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Modern approach to triaxial testing of overconsolidated clays with extreme swelling pressure – methodology study.

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ABSTRACT: Soils such as Mio-Pliocene clays of the Poznań Formation in Poland are a great challenge in the context of their study under effective stress conditions. Similar formations are encountered all over the world, for example London Clay, stiff Tertiary clay of São Paulo, Dueñas Clay Formation in Spain, to mention but a few. Often very high swelling pressure (in the range of up to 800kPa for Neogene clays from Poland area), very low permeability ($k=1x10^{-11}$m/s), high degree of overconsolidation (OCR up to, or even above 20) are the factors due to which the use of standardized (or otherwise well-established in the literature) testing procedures, commonly used for other soils, may lead to interpretation problems or giving false results. An example may be performing saturation in the triaxial compression test (TRX), where the common approach and fundamental assumption of most standards regulating it, is to use low effective stress, but higher than the value of the swelling pressure, which requires knowledge of its value prior to the test. Unfortunately sample swelling may remain unnoticed while standard isotropic saturation is attempted under too low effective stress. The paper presents an idea and results of modern approach to automatic identification and prevention (or control to the user-defined level) of swelling in TRX. Sample height is monitored and effective confining stress is adjusted to not allow height to increase, hence swelling. This is based on usage of an computerized triaxial testing systems controlled by bespoke software algorithms. Experimental tests of sample swelling being allowed and how this influence the results are also presented. Discussion, about whether such procedure might be potentially beneficial under certain circumstances, is undertaken.

KEYWORDS: Swelling pressure, triaxial test, tertiary clays.

1 INTRODUCTION

Triaxial test is considered as one of the most versatile tools in soil mechanics, for characterizing stress-strain characteristics of soils, and derive strength parameters for reliable geotechnical design. It allows recreation of the in-situ effective stress level acting on the sample, control over the saturation level and precise monitoring of the volume changes. With use of a modern, computerized and automatized triaxial test apparatus, we are virtually unlimited in stress path application approach. On the other hand, commonly used procedures, mainly given by various national standards are often, in my opinion, outdated, very limited in scope regarding complexity of the triaxial test on variable geological materials, and not consistent with each other.

One of the aspects of the triaxial procedures that is rather poorly covered in the standards (although present in the literature, for example Bilir 2011, Høien et al. 2019), is how to approach testing strength parameters of the soils which present high swelling potential. Traditional way is to test under the effective stresses higher than swelling pressure.

Comparing how is treatment of expansive soils regulated in couple of triaxial standards we may find that the guidance given in those procedures differs significantly. Australian standard seems to omitt the issue completely [AS 1289.6.4.2-188]. ASTM D7181 and D4767 give reasonably clear and unequivocal guidance for sample/apparatus preparation stage ("Dry mounting method advised for swelling soils"), and saturation stage ("Sample shall be not allowed to swell (…) by application of the difference between cell and back pressure higher than swelling pressure"). British standard BS 1377-8 1990 Part 8 also indicates general approach for saturation stage only, allowing for some exceptions ("Applied effective stress (…) "shall not be greater than the desired effective test pressure", but "should not fall below the level required to prevent swelling of soils that have a significant swelling potential (unless this property is to be investigated and steps are taken to make appropriate measurements)." Saturation at constant moisture content (method 5.4) is advised for swelling soils."). Exception given here seems to refer to the measurement of the swelling itself (in terms of volume change or volumetric strain), and does not translate into strength measurements. European CEN ISO/TS 17892-9 standard refers to this problem in sample/apparatus preparation section by advising: "Clay specimens shall be prevented from swelling by dry mounting method (and then further discs flushed under high effective stress), unless "it can be documented that the swelling occurring does not lead to significant softening of the specimen". Remark given here hints at the cases where swelling has negligible effect on the consistency and thus soil strength. None of the above standards give any information with reference to consolidation and shearing stages.

