

Effectiveness of various methods to determine stress history parameters in cohesive soils

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ABSTRACT: One of the major features that makes the difference between soil that incorporates skeleton and pores and other one-phase construction materials lies in sensitivity to acquired stress history. This fact results in considerable changes in shear strength, stiffness, and initial state parameters, especially in cohesive soils. For this reason, in any kind of numerical modeling of soil response to external loading, stress history parameters are very important input data. The prevailing methods based on the oedometer test to determine the highest vertical stress acquired by soil rest on the identification of the yield stress, which corresponds to the boundary between elastic and plastic (irrecoverable) strains. Since the first method for the determination of preconsolidation stress, σ'_p , proposed by Casagrande in 1936, accumulated experiences have revealed that many similar methods based on the interpretation of the oedometer test results do not provide a realistic value of preconsolidation stress, especially in heavy preconsolidated cohesive soils. Therefore, there is a necessity to reevaluate the effectiveness of standard methods and look for another solution to evaluate the yield stress σ'_y in natural soils. The paper presents the comparison between σ'_y determined for natural preconsolidated soils using standard methods based on the conventional oedometer test and yield stress determined on the basis of alternative procedures. Among these alternative procedures, the ones considered are based on shear wave velocity, unloading reloading deformation modulus E_{ur} , SHANSEP approach, and the Authors' method based on the dilatancy phenomenon. These alternative methods are based on tests carried out in a triaxial apparatus. The paper analyzed the correctness of the substantive premises of each of the methods considered. It concerns the method based on oedometer and triaxial tests as well. Comparison of the yield stress profile σ'_y obtained for natural overconsolidated soil layers on the basis of the considered methods is presented and discussed in the paper.

KEYWORDS: Stress history, yield stress, laboratory methods, overconsolidated cohesive soils.

1 INTRODUCTION

Solid bodies subjected to loads can exhibit both elastic and plastic properties. The proportions of the individual properties in the deformation process depend on the volumetric fraction of pores in the body and the magnitude of the load. Soil, as a porous body composed of two or three phases, is particularly susceptible to deformation under load. A proper representation of these two soil properties requires quantitatively defining the boundary between stress values at which elastic deformation predominates and stress values at which plastic deformation predominates. Defining this boundary is not straightforward because, in the case of soil, this boundary is not constant and depends on all post-depositional processes, the most recognizable of which is the soil's loading history.

It can be said that soil remembers the maximum load experienced in the past. This feature was used to determine values of preconsolidation stress for design purposes. As the first procedure proposed by Casagrande (1936), the majority of methods for the determination of σ'_p are based on laboratory oedometer tests where the soil sample is vertically loaded in stages in laterally constrained conditions. Results of such tests are presented in the form of a compressibility line where the effective stress applied is shown on the horizontal axis (in linear or log scale) and the vertical axis represents the change in volume represented by volumetric strain, change in sample height, or most often void ratio. In case of soft soils, with relatively low values of preconsolidation stress, it is easy to identify on the basis of the compressibility curve the range of highest stress to which a soil sample was loaded, as shown in Figure 1. The softer a soil sample is, the more visible a breakdown or yielding point on compressibility curves. The basic mechanism is based on the border between recoverable (predominantly elastic) and irrecoverable (predominantly plastic) strain. The large majority of methods used in geotechnical practice for the determination of preconsolidation stress σ'_p rests on this concept of the border between recoverable and irrecoverable strain.

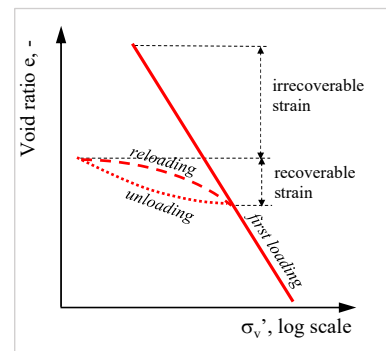


Figure 1. Concept of standard approach to determine preconsolidation stress in soil based on recoverable and non-recoverable strain.

