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Collapsible behaviour of a compacted lateritic sandy soil

Isabela Augusto Silveira[1#], *Heraldo* Luiz Giacheti[1], *Breno* Padovezi Rocha[2] and *Roger* Augusto Rodrigues[1]

[1]*São Paulo State University (UNESP), School of Engineering, 14-01 Luiz Edmundo Carrijo Coube Avenue, Bauru, São Paulo, Brazil*

[2]*Federal Institute of Education, Science and Technology of São Paulo (IFSP), 164 Alameda Tucurupi, Ilha Solteira, São Paulo, Brazil*

[#]*Corresponding author: isabela.silveira@unesp.br*

ABSTRACT

Collapsible unsaturated soils are characterized by a low-density composition and exhibit sudden settlement after wetting while maintaining in-situ stress levels. This issue is effectively mitigated by compaction, a simple and economical technique that improves the soil properties and geotechnical behaviour. In this study, the collapsible behaviour of a compacted sandy laterite soil is analysed, focusing on the influence of relative compaction, water content, initial suction and inundation stress. The primary aim is to analyse the effect of initial compaction conditions on collapse potential. Conventional and suction-controlled oedometer tests were conducted on soils from Ilha Solteira, São Paulo, Brazil, where there is a large amount of geotechnical data available. The laboratory data reveal that collapse deformations of compacted soil depend on relative compaction, initial water content, soil suction, and inundation stress. Poorly compacted soils exhibit greater susceptibility to collapse when wetted, and the magnitude of collapse potential varies with water content. Additionally, this study shows the influence of initial suction on collapsibility of less compacted soils. The laboratory results highlighted the importance of considering suction and inundation stress in understanding the collapsible behaviour of compacted soil, whereas traditional empirical methods often emphasize low density and water content as primary factors predisposing soils to collapse.

Keywords: collapsible soils; compacted soils; laboratory test; unsaturated soils.

1. Introduction

Several practical applications in geotechnical engineering deal with the use of compacted soil in the unsaturated condition, including embankments, foundations, and roads. Understanding the behaviour of compacted soils is particularly complex due to the coexistence of three different phases: solid, liquid, and gas phase, which interact with each other.

Research has focused on studying compacted soils under unsaturated conditions, as evidenced by experimental approaches varying compaction conditions (Gao et al. 2019), numerical approaches (Sivakumar and Wheeler 2000; Zhou and Sheng 2015), and approaches considering the structure of compacted soils (Alonso, Pinyol, and Gens 2013; Ng et al. 2016).

The geotechnical behaviour of compacted soil depends on dry density, compaction water content, and acting suction, among other factors (Alonso, Pinyol, and Gens 2013), with suction considered as an independent state variable for unsaturated soil (Fredlund and Morgenstern 1977).

Collapsibility is one of the main concerns related to unsaturated soils. Soil collapse is a deformation triggered by soil wetting without significant variation in applied loads. Collapsibility does not necessarily prevent engineering works from being directly supported by these soils. Techniques are employed to reduce or mitigate collapse settlements, with compaction standing out as a method that improves soil properties.

The technical literature presents numerous studies on compacting unsaturated soils. However, few have addressed the use of compaction as a method to improve collapsible soils (e.g. Booth 1975; Houston, Houston, and Lawrence 2002), especially utilizing concepts from unsaturated soil mechanics, such as the effect of the suction after compaction.

Compaction can significantly reduce or eliminate the effects of collapsibility when rigorously performed and it can be a cost-effective technique. Nonetheless, soils with compaction deficiencies may experience collapse issues influenced by dry density, compaction water content, acting suction, and inundation stress (Rao and Revanasiddappa 2000; Suriol, Gens, and Alonso 2002).

Structural damage may arise from volumetric deformation due to soil collapse when the compaction control is inadequate. Methods, such as the one proposed by Vilar and Rodrigues (2015), indicate that the boundary between collapsible and non-collapsible soil lies at a relative compaction of 90% at optimum water content, without considering other variables such as inundation stress and acting suction.

This paper focus on the collapsible behaviour of compacted soil, employing both conventional and suction-controlled oedometer tests. Initially, three sandy, collapsible soils underwent conventional oedometer tests to identify the soil with the highest susceptibility to collapse. Subsequently, this soil was chosen to investigate its collapse behaviour under compaction. The variables of interest include the relative compaction, as-compacted water content (the water content at which specimens were molded and tested), initial suction, and inundation stress. The findings of this study is particularly relevant in cases where compaction deficiencies can lead to settlement problems due to collapse-induced deformations.

2. Studied Site and Historical Information

The soils of Bauru, Ilha Solteira, and Pereira Barreto cities underwent initial testing to determine which soil exhibits the most significant collapse potential. These soils were selected due to their importance and known collapsible behaviour.

