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Experimental evaluation of the classical and alternative consolidation theories in predicting the volumetric change of contaminated and non-contaminated soil

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Article

Keywords
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Abstract

Several regions in Brazil and the world suffer from the presence of collapsible soils. The development of theories for understanding the phenomenon is significant because the increase of water content is associated with several reasons (e.g., precipitation, rupture of sewage, and water systems). Although some theories explain the behavior of various types of soils, they fail to explain collapsible and structured soils. In this research, an alternative interpretation of the consolidation theory is verified and calibrated for collapsible soil. The alternative model was applied to experimental data from a latosol from southeastern Brazil, and comparisons with the classical theory showed a difference in the saturated hydraulic conductivity of around 100 times. The observation showed promising results compared with the saturated hydraulic conductivity of the field (Guelph Permeameter). Furthermore, consolidation tests verified the collapse potential, the variation of consolidation coefficient and saturated hydraulic conductivity, and the total settlement prevision due to the presence of bleach and washing powder.

1. Introduction

One of the phenomena widely known in Geotechnical Engineering, especially in hot and humid regions, is collapse. The definition of collapse is vast and different interpretations associated with volume decrease due to increasing saturation exist. The fields of interpretation are related to changes in load or stress state, soil strength components reduction, and changes in physicochemical properties affecting soil cementation and interaction between particles, consequently influencing soil collapse.

Soil wetting is related to rising soil water levels, leaking sewage pipes, and fuel leaks. The impacts caused are especially important on constructions in collapsible soils. Building on collapsible soils requires designing structures that can withstand significant ground movement or treating the soils to make them less sensitive to water content variation (Abbeche et al., 2010). Natural clayey soils rarely meet the requirements of modern geotechnical engineering projects (Cheng et al., 2020).

Besides, there is a difference between truly collapsible soils and conditionally collapsible soils (Reginatto & Ferrero, 1975). The collapsible soils are those that undergo a reduction of volume only with increasing saturation. On the other hand, the conditionally collapsible soils reduce volume by increasing both saturation and external load. The increase in water content can be associated with contamination of the soil.

Understanding soil collapse is associated with increased water content because water or contaminants change the soil's physical-chemical properties. According to Hu et al. (2021), there is a deterioration mechanism regarding the microspores exposed to the contaminants. Also, the resultant macrospores' mechanical properties correlate with the deteriorated microspores' structural characteristics. Khodabandeh et al. (2020) showed that changes in soil collapse potential are much more significant in acidic conditions than alkaline conditions.

Geotechnical engineers face significant challenges due to the risk of building constructions on collapsible soils whose volumes tend to drop abruptly once moistened (Nokande et al., 2020). Research about collapsible and unsaturated soil due to the change in moisture has been an area of geotechnics with significant interest. These studies take into account physical indexes, field, and laboratory tests.

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The physical index methods consider the variation of the degree of saturation (Jennings & Knight, 1975), the volumetric moisture content, and the void ratio. The most widely used laboratory tests are the single and double consolidation tests (Jennings & Knight, 1975; Vargas, 1978) and the X-ray diffraction test for the information provided on the soil microstructure.

Thus, the studies to identify the collapse and its understanding made geotechnical engineers search for an approach to measuring volumetric change. Therefore, the one-dimensional consolidation theory of Terzaghi (1943), proposed for variable loading over time in saturated soils, had an essential contribution to developing new consolidation theories applied to unsaturated, structured, and collapsible soils.

Fredlund & Morgenstern (1976) proposed and verified the relationship between the volumetric change of unsaturated soils and the state variables experimentally. In later research, Fredlund & Hasan (1979) proposed a consolidation theory for unsaturated soils considering the dependence between state variables and vertical deformation. In this model, collapse behavior decreases resistance associated with reducing suction due to wetting (Fredlund & Gan, 1995).

The analysis of the deformation of unsaturated soils and collapse were later addressed by elastoplastic models (Lloret & Alonso, 1980; Alonso et al., 1990; Gens & Alonso, 1992). Such models show promising results to estimate the volumetric variation of soils. However, a large number of parameters taken from experimental tests are necessary. From the perspective of the collapse, it requires a smaller number of parameters. Nevertheless, other parameters are necessary for different types of soils and even soils with different natural conditions. Therefore, despite the good results, the use of the method becomes complex (Li et al., 2016).

This research discusses an alternative model of Terzaghi's theory since his theory underestimates the saturated hydraulic conductivity values observed in the field. The values for k_s from the in situ tests are usually higher than those from the lab tests (Reynolds & Zebchuk, 1996; Nam et al., 2021).

Thus, in the new approach, the coefficient of consolidation (c_v), obtained by graphical methods, and the saturated hydraulic conductivity, obtained from c_v, are unsuitable for use in unsaturated soils. In these soils, micro-collapses occur. Consequently, there are increases in pore pressure, not only a decrease, as proposed by Terzaghi. According to Ozelim et al. (2015), the increase in pore pressure is due to the momentary loss of support of the porous matrix due to the occurrence of collapse.