Considering practical side of application of the above guidance (more or less vague or specific), traditional way of approaching usual first stage of triaxial test, which is saturation in isotropic stress conditions, may lead to the situation of sample swelling being unrecognized. Whether performing saturation in a step-wise way or ramping cell and back pressures gradually (with constant effective confining stress of our choice), we will observe water going into the sample (back volume) regardless of sample swelling or not. In proper scenario this volume reflects volume of the air being dissolved and replaced with water in the pores (with volume of the sample being constant). In unwanted case of sample swelling this water volume translates to sample volume change, and inevitable increase of liquidity index.

To prevent that, usage of proper effective stress to overcome swelling is needed. Swelling pressure may be derived from other tests (for example 1D), but that requires additional testing, material, time, costs. Proposal of this paper is to include swelling pressure identification stage into triaxial procedure, whenever there is any indication that material tested may have swelling potential.

On the other side of this problem, question arises, how sample swelling influences the overall C-M envelope characteristic and thus strength parameters resulting from the triaxial test? Couple of examples and some discussion is also presented.

2 MATERIALS

All tests for this research have been performed on undisturbed samples of Tertiary (Neogen, Miocen-Pliocen) overconsolidated clays of Poznań Formation, of an alluviallacustrine basin sedimentation origin, from the central part of the basin (Bydgoszcz area). Detailed information about Poznań Formation extents, summary of the geological history, physical properties, mineralogical composition, and references can be found in Izdebska-Mucha & Wójcik (2013).

For proper understanding of the presented results it is important to note that tested clays are highly glacitectonically disturbed, overconsolidated and not homogeneous in terms of grain size distribution and mineralogical composition alike, even if visually often may seem to be. As an example, samples used for automatic swelling pressure identification, shown on Figure 1, are from one Shelby tube sampler (length 0,7m), differ only about 2% in terms of moisture content, but has shown wide spread of swelling pressure values (240 – 435 kPa) (derived from triaxial test and confirmed with one dimensional swelling pressure test).

Figure 1. Samples used for automatic swelling pressure identification.

3 METHODS

3.1 *Automatic identification of swelling pressure*

For immediate identification of the sample swelling in a triaxial test, a direct measurement of the sample dimensions changes is necessary. There are different ways of achieving that. Using on-sample small strain transducers (vertical and radial) is probably the most accurate technique, but it is still hard to classify that neither as a commonly available in commercial labs, nor most economical. Nevertheless, such arrangements are more and more widely used for advanced projects research, and has much broader field of application (quantification of stiffness parameters, K0 conditions, or Poisson ratio), and be necessary solution in case of highly anisotropic soil, where basing only on axial height measurement may not be representative.

For presented test results, simpler and commonly used equipment arrangement was used, namely standard triaxial automated system (GDSTAS by GDS Instruments). This apparatus is computer controlled by the dedicated software. Important functionality of this (and other similar) system is possibility to use axial stress control mode during required stages. That allows keeping in contact load ram (with attached displacement measurement device) with the sample top cap anytime, and measuring any sample height changes, that may happen due to swelling, or consolidation. Such functionality allows to identify sample swelling at any point, and engage further action to prevent it. As the reaction should be as quick as possible (to minimize any material changes), user input should be avoided, and an automatized approach is preferred. As such functionality in terms of a dedicated test procedure was not implemented before, attempt was made to create it, with use of custom scripting capabilities of the GDSLAB 2025 software (courtesy of GDS Instruments).

3.1.1 *Procedure outline*

To identify and prevent swelling, following steps have been programmed to take place automatically:

1. Sample docking, to enable measurement of the height changes from the start of the procedure. Constant deviatoric stress (7kPa in case of presented results) is maintained. Custom parameter called Sample Height Differential is monitored from this point on.
2. Cell (confining) pressure and back pressure application, to establish initial effective stress. Value of the initial effective stress may depend on the material, in case of the tested clay it was 35kPa, while back pressure (constant throughout the whole procedure) 10kPa.
3. After application of the initial effective stress system was programed to increase it as soon as parameter Sample Height Differential is bigger than 0 (which would mean sample is swelling beyond its initial height). Value of pressure increase was tested on the levels, 50, 20, 10kPa.
4. Each pressure increase was followed by 2 min period of stabilization, before system again reacts on sample height changes.
5. The loop between points 3 and 4 continues until sample is not swelling during defined time of being under constant effective stress, in case of this research it was 60min. Swelling pressure is estimated as a value between last and previous effective stress.
6. After reaching the swelling pressure and meeting the time with no swelling condition, system switches to the saturation stage, keeping achieved effective stress. Sample height monitoring still takes place, in case swelling would occur during saturation, program would apply another effective stress increase.

