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Undrained Shear Strength of over Consolidated Clays Based on Creep Pressure Results from Pressuremeter Tests

Résistance non drainée au cisaillement des argiles surconsolidées en fonction des résultats de pression de fluage dans des essais pressiométriques.

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ABSTRACT: Undrained shear strength (S_u) of over consolidated clays is a determining parameter in geotechnical practice, especially when related to deep foundation designs. When determined from laboratory tests, obtained results are usually lower than they should be for this kind of stiff clayey soils. This strength is usually related to the net limit pressure, which can be determined only for "good quality" tests in which many pressure steps have been carried out over the creep pressure. Even in those cases, transcendental (non-algebraic) equations must be solved. Provided that the creep pressure is related with the border between elastic and plastic behaviour, in the case of cohesive soils, this pressure can be related to S_u. Several authors have rejected this interpretation concluding that it could lead to an overestimation of this strength. Nevertheless, as it is discussed in this paper, this rejection could be based on the assumption of several hypotheses that are probably very restrictive, and that could be especially unlikely for over consolidated clays. In summary, an alternative interpretation in this respect is proposed in this paper with the intention that it at least provokes further discussion on the matter. It leads to consider ably optimistic results, much higher than those obtained from laboratory tests, but in accordance with over consolidated clays nature and their effective stress history.

RÉSUMÉ : La résistance au cisaillement non drainée (Su) des argiles surconsolidées est un paramètre déterminant dans la pratique géotechnique courante, en particulier lors de son utilisation dans la conception de fondations profondes. Les résultats obtenus pour cette résistance à partir de tests de laboratoire sont en général inférieurs à ce qu'ils devraient être pour ce type de sols argileux raides. Cette résistance est généralement liée à la pression limite nette de Menard, qui ne peut être déterminée que pour des essais de très bonne qualité et dans lesquels des nombreuses phases de pression au-dessus de la pression de fluage sont effectuées, et même dans ces cas des équations transcendantes (non-algébriques) doivent être résolues. Etant donné que la pression de fluage est liée à la limite entre le comportement élastique et plastique, cette pression peut être liée à Su dans le cas des sols cohésifs. Plusieurs auteurs ont rejeté cette interprétation en concluant que cela pourrait conduire à une surestimation de cette force. Néanmoins, comme le montre la réflexion exposée dans ce document, ce refus pourrait être fondé sur la supposition de plusieurs hypothèses qui sont probablement très restrictives et qui pourraient être particulièrement improbables, précisément pour des argiles surconsolidées. Cependant, une réflexion plus en détail est nécessaire sur cette question, car l'interprétation proposée conduit à des résultats très optimistes ; beaucoup plus élevés que ceux obtenus à partir de tests de laboratoire, mais en conformité avec la nature des argiles surconsolidées et l'histoire de leurs contraintes effectives.

KEYWORDS: Undrained shear strength, over consolidated clays, pressuremeter test, creep pressure, Menard limit pressure.

MOTS-CLÉS : résistance au cisaillement non drainé, argile surconsolidée, essai pressiométrique, pression limite Ménard.

1 INTRODUCTION

The concept of unconfined shear strength of cohesive soils is a relatively complex concept to be addressed.

It is widely accepted that actual unconfined shear strength value is higher than typical values obtained from laboratory tests. As an example, even when it is really difficult to achieve laboratory tests results higher than 400 – 500 kPa for "Tosco" soils (typical clayey Miocene soils in metropolitan Madrid area), it has been usual practice designing piles for a working load of 4 MPa with an embedment length of 4 diameters. According to common expressions, this working load would correspond to undrained shear strength figures about 1000 – 1200 kPa (García de la Oliva, 1991).

Nevertheless, international practice requires supporting geotechnical projects on investigation works results, apart from professional experience, results that are not always available, alternatively, on excessively conservative ones from laboratory tests.

