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Reliability of Methods for Determination of Stress History Parameters in Soils

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Abstract: Stress history acquired by any cohesive soil influences, to a large extent, three groups of fundamental properties indispensable in geotechnical design i.e. state of soil, shear strength, and stiffness characteristics. The basic stress history parameter (from which other parameters are derived) determined directly from laboratory tests is a preconsolidation stress σ'_p. Since the first method proposed by Casagrande in 1936, value σ'_p is determined in the oedometer test as a border between overconsolidated (OC) and normally consolidated (NC) zones. Approach based on division between predominantly elastic, (recoverable) strain, and plastic (irrecoverable) strain is a main principle of several methods of σ'_p determination, which have been proposed over the past eighty-six years.

Accumulated experiences have revealed that any laboratory procedure based on the oedometer test does not provide realistic value of preconsolidation stress, especially in heavy preconsolidated soils. The major reason for that results from the fact that the mechanism responsible for natural overconsolidation is more complicated than mechanical preloading. Therefore, there is a necessity to reevaluate effectiveness of standard methods and look for another solution of evaluation yield stress σ'_Y in natural soils.

This article presents the comparison between σ'_Y determined for various soils with use of standard methods based on conventional oedometer test and yield stress determined on the basis of alternative procedures. The latter are represented by various approaches as e.g. based on SHANSEP procedure or initial shear modulus and others. The most promising among these alternative methods is a new concept based on dilatancy phenomenon that takes place during shearing of a dense soil. The parameter reflecting stress history is derived from pore pressure response and is based on characteristic values of Skempton's parameter A record. Consistency of data concerning stress history parameters profile obtained for deep subsoil on the basis of various methods is shown for comparison.

Keywords: cohesive soils, stress history, preconsolidation stress, lab methods

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1 Introduction

Characterization of soil strata in geology requires some data related to lithology and stratigraphy of material under consideration. This approach is based rather on qualitative description. Such physical properties as color, texture, grain size, and composition usually do not have numerical representation. Quite different point of view is represented by geotechnical and structural engineers. Proper site characterization for geotechnical purposes requires information concerning soil properties of investigated area in the form of representative material properties expressed in numbers. Besides index properties, most desirable for engineers are mechanical characteristics that describes shear strength and stress–strain characteristics of soil, which are indispensable for proper prediction of soil response to complex loading. Unlike other construction material such as steel or concrete, granular materials are sensitive to the history of loading. It can be said that soil memorizes maximum load experienced in the past. This load, converted into stress, correlates very well with the most important three groups of mechanical parameters i.e. initial state variables, shear strength, and stiffness of soil. Correct determination of these parameters decides the accuracy of predictions concerning safe performance of any structure, which includes ultimate and serviceability limit states. This is schematically shown in Fig. 1. As depicted in the scheme, stress history parameters have an epicenter position in the formation of value of major soil properties. Therefore,

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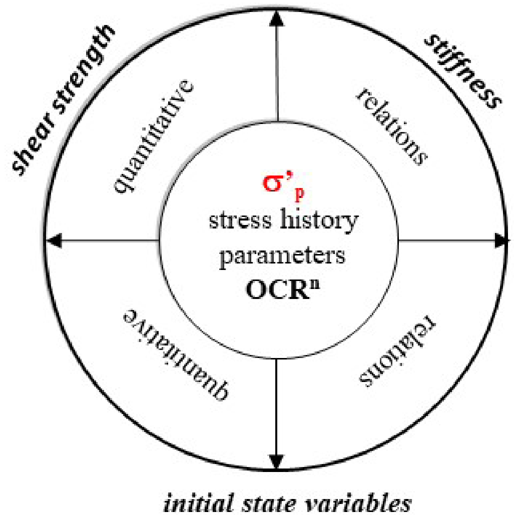

Figure 1: Significance of stress history of soil for key geotechnical parameters.

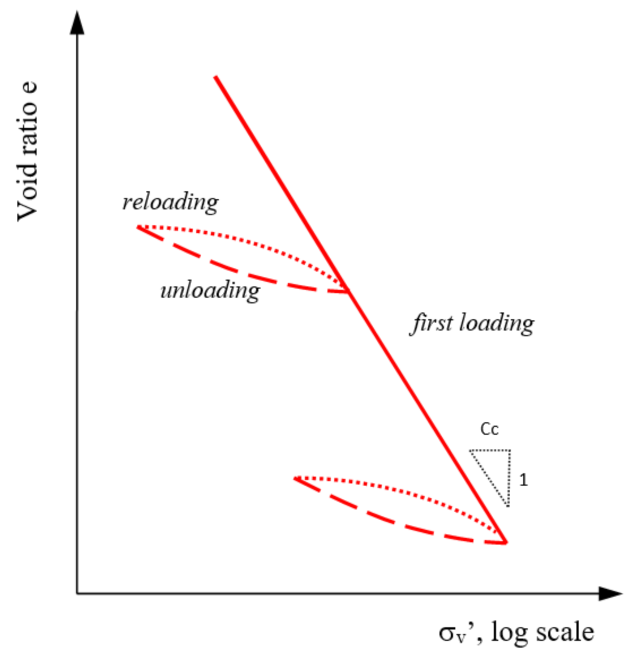

Figure 2: Common approach to determine preconsolidation stress of soil on the basis of oedometer test.

accurate determination of stress history parameters is one of the most important tasks in engineering geology or geotechnical engineering issues.

In areas of Poland that experienced a few glaciations, majority of soil were overloaded with ice sheet. Reliable knowledge of this period could have been a premise to evaluate stress history parameters. Unfortunately, up-to-date research of geologists is focused on evaluation of the extent of glaciations (Marks, 2005). There is no reliable quantitative information concerning the map of thickness of ice sheet in areas of Poland. Therefore, data concerning stress history of soil must be collected in another, indirect way.