Bauru (São Paulo State, Brazil) houses the São Paulo State University (UNESP) experimental research site, where several in situ and laboratory tests have been conducted. Ilha Solteira and Pereira Barreto, also situated in São Paulo State, are home to important hydroelectric power plants. Additionally, Ilha Solteira hosts an experimental research site of UNESP.

Bauru soil consists of fine, slightly clayey sand, comprising 81% sand, 4% silt, and 15% clay. It has a liquid limit of 17%, an optimum water content of 11%, and a maximum dry specific mass of 1.94 g/cm^3. The Pereira Barreto soil is composed of 75% sand, 5% silt, and 20% clay, with a liquid limit of 19%, an optimum water content of 9.6%, and a maximum dry specific mass of 2.05 g/cm^3.

Further details regarding the soil from Ilha Solteira, selected for evaluating the variables influencing the collapse potential of compacted soils, will be provided.

Ilha Solteira (São Paulo, Brazil) is located within a region hosting three significant hydroelectric power plants (HPP): *Três* Irmãos HPP, *Engenheiro Souza Dias* HPP and *Ilha Solteira* HPP. The latter two constitute the sixth-largest hydroelectric complex globally.

The climate in this area is humid subtropical, featuring hot and humid summers along with mild and dry winters. Both weather and geology of Ilha Solteira have contributed to the formation of extensive unsaturated profiles and groundwater table deeper than 20 meters.

The topsoil horizon is collapsible, porous, and lateritic, with stable minerals resulting from the soil lixiviation induced by intense summer rainfalls.

The natural soil is a reddish-brown clayey sand, with key properties such as specific gravity (G_s) of 2.619, dry density (ρ_d) of 1.41 g/cm^3, optimum water content (w_{opt}) of 11.4%, maximum dry density (ρ_{dmax}) of 1.965 g/cm^3, plastic limit (*PL*) of 13%, and liquid limit (*LL*) of 21%. The grain-size distribution consists of 27% clay fraction, 12% silt fraction and 61% sand fraction. It is classified as SC according to the Unified Soil Classification System (Rodrigues, Soares, and Sanchez 2021). Fig. 1 shows the standard Proctor compaction curve.

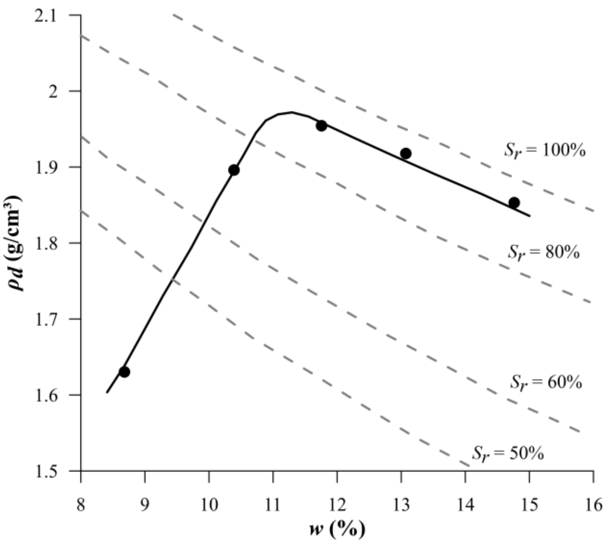

Figure 1. Standard Proctor Compaction Curve (Rodrigues, Soares, and Sanchez 2021).

The economic and energy importance of this region due to the presence of hydroelectric plants has led to studies and research to better understand the behaviour of the soil. Souza (1993) constructed two footing prototypes and monitored the settlements during loading and soaking. One footing was built on a natural and potentially collapsible soil, while the other was built on a compacted soil layer beneath the foundation. The soil was compacted at optimum water content (±2%) and achieve a 94% relative compaction, following the standard Proctor test.

Under loading condition up to 60 kPa, the settlement recorded for natural and compacted soil footing prototypes were 8.7 mm and 4.0 mm, respectively. Subsequently, after flooding under constant stress, the additional settlements were 19.4 and 1.6 mm for natural and compacted conditions, respectively. The field data from Souza (1993) underscore the better performance of the prototype constructed on compacted soil, highlighting the benefits of soil compaction in reducing settlement during both loading and soaking situation.

Rodrigues, Soares and Sanchez (2021) numerically simulated the field test in order to understand the effect of compaction on the settlement of collapsible soils based on the field data presented by Souza (1993). The authors used the finite element program CODE_BRIGHT and employed the Barcelona Basic Model (BBM) as a mechanical model. The authors conducted additional analyses to encompass varying stress levels in the field and different compaction depths considering the stress bulb concept.