Experimental data is present in this research, justifying the applicability of the consolidation theory induced by micro-collapses (Ozelim et al., 2015). Furthermore, complementary odometer tests using contaminants show the importance of knowing the liquid of inundation in the collapse potential and the prevision of settlement. Because the inundation liquids used are present in the water supply system and residential sewage, which can break and cause soil collapsibility.

2. Problem overview

Among the various ways of identifying collapse, laboratory ones are very satisfactory. One can mention the simple and double consolidation tests. Simple consolidation tests are those that consist of applying successive loads to a sample with natural moisture content. In a given vertical stress, the inundation of the specimen occurs, and the test continues by the application of successive loading and, in the end, unloading. For the double consolidation test, two identical samples are prepared. One will be inundated entirely from the beginning of the test. The other will remain with the natural water content throughout the experiment.

Among the most relevant laboratory forms of verifying collapse from consolidation tests are the Jennings & Knight (1975), Vargas (1978), and Reginatto & Ferrero (1975) approaches

Jennings & Knight (1975) proposed a classification based on the severity of collapse and volumetric variation of collapsing soils through simple and double consolidation tests. For the simple consolidation test, it is possible to calculate and classify the collapse potential as:

$$CP = \frac{\Delta e}{1+e_0} \times 100 \tag{1}$$

where Δe = the void ratio difference before and after inundation (dimensionless); e_0 = the initial void ratio of the experimental test (dimensionless).

The collapse potential (CP) calculated by Equation 1 can be classified as none (0 to 1%), moderate (1 to 5%), problematic (5 to 10%), severe (10 to 20%), and very severe (up to 20%).

The wetting-induced collapse deformation can be calculated by (Hanna & Soliman, 2017):

$$CP = \frac{\Delta e}{1+e_i} \times 100 \tag{2}$$

where e_i = the void ratio before the inundation (dimensionless). Thus, in soils where $CP > 2\%$, this is considered collapsible (Vargas, 1978).

Reginatto & Ferrero (1975) described ways to identify the collapse from the double consolidation tests. For double consolidation tests, the collapsibility coefficient (C) is determined by:

$$C = \frac{\sigma'_{0,s} - \sigma_{v0}}{\sigma'_{0,n} - \sigma_{v0}} \tag{3}$$

where $\sigma'_{0,s}$ = preconsolidation stress of saturated soil (F L^{-2}); $\sigma'_{0,n}$ = preconsolidation stress in the natural condition (F L^{-2}); σ_{v_0} = vertical geostatic stress (F L^{-2}).

The collapsibility coefficient (C) value determines what type of collapse the soil will be subject to and even if the soil shows a collapsing behavior. The soil can be truly collapsible ($C < 0$), conditionally collapsible ($0 < C < 1$), not collapsible ($C = 1$) and collapsible and normally consolidated ($C \rightarrow -\infty$).

In addition to verifying the collapse, studies in the literature seek to understand the collapse with other inundation liquids besides distilled water (Rodrigues & Lollo, 2007). Then, it is possible to understand the behavior of soils contaminated by other residues such as washing powder, bleach, sanitary sewage, oil, and others. One of the reasons for the inundations, for example, is due to ruptures in plumbing in the sewage systems (surrounded by collapsing soils). Thus, Rodrigues & Lollo (2007) show the behavior of Brazilian soil, inundated with different liquids under specific concentrations, because of its presence in sanitary sewage.

The consolidation theory proposed by Terzaghi (soil-spring analogy) is of great value to explain most saturated soils' behavior. However, for soil that has experienced significant weathering processes, the behavior of a spring is not coherent because the soil's porous matrix is constantly collapsing. Terzaghi's theory does not take such behavior into account. So a new approach is still a challenge for Geotechnical Engineering.

3. Description of the new consolidation theory

Ozelim et al. (2015) presented a new model as an alternative way of interpreting the consolidation theory discussed by Terzaghi. Water pore pressure does not gradually decrease in the model, as is interpreted in the conventional consolidation theory. However, the soil undergoes micro-collapses allowing the pore pressure to increase in certain stages of the consolidation.

The proposed theory considers the soil as a collapsible telescopic structure associated with springs, unlike the Terzaghi model, which presents the saturated soil as just a spring. The idea of a telescopic structure is justified because it can represent a wide variety of soil behaviors, such as different cementations in soils and the effect of stress on the collapse of the structure.

In the Terzaghi approach, during consolidation, there is no increase in pore pressure. Therefore, the impression is that the saturated hydraulic conductivity is lower as water takes longer to percolate. Consequently, this is the only consideration that the new theory disagrees with Terzaghi's approach. Accordingly, the mathematical way of calculating the average degree of density does not change:

$$U_c(T_v) = 1 - \sum_{m=0}^{\infty} \frac{2}{M^2} \exp\left[-M^2 T_v\right] \tag{4}$$

and

$$M = \frac{\pi(2m+1)}{2} \tag{5}$$

However, the time factor (T_v) must undergo a time dilation, meaning that the collapse will decrease the average degree of consolidation. Thus, the need to reduce the time factor is justified (Ozelim et al., 2015).