As mentioned, granular materials are capable of memorizing the biggest load ever experienced. This is due to the elastoplastic nature of stress–strain characteristic. Elastic strain is recoverable but plastic is not. Range of elastic strain in soil is very small, especially with regard to soft soils. Therefore, an achievement of plastic strain during the first loading leaves a trace in the form of yielding on the stress–strain curve. Such a test can be carried out in the laboratory using oedometer apparatus. Oedometer ring confines soil sample, so with respect to strain state the test is one-dimensional. For this reason, it is convenient to present stress–strain characteristic in the form of compressibility curve where axis of strain is represented by void ratio and vertical effective stress is in log scale. Example of such a chart is shown in Fig. 2. At the point that corresponds to the largest stress experienced by tested soil in the field, there is a breakdown observed. When stress applied in the laboratory exceeds the highest stress that the soil acquired in situ, then compressibility of soil increases.

The concept of yield stress determination visualized in Fig. 2 was proposed by Casagrande in 1936. Originally, he named it preconsolidation load. Since that time the name of this parameter changed. At the beginning (and later up to the 1980s) it was referred to as preconsolidation pressure, often marked with symbol σ'_p. Later, in order to distinguish between vertical and horizontal components, engineers started to use the term *preconsolidation stress*. To make the difference between preconsolidation stress σ'_p caused by simple preloading and stress history acquired not only mechanically but also by other mechanisms (e.g. desiccation, cementation, and creep), Burland (1990) proposed the term *yield stress* marked with symbol σ'_Y, which is commonly accepted. Previously, Casagrande proposed yield stress to be a criterion to distinguish between normally consolidated (NC; first time loaded) and overconsolidated (OC; already acquired loading–unloading cycle) soils. It is just a commonly accepted nomenclature that the soil is normally consolidated when the yield stress σ'_Y just equals the existing effective vertical overburden pressure σ'_{V0} (i.e. $\sigma'_Y = \sigma'_{V0}$). If one considers the soil in which yield stress is greater than the existing overburden effective stress (that is, $\sigma'_Y > \sigma'_{V0}$), then we say the soil is overconsolidated (or preconsolidated). Having these two values of stress the overconsolidation ratio (*OCR*) (or yield stress ratio *YSR*) is defined, as the ratio of the yield stress to the existing vertical effective overburden stress. Thus, in order to describe stress history in soil, usually both values are used: yield stress σ'_Y and, resulting from it, *OCR* (*YSR*).

This article presents a critical review of the common approach for determination of stress history in cohesive soils. Evolution of view on factors affecting the value of yield stress is presented. Weak points of assumption of the general method are indicated and exemplified by various test results. Constraints of standard methods are depicted. Some alternative approaches for determination of yield stress are presented. Comparison of the effectiveness of various approaches is shown with the use of material sampled from deep subsoil.

2 Methods for determination of yield stress

Casagrande, who defined the preconsolidation pressure as "the largest overburden beneath which the soil had once been consolidated," also proposed the first laboratory procedure based on oedometer test to determine this parameter in cohesive soils. Data from incremental one-dimensional consolidation test carried out on undisturbed samples are presented in the form of compressibility line where void ratio is shown against vertical effective stress in log scale (Fig. 3).

Casagrande's procedure is the graphical one. The first step is to choose by eye the point of minimum radius (i.e. maximum curvature) of compressibility curve. This is represented by point A in Fig. 3. Next, from this point two lines are drawn, a horizontal one and a tangent to the compressibility curve. Then, one should bisect the angle created by these two lines. Intersection of the angle bisector line with extended straight-line portion of the virgin part of compressibility curve represents preconsolidation stress. Although Casagrande's procedure is probably the most popular, many methods have been proposed since that time. Some of the methods proposed in the previous century is presented in Tab. 1. All of them are based on oedometer test.

For the sake of better description of the methods, vertical and horizontal axes of compressibility chart are specified in Tab. 1. Majority of these methods are graphical ones, which means that they require some kind of geometric procedure. There are also some direct methods in which yield stress can be directly read from the chart without any graphical procedure. Graphical representation of three methods from the examples presented in Tab. 1 are shown in Fig. 4. There are one graphical and two direct methods. Representation of the graphical one is Sällfors method (1975), which is adjusted to results carried out in consolidometer, in which a soil sample is loaded continuously with constant rate of

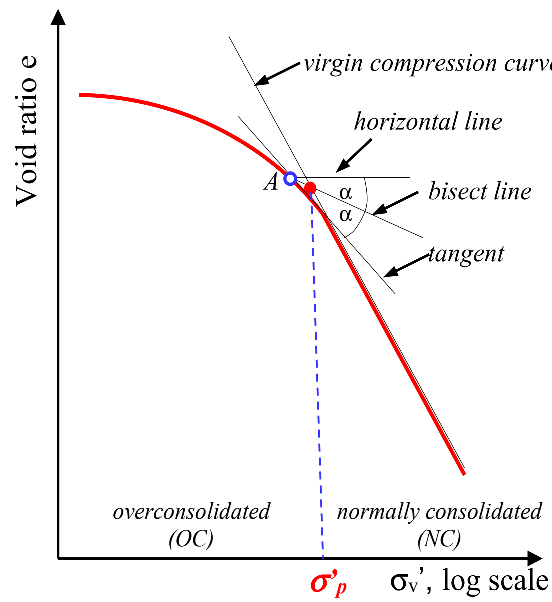

Figure 3: Casagrande's procedure (1936) for determination of preconsolidation stress in soils.

Table 1: Examples of methods for determination of preconsolidation stress.

METHOD	PROCEDURE	HORIZONTAL AXIS	VERTICAL AXIS
Casagrande (1936)	Graphical	log s'	e
Van Zelst (1948)	Graphical	log s'	e
Burmister (1951)	Graphical	log s'	e
Schmertmann (1955)	Graphical	log s'	e
Pacheco Silva (1970)	Graphical	log s'	e
Sällfors (1975)	Graphical	logs'	e
Becker et al. (1987)	Graphical	s'	W-Energy Work
Jose et al. (1989)	Graphical	log s'	loge
Şenol, Seglamer (2000)	Graphical	log s'	s'e
Janbu (1969)	Direct	s'	e,M
Janbu, Senneset (1979)	Direct	s'	e, M,C_v
Tavenas et al. (1979)	Direct	s'	s'•e
Butterfield (1979)	Direct	log p'	lnV =[ln(1+e)]

