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Laboratory evaluation of liquefaction potential for coarse-grained soils

Évaluation expérimentale de potentiel de liquéfaction pour les sols à grains grossiers

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ABSTRACT: Laboratory investigations of soil liquefaction are being performed mostly by means of undrained cyclic triaxial tests, which are complicated and time-consuming. Also, not all geotechnical laboratories have the possibility to perform cyclic triaxial tests, since the necessary equipment is very expensive. The objective of the outlined research is to evaluate the liquefaction potential of coarse-grained soils using simple method. This method enables a fast setup of the tested specimen and a subsequent investigation of the pore water pressure build-up during cyclic shearing within a short time period. The new experimental method has been validated in first tests confirming a realistic build-up of pore water pressure. It has been confirmed that the build-up of pore water pressure depends on the initial density. When comparing different soils, it is shown that the liquefaction potential depends on the granulometric properties (e.g. grain size distribution) of the tested soil. The aim of the further investigations is to establish a simple index test for laboratory determination of the soil liquefaction potential under various factors.

RÉSUMÉ: Les analyses en laboratoire de la liquéfaction du sol ont été effectuées principalement au moyen d'essais triaxiaux cycliques non drainés, qui sont compliqués et chronophages. Pas tous les laboratoires géotechniques ont la possibilité d'effectuer des essais triaxiaux cycliques, car l'équipement nécessaire est très coûteux. L'objectif de cette recherche est d'évaluer le potentiel de liquéfaction des sols à gros grains en utilisant une autre méthode beaucoup plus simple. La méthode permet une installation rapide de l'échantillon testé et une étude ultérieure de la pression de l'eau interstitielle lors d'un cisaillement cyclique sur une courte période. La nouvelle méthode expérimentale a été validée avec des premiers tests confirmant l'accumulation de la pression interstitielle. Il est prouvé que l'accumulation de la pression de l'eau interstitielle dépend de la densité initiale.
En comparant des sols différents, il est montré que le potentiel de liquéfaction dépend des propriétés granulométriques du sol (par exemple la distribution granulométrique). Les résultats présentés et d'autres recherches visent à établir un test d'index simple pour la détermination en laboratoire du potentiel de liquéfaction du sol sous divers facteurs.

Keywords: liquefaction, granulometric properties, index test

1 INTRODUCTION

Soil liquefaction is a phenomenon that occurs in loose, saturated, coarse-grained soils under (cyclic) shear loading. The highest tendency to liquefaction have sands. Investigations of soil liquefaction are usually carried out as cyclic tests in a triaxial apparatus (Kramer 1996, Ishihara

1993, Castro 1969, Ishihara K. & Yasuda S. 1972). However, testing in cyclic triaxial device is rather complicated and time-consuming. The installation of the specimen and a reliable acquisition of the measured quantities pose high demands on equipment and working staff that only specialized geotechnical laboratories can fulfil. Until now there is no possibility to quickly investigate the tendency of soil to liquefy nor there is a simple method for a comparison of this tendency for different soils. For such investigations, a simple identification or index test would be suitable.

Such a simple identification test that assesses the tendency to liquefaction has been developed at the Institute for Geotechnical Engineering at the TU Dresden. In this test the evolution of excess pore water pressure (PWP) in a water-saturated specimen under horizontal cyclic shearing is measured. By testing several different sands, an information about the tendency of each of the tested sands to liquefaction is obtained.

Since the tendency to liquefaction is different for different sands it can be classified as an index property of the sand (analogy to the test for determination of minimum and maximum densities of the soil). As the liquefaction potential depends on granulometric properties, in this way it is also possible to detect differences in the soil granulometry, if the initial density and the preparation of the specimen remain unchanged.

2 IDENTIFICATION TEST

2.1 Experimental set-up and procedure

The sketch of an experimental set-up of the identification test is presented in Figure 1. At the beginning of the test, a loose sand specimen (1) of dimensions $D/H = 50/100$ mm is installed in a rubber membrane using a dry funnel pluviation method. The specimen is then slowly saturated from bottom to the top (2). The degree of saturation is determined measuring the mass of

water in the specimen. In this way, a degree of saturation of approx. 90% can be achieved. In this case it can be assumed that the water phase in the specimen is continuous and the air phase is only present as isolated air bubles in water (e.g. Kamata et al. 2009). After saturating the specimen, the excess PWP and the effective stress are equal to zero. The external loading (total stress, p) in the test is the relative air pressure (3). The total stress remains unchanged and equal to zero during the entire test. In order to increase the initial effective stress in the specimen, a suction (negative PWP) is applied to the bottom of the specimen (4). Considering that the total stress is equal to 0, the effective stress (p') is increased to the value of the negative PWP (u). The value of the initial effective stress can be calculated using the equation (1):