Although the consideration is simple, knowing the exact moment of collapse in real applications is not viable due to the complex measurement. Instead of predicting the precise moment of the collapse, there is the consideration of a given collapse frequency f. Besides, the increase in pore pressure and the frequency at which collapses occur are related to a parameter called the collapsibility index, η, introduced by Ozelim et al. (2015).

The general equation for the average degree of consolidation for collapsible soils is given by:

$$U_c(T_v, \eta) = \frac{1 - \exp(-[5.9(1-\eta)T_v]^{2/3})}{1 + \exp(-[5.9(1-\eta)T_v]^{2/3})} \tag{6}$$

The authors pointed out that $0 \leq \eta \leq 1$, and the time factor is mathematically related according to the proposed by Terzaghi:

$$T_v = \frac{c_v t}{{H_d}^2} \tag{7}$$

where c_v = coefficient of consolidation (L^2 T^{-1}); t = time (T); H_d = drainage path length (L).

Also, the method shows that when η = 0, the collapse mechanism does not occur, so the conditions established by Terzaghi are valid. However, if η = 1, there is no pore pressure dissipation, so the consolidation has infinite duration.

Ozelim et al. (2015) show that a combination of consolidation and permeability experiments is necessary to determine the collapsibility index. Therefore, when the value of η is known from the consolidation test, it is possible to calculate the saturated hydraulic conductivity value. Once the value of η is found can be established regionally, with the possibility of being estimated.

Ozelim et al. (2015) point out that by relating the value of the coefficient of volumetric variation, m_v ($L^2 F^{-1}$), obtained from the consolidation test, with the value of the saturated hydraulic conductivity, k_s ($L T^{-1}$), obtained from the permeability test, the c_v can be estimated using the known equation:

$$c_v = \frac{k}{m_v \gamma_w} \tag{8}$$

where γ_w = specific weight of the water ($F L^{-2}$).

According to Ozelim et al. (2015), if the value of η is not known, it can be calculated as follows:

$$\eta = 1 - \frac{1000}{2086} \frac{|m|^{3/2} H_d{}^2 m_v \gamma_w}{\Delta h^{3/2} k} \tag{9}$$

where m = slope of the beginning of the curve of the graph h versus $t^{2/3}$ ($LT^{-2/3}$), h = height of the sample in the considered step of the consolidation test (L), Δh = height variation of the sample in the considered step of the consolidation test (L), therefore, η can be calculated for each step of the consolidation test.

Using Equation 9 and calculating η, the coefficient of consolidation can be adjusted as follows:

$$c_v = \frac{1000}{2086} \frac{|m|^{3/2} H_d{}^2}{\Delta h^{3/2} (1-\eta)} \tag{10}$$

To verify the method's suitability for these types of soils, comparing the field saturated hydraulic conductivity (k_s) with the obtained from the technique is necessary. Thus, there are ways to get k_s from field experiments (e.g., Guelph permeameter test). Therefore, the test consists of determining the k_s by the one or two-stage method. These consist of applying one or two successive heights of the water column in the Guelph permeameter. The main discussion is if the model prevision of the saturated hydraulic conductivity value is close to the field measure.

The settlement estimation and its change in time use edometric tests and the assumption of consolidation. When the incremental stress plus the initial stress is higher than the preconsolidation stress, the settlement (S_T) prevision is in the form:

$$S_T = \frac{C_s H}{1+e_0} \log\left(\frac{\sigma'_c}{\sigma'_0}\right) + \frac{C_c H}{1+e_0} \log\left(\frac{\sigma'_0 + \Delta\sigma'}{\sigma'_c}\right) \tag{11}$$

where C_s = swell index, H = length of the layer (L), C_c = compression index, σ'_c = preconsolidation stress ($F L^{-2}$), σ'_0 = in situ effective overburden pressure ($F L^{-2}$) and $\Delta\sigma'$ = incremental stress ($F L^{-2}$).

The time-dependent settlement (S_t) can be calculated considering the degree of consolidation of Equation 4 (Terzaghi, 1943) or Equation 6 (Ozelim et al., 2015):

$$S_t(t) = U_c(t) S_T \tag{12}$$

The ratio of the non-conventional and traditional degrees of consolidation (R_{DC}) is a helpful manner of understanding the differences between both methods:

$$R_{DC} = \frac{U_c(T_v, \eta)_{\text{Ozelim}}}{U_c(T_v)_{\text{Terzaghi}}} \tag{13}$$

4. Materials and methods

The experimental data comes from the city of Rio Paranaíba, located in the state of Minas Gerais (19º 12 '46 "S and 46º 13' 57" W). The location is 532 km from the capital of Brazil (Brasilia/DF) city already identified with collapse problems.