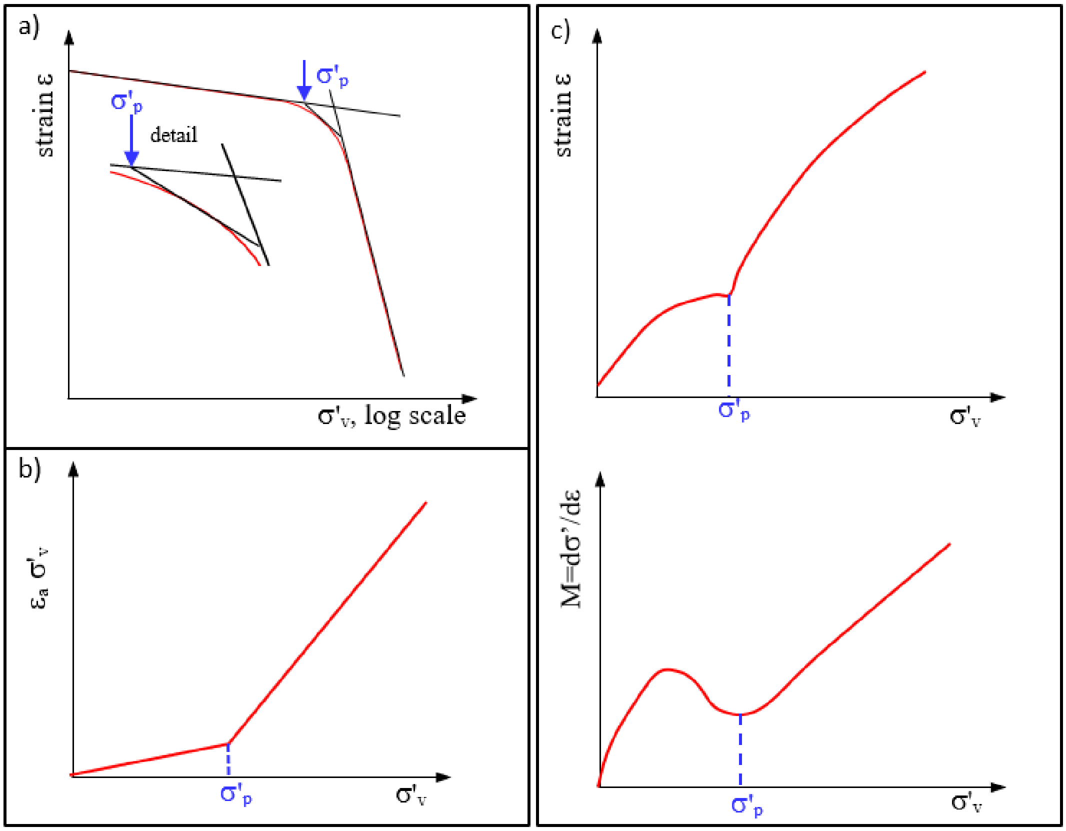

Figure 4: Examples of methods for determination of preconsolidation stress: a) Sällfors (1975), b) Tavenas (1979), and c) Janbu (1969).

strain (CRS). Since it is strain-controlled method, a test is relatively fast and is intended for soft soils. Another method shown in Fig. 4 was proposed by Janbu (1969).

It represents direct methods, and it is also intended for soft soils. In this method, the scale of effective vertical stress axis is linear and yield stress corresponds to irregularity of curvature on the compressibility curve and apparent dropdown in distribution of constrained modulus is shown against vertical effective stress. The third method shown in Fig. 4 is the Tavenas method in which strain energy is represented along the vertical axis. In the case of all methods presented in Tab. 1, with emphasis put on graphical ones, the kernel part is to find the point of maximum curvature of compressibility line. This issue will be addressed in the following paragraphs.

3 Factors affecting determined value of yield stress σ'_Y

Regarding the factors affecting yield stress, two groups (i.e. inherent and epistemic) can be distinguished. In the case of the first group, it is convenient to assume (for simplicity) that horizontally layered deposits are considered. In such case, one can focus on the actual causes of preconsolidation. The first one is associated with a nature of the phenomenon i.e. acquired stress history caused by vertical preloading existing in the past overburden (e.g. glacier). In the case of the latter, reliable knowledge concerning the thickness of ice sheet would be very useful, but this kind of data is usually not available in geological text books or articles. The second factor contributing to the actual value of yield stress are all postdiagenesis processes, which can considerably change the compressibility characteristic of soil. Characterization of major mechanisms that determine the actual stress history profile was given by Jamiolkowski et al. (1985). The essence of these information is presented in Tab. 2.

From the results shown in the table, a value of preconsolidation pressure, which is an effect of mechanical overburden, can be changed by many postdepositional processes like secondary compressibility due to aging, cementation, drying, and others. Problems with quantitative description of preconsolidation phenomenon created premises for making a certain

Table 2: Characterization of mechanisms contributing to distribution of yield stress in a soil profile (on the basis on Jamiolkowski et al. (1985)).

Category	Description	Stress History Profile
A) Mechanical One-Dimensional	1) Changes in total vertical stress (overburden, glaciers, etc.) 2) Changes in pore pressure (water table, seepage conditions, etc.)	Uniform with constant s'_p-s'_{v0} (except with seepage)
B) Desiccation	1) Drying due to evaporation vegetation, etc. 2) Drying due to freezing	Often highly erratic
C) Drained Creep (Aging)	1) Long-term secondary compression	Uniform with constant s'_p/s'_{v0}
D) Physicochemical	1) Natural cementation due to carbonates, silica, etc. 2) Other causes of bonding due to ion exchange, thixotropy, “weathering,” etc.	Not uniform