$$p = p' + u = 0 \rightarrow p' = -u > 0\ kPa \quad (1)$$

Herein, the stresses are considered positive in case of compression. Subsequently, the specimen is cyclically loaded in undrained conditions in horizontal direction (5). The loading is performed by horizontally translating the top plate of the specimen.
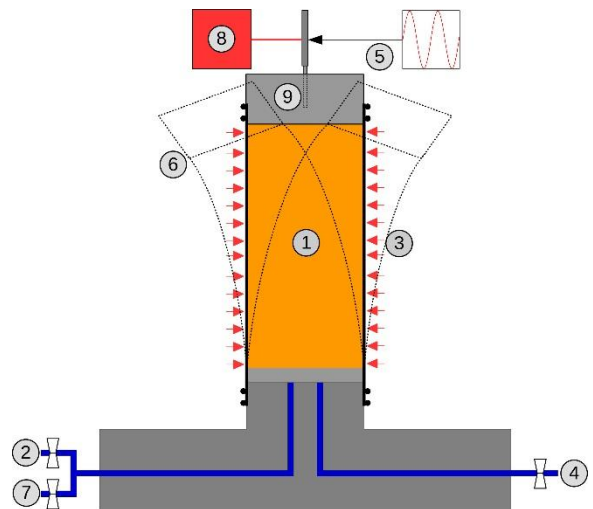

Figure 1. Experimental set-up of an identification test

In this way, the specimen swings in direction of loading (6) and a kind of simple shearing is achieved. The cyclic loading continues under controlled displacement and frequency.During the test, the air pressure and the excess PWP are measured and evaluated. The measurement of the excess PWP occurs at the bottom of the specimen (7). The displacement of the top plate is measured without contact using a laser distance sensor (8). Additionally, the top plate is monitored in order to measure the vertical displacement of the specimen during the test (9). The duration of one complete test is approximately 30 minutes.

The test procedure can be divided into three steps (Figure 2). In the first step (1), the specimen is installed in the rubber membrane and the total and effective stress, as well as the excess PWP are equal to 0 ($p' = p = u = 0$ kPa). In the second step (2), the effective stress (p'_0) is increased by applying suction to the specimen. During this step, the total stress remains zero ($p'_0 = -u_0$; $p = 0$ kPa). In the final third step (3), the specimen is cyclically sheared. The total stress remains unchanged and equal to zero. The effective stress decreases until p'_E while the PWP is increasing ($\Delta p' < 0$ kPa; $\Delta u > 0$ kPa; $p = 0$ kPa). The test is finished when p' decreases to a certain minimum value p'_E.
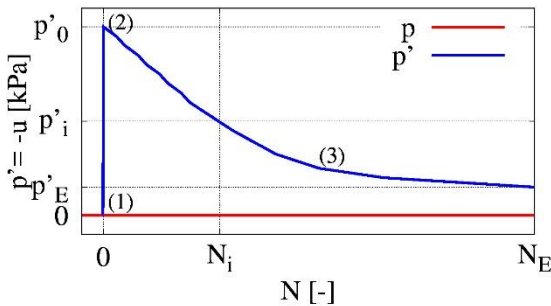

Figure 2. Stages of the identification test

2.2 Tested material

Three different sands were chosen for the first series of the test. The grain size distribution curves of these sands are shown in Figure 3. All sands have narrow grain size distribution curves ($C_u < 6$). The Sands 1 and 2 are coarse and very uniform in the grain size while the Sand 3 has a higher percentage of the fines and a smaller medium grain size.

For these sands a determination of the grain shape has been also performed. The scanned images of 150 grains from different fractions were analysed using a software ImageJ with the plug-in "Shape Descriptors". The grain shape is here represented by the circularity coefficient (f_{circ}). This coefficient has the value of 0 for infinitely long grains and the value of 1 for perfect sphere. The average circularity coefficient for the sand specimen is calculated from the relation (2),

$$f_{circ} = \frac{\sum P_i \cdot f_{circ,i}}{100} \tag{2}$$

where P_i (%) is the percent (by weight) of particles retained in the sieve fraction, and $f_{circ,i}$ is the circularity coefficient of the sieve fraction. The values of circularity coefficients are listed in Table 1 together with the index properties of the sands.