2 METHODS BASED ON THE IDENTIFICATION OF THE YIELD POINT IN OEDOMETER TESTS

2.1 Factors affecting the shape of compression curves

The procedure for determining preconsolidation stress, based on oedometric tests and the separation of strains into reversible and irreversible, worked well for slightly mechanically overconsolidated soils, and over time has been increasingly applied to natural soils. However, post-depositional processes, including complex glaciotectonic processes, which subjected the soil to loads several dozen times greater than present, as well as the inevitable disruption of the soil structure during sampling from great depths, contribute to a fundamentally different compression curve compared to soft soils. Difficulties in applying standard procedures led to a growing interest in the causes determining the value of preconsolidation stress. As early as the mid-1980s, many researchers began to realize that the magnitude of preconsolidation stress resulting from mechanical overloading could be influenced by various post-depositional processes, such as secondary compression, cementation, soil aging, temperature changes, and others (Jamiołkowski et al., 1985). A summary of all these factors affecting the values of preconsolidation stress in soils is presented in Table 1.

Table 1. Factors affecting the location and shape of compression curves.

Factors resulting from IN SITU CONDITIONS		Factors resulting from LABORATORY TEST PROCEDURE	
Mechanical preloading	Non- mechanical natural mechanism	Sampling	Laboratory test procedure
1. Overburden (e.g., Glacier) 2. Change of pore water pressure	1. Drying due to evaporation and freezing 2. Drained creep (aging) Due to long-term secondary compression 3. Natural cementation Bonding due to iron exchange: Thixotropy, wheathering	1. Change in compression curves due to sample disturbance	Test procedure in the oedometer test: 1. LIR – (Load increment ratio) 2. Time of load application at each stage

Difficulties in quantitatively describing the complex phenomenon of preconsolidation were the direct reason for Burland's (1990) proposal to reorganize the nomenclature associated with the phenomenon of preconsolidation. He proposed that the term "preconsolidation" be reserved for situations in which a break in the stress-strain curve results solely from the mechanical action of load on the soil. However, if this collapse results not only from mechanical preconsolidation but also from other post-depositional processes, then the value of the stress component corresponding to the significant change in the compression characteristics can be called yield stress and marked with the symbol σ'_y .

As already mentioned, compression characteristics obtained for soft soils are different from those determined on undisturbed samples of overconsolidated material. It can be well illustrated by comparison of the compression curves of undisturbed and reconstituted high plasticity clay shown in Figure 2. Reconstituted material, with erased stress history, had a liquidity index $LI = 0.45$, while the undisturbed sample $LI = -0.15$. Both samples underwent a similar procedure of loading, i.e., unloading–reloading cycles were applied. As it results from the chart, for reconstituted material, it is easy to identify the greatest curvature in the reloading curve, so the application of any method for the determination of preconsolidation stress would be successful. The situation is quite different in the case of an undisturbed sample of unknown stress history. The compression curves are flattened, and it is difficult to find the point corresponding to the greatest curvature. In such a case application of methods based on the separation of elastic and plastic deformations might not be successful.

2.2 Differences in σ'_y determined by various methods

The example given in Figure 2 gives some premise to assume that in case of overconsolidated undisturbed sample identification of yield point might not be unequivocal. This situation has led to the emergence of more than a dozen different proposed procedures for determining preconsolidation stress over the years, intended to provide a better (more accurate) determination of preconsolidation stress. There are many of proposed methods are given in the works of e.g. Casagrande (1936), Janbu (1969), Pacheo Silva (1970), (Sällfors (1975), Buterfield (1979), Becker et al. (1987), Senol