The collapse behaviour, particularly in lateritic soils such as the soil from Ilha Solteira city, does not prevent the construction of engineering works. The lateritization process yields favourable post-compaction properties, including enhanced strength and reduced permeability when compacted near the optimum water content.

3. Experimental Framework

The Bauru, Ilha Solteira and Pereira Barreto soils in their natural state were initially subjected to conventional oedometer tests, inducing collapse at stresses of 50, 100, 200, and 400 kPa. The aim of these tests was to identify the soil with the highest collapse potential.

The Ilha Solteira soil was selected for the experimental framework illustrated in Fig. 2, designed to investigate collapsible behaviour following compaction process. Silveira and Rodrigues (2020) detail this experimental setup. The experimental program was designed to evaluate the factors that influence soil collapse behaviour, including relative compaction (RC), as-compacted water content, initial suction prior to inundation, and applied load during inundation.

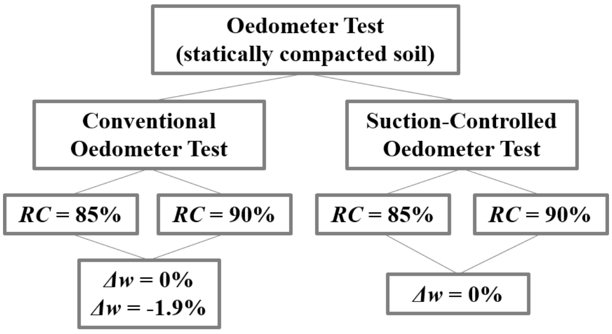

Figure 2. Experimental framework

The chosen relative compaction for this study was selected to address scenarios where compaction deficiencies might result in soil collapse, based on the collapsible soil classification criterion proposed by Vilar and Rodrigues (2015). A soil compacted with RC = 90% a priori is a non-collapsible soil, whereas RC = 85% represents a suboptimal compaction.

3.1. Conventional Oedometer Test

The compacted specimens used in the conventional oedometer test have a diameter of 70mm and a height of 20mm. These specimens are subject to loads up to the target inundation stress of 50, 100, 200, 400 and 800 kPa, following the procedure outlined by Jennings and Knight (1975). The soil collapse is triggered by wetting, resulting in a reduction in suction. Therefore, the soil specimens are saturated, and vertical displacement occurs under constant stress. Following complete collapse, the soil is subsequently reloaded. The collapse potential (CP) is defined as the ratio of the decrease in specimen void ratio due to inundation ($\Delta e = e_i - e_f$) over the specific volume just before collapse ($1 - e_i$) (Jennings and Knight 1975).

The soil suction was assessed using the filter paper technique (ASTM D5298-16, 2016) and it is not controlled in the conventional oedometer tests. Post-compaction, the soil suction was estimated using Whatman's no. 42 paper and the equation proposed by Chandler, Harwood and Skinner (1992).

3.2. Suction-Controlled Oedometer Tests

The suction-controlled oedometer test enables the application of soil suction using the axis translation technique (Hilf 1956) employing a hermetic chamber and a high air entry value (HAEV) porous disk (Escario and Saez 1973).

Compacted specimens were subjected to a suction of 100 kPa to represent the field conditions. This suction was maintained constant up to the desire inundation stress (50, 100, 200, 400 and 800 kPa), after which it was reduced to zero suction, indicating saturation and triggering soil collapse. The calculation of collapse potential followed the same methodology used in the conventional oedometer test.

4. Results and Discussions

4.1. Selecting the collapsible soil

Conventional oedometer tests were carried out on three soils from Ilha Solteira, Bauru and Pereira Barreto in their natural state. The objective was to evaluate their collapse potential under varying inundation stresses (50, 100, 200, and 400 kPa). Figs. 3, 4, and 5 present the results of the oedometer tests performed on the soils from Ilha Solteira, Bauru, and Pereira Barreto, respectively.

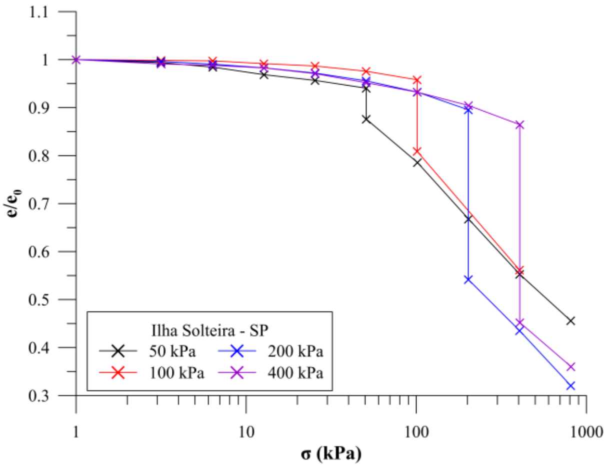

Figure 3. Oedometric curves for the conventional tests of the Ilha Solteira soil under the inundation stresses of 50, 100, 200 and 400 kPa