Table 1. Properties of the tested sands

Sand	d_{50} [mm]	e_{min} [-]	e_{max} [-]	ρ_s [-]	f_{circ} [-]
1	0.94	0.579	0.865	2.65	0.78
2	1.27	0.622	0.918	2.64	0.77
3	0.51	0.417	0.713	2.64	0.84

2.3 Test results and evaluation

In the first series of experiments, the reproducibility of the results and two major factors that influence the soil liquefaction potential were tested. These factors are the density of the soil and the soil structure induced through the specimen installation. In the evaluation of the test results, a number of cycles (N) necessary for the decrease of effective stress for $\Delta 20\ kPa$ was considered. Sand specimens in
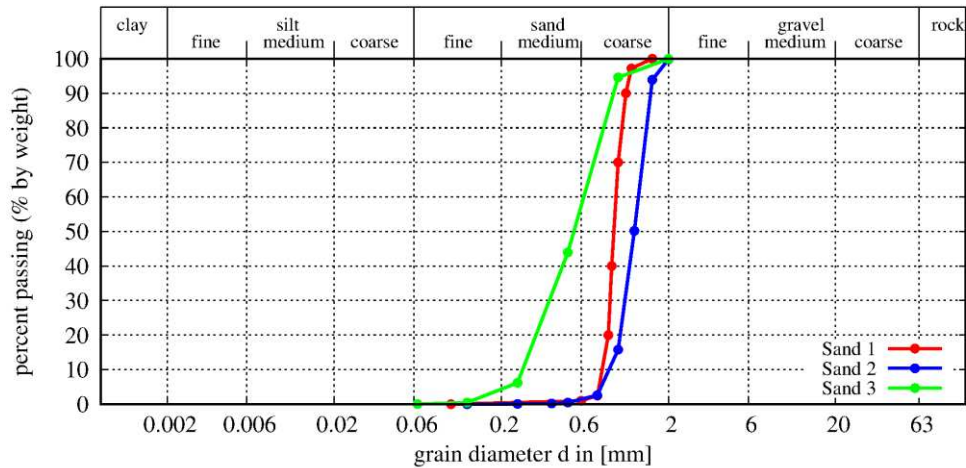
Figure 3. Grain size distribution of the tested sands

these first tests were tested under low initial effective stress ($p_0' = 30$ kPa). The shearing was continued until the efective stress in the specimen reached $p_E' = 10$ kPa.

The loading frequency was set to 1 Hz. It can be assumed that the inertial effects occuring at this frequency are insignificant. Due to the low frequency, the specimens are loaded under quasi-static and not dynamic conditions (Wichtmann 2005). The amplitude of the displacement was about 4.5 mm.

2.3.1 Reproducibility of the results

Three test were performed on Sand 1 under the same initial and loading conditions to investigate if the initial state of the soil specimen (represented through initial density and saturation degree) and the results obtained in the tests are reproducible. Initial states of the sand specimens and the number of cycles obtained in the tests are summarized in Table 2.

Table 2. Initial states and number of cycles in the re-producibility tests on Sand 1

Test	I_{D0} [-]	S_r [%]	N [-]
1	0.431	91	68
2	0.411	89	71
3	0.439	88	85

Figure 4 shows the measured PWPs in the reproducibility tests. The results show that the initial state as well as the number of cycles necessary for defined decrease of effective stress are reproducible within a certain range.
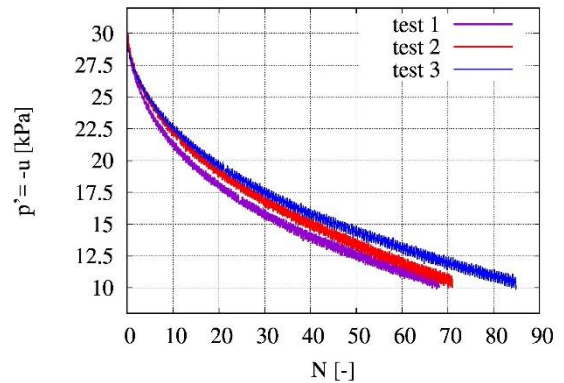

Figure 4. PWP build-up in the reproducibility tests on Sand 1

2.3.2 Influence of the initial relative density

Figure 5 shows the behaviour of Sand 1 with different initial densities of the specimens. The results show clearly that the build-up of PWP and therefore the decrease of effective stress depends on the initial relative density of the specimen. The higher the density of the soil, the slower the build-up of PWP.