3.2 *Allowing swelling*

The opposite procedural approach to preventing swelling, is to deliberately allowing it to happen in a fully monitored and controlled way. This procedure is not standardized or commonly used. The reasons for considering it might be:

- Lowering effective stress for testing, to reflect more realistically in-situ stress conditions.
- Gather additional information about potential heave or volume changes if swelling would occur in-situ.

Due to Mohr envelope being inherently non-linear, usage of the simplified linear C-M criterium is common. Although, for the strength parameters to be reliable, there is an assumption, that the confining effective stress used during the test is somehow close to the estimated in-situ conditions under investigated engineering structure. For example if predicted stresses under foundation is going to be say 100kPa, and there is a soil with swelling pressure 400kPa, we have to use at least such confining stress to overcome swelling during sample saturation. Operating in such different range of stress during the test comparing to in-situ may lead to inadequate strength parameters estimation.

Second reason for allowing swelling would be assessment of the volumetric strain changes to be expected if that happens in-situ when overall stress level under the structure is lower than swelling pressure and water will access the clay.

3.2.1 *Procedure outline*

To benefit from the knowledge of the swelling pressure value, identification of it is proposed in the first place:

1. Following the points 1-5 from the section 3.1.1. to identify swelling pressure.
2. Decreasing effective stress to the demanded level (final consolidation stress value) and monitoring height of the

sample and back volume (volume of water flowing into the sample) changes, until stabilization occurs. Effective stress change shall be done by increasing back pressure, which boosts the efficiency of the saturation process taking place together with sample swelling.

3. B-check procedure and further saturation stages if needed before commencing shearing.

3.3 *Shear strength characterization*

Presented results from triaxial CU tests, include samples treated with one of the above approaches (swelling identification or swelling identification and allowing swelling), although it's important to note, that have been performed with older version of the controlling software without custom scripting capabilities, but in more manual, user control manner. That was highly engaging and time consuming process, nevertheless results are considered equivalent to automatized approach. Saturation, consolidation and shearing stages have been performed in a standard way.

4 RESULTS

4.1 *Automatic swelling pressure identification results*

Three examples of automatic swelling pressure identification are presented below. Orange lines represent sample height changes. Each time this line goes negative (sample swelling beyond its initial height), system applies higher effective radial stress (blue lines), by the value set in the procedure. This increase was programmed to be 50, 20 and 10 kPa in sample 1 (Figure 2), sample 2 (Figure 3), and sample 3 (Figure 4) respectively. Final effective stress is considered to be above swelling pressure, which exact value lays within last stress increase range. Smaller the stress increase steps, more accurately swelling pressure value can be estimated.

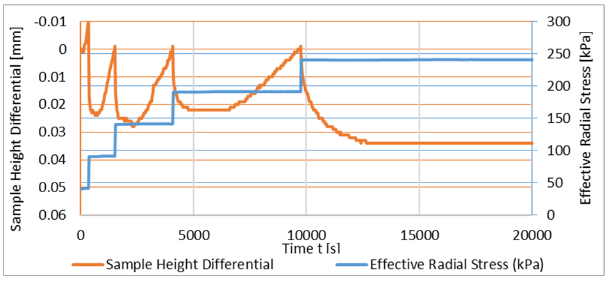

Figure 2. Sample 1 swelling pressure identification

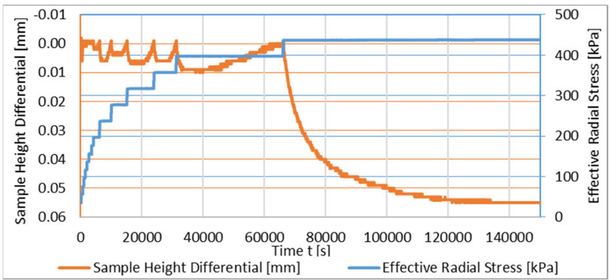

Figure 3. Sample 2 swelling pressure identification

As mentioned in chapter 2, differences in diagnosed swelling pressure for these samples are the result of non-homogeneity of the material, not influenced by the details of the procedure (as values have been confirmed by another method to be within 10% difference).