(1997) and others. The list of the proposed methods is certainly longer, however all of them rest on graphical construction of results of oedometer test. Comprehensive review of methods based on oedometer tests with various graphical construction can be found in geotechnical literature (e.g., Grodzic et al. 2003; Boone, 2010). It is tempting to conclude that the multitude of these proposals might indicate their imperfections. It should also be remembered that all these methods are based on oedometric tests and are subject to various interpretations resulting from the approximation of the compression curve, which are expressed by differences in the preconsolidation stress values determined using different methods. To confirm this statement, one can consider the example shown in Figure 3, where three methods (from the above-mentioned ones) were applied for the determination of yield stress on a few undisturbed clay samples of low plasticity. As can be seen from the histograms, each method delivers different values, but none of them seems to be probable, and "the true value" remains unknown. It is worth emphasizing that the plasticity index of the tested sample was in a relatively narrow range (9,9 – 12,7%). It might be expected that in high plasticity clay, the scatter of data would be bigger.

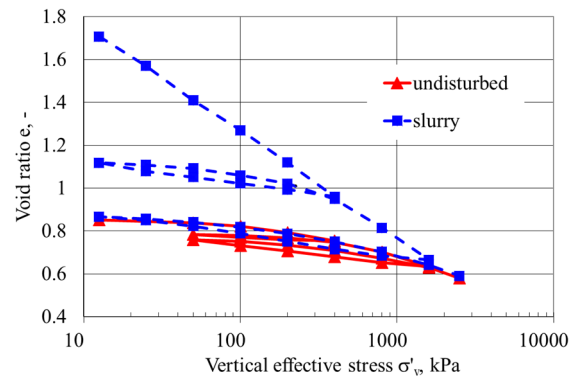


Figure 2. Comparison of compression curves from oedometer tests carried out on undisturbed and reconstituted high plasticity clay.

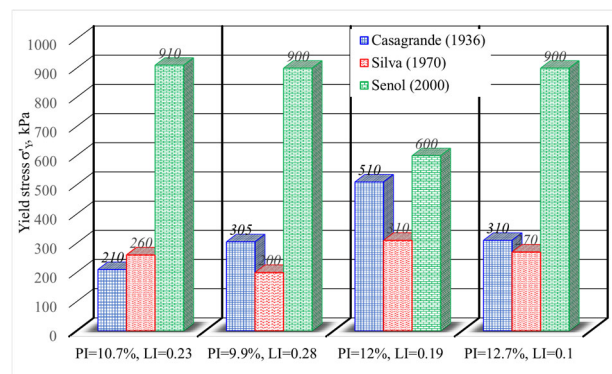


Figure 3. Comparison of yield stress determined by various methods based on standard oedometer tests.

3 ALTERNATIVE APPROACHES TO THE DETERMINATION OF YIELD STRESS

3.1 Convergence of compression curves (CCC)

One of the conceivable and conceptually natural alternative approaches to the graphical construction of the determination of yield stress rests on the comparison between the compressibility line obtained for the undisturbed sample and such a characteristic for the remolded material. This concept seems natural because it refers to the definition of preconsolidation stress caused by mechanical overload. Void index I_v , proposed by Burland (1990), is constructed on this

concept. The logic of this approach assumes that the compression curve for an undisturbed material with an intact structure after reaching the stress corresponding to the highest value to which the material was loaded should fit the intrinsic compression curve obtained for remolded soil. The point where both curves converge determines the value of the preconsolidation stress on the stress axis. The result of such a comparison is shown in Figure 4. The chart presents the results of CRS tests carried out in a consolidometer on two samples, undisturbed and remolded. It should be emphasized that the condition of intersection of two curves might not be fulfilled, especially in the standard oedometer test, where the change in void ratio due to sample disturbance is significant. In such a situation, the condition of parallelism of curves, which means equality of the constrained modulus, is sufficient.

