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Undrained behaviour of tailings under monotonic loading

Le comprotement non drainé des résidus miniers sous des conditions de chargement monotone

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ABSTRACT: The undrained shear strength is a key parameter used for tailings dam stability analyzes. In areas where seismic loads occur, induced by mining activities or earthquakes, a phenomenon that may threaten the stability of the dam is the liquefaction of tailings. When it comes to static liquefaction, this issue becomes particularly important for high dams where the dam body is subject to high effective stresses. The technology of tailings deposition by spigoting process leads to the natural segregation of tailings. Therefore, the material in the tailings storage facility is diversified in terms of fines content and triggers different response under undrained conditions. The paper presents triaxial test results on tailings. The analyzes were performed based on the results of laboratory tests carried out on samples reconstituted in special sedimentation tanks. The tests were performed for several groups of tailings characterized by various fines fraction content (FC <0.075mm).

RÉSUMÉ: La résistance au cisaillement non drainé est très important paramètre utilisé pour exécuter les analyses de la stabilité des diques. Dans des régions où des charges sismiques sont présents à cause des travaux miniers ou tremblement de terre, un phénomène qui peut endanger la stabilité des diques est la liquéfaction des résidus. Quand il s'agit de la liquéfaction statique, le problème devient particulièrement important pour des diques elevee soumis à contraint effectif très élevé. La technologie du dépôt par spigoting cause la ségrégation naturelle. Par conséquent, le matériel dans le dispositif de stockage des résidus est diversifié en termes de la teneur en fines et montre la response différent dans des conditions non drainées. Cet article présent des essais triaxial des résidus. Les analyses étaient realisées basé sur des essais laboratoires aux échantillons reconstitués dans des réservoirs sédimentaires. Les essais étaient realisées pour quelques groupes des résidus characterié par la teneur en fines différente (FC < 0.075 mm).

Keywords: Reconstituted samples, Triaxial tests, Undrained Shear strength, State parameter

1 INTRODUCTION

The undrained shear strength is one of key parameters used in the dam stability calculations. In particular it plays a considerable role in the design of dam of tailings storage facilities, especially when dams are constructed by upstream method. In this case every new higher embankment is built on the spigotted material. Consequently, the influence of granulation (from sand to silty sand, silt and clay) and stress change play a significant role regarding to the geotechnical parameters estimation to design the dam with higher elevation. The effective stress increase is one of the most important factors affecting static liquefaction.

The authors of this paper have performed the tests on artificial material. It has been assumed that material without stress history and influnce of other factors like cementation, wind and temperature would be tested. Therefore, it was possible to focus only on two factors: grain size distribution and stress change.

The impact of fine fraction content on behavior of sandy soils in undrianed conditions is discussed in many publications and scientific papers (e.g. Yamamuro and Lade (1997), Cubrinowski and Ishihara (2002), Thevanayagam (2002), Md. Mizanur Rahman (2009)), Sean David Rees (2010)). The authors of the above works point out that the increase of fine fraction content in sandy soils changes the internal structure of soils, which affects soil ability to transfer effective stresses. Analyzing the steady state lines, it is noticed that the increase of fine fraction content in sandy soils results in lower location of steady state lines in e-log(p') space and after exceeding a certain fine fraction content, this trend becames reverse (a.o. Zlatovic and Ishihara 1995). The content of fine fraction changing this trend is called threshold fines content (TFC) and is related to the transition of the "fines in sand" to "sand in fines" soil type.

2 TESTED MATERIAL

In order to analyze the influence of fine fraction content on the undrianed shear strength, six groups of tailings with different fine contents were prepared. On the basis of grain size analyzes, SFR index was calculated for each group. It allowed to differentiate the tested material in terms of grain-size distribution.

$$SFR = \frac{f_{>0.075mm}}{f_{<0.075mm}} \tag{1}$$

gdzie:

$f_{>0.075mm}$ – fraction content over 0.075mm

$f_{<0.075mm}$- fraction content under 0.075mm

The samples preparation process consisted of multiple selection and mixing of tailings with high fine fraction content with tailings with low fine fraction content. After mixing, the SFR was checked. The tested tailings with SFR and fines content values are listed in Table.1

Table 1. SFR values for each group.

Group	SFR	Fine content $FC_{<0.075mm}$ [%]
I	7.39	12
II	4.56	18
III	2.49	28.7
IV	1.53	39.5
V	0.63	61.3
VI	0.001	99.9

3 SAMPLES PREPARATION

In order to prepare samples for tests in the triaxial apparatus, special sedimentation tanks were made - metal chambers with a diameter of 600mm and a height of 500mm, with a perforated base and an upper plate allowing for setting small loads. The design of the tank allows monitoring consolidation process (density and void ratio changes) at each stage of sample preparation. The change in the height of the tested tailings in the constructed tanks can be controlled by non-contact laser sensors and LVDT type displacement sensors. The scheme of the tank used for sedimentation is shown in Fig. 1.