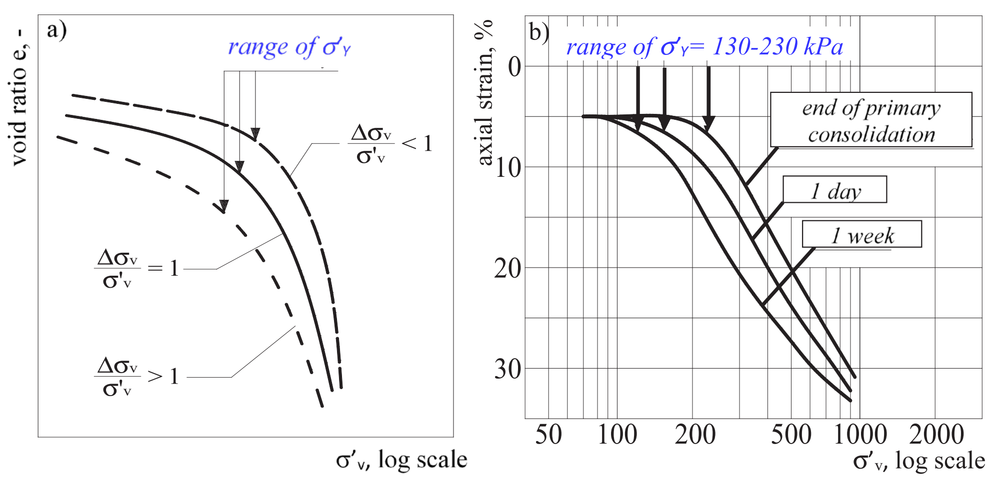

Figure 5. Influence of a test procedure on determination of value of preconsolidation stress (a-Das, 1983, b-Crawford, 1964).

semantic order in nomenclature. Burland (1990) proposed that the term “preconsolidation pressure” should be used for situations in which the magnitude of overburden might be established by geological means. Similarly the term “overconsolidation ratio” (OCR) should be reserved for describing a known stress history. In the case of natural soils, where cumulative effect of mechanical preloading and other postdepositional phenomena is unknown, the relevant term for stress corresponding to breakdown in the stress–strain curve is yield stress σ'_Y. In this case, OCR should be substituted by YSR (yield stress ratio) (Burland, 1990, Boone, 2010, Grønbech et. al, 2015, Kootahi and Mayne, 2018).

The second group of factors affecting the determined value of yield stress are of epistemic nature. The most important of them refer to test procedure. As an example, two aspects regarding incremental loading during oedometer test can be recalled here. They are illustrated in Fig. 5. The first one (Fig. 5a, Das 1983) refers to load increment ratio ΔP/P. In standard procedure this value is equal to unity, which means that in each stage a load is doubled. If load increment ratio (LIR) is less than 1, thus obtained compressibility curves move to the right side, which results in bigger value of determined yield stress. When LIR is bigger than 1, the time required to do the test is smaller, compressibility curve moves to the left, thus yield stress is underestimated.

The second aspect regarding loading refers to the duration of each loading step (Fig. 5b, Crawford 1964). The reference time of loading corresponds to the end of primary (EOP) consolidation. Depending on the permeability of tested cohesive soil, it can be from several minutes to couple of days. For this reason, in many laboratories, standard time for each loading is 24 hours (one day). In general, the longer the duration of loading, the smaller the value of determined yield stress. So, it can be summarized, that loading conditions can significantly change a determined value of yield stress.

Besides the procedure of loading conditions, there is another issue that considerably diminish the reliability of determined value of σ'_Y. It refers to sample disturbance. This phenomenon is inevitable during sampling procedure

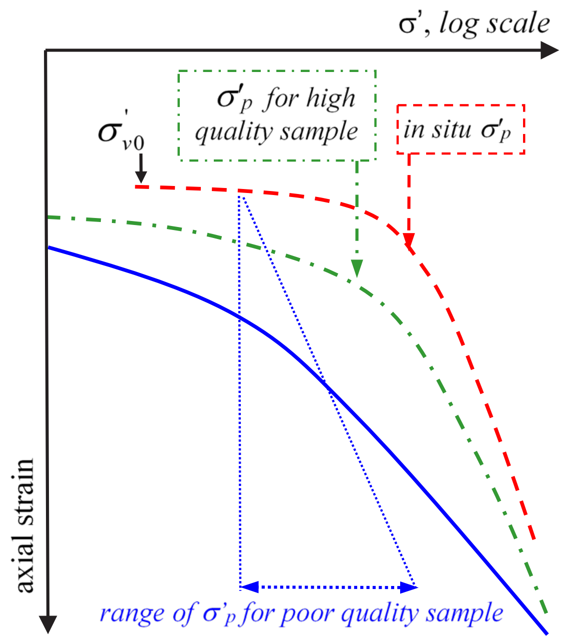

Figure 6: Influence of sample disturbance on shape of compressibility curves of soil (on the basis of Ladd (1977)).

and since it can't be avoided one can only minimize its consequences. More severe sample disturbance, the bigger change in the shape of compressibility curve compared to in situ conditions. Fig. 6 shows an example of sampling effect on the compressibility curve. Besides the hypothetical curve representing field condition, there are two curves corresponding to low and high sample disturbance. It is worth noticing that sample disturbance changes the curvature of compressibility characteristic, which is a kernel point in majority of methods for determination of yield stress. Therefore, the bad quality of a sample is a severe source of error in determination of the true value of yield stress.

4 Problems with determination of yield stress σ'_Y in oedometer test

As exemplified in Tab. 1, there are numerous methods proposed for determination of yield stress in cohesive soils. It can be sarcastically commented that the existence of large number of methods proves that none of them is perfect. Every day practice provides arguments for that. When one compares results of yield stress determination by various methods, the results are usually different. Fig. 7 shows such comparison carried out on five samples of preconsolidated low plasticity clay with liquidity index I_L in the range -0.18÷0.28. Yield stress value for each sample was determined by three methods (i.e. Casagrande, 1936, Tavenas et al., 1979, and Şenol et al., 2005). As depicted in the presented histograms, the differences are significant and in some cases exceed 100%. This does not seem to be accepted. Therefore, it is necessary to look carefully on the effectiveness of methods for determination of stress history parameters in oedometer test.

