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A simplified cyclic shear test for pore water pressure build-up of different soils

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ABSTRACT

Pore water pressure (PWP) build-up essentially takes place in loose, water saturated, coarse-grained soils causing the reduction of effective stresses and soil stiffness (soil liquefaction). Considering the same internal structure (soil fabric), stress level, loading amplitude etc. the response of different soils to external disturbance is different. Therefore, the increase of PWP or tendency to soil liquefaction is dependent on the granulometric properties of soils. This paper reveals a simple cyclic shear test that enables the comparison of the sensitivity of PWP build-up to density changes for different sands. The presented test allows a fast installation of a soil specimen and a subsequent constant volume cyclic shearing within a short time period (ca. 30 minutes). The results successfully confirm the repeatability of the method as well as the dependence of the PWP build-up on the initial relative density and saturation degree. It is also shown that the soil fabric has an essential influence on the build-up of PWP. The method aims to allocate an index value to every tested sand and thus to quantify a sensitivity of different sands to density changes with respect to liquefaction.

Keywords: cyclic shear test; liquefaction; index value; soil fabric.

1. Introduction

It has already been acknowledged that saturated, coarse-grained soils are susceptible to pore water pressure (PWP) evolution. While loose coarse-grained soils tend to contract and decrease their volume during shearing, which results in PWP build-up, dense soils tend to increase in volume and lead to a reduction of PWP.

Testing of PWP build-up in soil mechanics laboratories occurs usually by performing several undrained cyclic triaxial tests on specimens with different initial relative densities. These tests are very complicated, time-consuming and demand a certain level of working experience and expertise. Also, no unique testing procedure is available for researchers to follow in order to obtain comparable and plausible results. This applies for the specimen installation procedure, testing conditions (stress level, loading stress/strain amplitude) as well as for the test termination criterion (criterion for the determination of the onset of liquefaction) (Castro 1969, Ishihara 1993, Ishihara and Yasuda 2011, Kramer 1996, Seed and Lee 1966, Wichtmann et al. 2019, Goudarzy et al. 2022, Akhila et al. 2019). A simple procedure for laboratory testing of PWP build-up would increase the accessibility and flexibility in its evaluation and comparison for different soils.

Sands are granular materials most prone to PWP build-up during shearing. Besides their intrinsic properties such as grain size, grain shape and grain surface roughness, also the orientation and spatial arrangement of the sand particles and associated voids play an important role in controlling of the PWP build-up. This spatial arrangement, also known as the soil fabric (Oda 1972), is established through the specimen installation method.

Taking into account the same specimen installation method as well as the testing conditions (stress level, loading, specimen size and shape, etc.), the evolution of PWP in case of different sands under variation of relative density will be different. By keeping the installation procedure and loading conditions unchanged and varying only the initial relative density, a sensitivity of different sands to density changes with respect to PWP build-up can be obtained. Also, a comparison of the rate of PWP build-up in case of one specific relative density for different sands will yield an information on different soils susceptibility to PWP generation at the given relative density. Obviously, such method enables a comparison of different sands among each other and can be useful for the design of densification procedures in situ as a countermeasure for soil liquefaction.

2. Cyclic shear test

The concept of the cyclic test is based on the PWP build-up in water saturated coarse-grained soils (sands with small amount of fines and gravel grains) during a constant volume cyclic shearing. The test comprises a fast and reproducible installation of highly saturated triaxial sand samples without additional saturation phase by back pressure. Cyclic shearing of a soil specimen (combined with a slight bending) is imposed by applying a deflection of a certain amplitude and frequency to a specimen's top cap in horizontal direction. Considering the undrained conditions during the test, the PWP evolves with the number of loading cycles. The rate of

PWP build-up can be determined as an indicator of a soil's tendency to liquefaction under certain loading and installation conditions.

2.1. Experimental method

The testing procedure of the proposed cyclic shear test can be divided into three main steps. These are: the installation of a highly saturated sand specimen (essential for repeatable and plausible test results), consolidation of soil specimen via suction and, finally, cyclic shearing under constant volume conditions. A schematic representation of the experimental set-up of the cyclic shear test can be taken from Fig. 1.

Prior to the specimen installation, sand is mixed with demineralized water and de-aired in a vacuum chamber. Following this, the de-aired sand-water mixture is poured through a funnel into a supported rubber membrane and sealed with a top cap. The dimensions of the installed sand specimen (1) are D/H = 50/100 mm. The initial relative density of the soil D_{r0} after the underwater installation varies from sand to sand and ranges from loose to middle dense state (in terms of conventional density index). Soil saturation is determined by measuring the mass of water in the specimen at the end of the test.