The process of preparing the material for testing in the sedimentation tanks consisted of several stages. At the beginning, the tanks were partially filled with water. The dry tailings were then added in small portions, allowing free fall of the tailings particles in the water. After the completion of sedimentation process, the outflow of water from the tank was allowed (consolidation), and then vertical stress (about 10 kPa) was applied. The consolidation process was monitored. After the consolidation process, samples were collected from such prepared tailings for further tests.

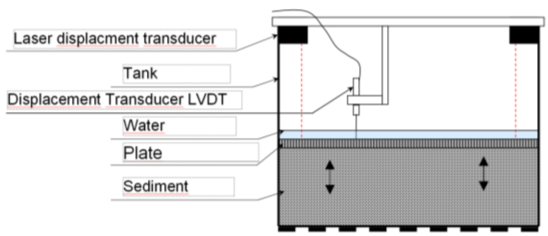

Figure 1. Scheme of the sedimentation tank

The preparation process of one material group lasted from 2 weeks for sediments of the lowest content of fine fraction, up to 7 weeks for the finest sediments. This solution allowed to have a few homogeneous samples for each group.

Fig. 2 presents the initial void ratio values of samples intended for triaxial tests for each group of tailings.

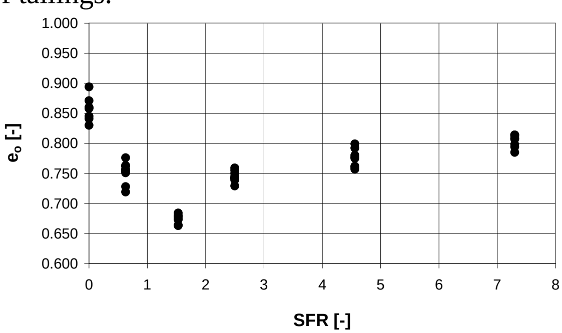

Figure 2. Initial void ratio of tested samples

4 TRIAXIAL TESTS

In triaxial apparatus the tests were carried out on samples with a diameter of ≈ 6.67 cm, height ≈ 14.0 cm. In order to continuously monitor the dimensions of the sample (void ratio), from the beginning of the test a change in height and diameter of the sample was observed with the use of GDS Hall effect local strain transducers.

The tests included the following stages:

- Specimen was flushed with carbon dioxide CO_2.
- Specimen was initially saturated by gravitation.
- Saturation procedure based on back pressure method was applied. The saturation of the specimen was considered complete after reaching Skempton's parameter $B \geq 0.96$.
- The specimens were consolidated at anisotropic state of stress $\sigma'_v > \sigma'_h$ with very small vertical and horizontal stress increments. The ratio of effective horizontal stress and effective vertical stress at the end of consolidation stage was 0.5. For the finests tailings this ratio was 0.7 (for SFR=0.001).
- The specimens were sheared along standard path (*compression loading* test) i.e. by constant cell pressure and by increasing value of vertical stress. The constant shearing rate applied was equal to:

a) for the tailings from the groups SFR=7.39, SFR=4.56, SFR=2.49 and SFR=1.53 the rate of strain was 0.1 mm/min,

b) for the tailings from the group SFR=0.001 and SFR=0.63 the rate of strain was 0.05 mm/min.

5 RESULTS

Below, in Figures 3-8, the paths of effective stresses obtained from the triaxial tests were presented.

Based on the results of triaxial tests, three types of responses of the tested material were distinguished: a contractive reaction, a dilative reaction and a contractive-dilative reaction.