Undrained shear strength is expressed in total stresses, but it is determined by effective stresses history. There are expressions relating undrained shear strength for normally consolidated soils depending on the effective vertical stress, for instance, the one proposed by Skempton (1970). Apart from chemical processes, the undrained shear strength of over consolidated clays is determined by their preconsolidation pressure (Terzaghi, Peck & Mesri). This should lead to high figures for laboratory test results which are not achieved mainly because of the following two reasons:

- When samples are taken and prepared for testing, they are inevitably disturbed. Therefore, preconsolidation effect is neglected.

- Usual laboratory tests carried out for determining undrained shear strength, such as unconfined compressive strength (UCS) and triaxial unconsolidated and undrained (TX/UU) tests, could be not appropriated tests as far as no disturbance of the sample is assumed. This hypothesis is not realistic, especially taking into consideration that samples are not consolidated before testing. (Consolidated and undrained triaxial tests TX/CU interpreted in total stresses can be considered much more reliable than the others because, even when these tests do not avoid disturbance of the samples, they allow restoring samples stresses by consolidation process. Obtained results are conservative as well, but higher and more realistic than in UCS and/or TX/UU tests).

Definitively, undrained shear strength of over consolidated clays is supposed to be much higher than usual results obtained form not appropriated laboratory tests which do not avoid sample disturbance, being this disturbance especially intense for this particular type of soils.

2 PRESSUREMETER TESTS AND S_U

As a general rule, determining accurate figures for the contact pressure, the pressuremeter modulus and the creep pressure is not a difficult issue for major part of typical pressuremeter tests.

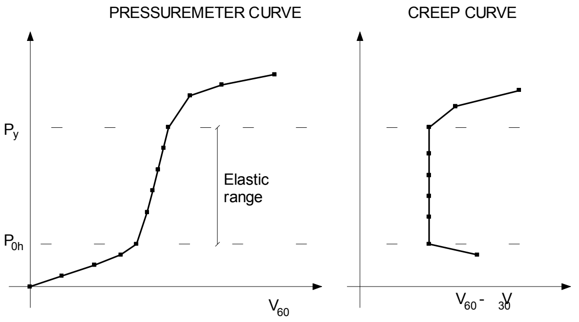

Figure 1. Typical Pressuremeter and creep curves from a pressuremeter test.

In those cases in which the test curve is not of a very good quality, determining contact pressure is a little more difficult, and a significant loss of accuracy is to be considered for determining pressuremeter modulus. Even in those cases, determining an approximate value for creep pressure is not so complicated.

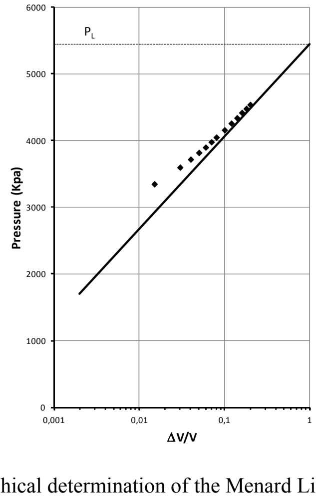

Figure 2. Graphical determination of the Menard Limit Pressure.

Nevertheless, estimation of the net limit pressure from a pressuremeter test result is just possible for good quality tests, in which many pressure steps have been carried out over the creep pressure, requiring a graphical interpolation process.

In fact, this limit pressure is a theoretical situation corresponding to pressures much higher than the maximum ones achieved during the test.

As shown in figure 2, pressure steps are supposed to have an asymptote if represented in a logarithmic graph. The intersection of that asymptote with the vertical line corresponding to $\Delta V/V = 1$, is defined as the Limit Pressure.

It can be stated that the determination of undrained shear strength from pressuremeter tests results is addressed as a minor issue for major part of specialised bibliographic references, and in all those cases, this strength is estimated from the net limit pressure on pressuremeter tests.

