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A new saturation-based framework for compaction quality control

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A new saturation-based framework for compaction quality control

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Field compaction control is arguably the most common yet critical quality control procedure in geotechnical engineering. Since the early 1930s, the systematic process for performing quality control of compacted soils has often been performed by measuring the in-place dry unit weight (or density) and as-compacted soil moisture content after placement in a fill. However, the current practice overlooks several facts resulting from comparing soil prepared and compacted in the laboratory to soils placed and compacted in the field. These issues include comparing the compaction energy in the lab versus what is applied in the field, and the behavior of saturated soils in the laboratory to the performance of unsaturated soils in the field. To address some of these gaps, this study presents a new saturation-based framework for compaction quality control. The aim of this new framework is to reduce the uncertainties and assumptions of the compaction control process and provide practicing engineers with further insight into the key engineering attributes of compacted soils. The proposed saturation-based approach compares a degree of saturation difference to a normalized dry unit weight ratio, making saturation upon compaction the controlling diagnostic variable and the focus of the monitoring effort. In essence, the optimal compaction conditions will be referenced to a characteristic saturation state near 80%. Compared to the conventional quality control system for field compaction, the saturation-based approach is developed with the same field and reference data collected for most earth fill projects. The results of this approach enhance the engineering judgment required to match the laboratory reference values to the field conditions. For illustration purposes, the proposed saturation-based framework is applied to compaction control data of a large earth dam and compared against the conventional method side-by-side. The proposed framework builds on the unique physical features of the "family of curves" and expands the ability of the user to select the compaction criterion using that relationship to produce project design properties. Overall, the proposed approach enhances the knowledge of the physical behavior of compacted soils and provides a more comprehensive understanding of the long-term performance of compacted fills.

DEDICATION

This dissertation is dedicated to my wife, Debby, for her support, patience, and encouragement throughout this endeavor. I am very blessed to share my life with you.

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TABLE OF CONTENTS

CHAPTER

APPENDIX

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Background

Compaction is the process of mechanically densifying soil by removing air voids. It has been demonstrated that compaction plays a crucial role in controlling several key engineering characteristics of compacted soils, including shear strength, compressibility, and permeability (Hilf, 1956, 1975; Holtz et al., 2011; Kodikara et al., 2018). Inadequate compaction during construction is frequently cited as the cause of many failures in slopes and earthen structures (e.g., Luo and Bathurst, 2018). For example, Koerner and Koerner (2018) compiled a database of 320 failed mechanically stabilized earth (MSE) walls and found that 76% of failures were due to poor to moderate backfill compaction. It is evident that compaction is a critical quality control procedure in geotechnical engineering, as it directly influences the behavior and performance of compacted soils. Therefore, proper compaction control is essential to ensure the long-term stability and safety of earthen structures.

Systematic compaction control of earth fills has been performed since the 1920s. Kodikara et al. (2018) presented a historical overview of soil compaction development, including two major developments from the 1920s and 1930s: the Proctor Compaction curves for compaction specification and the California Bearing Ratio (CBR) for pavement design (Proctor, 1933). Historically, the quality control for the placement of soil fill has been accomplished with documentation of three primary aspects of the compaction process: (a) the in-place, compacted dry unit weight; (b) the moisture content of the soil at the time of compaction; and (c) the consistency of the compaction method in the layer of remolded soil being measured (such as lift thickness, consistency of borrow materials, number of passes of compaction equipment) (Kodikara et al., 2018).

Several alternative compaction quality control methods have been proposed and used since the early 1930s (e.g., Liu et al., 2012, Riad et al., 2023). For instance, Mokwa (2005) reported a soil air voids method used by the Montana Department of Transportation in the 1970s as an alternative to the Proctor method of field compaction control. Using this method, the field inspector could rapidly determine if the compacted soil layer met the specified compaction criterion without needing laboratory Proctor compaction testing. More recent efforts include the use of stiffness-based compaction control methods (e.g., Meehan et al., 2012), the application of advances in sensing technologies for continuous compaction control (CCC), or intelligent compaction (IC) (e.g., An et al., 2020, Shi et al., 2022). Nevertheless, the dominant systematic process for performing quality control of compacted soils has been to measure the in-place dry unit weight (or density) and as-compacted moisture content of the soil after placement in a fill. The amount of water in the soil is one of the primary variables in the compaction process. The amount of water in the soil remains relatively constant throughout the compaction process. However, for a given compaction effort, the dry unit weight depends on the moisture content during the compaction process. The same is true for the degree of saturation. Therefore, the fraction of water in the soil during the compaction remains a key control parameter for both unit weight and degree of saturation.

The current compaction control practice in geotechnical engineering fails to consider several critical factors that arise when comparing soil prepared and compacted in the laboratory to soils placed and compacted in the field. These factors include the differences in compaction energy between the laboratory and the field, the behavior of saturated soils in the lab versus the performance of unsaturated compacted soils in the field, and the lack of consideration for the advances in unsaturated soil mechanics in assessing compaction performance (Miller and Vahedifard, 2023).

1.2 Objective

The main objective of this dissertation is to present a new compaction control framework, referred to as the "saturation-based framework.” The proposed framework aims to provide practicing engineers with a more comprehensive approach to compaction control, which considers a broader range of compaction energy and provides insight into the key engineering attributes, such as strength and compressibility, of the resulting unsaturated compacted soils. Compared to the conventional quality control system for field compaction, the saturation-based framework can be developed using the same data collected in most earth-fill projects. This makes it easier for engineers to incorporate the framework into their existing compaction control procedures.

1.3 Scope and Organization of Dissertation

This dissertation is divided into six chapters. Chapter 1 provides the background for the study and lists the dissertation's main objectives and scope. Chapter 2 reviews the literature and synthesizes factors affecting compaction control.

Chapter 3 discusses the rationale for the need to revisit the existing Procotr-based compaction control method. The chapter compares the Proctor-based method with the proposed saturation-based framework regarding uncertainties and assumptions in engineering applications. The main motivation behind revisiting the well-established Proctor-based compaction control procedure is to reduce the uncertainties and assumptions of the compaction control process and enhance the outcome for engineering applications. The chapter discusses how the proposed framework can contribute toward Achieving more uniform compaction energy, avoiding over-compaction, and reducing possible errors due to field judgment,

Chapter 4 presents the proposed saturation-based quality control system and compares the proposed saturation-based framework with the conventional Proctor-based methodology. The acceptance criteria and step-by-step procedure are presented and discussed for the proposed saturation-based framework. Further, this chapter provides steps to be taken by engineers (designers), earthwork inspectors, and contractors for the Proctor-based method and the proposed saturation-based framework

Chapter 5 presents a case study in which the benefits of the saturation-based approach are illustrated by applying it to the compaction data from a real-world case study and compared to the conventional method. The case study involved the construction of an earth dam as part of the Lake Winnebago Dam expansion program in western Missouri. The dam comprised several zones of earthen construction, and we also examined the shear strengths in the upper lifts of compacted embankment soil.

Chapter 6 provides the conclusions and recommendations for future works. Appendix A provides the compaction test results.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Soil compaction is a process that involves reducing the volume of voids in soil by applying mechanical pressure (Hilf, 1956, 1975; Lambe and Whitman, 1969; Holtz et al., 2011). It is widely used in engineering applications to improve the load-bearing capacity and stability of soils, particularly in the construction of embankments, dams, slopes, roads, foundations, and other infrastructure. The goal of soil compaction is to increase the density and strength of the soil, which can help to prevent settlement, improve soil stability, and reduce the risk of damage to structures built on or near the soil.

Soil compaction is typically achieved by applying mechanical loading using specialized equipment, such as compactors or rollers, to apply a series of repeated loads to the soil surface (Bowles, 1997; Das, 2006). The process can be carried out in situ, where the soil is compacted in place, or in a laboratory, where soil samples are subjected to controlled pressure and moisture conditions. In either case, the compaction process involves applying a specific amount of compactive energy to the soil, usually measured in terms of the weight of the equipment or the number of passes made over the soil surface.

There are several factors that can affect the success of soil compaction, including soil type, moisture content, compaction equipment, and compaction energy. The degree of compaction required depends on the intended use of the soil, as well as the type and weight of the structures that will be built on or near it. In general, denser soils are better able to support heavy loads and resist deformation under stress, making them ideal for building foundations and other load-bearing structures. However, excessive soil compaction can also have negative effects, such as increasing construction cost, reducing soil permeability, and increasing soil erosion. Therefore, it is important to carefully consider the amount and intensity of soil compaction required for a given application and to monitor soil conditions carefully during and after the compaction process.

There are several different methods for measuring and analyzing soil compaction, including standard penetration tests, cone penetration tests, and laboratory compaction tests. These tests can be used to determine the degree of compaction achieved, as well as the soil's density, moisture content, and other physical properties.

Soil compaction is an important process for improving the load-bearing capacity and stability of soils in engineering applications. However, it is important to carefully consider the amount and intensity of soil compaction required and to monitor soil conditions carefully to avoid negative effects. Understanding the factors that affect soil compaction, as well as the various methods for measuring and analyzing soil properties, is essential for ensuring the success of engineering projects that rely on compacted soil.

2.2 Early Development of Soil Compaction

Soil compaction has a long history that can be traced back to the Roman Empire (Ebels et al., 2004). The Romans were known for their advanced engineering skills and built many roads using a process that involved compacting layers of soil and rocks in creating a stable foundation for the road surface. Over time, this process has been refined and improved, leading to the development of modern soil compaction techniques.

The development of compaction equipment for road pavement construction started in France in 1830 with the introduction of rollers drawn by horses (Ebels et al., 2004). After the invention of steamrollers in 1860, road building took a new turn as the level of compaction changed completely. The sheep foot roller was invented in the United States in 1906, inspired by cattle and sheep used in England in 1820 to compact material in earthfill dams (Kodikara et al., 2018).

The invention of the internal combustion engine in 1876 led to the development of heavier rollers. Most subsequent developments in sheep foot rollers were not weight-wise but in the shape of the foot and mechanical developments (Hilf, 1956, 1975; Kodikara et al., 2018). After the Second World War, most significant developments took place in the field of vibratory compaction (Ebels et al., 2004). At present, vibrating rollers feature very prominently in road construction and have become very effective in producing high-density granular pavement layers (Kodikara et al., 2018).

The history of soil compaction is long and varied, with significant advancements made over the centuries. From the early days of manual labor to the modern use of advanced compaction equipment, the goal has always been to create a stable foundation for roads and other infrastructure. With ongoing research into sustainable practices, it is likely that soil compaction techniques will continue to evolve and improve in the coming years.

2.3 Factors Affecting Compaction Level

Soil compaction level can be influenced by several factors that affect the soil's ability to be compacted. These factors include soil type, moisture content, degree of saturation, compaction effort, compaction equipment, and compaction methods (Lambe and Whitman, 1969; Holtz et al., 2011; Tatsuoka, 2015; Kodikara et al., 2018).

Soil type plays an important role in soil compaction, as the particle size distribution, mineralogy, and organic matter content can affect the soil's ability to be compacted. Coarse-grained soils, such as gravel and sand, can be easily compacted with minimal effort, while fine-grained soils, such as clay, are more difficult to compact due to their cohesive properties and tendency to retain moisture. Organic soils are also difficult to compact due to their high water content and low density.

Moisture content is another significant factor that influences soil compaction. The optimal moisture content for soil compaction varies depending on the soil type, but in general, soils with a higher moisture content are more easily compacted. However, if the soil is too wet, it can become saturated and lose its ability to be compacted effectively.

Soil degree of saturation, which refers to the ratio of the volume of water in the soil to the total soil volume, can affect soil compaction levels in several ways. The amount of water in the soil affects its consistency and, consequently, its compaction properties. The optimum degree of saturation for soil compaction varies depending on the type of soil, its composition, and the intended use of the compacted soil (Tatsuoka, 2015). In using a saturation-based compaction control approach, the specific gravity of the soil matrix becomes more important. Holtz et al. (2011) notes that the exact position of the degree of saturation curves depends only on the value of the density of the soil solids or specific gravity. It should also be noted that at high water contents, the Proctor curve never actually reaches the the 100% saturation curve. ASTM D854 supplies the standard test method for specific gravity soils by water Pycnometer. Chapter 4 discusses an approximation approach to achieving a useable specific gravity value for the soils based on Proctor test points compacted at higher moisture contents.

Compaction effort refers to the amount of force applied to the soil during the compaction process. Higher compaction effort leads to higher soil density and better soil strength, but excessive compaction effort can result in soil deformation and damage. The compaction effort required varies with soil type, moisture content, and compaction equipment.

Compaction equipment is another important factor in soil compaction. Different types of equipment, such as vibratory rollers, sheepsfoot rollers, and smooth rollers, produce different compaction levels and affect soil behavior differently. The choice of equipment depends on the soil type, the required compaction level, and the project specifications.

Finally, compaction methods are also crucial in determining soil compaction level. Different methods, such as static, vibratory, or impact compaction, can produce different compaction levels and affect soil behavior differently. The choice of compaction method depends on the soil type, the required compaction level, and the project specifications.

Overall, the factors that affect soil compaction level are interdependent, and an understanding of their interactions is essential to achieving optimal soil compaction.

2.4 Laboratory Compaction Tests

Based on standard laboratory test procedures, the Proctor method is a widely used approach for determining the field soil types that match laboratory dry unit weight versus moisture (Figure 2.1). The standard (ASTM D698) and modified (ASTM D1557) Proctor tests are commonly used in the United States. These tests are distinguished by the amount of compaction effort applied to the soil. The Standard Proctor generates 600 kN-m/m^3 of compactive effort, and the Modified Proctor generates 2,700 kN-m/m^3 of compactive effort in the laboratory. The theoretical energy is calculated by multiplying the number of layers in the mold by the number of blows by the rammer per layer by the rammer's height by the rammer's weight, divided by the specimen's volume. The compaction results are displayed on a plot of the dry unit weight versus the water content in which each compaction effort will produce a particular curve. It is also common practice to plot lines of equal saturation. Applying greater compaction energy to the same soil results in compaction curves that display optimal dry densities at decreasing water content. This line of optimums tends to lie parallel to contours of equal saturation, indicating that the degree of saturation determines the optimal condition for compaction. This relationship, referred to as the line of optimums, generally lies near the 80% saturation contour. Li and Sego (2000) modeled this behavior and developed the "family of curves" concept, which is used in the compaction control procedure called the One-Point Method. AASHTO developed the specification T 272-21 (AASHTO T 272-21) for determining the Proctor density along the designated and defined family of curves.

