A new method for evaluation of yield stress in cohesive soils

Une méthode nouvelle d'évaluation de la contrainte limite d'écoulement des sols cohérents

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ABSTRACT: The paper presents an alternative approach to evaluate a key stress history parameter which is yield stress. It should be emphasized here that any laboratory procedure based on oedometer test does not provide a realistic value of yield stress, especially in heavily overconsolidated soils. The new concept is based on dilatancy phenomenon which takes place during shearing of dense soil. A measure of this dilatancy is strictly related to a state of soil resulting from stress history. The proposed new approach is based on triaxial undrained shearing preceded by an isotropic consolidation. The major characteristic monitored during shearing is a pore pressure response and more precisely a 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}. This measure correlates very well with yield stress σ'_Y for natural heavy overconsolidated soils as well as with preconsolidation stress σ'_P for reconstituted soils preconsolidated mechanically.

RÉSUMÉ : L'article présente une approche alternative pour évaluer un paramètre clé de l'histoire de la contrainte, La contrainte limite d'écoulement des sols. Il convient de souligner ici que toute procédure de laboratoire basée sur des essais oedométriques ne fournit pas une valeur réaliste de la contrainte limite d'écoulement en particulier dans les sols fortement préconsolidées. Le nouveau concept est basé sur le phénomène de la dilatance qui se déroule pendant le cisaillement du sol dense. Une mesure de cette dilatance est strictement liée à un état des sols résultant de l'histoire de la contrainte. L'approche nouvelle proposée est basée sur l'essai non drainé triaxial précédée par une consolidation isotrope. Le paramètre surveillé pendant l'essai est une réponse de la pression interstitielle et plus précisément un dossier de paramètre *A* Skempton. Sur la base du paramètre *A*, un nouveau paramètre est dérivé : normalisé ΔA_{EN} paramètre différentiel. Ce paramètre a une très bonne corrélation avec le contrainte σ'_Y pour des sols preconsolidées naturellement ainsi qu'avec σ'_P contrainte de préconsolidation pour les sols reconstitués preconsolidées mécaniquement.

KEYWORDS: overconsolidated stiff cohesive soils, yield stress, new method, dilatancy.

1 INTRODUCTION.

Soil behaviour under complex loading conditions is subject to much more factors than it is a case of other materials used in civil engineering. This means that with respect to stress strain characteristic this material is much more non linear than e.g. steel, concrete or other construction materials. This nonlinearity results to large extent from the fact that soil is a three or at least two phase medium. This fact, together with diversity in granulometric and mineralogical composition, decides that soils exerts elastic, plastic and viscous properties in various proportions. Due to the difficulties in description of viscous properties, the most common representation of soil used in geotechnical engineering practice are elasto-plastic models. A proper reflection of these two features requires quantitative identification of stress to which material reveals predominantly elastic (recoverable) strain. Stress exceeding this value is associated with plastic (irrecoverable) strain. Identification of commencement of plastic strain can be traced on compressibility line, which is a basic mechanical characteristic of soil behaviour obtained in the laboratory during one dimensional loading of a soil sample. Figure 1 depicts such compressibility line in the form of void ratio against vertical effective stress shown in log scale. At the point which 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 which soil acquired *in situ* then compressibility of soil increases.

This phenomenon was described by Casagrande (1936). He proposed the first method for determination of the highest stress experienced by a soil called a preconsolidation stress. Since that time, preconsolidation stress σ'_P is commonly accepted as a parameter which influences to large extent three groups of fundamental properties indispensable in geotechnical design i.e. state of soil, shear strength and stiffness characteristics.

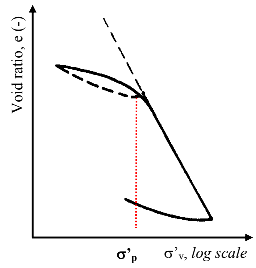

Figure 1. Common approach to determination of preconsolidation stress.

Preconsolidation stress σ'_P is a criterion to distinguish between normally consolidated and overconsolidated soils. We say that the soil is normally consolidated when the preconsolidation stress σ'_P just equals the existing effective vertical overburden pressure σ'_{V0} (that is, $\sigma'_P = \sigma'_{V0}$). If we have a soil which preconsolidation stress is greater than the existing overburden effective stress (that is, $\sigma'_P > \sigma'_{V0}$) then we say the soil is overconsolidated (or preconsolidated). We can define the overconsolidation ratio *OCR*, as the ratio of the preconsolidation stress to the existing vertical effective overburden stress. Thus in order to describe stress history in soil we use both values: preconsolidation stress σ'_P and resulting from it overconsolidation ratio *OCR*.