The experimental data are from a depth of 1.5 meters, aiming at depths where water supply pipes and sewage systems are commonly placed and subject to ruptures. Disturbed samples for the soil characterization tests and undisturbed samples for the consolidation tests were collected. The undisturbed specimens were removed, maintaining the natural characteristics, and stored with paraffin.

The grain size distribution was based on the sieve and hydrometer analysis (ASTM, 2007 and ASTM, 2017a). The natural moisture content was obtained using the drying method. The liquid and plastic limit tests are according to ASTM (2017b). The standard Proctor compaction test was according to ASTM (2012).

After soil characterization, the simple and double consolidation tests investigated the collapsible soil characteristics (ASTM, 2003). Besides, three different liquids were used for further verification: distilled water, distilled water with bleach (1: 120 by volume), and distilled water with washing powder (1: 120 by mass).

The consolidation test specimens were from the undisturbed sample in a confining ring with a diameter of 8 cm and a height of 1.99 cm. The simple consolidation test was initiated by applying the initial stress with the specimen in the natural water content until the stress of 156.1 kPa. The choice of this value (156.1 kPa) is because it is in the virgin consolidation curve and is close to values used in the literature to verify the collapse potential (Jennings & Knight, 1975). The test ended in the stress of 1249 kPa, ending with the unloading.

The double consolidation test consisted of two specimens with identical conditions, preserving the undisturbed samples collected. One of the tests started with natural moisture, and the other was inundated from the beginning. The latter allows to obtain all parameters of Equation 11 and calculate settlement of hypothetical layers.

For both consolidation tests, the inundation was performed with substances commonly found in domestic sewage and treated water pipes. Thus, this research also makes it possible to verify the collapse under the influence of the inundation liquid.

The consolidation theory induced by micro-collapse requires a set of consolidation and permeability tests for its verification. Thus, consolidation tests obtained all the required parameters and, therefore, the corrected coefficients. The considered value of η is an average of the values calculated per load since it is a soil property.

After obtaining the value of η, a consolidation test was carried out to correct the coefficient of consolidation (Equation 10). From the parameters taken from the test, the value of c_v is obtained per vertical stress. Thus, having both c_v and volumetric compressibility coefficient (m_v), the corrected saturated hydraulic conductivity value measured in the consolidation test is obtained (Equation 8).

Although the consistency of the method is comparing it with values obtained in the field, Ozelim et al. (2015) not executed it. Thus, in this research, the authors check the consistency of the method through the Guelph Permeameter. Furthermore, some comparisons of the alternative and classical theories were executed with contaminated and non-contaminated soil.

5. Results and discussion

Table 1 shows the main soil physical indexes. Figures 1 and 2 show the particle-size distribution and compaction curves, respectively, of the studied soil.

Table 1. Soil physical indexes.

Parameter	Value
Natural Specific Gravity ($kg \cdot m^{-3}$)	1410
Natural Void Index	1.33
Saturated Preconsolidation Stress (kPa)	150
Porosity (%)	57
Specific Gravity of Solids ($kg \cdot m^{-3}$)	2780
Maximum Dry Density ($kg \cdot m^{-3}$)	1390
Optimal Water Content (%)	32
Liquid Limit (%)	42
Plastic Limit (%)	32
Plasticity Index (%)	10
Clay (%)	47
Silt (%)	11
Sand (%)	42

Figure 3 shows the relationship between void ratio and vertical stress for the simple consolidation test. The potential collapse - Equation 1, according to Jennings & Knight (1975), for water, washing powder, and bleach are 7.56, 8.90, and 5.32. The potential collapse, according to Vargas (1978) – Equation 2, for water, washing powder, and bleach are 8.26, 9.92, and 6.52. Thus, according to Jennings & Knight (1975), the severity of the problem would be problematic for

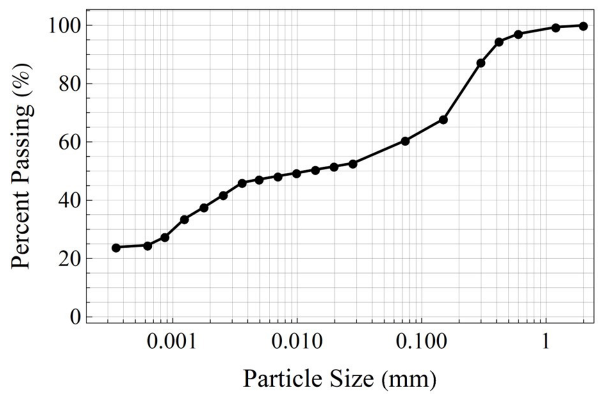


Figure 1. The particle-size distribution curve of the soil.