At first, it is worth to look on the graphical procedure for σ'_Y determination. As it results from the description in Table 1, majority of methods assume that the axis of effective vertical stress should be plotted in log scale. This requirement might be a source of certain ambiguity. To prove this, a simple example is presented in Fig. 8. Straight line, which represents hypothetical compressibility, is shown in two charts where effective vertical stress is plotted in linear and log scale. As depicted in the charts plotted with log scale, if one uses Casagrande graphical procedure, yield stress around 330 kPa can be determined. However, in the light of what is seen on the previous chart, this determined value doesn't seem to be true. This provides an argument for the statement that graphical procedures based on oedometer test introduce some ambiguity in determination of σ'_Y value. Therefore, it is interesting to know if this is the only drawback of these methods or there are other causes that might objectively influence the final results. Since all of the methods for determination of yield stress are dedicated to all cohesive soils, which covers very wide range of materials, perhaps these methods are not so universal and cannot be applied automatically to all kinds of soil. The best way to check this is to examine the behavior of cohesive soils of various plasticity. In order to do that, one should consider various soils of different stress history. At first, soil kind with known stress history should be considered. Fig. 9 shows the comparison of compressibility curves of low- and high-plasticity clays obtained from tests on reconstituted material that have acquired known stress history.

This represents mechanical source of preconsolidation. As results from the charts, the obtained characteristics are considerably different. In the case of low plasticity clay (Fig. 9a) there is a distinct border between virgin loading (line segment BC), representing NC soil, and reloading curves (line segments DB) corresponding to OC soil. In point B, which represents preloading stress of 400 kPa, there is very clear change in the direction of compressibility curve, which allows to determine the yield stress without graphical procedure. In the case of high-plasticity clays (Fig. 9b), the situation is different. In point B, there is no breakdown or visible sharp change in the curvature of compressibility line. Additionally, it

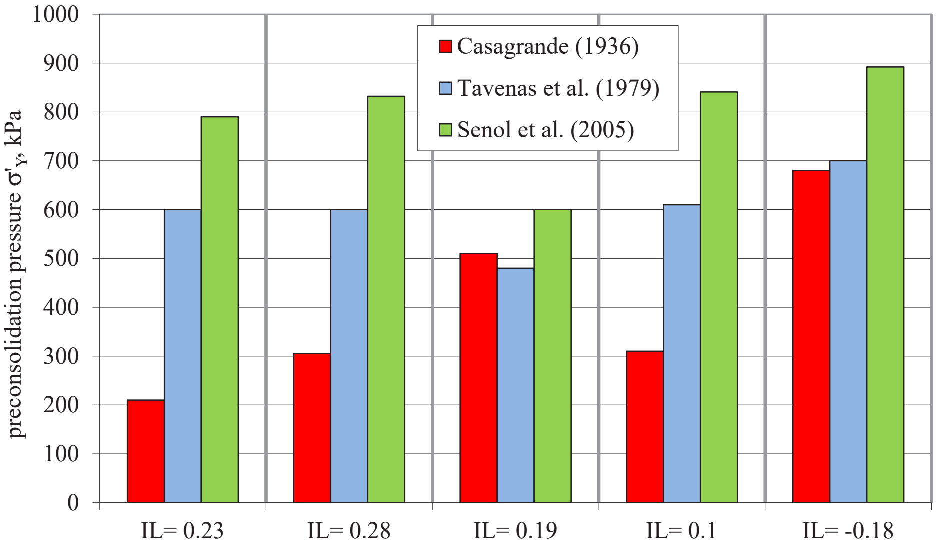

Figure 7: Comparison of yield stress determined by various methods (Wdowska, 2010).

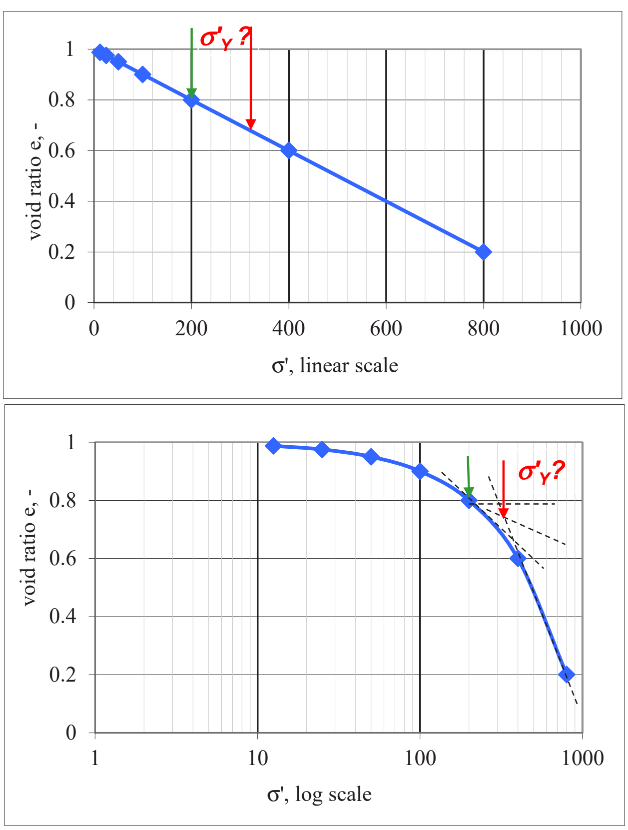

Figure 8: Schematic diagrams of compressibility curves in linear and logarithmic scale of vertical stress.

is worth noticing the difference in shape of the reloading curves DB for both materials. Two charts explicitly prove that plasticity of soil influences the efficiency of the oedometer-based methods for determination of yield stress. If it is so, in a simple case as mechanical preloading mechanism, it is probably less efficient in the case of soil with unknown stress history where tests are carried out on undisturbed material. Analogous charts to these shown in Fig. 9 presenting compressibility curves for reconstituted materials are shown in Fig. 10 for undisturbed samples. Both characteristics, for low (Fig. 10a) and high (Fig. 10b) plasticity clays are very obscure with respect to searching the point of maximum curvature. In both cases, compressibility curves are less "susceptible" to successful interpretation than in the case of characteristic shown in Fig. 9b. This statement can be supported by many working examples of yield stress determination for low- and high-plasticity clays.

