

Sample E

Sample E exhibits the same logarithmic trend as shown for other samples with a reliable fit provided by the trend line (R^2=0.7785). This set of data, is shown below in Figure 28. It is noted that whilst the trend line provides a strong relationship, the data suggests that application of subsequent blows would result in very small bulk density increase, which suggests an asymptote occurring. Hence, the trend line may be over predicting the impact of future blows on soil density.

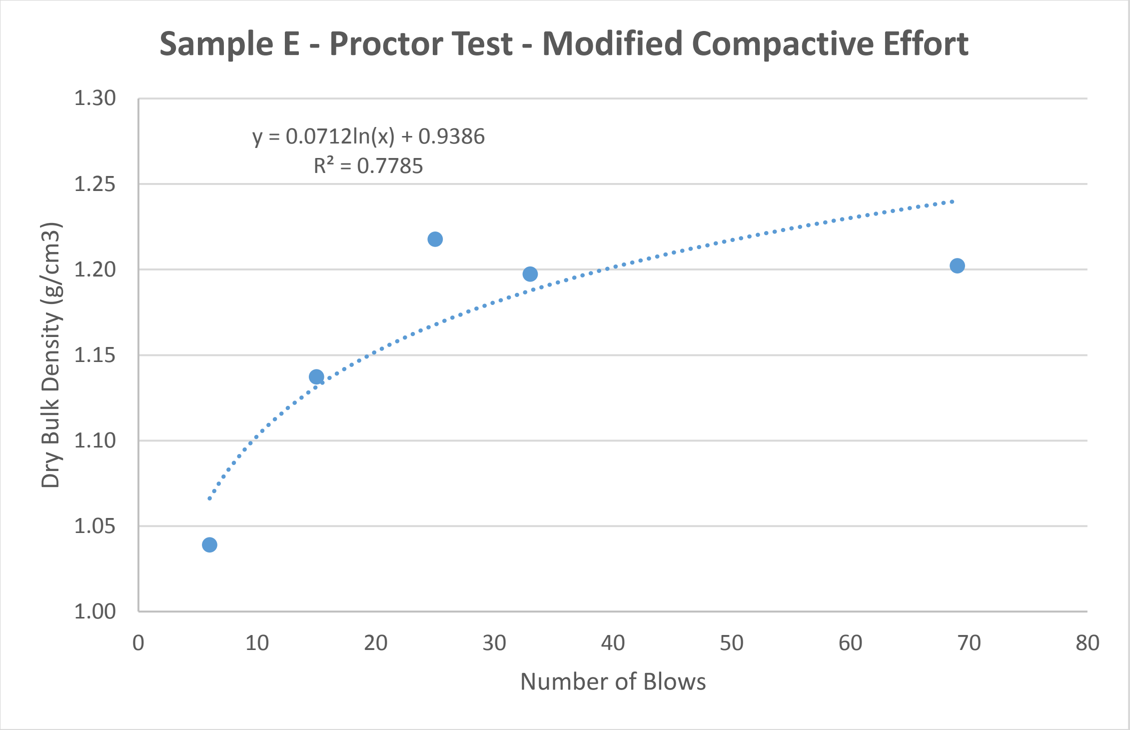


Figure 28: Proctor Test graph for Sample E showing a logarithmic relationship between the number of blows and bulk density. Displayed points are the average of values presented in Appendix H

Summary

Across all tested samples the increase in compactive effort has a logarithmic relationship with the dry bulk density achieved, with most samples exhibiting an R^2 value above 0.7 (Sample D shows a poorer fit with an R^2 value of approximately 0.4). All samples followed a trend that suggests a an asymptote density well before the specific gravity of the particles, although it is important to note that if trend lines are extrapolated forward that bulk density is allowed to exceed specific gravity, which is physically impossible. Hence, boundary conditions must exist and this needs to be considered in interpreting the results.

5.3 Uniaxial Compression Test

As described in Chapter 4 (Methodology), the uniaxial compression test was carried out at a variety of loadings, equivalent to the loading the modified proctor test was carried out at; allowing direct comparison between tests. Across all samples a logarithmic trend was generally produced. This shows that an increase in the lower loadings resulting in a large increase in bulk density relative to the gradient of the slope at higher loadings.

Sample B

The data gained through the testing of Sample B has resulted in a reliable fit between the average and the applied logarithmic trend, shown below in Figure 29. This has allowed the data (Appendix I) to produce an R^2 value of 0.9476.

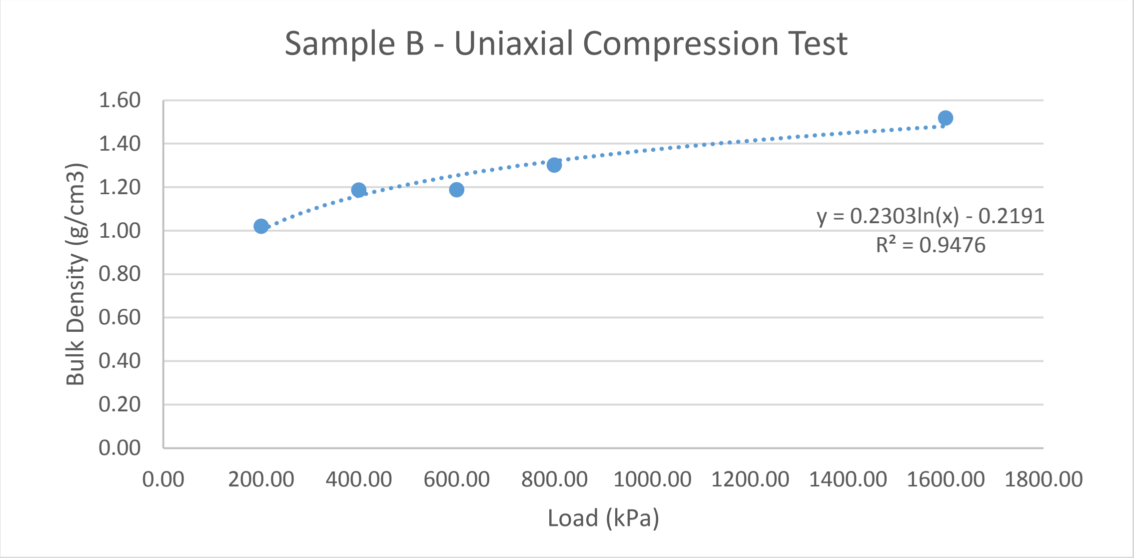


Figure 29: Plot describing the logarithmic relationship between the increasing static load in the uniaxial compression test and the bulk density of Sample B

Sample C

The trend of the averaged bulk densities shows a strong propensity towards a logarithmic trend, displaying an R^2 value of 0.9019, shown in Figure 30 below.

It is worth noting that the logarithmic trend fitted to this set of data shows the change in bulk density at higher loadings producing a relatively high gradient.

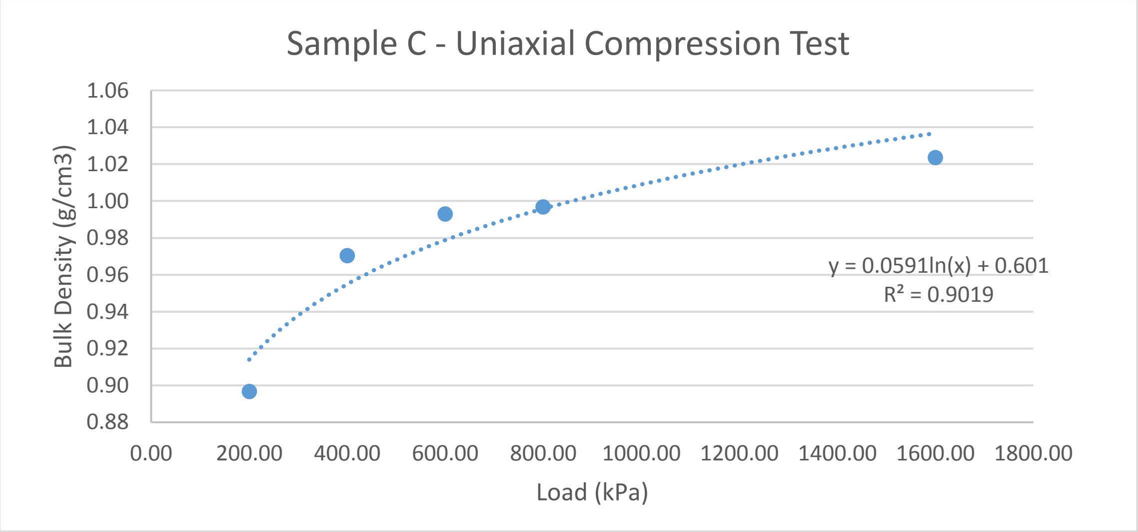


Figure 30: Plot describing the logarithmic relationship between the increasing static load in the uniaxial compression test and the bulk density of Sample C

Sample D

The results from testing Sample D are shown in Appendix I. As previously mentioned the fit applied is of logarithmic nature and in this case the trend is described by an R^2 value of 0.9964 which does suggest an extremely good fit. This can be seen in Figure 31.

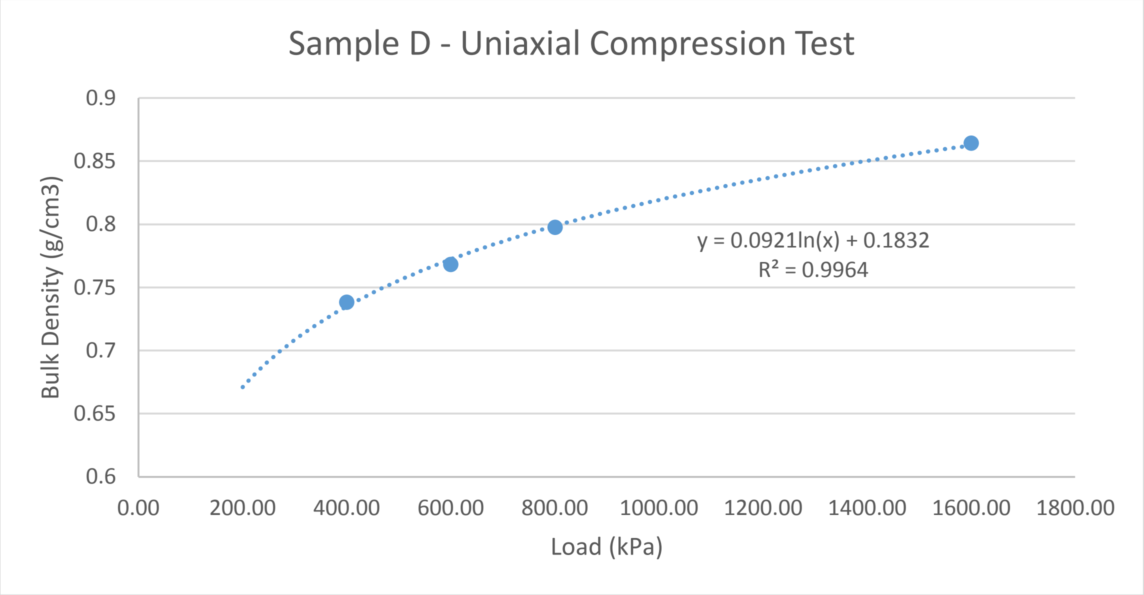


Figure 31: Plot describing the logarithmic relationship between the increasing static load in the uniaxial compression test and the bulk density of Sample D

Sample E

The data set gathered from uniaxial testing of Sample E shows greater variation, but still provides a strong fit to the logarithmic trend within R^2 value of 0.7226. The values gathered in testing are shown in Figure 32.

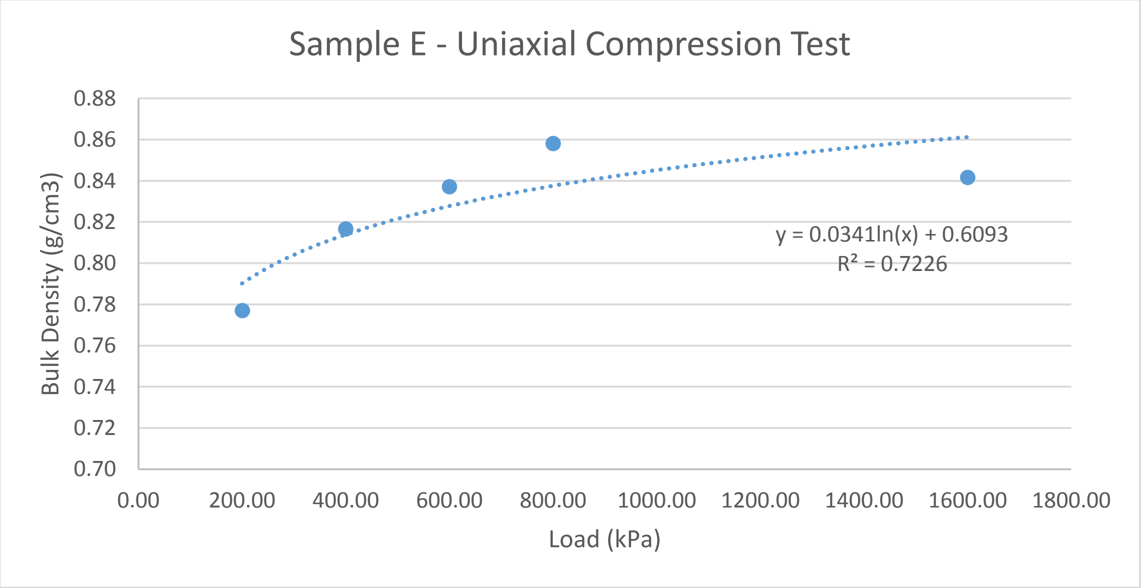


Figure 32: Plot describing the logarithmic relationship between the increasing static load in the uniaxial compression test and the bulk density of Sample E

Summary

As shown above the data produced for each sample shows a logarithmic relationship between the increasing load and bulk density. In investigating this trend functions have been fitted to the data. These functions typically show a very strong fit to the data; generally producing R^2 values greater than 0.9. Once again, boundary conditions must exist for these trends because extrapolation for higher compactive effort results in bulk densities greater than the specific gravity. Hence, this needs to be considered in results interpretation and extrapolation of the results to higher static loads.

5.4 Comparison between Tests

The trends produced by each test are similar (logarithmic with a base of *e*) and typically had a difference of between 0.25 and 0.35 g/cm3 although this tended to change between soils and between the applied loads. In all cases the proctor test generated a higher bulk density. Shown in Figure 33 the differences between the tests vary with two samples becoming more similar as the load increases and two becoming less similar. This variance is calculated by subtracting the values predicted by the trends fitted to the uniaxial test from those predicted from the Proctor Test.

In addition to this general difference between the tests the figure below also seems to indicate that there is a logarithmic or similar relationship between the variance and the increasing bulk density, although some samples produced a positive trend and some negative.