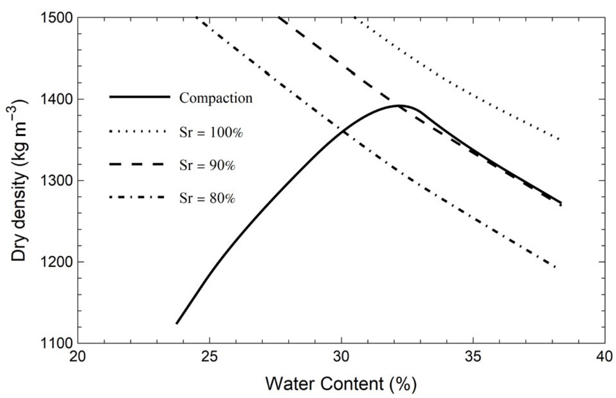


Figure 2. Compaction and saturation curves of the soil.

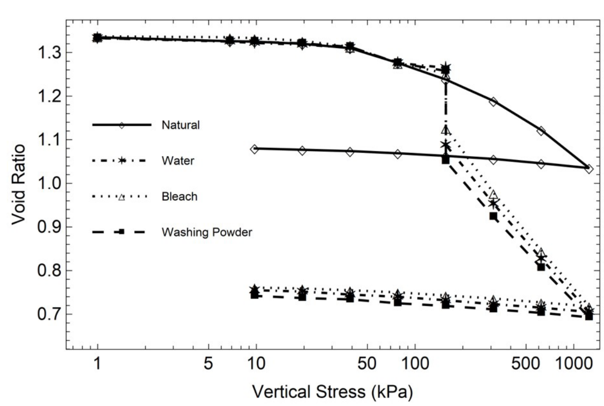


Figure 3. Relationship of void ratio and vertical stress for the simple consolidation test.

all inundation fluids. Moreover, according to Vargas (1978), for all inundation liquids, the soil has a collapsible behavior.

The type of collapse was verified in the double consolidation test, as proposed by Reginatto & Ferrero (1975). Figure 4 shows the relationship between void ratio and vertical stress for the double consolidation tests. The results of the collapsibility coefficient for water, washing powder, and bleach are 0.91, 0.25, and 0.58, respectively.

Thus, assuming the considerations of Reginatto & Ferrero (1975), the soil is conditionally collapsible. All results show the collapse potential of the soil and its characteristics of collapsing soil.

In Figure 5, there are the values obtained using the Terzaghi theory for the coefficient of consolidation (Figure 5a) and the hydraulic conductivity (Figure 5b) varying with the vertical stress. The coefficient of consolidation of the unsaturated condition (natural) was the highest one for all cases in higher stresses. Then, the consolidation process takes more time in the unsaturated condition.

5.1 Correction using the non-conventional consolidation theory

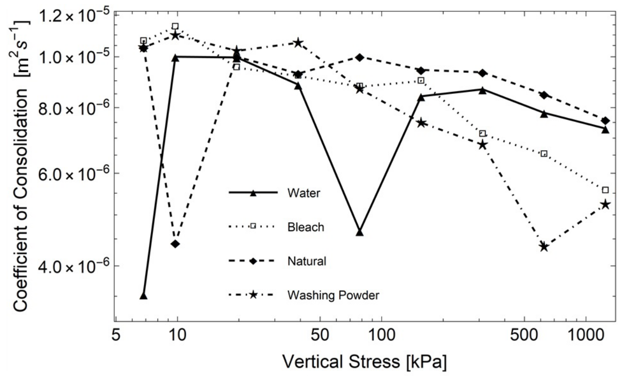
The input parameters proposed in Equation 9 are from the conventional consolidation test (I) (Figure 6) and its data. The preconsolidation stress calculated using the Casagrande method (Casagrande, 1936) is 150 kPa. Thus, the loading steps for validating the method are above this value.

Therefore, through the consolidation test, all the necessary parameters and the results obtained for the collapsibility index proposed by Ozelim et al. (2015) are found in Table 2.

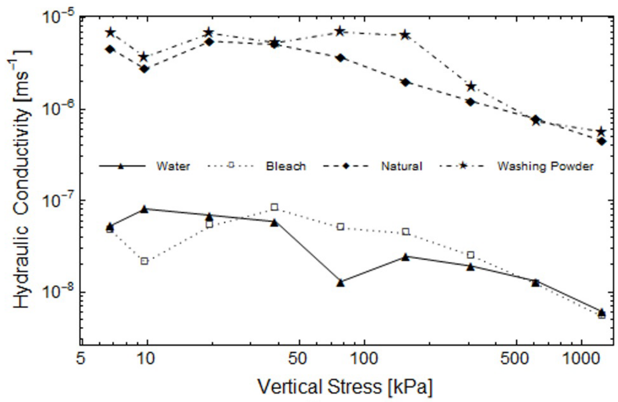
Utilizing the η values obtained, it was then possible to correct the coefficients of consolidation of each step (Equation 10) and the hydraulic conductivity values (Equation 8). Figure 7 shows the relationship of void ratio and vertical stress for the other consolidation test (II) to correct the mentioned parameters.

