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Undrained shear strength of soils with fine fraction content derived from compression and extension loading triaxial tests

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ABSTRACT

In the stability analysis of dams or deep excavations a calculation scheme of soil response is assumed that considers the rotation of main stresses. In the case of tailings dams constructed of granular material with fine fraction content (FC <0.075 mm), an additional factor is to be considered i.e. liquefaction phenomenon. Soil response to undrained shearing in compression loading (increase of vertical stress) and extension loading (increase of horizontal stress) differs significantly, giving various strength values. The paper presents the results of triaxial tests carried out on soils with fine fraction content. The tests were performed under compression loading and extension loading conditions. The test results' analysis was performed, considering grain size impact and main stresses application method at the shearing stage.

Keywords: compression and extension loading triaxial tests; tailings; fine fraction

1. Introduction

The factors affecting soil strength properties include type of soil - grain size, consistency, stress history, void ratio, chemical factors, e.g. cementation, salinity. When analyzing the stability of embankments, dams or deep excavations, the rotation of main stresses should also be taken into account (Fig. 1). Three types of soil working schema may be defined in the engineering analysis: compression loading, extension loading and simple shear. Bjerrum 1973 paid attention to the significant problem of strength anisotropy resulting from soil stress conditions. In the paper the shear strength values from undrained triaxial tests performed under compression and extension loading conditions are described. Anthropogenic undisturbed soil samples collected by Gel-Push Sampler were tested.

Soil strength properties are different for compression and extension loading conditions. Jamiolkowski et al. 1985 compared the values of normalized undrained shear strength depending on plasticity index from various types of tests. The results obtained under compression loading and extension loading conditions and in simple shear conditions were compared. The lowest values were obtained from the tests under extension loading conditions, while the highest values from the tests under compression loading conditions. An increase of plasticity index value was accompanied by an increase of normalized undrained shear strength under extension loading conditions.

De Gennaro et al. 2004 presented results of triaxial test obtained for Hostun sand. The monotonic triaxial tests were performed under compression and extension loading conditions. There were observed significant differences between soil response under both conditions. Friction angles from undrained and drained triaxial tests in extension conditions were smaller than the ones in compression loading. The soils subject to extension loading tests were more liquefiable than the soils in compression loading tests. Similar phenomenon was described in the paper by Zdravković et al. 2019 that presented results of undrained shear strength in compression loading and in extension loading for Mucking clay. Also Gao 2013 presented the results of triaxial tests for Shanghai clay, which showed yielding occurred at significantly lower stress values under extension loading conditions than under compression loading conditions.

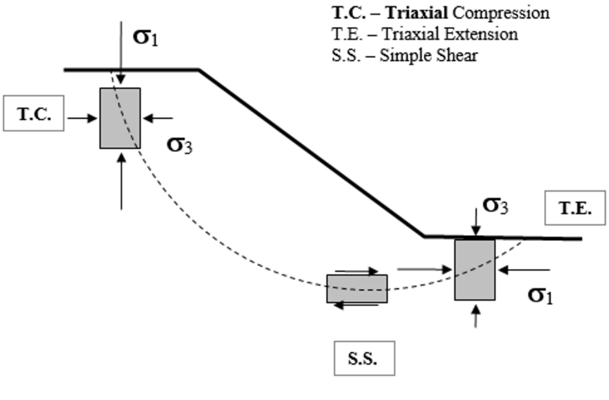

Figure 1. Rotation of principal stress directions along potential failure surfaces.