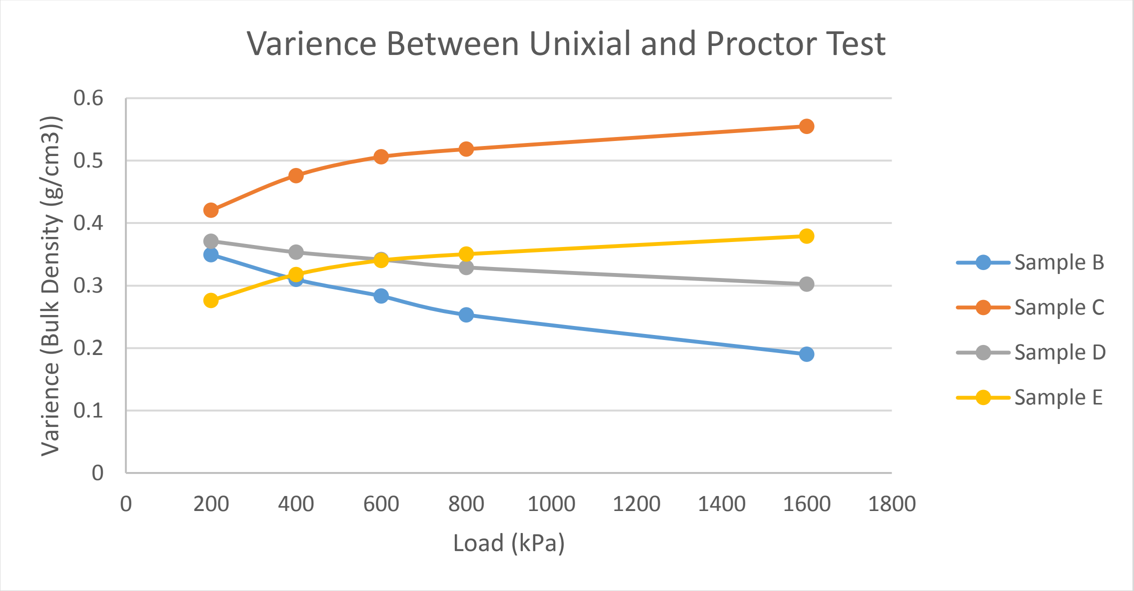


Figure 33: Plot showing the variance between the proctor test and uniaxial compression test over the loads sampled (Variance calculated by the proctor test bulk density minus the uniaxial test bulk density)

5.5 In Situ Bulk Density Data

In order to allow comparison between these laboratory tests and field results, the *in situ* bulk density data for each field will be examined. This data has been collected as part of a larger project at The University of Southern Queensland (USQ) through the National Centre for Engineering in Agriculture (NCEA) funded by the Cotton Research and Development Corporation.

Sample B

In field compaction data for Sample B was collected using soil cores to a depth of 75 cm (with samples collected every 10 cm starting from 5 cm), with multiple replications taken at each measured depth. This data was gathered under the centreline of the front wheel both before and after compaction. The gravimetric moisture content over the measured depth is shown below in Figure 34, measured on the same day as compaction occurred. This figure shows the moisture content generally decreasing with depth after a slight increase at 15 cm. This results in a moisture content of approximately 30% at 5cm, increasing to approximately 31% before decreasing to 21 % at 75 cm.

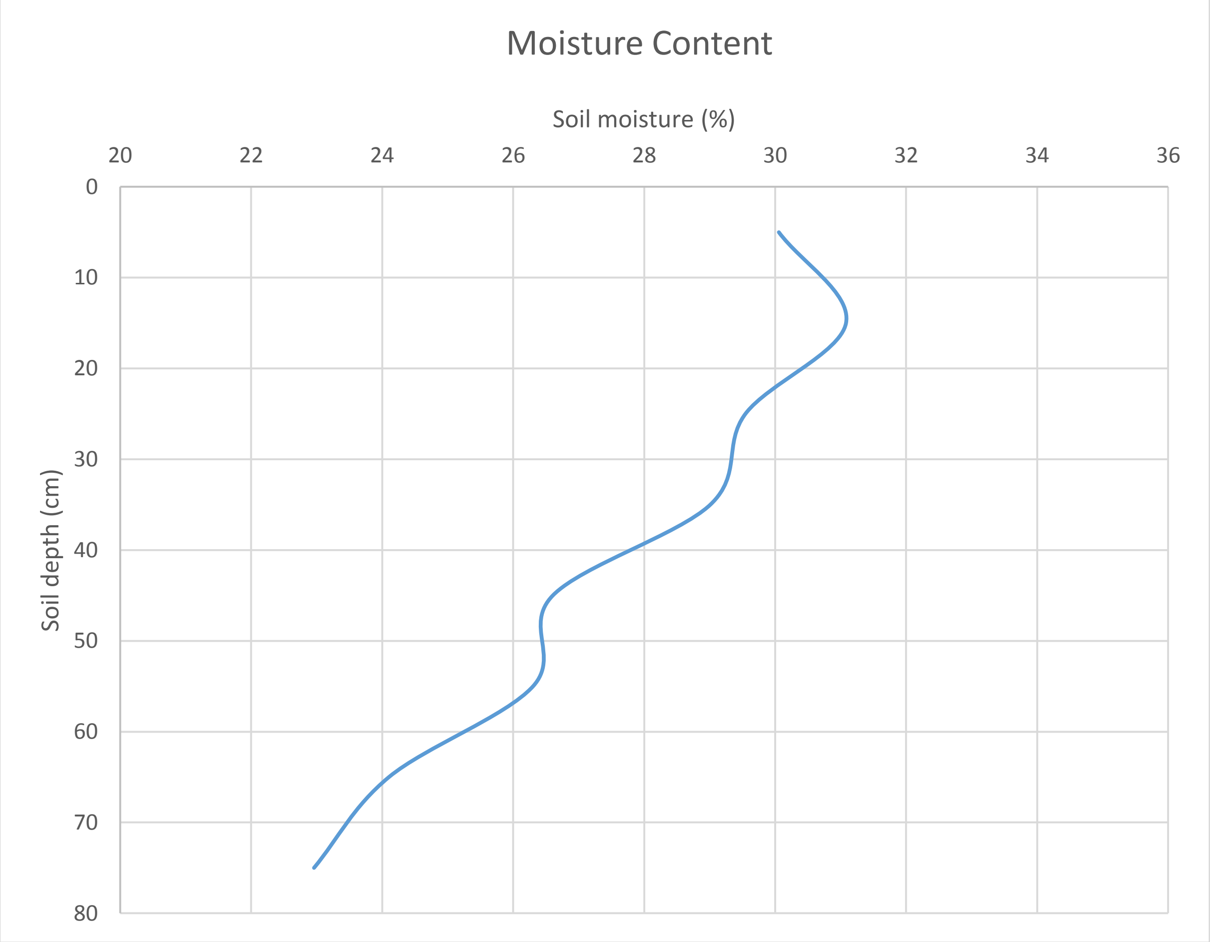


Figure 34: Distribution of in situ *gravimetric moisture content with depth in field for Sample C*

Figure 35 shows the distribution of bulk density with depth for both before and after compaction occurs. In showing this the trends can be extracted with the aim of furthering future comparisons. Before compaction by the JD7760 the bulk density linearly increases from the 5 cm value of approximately 1.27 g/cm^3 to 1.74 g/cm^3. This trend is interrupted at a depth of 25 cm where the bulk density decreases to 35 cm depth, shown in the jump on Figure 35.

After compaction occurs the bulk density is shown to have a surface bulk density of 1.46 g/cm^3 and linearly increases at a faster rate (than the before compaction bulk density) to a depth of 55 cm where the bulk density roughly matches the before compaction data.

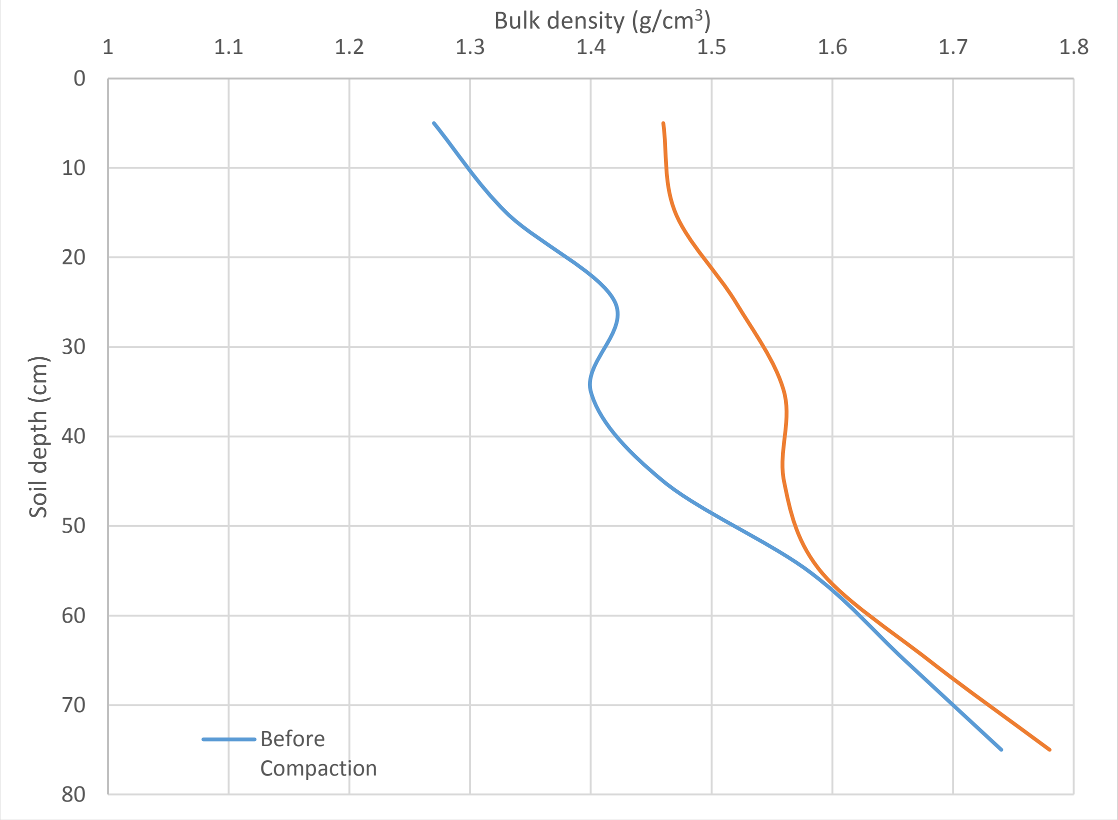


Figure 35: In field bulk density before and after compaction for Sample B (Before shown in blue and after shown in Red)

Sample C

Similar to Sample B the *in situ* bulk density data was collected at depth intervals of 5 cm to a depth of 75 cm with multiple replications taken to ensure accuracy. This occurred under the centreline of the front wheel before and after compaction. In addition to this the moisture content was measured over the same depth, shown in Figure 36.

Figure 36 shows a peak of approximately 23% in the moisture content at a depth of 15 cm before which the moisture content increases from about 19%. Following this the moisture content is shown to decrease to roughly 18%.

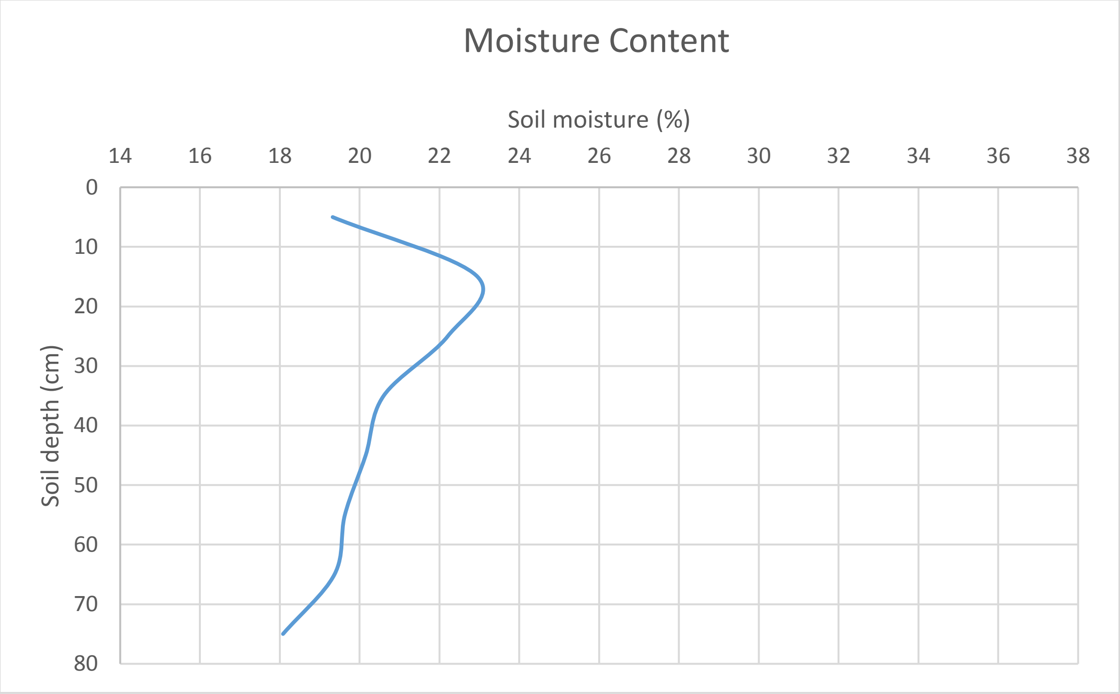


Figure 36: Distribution of in situ *gravimetric moisture content with depth for Sample C*

Figure 37 below shows the bulk density both before and after compaction by the JD7760 in a standard configuration. The bulk density data shown below shows an almost sinusoidal trend after an initial increase between 5 and 15 cm (1.22 g/cm^3 to 1.47 g/cm^3). This sinusoidal trend shows the bulk density oscillating between a peak of 1.56 g/cm^3 at a depth of 25 cm and 1.43 g/cm^3 at 55 cm.

After compaction occurred the bulk density linearly decreases from a value of 1.35 g/cm^3 at the surface to a depth of 30cm. At this point the gradient of the linear relationship steepens to concluding at a value of 1.6 g/cm^3 at a depth of 75 cm.

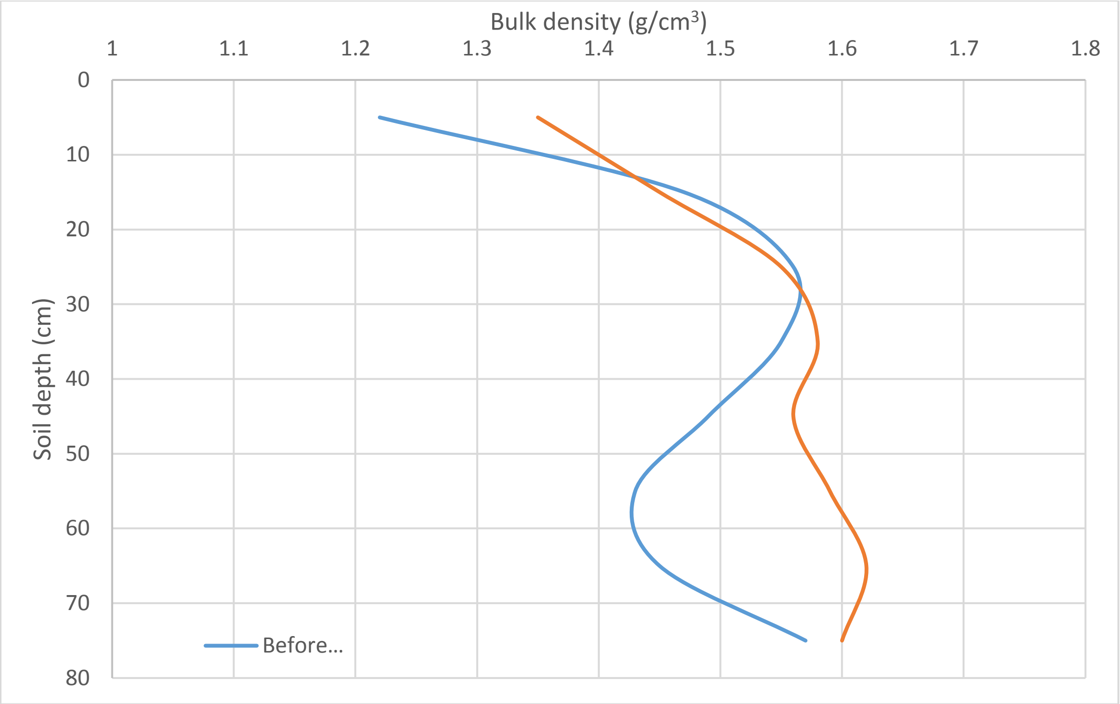


Figure 37: In field bulk density before and after compaction for Sample C (Before shown in blue and after shown in Red)

Sample D

In order to determine in in field bulk density for Sample D, soil cores were taken from the field at a gravimetric moisture content between 50 and 55% (Figure 38) over a depth of 80 cm (note: cores were not taken from the first 10 cm of soil as is standard practice). Multiple replications were gathered for each depth. The cores were gathered for both the centreline of the front inner wheel for trafficking of a JD7760. The inner wheel track experienced compaction by both the front and rear wheel as the machine moved over the soil.