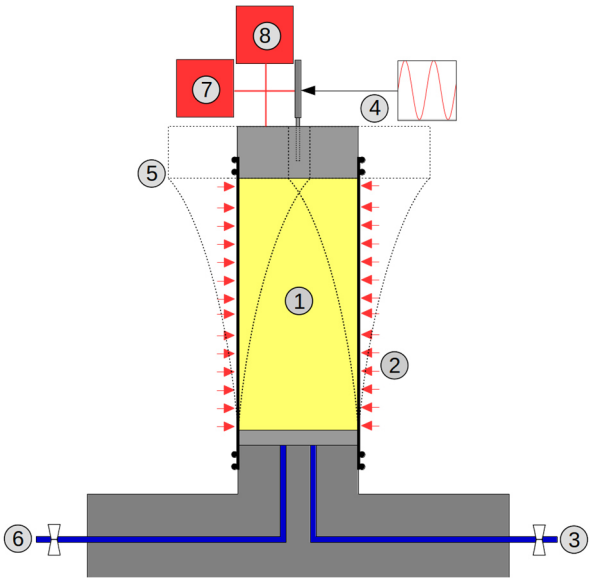

Figure 1. Experimental set-up of the cyclic shear test.

After the specimen installation, the effective stress in the specimen is coming solely from the own weight of the specimen and can be considered negligible. The total stress is resulting from the relative air pressure acting on the rubber membrane around the specimen (2). It remains unchanged and equal to zero during the entire test. Specimen consolidation takes place by applying suction (negative PWP) at the bottom of the specimen (3). Taking into account that the total stress p is equal to 0, the effective stress p' is increased to the value of the negative PWP u. This follows from Eq. (1), where the compression stresses are considered positive.

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

Following the specimen consolidation, the cyclic shearing of the specimen (4) is performed by rigidly deflecting the top cap of the specimen in horizontal direction with a defined deflection amplitude and frequency. The cyclic loading is applied by an electric motor, where the rotational motion is converted into the translational (reciprocating) motion. This shearing occurs in undrained conditions by keeping the suction valve closed (3). As the top cap is rigidly translated, the specimen swings in the horizontal direction and a mode of simple shearing is achieved (5). During the test, the relative air pressure around the specimen and the excess PWP at the bottom of the specimen are measured and evaluated. Forces are not being measured, so no information on the stiffness is obtained. Furthermore, two laser distance sensors are used for measurement of the top cap deflection (7) and the top cap settlement (8) during the test. These measurements are performed contactless. One single test, including the specimen installation, lasts approximately 30 minutes. The test has been successfully tested against repeatability of the results and also validated using the results of the undrained cyclic triaxial test (Bacic and Herle 2020).

A typical evolution of the excess PWP (decrease of effective stress) with the number of cycles in a cyclic shear test is shown in Fig. 2.

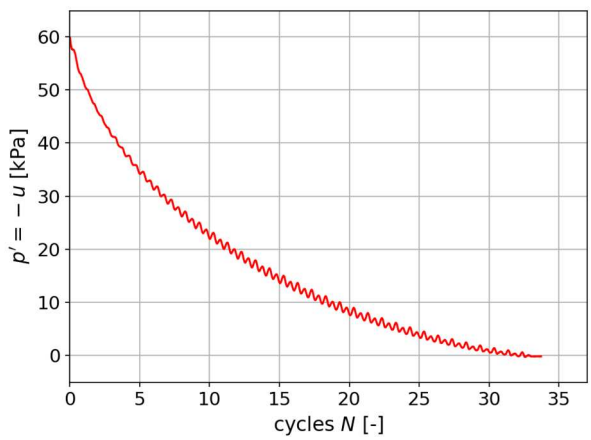

Figure 2. Build-up of PWP in the cyclic shear test.

2.2. Sands tested in this study

Five differently graded sands were used in this experimental study. The grain size distribution curves of these sands are shown in Fig. 3 while the classification properties can be taken from Table 1. Sand 1 and Sand 4 are clean sands, while Sand 2, Sand 3 and Sand 5 contain a very small amount of fines and gravel grains.