When test pressure is over the creep pressure, radial (principal) stress on the cavity can be expressed depending on S_u, shear modulus (G), contact pressure (P_{0h}) and the instant volume of the measuring cell (V), according to the following widely accepted general expression:

$$\sigma_r = p_{h0} + S_u \cdot \left[1 + \ln\left(\frac{G}{S_u}\right)\right] + S_u \cdot \left[\ln\left(\frac{\Delta V}{V}\right)\right] \qquad (1)$$

When test pressure is equal to the limit pressure, the foregoing expression can be expressed in the following way (Menard, 1957). It must be noted that P_L* corresponds to the net limit pressure i.e. the limit pressure minus the contact pressure.

$$P_L^* = S_u \cdot \left[1 + \ln\left(\frac{G}{S_u}\right)\right] \qquad (2)$$

$$\beta^* = \left[1 + \ln\left(\frac{G}{S_u}\right)\right] \qquad (3)$$

$$S_u = \frac{P_L^*}{\beta^*} \qquad (4)$$

As an alternative to solve this transcendental equation, "β*" can be considered constant for each kind of soil, being higher for stiffer soils. For instance, and according to Cano (2007), Marsland and Randolph (1977) considered a figure of β* = 8 for stiff clays, while Menard (1957) proposed values from 2 to 5 for normally consolidated clayey soils. Therefore, the undrained shear strength can be estimated as follows:

$$S_u = \frac{P_L^*}{8} \quad (5)$$

It must be noted that these values proposed for constant "β*" are correlating the limit pressure with usual figures for undrained shear strength obtained from typical laboratory tests. As a general rule, the reliability of typical results from laboratory tests is not questioned, and so, these expressions are likely underestimating too the undrained shear strength, in the particular case of over consolidated clays.

In summary, and additionally to the inherent difficulties of determining the limit pressure from pressuremeter tests, the way that undrained shear strength can be obtained from this pressure requires solving complex equations or the application of empirical and conservative correlations as the one shown above (5).

3 THE CREEP PRESSURE AND S_U

Provided that the creep pressure is related to the border between elastic and plastic behaviour, in the case of cohesive soils, this pressure can be related to the undrained shear strength.

While test pressure is through the elastic range, stress tensor is not tangential to failure criterion surface (Tresca criterion for cohesive soils). When the creep pressure is achieved, at least one point of the cavity has reached the failure condition.

Additionally, into the elastic range, stress tensor is extremely easy to be determined according to elasticity theories. Assuming axial symmetry, (corresponding the symmetry axis to the cavity axis), principal stresses at any point of the cavity will be radial σ_r, vertical σ_z, and circumferential stress σ_θ, being radial stress the pressure given by the pressuremeter cell, and being complied the following conditions for plane deformation:

$$\Delta\sigma_z = 0; \quad \Delta\sigma_r = -\Delta\sigma_\theta \qquad (6.1) \text{ and } (6.2)$$

When failure occurs, maximum deviatoric stress is produced between radial and circumferential principal stresses as shown in figure 3.

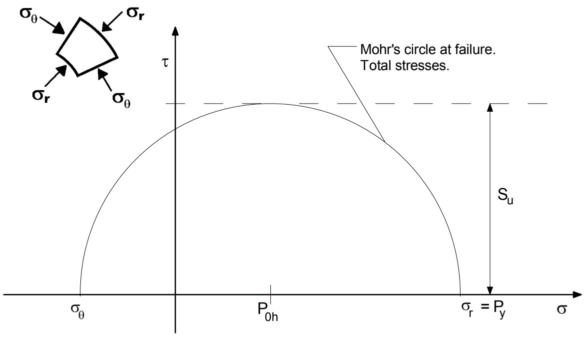

Figure 3. Mohr's circle when creep pressure is achieved.

According to figure 3, undrained shear strength of the soil can be obtained from the following typical expression, widely known as the yield pressure method.

$$S_u = P_y - P_{0h} \qquad (7)$$

It must be noted that when ground yielding is achieved, expressions (6.1) and (6.2), are not complied, and so, determining principal stresses would not be so easy, and expression (7) would not be valid.

Undrained shear strength figures, obtained by applying the foregoing simple expression, are much higher than the typical ones derived from laboratory tests, or from the limit pressure. Thus, several authors have rejected this interpretation method due to its optimistic results.