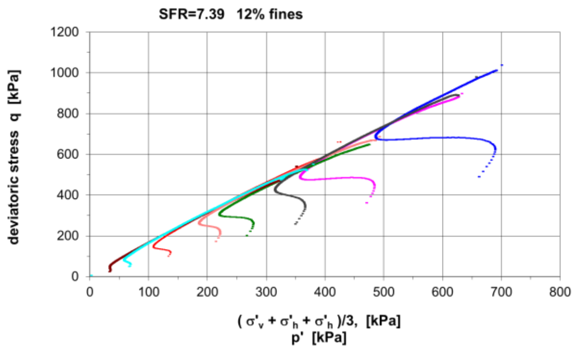

Figure 3. Effective stress paths for SFR=7.39

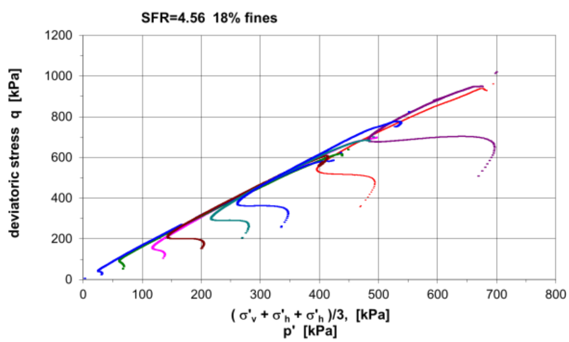

Figure 4. Effective stress paths for SFR=4.56

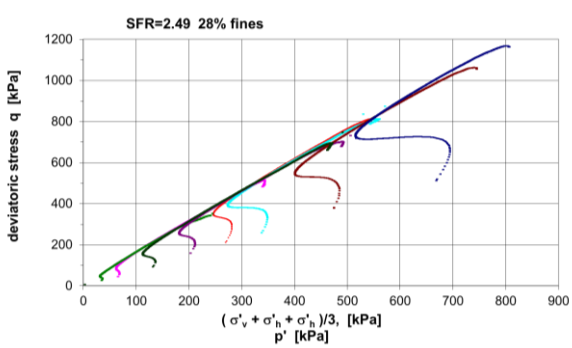

Figure 5. Effective stress paths for SFR=2.49

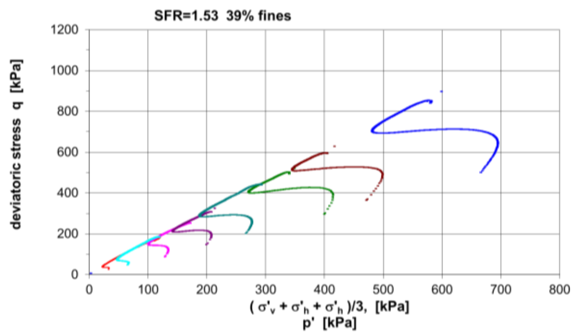

Figure 6. Effective stress paths for SFR=1.53

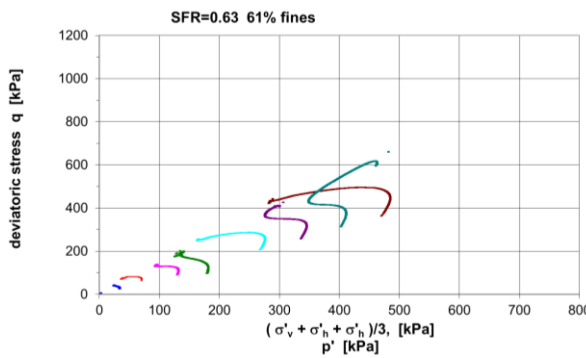

Figure 7. Effective stress paths for SFR=0.63

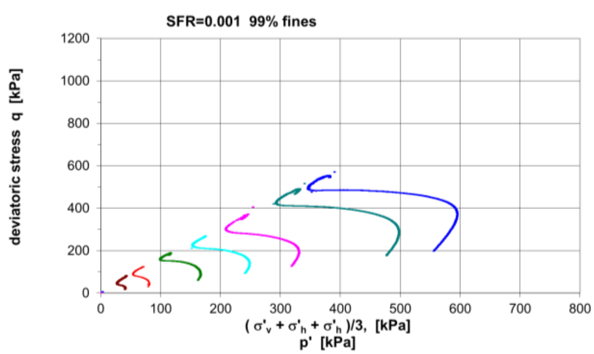

Figure 8. Effective stress paths for SFR=0.001

Only contractive reactions (Figure 9) and contractive-positive reactions were selected for the analysis (Figure 10)

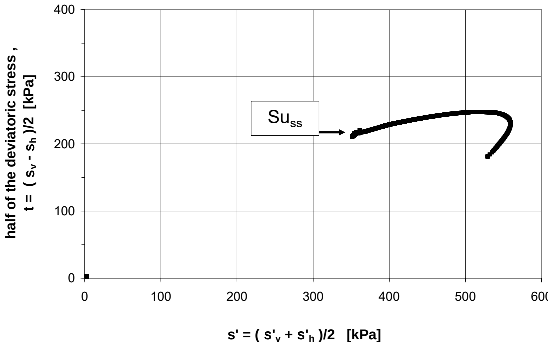

Figure 9 Contractive response- example

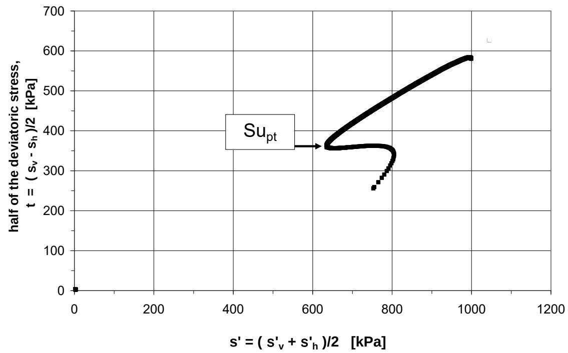

Figure 10 Contractive-dilative response- example

On the basis of obtained test results in Fig. 11, the relations between undrained shear strength in the transformation phase (Su_{pt}), undrained shear strength in the steady state (Su_{ss}) and the void ratio at the end of the consolidation stage (with regard to SFR) were presented.