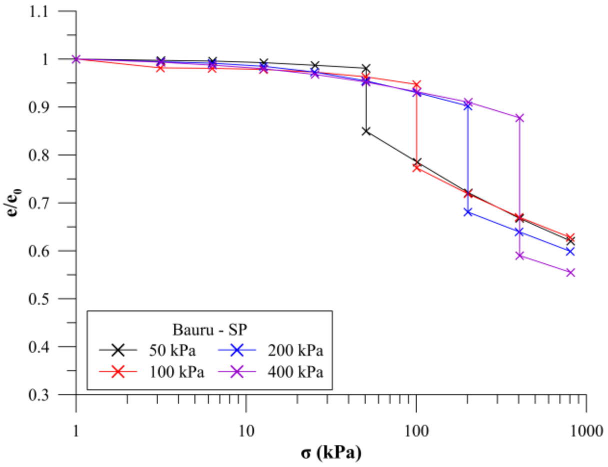

Figure 4. Oedometric curves for the conventional tests of the Bauru soil under the inundation stresses of 50, 100, 200 and 400 kPa

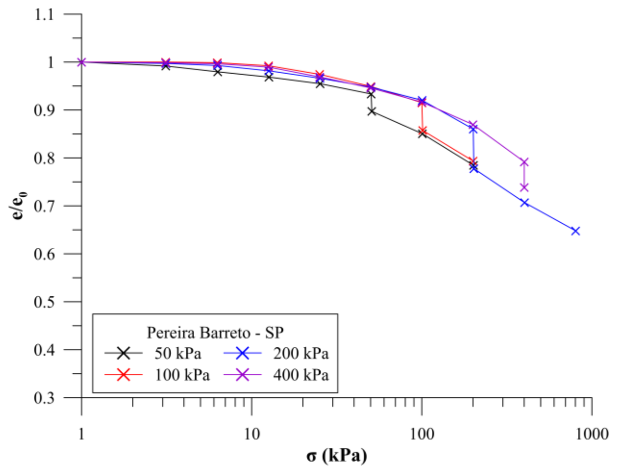

Figure 5. Oedometric curves for the conventional tests of the Pereira Barreto soil under the inundation stresses of 50, 100, 200 and 400 kPa

Table 1 presents the calculated collapse potentials from the oedometer curves for the three soils.

Table 1. Collapse potential for the soils of Ilha Solteira, Bauru and Pereira Barreto – Inundation stress of 50, 100, 200 and 400 kPa

	Ilha Solteira	**Bauru**	**Pereira Barreto**
50 kPa	2.9%	5.9%	1.7%
100 kPa	7.0%	8.4%	2.8%
200 kPa	14.3%	10.8%	3.6%
400 kPa	17.5%	12.9%	2.2%

Ilha Solteira and Bauru soils exhibited notable collapse potentials under the investigated inundation stresses. Consequently, the Ilha Solteira soil was selected for the experimental study on collapsible behaviour following a compaction process. The compaction conditions are illustrated in Fig. 2.

4.2. Expedite methods to identify collapse soils

Expedite methods for identifying collapsible soils are particularly useful during the initial stages of design. These methods generally focus on low-density soil. Gibbs (1961) introduced a method for fine-grained soils based on in-situ dry unit weight and liquid limit, known as the Gibbs and Bara method. Fig. 6 depicts this method, and it displays the plot of the three distinct natural soils from Ilha Solteira, Bauru and Pereira Barreto, as well as the compacted soil from Ilha Solteira.

Case I is a soil with volume of voids exceeding the amount required to retain the volume of water necessary to reach the liquid limit. Consequently, soils falling under this case exhibit a high collapse potential. Case III represents the soil for which the volume of voids is less than required to hold the water content at the liquid limit.

According to the Gibbs and Bara Method, all three soils at natural state, as well as the soil compacted with RC =85%, exhibit collapsible behaviour. The soil compacted with RC = 90% falls into the non-collapsible category, as indicated by its positioning within the Case III region (Fig. 6).

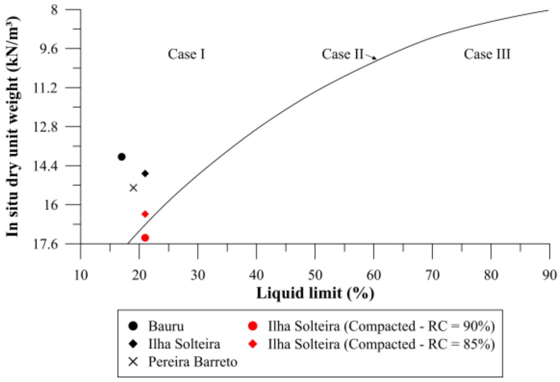

Figure 6. Gibbs and Bara Method for identifying collapsible soils.