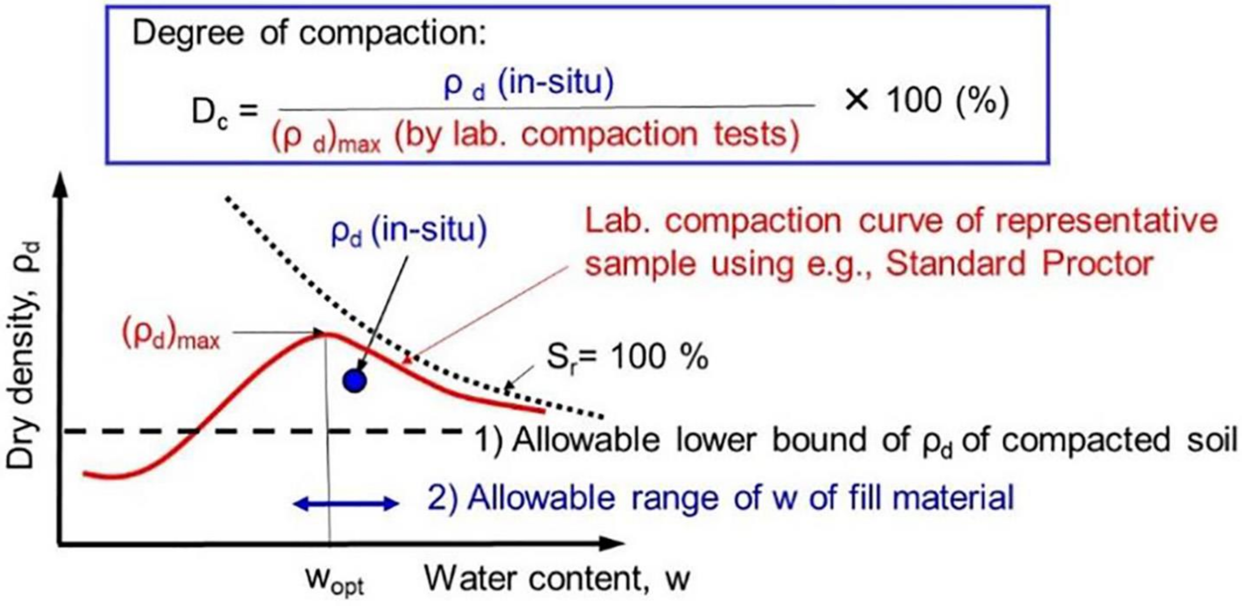

Figure 2.1 Typical conventional Proctor-based compaction control (Tatsuoka and Correia, 2018).

Besides the Proctor test, California Bearing Ratio (CBR) Test (ASTM D1883) is another commonly used laboratory test for compaction. This test CBR involves compacting soil in a cylindrical mold, then conducting loading tests on the soil surface using a plunger. Based on the load-displacement curves obtained, the CBR value is calculated as a percentage ratio of the load measured at specific displacements to standard loads at those displacements. As the loads are referenced to particular displacements, the CBR is a measure of the relative stiffness of the compacted soil under monotonic loading. The CBR test can be conducted in unsaturated or as-compacted conditions or after conditioning to a known moisture content, such as the expected equilibrium moisture content under field conditions or under soaked conditions to simulate water-logged scenarios.

2.5 Stiffness- or Strength-Based Compaction Control

Filed specifications to monitor and control soil compaction processes typically rely on the measurement of in situ soil moisture and density (or unit weight) by field technicians using various testing methods, such as the sand cone method (ASTM D 1556), rubber balloon method (ASTM D 2167), or nuclear-based test devices (ASTM D 2922, ASTM D 3017). However, with the increased use of mechanistic-empirical pavement design methodologies (e.g., NCHRP 2004), there is a growing need for alternative quality control and quality assurance (QC/QA) procedures that use a stiffness- or strength-based criterion instead of density-based criterion.

Various non-destructive, strength-based or modulus-based in situ tests have been proposed to address this need, including the plate load test (ASTM D 1195, ASTM D 1196), falling weight deflectometer test (ASTM D 4694), light weight deflectometer test (ASTM E 2583), dynamic cone penetrometer test (ASTM D 6951), Clegg impact hammer test (ASTM D 5874), and soil stiffness gauge test (ASTM D 6758), also known as the geogauge test. These tests measure different aspects of soil strength or stiffness, such as the soil's ability to resist deformation, its bearing capacity, or its elastic modulus. Han (2015) provided a list of field tests for quality assurance of compacted soil fills, as shown in Table 2.1. Each of these methods has inherent limitations and accuracies that affect the field measurements of density and moisture content. The accuracy of the measured quantity of water in the soil at the time of compaction directly impacts the laboratory-determined moisture content, which may have a wider range of accuracies.

Table 2.1 Field Tests for Quality Assurance of Compaction.

Test Method	Measurement	Standard
Sand cone	Density	ASTM D1556
Rubber balloon	Density	ASTM D2167
Nuclear gauge	Moisture content and density	ASTM D6938
Dynamic cone penetration	Penetration index	ASTM D6951
Soil stiffness gauge	Stiffness	ASTM D6758
Falling weight deflectometer	Stiffness	ASTM D4694
Light weight deflectometer	Stiffness	ASTM E2583
Electrical density gauge	Density	ASTM D7830
Time domain reflectometry	Moisture content	ASTM D6565

Using a strength- or stiffness-based criterion for compaction QC/QA offers some advantages over density-based criteria. For example, these tests can provide more direct measurements of the soil's engineering properties, such as its shear strength, compressibility, and permeability, which are critical for evaluating the soil's ability to support loads and resist deformation. Furthermore, using these tests can allow for more precise and efficient compaction control, since they can detect changes in soil behavior that may not be reflected in density measurements alone.

2.6 Intelligent Compaction Systems

Over the past two decades, attempts have been made to enhance field compaction control practices by employing intelligent compaction (IC) systems for soils (Mooney 2010; Cai et al., 2017; Hu et al., 2020; Liu et al., 2020). Intelligent soil compaction systems are technological solutions that aid in the construction and maintenance of roads, buildings, and other structures. These systems use advanced sensors and real-time data analysis to optimize the compaction process, ensuring that the soil is compacted to the desired level of density. The system typically consists of a compactor machine equipped with sensors that measure the soil's density and moisture content. The data is transmitted in real-time to a control unit, which analyzes the information and provides feedback to the operator. The operator can then adjust the compactor's settings to ensure optimal compaction. Intelligent soil compaction systems are particularly useful in construction projects where soil compaction is critical for the structure's stability and longevity. By using these systems, contractors can ensure that the soil is compacted evenly, reducing the risk of settling and other long-term problems. Figure 2.2 schematically shows the processes of IC systems (Liu et al., 2020).

Despite the advantages offered by IC, the technology has not been widely adopted in practice for field compaction control purposes. There are several reasons why intelligent soil compaction systems are not yet widely adopted in practice. For instance, The cost of intelligent soil compaction systems can be higher than traditional compaction equipment. This can be a significant barrier for smaller construction companies or those operating on tight budgets. Further, many contractors and construction companies may not be aware of the benefits of intelligent soil compaction systems, or they may not have a clear understanding of how they work. Using intelligent soil compaction systems requires specialized training and expertise. Some operators may be resistant to adopting new technology and prefer traditional methods that they are already familiar with. Also, intelligent soil compaction systems may not be readily available in all regions or countries. The lack of availability can limit their adoption, especially in remote areas. The adoption of intelligent soil compaction systems may be hindered by the lack of regulatory requirements or guidelines. This can result in a lack of standardization and hinder widespread adoption. Overall, while intelligent soil compaction systems have the potential to improve construction efficiency and reduce the cost of maintenance, their adoption may be limited by various factors. As the technology becomes more widely available and awareness increases, their adoption may increase in the future.

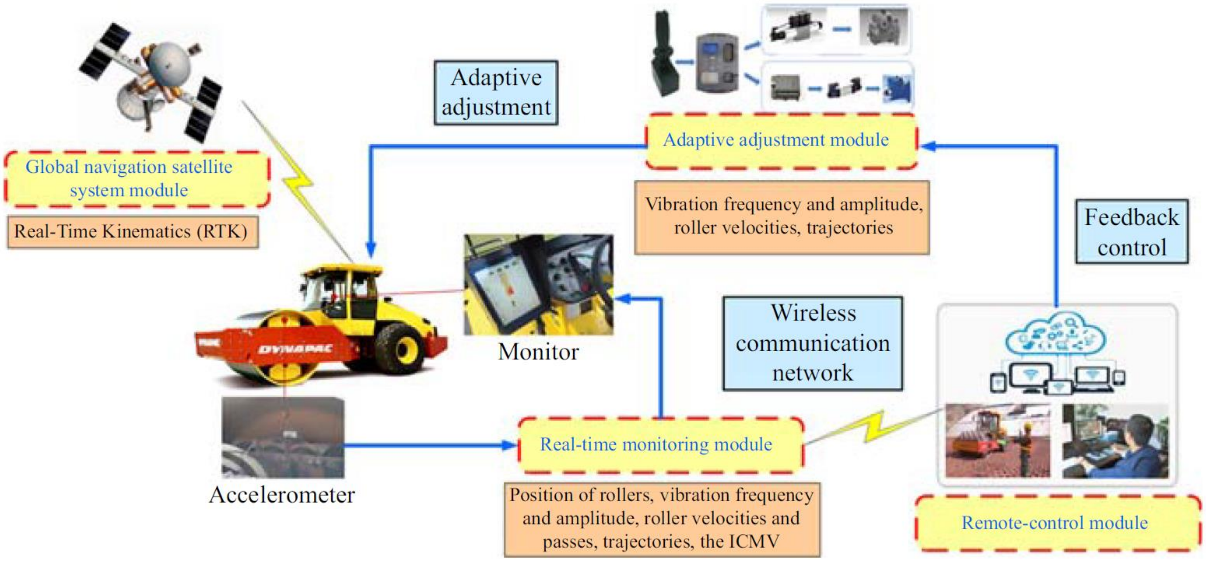

Figure 2.2 Processes of soil intelligent compaction (IC) systems (Liu et al., 2020).

2.7 Recognizing the Role of Saturation on Compaction Effectiveness

The current compaction control practice overlooks the fact that saturation has a major effect on compaction effectiveness. Unsaturated soils (e.g., compacted soils) derive strength from interstitial water that resists compaction. As the water content is increased, the resistance from partial saturation is reduced and greater compaction is achieved. However, at the characteristic degree of saturation, pore water comes into play, reducing saturation. Therefore, the optimal point on any compaction curve demarks the point where the effects of saturation as a resistance mechanism are overtaken by the necessity of moving pore fluid. Thus the saturation at which this resistance mechanism occurs appears to be a characteristic of the soil and lies within a small range for all soils. This relationship can be observed in the compaction plot used in the Proctor method but is not directly used in the compaction control process. Recognizing this limitation, Tatsuoka (2015) and Tatsuoka and Correia (2018) presented the concept of the optimum degree of saturation (S_{opt}) (Figure 2.3) and the $\gamma_d/\gamma_{d,max}$ versus $S\text{-}S_{opt}$ relationship, where S_{opt} is defined as the degree of saturation when the maximum dry unit weight is obtained for a given compaction energy level (CEL) and a given soil, γ_d represents the dry unit weight from the field, $\gamma_{d,max}$ denotes the maximum dry unit weight obtained from the laboratory compaction test (Proctor), and S is the degree of saturation of the compacted soil. They showed that the $\gamma_d/\gamma_{d,max}$ versus $S\text{-}S_{opt}$ relationship is independent of CEL but is related to the physical properties of compacted fills. Tatsuoka and Correia (2018) proposed their compaction quality control methodology based on controlling compacted fills with the values of S_{opt} and the unified compaction curves for a site in terms of the $\gamma_d/\gamma_{d,max}$ versus $S\text{-}S_{opt}$ relationship.

Tatsuoka (2015) and Tatsuoka and Correia (2018) highlighted the importance of controlling the degree of saturation in soil compaction. Tatsuoka (2015) and Tatsuoka & Correia (2018) investigated the physical properties of compacted soils, including their strength, deformation characteristics, hydraulic conductivity, and stiffness indexes before and after saturation. These properties were found to be dependent on the dry unit weight and degree of saturation at the time of compaction. The studies also considered the CEL component in evaluating field-compacted states. Tatsuoka et al. (2021) further demonstrated that compacted soil's stiffness index is related to compacted dry unit weight and degree of saturation at the time of compaction. They proposed a soil compaction control methodology that monitors the soil stiffness index during compaction to achieve a constant compaction effort and soil type while approaching the optimum degree of saturation. This methodology accounts for the fact that the optimum degree of saturation is relatively insensitive to variations in soil type and CEL, unlike the maximum dry unit weight and optimum water content. The current study builds upon Tatsuoka's previous work (Tatsuoka, 2015; Tatsuoka & Correia, 2018) by providing a more detailed and comprehensive analysis of the degree of saturation at the time of compaction in soil compaction control.

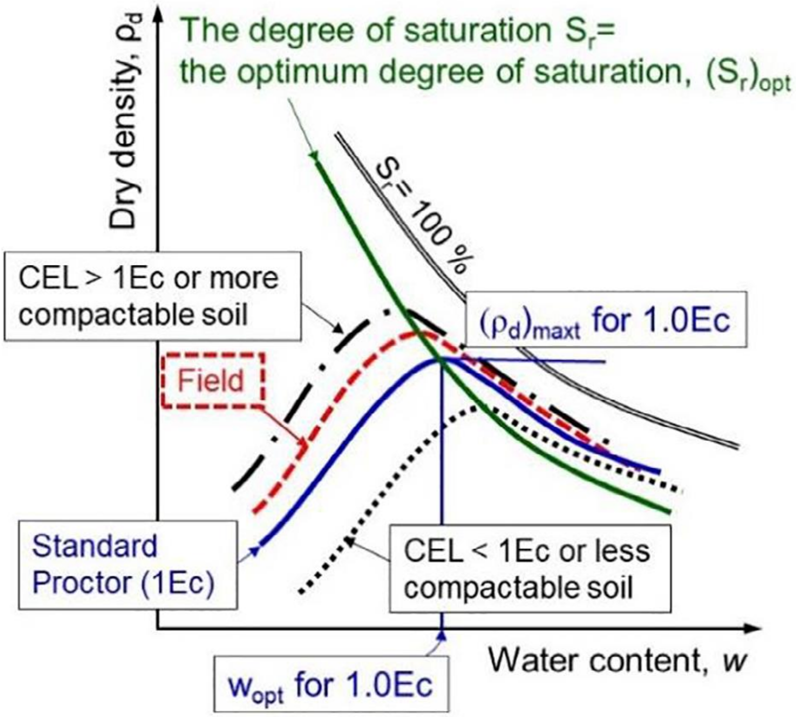

Figure 2.3 Schematic of the optimum degree of saturation and shifting of compaction curve by changes in CEL and soil type and the optimum degree of saturation (Tatsuoka and Correia, 2018).

CHAPTER III

RATIONALE FOR THE NEED TO REVISIT THE EXISTING METHOD

3.1 Introduction

The ideal level of saturation for compaction of fine-grained soils is typically around 80%. Control parameters for compaction can be established based on the required water content to achieve this saturation level for a given in-place dry unit weight. However, the compaction effort needed to achieve the target dry unit weight may or may not align with the results from standard or modified Proctor tests. Therefore, the goal of compaction control is to adjust the compaction effort, lift thickness, and moisture content in the soil to achieve optimal saturation at the target dry unit weight. While water content and compaction effort can be controlled in the field, dry unit weight is the parameter that requires monitoring. The saturation level after compaction is the critical diagnostic variable and should be the focus of monitoring efforts.

Table 3.1 compares the Proctor-based method with the proposed saturation-based framework regarding uncertainties and assumptions in engineering applications. The main motivation behind revisiting the well-established Proctor-based compaction control procedure is to reduce the uncertainties and assumptions of the compaction control process and enhance the outcome for engineering applications. The proposed saturation-based framework compares field-measured dry unit weight normalized by the average maximum dry unit weight and moisture content, which is converted to percent saturation and reported as a difference with respect to the average optimum saturation. The field and laboratory conversion of moisture content to percent saturation is based on the specific gravity of the soil. The average maximum dry unit weight and the average optimum saturation values are derived from an accumulation of Proctor tests completed for each source of soil for the project. Initially, the acceptance criterion is based on a collection of Proctor tests with common compaction energy. However, the acceptance criterion can be based on variables other than compaction energy and initial water content, such as fabric, plasticity, gradation, and other physical properties. Based on the calculated average maximum dry unit weight and average optimum water content, a range of field dry unit weights represents normalizations with respect to the average maximum dry unit weight.