2. Performed tests

The paper presents the results of triaxial tests performed on undisturbed samples of normally consolidated (OCR≈1) silty sands, silts and silty clays. Borehole BH2 where samples were collected for triaxial testing was used for cross-hole test (CH). SCPTU test was performed in the vicinity as well. The values of shear wave velocities form laboratory (Vs_{LAB}) tests and field tests (Vs_{CH}, Vs_{SCPTU}) were compared and used to assess the samples' quality. The ratio of Vs_{LAB} / Vs_{CH} and Vs_{LAB} / Vs_{SCPTU} were in the range of 0.72÷0.99. According to the criteria presented by Ferreira et al. 2011 it means that samples' quality was very good and excellent. The tested soils were of fines content (FC <0.075mm) in the range of 13 ÷ 100% and clay fraction content in the range of 0 ÷ 43% (more information about index properties of soils is presented in point 3 of the paper). The value of void ratio was in the range of 0.596 ÷ 0.824. Triaxial tests were carried out in so-called hybrid cells, with a rigid connection between the piston rod and the top cap. The tests were conducted under anisotropic multi-stage consolidation conditions where the ratio of main stresses at the end of the consolidation stage was $\sigma'h$ / $\sigma'v$ = 0.5. In the triaxial tests carried out along standard stress path (increase of vertical stress at constant value of total horizontal stress) a shearing rate of 0.05 mm / min was applied. Extension loading tests were carried out under increasing horizontal stress with constant value of total vertical stress (load controlled type tests). The increase rate of horizontal stress was 2 kPa / min. In Fig. 2 there are examples of photographs of soil samples after tests in compression loading (a) and extension loading (b).

3. Analysis of the test results

The triaxial tests were performed on undisturbed samples. Due to the fact that the samples were not reconstructed in the laboratory, the individual factors (initial boundary conditions) differed in relation to the number of tests carried out, that allowed only for a general analysis of test results. Fig. 4 shows examples of effective stress paths obtained from the tests. No contractive response was obtained - no liquefaction phenomenon occurred. This behaviour was verified by using a simple "Chinese Criterion" proposed by Wang 1979 (Fig. 3). For further analysis normalized undrained shear strength values in the transformation phase (Su_{pt}/σ'_v) or normalized deviator values corresponding to this phase (q_{pt} / σ'_v) were taken into account - changes in the character of the stress path from contractive to dilative (Fig. 4).

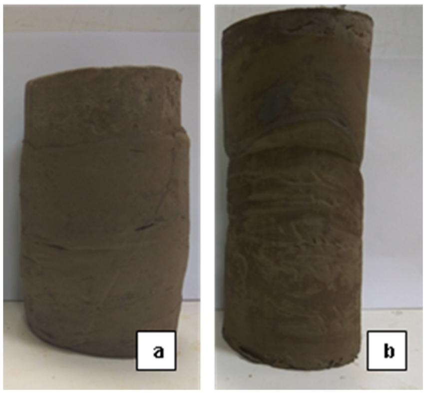

Figure 2. Photographs of soil samples after tests in compression loading (a) and extension loading (b).

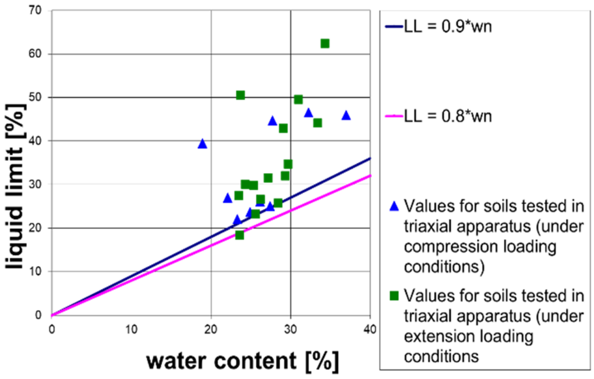

Figure 3. Liquid Limit and water content of tested soils – Chinese Criteria for liquefaction potential verification.