Sample 3 test was performed with increased resolution set on the displacement transducers reading (to 0.0001mm), and the smallest step for radial stress increments (10kPa), which helped to minimize height changes to about 0.01mm (0.013% strain), throughout the test. Author's main concern before commencing this series of tests was that using too small stress increments would cause the sample swelling not being stopped effectively enough, and time efficiency of such approach would be poor, which proved to be not the case. With enough accuracy and resolution of the measurements, and responsiveness of the hardware-software tandem, this kind of control loop keeps the behavior of the material well under narrow constraints.

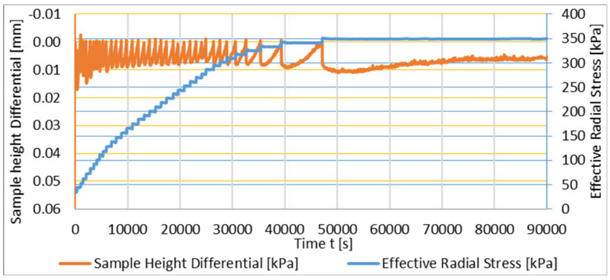

Figure 4. Sample 3 swelling pressure identification

4.2 *Allowing swelling*

Four of triaxial CU test results are presented below, where sample swelling was allowed in the controlled way. Swelling pressure is indicated on the graphs, all samples below those values have been subjected to swelling.

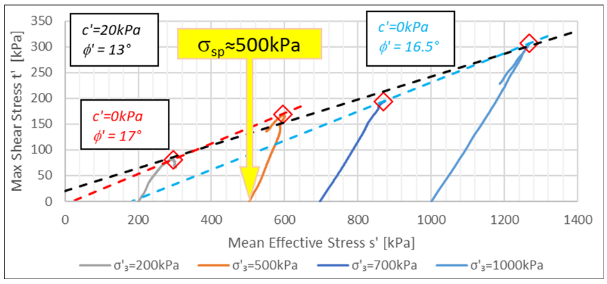

Figure 5. Example 1 TXCU results

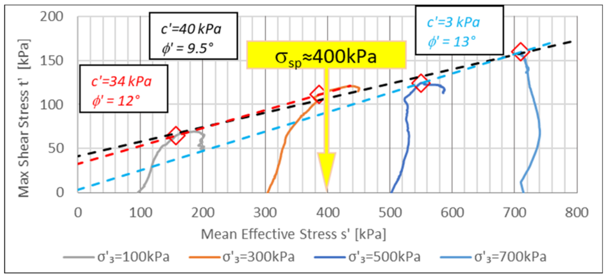

Figure 6. Example 2 TXCU results

In examples 1 and 2 (Figure 5 and Figure 6), consisting 4 samples each, overall envelope is shown as black dashed line. Additionally interpretation based only on two samples below swelling pressure is shown as red dashed line, and interpretation based on two samples above swelling pressure is shown as blue dashed line. Cohesion and angle of internal friction values are shown in boxes with corresponding color fonts. In example 1 the fact of "negative cohesion" error indicated by the envelope is ignored.

Example 3 (Figure 7) consist also of four samples, but three are above and one below swelling pressure. Thus two interpretation lines are shown, for all samples (black), and for three from above swelling pressure (again, "negative cohesion" error is ignored).

General main observation from first two examples is that the angle of internal friction interpreted based on all samples tested below (swelled), and above swelling pressure are smaller, than interpreted only on samples from above or only from below swelling pressure. This is also true for the third example, where applicable, as there is only one sample below swelling pressure.