Starting with a given water content, which is typically field-determined at the source (barrow), the target dry unit weight can be determined based on the optimal saturation value. The field compaction effort to obtain the target dry unit weight might not necessarily be represented by the standard or modified Proctor tests. Therefore, proper field control is achieved by applying the appropriate compaction effort to obtain optimal compaction results. If the field compaction effort fails to produce the unit weight needed to meet the performance criteria, the water content must be adjusted to achieve the optimal state of saturation. Thus, the goal of compaction control is to adjust compaction effort, lift thickness, and water content such that the optimal saturation is obtained. The design objective for the soil fill determines the limits of the quality control criteria, whether it is for shear strength, permeability, compressibility, or some combination of objectives. Using results that are assessed based on the state of saturation takes advantage of the limited range of the optimum saturation.

Table 3.1 Comparisons of the Proctor-Based Method and Proposed Saturation-Based Framework Method Regarding Uncertainties and Assumptions in Engineering Applications.

Primary Field Compaction Control Variables Fine-Grained Soils	Proctor-Based Method		Saturation-Based Framework	
	Features	Uncertainties and Assumptions in Engineering Applications	Features	Uncertainties and Assumptions in Engineering Applications
Applied Energy • Types of Field Compaction • Static • Kneading • Vibratory • Lift thicknesses • Number of Passes	• Two compaction energy levels (600 and 2,700 kN-m/m^3) used • Kneading compaction • Min γ_d 90-95% max. γ_d	• Depth of soil improvement • Uniform compaction in a large area • No limits for over-compaction • No adjustment for field to lab compaction energy adjustments	• Same initial compaction energies and models as PM • Average Max γ_d from soil types normalizes Field γ_d values. • Upper boundary to normalize Field γ_d proportional field to average max lab γ_d	• Depth of soil improvements • The range of compaction energy is implied in average values used • The range of Proctors initially used remain representative of specific soil types.
Initial Water Content • Time of process • Range of acceptability	• The goal of effective compaction of highest γ_d at $w_{n,opt}$ • Typical 4% w_n percent range (-2 to +2%, -1 to +3%, etc.) • % w_n function of γ_d	• % water content varies with field changes • %w_n fixed to optimum of lab test even with variable compaction energies	• Compaction as close to $(S_r)_{opt}$ with max γ_d ratio • $(S_r)_{opt}$ approximately aligns with Line-of-Optimums (LOO) • Lower initial w_n at compaction than lab	• Saturation to be converted to a w_n to make corrections in the field (add water or dry) • The average optimum saturation range varies with specific gravity.
Soil Type • Specific Gravity • Shape & Fabric • Gradation & % CF	• Oversize corrections applied based on top size gradation • Some correlations to Atterberg Limits	• Each test tied to an arbitrary but specific combination of Soil Types • Shape, Fabric, and Gradation not tied to Lab %w_n or γ_d • Oversize corrections	• S_r in field corresponds to partial saturation behaviors relating empirical comparisons from index values to physical properties	• Saturation tied specifically to SG and field γ_d • Oversize corrections
Previous Layer Effects	• Not directly considered in PM	• Impacts compaction energy and w_n	• S_r of the previous layer to model impact	Potential for both wet and dry soil water retention curve behavior possible

3.2 Achieving More Uniform Compaction Energy

One of the primary issues with the Proctor-based method is the comparison of variable field results with the laboratory-generated standards (standard or modified Proctor). This comparison becomes even more complicated when multiple laboratory standards are generated. Altschaeffl and Lovell (1968) summed up compaction variables by saying, "It is vital to recognize that the relationships generated in standardized laboratory tests are valid for arbitrary single levels of other potentially important variables." Several authors point out that actual field compaction energy is different than the compaction energy of the laboratory Proctor test. The conclusion is that it is used anyway and typically because of the difficulties of performing field compaction tests for a variety of soils and combinations of soils. It is difficult to track the variables of the compaction process with the two variables of dry unit weight and percent water content.

The Proctor Test is performed at a specific laboratory compaction energy, usually, 600-kN-M/M^3, where the primary variable is the moisture content of the soil during compaction. However, the process of soil compaction in the field involves more variables than just moisture content, such as particle size, gradations, specific gravity, chemical activities of clay fractions, and placement techniques. Placement techniques can affect compaction energy per lift by varying the thickness of layers, using different equipment, and changing the number of passes.

In theory, it is easy to achieve uniform compaction energy by maintaining uniformity in passes, thickness, and equipment consistency. However, the reality is that a particular lift may receive a different compaction effort than the laboratory standard, and the compaction effort can vary from one lift to another. To address the uniqueness of the Proctor test to more soil variations, it is common practice to perform multiple Proctor tests on different soil types and create boundary limits for soil compaction within those physical limits (Figure 3.1). While this procedure can account for physical variability, it does not consider variability caused by placement techniques.

When constructing earthen structures, a larger volume of soil is used, increasing the chances of variability in soil from single or multiple borrow sites. In such cases, a Proctor curve for each physical type of soil must be generated to ensure proper compaction control (Figure 3.1). The construction process involves blending multiple soil types on-site, necessitating even more Proctor curves for the compaction control program. The use of multiple individual Proctor tests leads to the need to identify which Proctor relationship or curve is related to a given field measurement. It should also be noted from Figure 3.1 that the convergence of the "wet" side of the various levels of compaction energies typically ranges from 90 to 95% saturation.

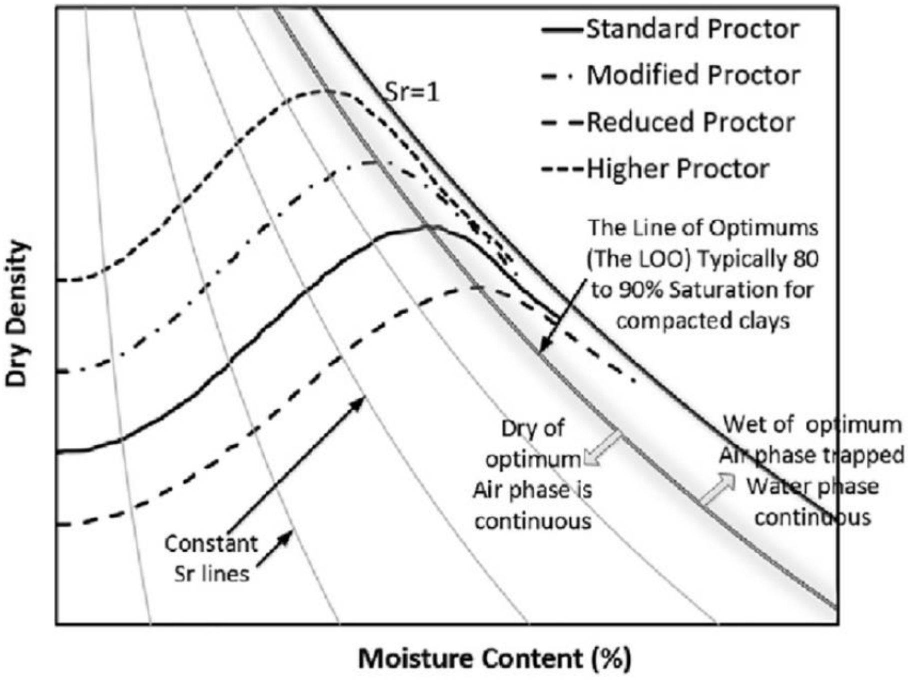

Figure 3.1 Schematic compaction curves for Proctor tests (from Kodikara et al., 2018)

One way to improve the consistency of the compaction control process is by utilizing historically known behavior, such as the saturation of compacted soil, which typically follows a common trend through soil types and compaction efforts. Incorporating such trends into the compaction control process can help reduce variability caused by placement techniques and ensure that proper compaction is achieved throughout the project.

3.3 Reducing Possible Errors Due to Field Judgment

A primary assumption or uncertainty in using the Proctor method is the judgment of field personnel to match the soil compaction results to a Proctor or multiple Proctor tests, as noted by several authors (Lambe and Whitman, 1969; Holtz et al., 2011; Handy and Spangler, 2007). Traditionally, the Proctor test plot is used as a reference, and the results are directly plotted onto the plot to create "judgment" zones. However, variations in soil properties, compaction energy, and placement techniques can introduce uncertainties and assumptions in this step. The Saturation-Based framework can reduce some of these difficulties by providing a wider range of soil types and compaction energies.

3.4 Avoiding Over-Compaction

One of the primary assumptions or uncertainties when using the Proctor Test to compare field compaction results is the amount of compaction energy used. If the field compaction energy exceeds the Proctor Test energy (1Ec), the soil's behavior changes, resulting in a higher maximum dry unit weight and lower optimum moisture content. However, caution must be exercised when the field dry unit weight exceeds 100%, as it is typically referenced to the original moisture range, which may have an expanded wet range. For example, landfill liners may have a wet range of 0 to +4. If higher field compaction energy is applied to such soil, it could result in an over-compaction condition, particularly when the soil state approaches full saturation, and greater compaction effort is needed to overcome an impossible condition on the wet side of the line of optimums.

Multiple references have raised the issue of over-compaction. According to Handy and Spangler (2007), if compaction is continued for too long or if the soil is too wet, compaction pressure is transferred to the soil water, which has no resistance to shearing. This results in the soil shearing internally, reorienting and smearing clay particles along the shear planes. Such soil is said to be over-compacted and is permanently damaged by shear planes and slickensides. Moreover, continued application of compactive effort after soil reaches near-saturation point not only wastes energy but also redirects the energy into shearing and remolding the compacted and nearly saturated soil. Mitchell and Soga (2005) indicates that for water content wetter than the optimum if the compaction effort is high enough, the compaction rammer penetrates the soil surface due to a bearing capacity failure under the rammer face. This leads to the alignment of particles along the failure surfaces. Tatsouka (2015) notes that compaction at water content higher than "w_{opt} for 1Ec" is often recommended in practice to avoid large collapse deformation and a large decrease in the strength and stiffness upon wetting. However, "w_n higher than w_{opt} for 1Ec" becomes considerably higher than "in-situ w_{opt} " if the field CEL is much higher than 1Ec. In that case, compaction would become inefficient, and even over-compaction may take place.

Overcompaction is a situation that should be avoided in the field as it is a condition where increased compaction energy does not result in a consistently increased dry unit weight of the soil. In practice, some people keep rolling a lift until it "dries out." However, this is not a recommended approach. The superimposed graph of Proctor tests and field data points shows that there is a potential for choosing a Proctor that would indicate that over-compaction is possible or that it was a passing test depending on the choice made in the field. As more compaction energy is applied to each lift, the optimum water content will shift drier, and the actual placement water content will approach an over-compaction condition. The saturation-based methodology tends to correct this by being a vertical relationship with increased compaction energy with respect to the optimal degree of saturation and by placing upper limits on the target compaction goals.

3.5 Untapping Advances in Unsaturated Soil Mechanics

The compaction of soil, by definition, requires that the soil be placed and compacted in an unsaturated state. However, the practice has been to compare the Proctor test results to laboratory test results performed on saturated specimens. Multiple studies demonstrate soils compacted in unsaturated states can exhibit significantly different physical properties as compared to the results of saturated laboratory tests (Nishimura et al., 1999; Ng et al., 2007). For example, the compaction of soil with low water contents can create an apparent strength that cannot be sustained upon saturation (Sun et al., 2004).

In 1956, Hilf demonstrated that the pressure within the voids of a soil mass, u_a, that has been compressed without allowing the escape of pore fluids, can be calculated by combining Boyle's law of compressibility of air and Henry's law of solubility of air in water:

$$Iu_a = \frac{P_a * \Delta e}{e_{a_1} + h * e_w} \tag{3.1}$$

Where: P_a = atmospheric pressure

Δe = change in void ratio during compression without drainage

e_{a_1} = air void ratio after compression

e_w = water void ratio

H = coefficient of solubility of air in water by volume

The equation illustrates the method for calculating pore water pressure within partially saturated compacted fill materials. Later, we will explore how this calculation affects the shear strength and compressibility of the compacted fill material during placement.

The initial remolding water content significantly affects the soil-water retention curve (SWRC) and the soil fabric (Tinjum et al., 1997; Taylor et al., 2017). The SWRC is useful for showing how compaction conditions, index properties, and mineralogy affect the unsaturated physical properties (Tinjum et al., 1997). The same initial remolding water content has been demonstrated to affect the shape (generally flattening from cohesionless to cohesive soils) of the SWRC, as shown in Figure 3.2. However, in typical fine-grained soils, increasing compactive effort results in smaller pores. For the same compaction water content, the air-entry suction (typically the differential pressure between the air and water required to cause desaturation of the largest pores) is generally higher, and the slope is slightly steeper for soils compacted with greater compactive effort. The higher air entry suctions are obtained for more plastic soils and when compacting wet of optimum water contents or higher compaction effort.

According to Vanapalli et al. (1996), the distinguishing features of the SWRC depend on several factors such as soil structure, initial molding water content, void ratio, type of soil texture, mineralogy, stress history, and method of compaction. Figure 3.2 shows that typical ranges of initial water content are in the transition zone of the SWRC. Of the factors stated, the stress history and initial molding water content seemingly have the most influence on the soil structure, which in turn dominates the nature of the SWRC for fine-grained soils. Resistance to desaturation of remolded soils is relatively low in the dry of optimum specimens compared to optimum and wet of optimum soils. Compared to soils compacted dry of optimum, the microstructure in the specimens compacted wet of optimum controls and resists the desaturation characteristics of the soil. This creates an SWRC that is flatter for the wet of optimum soil compared to the dry of the optimum initial water content soil, which has a lower suction range where the desaturation was attained by liquid-phase drainage (Vanapalli et al., 1996). Several of these studies identify soils compacted at optimum to the wet of the optimum conditions were less dependent on stress history. Table 3.2 lists the implications of the SWRC on compacted fine-grained soils.

By incorporating partial saturation behavior at a designated or optimum degree of saturation, the compaction process becomes more predictable and controlled. Considering the state of soil saturation during compaction provides insights into the as-compacted layer's shear strength, compressibility, and permeability, using unsaturated soil mechanics. Implementing a saturation-based quality control program enables current compaction practices to monitor the potential risks associated with over-drying the soil, which can result in inadequate long-term strength and compressibility behavior.

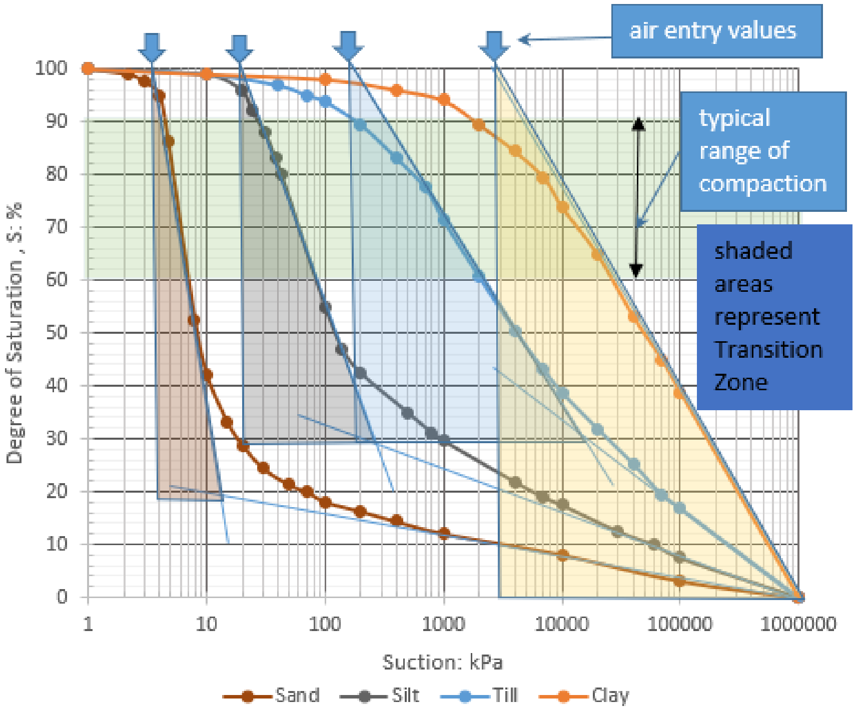

Figure 3.2 Typical soil-water retention curves for different soil types along with the range of compaction saturation.