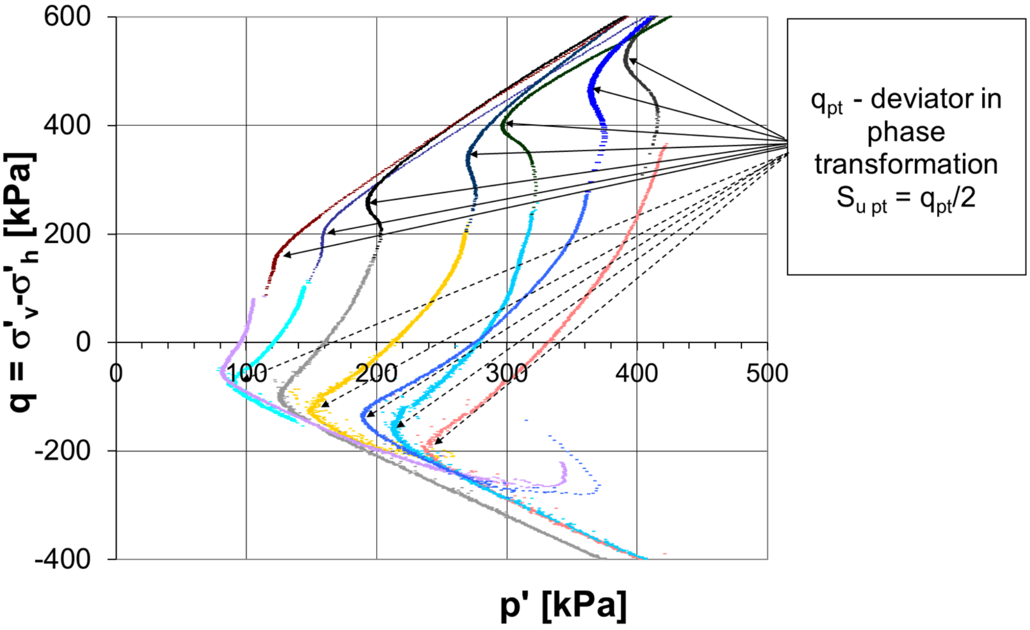

Figure 4. Typical effective stress paths obtained from TXCAU triaxial tests under compression and extension conditions.

Based on test results, it can be concluded that there is a significant difference between the values of undrained shear strength determined from the compression loading and extension loading tests. (Fig. 4). The results obtained from extension loading tests are (T.E.) definitely lower than the ones from compression loading tests (T.C.).

Fig. 5 presents the profiles of the clay fraction content and the fine fraction (FC < 0.075 mm) content as well as the values of the normalized undrained shear strength in the phase transformation ($Su_{pt}/\sigma'v$) from the compression loading and extension loading tests.

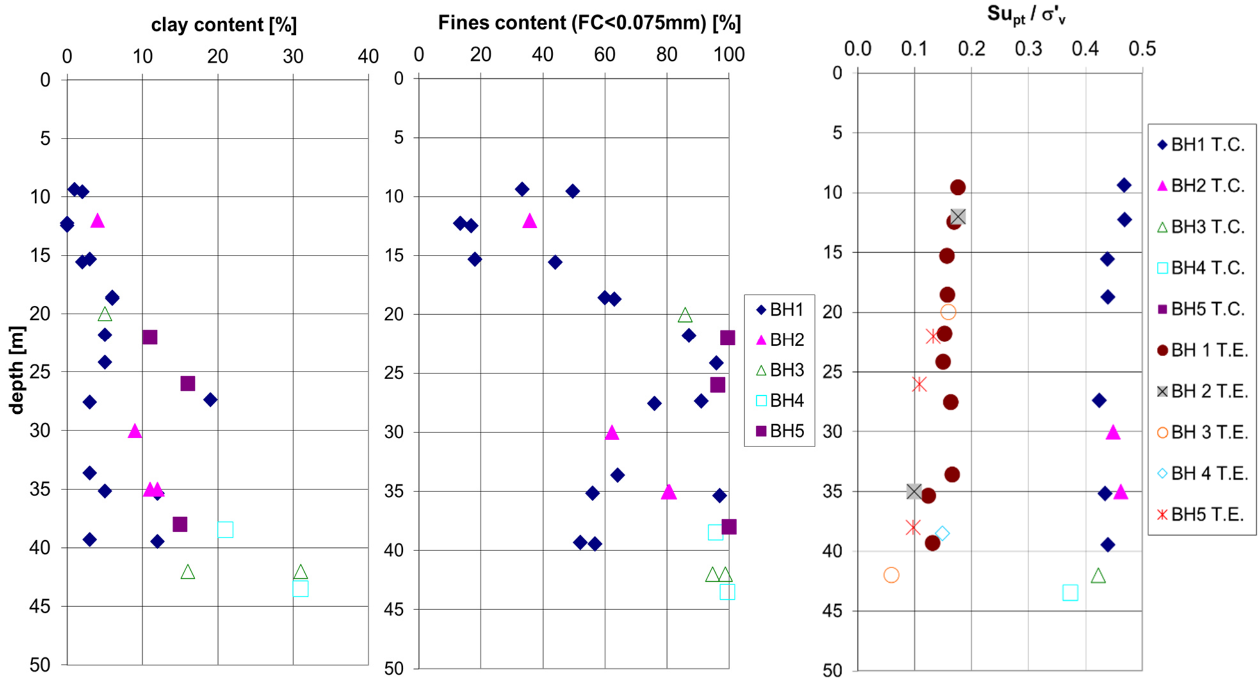

Figure 5. Profiles of normalized undrained shear strength, clay content and fines content