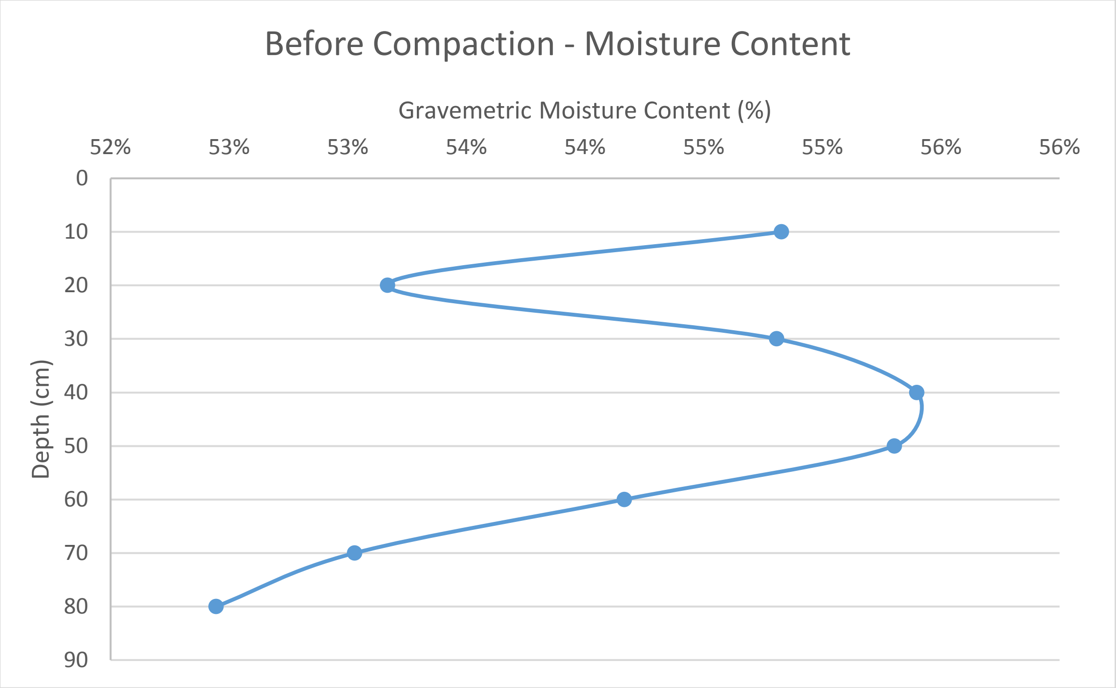


Figure 38: Distribution of in situ *moisture content with depth for Sample D*

This data is collected for the soil both before and after compaction and is reproduced from works by Roberton (unpublished).

In Figure 39 below the bulk density and its variance with depth before and after trafficking is depicted. The before compaction data shows a linear trend over the entire depth profile, close to the surface the bulk density is approximately 0.955 g/cm^3 increasing to approximately 1.04 g/cm^3 in the aforementioned linear fashion.

After trafficking the data gathered for each wheel shows a similar linear trend, visualised below in Figure 39. After tracking the data appears to follow a generally linear trend decreasing from 1.05 – 1.06 g/cm^3 to 1.12 – 1.14 g/cm^3. This trend has a high degree of variability as depth increases typically operating over a range of 0.03 g/cm^3.

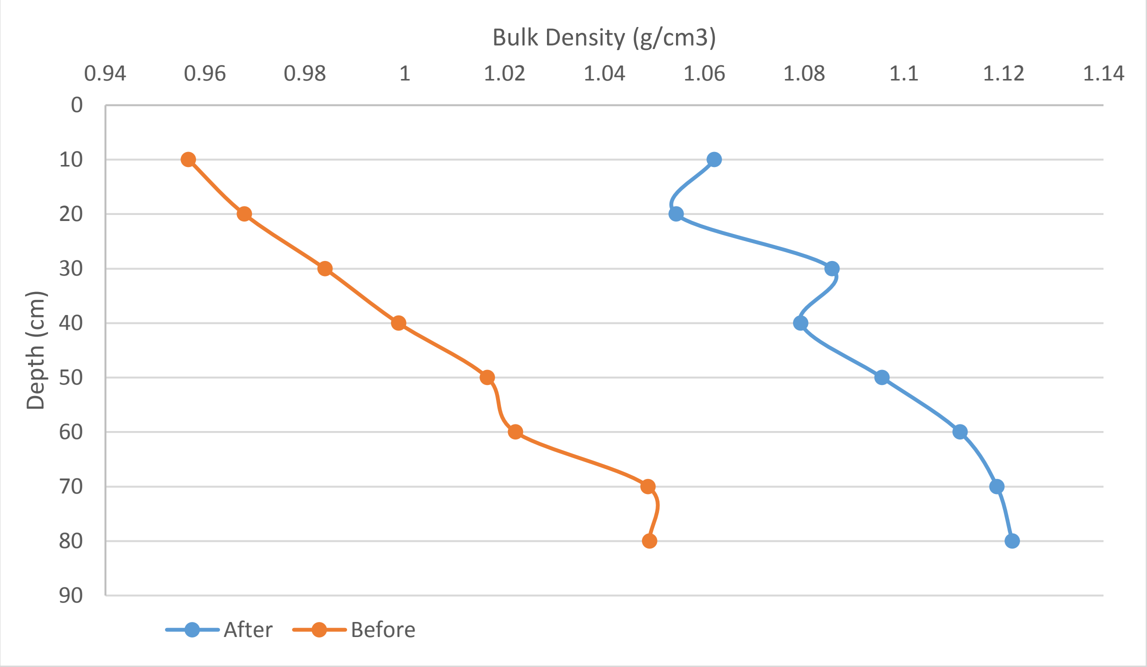


Figure 39: In situ *distribution of bulk density with depth for Sample D. Before compaction is shown in blue and after compaction is shown in red*

Sample E

The infield bulk density data gathered from this site has received compaction by a JD7760 picking six one meter rows. The tires were inflated at 100% of the recommended pressure and the machine was set up in a dual wheel configuration. The cores were taken from both before and after trafficking. The data captured and represented as un-trafficked or control data has been free from traffic for 15 years and thus represents a true control. These samples have been taken over a depth of 80 cm (again, excluding the top 10 cm) with 3 replicates taken for each depth.

As seen below in Figure 40 the bulk density before trafficking typically started at quite a low bulk density, 0.95 g/cm^3, from this point there is a steep linear increase to approximately 1.15 g/cm^3 over approximately 7.5-10cm depth. Following this the average trend increases linearly from 1.15 g/cm^3 to 1.225 g/cm^3 over the remaining 70 - 72.5 cm.

Figure 40 below also shows the dry bulk density values after compaction by the JD7760. The compaction generated at in the inner wheel shows a parabolic relationship between depth and compaction. The compaction starts at a peak of approximately 1.24 g/cm^3 the bulk density then steadily decreases with depth to a minimal value of 1.18 cm/g^3 at 45 cm. From here the bulk density is shown to increase back to the 1.24 g/cm^3 which is similar to the control value of 1.23 g/cm^3.

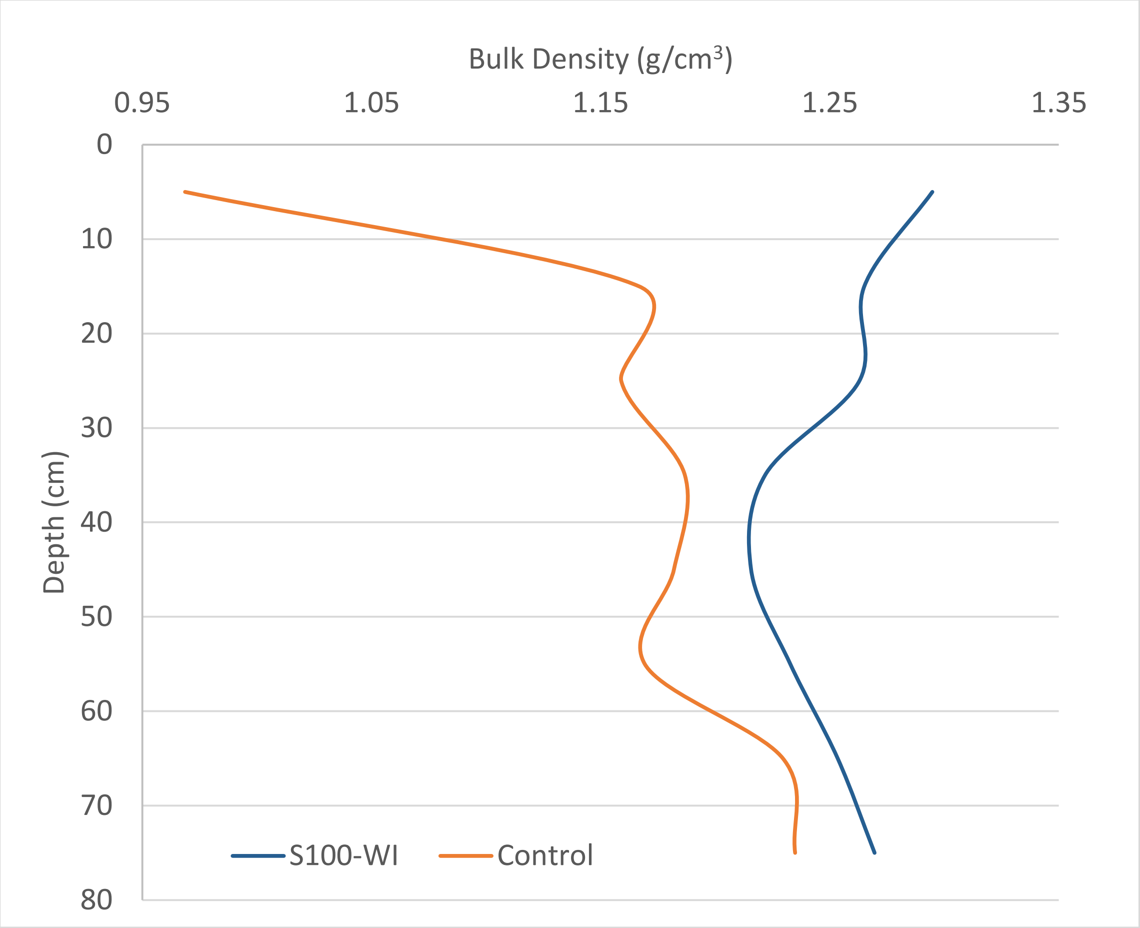


Figure 40: In situ distribution of bulk density with depth for Sample E. Before compaction is shown in light blue and after compaction is shown in dark blue

Summary

As seen across the majority of the soil samples the bulk density is typically at a maximum at the maximum depth, this maximum varies according to the sample. The moisture contents were shown to vary greatly and will need to be accounted for in the coming chapters.

Chapter 6 – Evaluation of Modified Methods

6.1 Introduction

With the results presented in Chapter 5 it becomes possible to undertake a discussion examining the highlighted trends and providing reasoning and support for these occurrences. Once this has occurred a number of comparisons must be made in order to facilitate the selection of an applicable load and test. This will directly satisfy the aim stated as: experimental validation and evaluation of modified methods.

In order to achieve this the discussion has been split into five sections discussing: the results from the Proctor test, the results from the uniaxial test, general comparisons between the two tests, a brief comparison between the in-situ data and the SoilFlex output, comparisons between the testing methods and the in-field data, and, finally, selection of an applicable loading and test.

6.2 Procter Test

6.2.1 Standard Compactive Effort

Most samples tested produced the results that would be expected from the proctor test, this has allowed the selection of optimum moisture contents and maximum bulk density, determined by the parabolic trend present. Such a result is demonstrated numerous times within the literature (Hamza & Anderson 2005, Rollins, Jorgensen & Ross 1998, DAS 2010) as well as with in the relevant Australian Standards (AS1289.5.1.1).

As seen in Table 7 Samples A and F did not produce conclusive results. As earlier suggested the soil was surpassing its plastic limit and was approaching the liquid limit, meaning that the apparatus no longer functioned as intended and with each strike significant volume of sample was remove with the hammer. This prevented the un-obstructed fall of the hammer, reducing the energy input into the soil. Whilst temporal constraints limited further investigation of these effects, it is suggested that a lower range of moisture content would result in a successful outcome. However, such a range would not be considered typical of Vertosols soil, which the tests were carried out for (Kirby 1991).

As has been discussed within the literature review (University of Southern Queensland 2013) the liquid limit is defined as the moisture content where soil cohesive forces are completely overcome and the material behaves as a fluid, usually associated with the pores being completely saturated–super-saturated; this decreases compaction generated by a given force, as well as this the load bearing capacity is severely reduced. When proctor testing was carried out on Samples A and F the hammer was seen to cause significant depressions in the soil surface whereby soil was vertically displaced around the hammer, suggesting that the soil was not capable of supporting the applied load due to the liquid limit being overcome or proximal. This occurred on close to every blow and resulted in the clay displaced by the hammer raising up around the edges, coming into contact with the sides of the proctor testing rig. Hence, this further worsened the variability of the compactive effort.

Because Samples A and F were excluded from testing it is necessary to investigate the effects that this may have on the conclusions that are drawn as a result of further testing. Since whole samples have been excluded as opposed to replacing the test with a different method of determining the optimum moisture content the only significant impact on the testing on a whole will be a reduced confidence in any conclusions drawn (as opposed to inconsistencies in testing methods causing incomparable results). This will only be a minor loss of confidence as the remaining four samples exhibit strong results over many replicates allowing substantial weight to be given to any conclusions drawn.

This prompts important questions as to the effect of changing the moisture content over a larger range of moisture contents. The parabolic function suggests that as the moisture content increases or decreases outside of the tested range the bulk density reduces to zero (which would suggest a void) and this is obviously not the case. When utilising the data extending over a larger set of moisture contents the results indicate a plateau either side of the maximum dry bulk density, which is commensurate with boundary conditions occurring. These conditions represent the lowest density achievable which is defined by void space and gravity, and the specific gravity of the soil constituents (sand, silt and clay) which is the theoretical density occurring where no void space exists and the total volume is solid.

6.2.2 Modified Compactive Effort

Testing Samples B through E using the proposed modification of the proctor test for estimated compactive effort (static load equivalent) provided results with good confidence and a general logarithmic trend approaching an asymptote well before specific gravity. However, trend lines reach asymptotic behaviour well beyond the specific gravity (constant values for all soil constituents), which is impossible. Further testing would be required to define the bulk density upper limit, but the observed trend is applicable for the observed data representing equivalent static loads well beyond that expected to ever occur in agricultural fields.