3.6 Relating the Design Shear Strength of Compacted Fill to Field Shear Strength

Soils compacted at different degrees of partial saturation can exhibit significant differences in their physical properties, including shear strength. Compaction water content, compactive effort, and plasticity can affect the SWRC, as demonstrated by Tinjum et al. (1997). Empirical equations have been developed that relate the van Genuchten parameters α and n to compaction conditions and plasticity index, providing a means to describe the SWRC during the design phase. Relating these compaction parameters to the unsaturated soil behavior model helps in adjusting the saturation-based model limits.

In the laboratory, shear strength is typically measured in a completely saturated state, while field conditions involve unsaturated soils. Hence, it is essential to document the design shear strength of the soil required for a project through a quality control program. For example, where a design requires an effective friction angle of 30 degrees to maintain the exposed designed slope of an embankment at a specified factor of safety, the acceptance criterion should result in at least an effective friction angle of 30 degrees. Therefore, it is crucial to understand the impact of partial saturation on field data when compared to the required design strength parameters. Until the post-compacted soil in the field is fully saturated, either by compression from additional lifts of soil or the influx of water from percolation of surface water or by seepage, the actual strength of compacted soil is controlled by the partial saturation state conditions.

Table 3.2 Implications of the SWRC on Compacted Fine-Grained Soils

Implications of SWRC on Compacted Fine-Grained Soils	**SWRC Features**	**Dry of Optimum Saturation**	**At Optimum Saturation**	**Wet of Optimum Saturation**
General Characteristics	• SWRC features depend on: • soil structure, • initial molding • water content, • void ratio, • soil texture, • mineralogy, • stress history, • compaction method • Defining different compaction behavior with zones within SWRC • Shape of the SWRC is independent of γ_d	• Soils contain a bimodal pore-size distribution with the larger macropores between clods not remolded in compaction • Resistance desaturation is relatively low compared to opt. and wet of opt. soils.	• Slope of SWRC is independent of γ_d	• Ψ_a does not appear to be strongly dependent on the applied stress history
Compactive Effort or Energy	• Compaction w_n influences SWRC more than density. • SWRC and saturated shear strength parameters predict variations in strength wrt suction	•	• Increasing compactive effort results in smaller pores and thus affects the shape of the SWRC. • Ψ_a is generally higher and the slope is steeper for soils compacted with greater compactive effort	
Type of Soil	• More plastic soils should exhibit higher Ψa because more plastic soils typically have smaller effective pore sizes. • Soils that have broad unimodal pore-size distribution that contains microscale pores. Soils compacted to the same γ_d at compaction w_n dry and wet of optimum content have different pore-size distributions.	• Macrostructure governs the SWRC behavior for specimens compacted dry of optimum.	• Higher plastic soils should exhibit higher Ψ_a Higher plastic soils have smaller effective pore sizes. • Higher Ψ_a are obtained w/ higher plastic soils when compacting wet of optimum water content or with higher compactive effort.	• Higher Ψ_a are obtained for higher plastic soils when compacting wet of optimum w_n or with higher compactive effort • SWRC is steeper for and slightly shallower for higher PI • Microstructure governs the SWRC behavior of specimens compacted wet of optimum.
Initial Remolding Water Content	• Stress history and initial molding w_n have high influence on the soil structure dominates the SWRC • Higher initial water contens results in higher AEV			Pore spaces in clay are not generally interconnected or are in an occluded state.

CHAPTER IV

PROPOSED SATURATION-BASED COMPACTION CONTROL FRAMEWORK

4.1 Introduction

Figures 4.1a and 4.1b are illustrative to assist in the description of what the proposed saturation-based methodology proposes. Figure 4.1a provides an illustrative example of multiple potential Proctor outcomes based on different laboratory Proctor results. It depicts an example field unit weight point plotted in relation to four laboratory Proctor points. When assessing the field results in comparison to the laboratory Proctors, engineers typically rely on their judgment to align the field results with a laboratory Proctor curve. This figure aims to demonstrate that the chosen judgment can significantly impact the anticipated engineering properties of the soil. Figure 4.1b illustrates the proposed saturation-based methodology to address the scenario depicted in Figure 4.1a. The underlying principle of the proposed methodology is to establish a critical degree of saturation for a group of soils, reducing the need for subjective judgment in the field. By implementing a methodology based on saturation, the potential for variations introduced by field judgment is minimized, offering a more objective approach to soil assessment. These figures serve to highlight the importance of decision-making in soil compaction analysis and its impact on engineering properties. The proposed saturation-based methodology offers a promising alternative by providing a more standardized and reproducible approach to assess soil compaction characteristics.

Figure 4.1a presents a typical Proctor test, showing the relationship between dry unit weight and moisture content. In contrast, Figure 4.1b displays the ratio of the maximum dry unit weight to the saturation difference relative to the optimum degree of saturation employed in the proposed saturation-based framework. Tatsuoka (2015) found that this saturation-based relationship with normalized dry unit weights is less sensitive to the variability of the applied compaction energy and the soil type in the field and the laboratory. Other studies (e.g., Taylor et al. 2017) have also used normalized unit weight to relate the relative behavior of multiple soils with similar characteristics. Figure 4.1b shows the normalized, saturation-based display of multiple standard Proctor tests and the proposed saturation-based compaction criterion. In Figure 4.1b, the labels -1% and +3% represent the degree of saturation corresponding to -1% and +3% of the optimum moisture content, respectively. The constant moisture content lines in the figure are not linear but exhibit slight curvature. It should be noted that Figure 4.1b is primarily intended as an illustrative representation, and alternative limits (e.g., -2%/+2%) can be adopted based on the specific requirements and specifications of individual projects.

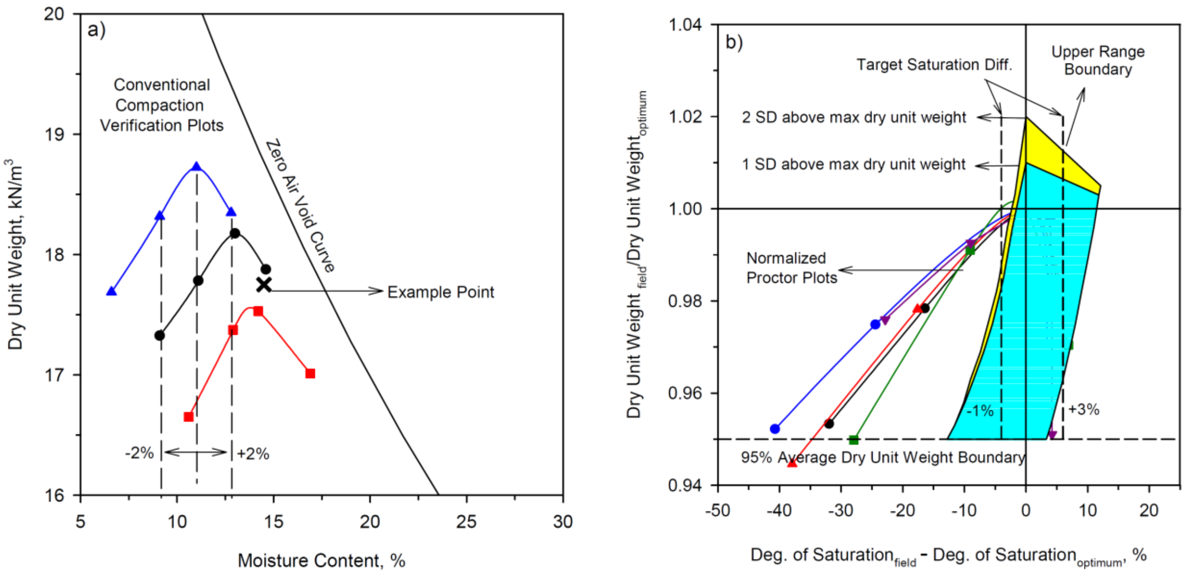

Figure 4.1 Schematic compaction curves, a) range of values for Proctor tests, b) saturation-based framework.

4.2 Acceptance Criteria

The conventional Proctor-based method uses a combination of moisture contents and dry unit weights as the acceptance criterion. The range of moisture contents is typically -2% to +2% (or -1% to +3%) of the optimum moisture content (OMC), and the dry unit weight should be 95% or more of the specific test (Figure 4.1a). In contrast, the saturation-based controlled fill's acceptance criterion is expressed as a ratio of the maximum dry unit weight, and the ratio is plotted against the saturation difference to the optimum degree of saturation (S_{opt}) for a range of soil tests (Figure 4.1b). The x-axis of the proposed saturation-based compaction criterion shows the difference between the field-measured degree of saturation and the optimal average saturations from the laboratory Proctor standard. The y-axis in Figure 4.1b displays the normalization of measured dry unit weights with respect to the maximum dry unit weight of each compaction curve obtained at a specific CEL and soil type. This normalization ensures that the maximum value of y is always equal to 1.0 for each compaction curve. Subsequently, Figure 4.1b plots each field data using a y-axis that indicates the normalization of field-measured dry unit weights with respect to the average maximum dry unit weight. The proposed criterion's right and left boundaries are set based on saturation differences that relate to moisture control in the field, and the upper and lower boundaries are set concerning the normalized dry unit weight. The field dry unit weight is normalized by the average of the maximum dry unit weights from the laboratory Proctor tests.

Figure 4.1b presents the boundaries for positive and negative saturation differentials. It should be noted that the negative saturation differential boundary depicted in Figure 4.1b may not identify inadequate compaction at very low saturation levels, with dry unit weights only slightly above the permissible lower limit (95% of the maximum dry unit weight). In such cases, the coefficients of hydraulic conductivity may be very high. Further research is necessary to determine the allowable upper and lower boundaries of S-S_{opt}. Tatsuoka and Miura (2019) presented a case study on soil compaction control for the construction of an earth fill dam, in which a suitable lower bound of the degree of saturation was set to reject subpar compaction states. Based on the case histories, vertical limits of the saturation differential were found to be in the range of 10-12% total differential. For instance, a target range of -4% to +8% could be considered as a good benchmark for most of the data. The target saturation area in Figure 4.1b was developed using the broadest available field data collected. However, further refinement of the saturation limits might be necessary to improve the accuracy and applicability of the criteria. The findings of Tatsuoka and Miura (2019) provide valuable insights and suggest the need to revisit and fine-tune the saturation boundaries.

The proposed saturation-based methodology's upper and lower boundaries share similarities with the Proctor-based method. The lower boundary for both approaches is set at 95% of the average maximum dry unit weight. The upper boundary (Figure 4.1a) is extended above the level represented by the average of the maximum dry unit weight ratios. A two-part boundary is defined using the average maximum dry unit weight ratio that reflects the bandwidth of the average ratio. The upper target is increased by one and two standard deviations of the average maximum dry unit weight ratios at the point represented by the average optimum saturation. The positive saturation differential boundary intercepts with the projections of the high dry unit weight ratio with the zero-air-ratio saturation difference. Figure 4.1b shows a vertical line at the differential saturation value of zero. The positive saturation differential boundary lies to the right of this vertical line and intercepts at the maximum average optimum dry unit weight ratio value of 1.0. The negative saturation differential boundary lies to the left of this vertical line. An upper boundary is required because a maximum average optimum dry unit weight ratio is being used and target increases of one and two standard deviations of that average were set as target limits that were expected to occur.

4.3 Step-by-Step Process

The flowchart presented in Figure 4.2 facilitates a comparison between the proposed saturation-based method and the conventional method for the field compaction quality control system. The side-by-side comparison of the steps performed in the proposed saturation-based method and the conventional method is presented in the flowchart. Table 4.1 compares the steps to be taken by engineers (designers), earthwork inspectors, and contractors for each method.

The overall procedure of compaction control is grouped into three different zones, as shown in Figure 4.2. Zone I represents the pre-construction activities for both methods. In this pre-construction preparation, the borrow source materials are identified and tested for index testing, such as visual descriptions, grain size distribution, specific gravity, and Atterberg Limits. For each specific soil group identified, a Proctor test is performed. Depending on the intended application of the soil materials, it may be necessary to conduct additional tests to determine minimum shear strengths, maximum permeability, swelling potentials, and compression characteristics. These tests are performed at predetermined quality control reference limits, which are typically established during the design phases of the soil structure. The specific quality control reference limits can vary depending on the desired use of the soils. These limits can be established through laboratory testing or empirical correlations, depending on the suitability and availability of the respective approaches. The purpose is to ensure that the soil materials meet the necessary requirements for their intended application, and the establishment of these quality control reference limits aids in achieving the desired performance and durability of the soil structure.

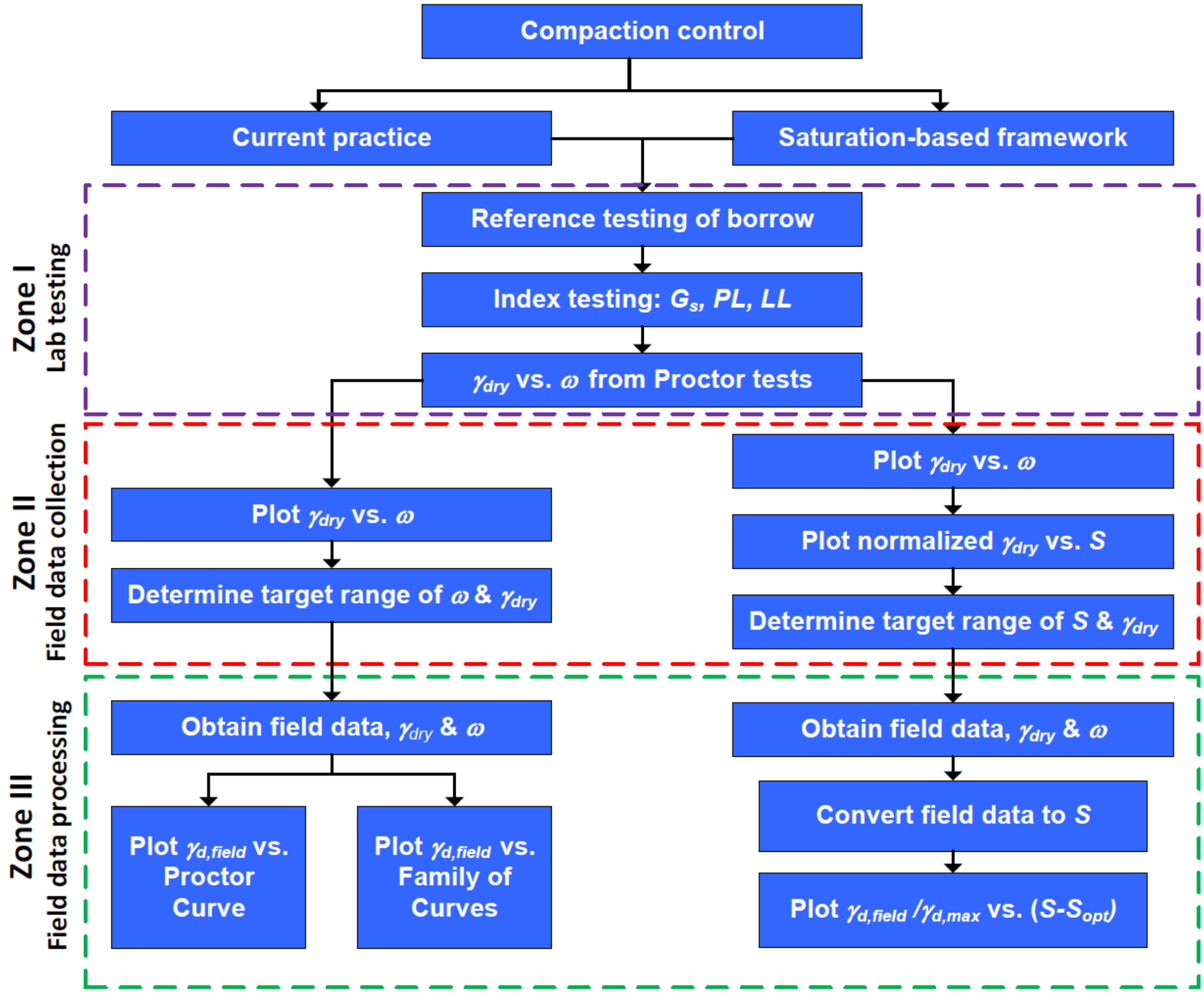

Figure 4.2 Proposed saturation-based framework versus the conventional method for field compaction quality control system.