The Gibbs and Bara method is widely recognized and has been effectively used to identify collapsible soils. However, a limitation of this method lies in its inability to identify non-plastic collapsible soils. Rodrigues and Vilar (2015) proposed a method to address this gap considering the typical looseness of such soils through compaction parameters. This alternative approach incorporates relative compaction and water content deviation (Δ*w*) to identify collapsible soils.

Fig. 7 illustrates the methodology outlined by Rodrigues and Vilar (2015), and the plots representing natural soils from Bauru, Ilha Solteira, and Pereira Barreto, as well as the compacted soil from Ilha Solteira.

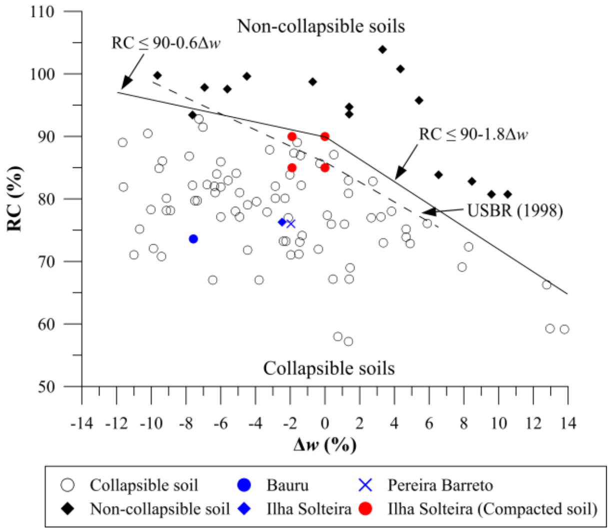

Figure 7. Method for identifying collapsible soils proposed by Rodrigues and Vilar (2015)

According to this method, all three natural soils and the compacted soils from Ilha Solteira exhibit collapsible behaviour. Only the soil compacted at the optimum water content, with a relative compaction of 90% was on the threshold between collapsible and non-collapsible classification.

Expedient methods are useful for the preliminary identification of collapsible soils, but they do not account for other variables that influence the collapse potential. The compacted soil from Ilha Solteira, with compaction conditions as specified in item 3, was selected to analyse the effects of relative compaction, water content, initial suction, and inundation stress on collapse potential.

4.3. Factors influencing collapsible behaviour in compacted soil

The results from both conventional and controlled-suction oedometer tests were gathered based on the inundation stress to trigger soil collapse (Figs. 8 to 12). In these figures, black curves represent conventional tests without suction control, while red curves represent tests with suction control (SC). Additionally, solid lines correspond to a relative compaction of 90%, whereas dashed lines represent a relative compaction of 85%. The arrows indicate the inundation stress at which the soil experienced induced collapse. Silveira and Rodrigues (2020) initially presented and discussed the results of these tests.

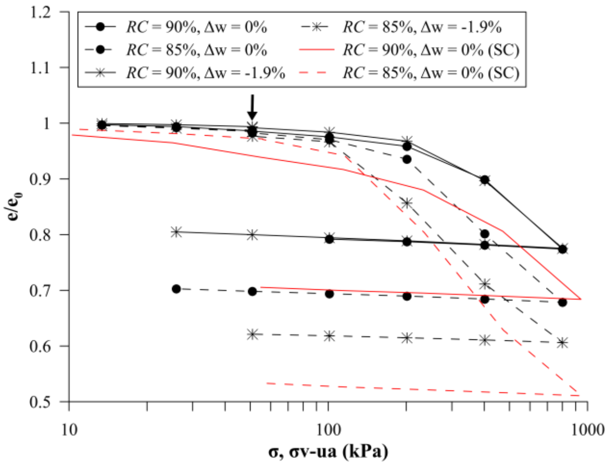

Figure 8. Oedometric curves for both the conventional and suction-controlled tests for the inundation stress of 50 kPa (Silveira and Rodrigues 2020).

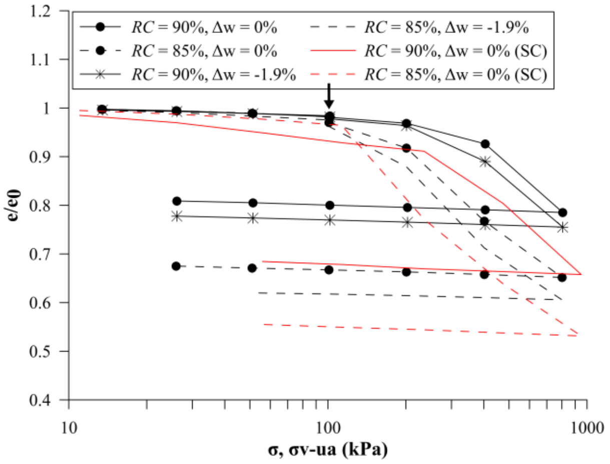

Figure 9. Oedometric curves for both the conventional and suction-controlled tests for the inundation stress of 100 kPa (Silveira and Rodrigues 2020).