4 THE YIELD PRESSURE METHOD. MAIN BIBLIOGRAPHIC REFERENCES

It can be stated, that finding references to the possibility of determining undrained shear strength from the creep pressure is not easy. As a general rule, the yield pressure method is rejected because it is widely assumed that it could lead to an over estimation of the undrained shear strength. Authors referred other authors for stating this, but it is really difficult to track original reasons for this rejection.

In fact, most part of the proposed reasons for rejecting this approach, are originally related to the possibility of determining the undrained shear strength, not from the creep pressure, but from a more or less precise shear stress-strain curve, derived from the pressuremeter tests curve assuming ideal undrained conditions.

The most specific reference found for rejecting the yield pressure method corresponds to Briaud (1992):

> "*The yield pressure method is not recommended as it typically overestimates the undrained shear strength. It is possibly because the creep pressure is determined to be too high on the PMT curve (recompression of the soil), or because of the finite length to diameter ratio of the PMT, or because contact pressure is underestimated*".

As shown, none of these three possible reasons are determined from a quantitative point of view. For instance, correction factor depending on the probe shape (finite length to diameter ratio) is supposed to be a low figure, even lower than 1,1. This possible effect could be a minor reason for rejecting the yield pressure method. In fact, if a correction factor was applied to the creep pressure, this possible effect could perfectly be neglected.

Regarding the possible recompression of the soil, probably it is much more unlikely for cohesive soils in which the pressuremeter test can be considered almost a test under undrained conditions. Obviously, it cannot be stated that recompression effect is not possible, but assuming increases in the creep pressure higher than 10-20% would not be in accordance with any actual soil model.

Finally, it would be extremely easy being sure that the contact pressure is not underestimated, just considering a high bound value for this pressure.

As a result, the yield pressure method cannot be rejected for the foregoing possible reasons, and introducing some correction factors into the model could make this not recommended method become into a valid method.

According to Clarke (1995), Marsland and Randolph approach for determining the contact pressure from a pressuremeter tests curve, which is widely accepted, is based on the same assumptions than the yield pressure method. Obviously, in this particular case, these assumptions are not leading to a possible overestimation of the soil strength, but their validity should not depend on obtained results.

Additionally, a large and interesting chapter for Clarkes's book is dedicated to several discussions about how to determine S_u from the pressuremeter test, but all of them are based on the limit pressure and on the possibility of defining a shear stress – strain curve. This chapter is not explaining why the yield method is not appropriated for determining the undrained shear strength.

Probably, the most detailed of the consulted references corresponds to Baguelin, Jezequel and Shields (1978). Once again, authors try to determine S_u from shear stress–strain curves. In fact, the authors propose two different curves, a first one for an ideal undisturbed cohesive soil, and a second one considering the presence of a remoulded annulus of sensitive clay around the cavity, between the probe and the surrounding undisturbed cohesive soil.

Once both curves are defined, authors propose an interesting exercise consisting in comparing obtained results for the same (given) pressuremeter curve, by the application of the both curves previously mentioned.

The conclusion achieved by the authors is that if a remoulded annulus existed, and was not considered for test interpretation, obtained results would be a lower (conservative) figure for pressuremeter modulus, but a higher (overestimated) figure for undrained shear strength.

But following questions must be noted:

- Pressuremeter curve for undisturbed cohesive soil would never be the same than the one for a remoulded annulus of sensitive clay around the cavity, and so, comparison can not be made for the same given pressuremeter curve.

- Undrained shear strength is obtained from the shear stress – strain curve, considering that this strength corresponds to the peak value for the shear stress, but it is not derived from the creep pressure.

As a result, it can be stated that this explanation cannot be used for rejecting the yield pressure method, as far as it is related to a different method for determining undrained shear strength, and it is based on the comparison of two theoretical scenarios that cannot occur at the same time.

Anyway, it is widely accepted that, according to these sophisticated analyses, there is an inherent risk of overestimation of the undrained shear strength when obtained from the pressuremeter test. As far as more rudimentary methods (as the yielding pressure method) lead to even more optimistic results, they are directly rejected, unless no technical justification has been addressed for this rejection.

Additionally, no alternative method is available for validating these optimistic results and so, clearly underestimating results from laboratory tests or the limit pressure are considered for design purposes.