At this point, the target limits to be generated by the field compaction will be generated for the Proctor and saturation-based methods. The Proctor-based methodology will present target ranges of dry unit weight versus moisture content at the dry unit weight for specific Proctor tests. In contrast, the saturation-based methodology is based on having at least five Proctor tests initially. From the multiple Proctor tests, an average maximum dry unit weight with an average optimum percent saturation for the collection of Proctor tests will be generated. The saturation values will be calculated from the water contents of the Proctor tests by using either the assumed specific gravities (not preferred) or the average specific gravities of the soils collected. Based on these values, target limits for soils being placed will be represented by a normalized dry unit weight and a difference between the field saturation and the average optimum saturation. The saturation-based framework's target limits will be based on the normalized dry unit weight and the difference between the field saturation and the average optimum saturation. These target limits will allow the comparison of the field's performance to the design performance of the fill materials, enabling real-time adjustments of the compaction equipment to meet the design requirements.

In Figure 4.2, Zone II represents the actual field data collection. Both methodologies require measuring the in-place wet unit weight and water content of the compacted soil. There are various ways of obtaining these measurements, including drive tubes, balloon methods, sand cones, and nuclear densitometers for measuring wet unit weight. The procedures for obtaining water content also vary, such as field drying with hot plates and scales, chemical (speedy carbide), electrical, and nuclear procedures. Despite the accuracies, uncertainties, and assumptions of these methods, dry unit weight and water content are obtained at each location tested. Other information is collected, such as the source of soil material, lift thickness, location of tests horizontally and vertically, air temperature (and perhaps humidity), equipment used, and the number of passes, to varying degrees of consistency. In the saturation-based framework, in addition to calculating the dry unit weight, the dry unit weight ratio, the saturations, and the saturation difference will also be calculated.

Zone III shows the actual field data plotted against the established criterion for acceptable performance in Zone II. To illustrate this, a single representative data point is plotted on both methodologies in Figures 4.1a and 4.1b. The data point in Figure 4.1a could belong to any of the three different Proctor relationships shown: a point that is very wet of the optimum moisture content at a low dry unit weight; a point within the acceptable wet range from the optimum moisture content at an acceptable dry unit weight; or a point near the optimum moisture content and at a higher than maximum dry unit weight. A field evaluation is needed to determine which Proctor relationship the field density data point belongs to and to accept or reject that field test. The same data point is plotted from the same field information on the saturation-based curves and is shown in Figure 4.1b. Both plots show a typical range of results acceptable for the designed performance for the remolded soils. The normalized saturation plots show a more focused "target" area for the groups of soil being compacted at the fill site. Figure 4.1b normalizes each Proctor test based on the results of the individual Proctor and shows the proposed compaction acceptance criterion developed from the case history. As more data points are obtained, the saturation-based framework provides a more focused means of providing quality control.

4.4 New Features and Proposed Changes

The proposed saturation-based framework introduces several new features and changes that offer advantages over traditional methods:

Instead of relying on a single test result, the methodology considers a range of tests to provide insights into variables such as gradation, fabric, and soil type that can impact compaction performance. For example, on a large project with multiple laboratory Proctor relationships for multiple borrow areas, the performance acceptance criteria is based on the site instead of individual Proctor tests. This reduces the complications involved in selecting the Proctor results that match to a placed material. It also reduces the occurrence of selecting a Proctor result that provides a “passing” target value without matching it to an accurate material type.

The normalization of the dry unit weight with the average maximum dry unit weight and the average optimum degree of saturation takes advantage of the relationship between compaction effort and moisture content. This results in a more precise vertical positioning on the plot, as the degree of saturation remains relatively constant even as the dry unit weight increases and the moisture content decreases.

To ensure the effectiveness of the methodology, the range of collected Proctor tests needs to be grouped into limited zones rather than being left to visual classification by field personnel. This approach allows for additional data to be added to the groups as the project proceeds, enabling adjustments to be made to the group results. This is similar to how the line of optimum is adjusted over time with additional Proctor tests. However, it should be noted that the methodology is not a one-size-fits-all solution, and specifications may require additional testing based on the volume of material placed. By incorporating these additional data points into the groupings, the methodology can remain effective even as new data is collected over the course of the project.

Further, the proposed saturation-based methodology presented in this study distinguishes itself from the prior related works (Tatsuoka, 2015, Tatsuoka & Correia, 2018, Tatsuoka & Miura, 2019) by utilizing a group of soils to determine an optimal saturation level for a specific set of borrow soils. This methodology also normalizes the optimal average level of saturation to the maximum dry unit weight. The proposed methodology relies on leveraging existing historical data and categorizing the soils into appropriate groups based on relevant criteria. By grouping the soils accordingly, it becomes possible to establish an optimal saturation level specific to each soil group. This optimal saturation level is then correlated with the maximum dry unit weight, providing a normalized reference for compaction assessment. By employing this approach, the proposed methodology offers a practical and efficient means of determining the ideal saturation level for different groups of borrow soils. This utilization of existing historical data not only streamlines the process but also enhances the reliability and applicability of the methodology.

Table 4.1 Steps to be Taken by Engineers (Designers), Earthwork Inspectors, and Contractors for Proctor-Based Method and Proposed Saturation-Based Framework

	Proctor-Based Method	Saturation-Based Framework
Engineer (Designer)	- Determine minimum physical properties to be achieved by the compaction quality control program, such as the undrained shear strength at the end of construction, drained (long-term) shear strength, permeability, and compressibility. - Assess the available borrow materials to relate the above properties to laboratory or empirical relationships: γ_d and $\%m_w$ from Proctor testing and index testing, amount of material placed per lift, source and consistency of the soil materials used, rate of construction - Prepare specifications to achieve the design results - Prepare instructions for what can be done for soil materials that fail the job specifications.	- Determine minimum physical properties to be achieved by the compaction quality control program, such as the undrained shear strength at the end of construction, drained (long-term) shear strength, permeability, and compressibility. - Assess the available borrow materials to relate the design properties to the laboratory or empirical relationships: o Collect from each borrow area and soil type a representative amount of Proctor testing and index testing (including specific gravity) based on potential volumes. o Determine for each source an average optimum degree of saturation and an average dry unit weight and assess the number of criteria zones needed. o Determine limits to attain the design parameter for project o Adjust the limits based on anticipated partial saturation behavior from tests or empirical o Prepare Specifications to achieve the design results o Prepare measured dry unit weight to degree of moisture content based on average optimal degree of saturation (so moisture added or to be dried can be estimated in the field)
Earthwork Inspector	- Document the placement of remolded soils relative to the following: source of the borrow material, moisture content at borrow site, moisture content of received soil, Atmospheric conditions (temperature, humidity, precipitation, etc.), the elevation of the lift being placed, location of the lift being placed, the thickness of the lift being placed, truck count estimate of the volume of material delivered to lift, equipment being used on the lift being placed, number of passes on lift being placed, location and elevation of moisture and density test - Check the type of Proctor test that should be used - Check against the specifications for compaction criteria: plot results on Proctor used for reference criteria, proper dry unit weight, proper moisture content - If the criterion was not met, then: based on γ_d and $\%m_w$ make a decision to perform a new Proctor or Develop a LOO and perform a 1-point Proctor	- Document the placement of remolded soils relative to the following. The same items as Proctor test down to "type of test" then: o Assess which criteria zone should be used based on the source - Check against the specifications for compaction criteria: compute dry unit weight ratio, degree of saturation, and the saturation difference with the average optimum degree of saturation, and plot the results - If outside acceptance criteria to the right, assess what % moisture needs to be reduced. If outside to the left, assess how much additional water needs to be added. If outside below, increase compaction effort, decrease lift thickness, and add or reduce water according to location. If outside above, assess if the criteria zone is correct or needs additional data.
Contractor	- Determine the effort needed to achieve the site specifications - Determine the time needed to perform the testing - Determine the time needed to receive the results back for making changes - Assess the delay required for a failing test	- May be some initial delays in developing the results on site due to familiarity, which should taper off with time. - Produces the same information needed from Proctor testing.

CHAPTER V

CASE STUDY: LAKE WINNEBAGO DAM EXPANSION PROGRAM

5.1 Introduction

To illustrate the benefits of the saturation-based approach, we applied it to the compaction data from a real-world case study and compared it to the conventional method. The study involved the construction of a large earth dam as part of the Lake Winnebago Dam expansion program in western Missouri. The dam comprised several zones of earthen construction, and we also examined the shear strengths in the upper lifts of compacted embankment soil. Compaction control is critical during the construction of large earth dams as it ensures the proper placement and density of soil materials used in the dam's construction. The dam's strength, stability, and durability depend on the quality of the construction and, in particular, the compaction of the soil used to build the dam. If the compaction process is not controlled correctly during dam construction, it can result in soil voids, uneven settlement, and poor shear strength. This can lead to a decrease in the dam's stability, an increase in seepage and erosion, and ultimately, failure of the dam. To ensure proper compaction, compaction control is typically achieved through a quality control program that involves frequent field testing and laboratory analysis of soil samples to ensure that the soil is compacted to the desired density and meets the required specifications. Compaction control is essential during the construction of large earth dams to ensure the safety, stability, and long-term durability of the dam.

5.2 Dam Geometry and Soil Properties

Figure 5.1 depicts the cross-section of Lake Winnebago Dam and the plan area where the borrow materials were obtained. The embankment dam featured upstream and downstream slopes of 3:1, with a 12-meter-wide berm on the downstream face constructed at the elevation of the permanent pool. This provided an effective width of over 46 meters at the elevation of the permanent pool. The dam was 20 meters high and 305 meters long at the crest, with a designed storm volume capacity of 1,345 hectares-meters. Table 5.1 provides the physical characteristics of the high and low-plasticity clays that were identified during the field investigation. The plan view shows the location of the borrow areas where the Proctor tested were obtained.

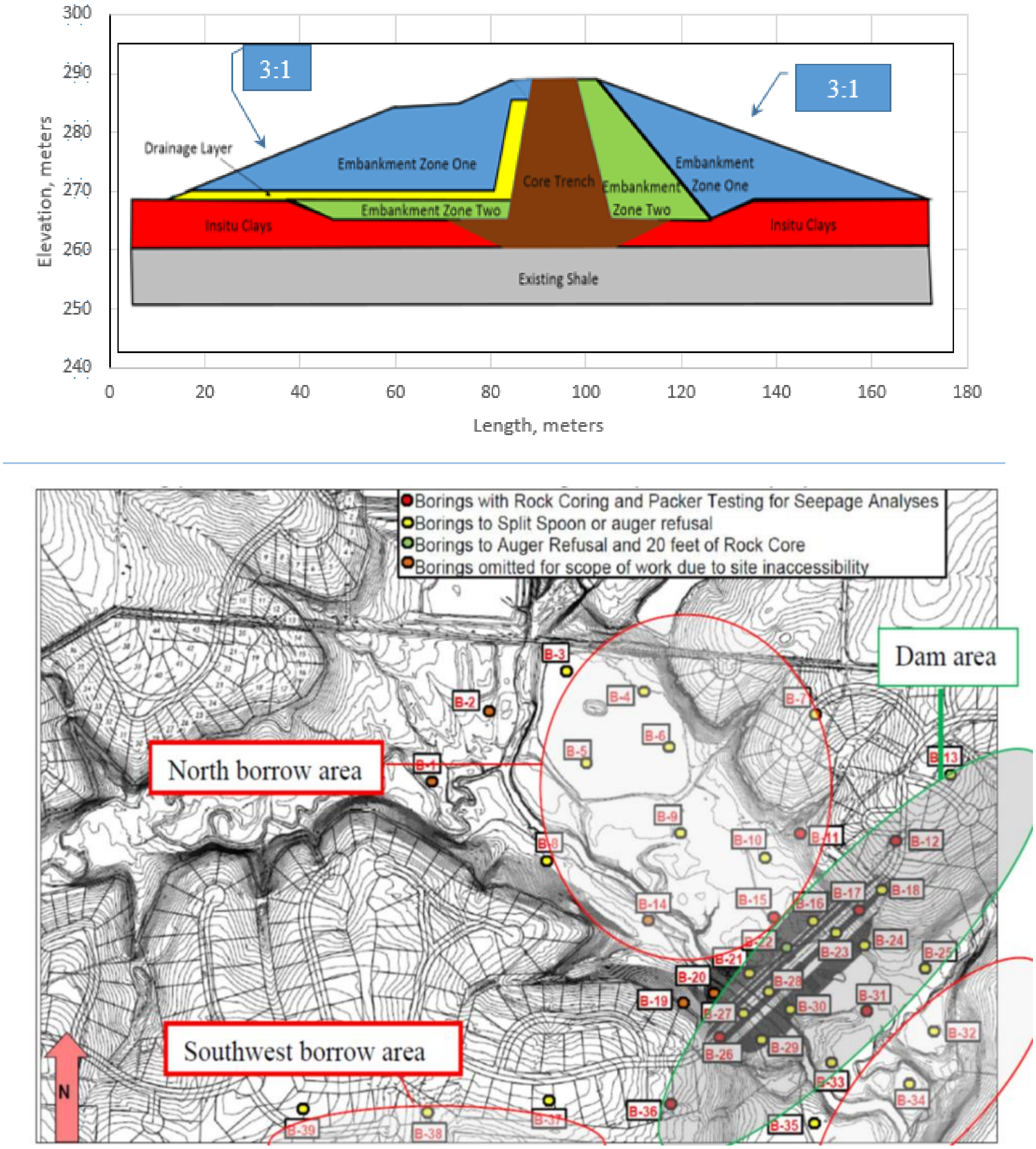

Figure 5.1 Cross-section and plan view of Lake Winnebago Dam in western Missouri.

Table 5.1 Range of Soil Properties for Two Borrow Areas used for Clay Core.

Borrow Areas	Moisture Content, %	Dry Unit Weight, kN/m^3	Unconfined Compressive Strength, Qu (kPa)	Liquid Limit, %	Plastic Limit, %	Percent Fines, %	Permeability, cm/s	Optimum Moisture, %	Maximum Dry Unit Weight, kN/m^3
High Plasticity	21-36	12.72 -15.24	95.76 - 201.10	50-86	14-27	97.1%	1.8×10^{-8}	18.0 - 25.5	15.10 - 16.12
Low Plasticity	21-27	13.51 -14.92	19.15 - 134.06	34-47	17-23	97.7- 99.2	2.42×10^{-8}	17.5- 19.0	16.10- 16.92

A construction timeframe of 2+ years generated 2,460 field density tests collected from three basic zones of the dam while placing approximately 300,000 m^3 of soil. The following summarizes the results for each zone:

- Central core zone – 860 tests in silty clay soils placed up to +3% wet of optimum
- Upstream structural shell zone – 1100 tests in silty clay soils placed -1 to +3% wet of optimum
- Downstream structural shell zone – 500 tests in silty clay soils placed -1 to +3%wet of optimum

The analysis in this dissertation focuses solely on the data collected from the central core zone clay soils of the Lake Winnebago Dam. To compare the proposed saturation-based approach with the conventional method, we selected three of the 26 Proctor soil groups used as quality references, enabling us to work with smaller subsets of 100 to 200 field dry unit weight data. Figures 5.2a and 5.2b present the 26 Proctor curves for the compacted core clay soils, plotted against the proposed saturation-based compaction criterion. Figures 5.3, 5.4, and 5.5 illustrate smaller groupings of field data collected at different times during construction and compare the Proctor-based criterion with the saturation-based compaction criterion. These figures demonstrate how the proposed approach provides additional insights, especially in the core zone, where dry unit weights ranged from 15.6 to 16.8 kN/m^3, and moisture content was between 18% and 22%. In the central core zone, we conducted 26 standard Proctor (E1) tests, the results of which are summarized in Table 5.2.