It was noted that at 33 and 69 blows (800 and 1600 kPa estimated equivalent; Raghavan & Ohu 1985) the sample began to deform and surround the hammer i.e. hammer strikes one side of the sample caused localised deformation resulting in the other side of the sample to rise, however this was only by a few millimetres. This was only experienced at higher loadings and did not present during lower compactive efforts. Such behaviour should be expected as soils approach the maximum compactive density. However, also affecting this phenomena is the relationship between OMC and load. soils exhibiting this have been shown by Rollins et al. (1998), using silty (70%) soil samples, showed that such behaviour can occur because as the compressive load increases (using the proctor test) the optimum moisture content becomes slightly smaller, with each increase in load, and the peak bulk density rises for each small reduction in OMC (Hillel 2004). This suggests that the optimum moisture content selected from a lower compactive effort would be greater than the actual optimum moisture content. From the literature review it is known that moisture contents above the optimum moisture content are not as suited to bearing loads, especially as the liquid limit becomes proximal (Hillel 2004). When this is considered it is suggested that this lack of bearing capacity causes also contribute to the small deformation of the sample.

When examining the results it can be seen that the bulk densities predicted by the model for higher compactive efforts are generally greater than those experienced in the testing. Examining the results presented by Rollins et al. (1998) (page 702, Figure 3) it can be seen that an increase in compactive effort can result in an equal bulk density to that of a lower compactive effort, suggesting that a more applicable trend would be one where the bulk density approaches an asymptote. This is not totally provided by the logarithmic trend but its use over the range tested is applicable in this situation. The use of the logarithmic trend is supported by Blotz et al (1998) stating similar rationale with clayey soils.

Another reason the increase in bulk density becomes limited at higher blow counts is due to the nature of the testing method. The use of impact loads and the differences between this and static loading have been discussed in the literature review, however the repetitive application of a small load must be considered. Using the standard proctor test it is known that each blow has an impact loading of 22.37 kPa (equivalent to an 88.8 kPa static load).

Once the soil has reached a certain level of compaction it is plausible that a single impact of the hammer may not be capable of inducing compaction, thus increasing the number of blows would not necessarily result in an increase in bulk density past a certain bulk density. This is seen to add weight to the use of a logarithmic trend that is fitted to the data; showing the change in bulk density decreasing as the load increases.

The expected discrepancy described above between applied force and the compactive effort has fuelled the decision to relate the compaction in the proctor tests to the number of blows as it is more correct than relating it to a net compactive effort, although the two are linearly related at lower efforts.

6.3 Uniaxial Compression Test

The uniaxial compression test was carried out as per the procedure set out in Chapter 4 (Experimental Procedure) and generally the results showed a logarithmic trend with some degree of variability between replications.

The reasoning behind the logarithmic trend is mostly the same as for the Proctor Testing in regards to moisture content although the uniaxial test is not limited by the stepped loadings provided by the proctor hammer.

As discussed earlier the optimum moisture content decreases as the load on the soil increases. In the testing that this procedure is based on, Häkansson (1990) uses a drained cylinder loaded for 2–4 days. After this time period it was found that the optimum moisture content was reached as a by-product of the draining caused by compaction. Within this project a drained mould covered with filter paper was used for a loading period of 5 minutes. Whilst some drainage was experienced during the loading the loading time was not sufficient to induce enough drainage to reach an optimum moisture content, this suggests that the same logarithmic style trend is applicable in this case as discussed when considering the proctor test. However, it is also noted that Suzuki et al (2013) demonstrated that static loading for short periods (i.e. 5 min) produced densities comparable to those produced over the 2–4 days. Hence, it may be that whilst the true OMC for the compactive effort applied is unknown, the trend in density should not be expected to change significantly, even if load was supplied to its corresponding true bulk density. On the other hand, a conceptual diagram of a family of proctor curves for increasing load (Hillel 2004, p251) shows that OMC can have a drastic effect on the maximum dry density depending on the load. Whilst this appears in direct contradiction to Suzuki et al. (2013), and the results presented here, the shift of OMC and subsequent magnitude of change in the maximum dry density is a function of the applied load. Thus, in order to satisfy both observed conditions of Hillel (2004) and Suzuki et al. (2013) it is suggested the sensitivity to increasing load is not great within the tested range of the current project.

In testing it was found that the test featured a relatively high degree of variability between replications. This was found to be due to the design of the testing apparatus: Because a shop press was used to apply the load, the pressure within the press had to be constantly altered to match the required loading. This was due to the deformation of the soil: i.e. the as the soil was compacted the load had to be increased to make up for the corresponding decrease in load. Because of this the pressure on the soil tended to fluctuate ± 27 kPa although in some tests (typically in the 1600 kPa test) the load was seen to vary + 53.3 kPa, -27 kPa. This variation is relatively low when compared to the total loading however it still had effect on the results.

Variability also entered into the testing procedure for the higher loads where some of the sample was forced up between the load plate and the edge of the mould. This gap was very small and the occurrence was minimal, but small changes in volume can effect density substantially. Further variability might have been incurred by the pre-compression of the soil by the load plate and cell (approximately 2 kg each) although this is likely to have had close to nil effect on the end result given the loads applied were significantly greater than this.

6.4 General Comments on the Tests

General comparisons between the two tests can also be made relating to areas such as reproducibility, ease of testing, time and labour requirements as well as changes to the tests that may improve the results or the tests relative usefulness.

As mentioned previously the tests for most soils occurred at a moisture content that was higher than that provided by the initial uniaxial compression test. As suggested in the literature review this will have a considerable effect on the bulk densities reached by the tests; typically resulting in values lower than might be expected.

The results gathered indicate that the reproducibility was typically better in the proctor test when comparing the variance between the replicates at each applied load (Tables 13 – 26 (Appendix H and I)). However, it should be stated that the reproducibility of the uniaxial test could be vastly increased with some minor modification of the procedure.

This modification would see the loading apparatus become computer operated such that the compressive load is held at relatively constant loading, in addition to this a rubber mat should be included between the soil and the load plate as suggested by Häkansson (1990). This mat should be same diameter as the mould or slightly larger such that the sample is prevented from passing up the side of the load plate. Obtaining a mat for these data with the required accuracy was outside the logistical constraints of the project.

The time and labour requirements between each test are largely the same with approximately 10 min required of one operator to collect one data point (this varies for the proctor test; obviously performing 69 blows a layer takes far more time than 6 blows per layer). This excludes the preparatory work that must occur first, which includes drying and moistening the soil to the required moisture contents, but these should be considered as approximately equal for both tests. Whilst the proctor test does have the same operating requirements in terms of labour and time it is a much more “hands on” test. The operator is required to input the compaction to the soil manually using the hammer. This is not a large issue when a small number of impacts are used however as the blows increase to 69 the operator is required to perform a very repetitive task. This leaves some scope for possible repetitive strain injuries as discussed in the safety section. In addition to this the hands on nature of the work leaves a larger scope for operator error (for example: miscounting number of blows), assuming the load produced by the uniaxial compression test can be stabilised.

6.5 Compare In-Situ Data with SoilFlex

Comparisons between the data gathered in-situ and the trends produced by SoilFlex in Chapter 3 can be used to help validate the SoilFlex output produced.

SoilFlex typically produced a logarithmic distribution of stress with depth generating a change in bulk density that generated a logarithmic change in bulk density with depth. Chapter 5 (Results) shows the infield bulk density changing logarithmically with depth. However this trend is mirrored to that predicted by SoilFlex, with the surface of the sample typically producing a lower bulk density that increases with depth. Conversely, the bulk density predicted by SoilFlex shows a peak bulk density at the surface of the soil, decreasing with depth. This is primarily due to two factors: 1) a shallow soil surface that is highly friable (loose) due to the self-mulching nature of Vertosols (McGarry 1996) and 2) increased strength of surface aggregates due to being much drier (evaporation even at low temperatures due to atmospheric boundary) meaning much lower moisture content than the soil bulk. In modelling with SoilFlex there factors must be ignored as the model can only use one assumed moisture content and initial bulk density throughout the soil profile (Keller et al. 2007).

When the bulk density is considered with a comparison between before and after compaction values a logarithmic trend is produced that follows the SoilFlex output closely. This suggests that the SoilFlex model supports the infield bulk densities, confirming their relevance.

6.6 Comparisons between Tests and In-Situ Bulk Density

Using the information presented above it becomes possible to compare the tested and infield bulk densities on a case by case basis with the aim of selecting a reference loading and test. This will be achieved through the use of tables 9 through 12, where the compaction experienced in field is compared to the bulk density achieved using each method in the laboratory. The degree of compaction is then calculated using the ration of in field bulk density to the reference bulk density as presented in the section 2.7. The infield data shown are the average bulk densities produced by the maximum load cases in the sampled depth (20cm).

Sample B

Table 9 below shows that the degree of compactness is most applicable using the proctor test with a compactive effort of between 800 and 1600 kPa. The moisture content at which the *in-situ* data was collected is significantly higher than the calculated optimum, this suggests that it is likely that higher bulk densities could conceivably be achieved under the right conditions.

Table 9: Comparison of laboratory bulk density with in situ *bulk density for Sample B*

		In Situ			Laboratory		
Load in Test (kPa)	**Test Method**	**Depth (cm)**	**Bulk Density (g/cm^3)**	**Moisture Content**	**Optimum Moisture Content**	**Bulk Density (g/cm^3)**	**Degree of Compactness**
200	**Proctor**	Ave 5 -15	1.47	31%	17%	1.35	109%
	Uniaxial					1.00	147%
400	**Proctor**	Ave 5 -15	1.47	31%	17%	1.47	100%
	Uniaxial					1.16	126%
600	**Proctor**	Ave 5 -15	1.47	31%	17%	1.53	96%
	Uniaxial					1.25	117%
800	**Proctor**	Ave 5 -15	1.47	31%	17%	1.57	93%
	Uniaxial					1.32	111%
1600	**Proctor**	Ave 5 -15	1.47	31%	17%	1.67	88%
	Uniaxial					1.48	99%

Sample C

The comparison of data for Sample C is provided below in Table 10 and show both the infield and laboratory moisture contents to be above the optimum of 16%, suggesting that there is scope for both to generate higher bulk densities.

Table 10: Comparison of laboratory bulk density with in situ *bulk density for Sample C*

		In Situ			Laboratory		
Load in Test (kPa)	**Test Method**	**Depth (cm)**	**Bulk Density (g/cm^3)**	**Moisture Content**	**Tested Moisture Content**	**Bulk Density (g/cm^3)**	**Degree of Compactness**
200	**Proctor**	Ave 5 -15	1.40	21%	19%	1.34	104%
	Uniaxial					0.93	151%
400	**Proctor**	Ave 5 -15	1.40	21%	19%	1.44	98%
	Uniaxial					0.97	145%
600	**Proctor**	Ave 5 -15	1.40	21%	19%	1.49	94%
	Uniaxial					0.99	142%
800	**Proctor**	Ave 5 -15	1.40	21%	19%	1.52	92%
	Uniaxial					1.00	139%
1600	**Proctor**	Ave 5 -15	1.40	21%	19%	1.59	88%
	Uniaxial					1.04	134%

Sample D

The values presented for Sample D below in Table 11 show the in situ moisture content to be significantly higher than the optimum moisture content of 28%, suggesting that a significant increase in bulk density could be expected at optimum conditions. The effect of this will be somewhat limited by the tested moisture content being 3% higher than the optimum.

Table 11: Comparison of laboratory bulk density with in situ *bulk density for Sample D*

		In Situ			**Laboratory**		
Load in Test (kPa)	**Test Method**	**Depth (cm)**	**Bulk Density (g/cm^3)**	**Moisture Content**	**Tested Moisture Content**	**Bulk Density (g/cm^3)**	**Degree of Compactness**
200	**Proctor**	Ave 10 -20	1.07	53%	31%	1.05	101%
	Uniaxial					0.74	144%
400	**Proctor**	Ave 10 -20	1.07	53%	31%	1.09	98%
	Uniaxial					0.77	138%
600	**Proctor**	Ave 10 -20	1.07	53%	31%	1.11	96%
	Uniaxial					0.79	135%
800	**Proctor**	Ave 10 -20	1.07	53%	31%	1.12	95%
	Uniaxial					0.80	132%
1600	**Proctor**	Ave 10 -20	1.07	53%	31%	1.14	93%
	Uniaxial					0.84	127%

Sample E

The data presented in Table 12 below shows both the tested and in field moisture contents being equal at 28%, again above the peak of 22%, suggesting the bulk densities listed could become higher in more optimum conditions.

Table 12: Comparison of laboratory bulk density with in situ *bulk density for Sample E*

		In Situ			Laboratory		
Load in Test (kPa)	**Test Method**	**Depth (cm)**	**Bulk Density (g/cm^3)**	**Moisture Content**	**Tested Moisture Content**	**Bulk Density (g/cm^3)**	**Degree of Compactness**
200	**Proctor**	Ave 5 -15	1.28	28%	28%	1.06	121%
	Uniaxial					0.79	162%
400	**Proctor**	Ave 5 -15	1.28	28%	28%	1.12	114%
	Uniaxial					0.81	157%
600	**Proctor**	Ave 5 -15	1.28	28%	28%	1.16	110%
	Uniaxial					0.83	155%
800	**Proctor**	Ave 5 -15	1.28	28%	28%	1.18	108%
	Uniaxial					0.84	153%
1600	**Proctor**	Ave 5 -15	1.28	28%	28%	1.23	104%
	Uniaxial					0.86	149%

6.7 Selection of Applicable Loading/Test

The Tables presented in Tables 9 to 12 above show that the most applicable reference loading occurs at the 800 or 1600 kPa values through the use of the proctor test. As noted from the graphs presented in Chapter 5 above the logarithmic trend suggests that causing a meaningful increase in bulk density from 800 to 1600 kPa and beyond would require the input of a significantly greater load. As such the selection of 1600 kPa using the proctor test is logical as it presents the degree of compactness in the most consistently usable fashion (>90%). The use of 800 kPa is possible and has a lessor labour requirement however produces a higher degree of compaction (between 2 and 5%). This is a small change in percentage, however given that higher bulk densities are feasible (as suggested by the moisture content) it is suggested that the 1600 kPa proctor test will be more applicable.

Chapter 7 – Conclusions and Future Work

The aim of this project was to investigate the applicability of the standard load used in the Uniaxial Compression Test to describe the impact of large harvesting machines, such as the John Deere 7760 cotton picker (JD7760), on the soil. In doing so a number of aims were identified: review of best practice for measurement of agricultural compaction, analysis of selected methods and modification of these to suit and assess increased weight of agricultural machinery and experimental validation and evaluation of modified methods which have been achieved.

The literature review has identified that the Uniaxial Compression Test with a load of 200 kPa has been used in the pass to generate a reference maximum bulk density. This test has been used as the Proctor Test was seen to generate a load greater than that typically experienced under farm machinery.

However, due to a vast increase in the size and weight of farming machinery it is not uncommon to find soils that have experienced a loading of as much as 600 kPa (JD7760). This has been confirmed through the use of the SoilFlex model. In doing so; outputs have been generated to describe the idealised distribution of both the bulk density and stress with depth as a result of the JD7760 contact pressure. This has shown a stress distribution of 200 – 600 kPa over a depth of 1m.

This has confirmed the need to either redefine the load used in the Uniaxial Compression Test or revert to the Proctor Test such that the reference compaction generated is representative of that experienced in the field. To achieve this, these testes have been conducted on four Australian Vertosol soils utilising loads of 200, 400, 600, 800 and 1600 kPa. Initial testing was conducted on six soils with inconclusive results produced for the first and last. These two soils should be re-tested to further validate the results.

Testing found that across all samples and testing the bulk density was related to the increasing load with a logarithmic trend, this, coupled with the concept of a theoretical no air voids maximum bulk density suggests that the logarithmic trend would continue to increase until reaching an asymptote.

These values were then compared to the *in-situ* bulk densities with consideration made to the moisture content of the soils at the time of testing. This comparison led to the selection of 1600 kPa as the most applicable, shown in Tables 9 - 12.

