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Novel method for stress history analysis in normally consolidated clays

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Abstract. The historical investigation of stresses in a clay material is essential to predict the compressible behaviour of a soil layer that, in most cases functions as a foundation support of superstructures. Because the stresses underwent in the geological past provide useful information to understand the response of the soil today. There are numerous methods for the interpretation of the preconsolidation stress, defined by the standard unidimensional consolidation test. The concept of preconsolidation stress is extremely useful in the geotechnical field to analyze and estimate settlements in a clay deposit, in addition to normalizing other parameters for comparative purposes. Through mineralogical analysis and consolidation tests based on different models for the estimation of the vertical consolidation coefficient, preconsolidation stress is evaluated by applying disparate constitutive methods. In order to observe the dispersion of results for a particular soil. A new technique is proposed for the determination of the preconsolidation stress prescribed in differential terms and with a high degree of objective interpretation.

1. Introduction

The stresses experienced by a soil deposit during its geological chronology are caused by the self-weight of the upper layers and anthropic factors, as well as by the reconfiguration of the particles and the excess pore pressure produced by the expulsion of water from the interstices of the material. This conjunction of agents leads to the characteristic consolidation process [1]. To recreate the individual paths of this process, fine-grained compressible soils build up a memory of the stresses to which they have been subjected. This record is often presented by the preconsolidation stress (σ'_p), corresponding to the maximum effective stress experienced by a particular stratum [2]. σ'_p is the pseudo elastic boundary that separates the elastic behavior before creep from the plastic behavior after creep of a soil [3]. In geotechnical engineering, σ'_p is a key parameter for analyzing and predicting settlement paths, over consolidation ratio, stress history and short-term stability problems in soft clays [4-6].

Numerous methods for the evaluation of σ'_p have been documented in the literature, some with significant levels of variability. Casagrande's method [2] relies on the identification of the point of maximum curvature on the e-log σ'_v curve to determine σ'_p . Most of these methodologies focus on the assumption that at stresses close to σ'_p , soil samples exhibit variations in stiffness. However, the interpretation of σ'_p values is also entirely tied to personal judgment and subjective observation. Recently, [7] suggested using the dissipated energy of plastic deformations to optimize the behavioral variability of soil consolidation before and after σ'_p .



The current approaches commonly determine the σ'_p from graphical interpretation procedures of the bilinear void ratio (e) versus the effective vertical stress ($\log \sigma'_v$), with consecutive unloading-reloading loops for fitting consolidation data, Figure 1. In this way, the consolidation coefficient (C_v) can be estimated using the evaluation of σ'_p with different loading configurations. By quantitatively defining C_v , it is possible to predict the degree of settlement for a stress path, at a time t , and to model the hydro mechanical behavior of the particular skeleton [8].

This research experimentally addresses the deformability of intact samples of normally consolidated clays by means of standardized and regulated consolidation tests. The determination of C_v uses the numerical comparison of different theoretical methods, in addition to the consequent analytical interpretation. For the estimation of σ'_p , a new technique prescribed in differential terms is proposed. The results were cross-checked with other constitutive models to establish σ'_p .

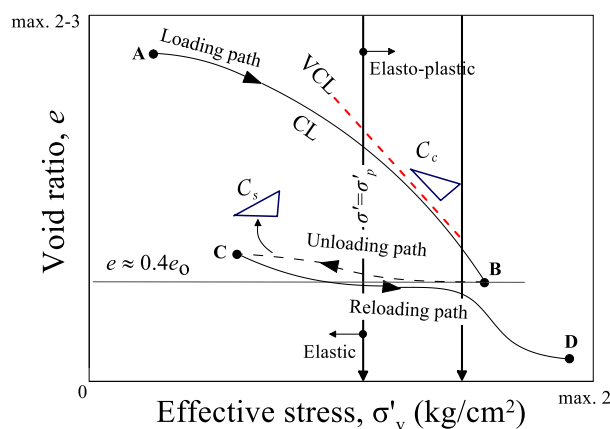


Figure 1. Consolidation paths.