Table 5.2 Summary of Standard Proctor Results for Central Core Zone.

Parameter	Dry Unit Weight (kN/m^3)	Optimum Moisture Content (%)	Optimum Degree of Saturation (%)
Maximum	16.78	24.8	92.3
Minimum	14.73	16.7	78.8
Average	16.20	18.9	83.0

5.3 Compaction Control Results and Discussion

Figure 5.2a presents the field Proctors utilized for a specific zone in the embankment, showcasing the comprehensive range of data points. Figure 5.2b illustrates the relative positions of each Proctor with respect to individual saturation differences and maximum dry unit weights. Furthermore, Figure 5.2c combines the data from Figure 5.2b to create a composite representation, considering the average optimum saturation differential and the average maximum dry unit weight. It is noted that further refinement beyond an overall average might be necessary. Recognizing the inherent variability within the field data, additional analysis and fine-tuning are warranted to capture more nuanced trends and patterns. By conducting a more detailed examination of the data, we can gain a deeper understanding of the specific factors influencing the Proctor measurements in the given embankment zone. This refined analysis will enable us to make more informed decisions and develop appropriate strategies that better reflect the unique characteristics of the area under consideration.

Figure 5.3a depicts the complete set of field data points for the clay zone, which were compared to a single specific Proctor test. Similarly, Figures 5.4a and 5.5a also represent the field data in comparison to a single specific Proctor test. On the other hand, Figures 5.3b, 5.4b, and 5.5b showcase the field data in relation to averaged saturation-based criteria, which were developed using multiple Proctor tests. These figures aim to demonstrate how the averaged saturation-based criteria compare to the single Proctor test comparisons.

In Figures 5.3b, 5.4b, and 5.5b, a composite average of the saturation-based data obtained from the field was utilized to establish the limits, considering the entirety of the data points collected for the specific placement location. These figures present a comparison between the historical data, which were derived from a single Proctor test, and the composite saturation-based comparison. By incorporating the composite average derived from multiple field data points, it is aimed to capture a more comprehensive and representative understanding of the saturation characteristics at the placement location. This approach allows for a more nuanced and accurate assessment when comparing it to the historical data derived from a single Proctor test.

The process of establishing field control limits for the soils involves index and reference testing, which helps determine the acceptable ranges of the results. Zone II in Figure 4.2 displays the established limits. For instance, after performing 26 standard Proctor tests on the soils in the core zone, the degree of saturation was calculated for each point along the Proctor curve (assuming a specific gravity of 2.65). The proposed saturation-based compaction criterion, based on Tatsuoka and Miura's (2019) methodology, normalized the dry unit weights of the Proctor points with respect to the maximum dry unit weights for each individual Proctor test and plotted them against the difference between the test saturations and the optimum saturations for the soil (Figures 5.2a and 5.2b).

While Figure 5.2b illustrates the original normalization of the Proctor curves, it requires identifying individual Proctor tests for normalization. Therefore, to simplify the process, the Proctor curve and field data were normalized based on the average dry unit weight ratio and average optimum saturation difference. The saturation-based compaction acceptance criteria were set to represent the normalized limits of all 26 Proctor tests and the ranges for each Proctor (i.e., >95% maximum dry unit weight, within -1% to +3% optimum moisture content). The horizontal value of 1 and vertical value of 0 represent the average dry unit weight and the average optimum saturation difference obtained from the 26 Proctor tests, respectively. Note that the "0" value on the x-axis represents a saturation value of 83%, which is a good representation of the "break-point" value for the broader range of maximum saturation values.

To account for the use of an average value, the compaction acceptance range was expanded on the upper boundary (Figure 5.2b). Specifically, it was extended above the average dry unit weight ratio by 1 and 2 standard deviations of the normalized averages. These two boundaries were extended to 95% of the dry unit weight ratio limit on the negative saturation difference side. On the positive saturation difference side, a truncated limit towards the convergence expanded limits as that boundary approached the zero-air-voids condition (Figure 5.2b). Two of the 26 original normalized Proctor curves were found to be well outside and below the proposed compaction criterion, as shown in Figures 5.2b and 5.2c.

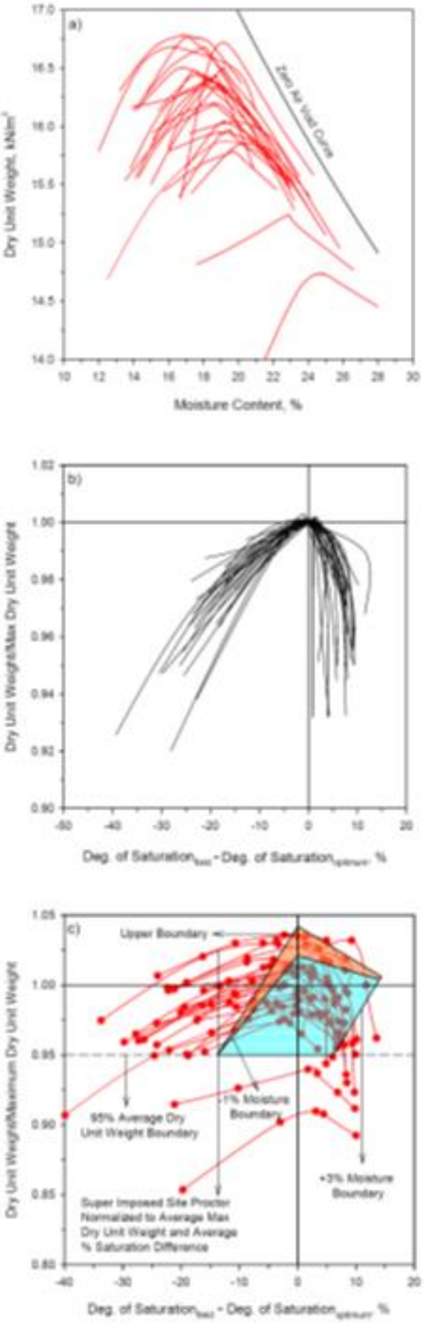

Figure 5.2 Compaction data, a) Standard Proctor curves, b) Standard Proctor curves plotted against saturation-based graph, c) Saturation-based Proctor curves normalized to average max dry unit weight.

To begin Zone III (as outlined in Figurer 4.2) activities, the actual field dry unit weight ratios were plotted on both the Proctor-based and saturation-based compaction acceptance criteria. Figures 5.3 to 5.5 illustrate a side-by-side comparison of these two criteria at different times during the construction phase. These plots reflect the core zone with the dry unit weights occurring within 15.6 and 16.8 kN/m3 and the moisture contents between 18% and 22% for the core materials. The field data were collected in smaller sub-sets of 100 to 200, and the results were compared to three of the 26 Proctor soil groups used for quality reference.

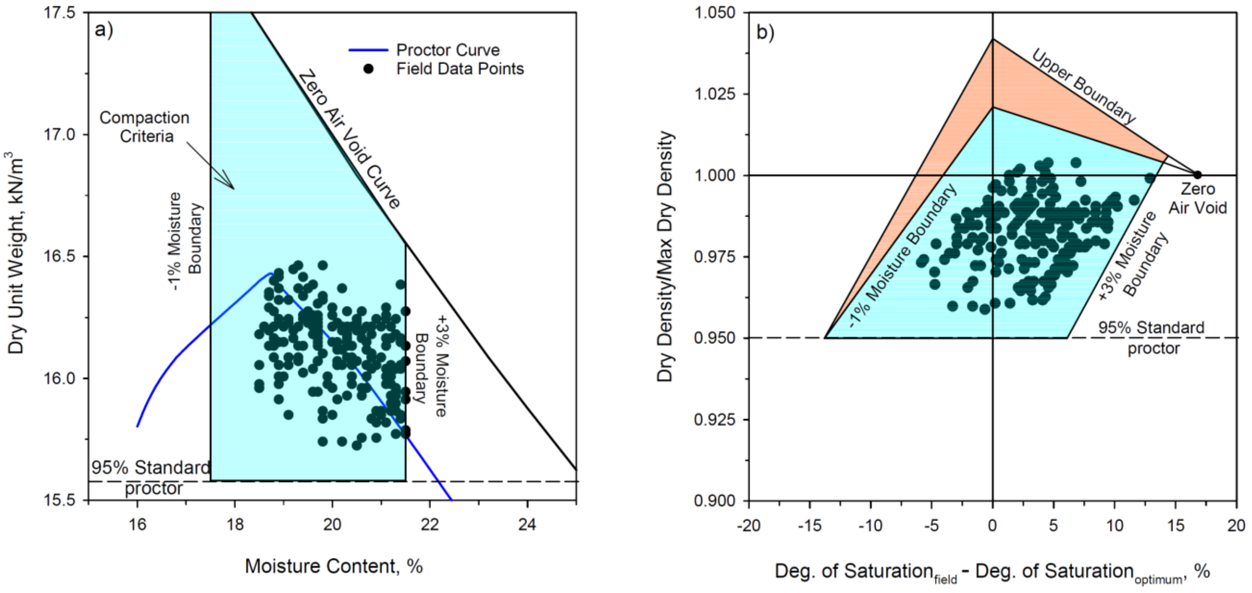

Figure 5.3 Field compaction data at the early stages of the embankment construction, a) Standard Proctor, b) Saturation-based plot.

The data presented in Figures 5.3a and 5.3b were collected during an early phase of the project, which occurred in a seasonally wet period. The borrow areas were selected based on the in-place water contents, which were initially on the wet side of the optimum moisture content. In contrast, Figure 5.4a illustrates the conventional and historical approach to monitoring compaction results. Note the compaction acceptance criterion limits of 95% maximum dry unit weight within a moisture range of 0 to +3% of the optimum moisture content and the "zero air" void curve. As shown, the saturation-based criterion has a better-defined upper boundary.

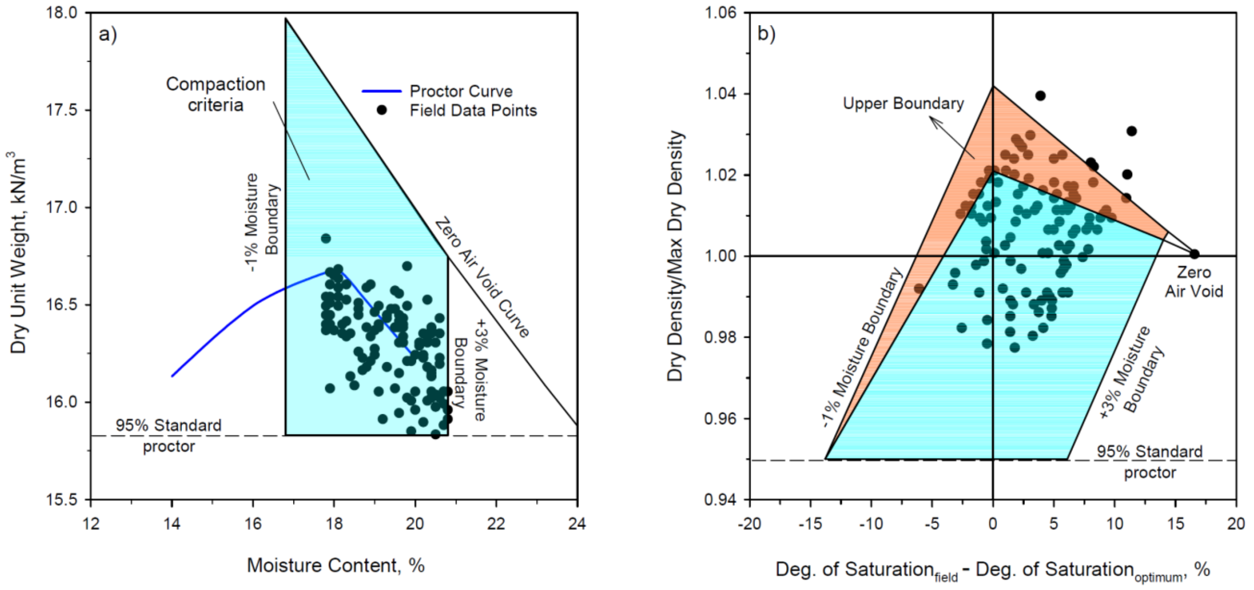

Figure 5.4 Field compaction data at an intermediate portion of the embankment construction, a) Standard Proctor, b) Saturation-based plot.

Figures 5.4a and 5.4b represent quality control points for an intermediate phase of the embankment construction, where the borrow sources were the same as those in Figures 5.3a and 5.3b. Due to the high rate of construction, the layers were compacted with the minimum passes of equipment necessary to meet the specifications. Any documented failing tests were promptly addressed by scarifying and recompacting the corresponding layers. The borrow sources for this phase were close to the upper limits of acceptable moisture content during placement, and some layers dried during construction and failed due to being drier than the optimum moisture content.

To rectify this, these layers were scarified, water added, disced to mix, and recompacted. Many of the layers with higher moisture content were worked with compaction equipment and disced until they dried sufficiently to pass the optimum moisture content. This is indicated by the "bunching" of data points near the optimum and high on the Proctor curve. The saturation-based plot shows a similar distribution of data within the acceptance zone, even though it is based on the average S_{opt} from 26 Proctor curves. Note that the compaction criterion limits of 95% maximum dry unit weight within a moisture range of 0 to +3% of the optimum moisture content and the "zero air" void curve are still present in these figures.

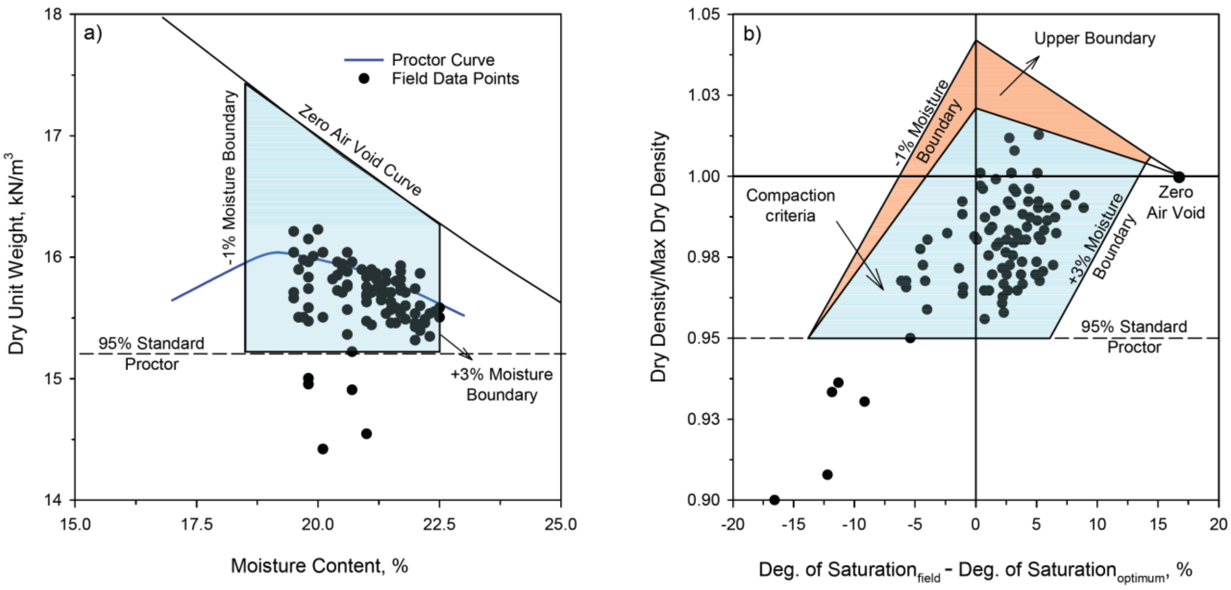

Figure 5.5 Field compaction data at later parts of the embankment construction, a) Standard Proctor, b) Saturation-based graph.