Fig. 6 presents the impact of clay fraction on the value of vertical strain in the transformation phase. It may be concluded that the vertical strain values for the transformation phase are lower under compression loading conditions than under extension loading conditions. An increase of clay fraction is accompanied with an increase of strain for which the transformation phase occurred. The results from extension loading tests present a less clear trend than the results from compression loading tests.

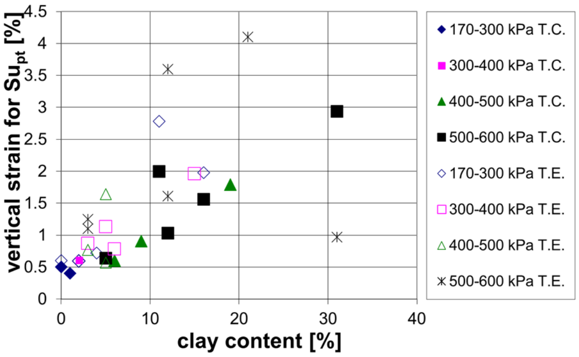

Figure 6. Clay content impact on the value of vertical strain in the transformation phase.

Based on the figures, it may be stated that under compression loading conditions for vertical strain values equal to 0.5% and 1% and the for vertical strain values corresponding to the transformation phase, the impact of clay fraction on the normalized deviator value is negligible. Only for vertical strain value equal to 5%, a clear impact of the clay content on the value ($q_{pt} / \sigma'v$) is observed - the value ($q_{pt} / \sigma'v$) decreases as the content of clay fraction increases.

As for the tests carried out under extension loading conditions, similar behavior is observed, however, for the vertical strain values equal to 0.5%, 1% and the vertical strain corresponding to the transformation phase, clay fraction impact is slightly stronger than under the compression loading conditions. The greatest changes in the normalized deviator obtained for vertical strain value equal to 5% are observed for material of clay fraction content in the range of 0-15%.

The similar observations can be made when analyzing the effect of fine fraction content (FC <0.075%). Depending on the classification standard adopted, the fines content limit is considered 0.063 mm, 0.075 mm, 0.05 mm or 0.04 mm (Dhadli 2012). However, in the analysis of fine fraction impact on the behaviour of fine-grained materials, the value FC=0.075 mm is usually used (e.g. Rahman 2009) and this value was used in the analyzes carried out for the purposes of this paper. Fig. 7÷10 show the impact of clay content and fines fraction content on the normalized deviator value corresponding to the transformation phase and for 5%, 1% and 0.5% of vertical strain for compression loading and extension loading conditions.

In view of the above, it can be stated that until the transformation phase, no impact of clay fraction on the normalized deviator value is observed, and therefore the main factor affecting the deviator value is the effective stress value at the end of the consolidation stage. Only after reaching the transformation phase, the grain size (in this case the clay and fine fraction content) begins to influence the deviator value.

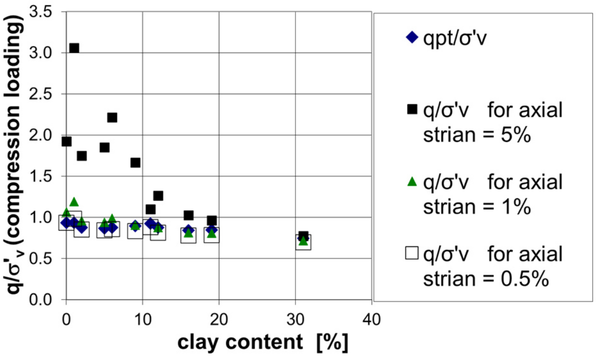

Figure 7. Clay content impact on normalized deviator value for various vertical strain values under compression loading

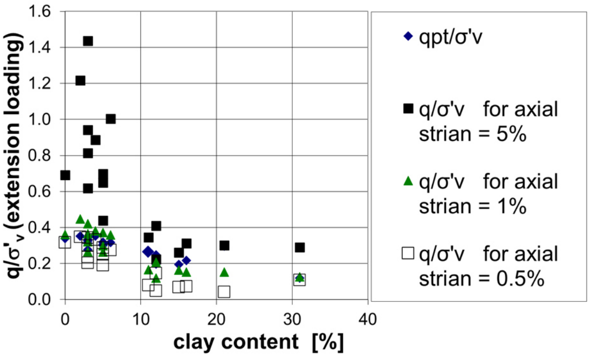

Figure 8. Clay content impact on normalized deviator value for various vertical strain values under extension loading conditions.