1.1. Empirical methods for predicting preconsolidation stress

σ'_p , according to [2], is the "highest overburden at which a soil has consolidated". However, a soil may exhibit a σ'_p much greater than its maximum past stress. This contrast is mainly due to long-term secondary compression that generates a totally different soil deformation, compressibility and strength spectrum before and after σ'_p . To determine this variability threshold, a number of experimental alternatives [9-11] use different graphical distributions for e - $\log \sigma'_v$ where, for ordinary clays, the e - $\log \sigma'_v$ relationship is idealized through a straight line in the normal consolidation range. [12] and [13], provide a detailed and graphical discussion of the most commonly used models to establish the value of σ'_p .

[14] modified the conventional e - \log relationship σ'_v to predict σ'_p , by two straight lines in a neperian plane; the first defined by the volume, and the second by the average effective stress (p'). Studies related to the empirical validation of the log-log method, in $\log(e+1)$ vs $\log \sigma'_v$ planes, initially proposed by [15,16] and modified by [17]. [18] compares σ'_p in compactions induced using the log-log method, with those obtained by means of other models. The compression of compacted and chemically stabilized clayey soils evaluated through the normalization of e , C_v and additive content over the one-dimensional consolidation curve, constitutes a simple method proposed by [19] to determine σ'_p at any e_0 .

Traditionally, σ'_p has been defined based on one-dimensional consolidation tests for clays with well-defined breaks at stresses near σ'_p , using the e - \log plane σ'_v . However, these stress curves are not global. Graphical manipulations and superposition of different index parameters are frequently used to locate the experimental σ'_p values. [20] explores the intersection between the $C_{c_{max}}$ line and line parallel to the C_r line as σ'_p value, based on the dimensional applications of [21,22]. Optional archetypes with limited degrees of subjective inspection such as [12], which exploits the confluence of the void ratio and the tangent to the virgin compression line in the e - $\log(\sigma'_v)$ diagram to define σ'_p , for the point of maximum curvature in [13,23,24].

In conclusion, there are currently countless methods, both traditional and modern, to quantify the σ'_p , but it is the plurality itself, and the lack of consensus among methods, that makes it a poorly defined parameter in the geotechnical field.

2. Materials and methods

2.1. Characterization of the material

The changes in the textural information of the natural clay and the actual structure of the discrete and mixed multiphase layers are focused on the analytical interpretation of the positions of the basal reflections which are obtained by X-Ray Diffraction (XRD). Table 1 presents the chemical composition obtained by XRD analysis of the clay.

Table 1. Mineralogical composition by XRD.

Minerals (%)	Formula	Natural clay
Quartz	SiO ₂	59.38
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	31.33
Illite	(KH ₃ O)(AlMgFe) ₂ (SiAl) ₄ O ₁₀	1.86
Montmorillonite	(NaCa) _{0.3} (AlMg) ₂ Si ₄ O ₁₀ (OH) _{2-n} H ₂ O	7.43

The liquid limit (LL) and plastic limit (PL) of natural clay were determined using the Casagrande percussion instrument in accordance with [25]. Table 2 presents the index properties and classification of the soil studied. For the pseudo-elastic deduction, it is considered that the material does not have high plasticity, so that, when faced with abrupt moisture gradients, it can pass directly to the liquid state by reducing its shear strength. Likewise, the value of LL is essential to limit the numerical fluctuation of σ'_p , since there is a direct relationship between LL and the compression coefficient C_c .

Table 2. Physical properties of Cajicá clay.

Specific gravity (Sg)	Liquid limit (LL) (%)	Plastic limit (PL) (%)	Plasticity index (PI) (%)	Shrinkage limit (SL) (%)
2.73	58	27.1	30.9	15.6

2.2. Proposed interpretation principles and method

Due to the level of subjectivity with graphical approaches to interpret data in one-dimensional consolidation tests, especially of normally consolidated clays, which do not exhibit an accentuated yielding point. A new descriptive method is proposed based on visual logic that has a direct physical significance in the overall behavior of σ'_p , and can be easily incorporated into the conventional semi-logarithmic scale of e - $\log(\sigma')$, to obtain a single unambiguous value result corresponding to σ'_p .