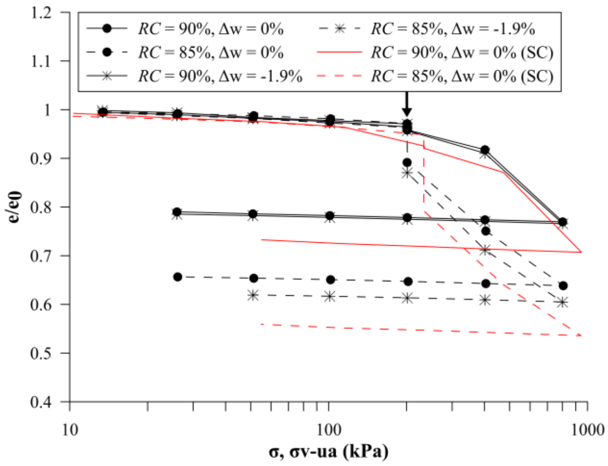

Figure 10. Oedometric curves for both the conventional and suction-controlled tests for the inundation stress of 200 kPa (Silveira and Rodrigues 2020).

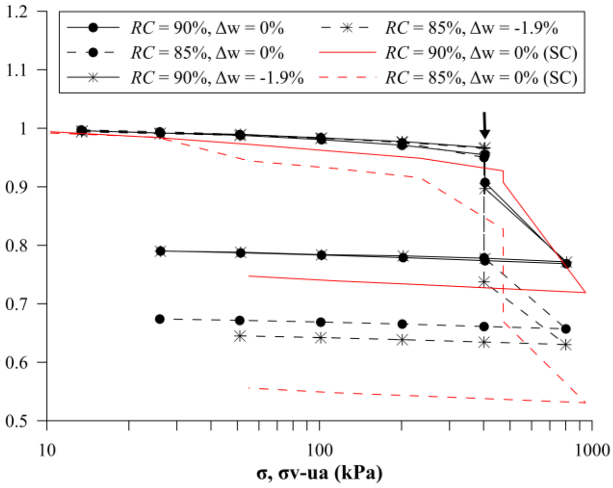

Figure 11. Oedometric curves for both the conventional and suction-controlled tests for the inundation stress of 400 kPa (Silveira and Rodrigues 2020).

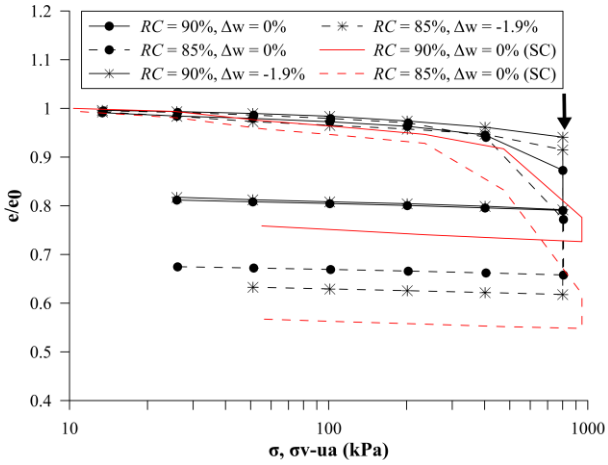

Figure 12. Oedometric curves for both the conventional and suction-controlled tests for the inundation stress of 800 kPa (Silveira and Rodrigues 2020).

A straightforward analysis of the oedometer curves (Figs. 8 to 12) reveals that the soil compacted with RC=90% exhibited a lesser reduction in void indices compared to the soil compacted with RC=85% when subjected to compression. Moreover, minimal deformation is generally observed under unsaturated conditions and when the soil is solely subjected to loading. This behaviour supports the fundamental proposition of enhanced soil compressibility resulting from compaction.

Figure 13 illustrates the collapse potentials under various inundation stresses for both conventional and controlled suction tests. Specimens with the lowest dry relative compaction (RC=85%) were notably affected by wetting, with a collapse potential exceeding 2% at relatively low inundation stress levels, approximately 150 kPa. According to Vargas' criteria (1978), the soil is collapsible if collapse potentials is greater than 2%. This behaviour occurs because the diminished compaction results in a smaller elastic domain.

Concerning the as-compacted water content, soils drier than the optimum water content exhibited escalating collapse for both relative compaction within the studied stress range. Specifically, when compacted at the optimum water content, the soil with RC=85% exhibited a continuous increase in collapse up to 400 kPa of stress, followed by a subsequent decrease in collapse.