The soil specimens with a higher initial relative density need to be sheared under higher number of cycles to reach the defined value of PWP.
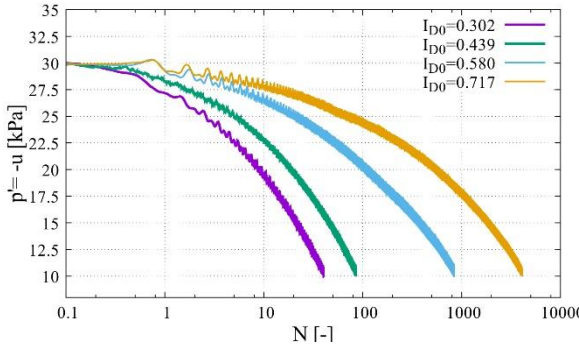

Figure 5. PWP build-up at different initial relative densities (Sand 1)

Figure 6 quantifies this tendency in more detail. It can be clearly seen that the number of loading cycles increases exponentially with the increase of the initial density of the soil.
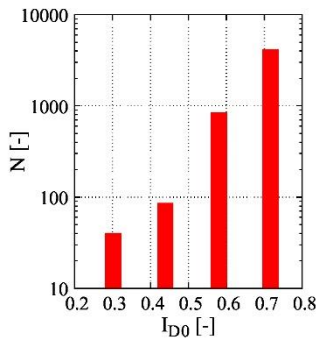

Figure 6. Dependency between the number of cycles and the initial relative density in the identification tests (Sand 1)

2.3.3 Influence of the soil structure

The structure of the soil obtained through the specimen installation plays an important role in the determination of the tendency to soil liquefaction (Mulilis et al. 1977). Orientation of the particles and particle contacts as well as the interparticle forces control the fabric of the soil.

All sand specimens in this study were installed in the same way, using a dry funnel pluviation method. Subsequently, the specimens were slowly saturated from the bottom to the top. Consequently, it is reasonable to assume that all sands posses the same structure (fabric) after the installation, i.e. in the initial state.

The initial states of the specimens and the number of cycles for $\Delta p' = 20\ kPa$ in the tests are listed in Table 3. In case of Sands 1 and 2 almost the same initial densities were obtained after the specimen installation. These sands have also very similar grain size distribution curves. In case of Sand 3 a much lower initial density of the specimen was achieved.

Table 3. Initial states and number of cycles in tests on different sands

Sand	I_{D0} [-]	S_r [-]	N [-]
1	0.302	87	40
2	0.343	87	47
3	0.089	83	37

The results of the identification tests on these three sands are shown in Figure 7. It can be expected that lower soil density leads to faster build-up of PWP.
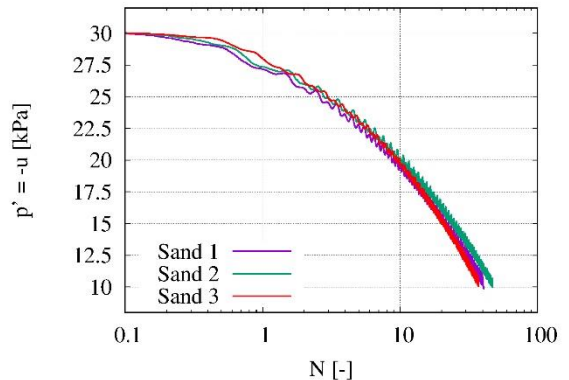

Figure 7. PWP build-up in tests on different sands

However, despite the differences in the initial densities, the results show very similar liquefaction potential in case of all three sands. Obviously, the same soil structure imposed

through the identical specimen installation is essential for the tendency to liquefaction. This soil structure still can be manifested through different soil densities.

3 CONCLUSIONS AND OUTLOOK

Considering the results of the newly developed simple procedure for testing of soil liquefaction of coarse-grained soils, it was shown that is possible to detect a tendency to soil liquefaction from the evoluion of the excess PWP.

Reproducibility of the test results was confirmed by performing three tests on one soil (with same initial and loading conditions). It was also confirmed that the tendency to soil liquefaction strongly depends on the soil relative density. More specifically, the results have shown that the number of loading cycles leading to liquefaction increases exponentially with the relative density of soil. Testing of different soils that were installed, saturated and loaded in the same manner have shown that the soil structure imposed by the specimen preparation has the crucial influence on the tendency of soil to liquefy. The same structure (fabric) can be reflected in different initial relative densities for different sands.

The new testing procedure enables fast investigation of the tendency to soil liquefaction under various conditions. Besides the variation of the inital and loading conditions it should be also possible to vary the soil structure obtained through the specimen installation.

A liquefaction index will be introduced in the next phase. This index should represent the evolution of the PWP in certain number of cycles for defined initial and loading conditions. With the liquefaction index it should be possible to classify the tendency to soil liquefaction for coarse-grained soils. By comparing the liquefaction index for different soils, it will be possible to compare the tendency to liquefaction for different soils.

4 ACKNOWLEDGEMENTS

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