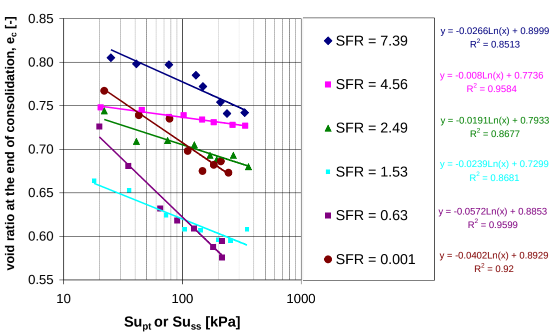

Figure 11 Relation between undrained shear strength and void ratio at the end of consolidation stage.

The above figure shows that the slopes of the designated lines changes with the change of fine fraction content (SFR). Fig. 12 shows the effect of the SFR index on the slope of the line describing the relationship between undrained shear strength and the void ratio.

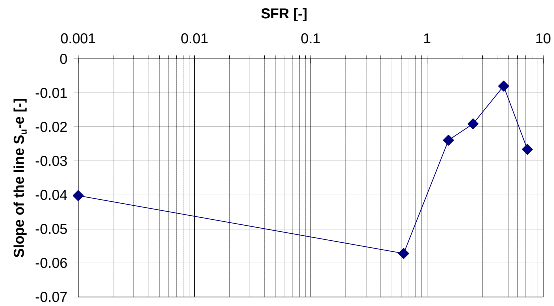

Figure 12. Effect of the SFR index on the slope of the line describing the relationship between undrained shear strength in and the void ratio.

Below in Fig. 13 the influence of fine fraction content on normalized undrained shear strength was presented for four selected values of vertical effective stresses.

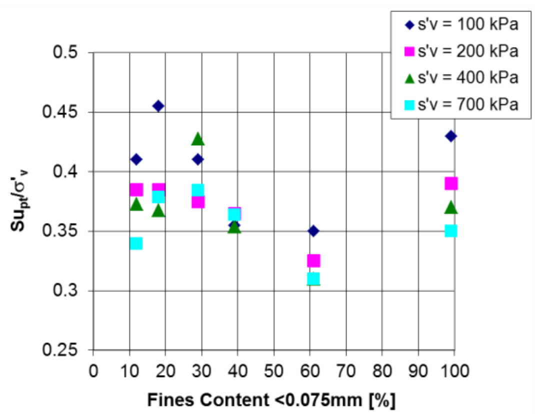

Figure 13. Influence of fine fraction content on normalized undrained shear strength .

It can be noticed that increase of the fine fraction content to approximately 60% in the tested tailings results in reduction of the normalized value of undrained shear strength. Exceeding 60% of fine fraction content causes an increase of normalized undrained strength value, which can be seen on the example of test results for tailings with the highest fine fraction content.

6 MODELING OF TAILINGS BEHAVIOUR

When it comes to tailings dams built by “upstream” method a risk of liquefaction should always be taken into account, as it was the case in Brasil when the dams collapsed (Carmo, Flávio Fonseca do (2017)). It was the one of the largest environmental disasters. Therefore, there is a great need to be able to evaluate the risk of tailings dams failure due to liquefation.

Next step of the authors’ work will be to apply one of the Critial State models like NorSand (Jefferies M. 1993, Jefferies M., Been K., 2015) and perform the numerical tests aimed at examination of accuracy of the model based on laboratory test results.

Afterwards, the Authors intend to create a new constitutive model which will be able to predict more accuratly the liquefation phenomenon. A new constitutive model will be created and implemented in Finite Element code as the Authors see a great need to predict the risk of liquefation in tailings dam design.

7 CONCLUSIONS

The following conclusions can be formulated on the basis of the test results:

I. For the tests carried out at present, the majority of responses induced by the monotonic loading in undrained conditions were of contractive-dilative character.

II. Fine fraction content influences location and slope of the lines characterizing of relationship of undrained shear strength vs. void ratio.

III. An increase of fine fraction content to approximately 60% results in a reduction of normalized undrained shear strength values. For tailings with a fine fraction content greater than 60%, an increase in normalized undrained shear strength is observed.

IV. The lowest values of normalized undrained shear strength were achieved for tailings with fine fraction content of 61%.

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