The percentages shown in these tables are higher than would be expected due to a calculative error inherent in testing causing the moisture content in testing to be higher than the optimum for most samples, reducing the achievable bulk density for a given load. As such further testing is required to confirm the data.

Despite this the recommendation of the 1600 kPa proctor test can occur as it produces data showing the bulk densities that would be most usable in reality. In its selection the proctor test was compared to the uniaxial test in terms of time, labour requirements and repeatability. Typically, the proctor test was found to be more reproducible than the uniaxial test. The repeatability of the uniaxial test could be increased through the mechanised stabilisation of the applied load. Whilst both test took a similar time to complete it was found that the uniaxial test was a less labour intensive and had less scope for operator error, this is as a result of the repetitive loading technique used in the proctor test.

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Appendices

Appendix A: Project Specification

University of Southern Queensland

FACULTY OF HEALTH, ENGINEERING AND SCIENCES

ENG4111 and ENG4112 Research Project

Project Specification

FOR: **Ronald James WILSON**

TOPIC: REDEFINING STANDARD COMPACTION TEST TO BETTER DESCRIBE THE USAGE OF COTTON PICKING MACHINES ON AUSTRALIAN VERTOSOL SOILS

SUPERVISOR: Dr John Bennett, NCEA

SPONSERSHIP: National Centre for Engineering in Agriculture (NCEA)

PROJECT AIM: Redefine the standard load used in the uniaxial compression test such that the resultant compaction is representative of that experienced under industry standard cotton harvesting machines

PROGRAMME:

1. Literature review
2. Gather un trafficked soil samples from sites around South East Queensland
3. Test samples using both the Proctor Test and the modified uniaxial compression test
4. Repeat uniaxial compression test varying the applied load
5. Compare results with those generated in related research project for
6. validation of most accurate applied load
7. Submit an academic research dissertation on the research

____________________ (Student) Dated: / /2015

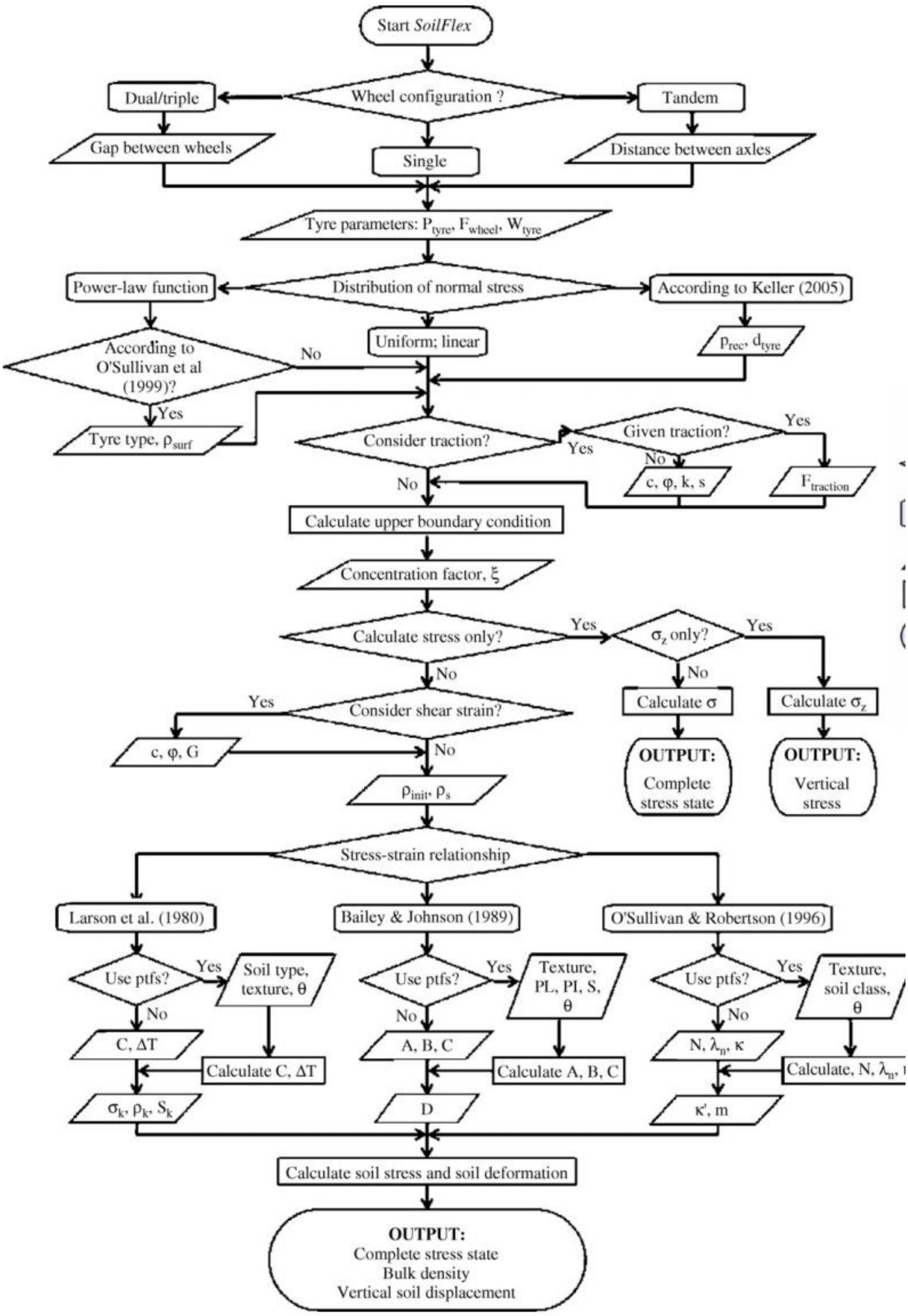
____________________ (Supervisor) Dated: / /2015

Examiner/Co-Examiner ________________________

AGREED:

Appendix B: SoilFlex Flow Chart

Reproduced from Keller et. al. (2007) pp. 395



Appendix C: SoilFlex Contact Stress Distribution Options

Reproduced from Keller et. al. (2007) pp. 396

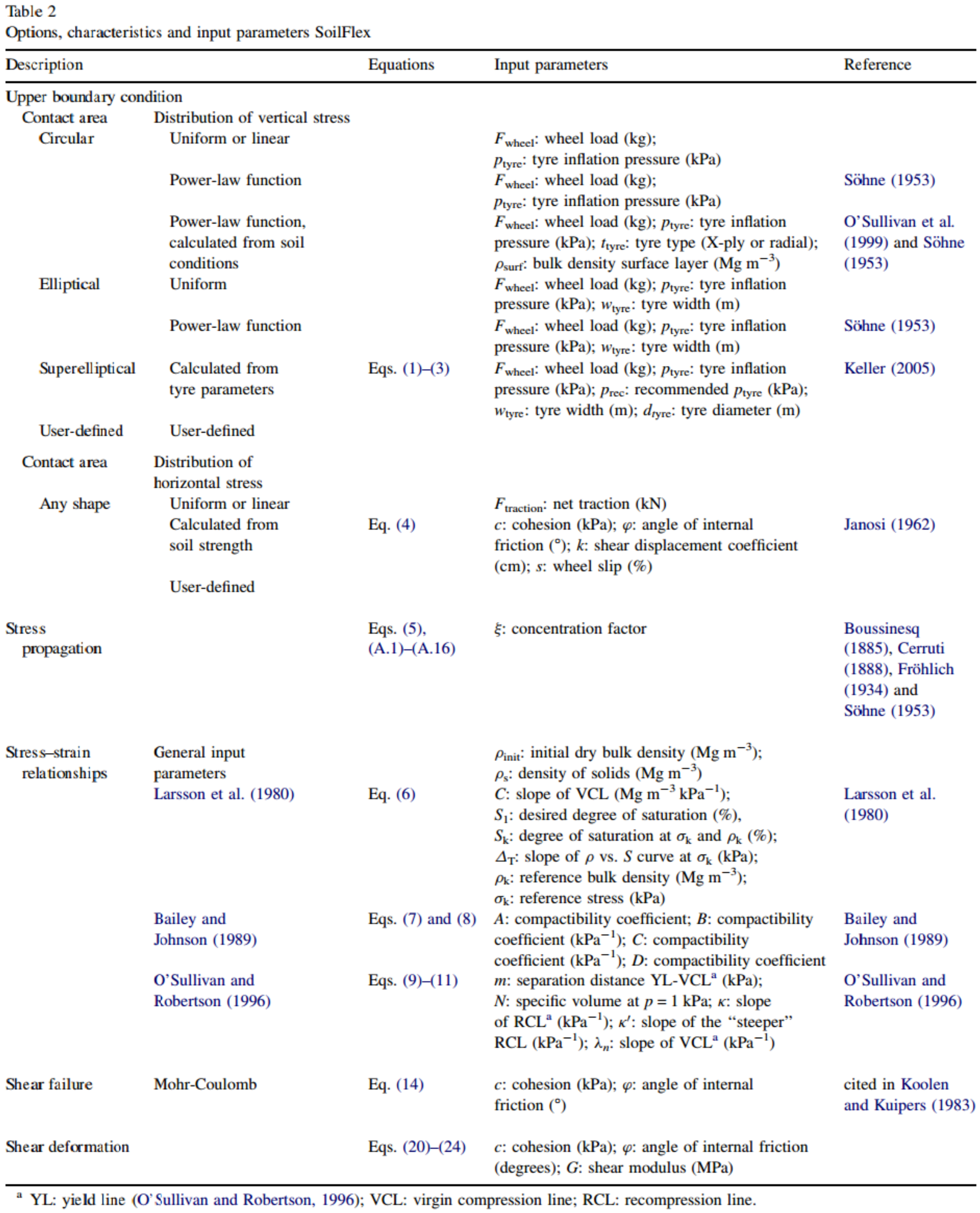


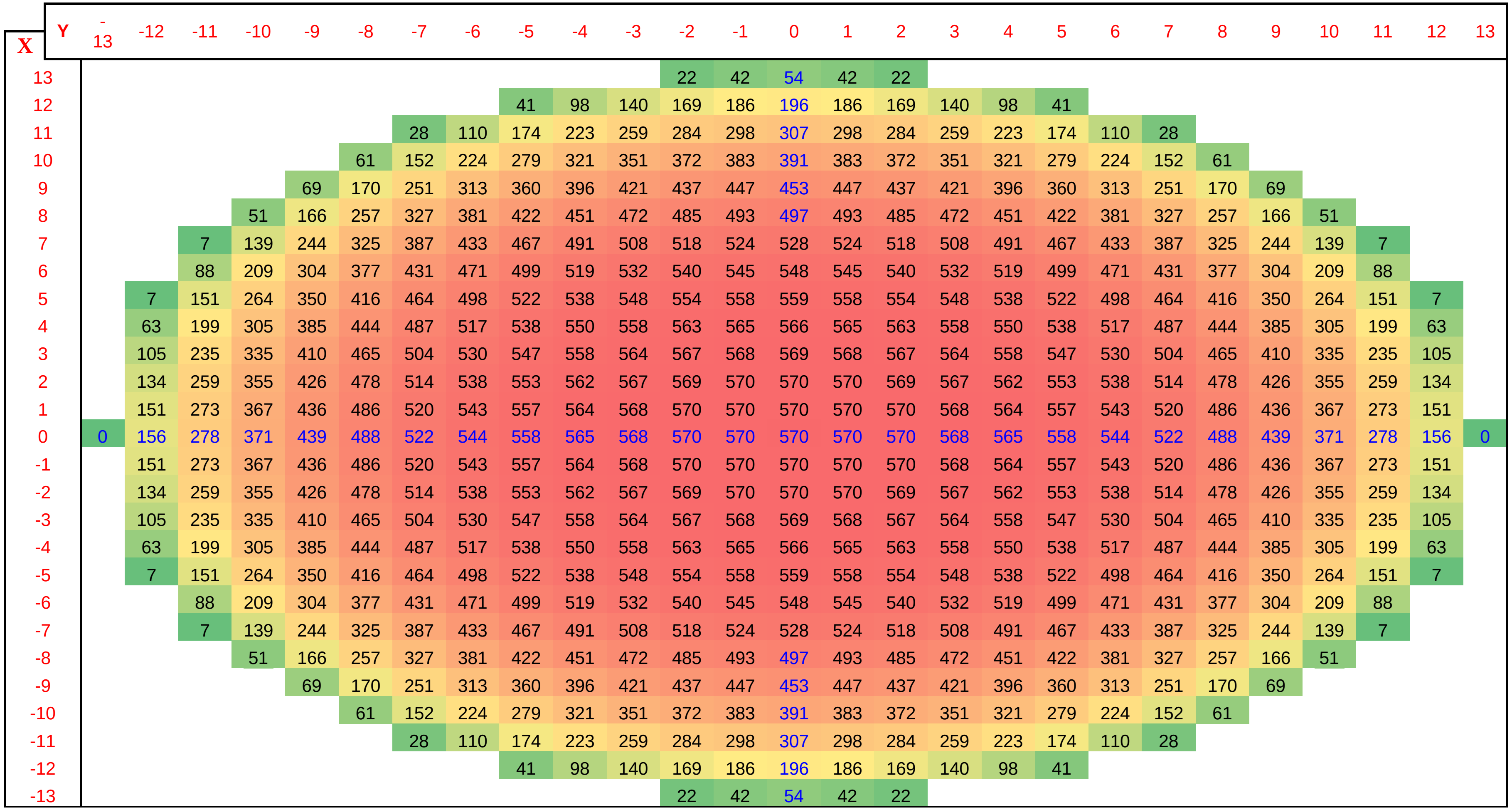
Table 2
Options, characteristics and input parameters SoilFlex

Description		Equations	Input parameters	Reference
Upper boundary condition				
Contact area	Distribution of vertical stress			
Circular	Uniform or linear		F_{wheel}: wheel load (kg); p_{tyre}: tyre inflation pressure (kPa)	
	Power-law function		F_{wheel}: wheel load (kg); p_{tyre}: tyre inflation pressure (kPa)	Söhne (1953)
	Power-law function, calculated from soil conditions		F_{wheel}: wheel load (kg); p_{tyre}: tyre inflation pressure (kPa); t_{tyre}: tyre type (X-ply or radial); ρ_{surf}: bulk density surface layer (Mg m^{-3})	O'Sullivan et al. (1999) and Söhne (1953)
Elliptical	Uniform		F_{wheel}: wheel load (kg); p_{tyre}: tyre inflation pressure (kPa); w_{tyre}: tyre width (m)	
	Power-law function		F_{wheel}: wheel load (kg); p_{tyre}: tyre inflation pressure (kPa); w_{tyre}: tyre width (m)	Söhne (1953)
Superelliptical	Calculated from tyre parameters	Eqs. (1)–(3)	F_{wheel}: wheel load (kg); p_{tyre}: tyre inflation pressure (kPa); p_{rec}: recommended p_{tyre} (kPa); w_{tyre}: tyre width (m); d_{tyre}: tyre diameter (m)	Keller (2005)
User-defined	User-defined			
Contact area	Distribution of horizontal stress			
Any shape	Uniform or linear		F_{traction}: net traction (kN)	
	Calculated from soil strength	Eq. (4)	c: cohesion (kPa); φ: angle of internal friction (°); k: shear displacement coefficient (cm); s: wheel slip (%)	Janosi (1962)
	User-defined			
Stress propagation		Eqs. (5), (A.1)–(A.16)	ξ: concentration factor	Boussinesq (1885), Cerruti (1888), Fröhlich (1934) and Söhne (1953)
Stress–strain relationships	General input parameters		ρ_{init}: initial dry bulk density (Mg m^{-3}); ρ_s: density of solids (Mg m^{-3})	
	Larsson et al. (1980)	Eq. (6)	C: slope of VCL (Mg m^{-3} kPa^{-1}); S_1: desired degree of saturation (%), S_k: degree of saturation at σ_k and ρ_k (%); Δ_T: slope of ρ vs. S curve at σ_k (kPa); ρ_k: reference bulk density (Mg m^{-3}); σ_k: reference stress (kPa)	Larsson et al. (1980)
	Bailey and Johnson (1989)	Eqs. (7) and (8)	A: compactibility coefficient; B: compactibility coefficient (kPa^{-1}); C: compactibility coefficient (kPa^{-1}); D: compactibility coefficient	Bailey and Johnson (1989)
	O'Sullivan and Robertson (1996)	Eqs. (9)–(11)	m: separation distance YL-VCL[a] (kPa); N: specific volume at $p = 1$ kPa; κ: slope of RCL[a] (kPa^{-1}); κ': slope of the "steeper" RCL (kPa^{-1}); λ_n: slope of VCL[a] (kPa^{-1})	O'Sullivan and Robertson (1996)
Shear failure	Mohr-Coulomb	Eq. (14)	c: cohesion (kPa); φ: angle of internal friction (°)	cited in Koolen and Kuipers (1983)
Shear deformation		Eqs. (20)–(24)	c: cohesion (kPa); φ: angle of internal friction (degrees); G: shear modulus (MPa)	

[a] YL: yield line (O'Sullivan and Robertson, 1996); VCL: virgin compression line; RCL: recompression line.