Ninety one-dimensional consolidation tests were used to examine the suitability of this research approach in a general application. These tests were performed on unaltered samples of a normally consolidated stratum (Cajicá clay), located at a depth between 3 m and 5 m in the analyzed region. The methodological arrangement used for these curves was based on the approaches proposed by [2,26,27], with a distribution of 30 tests per method to obtain the C_v .

On normally consolidated soils, the silhouette of the consolidation curve does not always allow the yield point corresponding to σ'_p to be perceived. Subjective models such as [12,13,28,29], circumscribe parametric interpretations to ideal consolidation curvatures, which results in the suppression of the real mechanical behavior and an overestimation in the values of σ'_p . For this reason, for the evaluation process of σ'_p , the novel method approach is constructed, whose principle is to objectively assess the σ'_p , through of the total derivative $de/d(\log \sigma')$. This technique, accentuates the inflection points, and the relative and total maxima and minima in the space $de/d(\log \sigma')$ vs $\log \sigma'$, for soils with $OCR = 1$. In general, the most accentuated local positions correspond to the value of σ'_p .

Figure 2 compares the proposed interpretation method with those by [12,13,28,29]; this Figure 2 illustrates that, among the methods examined, the values determined using the proposed approach are

more closely correlated with the empirical response of the consolidation curve than with the ideal assumption of the consolidation curve.

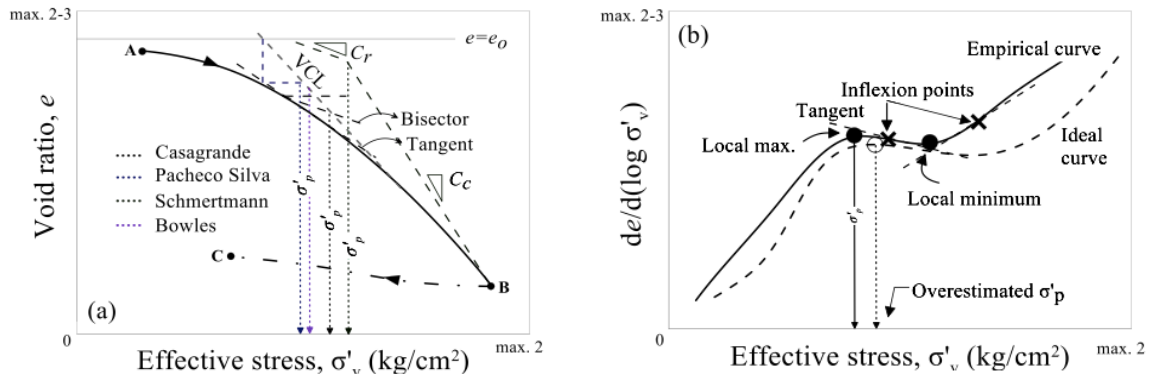


Figure 2. Interpretation of σ'_p using (a) Casagrande [13], Pacheco Silva [12], Schmertmann [28], Bowles [29] methods, and (b) proposed method.

3. Results and discussion

The results of the one-dimensional consolidation tests were analyzed to determine the vertical consolidation coefficient (C_v), with unloading-reloading loops in small steps for the calibration of the curves (Figure 3 to Figure 5) [30]. Regarding the examination of preconsolidation stresses (σ'_p), it is important to describe that, although the method for estimating the consolidation time in the tests must be defined and established, it does not seem to influence the σ'_p values.

Figure 3, Figure 4, and Figure 5, illustrate the comparison in the descriptive estimation range of σ'_p for each test using the identification: $\sigma'_p(C)$, [13]; $\sigma'_p(PS)$, [12]; $\sigma'_p(S)$, [28]; $\sigma'_p(B)$, [29]; and $\sigma'_p(N)$, proposed method. The values of σ'_p for each method tend to converge to the same value set in the graphical analysis.