The new values found for c_v e k_s according to the method is in Table 3.

After obtaining the new permeabilities adjusted by the proposed model, Equation 6 is helpful to compare the average degree of consolidation (U_c) for different values of η. Figure 8 shows the average degree of consolidation versus the



(a)



(b)

Figure 5. Vertical stress versus (a) coefficient of consolidation and (b) hydraulic conductivity (Terzaghi Theory)

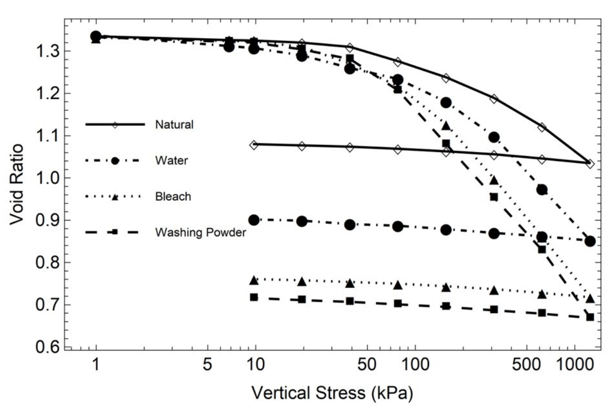


Figure 4. Relationship of void ratio and vertical stress for the double consolidation test.

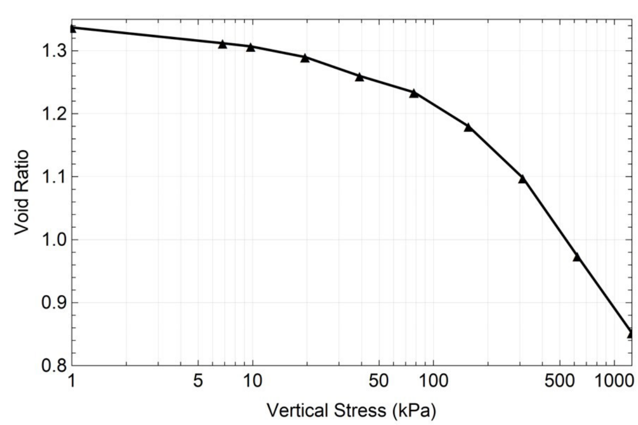


Figure 6. Relationship of void ratio and vertical stress (conventional consolidation test I).

Table 2. Collapsabilty index values (η) obtained from consolidation test I.

σ› (kPa)	m_v (kPa^{-1})	H_d (m)	c_v (m²/s)	k_s (m/s)	η
156.1	2,95 x 10^{-4}	1,90 x 10^{-2}	8,41 x 10^{-6}	2.43x10^{-8}	0.867
312.2	2,25 x 10^{-4}	1,86 x 10^{-2}	8,90 x 10^{-6}	1.96x10^{-8}	0.872
624.5	1,68 x 10^{-4}	1,78 x 10^{-2}	7,82 x 10^{-6}	1.29x10^{-8}	0.839
1249	8,4 x 10^{-5}	1,68 x 10^{-2}	7,30 x 10^{-6}	6.03x10^{-9}	0.848
				η (mean)	0.856

Table 3. Values of c_v and k_s corrected using η = 0.856.

σ› (kPa)	m_v (kPa^{-1})	H_d (m)	c_v (m²/s)	k_s (m/s)
156.1	4,94 × 10^{-4}	1,89 × 10^{-2}	4.00 × 10^{-6}	1.9 × 10^{-8}
312.2	3,53 × 10^{-4}	1,82 × 10^{-2}	6.23 × 10^{-6}	2.2 × 10^{-8}
624.5	1,88 × 10^{-4}	1,70 × 10^{-2}	4.38 × 10^{-4}	8.1 × 10^{-7}
1249	9,78 × 10^{-5}	1,59 × 10^{-2}	4.52 × 10^{-4}	4.34 × 10^{-7}

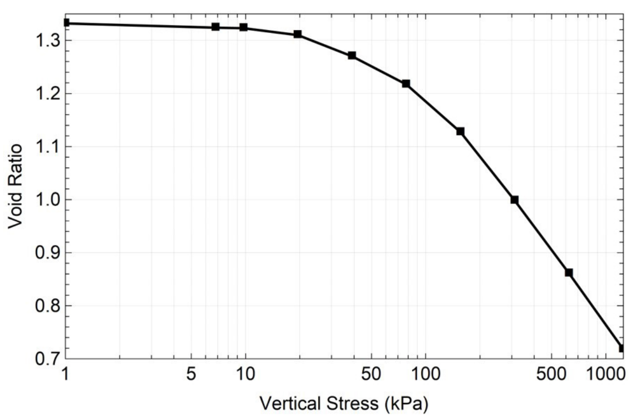


Figure 7. Relationship of void ratio and vertical stress (conventional consolidation test II).