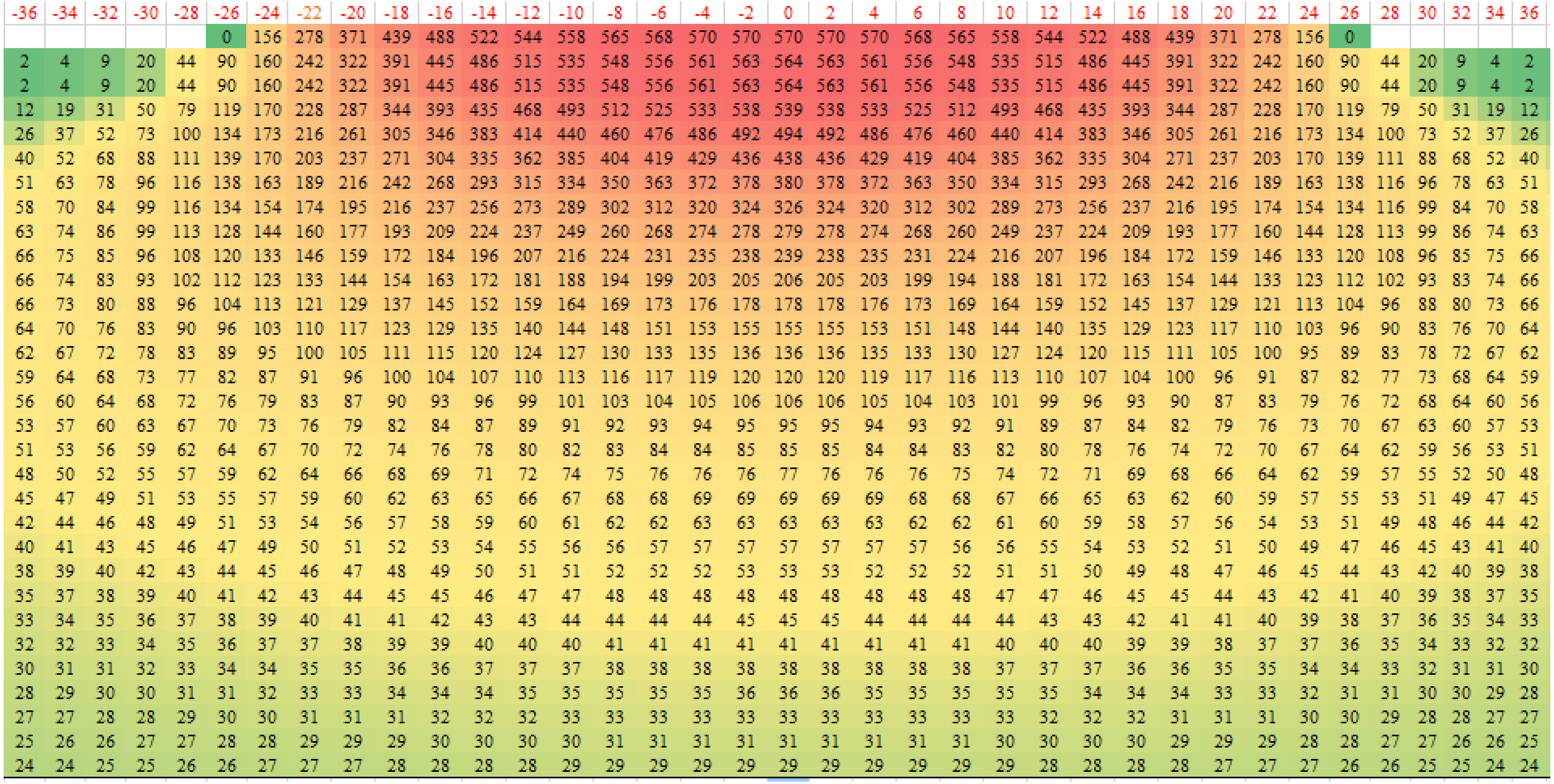
Appendix D: SoilFlex Output

Rear Wheel: Contact Stress



X \ Y	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13
13												22	42	54	42	22											
12									41	98	140	169	186	196	186	169	140	98	41								
11							28	110	174	223	259	284	298	307	298	284	259	223	174	110	28						
10						61	152	224	279	321	351	372	383	391	383	372	351	321	279	224	152	61					
9					69	170	251	313	360	396	421	437	447	453	447	437	421	396	360	313	251	170	69				
8				51	166	257	327	381	422	451	472	485	493	497	493	485	472	451	422	381	327	257	166	51			
7			7	139	244	325	387	433	467	491	508	518	524	528	524	518	508	491	467	433	387	325	244	139	7		
6			88	209	304	377	431	471	499	519	532	540	545	548	545	540	532	519	499	471	431	377	304	209	88		
5		7	151	264	350	416	464	498	522	538	548	554	558	559	558	554	548	538	522	498	464	416	350	264	151	7	
4		63	199	305	385	444	487	517	538	550	558	563	565	566	565	563	558	550	538	517	487	444	385	305	199	63	
3		105	235	335	410	465	504	530	547	558	564	567	568	569	568	567	564	558	547	530	504	465	410	335	235	105	
2		134	259	355	426	478	514	538	553	562	567	569	570	570	570	569	567	562	553	538	514	478	426	355	259	134	
1		151	273	367	436	486	520	543	557	564	568	570	570	570	570	570	568	564	557	543	520	486	436	367	273	151	
0	0	156	278	371	439	488	522	544	558	565	568	570	570	570	570	570	568	565	558	544	522	488	439	371	278	156	0
-1		151	273	367	436	486	520	543	557	564	568	570	570	570	570	570	568	564	557	543	520	486	436	367	273	151	
-2		134	259	355	426	478	514	538	553	562	567	569	570	570	570	569	567	562	553	538	514	478	426	355	259	134	
-3		105	235	335	410	465	504	530	547	558	564	567	568	569	568	567	564	558	547	530	504	465	410	335	235	105	
-4		63	199	305	385	444	487	517	538	550	558	563	565	566	565	563	558	550	538	517	487	444	385	305	199	63	
-5		7	151	264	350	416	464	498	522	538	548	554	558	559	558	554	548	538	522	498	464	416	350	264	151	7	
-6			88	209	304	377	431	471	499	519	532	540	545	548	545	540	532	519	499	471	431	377	304	209	88		
-7			7	139	244	325	387	433	467	491	508	518	524	528	524	518	508	491	467	433	387	325	244	139	7		
-8				51	166	257	327	381	422	451	472	485	493	497	493	485	472	451	422	381	327	257	166	51			
-9					69	170	251	313	360	396	421	437	447	453	447	437	421	396	360	313	251	170	69				
-10						61	152	224	279	321	351	372	383	391	383	372	351	321	279	224	152	61					
-11							28	110	174	223	259	284	298	307	298	284	259	223	174	110	28						
-12									41	98	140	169	186	196	186	169	140	98	41								
-13												22	42	54	42	22											

Rear Wheel: Distribution of Stress with Depth



-36	-34	-32	-30	-28	-26	-24	-22	-20	-18	-16	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
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2	4	9	20	44	90	160	242	322	391	445	486	515	535	548	556	561	563	564	563	561	556	548	535	515	486	445	391	322	242	160	90	44	20	9	4	2
12	19	31	50	79	119	170	228	287	344	393	435	468	493	512	525	533	538	539	538	533	525	512	493	468	435	393	344	287	228	170	119	79	50	31	19	12
26	37	52	73	100	134	173	216	261	305	346	383	414	440	460	476	486	492	494	492	486	476	460	440	414	383	346	305	261	216	173	134	100	73	52	37	26
40	52	68	88	111	139	170	203	237	271	304	335	362	385	404	419	429	436	438	436	429	419	404	385	362	335	304	271	237	203	170	139	111	88	68	52	40
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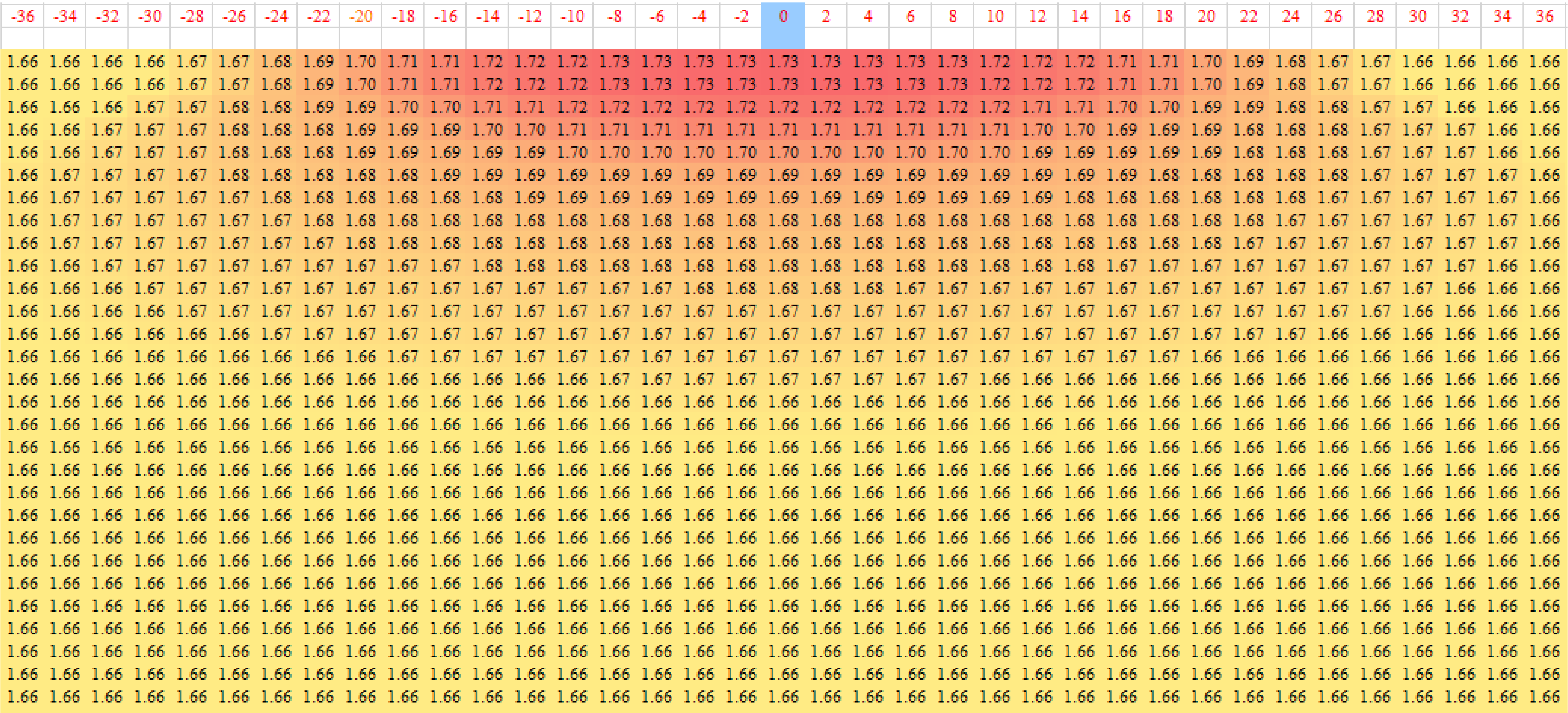
Rear Wheel: Distribution of Bulk Density with Depth



-36	-34	-32	-30	-28	-26	-24	-22	-20	-18	-16	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
1.66	1.66	1.66	1.66	1.67	1.67	1.68	1.69	1.70	1.71	1.71	1.72	1.72	1.72	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.72	1.72	1.72	1.71	1.71	1.70	1.69	1.68	1.67	1.67	1.66	1.66	1.66	1.66
1.66	1.66	1.66	1.66	1.67	1.67	1.68	1.69	1.70	1.71	1.71	1.72	1.72	1.72	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.72	1.72	1.72	1.71	1.71	1.70	1.69	1.68	1.67	1.67	1.66	1.66	1.66	1.66
1.66	1.66	1.66	1.67	1.67	1.68	1.68	1.69	1.69	1.70	1.70	1.71	1.71	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.71	1.71	1.70	1.70	1.69	1.69	1.68	1.68	1.67	1.67	1.66	1.66	1.66
1.66	1.66	1.67	1.67	1.67	1.68	1.68	1.68	1.69	1.69	1.69	1.70	1.70	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.70	1.70	1.69	1.69	1.69	1.68	1.68	1.68	1.67	1.67	1.67	1.66	1.66
1.66	1.66	1.67	1.67	1.67	1.68	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68	1.67	1.67	1.67	1.66	1.66
1.66	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.66
1.66	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.66
1.66	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.66
1.66	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.66
1.66	1.66	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.66	1.66
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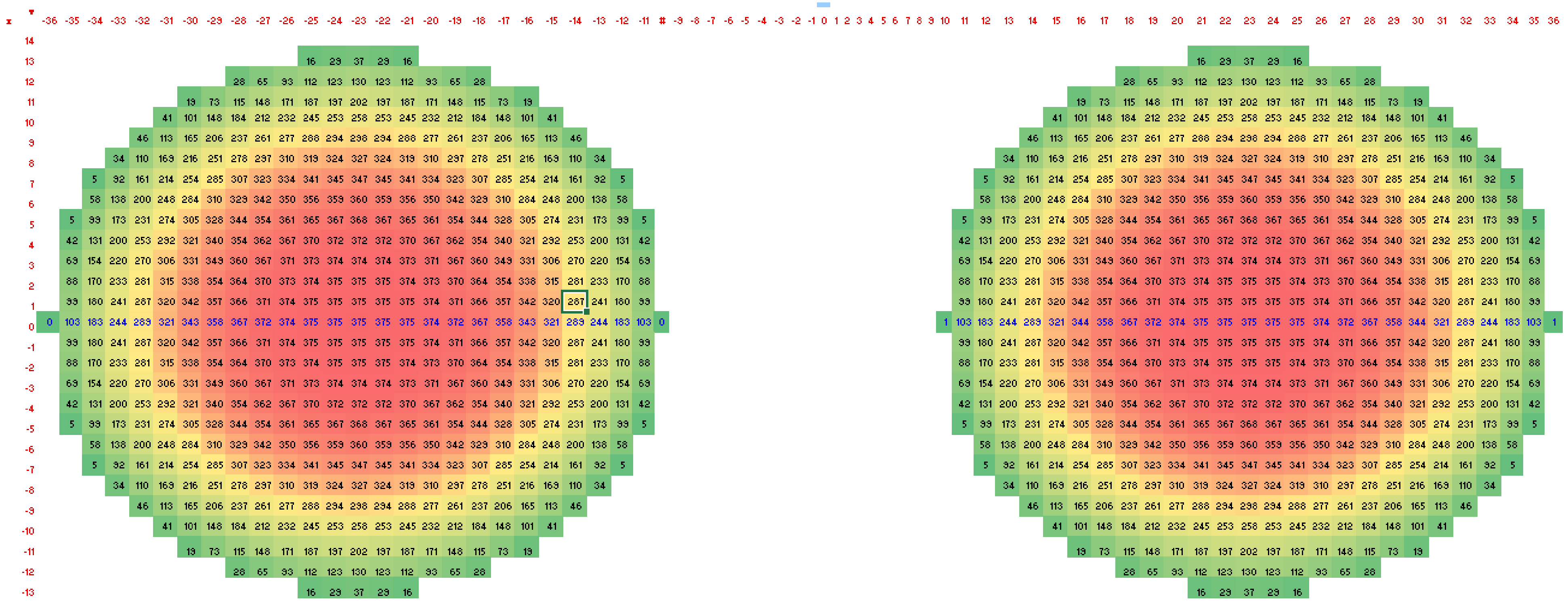
Front Wheel: Contact Stress