5 PROPOSED INTERPRETATION METHOD

Proposed interpretation method is considered valid just for over consolidated clayey soils.

This method is restricted to pressuremeter tests in which both the pressuremeter and the creep curves can be determined, and so, the creep pressure (P_y) can be estimated from these curves.

In order to ensure that the contact pressure (P_{0h}) is never underestimated, a high bound figure is to be considered for this pressure (P_{0h}*), being required a higher correction factor for lower quality tests. When contact pressure cannot be determined from the test curves, it can be estimated considering an at rest earth lateral pressure coefficient K_0 equal or higher than 1.

In order to ensure that the creep pressure is never overestimated, a low bound figure is to be considered for this pressure (P_y*), being required a higher correction factor for lower quality tests.

Finally, a global model factor of 1,5 is proposed. This factor will be used as a reduction factor for the obtained value of the undrained shear strength, as shown in equation (8).

$$S_u = \frac{P_y^* - P_{0h}^*}{1,5} \qquad (8)$$

6 A REAL CASE

Two years ago, our company was involved in a Design and Build scheme for a highway in Romania, in which we had the necessity of proving that the undrained shear strength for a Tertiary stiff clayey substrate at 30 – 40 m depth was higher than 400 kPa.

Obtaining undrained shear strength results higher than 400 kPa is not easy, but in this particular case there was an additional difficulty to manage. Maximum admissible figures for undrained shear strength of the stiffest clayey soils in Romania are about 300 kPa at 30 m depth and 400 kPa at 40 m depth, according to Romanian Local Standards for deep foundation design.

Tertiary substrate corresponded to soils classified as CH (according to US CS), with a fine content about 90%, a liquid limit over 30 and SPT results well over 50. According to the Geological Study, this substrate was supposed to be about more than 100-150 m thicker in the past, and so it was exposed to an intense over consolidation process for hundreds of thousands of years. Later erosion processes lead to the actual ground profile.

In a particular section of the alignment in which ground properties were considered homogeneous, 5 TX/CU tests and 16 UCS tests were carried out. Obtained results in carried out UCS tests were not clearly depending on depth, and were extremely variable. They were into the range 200 – 400 kPa, corresponding to undrained shear strength figures about 100 – 200 kPa. Results from TX/CU tests were slightly more optimistic corresponding to undrained shear strength figures into the range 300 – 400 kPa for depths between 20 and 30 m.

As previously mentioned, higher figures for undrained shear strength, according to their over consolidated nature, were expected.

Even when pressuremeter tests were not a usual practice in Romania, 8 dilatometric OYO test were carried out in this homogeneous section. Unfortunately, carried out tests were not of a very good quality, and it was not possible to have a reliable estimation neither of the net limit pressure nor the contact pressure. Nevertheless, an approximate enough figure for the creep pressure was determined for each test.

According to the over consolidated nature of the substrate, an at rest earth lateral pressure coefficient $K_0 = 1$ was considered for estimating a value for the contact pressure of each test.

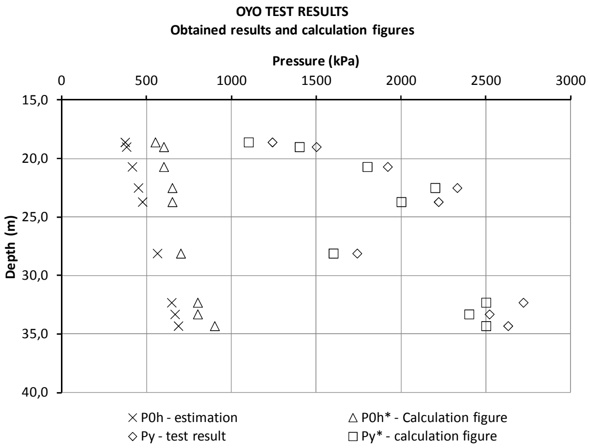

Figure 4. Test results and calculation figures after considering correction factors.

Considered test results are shown in figure 4. Calculation figures are shown as well. Taking into consideration that test quality was not very good, applied correction factors were considerably high.