In Fig. 11a, stress history parameter is determined by two methods on low plasticity clay of known stress history which in this case was 400 kPa of vertical stress. Since the mechanism of preconsolidation is a simple preloading of the relevant symbol for preconsolidation stress is σ'_P. As it results from charts shown in Fig. 11a, the Casagrande method appeared to be very accurate because it delivered exact value. With the use of the Şenol method the obtained value was 450 kPa, which results in overprediction, slightly higher than 10%. In practice, both results would be considered acceptable. Entirely different prediction results in the case of undisturbed samples of high-plasticity clays. In this case, yield stress σ'_Y was determined by the same methods. Although the soil was extruded from the same sampling cylinder, the results are quite different (Fig. 11b). The difference in the obtained results (i.e. values of 470 kPa predicted by the

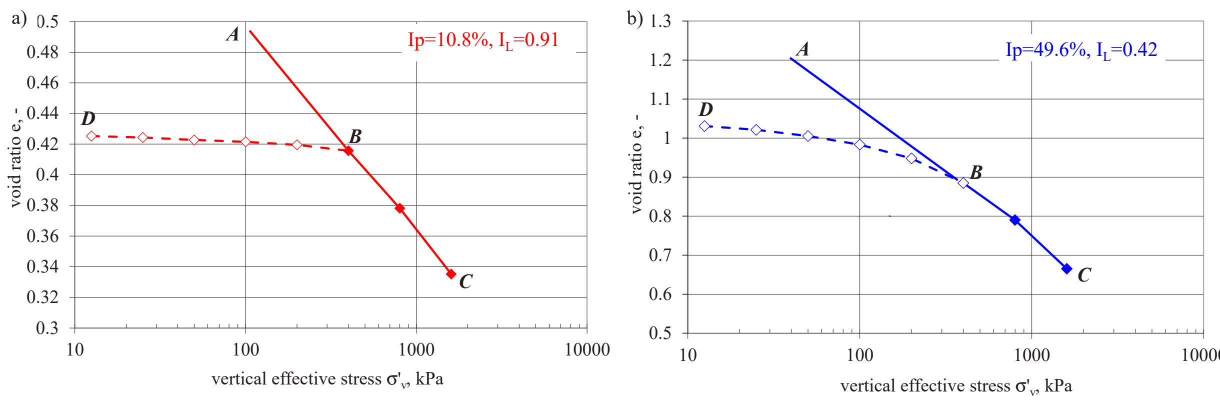

Figure 9: Compressibility curves for reconstituted samples: a) low-plasticity clay, b) high-plasticity clay.

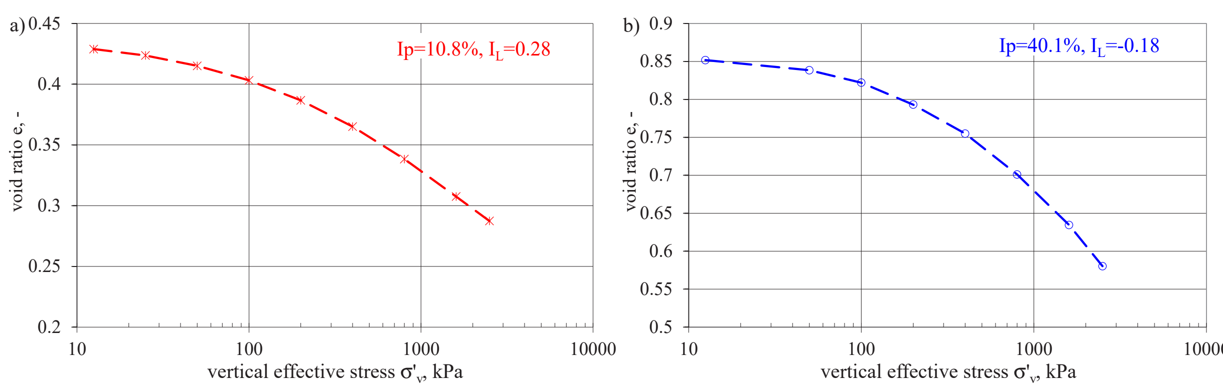

Figure 10: Compressibility curves for undisturbed samples: a) low-plasticity clay, b) high-plasticity clay.

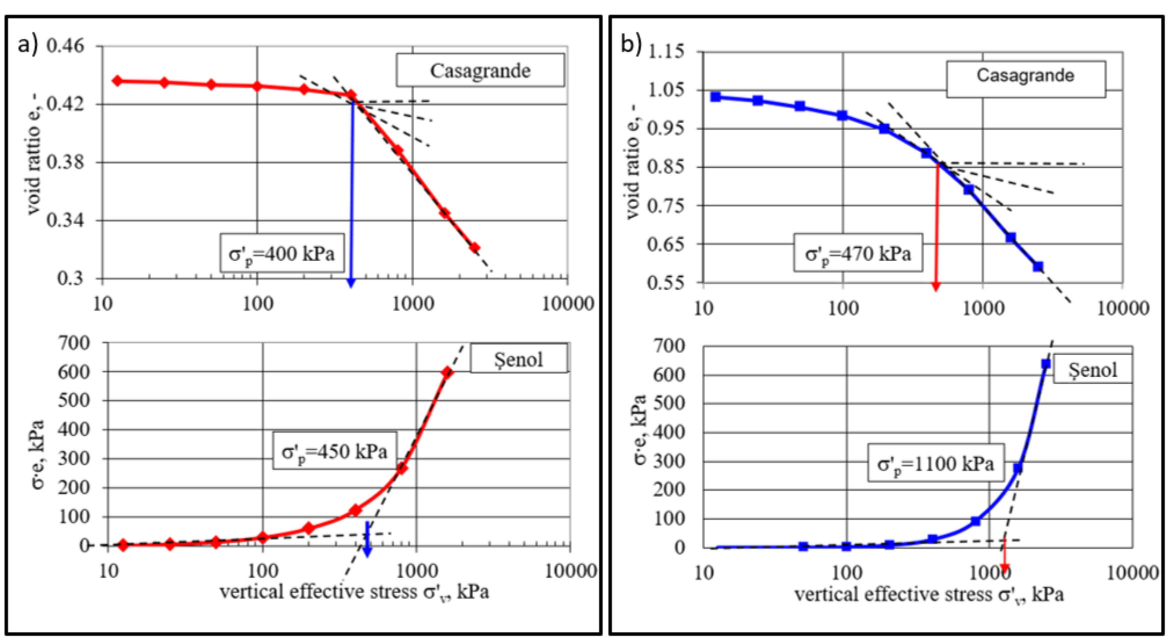

Figure 11: Examples of determination of preconsolidation stress on reconstituted material of low (a) and high (b) plasticity clays (Wdowska, 2010).