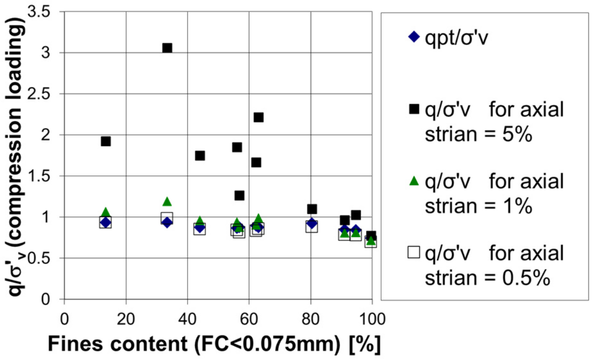

Figure 9. Fines content impact on normalized deviator value for various vertical strain values under compression loading conditions.

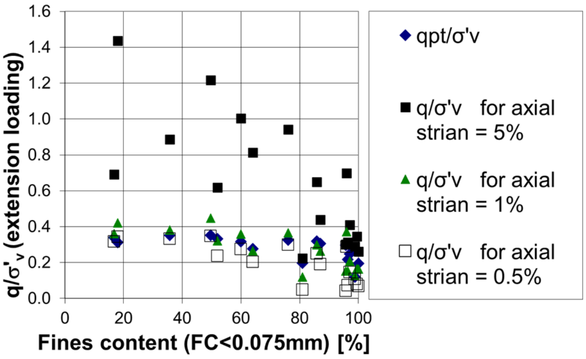

Figure 10. Fines content impact on normalized deviator value for various vertical strain values under extension loading conditions.

4. Conclusions

Fig. 11 presents the relation of deviator for vertical strain value equal 5% to deviator value in the transformation phase against clay content. As the content of clay fraction increases, this relation results in smaller values. However, attention was drawn to the fact that regardless of whether the conditions are compression loading or extension loading, the values and the tendency of changes are similar.

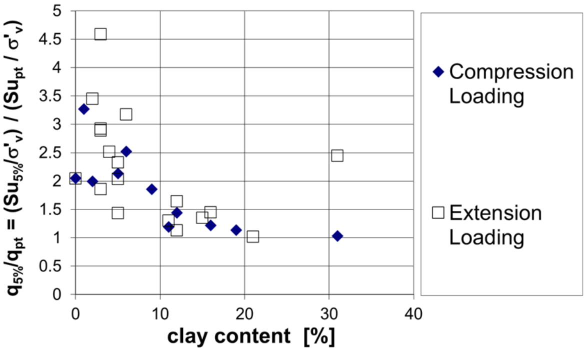

Figure 11. Relation of deviator for 5% of vertical strain to deviator value in transformation phase against clay content.

The paper analyzes the triaxial test results of silty sands, silts and silty clays of anthropogenic origin. The following conclusions have been formulated on the basis of test results:

- The results of normalized undrained shear strength in the transformation phase (Su_{pt} / σ'v) obtained from the extension loading tests (T.E.) are about three times lower than the ones from the compression loading tests (T.C.).
- Vertical strain values for the transformation phase are lower under compression loading conditions than under extension loading conditions.
- For vertical strain level equal to 0.5%, 1% and corresponding to the transformation phase, the impact of clay fraction and fines content on the normalized deviator value is very small. For vertical strain level of 5% deformation, the value (q_{pt} / σ'v) decreases significantly as the clay content increases.

- Until the transformation phase, no impact of clay fraction and fines content on the value of the normalized deviator is observed. In this case the main factor affecting the deviator value is the value of effective stress at the end of the consolidation stage. Only after reaching the transformation phase, the grain size (in this case the clay and fines content) begins to affect the deviator value.

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