2 PROBLEMS WITH DETERMINATION OF PRECONSOLIDATION STRESS

There are many reasons why a soil may be overconsolidated. It could be due to either a change in the total stress (e.g. glacier or erosion) or a change in effective stress by change in pore water pressure. Both changes would alter the effective stress. Desiccation of the upper layers due to surface drying will also produce overconsolidation. Sometimes an increase in σ'_P occurs due to changes in the soil structure and alternations of the chemical environment of the soil deposit. All the above factors contributing to preconsolidation stress resulted in some difficulties in a straightforward application of procedure for its determination. The elegant idea of identification of border point between elastic and plastic strain works quite well in mechanically, lightly preconsolidated soils. It can be easy demonstrated for remolded soil in the laboratory (Figure 2). However, for natural soils, especially when we have to deal with heavy overconsolidated deposit, compressibility curves do not look as good as for mechanically preconsolidated slurry (see also Figure 2).

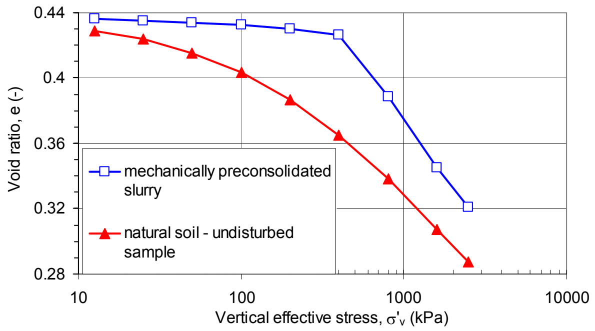

Figure 2. Differences in compressibility curves between mechanically preconsolidated slurry and naturally preconsolidated soil.

It was probably the major reason why since 1936 (when Casagrande proposed his laboratory procedure for determination of preconsolidation stress) several alternative procedures have been proposed to determine σ'_P. Long list of these methods is recalled by Ku & Mayne (2012). It might be noticed with a certain dose of sarcasm that great number of these methods reveals their weakness. It should be also emphasized that all these methods are based on oedometer test and procedures for determination of preconsolidation stress rely on various interpretation of the same compressibility curve. Many difficulties in application of standard procedures created much interest in phenomena which might contribute to the actual value of preconsolidation stress. As indicated by Jamiolkowski et al. (1985), a value of preconsolidation stress resulting from mechanical overburden, can be changed by many post depositional processes like secondary compressibility, cementation, aging, temperature change and others. Many problems with quantitative description of preconsolidation phenomenon created premises for making a certain order in nomenclature. Burland (1990) proposed that the term "preconsolidation pressure" should be reserved for situations in which the magnitude of such a pressure can be established by geological means. Similarly the term "overconsolidation ratio" should be reserved for describing a known stress history. In case of natural soils, where we do not know cumulative effect of mechanical prestress and other postdepositional phenomena the relevant term for stress corresponding to breakdown in stress strain curve is "yield stress" denoted as σ'_Y. In this case the ratio between it and the effective overburden pressure (σ'_Y/σ'_{V0}) could be termed "yield stress ratio" *YSR*.

The last terms are typical for cohesive natural soils. In spite of the fact that Burland's proposition introduced a certain semantic order a reliability of identification of yield stress in natural soils has not changed. It should be emphasized here that any laboratory procedures based on oedometer test do not provide a realistic value of yield stress, especially in heavy preconsolidated soils. It should be also underlined that sample disturbance in oedometer test can change significantly the final results. As an illustration of this, the results of preconsolidation/yield stress determination by 3 methods are compared in Figure 3. For each of tested samples the obtained results are considerably different. In such situation there is an evident need to work out an alternative method which would not have all drawbacks inherently associated with the oedometer test and which would make possible to determine reliable value of yield stress.

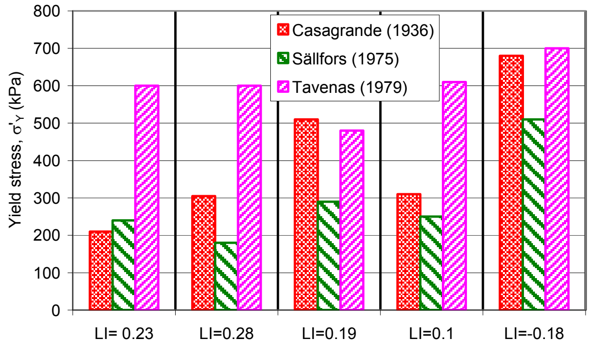

Figure 3. Comparison of preconsolidation stress determined by various methods.