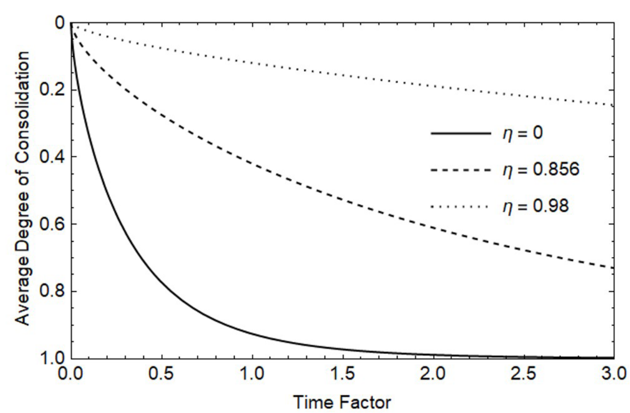


Figure 8. The average degree of consolidation (U_c) versus time factor (T_v), varying η.

time factor for different η. Figure 8 illustrates such behavior for the situation with no collapse (η = 0), the case of this research (η = 0.856), and the soil (η = 0.98) analyzed by Ozelim et al. (2015). As the consolidation coefficient proposed by Terzaghi, the collapsibility index is considered constant even varying with a load.

Analyzing Figure 8 can verify the importance of determining η for the correction of the average degree of consolidation and the effects of collapse causes in the degree of consolidation by considering the increase in pore pressure during micro-collapses.

5.2 Field saturated hydraulic conductivity of the soil (k_s)

The results of saturated hydraulic conductivity (k_s) obtained from the Guelph permeameter test were 7.6 × 10^{-7} m s^{-1} using a pressure head of 5 cm, 1.9 × 10^{-7} m.s^{-1} using a pressure head of 10 cm. Using the two-stage methodology (two pressure heads during the same test, H_1 = 5 cm e H_2 = 10 cm), the k_s was 7.3 × 10^{-8} m s^{-1}. The field saturated hydraulic conductivity (k_s) averages these values equal to 3.4 × 10^{-7} m s^{-1}.

The values obtained from the correction proposed by Ozelim et al. (2015), the field saturated hydraulic conductivity obtained by Guelph permeameter, and Terzaghi's theory are in Table 4. These results show that all saturated hydraulic conductivity was corrected. However, for the stress of 1249 kPa, the correction was up to 100 times. Moreover, the updated values had a better approximation of the actual value through the proposed theory, just the 156.1 kPa value that was similar.

Table 4. k_s comparison between the methodologies.

σ› (kPa)	$k_{s,cT}$ (m/s)	$k_{s,cO}$ (m/s)	$k_{s\ GP}$ (m/s)
156.1	2.43×10^{-8}	1.9×10^{-8}	3.4×10^{-7}
312.2	1.96×10^{-8}	2.2×10^{-8}	
624.5	1.29×10^{-8}	8.10×10^{-7}	
1249	6.03×10^{-9}	4.34×10^{-7}	

5.3 Settlement behavior

Using the results of the double consolidation tests (Figure 4), the swell index (C_s) for water, bleach, washing powder, and the soil in a natural condition are 0.024, 0.0159, 0.0188, and 0.0159, respectively. The compression index (C_c) for water, bleach, washing powder and the soil in a natural condition are 0.409, 0.4522, 0.4725, and 0.2571. The hypothetical saturated layer's thickness was considered 5 m and drained at both top and bottom. The considered incremental stress ($\Delta\sigma'$) was 1000 kPa. The value of the in situ effective overburden pressure was in the middle of the layer. The coefficient of consolidation of the traditional theory is in Figure 5a and the non-conventional in Table 3 for the vertical stress of 1249 kPa. All the remaining data is in Table 1.

In the analysis, the authors considered c_v fo the highest vertical stress (1249 kPa), although the collapsibility index was constant. The reason is that the higher the vertical stress, the higher is the adjustment of c_v.

According to Equations 11 and 12, the time-dependent settlement is present in Figure 9 for all inundation liquids. However, the application of the correction of the degree of consolidation of Ozelim et al. (2015) theory was just to the distilled water sample (Water-O). All other results in Figure 9 were calculated using the traditional Terzaghi theory for the degree of consolidation.

The highest value of the settlement (Figure 9) was the test with de powder, which had the highest collapse potential. The unsaturated sample presented the lowest settlement value mainly because of the strength increase due to suction compared with the saturated samples. Comparing the time-dependent settlement using the traditional (Water-T) and unconventional (Water-O) theories shows how collapse anticipates settlement.

The ratio of the non-conventional (Ozelim et al., 2015) and traditional (Terzaghi, 1943) degrees of consolidation (Equation 13) is helpful to understand how quickly the settlement occurs during the time. Figure 10 shows a result of varying thickness of drainage path length (H_d = 2.5, 5, and 10 m) in the degree of consolidation ratio. Because the coefficient of consolidation did not change in this situation, the maximum ratio was equal and approximately three times in all cases. However, the peak time differed, and the shorter the drainage path length, the faster the peak.