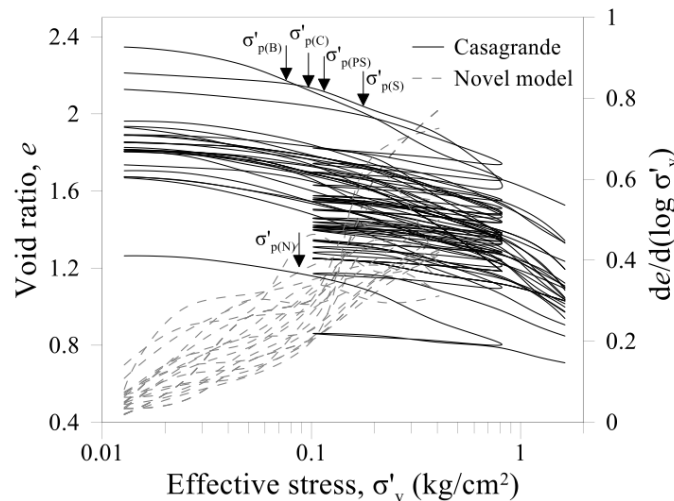


Figure 3. Thirty oedometer test curves for Casagrande [2] case, with unloading-reloading cycles, and estimated preconsolidation stress by [13] Casagrande, [12] Pacheco Silva, [28] Schmertmann, [29] Bowles and novel method.

Table 3 summarizes the unambiguous single values of σ'_p determined from the oedometer verification tests. The range of variability of σ'_p , is 0.05 to 0.23 kg/cm^2 . It is evident that, for each consolidation setting, [28] and the current proposal yield the highest and lowest values, respectively.

The approaches of [13] and [12] yield significantly higher average values than the proposed approach, indicating a higher degree of variability if the idealization principles suggested in these methods are considered applicable and relatively constant for soft clays.

Table 3. Summary of estimated preconsolidation stress values.

Test	$\sigma'_{p(C)}$ (kg/cm ²)	$\sigma'_{p(PS)}$ (kg/cm ²)	$\sigma'_{p(S)}$ (kg/cm ²)	$\sigma'_{p(B)}$ (kg/cm ²)	$\sigma'_{p(N)}$ (kg/cm ²)
Casagrande	0.10	0.11	0.17	0.08	0.09
Taylor	0.12	0.14	0.23	0.17	0.05
Asaoka	0.15	0.16	0.18	0.06	0.06

Note: interpretation methods $\sigma'_{p(C)}$, [13]; $\sigma'_{p(PS)}$, [12]; $\sigma'_{p(S)}$, [28]; $\sigma'_{p(B)}$, [29]; $\sigma'_{p(N)}$, proposed.

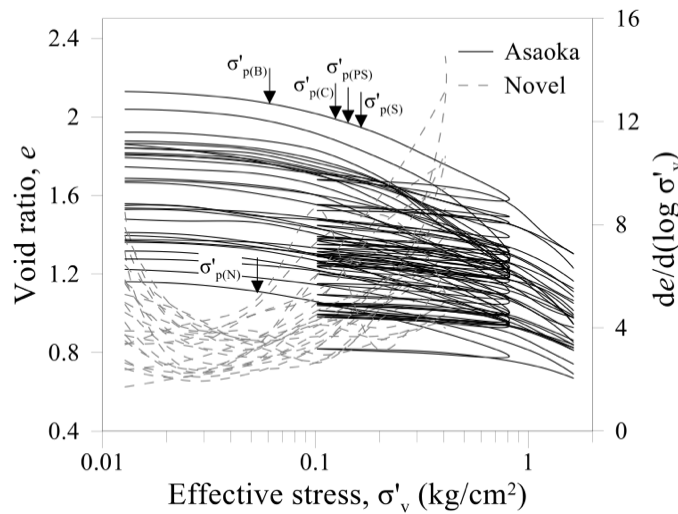


Figure 4. Thirty oedometer test curves for Asaoka [27] case, with unloading-reloading cycles, and estimated preconsolidation stress by [13] Casagrande, [12] Pacheco Silva, [28] Schmertmann, [29] Bowles and novel method.