Figures 5.5a and 5.5b depict data for a later phase of the embankment construction, during which borrow sources were obtained from multiple locations, resulting in some soil variation. Production was lower in the core zone due to the shrinking size of the cohesive zone, and portions of the borrow materials were directed to the structural shell of the embankment. In some cases, small quantities of the borrow material placed were sufficiently different from the previously tested materials, requiring new Proctor testing. This highlights that the average S_{opt} from 26 Proctor curves has limitations in terms of the range of borrow materials that can be used.

It is noted that Figures 5.4a and 5.4b present some contrasting trends compared to Figures 5.3a, 5.3b, 5.5a, and 5.5b. In the former, a significant portion of the data points indicate dry unit weight values below the maximum dry unit weight depicted in the Proctor curve shown in Figure 5.4a. Conversely, in Figure 5.4b, many data points exhibit ratios of the dry unit weight to the maximum dry unit weight higher than 1.0. Unlike Figures 5.3a, 5.3b, 5.5a, and 5.5b, where the data points followed more consistent patterns, the data observed in Figures 5.4a and 5.4b deviate from the expected trends. In Figure 5.4a, the dry unit weight values consistently fall below the maximum dry unit weight, indicating a potential issue with compaction or other factors influencing the embankment's unit weight. Conversely, Figure 5.4b reveals ratios exceeding 1.0, suggesting a potential over-compaction or variations in the embankment's composition. The examples depicted in Figures 5.3, 5.4, and 5.5 were presented to demonstrate the variations in construction periods across the embankment. As a result, a smaller and more diverse collection of Proctor test results was available to calculate the average optimum saturation and dry unit weight ratio. Since the target area was determined based on the total number of Proctor tests conducted within that specific embankment zone, there are expected to be discrepancies in the averages. Nevertheless, these observed changes align closely with the specific field modifications and, on the whole, demonstrate a reasonable correlation when compared to a specific Proctor test used as a benchmark.

The field measurements of in-situ dry unit weight and as-compacted moisture content were compared to either field-generated test pads or laboratory-generated dry unit weight to moisture content relationships. The laboratory test specimens were remolded and prepared using a specified compaction energy and then tested for strength and compressibility. Based on this data, the geotechnical designer makes an engineering assessment that if the specified soil is placed in a controlled manner and achieves a specified range of dry unit weights when compacted within a specified range of moisture contents at the time of compaction, certain reliability of strength and compressibility results can be achieved. Therefore, a procedure that normalizes the compaction effort would provide a more consistent tracking of the actual performance of the lift being compacted. At the same time, the normalized compaction data provides insight into the compaction effort used to achieve a particular stiffness. Normalization is important because it adjusts for differences in the amount of effort used to compact the soil. Because the field data is being documented relative to the soil saturation, it also becomes easier to monitor the partially saturated shear strengths achieved in the compaction process. Overall, the saturation-based plotting of data shows a similar distribution of data within the acceptance zone, except for the exception discussed above.

Earlier, the subject of variation of specific gravity in the soils would require monitoring in the saturation-based methodology. As an approximate check on the validity of the specific gravity used for the dam project, the Proctor results for the project were evaluated at the maximum degree of moisture content in each test. Figure 5.6 shows the degree of saturation based on the specific gravity of 2.65 at the maximum tested moisture content, shown as % greater than the optimum moisture content for that Proctor.

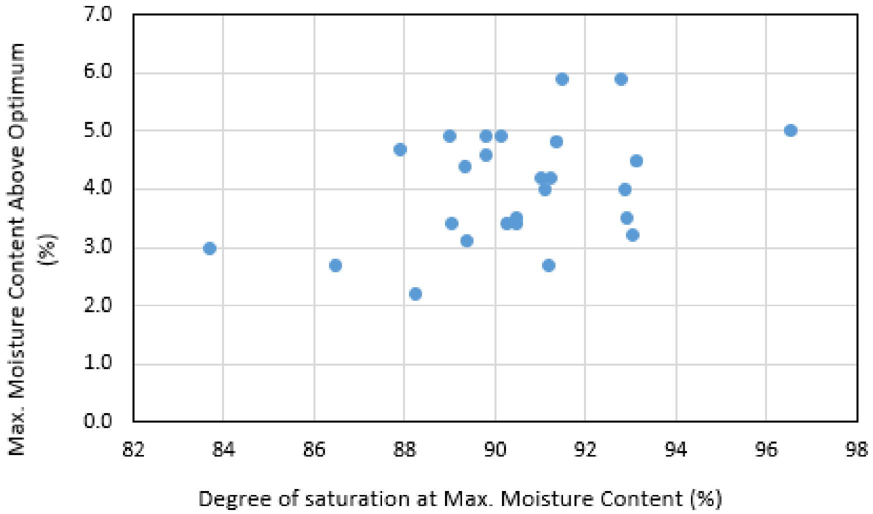

Figure 5.6 Degree of saturation at the maximum moisture content above the optimum moisture content from the Proctor tests.

The data from Figure 5.6 shows that where a Proctor point was performed more than 4% greater than the optimum and up to 6% greater than the optimum, the % saturation ranged from 88 to 96%. The majority of the data above 4% wet of optimum moisture content was between 88 and 93% saturation. Based on knowing that the wet of saturation side of the proctor has a tendency to converge near a saturation curve in the 90% range, and using the following relationship, the specific gravity was recalculated based on a 92% saturation level:

$$Specific\ Gravity = \frac{\gamma_d}{\gamma_w - \gamma_d * \frac{w_n}{Sat}} \tag{5.1}$$

where: γ_d = Dry Unit Weight of Soil

γ_w = Unit Weight of Water

W_n = Moisture Content

Sat = Degree of Saturation

Figure 5.7 shows the results of back-calculating the specific gravities. In this way, the approximated average specific gravity back-calculated from the Proctor tests that were completed with moisture contents in excess of 4% wet of optimum appears to be consistent with the specific gravity of 2.65 used for the field data.

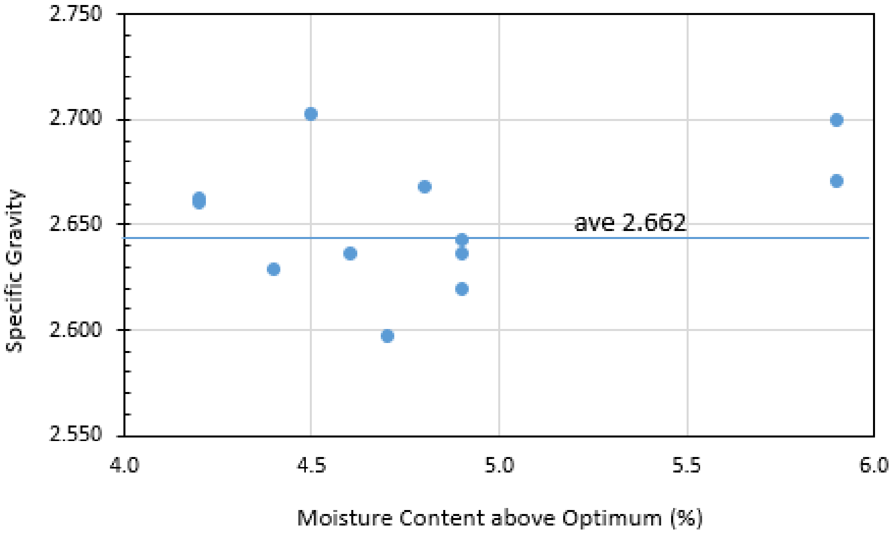

Figure 5.7 Back calculated specific gravities.

5.4 Application to Estimate Unsaturated Shear Strength

An advantage of using the saturation-based compaction criterion is the possibility of quantifying the variation of unsaturated shear strength with the degree of saturation of the compacted soil. Several models are available in the literature to estimate the shear strength of unsaturated soils using the classic shear strength parameters and the SWRC. For instance, the following model of Vanapalli et al. (1996) can be used for this purpose:

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\phi' \qquad (5.2)$$

where τ denotes the shear strength, c' is the effective cohesion, ϕ' is the effective friction angle, $(\sigma - u_a)$ is the net normal stress, θ is the volumetric water content, $(u_a - u_w)$ is the matric suction, θ_r represents the residual water content, θ_s is the saturated water content, σ is the total stress, u_a is the pore-air pressure, and u_w is the pore-water pressure. The term $\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)$ represents the effective degree of saturation.

Using c' and ϕ' (14.4 kPa and 28 degrees) obtained from Consolidated-Undrained triaxial testing performed on remolded samples from the borrow site, the relationship saturation difference versus shear strength (Figure 5.8) was calculated from Equation 5.2 and combined with the saturation data from the field. The data were also compared to those obtained from relationships in the literature (Stark et al. 2018). The shear strength calculation for this study was limited to the first two layers placed and compacted, which is represented by a 0.5 m depth of overburden. Therefore, the results plotted in Figure 5.8 graphically illustrate the compacted shear strength of the first two layers of compacted soil.

At this point, limiting the calculation to these surface layers keeps the focus on the immediate process of compacting the soil. When a compacted fill embankment is constructed, each lift is placed initially in a partially saturated state. At some point in the construction process, the soils can become saturated due to a combination of factors. This has been observed in dams that have been instrumented for pore water pressure. Where these dams have extended periods of stoppage (such as a winter shut down), the pore water pressures have been observed to climb to a pressure reflecting the full overburden pressure. In other earth structures, negative pore pressures due to partial saturation have existed for extended periods (Vahedifard et al., 2016). In Figure 5.8, the soil shear strength was calculated from the field degree of saturation data using the van Genuchten (1980) SWRC model to establish the relationship between the suction and the effective degree of saturation as follows:

$$\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) = \left[1 + \left(\frac{u_a - u_w}{a}\right)^n\right]^m \tag{5.3}$$

where a, m, and n are fitting parameters. These parameters were estimated from index relationships of plasticity index, PI, and percent fines (passing sieve #200) using the procedure outlined by Zapata (2000). Table 5.3 provides the soil parameters used to develop the SWRC. The process uses the physical strength data or empirical relationships and the laboratory index testing in the Zapata (2000) relationship to obtain the SWRC. From that SWRC, the suction is computed for the field-obtained volumetric water content. The suction is used in Equation 5.2 to calculate the shear strength of the soil in its compacted state. It is noted that the dry unit weight of the soil does not correlate well with the shear strength, as also reported by others in the literature (Tinjum et al. 1997). However, the dry unit weight correlates more closely to the degree of saturation, and thereby the saturation difference therefore valuable for monitoring with the saturation-based framework.

Table 5.3 Index Properties and SWRC Parameters

Void Ratio	0.603
Liquid Limit	44
Plastic Limit	18
Sand Content (<2 mm)	5
Fines Content (<0.075 mm)	95
Clay Fraction (<0.002 mm)	25
a	200 kPa
n	1.12
θ_r	0.07 cm^3/ cm^3
m	0.107143

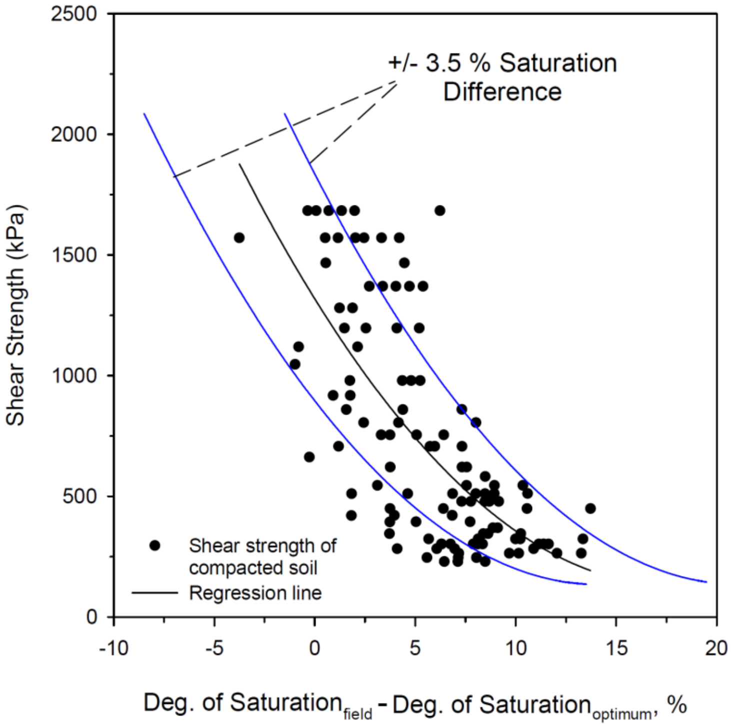

Figure 5.8 Shear strength of intermediate compacted soils.

In Figure 5.8, a curve representing the partially saturated shear strength of the soils placed in the field concerning the saturation difference was derived, but the scatter was rather large. The curve represented a plus or minus 3.5% saturation difference. However, the relationship does show the trend concerning saturation. The relationship between the shear strength and the field degree of saturations was amended to show the relationship of shear strength to the saturations difference in the proposed saturation-base compaction methodology. The data are plotted using a separate secondary axis to show the shear strength (Figure 5.9) for the data of the intermediate stage of construction presented earlier. By combining the saturation-based compaction method with the saturation-based shear strength, the resulting relationship shows graphically the effects of compacting soils in increasingly dryer physical states. As the field degree of saturation increases (high saturation difference), there is minimal impact by the pore air pressure because the pore spaces are nearly saturated. The shear strength is the normal stress times the tangent of the soil friction angle plus the cohesion intercept, which is zero in the drained condition. As the degree of saturation decreases, the unsaturated shear strength increases due to the contribution of matric suction. Should these soils become saturated, the shear strengths shown here would be a lower strength approaching the saturated condition. Adding the shear strength of the compacted layer to the compaction results increases what is known of the physical properties of the initial compacted soils layers.

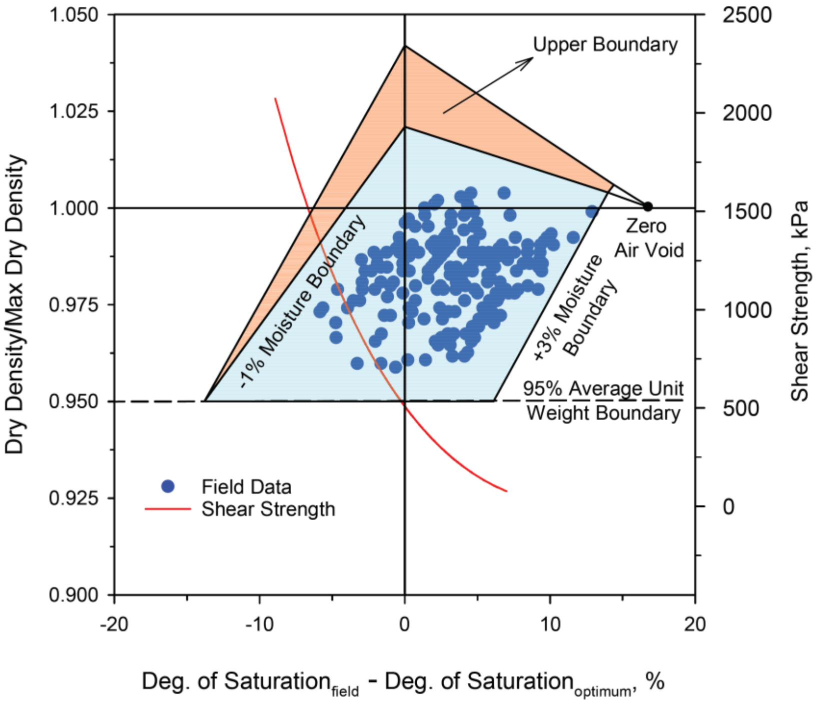

Figure 5.9 Shear strength of field data points to the saturation-based framework.