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14																											
13												16	29	37	29	16											
12									28	65	93	112	123	130	123	112	93	65	28								
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8				34	110	169	216	251	278	297	310	319	324	327	324	319	310	297	278	251	216	169	110	34			
7			5	92	161	214	254	285	307	323	334	341	345	347	345	341	334	323	307	285	254	214	161	92	5		
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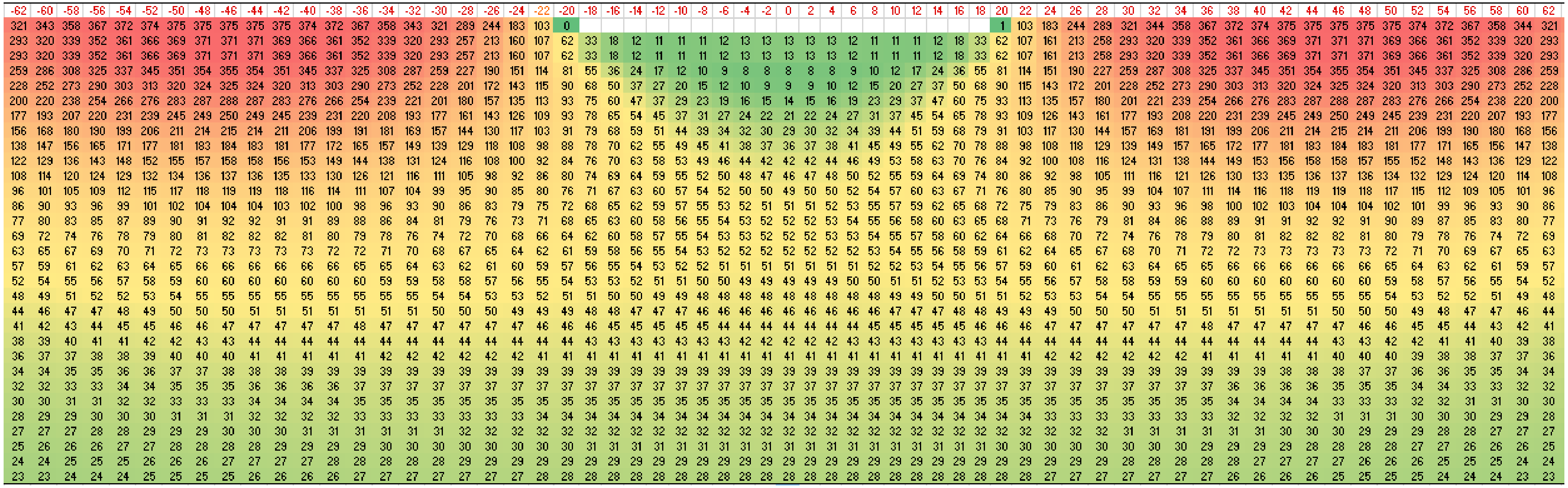
Front Wheel: Distribution of Stress with Depth



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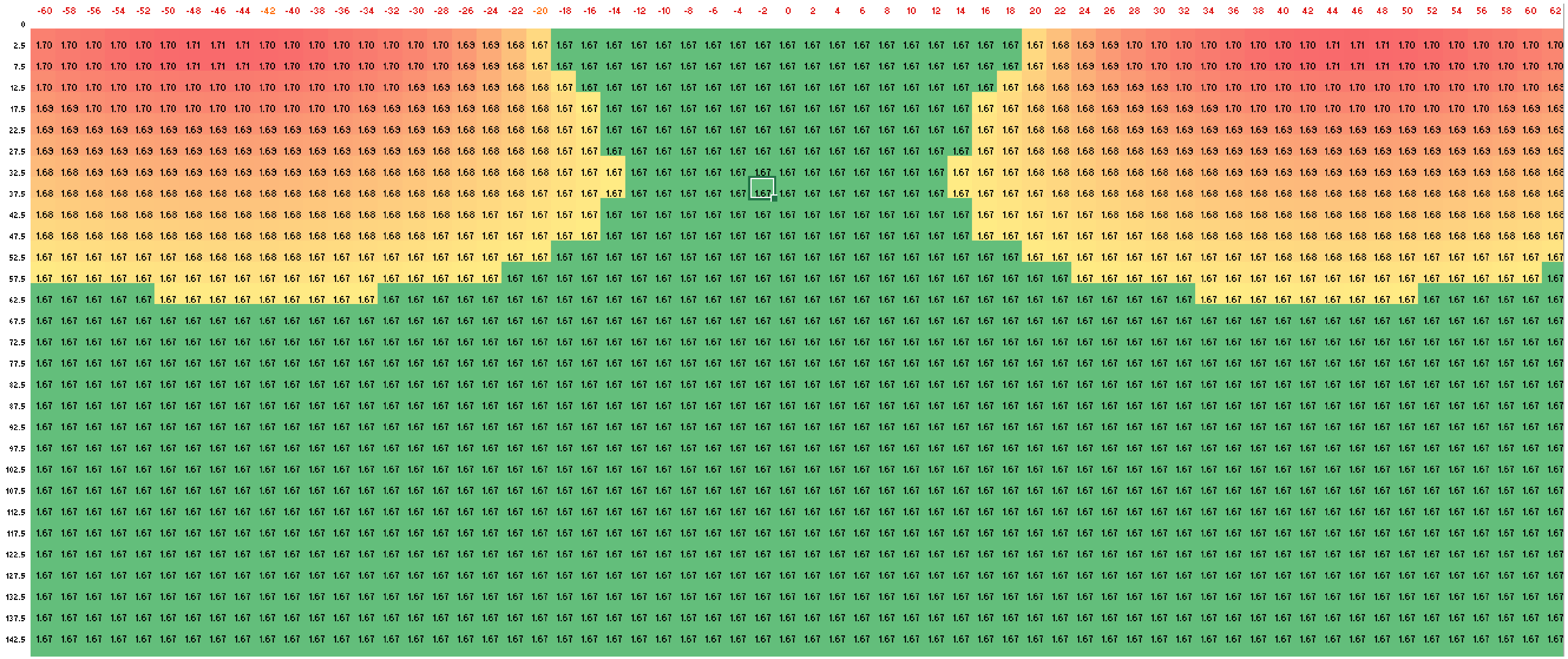
Front Wheel: Distribution of Bulk Density with Depth



	-60	-58	-56	-54	-52	-50	-48	-46	-44	-42	-40	-38	-36	-34	-32	-30	-28	-26	-24	-22	-20	-18	-16	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62
0																																																														
2.5	1.70	1.70	1.70	1.70	1.70	1.70	1.71	1.71	1.71	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69	1.69	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.69	1.69	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.71	1.71	1.71	1.70	1.70	1.70	1.70	1.70	1.70	1.70
7.5	1.70	1.70	1.70	1.70	1.70	1.70	1.71	1.71	1.71	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69	1.69	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.69	1.69	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.71	1.71	1.71	1.70	1.70	1.70	1.70	1.70	1.70	1.70
12.5	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69	1.69	1.69	1.69	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.69	1.69	1.69	1.69	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69
17.5	1.69	1.69	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.69	1.69	1.69
22.5	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
27.5	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
32.5	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.68	1.68	1.68
37.5	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68
42.5	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68
47.5	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.67
52.5	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.67	1.67	1.67	1.67	1.67	1.67	1.67
57.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
62.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
67.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
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77.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
82.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
87.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
92.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
97.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
102.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
107.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
112.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
117.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
122.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
127.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
132.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
137.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
142.5	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67

Appendix E: Proctor Static Equivalence Table

Number of Blows (Standard)	*Equivalent Static Load (kPa)*	*Number of Blows (Standard)*	*Equivalent Static Load (kPa)*
1	88.8	31	751.8
2	110.9	32	773.9
3	133	33	796
4	155.1	34	818.1
5	177.2	35	840.2
6	199.3	36	862.3
7	221.4	37	884.4
8	243.5	38	906.5
9	265.6	39	928.6
10	287.7	40	950.7
11	309.8	41	972.8
12	331.9	42	994.9
13	354	43	1017
14	376.1	44	1039.1
15	398.2	45	1061.2
16	420.3	46	1083.3
17	442.4	47	1105.4
18	464.5	48	1127.5
19	486.6	49	1149.6
20	508.7	50	1171.7
21	530.8	51	1193.8
22	552.9	52	1215.9
23	575	53	1238
24	597.1	54	1260.1
25	619.2	55	1282.2
26	641.3	56	1304.3
27	663.4	57	1326.4
28	685.5	58	1348.5
29	707.6	59	1370.6
30	729.7	60	1392.7

Appendix F: Photos of Testing

Proctor Tests

Figure 41: Image showing the proctor mould filled with uncompacted soil

Figure 42: Image showing the application of the proctor hammer to the soil (before first blow)

Figure 43: Surface of the soil after proctor compaction has occurred and the sample has been cut at the level of the mould

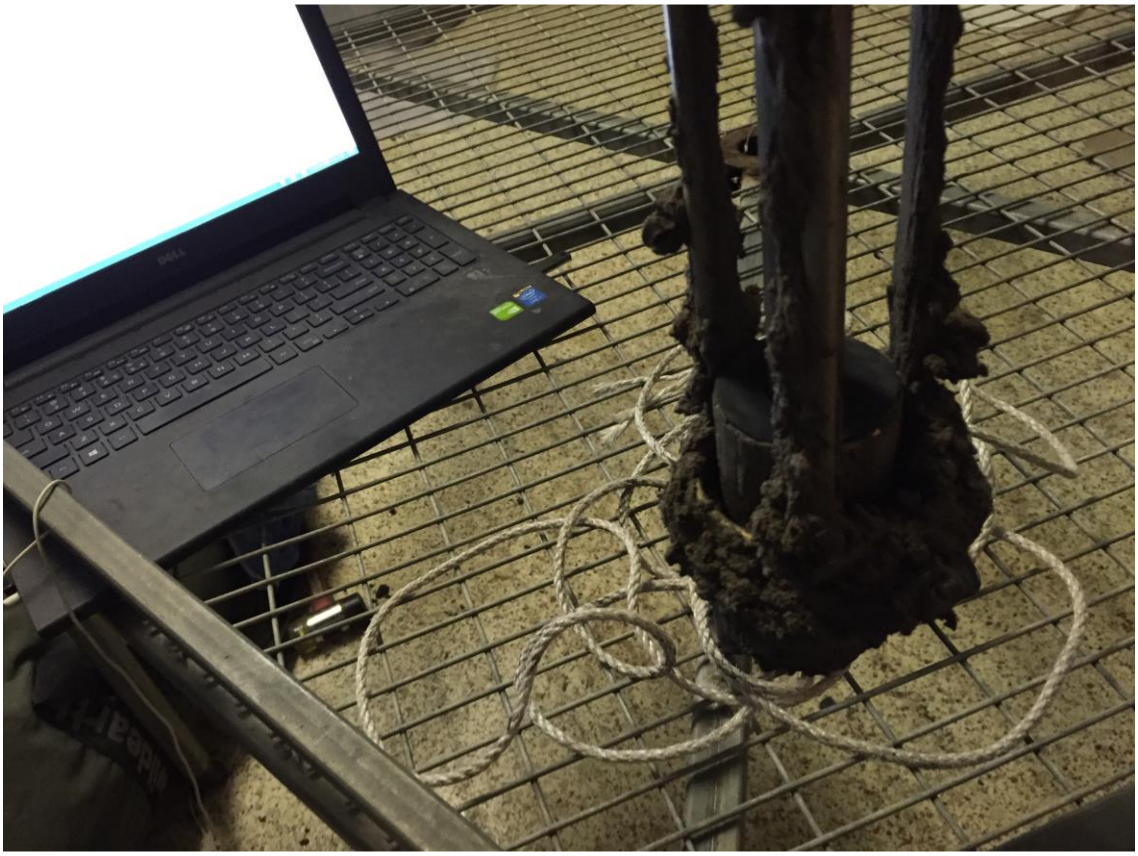

Figure 44: Photo from testing showing the clay sticking to the proctor hammer; reducing the compactive effort per blow

Uniaxial Test

Figure 45: Picture showing the uniaxial compression test

Appendix G: USQ Safety Form

Step 1 - Identify the hazards (use this table to help identify hazards then list all hazards in the risk table)		
General Work Environment		
☐ Sun exposure	☐ Water (creek, river, beach, dam)	☐ Sound / Noise
☐ Animals / Insects	☐ Storms / Weather/Wind/Lightning	☐ Temperature (heat, cold)
☒ Air Quality	☐ Lighting	☐ Uneven Walking Surface
☐ Trip Hazards	☐ Confined Spaces	☐ Restricted access/egress
☐ Pressure (Diving/Altitude)	☐ Smoke	☐
Other/Details:		
Machinery, Plant and Equipment		
☒ Machinery (fixed plant)	☐ Machinery (portable)	☒ Hand tools
☐ Laser (Class 2 or above)	☐ Elevated work platforms	☐ Traffic Control
☒ Non-powered equipment	☒ Pressure Vessel	☐ Electrical
☐ Vibration	☒ Moving Parts	☐ Acoustic/Noise
☐ Vehicles	☐ Trailers	☐ Hand tools
Other/Details:		
Manual Tasks / Ergonomics		
☒ Manual tasks (repetitive, heavy)	☐ Working at heights	☐ Restricted space
☐ Vibration	☒ Lifting Carrying	☒ Pushing/pulling
☒ Reaching/Overstretching	☒ Repetitive Movement	☒ Bending
☐ Eye strain	☐ Machinery (portable)	☒ Hand tools
Other/Details:		
Biological (e.g. hygiene, disease, infection)		
☐ Human tissue/fluids	☐ Virus / Disease	☐ Food handling
☐ Microbiological	☐ Animal tissue/fluids	☐ Allergenic
Other/Details:		
Chemicals Note: Refer to the label and Safety Data Sheet (SDS) for the classification and management of all chemicals.		