Once calculation figures for both the contact and the creep pressure are determined, undrained shear strength can be obtained from the proposed method. Results are shown in figure 5.

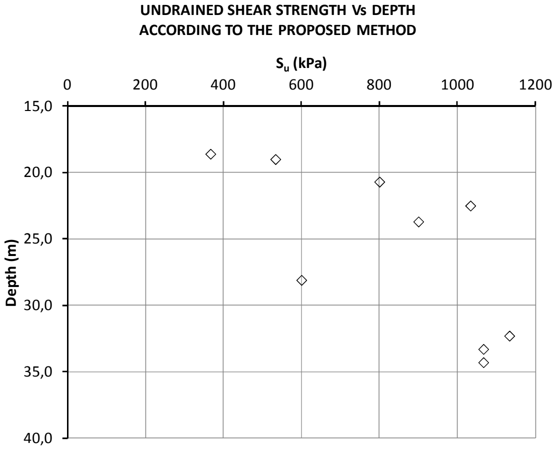

Figure 5. Undrained shear strength results obtained from the proposed method.

As shown, there is only one result lower than 500 kPa, and as a general rule, obtained results are higher than 800 kPa. Tests carried out at depths higher than 30 m lead to undrained shear strength results over 1000 kPa.

Finally, the Supervision Team for the works did not accept our design considerations (S_u = 500-600 kPa). This was the original reason for deciding spending time in consulting main existing international references, what finally lead to the submission of this paper.

7 CONCLUSIONS

According to usual expressions on geotechnical practice, border between elastic and plastic behaviour of the soils is related to their shear strength. In the particular case of pressuremeter tests on cohesive soils, failure is produced when test pressure is equal to the creep pressure, and shear strength is determined by the undrained shear strength. This interpretation method for the pressuremeter test, known as the yield pressure method, has been typically rejected as it leads to considerably optimistic shear strength results.

On the other hand, it is widely accepted that the undrained shear strength (S_u) of cohesive soils is determined by their effective stress history, and in the particular case of over consolidated clays, it is supposed to be determined by their over consolidation stress. According to this, S_u is supposed to be considerably high for stiff over consolidated clays. Nevertheless, usual results from laboratory tests are unlikely over 400 kPa. In fact it is extremely difficult to find laboratory tests results of unconfined compressive strength tests on cohesive soils or soft rocks into the range 800 – 3000 kPa.

We could assume that these clayey soils, stiffer than typical hard clays and softer than clayey rocks, do not exist. But probably, this is precisely the case of over consolidated clays, which intense disturbance is unavoidable before testing in the laboratory.

Main international bibliographic references have been consulted in order to track the original reasons for rejecting the yielding pressure method. It can be stated that no decisive reason has been found on in this respect, apart from identifying some possible reasons that could lead to higher results, such as the risk of dismissing the possible recompression of the soil during the tests, or overestimating the contact pressure. Overestimation derived from these possible interpretation mistakes is not quantified. Additionally, the reliability of typical results from laboratory tests is not questioned in any of the consulted references.

In fact, if obtained results from this method were not so optimistic, this method would probably be widely accepted. But risk of over estimation is something to be aware of in geotechnical practice.

Anyway, taking into consideration the aforementioned interpretation risks, a modified version of the yield pressure method is proposed, introducing correction factors for both the main input data and the model itself. As far as no alternative method is available for validating the proposed modified method, it should not be considered more than a theoretical exercise or a trigger to intensify the discussion.

In the last years, many pile load tests on monitored piles have been carried out. Obtained results have lead to the development of accurate design methods for deep foundation design based on the pressuremeter test results. As a general rule, main input data for these methods is the limit pressure. Undrained shear strength, is just an intermediate step, which determination in not required in most of the cases.

Records from all those carried out tests, which are not available for the author of this paper, could be extremely useful for checking the validity of the proposed method, and if possible, for calibrating the model.

In summary, it is just a possibility, that the pressuremeter test is showing us undrained shear strength of over consolidated clays is much higher than usually considered, but in accordance with over consolidated clays nature and their effective stress history.

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