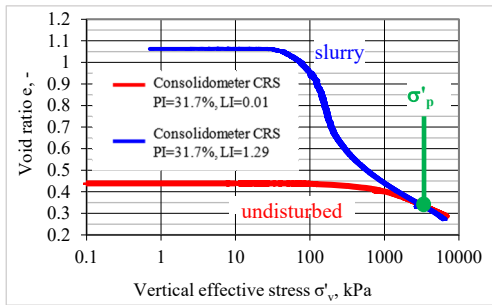


Figure 4. Convergence of compression curves (CCC) obtained from the consolidometer CRS test on undisturbed and reconstituted soil.

3.2 Derive preconsolidation stress σ'_p from SHANSEP approach

Another possibility of the derivation of stress history parameters is an indirect method based on the comparison of the normalized parameters of soil. The SHANSEP method proposed by Ladd & Foot (1974) links normalized parameters of OC soil and NC with OCR . Although the SHANSEP method applies to various kinds of parameters, it is most often used for undrained shear strength S_u . In this case, the formula takes the following form:

$$\frac{\left(\frac{S_u}{\sigma'_{v0}}\right)^{OC}}{\left(\frac{S_u}{\sigma'_{v0}}\right)^{NC}} = OCR^m \quad (1)$$

where:

$\left(\frac{S_u}{\sigma'_{v0}}\right)^{OC}$ - normalized undrained shear strength for overconsolidated soil

$\left(\frac{S_u}{\sigma'_{v0}}\right)^{NC}$ - normalized undrained shear strength for normally consolidated soil ($OCR = 1$)

m - empirical exponent.

Such an approach of back calculating preconsolidation stress from OCR , when undrained shear strength determined on undisturbed and remolded material is known, is very often used by practitioners and designers where they face the problem of input data to FEM analysis.

3.3 Correlation with stiffness parameters

An alternative to the oedometer test-based methods is approaches based on the determination of stiffness for a small strain range. It especially refers to initial stiffness determined on the basis of shear wave velocity measurement. The substantive basis for this approach results from the fact that the shear wave velocity depends on two components that make up the soil state, i.e., the stress state and void ratio (e.g., Lipinski

& Wdowska, 2019), and therefore two variables that constitute the compression curve. The approach based on shear wave velocity has an additional advantage, consisting of the possibility of realizing measurement in the laboratory and in the field as well. The large popularity of lab and in situ seismic techniques in recent years has brought about an increasing database, especially as the in situ technique is concerned. A large number of documented case histories was collected by Mayne (2007), who proposed a generalized formula for intact geomaterials in the following form:

$$\sigma'_p = 0.101 \cdot \sigma_{atm}^{0.102} \cdot G_{max}^{0.478} \cdot \sigma'_{v0}{}^{0.420} \quad (2)$$

where σ'_v and σ'_{atm} are respectively vertical effective stress (in MPa) and atmospheric (reference) pressure.

Another approach, which is seemingly very much alike the one based on initial stiffness, uses unloading–reloading deformation modulus E_{ur} with the resulting formula in the following form (Józsa, 2016):

$$\sigma'_p = 0.325 \cdot \sigma_{atm}^{0.506} \cdot E_{ur}^{0.435} \cdot \sigma'_{v0}{}^{0.059} \quad (3)$$

Although E_{ur} refers to a bigger strain range, it is still at least an elastic or hypoelastic region, as indicated by Lipinski et al. (2020). Besides, the good correlation between E_0 and E_{ur} to some extent justifies this approach.

3.4 Dilatancy method

Entirely different from all the above-described methods is that proposed by Lipinski & Wdowska (2017), which is based on the dilatancy phenomenon that takes place during the shearing of overconsolidated soils. A measure of this dilatancy is strictly related to a state of soil resulting from stress history. The proposed new approach is based on standard triaxial undrained shearing of samples realized after an isotropic consolidation. The major characteristic monitored during shearing is a pore pressure response traced in the form continuous record of Skempton's parameter A . On the basis of the A record, a new parameter is derived: named normalized differential pore pressure parameter ΔA_{EN} , which is the ratio of Skempton's pore pressure parameter A change during the dilation phase ($A_p - A_s$) to the change of this parameter during the prefailure stage ($A_p - A_0$):

$$\Delta A_{EN} = \frac{A_p - A_s}{A_p - A_0} = \frac{\Delta A_E}{A_p - A_0} \quad (4)$$

Symbol ΔA_E denotes the difference between peak A_p and stabilized A_s , and the values of A_0 refer to the initial part of the test. The premise to set up the dilatancy method is shown schematically in Figure 5.