3 A NEW APPROACH TO QUATIFY STRESS HISTORY IN SOILS

The proposed an alternative approach to evaluation of stress history in soil is based on dilatancy concept (Reynolds 1885). It rests on observation that tendency to dilation during shearing in soils changes with confining effective stress. The yield stress ratio also changes with effective stress what creates premise that a certain measure describing dilatancy might reflect quantitatively acquired stress history in soil.

Dilatancy can be observed during drained and undrained response to shearing. It can be conveniently observed during triaxial shearing since in this apparatus drainage conditions are easily controlled. One who would try to find an efficient measure of dilatancy should ask himself a question what kind of response: drained or undrained would be more convenient. From metrological point of view it is better when a measure of value is bigger with respect to full scale range of a transducer. Assuming this criterion, undrained conditions are much more favorable than the drained ones. This statement is additionally enforced when one compares consumption of time necessary to carry out undrained and drained tests in clays. This way of thinking leads inevitably to undrained triaxial shearing. Due to the constrains concerning volume of paper, a description of rational for selection CIU test (i.e. undrained shearing on fully saturated specimen preceded by isotropic consolidation) will not be described here. It will be only emphasized that pore pressure response reflects very well stress history. Normally consolidated soils generate positive pore pressure during shearing while heavy preconsolidated soils exert at certain stage of shearing only negative pore pressure increments. This fact is illustrated in effective stress paths showed in Figure 4. In order to describe pore pressure change Δu due to vertical and horizontal total normal stress increments ($\Delta\sigma_v$ and $\Delta\sigma_h$) one can use equation proposed by Skempton (1954):

$$\Delta u = B[\Delta\sigma_h + A(\Delta\sigma_V - \Delta\sigma_h)] \quad (1)$$

Pore pressure parameters B and A in this equation correlate well with degree of saturation and stress history, respectively. For fully saturated soil (B=1) sheared after isotropic consolidation along the standard stress path ($\Delta\sigma_h$=0) Skempton's pore pressure parameter A can be represented by the following equation:

$$A = \frac{\Delta u}{\Delta \sigma_V} \tag{2}$$

The fact that value of parameter A at failure corresponds to overconsolidation ratio value OCR is well known and appreciated (eg. Bishop and Henkel 1962; Jamiolkowski et al. 1985). However, if A_f is used alone, its capability in a wide range of OCR is limited to slightly and medium overconsolidated soils.

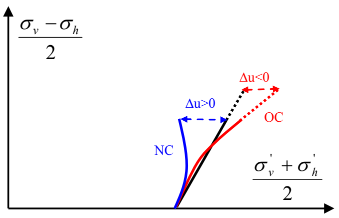

Figure 4. Influence of stress history on characteristics obtained from undrained triaxial test.

In order to extend the concept of description of tendency to dilation by A parameter it is worth to look at the whole course of shearing, not only at the failure stage. It is also worth to emphasize the major advantage of A parameter resulting from equation (2) which consists in coupling "the cause" ($\Delta\sigma_v$) and resulting from it "the result" Δu.

In order to show a potential of undrained TX tests to reflect stress history of soil, let us trace a change of A parameter during triaxial CIU tests carried out on three undisturbed samples of sandy clay which prior to shearing was consolidated to three various isotropic effective stresses 80, 200 and 400kPa. Tested samples had liquidity index I_L = 0.28, so it can be treated as a relatively firm soil. More on index properties of tested material can be found in another authors' paper (2011). Distribution of Skempton's pore pressure parameter A is shown in Figure 5 against vertical strain during shearing. An analysis of the data on the chart allows to formulate certain observations. The first one concerns maximum value of parameter A which usually is achieved at pre-failure stage of a test with vertical strain not exceeding 4%. The second observation concerns stabilization of A parameter for large strain, which can be assumed to appear at strain level of 20%.

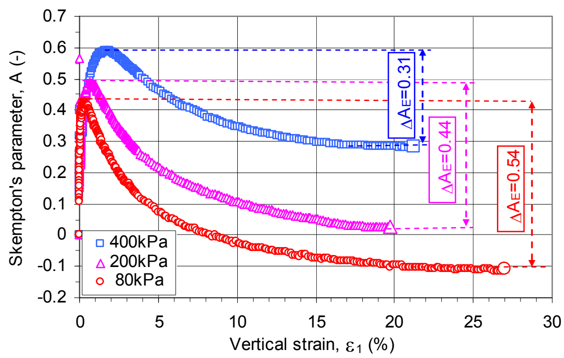

Figure 5. Change in Skempton's parameter A against vertical strain for various consolidation stress.