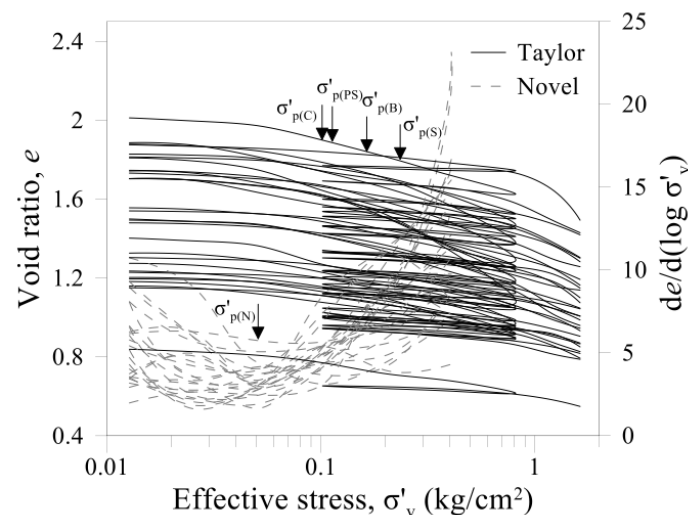


Figure 5. Thirty oedometer test curves for Taylor [26] case, with unloading-reloading cycles, and estimated preconsolidation stress by [23] Casagrande, [12] Pacheco Silva, [28] Schmertmann, [29] Bowles and novel method.

The method of [13] is the most commonly used technic for estimating σ'_p , so it is often considered as a basis for comparison with other methods. The values of σ'_p obtained by [13] were neither entirely the highest nor the lowest, but intermediate values. For the novel method, a technique similar to that of [13] is required, with the spatial modification $de/d(\log \sigma') - \log \sigma'$ for the maximum curvature point. The verification test results showed that all methods overestimated the σ'_p . Although good results are obtained, there are no revealing advantages of using this method over the others.

The value of σ'_p for $\sigma'_{p(N)}$ corresponds to the maximum local point on the derivative curves only in [2], since, unlike [26] and [27], the estimation of the vertical consolidation coefficient (C_v), considers a semi logarithmic graph space in the oedometric settings to establish the domain of the void ratio.

In terms of analysis, it was evident that the 90 curves obtained by the different methods of obtaining the consolidation coefficient, did not show any dependence on this parameter. However, if it was on the technique chosen to obtain the preconsolidation stress. The yield points shown in Figure 3 to Figure 5 show a high dispersion influenced by the high subjectivity of the methodologies based on a criterion-based starting point and graphical plots. Undoubtedly, the novel method fixes a locus that provides high objectivity and certainty when locating the geological history stress of the soil.

4. Conclusions

The consolidation tests analyzed of the normally consolidated clay under study, indeed show curves with little accentuated points of curvatures, compared to what can be easily perceived in an over consolidated clay. This aspect conditions the obtaining of an adequate preconsolidation stress, because most methods select a starting point close to a depression of the curve that is associated with this yield stress.

The methodologies used to estimate the consolidation curve, do not have a close influence on the behavior of the curve, nor on the possible choice of starting points in the selected techniques for obtaining the preconsolidation stress. However, as already mentioned in the analysis, the choice of the method to obtain the σ'_p has a great influence on the estimated value of the stress.

The novel method (this study), proved to be more effective than the previous ones in directly identifying the preconsolidation stress, due to the objective detection of any change in the curvature of the consolidation branch and being projected on the derivative of the curve $de/d(\log \sigma')$ vs $\log \sigma'$.

The implemented method is suitable for stress history analysis in normally consolidated clays. Which, in the virgin branch of consolidation, do not reveal any major shocks and where conventional methodologies may fail.

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