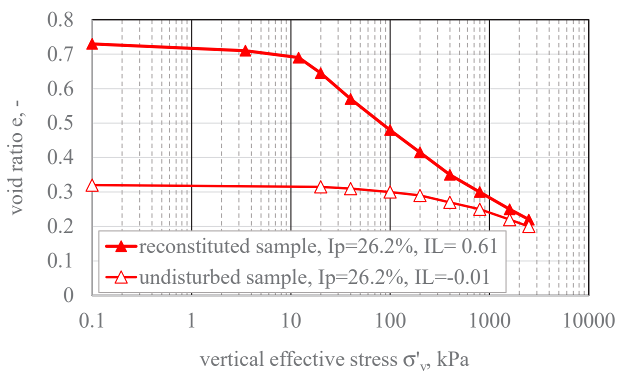

Figure 12: Comparison of compressibility curves of reconstituted and undisturbed material (I_p = 26.2%).

Casagrande method compared to 1100 kPa obtained by the Şenol method), are neither satisfactory nor acceptable. Therefore, it is necessary to look for alternative solution for more efficient determination of stress history parameter in natural soils.

5 Alternative approaches to determination of yield stress σ'_Y

The first step in looking for a different approach than the standard one based on division between recoverable and irrecoverable strains might refer to the concept of mechanical preconsolidation. Since preconsolidation stress is defined as the biggest stress experienced by soil at given depth, it is conceivable that if a soil sample is loaded to stress considerably higher than predicted value of σ'_p, then compressibility line will be much alike the compressibility curve for reconstituted material. It might be that for some reasons (e.g. due to a sample disturbance) the two characteristics will not be collinear. In such a case, we can assume that at the point on vertical effective stress where they become parallel, both compressibility characteristics are intrinsic ones and thus determine preconsolidation stress. Example of such comparison of compressibility characteristics for medium-plasticity clay (I_p = 26%) and with liquidity indices, respectively I_L = -0.01 and I_L = 0.61, is shown in Fig. 12. This approach is associated with some difficulties among which the most important seems to refer to the selection of criterion, which could be accepted for sufficient alignment of two compressibility curves. This method can be used for data obtained on the basis of incremental loading (IL) oedometer test and also in test carried out in consolidometer with constant rate of loading (CRL). Since two constrained moduli are compared, we will refer to this method as IL M_{OC}/M_{NC} or CRL M_{OC}/M_{NC}, depending on the mode of loading.

There are also approaches that enable to determine yield stress but not on the basis of one-dimensional (oedometric) compression test. One of them is based on initial stiffness represented by shear modulus G_0. Range of strain assigned to this parameter is very small (around 10^{-4}%), which means that the behavior of material is fully elastic (recoverable). Initial stiffness is often determined on the basis of shear wave velocity, which mainly depends on void ratio and state of stress and therefore G_0 can be considered as a measure of state, which is strictly related to preconsolidation stress. The approach based on shear wave velocity has an additional advantage consisting the possibility of realizing measurement in laboratory and in field as well. Large popularity of lab and in situ seismic techniques in recent years brings about increasing data base, especially as in situ technique is concerned. Large number of documented case histories was collected by Mayne (2007) who proposed generalized formula for intact geomaterials in the following form:

$$\sigma'_p = 0.101 \cdot \sigma_{atm}^{0.102} \cdot G_{max}^{0.478} \cdot \sigma'^{0.420}_{v0} \qquad (1)$$

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

It should be emphasized that the above formula was set on the basis of data collected for wide range of soils i.e. sands, silts, and clays.

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):

$$\sigma'_p = 0.325 \cdot \sigma_{atm}^{0.506} \cdot E_{ur}^{0.435} \cdot \sigma'^{0.059}_{v0} \qquad (2)$$

In spite of the fact that E_{ur} is as G_0 (in MPa), also a measure of stiffness, it should be emphasized that both moduli refer to different strain range. The process of unloading and reloading has nothing in common with initial state (very initial part of the first loading). This poses a question if stiffness at second cycle of loading can characterize state prior the first loading. On the other hand, existence of empirical relation between E_{ur} and E_{50} justify this proposal to some degree; however, it can't be treated as an approach derived on the basis of initial stiffness.

Another possibility of the derivation of stress history parameters is indirect method based on the comparison of normalized parameters of soil. SHANSEP method proposed by Ladd & Foot (1974) links normalized parameters of OC soil and NC with OCR. Although 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:

$$\frac{\left(\frac{s_u}{\sigma'_{v0}}\right)^{OC}}{\left(\frac{s_u}{\sigma'_{v0}}\right)^{NC}} = OCR^m \tag{3}$$

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 form is convenient to plot data in log–log axes, which gives essentially a straight line. It should be emphasized that SHANSEP was developed for mechanically OC soil. The test conditions are also important as imposed anisotropy during consolidation prior to shearing and kind of shearing (triaxial compression, triaxial extension, or simple shear). However, if one has in hand the characteristics for various stress levels for OC and NC materials, it is possible (with certain assumption) to determine OCR and then calculate preconsolidation stress. In the light of previous explanation concerning mechanical and actual overconsolidation, the resulting obtained parameters would be YSR and yield stress σ'_Y.

There is another recently developed approach to yield stress determination based on data from shearing of soil sample in standard triaxial test (Lipiński , Wdowska, 2017). It rests on the tendency for dilation in OC soil. Test procedure is based on triaxial consolidated undrained tests. Pore pressure is measured with mid-height suction probe, which considerably enhances precision of measurement. A new parameter reflecting stress history is derived from Skempton's parameter A. However, it doesn't refer to its value A_f during failure, as usually encountered in the geotechnical literature. The proposed parameter is based on the whole pore pressure response during shearing. Consolidation is isotropic in order to magnify pore pressure response. The parameter is based on that part of shearing characteristics when specimen dilates; therefore, the actual parameter reflecting stress history ΔA_{EN} is the ratio of Skempton's pore pressure parameter A change during dilation phase (A_p-A_s) to the change of this parameter during prefailure stage (A_p-A_0):

$$\Delta A_{EN} = \frac{A_p - A_s}{A_p - A_0} = \frac{\Delta A_E}{A_p - A_0} \tag{4}$$

Symbol ΔA_E denotes the difference between extreme (max A_p and min A_s) value of A while ΔA_{EN} means normalized differential pore pressure parameter. Owing to the fact that the defined parameter refers to an advanced part of shearing, it overcomes problems of sample disturbance to a large extent.