Before formulation of the most important observation it should be pointed out that for natural soils (with unknown value of yield stress σ'_Y), the fact that each sample was sheared at different effective stress means that every sample had different value of yield stress ratio YSR. Taking this into account it can be noticed that the bigger is the difference between maximum (peak) value of Skempton's pore pressure parameter A_P and its stabilized value A_S, the material is more preconsolidated, so the higher is yield stress ratio YSR. However the difference (A_P-A_S) alone cannot be a measure of preconsolidation since values of Skempton's parameter depend on effective stress prior to shearing. In order to solve this problem it should be realised that post peak A course is associated with dilation due to shearing while part of a test up to achievement of A_P refers to pre-failure stage. Therefore actual parameter reflecting stress history ΔA_{EN} is the ratio of Skempton's pore pressure parameter A change during dilation phase to change of this parameter during pre-failure stage:

$$\Delta A_{EN} = \frac{A_p - A_s}{A_p - A_0} = \frac{\Delta A_E}{A_p - A_0} \tag{3}$$

Symbol ΔA_E denotes the difference between extreme (max and min) value of A while ΔA_{EN} means normalized differential pore pressure parameter. Definition of this parameter is illustrated in Figure 6. As it was emphasized, the fact that for a cohesive soil in a given state any derived experimental parameter changes with effective stress change means that it might be related to OCR. This statement creates a firm premise for finding procedure capable to determine yield stress σ'_Y in natural soils.

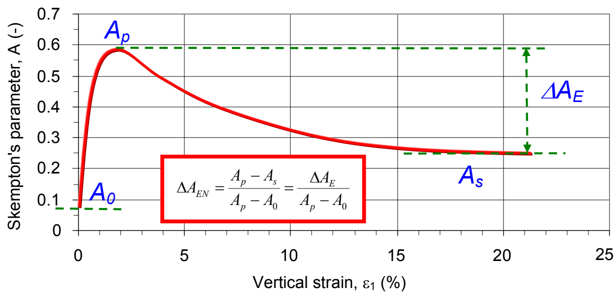

Figure 6. Definition of the new stress history parameter.

In order to take advantage of this premise it is necessary to create a chart showing analogy between overconsolidation ratio OCR and normalized differential pore pressure parameter ΔA_{EN}. Such a chart is shown in Figure 7. Change of overconsolidation ratio OCR was shown for two hypothetical samples which have preconsolidation stress σ'_P 160 and 640 kPa. The axes of the chart are shown in log scale what implies that:

$$\log OCR = \log \sigma_p' - \log \sigma_v' \tag{4}$$

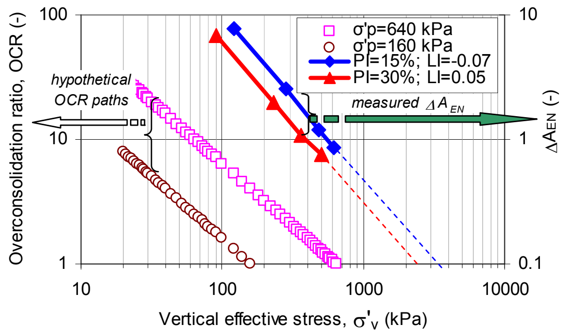

Figure 7. Analogy between overconsolidation ratio OCR and normalized differential pore pressure parameter ΔA_{EN}.

It results from the equation (and the chart as well) that intersection of straight lines with horizontal axis determines preconsolidation stress σ'_P for each hypothetical sample. Independently, on the same chart, there were shown test results of two series of tests for soils of various plasticity indexes I_P (15% and 30%) and consistency represented by liquidity index I_L (-0.07 and 0.05 respectively). The results of 8 tests are shown in the form of parameter ΔA_{EN} against vertical effective stress prior to shearing σ'_{v0}. Independent straight lines for each tested soil give a basis for an assumption that extrapolation of these lines will make possible to determine yield stress σ'_Y for each soil, provided that ΔA_{EN} value for YSR=1 is known.