Both Figures 5.8 and 5.9 indicate a substantial increase in shear strength in the partially saturated compacted soils. This would be expected to create substantial change in the behavior of these soils as the compaction process continues to add layers to the embankments. In a study by the Bureau of Reclamation (Farrar, 2000), a survey of over 20 earth dams concluded that compressible soils compacted wetter than 0.6% dry of the optimum moisture content exhibited undesirably high pore-water pressure that increased during construction. While dams constructed to an average of 1.5 to 0.5% dry of optimum had no significant build-up in excess pore water pressures. The increase in shear strength with a decrease of saturation is also shown as an increased "OCR Effect", Berney (2004), which shows that the compressibility of a partially saturated compacted soil can be expected to have a higher mean normal stress to achieve the same change in void ratio change as in a saturated compacted soil (see Figure 5.10).

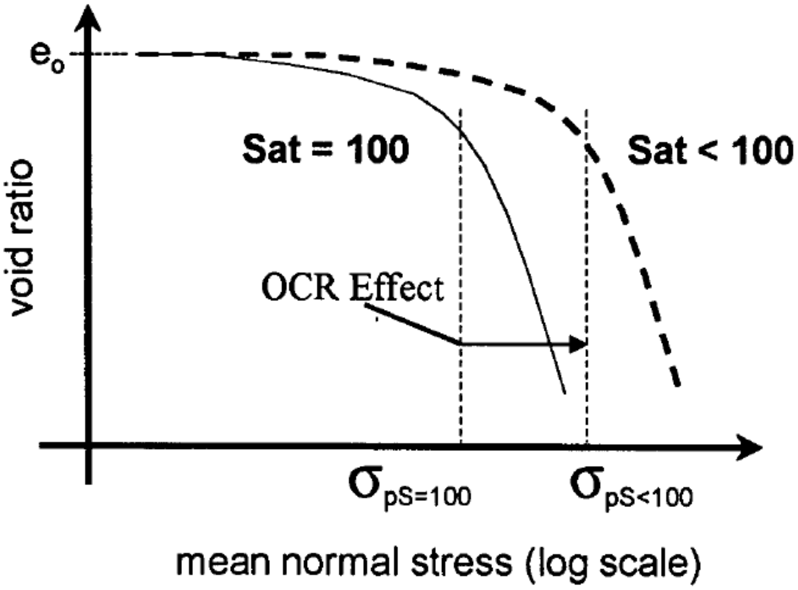

Figure 5.10 Illustration of the effect of saturation on the reference state of soil (from Berney IV, 2004).

Therefore, the increased stiffness of the partially saturated compacted soils is consistent with both the historical measured performance and the modeled shear strength increases. This would also indicate the ability to address the expected behavior of the pore water pressures generated during construction by monitoring the degree of saturation of the layers as they are being placed. In addition, if these partially saturated layers are at a later time to become saturated by the compression of the layers from additional overburden or changes in external seepage sources, the additional stiffness is expected to reduce.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study introduced a novel saturation-based framework for controlling field compaction that aims to reduce the number of Proctor tests required for evaluating a large volume of soil with varying physical properties. The framework also aims to minimize the uncertainties and assumptions in the compaction control process, leading to improved engineering outcomes. The proposed methodology utilizes field data collected for Proctor-based compaction control but offers new insights into the physical behavior of compacted soils.

By monitoring the degree of saturation instead of the percent moisture content, the proposed framework enhances the understanding of soil physical parameters and reduces the number of variables in the compaction process. The framework eliminates the need to match the field density to a specific Proctor curve for a wide range of soil variations. While the average optimum degree of saturation from multiple Proctor tests may not be effective for all soil types, it covers a broad range of soil variations.

Furthermore, the proposed saturation-based compaction control can easily track physical soil properties such as shear strength, compressibility, and permeability. This is because the shear strength of unsaturated soil is directly related to the soil's saturated state. By predicting the actual shear strength of compacted soils throughout the compaction process and understanding the impact of matric suction on the soil mass, a more comprehensive understanding of the long-term performance of compacted fills can be gained.

Practitioners who currently use Proctor-based quality control methodologies are encouraged to incorporate the proposed saturation-based methodology into their evaluations. As practitioners become more familiar with the new framework, they can confidently adopt the saturation-based approach independently. The proposed framework builds on the unique physical features of the "family of curves" and expands the user's ability to select the compaction criterion and produce project design properties. Overall, the proposed approach improves the understanding of the physical behavior of compacted soils and provides a more comprehensive view of the long-term performance of compacted fills.

6.2 Recommendations for Future Research

Based on the findings of this study, the following recommendations are made for future research in this area.

- Further investigation is recommended to determine the limits of the range of soils for which the average optimum degree of saturation from multiple Proctor tests can be effectively used. This would help identify which soil types are most suitable for the proposed saturation-based framework and which ones require additional modifications.
- More research is recommended to establish the relationship between the saturation-based framework and other physical soil properties, such as the coefficient of permeability, compressibility, and shear strength. This would provide a more in-depth understanding of the effects of matric suction on the soil mass and enable better predictions of the long-term performance of compacted fills.

- Further investigation is recommended to evaluate the proposed framework in various field settings to assess its effectiveness in real-world scenarios. This would help determine the framework's practicality and accuracy in a range of soil types, environmental conditions, and compaction equipment.
- Further research is needed to determine the impact of various factors such as soil type, compaction energy, moisture content, and environmental factors on the saturation-based framework's effectiveness. This would enable practitioners to better understand the strengths and limitations of the proposed framework and optimize its use for specific projects.
- Further research is recommended to monitor pore pressures in earthen embankments over an extended period of time. Partial saturation conditions may persist long after the completion of construction, and studying the saturation of these zones as they become fully saturated would be beneficial.
- It is noted that ensuring satisfactory shear strength and permeability after saturation is not directly linked to the saturated state of the compacted soil. Additional efforts are required to specify the appropriate acceptance zone based on the shear strength and permeability after saturation. Tatsuoka (2015) and Tatsuoka & Correia (2018) discuss this issue in detail.

Overall, these recommendations would help improve the understanding of the physical behavior of compacted soils and enhance the development of effective compaction control strategies.

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APPENDIX A

RESULTS OF COMPACTION TESTING

Table A.1 Compaction test results from the central core zone clay soils of the Lake Winnebago Dam

Proctor #	γ_d (pcf)	$W_{opt,n}$	LL	PL	PI	w_n	e	S (%)
	93.5	12.5					0.435	43.1
	97.9	15.2					0.408	58.5
	100.6	18.1					0.392	74.5
1-S1	**101.0**	**19.8**	**49**	**18**	**31**	**25.0**	**0.389**	**82.3**
	99.6	22.4					0.398	89.9
	96.5	24.6					0.416	91.4
	100.5	12.0					0.392	49.3
	105.2	14.4					0.364	66.7
	106.2	16.2					0.358	77.1
1-S2	**106.1**	**16.8**	**42**	**18**	**24**	**18.0**	**0.358**	**79.7**
	105.0	19.8					0.365	91.3
	102.7	21.0					0.379	91.2
	99.5	13.8					0.398	55.2
	103.0	15.9					0.377	69.6
1-S3	**104.2**	**17.9**	**43**	**18**	**25**	**21.0**	**0.370**	**80.8**
	104.1	18.1					0.370	81.5
	103.1	20.1					0.377	88.2
	99.0	22.8					0.401	90.1
	102.9	13.9					0.378	60.7
	103.4	16.1					0.375	71.2
1-S4	**104.2**	**18.1**	**39**	**17**	**22**	**29.0**	**0.370**	**81.7**
	104.1	18.2					0.370	82.0
	102.1	20.5					0.383	87.7
	98.5	23.0					0.404	89.8
	100.6	16.0					0.392	65.9
	102.4	16.8					0.381	72.4
1-S5	**104.4**	**18.5**	**46**	**19**	**27**	**34.0**	**0.369**	**84.0**
	104.3	18.9					0.369	85.6
	102.1	20.5					0.383	87.7
	97.3	23.2					0.412	87.9

Table A.1 (continued)

Proctor #	**γ_d (pcf)**	**$W_{opt,n}$**	**LL**	**PL**	**PI**	**w_n**	**e**	**S (%)**
	93.5	12.5					0.435	43.1
	97.9	15.2					0.408	58.5
	100.5	16.0					0.392	65.7
	101.3	18.0					0.387	75.4
2-S1	**101.5**	**19.1**	**47**	**18**	**29**	**29.0**	**0.386**	**80.4**
	101.0	20.8					0.389	86.5
	98.8	23.0					0.403	90.5
	95.9	25.0					0.420	91.5
	100.3	14.4					0.393	58.8
	102.0	17.7					0.383	75.5
2-S2	**102.4**	**19.2**	**47**	**18**	**29**	**26.0**	**0.381**	**82.8**
	102.2	20.0					0.382	85.8
	100.4	22.0					0.393	90.1
	99.4	22.6					0.399	90.3
	101.5	17.2					0.386	72.4
	101.8	18.3					0.384	77.7
2-S3	102.1	19.9	54	19	35	29.0	0.383	85.1
	101.3	21.8					0.387	91.4
	98.8	23.5					0.403	92.4
	95.2	25.8					0.424	92.8
	97.9	16.7					0.408	64.2
	104.2	18.0					0.370	81.3
6-S1	**106.4**	**19.3**	**47**	**18**	**29**	**27.0**	**0.357**	**92.3**
	103.1	21.6					0.377	94.8
	99.2	24.3					0.400	96.6
	103.8	13.2					0.372	59.0
	106.2	15.2					0.358	72.3
12-S1	**106.8**	**16.7**	**42**	**18**	**24**	**24.0**	**0.354**	**80.7**
	106.7	17.2					0.355	82.9
	105.0	19.0					0.365	87.6
	101.7	21.1					0.385	89.3
	99.1	14.3					0.401	56.7
	101.7	16.1					0.385	68.2
16-S1	**102.9**	**18.3**	**41**	**19**	**22**	**21.0**	**0.378**	**79.9**
	102.7	19.1					0.379	83.0
	100.3	21.7					0.393	88.7
	97.8	23.2					0.409	89.0

Table A.1 (continued)

Proctor #	**γ_d (pcf)**	**$W_{opt,n}$**	**LL**	**PL**	**PI**	**w_n**	**e**	**S (%)**
	102.7	14.0					0.379	60.8
	105.1	16.1					0.364	74.4
22-S1	**106.1**	**17.8**	**44**	**18**	**26**		**0.358**	**84.5**
	105.8	18.4					0.360	86.6
	103.3	20.0					0.375	88.2
	103.3	14.5					0.375	64.0
	106.4	16.6					0.357	79.4
22-S2	**106.7**	**17.5**	**47**	**17**	**30**	**23.0**	**0.355**	**84.4**
	106.4	18.4					0.357	88.0
	104.2	20.2					0.370	91.2
	99.0	14.1					0.401	55.7
	104.4	17.0					0.369	77.2
28-S1	**104.6**	**17.8**	**42**	**17**	**25**		**0.367**	**81.2**
	104.0	19.1					0.371	85.8
	102.1	20.9					0.383	89.4
	101.5	15.1					0.386	63.6
	102.5	16.7					0.380	72.2
40-S1	**103.1**	**18.4**	**43**	**18**	**25**	**26.0**	**0.377**	**80.7**
	102.7	19.4					0.379	84.3
	100.8	21.0					0.390	86.9
	98.5	23.0					0.404	89.8
	102.8	14.2					0.378	61.8
	104.8	16.2					0.366	74.3
68-S1	**105.0**	**17.1**	**39**	**17**	**22**	**28.0**	**0.365**	**78.8**
	104.4	18.5					0.369	84.0
	102.7	20.5					0.379	89.0
	98.3	15.7					0.406	61.0
	99.8	17.9					0.396	72.2
91-S1	**100.4**	**19.5**	**53**	**17**	**36**	**23.0**	**0.393**	**79.9**
	100.3	20.0					0.393	81.7
	98.4	22.2					0.405	86.5
	102.7	15.4					0.379	66.9
	104.5	17.2					0.368	78.3
146-S1	**104.6**	**17.9**	**43**	**20**	**23**	**24.0**	**0.367**	**81.7**
	103.6	19.2					0.373	85.3
	99.5	20.9					0.398	83.7

Table A.1 (continued)

Proctor #	**γ_d (pcf)**	**$W_{opt,n}$**	**LL**	**PL**	**PI**	**w_n**	**e**	**S (%)**
	98.9	13.5					0.402	53.2
	101.6	15.8					0.386	66.7
	104.3	18.0					0.369	81.5
172-S1	**104.4**	**18.3**	**58**	**20**	**38**	**19.0**	**0.369**	**83.1**
	103.6	19.8					0.373	88.0
	100.3	22.3					0.393	91.1
	99.6	17.0					0.398	68.2
	101.8	18.7					0.384	79.4
244-S1	**102.0**	**19.5**	**56**	**17**	**39**	**20.0**	**0.383**	**83.2**
	101.0	21.1					0.389	87.7
	98.8	23.0					0.403	90.5
	98.7	15.0					0.403	58.9
	101.8	16.8					0.384	71.3
	103.8	18.5					0.372	82.7
244-S2	**103.9**	**19.0**	**53**	**17**	**36**	**21.0**	**0.372**	**85.1**
	102.2	21.0					0.382	90.0
	98.7	23.2					0.403	91.0
	98.0	16.6					0.407	64.0
	101.2	18.8					0.388	78.6
257-S1	**101.6**	**19.6**	**65**	**24**	**41**		**0.386**	**82.8**
	101.1	20.0					0.389	83.4
	98.8	23.0					0.403	90.5
	101.1	15.1					0.389	63.0
	103.4	17.0					0.375	75.2
257-S2	**104.9**	**19.0**	**51**	**22**	**29**		**0.366**	**87.4**
	104.8	19.3					0.366	88.5
	102.5	21.2					0.380	91.6
	99.1	23.5					0.401	93.1
	88.0	21.0					0.468	63.3
	93.0	23.5					0.438	80.0
303-S1	**93.8**	**24.8**	**82**	**27**	**55**		**0.433**	**86.1**
	93.6	25.3					0.434	87.5
	92.0	28.0					0.444	93.1
	98.2	17.3					0.406	67.0
	100.6	19.6					0.391	80.6
303-S2	**100.9**	**20.6**	**57**	**21**	**36**		**0.389**	**85.4**
	100.4	22.0					0.392	90.1
	98.0	24.1					0.407	92.9

Table A.1 (continued)

Proctor #	**γ_d (pcf)**	**$W_{opt,n}$**	**LL**	**PL**	**PI**	**w_n**	**e**	**S (%)**
	93.5	12.5					0.435	43.1
	94.3	17.6					0.430	61.9
	95.5	20.1					0.422	72.8
313-S1	**96.9**	**22.6**	**65**	**24**	**41**		**0.414**	**84.8**
	96.6	23.2					0.416	86.4
	95.2	25.0					0.424	89.9
	94.0	26.6					0.432	92.9