6 Reliability of stress history parameters profile

Apart from drawbacks and advantages of each method of yield stress determination, the real check of effectiveness of each approach is the coherence of stress history parameters profile. In Fig. 13, profile of yield stress determined by various methods is shown. From among the methods based on one-dimensional compression (oedometer) tests in which evaluation of yield stress is derived from the shape of a compressibility curve, Casagrande, Janbu, and Senol's methods were selected. Other methods are those that were referred to in the preceded paragraph as the alternative approaches to determine yield stress, i.e.:

- convergence of constrained NC/OC moduli,
  - incremental loading test (IL M_{OC}/M_{NC}),
  - constant rate of loading (CRL M_{OC}/M_{NC}),
- initial shear modulus G_0,
- unloading–reloading deformation modulus E_{ur},
- derivation σ'_Y from SHANSEP method,
- dilatancy method.

For reference, vertical component of effective stress resulting from gravitational forces is also shown in the chart. The profile down to around 70 m consist of OC (by glacier in the past) cohesive soil of various plasticity index I_P, ranging from medium (16%) to high-plasticity (57%) clays. In general, tested soils are stiff or firm. Liquidity index for medium-plasticity materials is slightly above zero while for high-plasticity clay is around zero or slightly negative.

As it results from the chart, there is considerably scatter of data not only among methods but also within the same method. Points that delivered values smaller than geostatic stress at the same depth should certainly be neglected. Even at first glance, it is quite clear from the chart that alternative methods give higher values of yield stress. Taking into account that the sampling area was subjected to Plejstocen glaciation (Mindel and Riss), the higher values are more probable. Since accurate values of preconsolidation stress is unknown, important

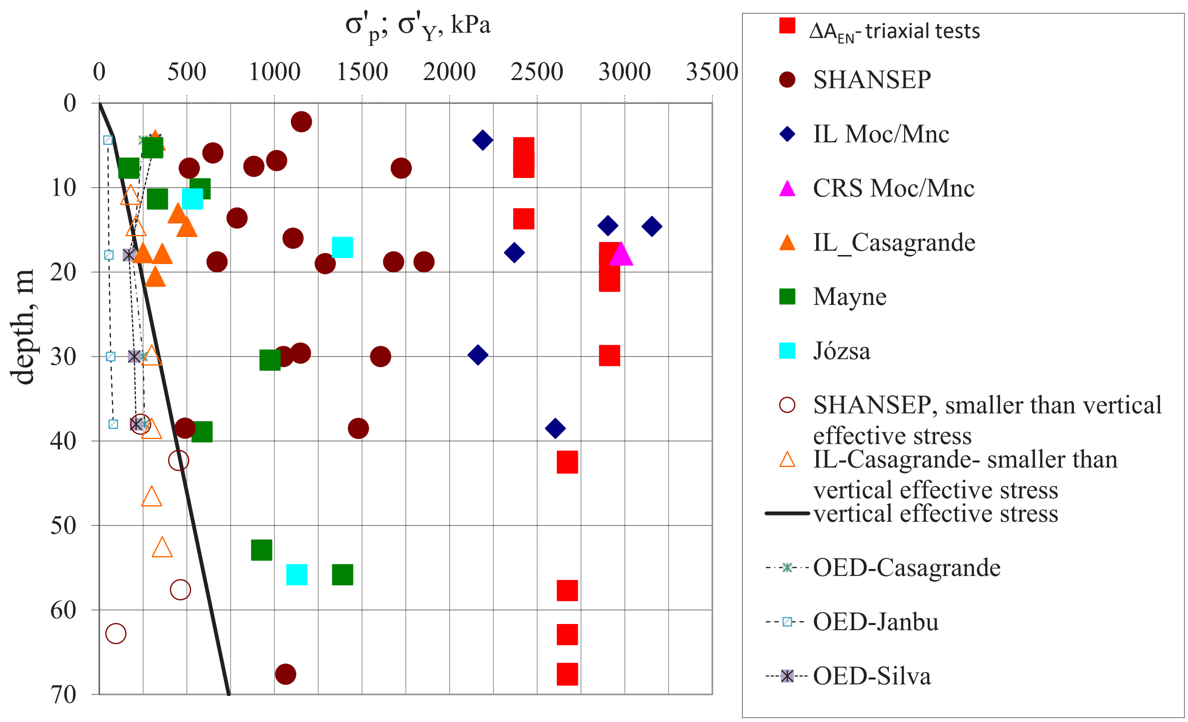

Figure 13: Comparison of determined preconsolidation (yield) stress with various methods.

criterion for evaluating reliability of a given method is the coherence of distribution of σ'_Y within one procedure. As it results from the chart, the best consistency of results is obtained for dilatancy method (Lipiński & Wdowska 2017). One of the possible explanations for that consist in the fact that this approach uses characteristics consisting of several points and not a single point. Besides, it rests on the response of soil at various stresses at phase when soil dilates during shearing; thus, the method seems to be less sensitive to sample disturbance.

7 Conclusions

The key geotechnical properties of soil as shear strength, stiffness, and initial state variables, to a large extent, depend on stress history parameters. Therefore, accurate determination of yield stress is of utmost importance for quality of analysis and safe performance of engineering structures. Standard methods for determination of preconsolidation (yield) stress are based on oedometer tests. Numerous methods using compressibility curve and graphical procedures have been developed for more than eighty-six years. Unfortunately, approach based on division between recoverable and plastic strains, which works correctly for slightly mechanically preconsolidated medium plasticity soil, was proved to be of small effectiveness in soils of higher plasticity and more complex stress history record. The examples supporting this hypothesis were presented in this article. The reasons of poor quality of prediction of preconsolidation stress have inherent and epistemic nature as well. Various alternative approaches to determine yield stress, which were briefly characterized in this article, appeared to deliver more reliable stress history profile than standard methods. Especially dilatancy method, which is based on pore pressure response during undrained shearing, gives repeatable results and consistent stress history profile.

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