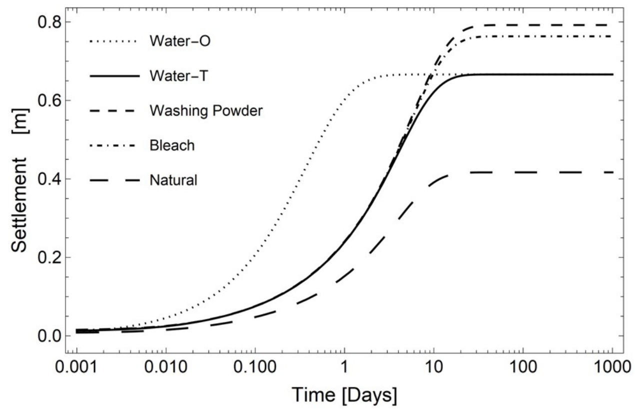


Figure 9. Time-settlement relation.

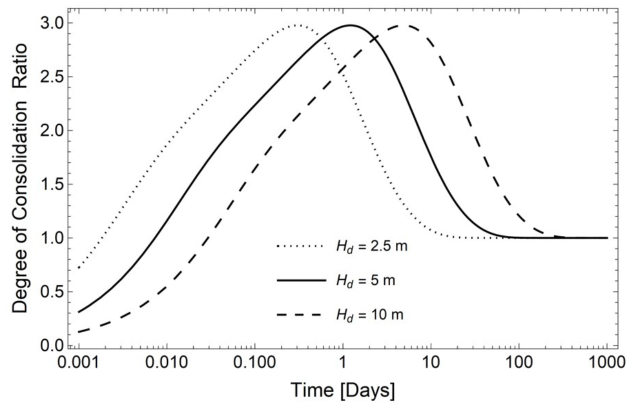


Figure 10. Predicted time history of degree of consolidation ratio.

6. Conclusion

Due to the soil characteristics in a region with a tropical and humid climate and a latosol that presents significant weathering, the soil shows collapsible features. The simple and double consolidation tests showed to be an essential measure to identify the potential of collapse. Therefore, it is recommended that more samples from other points at different depths are analyzed to understand the region's collapse spatially. One way to avoid doing many consolidation tests is to compare the soil characterization with other tests done in the area.

The alternative approach is relevant compared to the traditional one to estimate the consolidation and saturated hydraulic conductivity in consolidation tests. The results justify the new theory since the saturated hydraulic conductivity values by Terzaghi theory underestimates the saturated hydraulic conductivity values in collapsible and structured soils. The Guelph permeameter identified the hydraulic conductivity in the field. It was the tool utilized to compare the field with the laboratory parameters.

Although some of the corrected values show some discrepancy from the measured value in the field, it is essential to note that for all values, the hydraulic conductivity was updated. The method adjustment has come close to 100 times the value previously found by the conventional approach at specific stresses. Therefore, the method proposed is pertinent. Besides having a simple treatment, it was very relevant in places that have soils with collapsible characteristics.

Furthermore, if water content increases are associated with contamination instead of water, the collapse behavior changes significantly. This research shows that the presence of washing powder and bleach is associated with a higher collapse potential. In the settlement prevision, the contaminants had a higher total settlement compared with distilled water.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the paper's contents, and there is no financial interest to report.

Authors' contributions

Moisés Antônio da Costa Lemos: conceptualization, Data curation, Methodology, Visualization, Software, Writing – original draft. Lucas Martins Guimarães: conceptualization, Data curation, Investigation, Funding acquisition, Methodology, Resources, Supervision. André Luís Brasil Cavalcante: formal Analysis, Funding acquisition, Supervision, Methodology, Project administration, Resources, Validation, Writing – review & editing, Software.

List of symbols

CP	Collapse potential
C	Collapsibility coefficient
c_v	Coefficient of consolidation
e_0	Initial void ratio of the experimental test
e_i	Void ratio before the inundation
h	height of the sample in the considered step of the consolidation test
H	Length of the soil layer
H_d	Drainage path length
k_s	saturated hydraulic conductivity
m	Slope of the beginning of the curve of the graph h versus $t^{2/3}$
m_v	Coefficient of volumetric variation
R_{DC}	Ratio of the non-conventional and traditional degree of consolidation
S_T	Soil settlement
S_t	Time-dependent settlement
t	Time
T_v	Time factor
U_c	Average degree of consolidation
γ_w	Specific weight of the water
Δe	Void ratio difference before and after inundation
Δh	Height variation of the sample in the considered step of the consolidation test
$\Delta\sigma'$	Incremental stress
η	Collapsibility index
σ_c'	In situ effective overburden pressure
σ_0'	Preconsolidation stress
$\sigma_{0,s}'$	Preconsolidation stress of saturated soil
$\sigma_{0,n}'$	Preconsolidation stress in the natural condition
σ_{v_0}	Vertical geostatic stress

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