In order to determine such an offset value it is necessary to carry out one series of undrained traxial tests CIU consisting of 3 to 5 specimens prepared in the laboratory from a slurry based on a material tested previously as an undisturbed one. Before shearing each specimen should be consolidated and then unloaded in order to obtain predetermined value of overconsolidation ratio *OCR*. Only specimen with OCR=1 does not undergo loading-unloading procedure. All specimens should be sheared at the same effective vertical stress prior to shearing. At the end, one gets set of pairs (*OCR*, ΔA_{EN}) which allow to create a chart where from regression line corresponding to OCR=1, offset value of ΔA_{EN}^{NC} can be read. Detailed description of procedure for determination of this value is given by Wdowska (2010).

Once two series of tests on undisturbed material as well as on reconstituted one are completed, it is possible to draw a chart from which value of yield stress σ'_Y can be determined. Example of such chart is shown in Figure 8. The data concern stiff natural clay of plasticity index I_p=23% and liquidity index I_L=0.0. Offset value of ΔA_{EN}^{NC} determined on the basis of reconstituted material equals 0.3 and eventually determined yield stress σ'_Y is 1350 kPa.

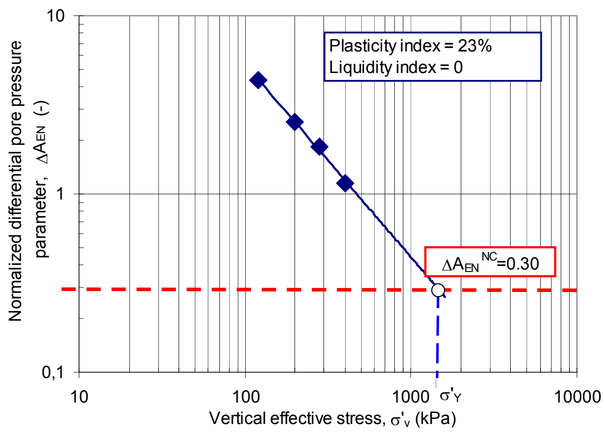

Figure 8. Example of yield stress σ'_Y determination for natural soil.

4 CONCLUSIONS

The paper presents an alternative (to standard approaches) determination of stress history parameters. The proposed method accounts for the difference between preconsolidation stress σ'_P and yield stress σ'_Y .The presented method for yield stress determination is based on undrained triaxial test TXCIU and it is methodologically more sound than standard method based on oedometer test. It results from the fact that proposed procedure is based on dilatancy concept which extent depends on the whole post diagenesis history of soil. Stress history parameter ΔA_{EN} proposed in the paper is based on pore pressure response during undrained shearing. It is important to note that the parameter refers to dilation phase during shearing what considerably minimizes influence of sample disturbance. Furthermore, yield stress is determined on the basis of series of tests what in turn significantly enhances objectivity of the method comparing to a single oedometer test. The proposed method is suitable for cohesive soils of various plasticity and consistency so it is applicable to slightly and heavily overconsolidated soils.

REFERENCES

Bishop A.W., Henkel D.J. 1962. *The measurement of Soil Properties in the Triaxial Test.* 2nd ed., Edward Arnold, London.

Burland J.B. 1990. On the compressibility and shear strength of natural clays. *Géotechnique* 40 (3), 329-378.

Casagrande A. 1936. Determination of the Pre-consolidation Load and Its Practical Significance. *Proceedings, 1st International Conference on Soil Mechanics and Foundation Engineering*, Cambridge, MA, Vol. 3, 60-64.

Jamiolkowski M., Ladd C.C., Germaine J.T. and Lancellotta R. 1985. New developments in field and laboratory testing of soils. *11th International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, 57–154.

Ku T. and Mayne P.W. 2013. "Yield stress history evaluated from paired in-situ shear moduli of different modes." *Engineering Geology*, Vol. 152, No. 1, 122-132.

Lipiński M.J., Wdowska M.K. 2011. A stress history and strain dependent stiffness of overconsolidated cohesive soil. *Annals of Warsaw University of Life Sciences-SGGW Land Reclamation,* No. 43(2), 207-216.

Reynolds O. 1885. LVII. On the dilatancy of media composed of rigid particles in contact, with experimental illustrations". *Philosophical Magazine* Series 5. **20** (127): 469–481.

Skempton A.W. 1954. The pore pressure coefficients A and B, *Géotechnique*, Vol. 4, 143-147.

Wdowska M. 2010. *Influence of stress history on evaluation of stiffness of cohesive soils*. Ph.D. thesis, WULS –SGGW Warszawa (in Polish).