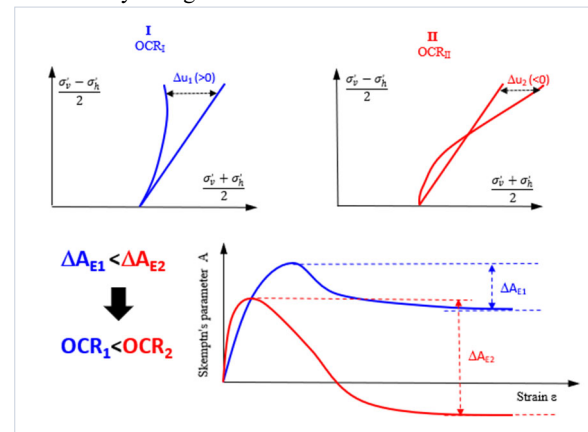


Figure 5. Premises for setting up the dilatancy method.

A more detailed presentation of the above review of all described methods was presented by Wdowska & Lipinski (2023).

4 CONCLUSIONS

The large majority of methods for the determination of preconsolidation stress are based on the concept of division between reversible and irreversible strain traced on the basis of the compression curve obtained during the standard oedometer test.

Examples of test results presented in the paper proved that these methods do not deliver a reliable value of preconsolidation/yield stress, especially for heavy overconsolidated material. Alternative methods described in the paper, i.e., convergence of compression curves (CCC), correlation with stiffness parameters, SHANSEP, and dilatancy method, are based on different premises than graphical construction on oedometer data. Reliability and consistency of results of application of all kinds of these methods can be visualized, or a deep profile of the subsoil overconsolidated by a glacier in the past, and presented in Figure 6.

As it results from the chart, the best consistency of results is obtained for the dilatancy method. One of the conceivable explanations for that consists of the fact that this approach uses a series of tests where soil is sheared at various dilatancy potentials and does not rely on a single test. Besides, it rests on the response of soil to various stresses at the phase when soil dilates during shearing; thus, the method seems to be less sensitive to sample disturbance. Other methods, when applied to deep overconsolidated subsoil, reveal a large scatter of data, which prompts the need to verify the effectiveness of the concept on which they are built and their usefulness in geotechnical practice.

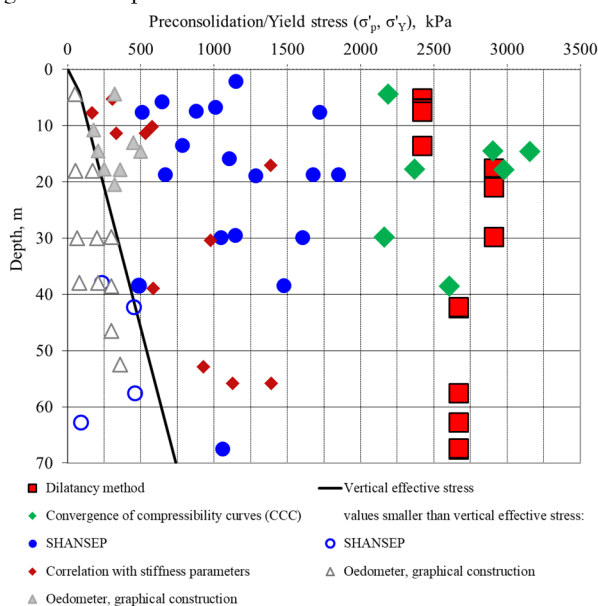


Figure 6. Comparison of yield stress determined by various methods

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