The susceptibility of a soil to collapse increases when the Loading-Collapse curve (LC curve, Alonso et al., 1990) demonstrates a rapid rise in yield stress with suction. Soils compacted in a dry state, away from the optimum water content, are expected to exhibit an LC curve shifted to the right when compared to soils compacted either wet or near the optimum, at the same dry density. Notably, variations in compaction procedures result in distinct soil characteristics, as compaction at different water contents essentially yields different materials (Alonso and Cardoso, 2010).

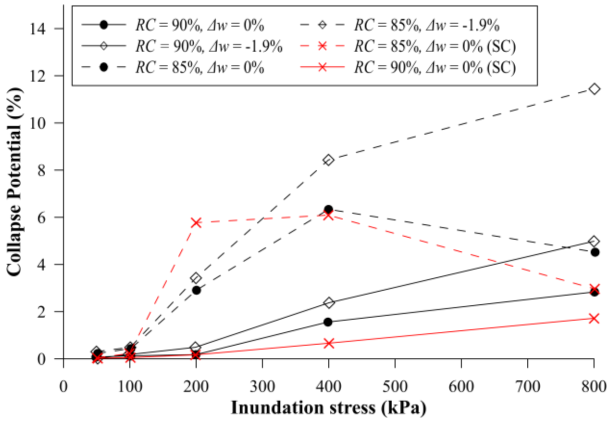

Figure 13. Collapse Potential with the inundation stress for both conventional oedometer test and suction-controlled oedometer test (SC) (Silveira and Rodrigues 2020).

Figure 13 also illustrates the impact of inundation stress on the collapse potential of compacted soils. For the RC=90% condition, the collapse potential exhibited an increase with stress, while for RC=85%, it increased only in the case of soils compacted dry of optimum water content. This rising trend in collapse potential with inundation stress diverges from the collapsible behaviour observed in lateritic soils in their natural state, where collapse tends to increase up to a certain stress level and then gradually decrease. However, this observation aligns with the findings of Basma and Tuncer (1992), who noted that compacted sandy soils generally exhibit an increasing collapse potential with rising inundation stress.

The filter paper technique was employed to measure the soil suction on the specimens used in conventional oedometer tests to investigate the impact of initial suction on the collapsibility of compacted soil. Figure 14 illustrates the compaction conditions of the specimens during the oedometer tests. The average degree of saturation (S_r) and initial suctions were plotted on the Proctor curve, aligning with the corresponding position of the target dry specific mass and as-compacted water content.

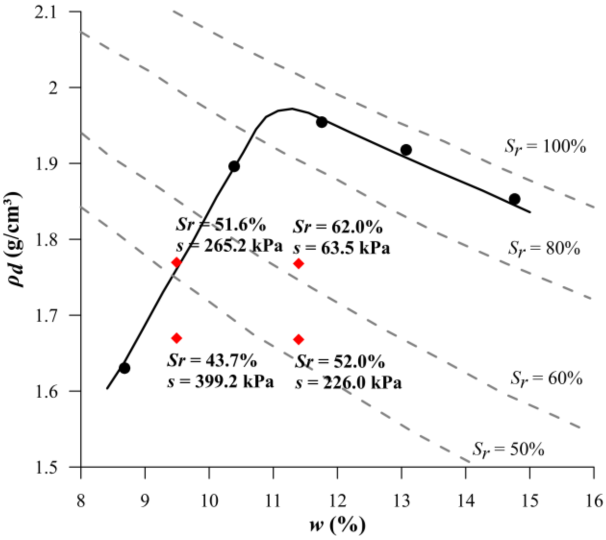

Figure 14. Degree of saturation and the respective soil suction for the studied conditions (Silveira and Rodrigues 2020).

Soil compacted with RC=90% and Δw=-1.9% and with RC=85% and Δw=0% exhibit similar initial suctions, suggesting proximity contours of equal suction or suction isolines. Suriol, Gens and Alonso (2002) observed that suction isolines are predominantly vertical at low water contents, gradually aligning parallel to the saturation line as the water content increases. These findings are consistent with the results depicted in Fig. 14, indicating a relationship between water content and dry density with suction.

A comprehensive understanding of the influence of compaction conditions on suction requires knowledge of the soil water retention curve (SWRC). Given that factors affect the uniqueness of the curve, such as the initial state of the soil, it is necessary to establish different curves for each compaction condition under investigation. In fact, low water content may position suction in the residual section of the SWRC, where the influence of relative compaction is minimal, resulting in nearly vertical suction isolines on the Proctor curve. Consequently, the initial suction depends on both water content and relative compaction, as these two variables influence the singularity of the SWRC.