On the other hand, there is also repeatable pattern in all three examples, that the first sample on the left from swelling pressure value (or at this value as in example 1), and first on the right show similar max shear stress, resulting in this range with flat envelope. In other words one seem to be overestimated the other underestimated, causing the effect of increased envelopes angle described in previous paragraph (when only samples from one side of swelling pressure are considered).

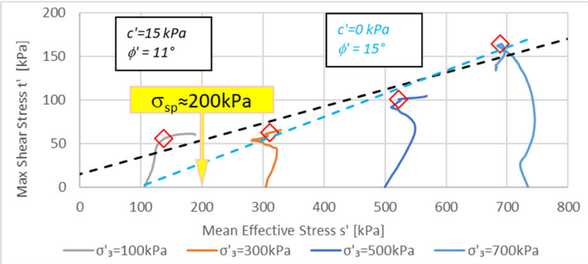

Figure 7. Example 3 TXCU results

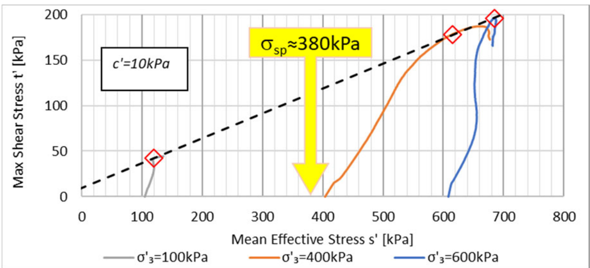

Figure 8. Example 4 TXCU results

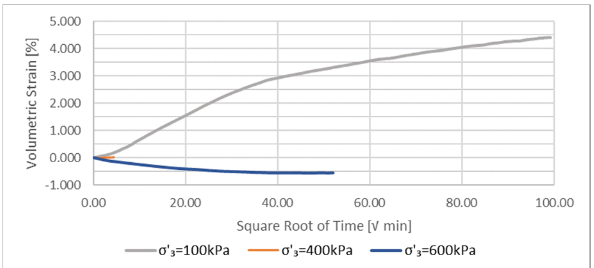

Figure 9. Example 4 volumetric changes during consolidation or swelling

Forth example (Figure 8) was based on three samples only, and is mainly presented here to show how significant volume changes may be involved and how time consuming this process can be. With swelling pressure at the level of 380kPa, sample consolidated to 600kPa changed volume by 0.5% during about a day, while sample let to swell under 100kPa stress, was increasing its volume by 4.5% for over a week.

5 CONCLUSIONS

Identification of swelling pressure value in triaxial testing as a step of a procedure seems to be necessity, regardless of the fact whether swelling is going to be avoided or allowed (in a fully conscious and controlled way). In any scenario this procedure is bringing the mindful approach to testing and results interpretation of a clay materials.

Capability of automatization of swelling pressure identification, as well as other non-standard procedures or unique research approaches, depends on the test system and simplifies otherwise cumbersome procedures. Equipment used for this research allowed precise sample height control by small step pressure increments (best results with 10kPa), which seems to be optimal way.

Results of triaxial tests including samples allowed to swell are not conclusive due to limited number, but generally seem to give results not diverging significantly from expected failure envelope trend, although giving angle on internal friction on the low end of its spectrum for this material. As pointed out in chapter 4.2, proximity of the chosen consolidation stress to the swelling pressure seem to influence the deviatoric stress at failure. To depict, confirm and understand shape of the C-M strength envelope in such scenario, the test with at least 6 or 8 samples is planned to be performed in the same manner, with half of the samples below (allowed swelling) and half above swelling pressure.

Author is aware that ignoring the fact that C-M envelopes indicated “negative cohesion”, may be arguable, it was deliberate, just to emphasize trends of interpreted angle of internal friction, when basing on particular set of samples form under or above swelling pressure.

One of the main disadvantages of swelling allowance approach seem to be time needed for this process to occur, often much longer than usual consolidation time for this material (as shown in Example 4, Figure 9.

6 ACKNOWLEDGEMENTS

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