☐ Non-hazardous chemical(s)	☐ ‘Hazardous’ chemical (Refer to a completed hazardous chemical risk assessment)	
☐ Engineered nanoparticles	☐ Explosives	☐ Gas Cylinders
Name of chemical(s) / Details:		
Critical Incident – resulting in:		
☐ Lockdown	☐ Evacuation	☐ Disruption
☐ Public Image/Adverse Media Issue	☐ Violence	☐ Environmental Issue
Other/Details:		
Radiation		
☐ Ionising radiation	☐ Ultraviolet (UV) radiation	☐ Radio frequency/microwave
☐ infrared (IR) radiation	☐ Laser (class 2 or above)	☐
Other/Details:		
Energy Systems – incident / issues involving:		
☐ Electricity (incl. Mains and Solar)	☐ LPG Gas	☒ Gas / Pressurised containers
Other/Details:		
Facilities / Built Environment		
☐ Buildings and fixtures	☐ Driveway / Paths	☒ Workshops / Work rooms
☐ Playground equipment	☐ Furniture	☐ Swimming pool
Other/Details:		
People issues		
☐ Students	☐ Staff	☐ Visitors / Others
☐ Physical	☐ Psychological / Stress	☐ Contractors
☒ Fatigue	☐ Workload	☐ Organisational Change
☐ Workplace Violence/Bullying	☒ Inexperienced/new personnel	☐

Risk register and Analysis

Step 1 (cont)	**Step 2**	**Step 2a**	**Step 3**			**Step 4**				
Hazards: **From step 1 or more if identified**	**The Risk:** **What can happen if exposed to the hazard with existing controls in place?**	**Existing Controls:** **What are the existing controls that are already in place?**	**Risk Assessment:** **(use the Risk Matrix on p3) Consequence x Probability = Risk Level**			**Additional controls:** **Enter additional controls if required to reduce the risk level**	**Risk assessment with additional controls:** **(use the Risk Matrix on p3 – has the consequence or probability changed?)**			**Controls Implemented? Yes/No**
			Consequence	**Probability**	**Risk Level**		**Consequence**	**Probability**	**Risk Level**	
Example										
Working in temperatures over 35^0 C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	Regular breaks, chilled water available, loose clothing, fatigue management policy.	catastrophic	possible	high	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
			Select a consequence	Select a probability	Select a Risk Level		Select a consequence	Select a probability	Select a Risk Level	Yes or No
Movement of dried dirt resulting in airbourne dust particals	Inhalation of dust particles causing respiritory problems	Workplace set up with open windows and doors etc. to allow cross breezes to carry away the dus particles	Moderate	Rare	Low	Conduct pouring of dirt outdoors if cross breeze is unavailable or where a respiritory if required	Minor	Rare	Low	No

Step 1 (cont)	Step 2	Step 2a	Step 3			Step 4				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Existing Controls:** What are the existing controls that are already in place?	**Risk Assessment:** (use the Risk Matrix on p3) Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls:** (use the Risk Matrix on p3 – has the consequence or probability changed?)			**Controls Implemented? Yes/No**
			Consequence	**Probability**	**Risk Level**		**Consequence**	**Probability**	**Risk Level**	
Example										
Working in temperatures over 35^0 C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	Regular breaks, chilled water available, loose clothing, fatigue management policy.	catastrophic	possible	high	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Shop Press: Pressure vessel	Jack on shop press bursts	Construction quaity of jack and safety glasses (hydraulic fluid)	Major	Rare	Low	None	Major	Rare	Low	No
Shop Press: Moving Parts	Fingers caught inbetween shop press and sample	Slow movement of moving parts and operator discretion	Moderate	Rare	Low	None	Moderate	Rare	Low	No
Shop Press: Sample slip	Sample and mould slip due to high pressures	Restrained sample and distance between operator and machine	Major	Possible	Moderate	Physical seperation of operator from the shop press	Insignificant	Rare	Low	Yes
Shop Press: Failure	Frame of shop press fails in spectacular fasion	See above and operator discresion	Minor	Rare	Low	See above	Insignificant	Rare	Low	Yes

Step 1 (cont)	Step 2	Step 2a	Step 3			Step 4				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Existing Controls:** What are the existing controls that are already in place?	**Risk Assessment:** (use the Risk Matrix on p3) Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls:** (use the Risk Matrix on p3 – has the consequence or probability changed?)			**Controls Implemented? Yes/No**
			Consequence	**Probability**	**Risk Level**		**Consequence**	**Probability**	**Risk Level**	
Example										
Working in temperatures over 35^0 C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	Regular breaks, chilled water available, loose clothing, fatigue management policy.	catastrophic	possible	high	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Proctor Hammer: Moving parts	Catch fingers in falling hammer	Operator discretion and design of hammer	Minor	Rare	Low	None	Minor	Rare	Low	No
Hand Tools	Cutting or stabbing of operator whilst using tools	Operator discresion	Insignificant	Unlikely	Low	None	Insignificant	Unlikely	Low	No
Manual Tasks	Strain or overstreaching as a result of incorrect lifting of movement techniques	Operator has undergone various lifting techinique safety presentations and practical exercises	Minor	Unlikely	Low	None	Minor	Unlikely	Low	No

Step 1 (cont)	**Step 2**	**Step 2a**	**Step 3**			**Step 4**				
Hazards: **From step 1 or more if identified**	**The Risk:** **What can happen if exposed to the hazard with existing controls in place?**	**Existing Controls:** **What are the existing controls that are already in place?**	**Risk Assessment:** **(use the Risk Matrix on p3)** **Consequence x Probability = Risk Level**			**Additional controls:** **Enter additional controls if required to reduce the risk level**	**Risk assessment with additional controls:** **(use the Risk Matrix on p3 – has the consequence or probability changed?)**			**Controls Implemented? Yes/No**
			Consequence	**Probability**	**Risk Level**		**Consequence**	**Probability**	**Risk Level**	
Example										
Working in temperatures over 35^0 C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	Regular breaks, chilled water available, loose clothing, fatigue management policy.	catastrophic	possible	high	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Repetative Movements	Proctor test repetative movements in lifting the hammer	See above	Insignificant	Rare	Low	None	Insignificant	Rare	Low	No

Appendix H: Proctor Test Result Tables

Standard Proctor Tests

Table 13: Raw data from the standard proctor test for Sample A

Standard Proctor Test - 25 Blows - Altering Moisture Content				
Sample A - Toobeah, QLD				
Required Moisture Content	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
8%	8.47%	1600	1464	1.46
12%	12.44%	1660	1454	1.45
15%	15.43%	1730	1463	1.46
20%	20.38%	1900	1513	1.51
23%	23.35%	2060	1579	1.58
24%	24.30%	1800	1363	1.36

Table 14: Raw data from the standard proctor test for Sample B

Standard Proctor Test - 25 Blows - Altering Moisture Content				
Sample B - Goondiwindi, QLD				
Required Moisture Content	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
12%	12.03%	1600	1408	1.41
15%	15.01%	1864	1584	1.58
20%	20.02%	1850	1480	1.48
25%	25.00%	1610	1207	1.21

Table 15: Raw data from the standard proctor test for Sample C

Standard Proctor Test - 25 Blows - Altering Moisture Content				
Sample C - Yelarbon, QLD				
Required Moisture Content	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
8%	9.51%	1510	1366	1.37
12%	12.01%	1670	1469	1.47
15%	14.98%	1750	1488	1.49
18%	17.97%	1770	1452	1.45
21%	21.00%	1840	1454	1.45
24%	24.01%	1690	1284	1.28

Table 16: Raw data from the standard proctor test for Sample D

Standard Proctor Test - 25 Blows - Altering Moisture Content				
Sample D - Aubigny, QLD				
Required Moisture Content	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
16%	15.98%	1440	1210	1.21
19%	19.02%	1490	1207	1.21
25%	25.88%	1610	1193	1.19
28%	27.99%	1690	1217	1.22
31%	31.11%	1710	1178	1.18
35%	34.99%	1590	1034	1.03
38%	38.18%	1580	977	0.98

Table 17: Raw data from the standard proctor test for Sample E

Standard Proctor Test - 25 Blows - Altering Moisture Content				
Sample E - Jimbour, QLD				
Required Moisture Content	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
24%	24.03%	1660	1261	1.26
27%	27.01%	1710	1248	1.25
30%	29.99%	1660	1162	1.16
33%	33.05%	1630	1091	1.09

Table 18: Raw data from the standard proctor test for Sample F

Standard Proctor Test - 25 Blows - Altering Moisture Content				
Sample F - Warren, NSW				
Required Moisture Content	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
20%	22.05%	1770	1380	1.379723267
23%	25.01%	1780	1335	1.334853194
24%	25.80%	1800	1336	1.335612621
25%	27.16%	1680	1224	1.223777749
26%	27.77%	1750	1264	1.264018073

Modified Proctor Tests

Table 19: Raw data from the modified proctor test for Sample B

Proctor Test - Constant Moisture Content - Altering Compactive Effort					
Sample B - Goondiwindi, QLD					
Number of Blows	**Equivalent Static Loading (kPa)**	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
6	200	17.02%	1640	1361	1.36
6	200	17.02%	1580	1311	1.31
6	200	17.02%	1540	1278	1.28
15	400	17.02%	1790	1485	1.49
15	400	17.02%	1820	1510	1.51
15	400	17.02%	1800	1494	1.49
25	600	17.02%	Calculated	1564	1.56
33	800	17.02%	1890	1568	1.57
33	800	17.02%	1930	1602	1.60
33	800	17.02%	1950	1618	1.62
69	1600	17.02%	1940	1610	1.61
69	1600	17.02%	1970	1635	1.63
69	1600	17.02%	1980	1643	1.64

Table 20: Raw data from the modified proctor test for Sample C

Proctor Test - Constant Moisture Content - Altering Compactive Effort					
Sample C - Yelarbon, QLD					
Number of Blows	**Equivalent Static Loading (kPa)**	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
6	200	18.66%	1700	1383	1.38
6	200	18.66%	1530	1244	1.24
15	400	18.66%	1800	1464	1.46
15	400	18.66%	1760	1432	1.43
25	600	18.66%	Calculated	1472	1.47
33	800	18.66%	1910	1554	1.55
33	800	18.66%	1950	1586	1.59
33	800	18.66%	1920	1562	1.56
69	1600	18.66%	1970	1602	1.60
69	1600	18.66%	1760	1432	1.43
69	1600	18.66%	2010	1635	1.63

Table 21: Raw data from the modified proctor test for Sample D

Proctor Test - Constant Moisture Content - Altering Compactive Effort					
Sample D - Aubigny, QLD					
Number of Blows	**Equivalent Static Loading (kPa)**	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
6	200	31.17%	1450	1445.49	1.00
6	200	31.17%	1450	1445.49	1.00
15	400	31.17%	1630	1624.93	1.12
15	400	31.17%	1590	1585.06	1.09
15	400	31.17%	1630	1624.93	1.12
25	600	31.17%	Calculated	1705.35	1.18
33	800	31.17%	1650	1644.87	1.14
33	800	31.17%	1650	1644.87	1.14
69	1600	31.17%	1620	1614.97	1.11
69	1600	31.17%	1620	1614.97	1.11
69	1600	31.17%	1610	1605.00	1.11

Table 22: Raw data from the modified proctor test for Sample E

Proctor Test - Constant Moisture Content - Altering Compactive Effort					
Sample E - Jimbour, QLD					
Number of Blows	**Equivalent Static Loading (kPa)**	**Moisture Content (%)**	**Density (wet) (kg/m3)**	**Density Dry (kg/m3)**	**Density Dry (g/cm3)**
6	200	28.02%	1450	1445.95	1.04
6	200	28.02%	1450	1445.95	1.04
6	200	28.02%	1430	1426.00	1.03
15	400	28.02%	1590	1585.56	1.14
15	400	28.02%	1590	1585.56	1.14
15	400	28.02%	1560	1555.64	1.12
25	600	28.02%	Calculated	1686.62	1.22
33	800	28.02%	1610	1605.50	1.16
33	800	28.02%	1720	1715.19	1.24
33	800	28.02%	1660	1655.36	1.19
69	1600	28.02%	1640	1635.42	1.18
69	1600	28.02%	1670	1665.33	1.20
69	1600	28.02%	1700	1695.25	1.22

Appendix I: Uniaxial Test Result Tables

Table 23: Raw data from the uniaxial test for Sample B

Uniaxial Compression Test - Constant Moisture Content - Altered Load				
Sample B - Goondiwindi, QLD				
Load (kPa)	**Final Moisture Content (%)**	**Density (wet) (kg/m2)**	**Density Dry (kg/m2)**	**Density Dry (g/cm3)**
200	16.42%	1354	1351	1.13
200	16.42%	1167	1165	0.98
200	16.31%	1142	1140	0.96
400	16.42%	1461	1458	1.22
400	16.42%	1506	1504	1.26
400	16.31%	1290	1288	1.08
600	16.31%	1348	1345	1.13
600	16.31%	1416	1414	1.19
600	16.31%	1499	1496	1.25
800	16.31%	1440	1438	1.21
800	16.31%	1549	1547	1.30
800	16.31%	1678	1675	1.40
1600	16.31%	1687	1685	1.41
1600	16.31%	1852	1849	1.55
1600	16.31%	1902	1899	1.59

Table 24: Raw data from the uniaxial test for Sample C

Uniaxial Compression Test - Constant Moisture Content - Altered Load				
Sample C - Yelarbon, QLD				
Load (kPa)	**Final Moisture Content (%)**	**Density (wet) (kg/m2)**	**Density Dry (kg/m2)**	**Density Dry (g/cm3)**
200	18.39%	1101	1099	0.90
200	18.39%	1096	1094	0.89
200	18.39%	1177	1174	0.96
400	18.39%	1111	1108	0.91
400	18.39%	1178	1175	0.96
400	18.39%	1279	1276	1.04
600	18.39%	1217	1214	0.99
600	18.39%	1326	1323	1.08
600	18.39%	1108	1106	0.90
800	18.39%	1242	1239	1.01
800	18.39%	1201	1199	0.98
800	18.39%	1336	1333	1.09
1600	18.39%	1223	1221	1.00
1600	18.39%	1256	1254	1.03
1600	18.39%	1283	1281	1.05

Table 25: Raw data from the uniaxial test for Sample D

Uniaxial Compression Test - Constant Moisture Content - Altered Load				
Sample D - Aubigny, QLD				
Load (kPa)	**Final Moisture Content (%)**	**Density (wet) (kg/m2)**	**Density Dry (kg/m2)**	**Density Dry (g/cm3)**
400	30.45%	1095	1092	0.76
400	30.45%	1028	1024	0.71
400	30.45%	1062	1058	0.74
600	30.45%	1202	1198	0.84
600	30.45%	1059	1056	0.74
600	30.45%	1053	1049	0.73
800	30.45%	1064	1061	0.74
800	30.45%	1187	1183	0.83
800	30.45%	1189	1186	0.83
1600	30.45%	1218	1214	0.85
1600	30.45%	1286	1282	0.89
1600	30.45%	1225	1221	0.85

Table 26: Raw data from the uniaxial test for Sample E

Uniaxial Compression Test - Constant Moisture Content - Altered Load				
Sample E - Jimbour, QLD				
Load (kPa)	**Final Moisture Content (%)**	**Density (wet) (kg/m2)**	**Density Dry (kg/m2)**	**Density Dry (g/cm3)**
200	27.53%	1091	1088	0.79
200	27.53%	1063	1060	0.77
200	27.53%	1062	1059	0.77
400	27.53%	1073	1070	0.78
400	27.53%	1143	1140	0.83
400	27.53%	1164	1161	0.84
600	27.53%	1112	1109	0.81
600	27.53%	1151	1148	0.83
600	27.53%	1203	1200	0.87
800	27.53%	1218	1215	0.88
800	27.53%	1225	1221	0.89
800	27.53%	1109	1106	0.80
1600	27.53%	1089	1086	0.79
1600	27.53%	1209	1206	0.88
1600	27.53%	1186	1183	0.86