Alonso and Cardoso (2010) state that suction is a continuously varying function when plotted in a (ρ_d , w) plane. The differences on volume changes in the soil can be explained by the variation in suction experienced during full saturation.

Fig. 15 illustrates the relationship between initial suction and the collapse potential for the inundation stress of 800 kPa. This stress level, although high, is emphasized because it leads to a more pronounced collapse.

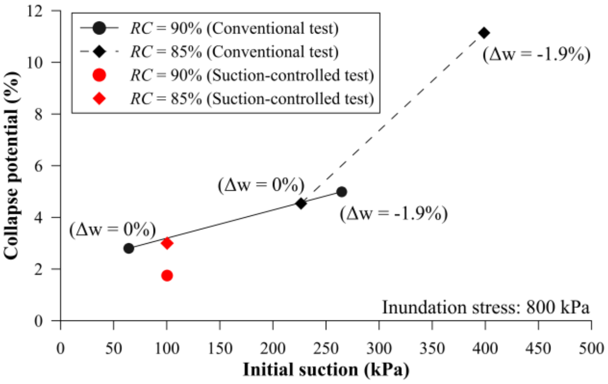

Figure 15. Collapse Potential with the initial suction for both conventional and suction-controlled oedometer tests (Silveira and Rodrigues 2020).

The collapse potential of the denser soil (higher RC) was less affected by variations in suction. The variation in the initial suction of the compacted specimens with RC=90% resulted in a comparatively smaller variation in the collapse potential under the same inundation stress, in contrast to the compacted soil with RC=85%. This trend aligns with the findings reported by Rao and Revanasiddappa (2000) for a clayey soil.

Moreover, the compacted specimen with RC=90%, subjected to controlled and constant initial suction until saturation, presented lower collapse potential compared to the conventional test. However, the collapse potential in this case remained low (less than 2%), and it can be considered to increase with suction, at the level of stresses analysed (Fig. 15).

Therefore, the experimental findings indicate that the initial suction influences the collapsible behaviour of the soil, showing clear associations with both relative compaction and inundation stress.

The results showed the influence of the relative compaction, as-compacted water content, soil suction, and inundation stress on soil deformation and collapsible behaviour. Empirical methods commonly used to identify collapsible soils rely on low density (or low relative compaction) and water content as primary indicators predisposing the soil to collapse. Although these factors are fundamental, they alone cannot predict or quantify soil collapse. It is evident that relative compaction and water content are crucial variables, but they alone cannot fully describe the collapsible behaviour of compacted soil.

The experimental results presented in this study, as well as in Silveira and Rodrigues (2020), along with the field data presented by Souza (1993) and the numerical simulation outcomes from by Rodrigues, Soares and Sanchez (2021) constitutes a significant collection of information detailing the behaviour of a compacted lateritic soil.

The investigations conducted by Souza (1993) and Rodrigues, Soares and Sanchez (2021) have demonstrated the effectiveness of the compaction technique for improving the behaviour of collapsible soils, particularly concerning volumetric deformation under loading and collapse in footings. The outcome of the study by Silveira and Rodrigues (2020) complements existing knowledge and highlights the mechanism of collapse of lateritic soils and the variables that influences the soil collapsible behaviour.

5. Conclusions

This study investigated the collapsible behaviour of a compacted lateritic soil using both conventional oedometer tests and suction-controlled oedometer tests. The Ilha Solteira soil was selected among three lateritic, sandy collapsible soils—Bauru, Pereira Barreto, and Ilha Solteira soils—due to its higher collapse potential under natural conditions.

Prior to the main testing phase, all three natural soils, along with the compacted Ilha Solteira soil under the experimental compaction conditions, were preliminary assessed using expedited methods to identify collapsible behaviour. According to both the Gibbs and Bara method and the Rodrigues and Vilar (2015) method, all three natural soils and the compacted soil with the lower relative compaction were collapsible soils. The compacted soil with a relative compaction of 90% at optimum water content falls on the threshold of between collapsible and non-collapsible classification.

The results for the compacted soils revealed that the magnitude of collapse deformations is influenced by the initial water content or suction before soil inundation, the inundation stress, and the relative compaction. Specimens with lower relative compaction (RC=85%) have more susceptibility to wetting, revealing significant collapse potential under relatively low inundation stresses.

As for the compaction water content, the soils compacted in the dry portion of the compaction curve showed an increasing tendency to collapse within the stress levels studied On the other hand, the sample with RC=85% initially presented a maximum collapse potential when compacted at optimum water content, which subsequently decreased under higher stress levels.

It became evident that the initial soil suction depends on both water content and the relative compaction. Furthermore, the collapse potential of compacted soil with a higher initial dry density at various water content levels proved to be less affected by variation in initial suction. In summary, the results highlighted the collapse mechanism in lateritic soils and elucidated the variables that influence their collapsible behaviour.

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