Table 1. Classification properties of the tested sands

Soil	ρ_s [g/cm^3]	φ_c [°]	e_{min} [-]	e_{max} [-]	C_u [-]
Sand 1	2.65	30.0	0.579	0.865	1.2
Sand 2	2.63	32.5	0.556	0.892	1.8
Sand 3	2.64	33.8	0.404	0.831	2.5
Sand 4	2.65	32.2	0.674	1.105	1.5
Sand 5	2.64	32.2	0.449	0.846	3.22

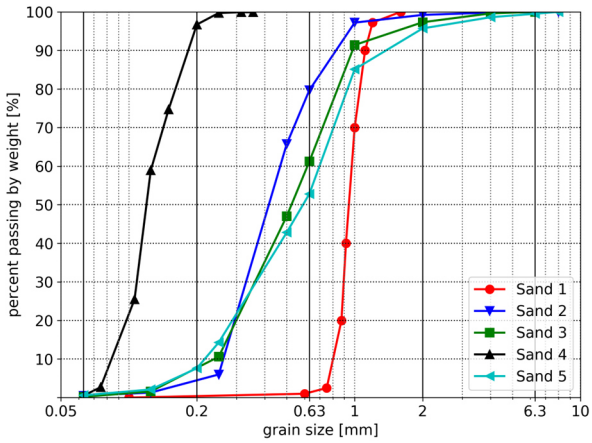

Figure 3. Grain size distribution curves of sands in this study.

2.3. Single test evaluation

Even though the measurement and evaluation of the PWP build-up in the cyclic shear test takes place at one point, this test is not a perfect element test. It can be treated as an index test where the specimen installation, soil consolidation and cyclic loading are performed according to a defined procedure. In this way, the soil state (e.g. fabric, stress level) is always the same and independent of the granulometric composition of the tested soils.

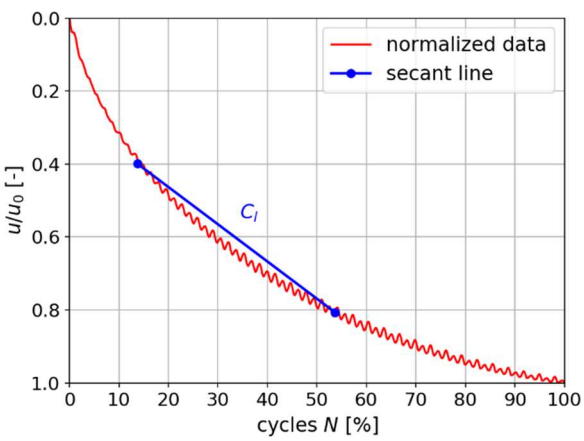

Figure 4. Evaluation of a single cyclic shear test.

The initial relative density after the specimen installation varies with different sands, as it depends on the soil's granulometric properties. Such method with a strictly defined procedure is convenient for a comparison of different soils and can be seen analogously to the conventional index tests such as determination of maximum and minimum soil densities in case of coarse-grained soils or the determination of liquid and plastic limits for fine-grained soils.

As known, all conventional index tests provide an index value that characterizes soil to a greater extent. This cyclic test delivers a dimensionless value which describes the average rate of PWP build-up linked to a relative density of the soil. In order to obtain a value without unit of measurement, the measured evolution of PWP during the test is normalized with the initial value of the PWP u_0. The rate of PWP build-up C_l is characterized through a gradient of a secant line to a normalized data curve in the N vs $p'/p'_0 = u/u_0$ graph, as shown in Fig. 4. This secant line is defined between the excess PWPs corresponding to 40 and 80 percent of the initial PWP, i.e. $u_{0.4}$ and $u_{0.8}$, respectively. The choice of C_l (in terms of the PWP range) for the determination of the rate of the PWP build-up doesn't influence the outcome of the test and comparison of different soils. Determination of C_l follows from Eq. (2). The minus sign in the equation yields positive values of C_l.

$$C_l = \frac{\Delta u/u_0}{\Delta N} = \frac{u_{0.8} - u_{0.4}}{N_{0.8} - N_{0.4}} \qquad (2)$$

2.4. Density dependent rate of PWP build-up

One of the most important factors influencing the evolution of excess PWP is the relative density of the soil (Belkhatir et al. 2013, Ishihara 1993, Seed and Idriss 1971).

The influence of the relative soil density on the evolution of PWP in the cyclic shear test was investigated using Sand 1. Several tests were performed on specimens with different initial relative densities. All specimens were first installed under previously described installation procedure (see section 2.1). To obtain denser specimens, a tapping on the wall of the installation mould of different duration was applied. Further testing conditions, such as consolidation stress p'_0, loading amplitude A and loading frequency f are listed in Table 2.

Table 2. Testing conditions in the cyclic shear tests

p'_0 [kPa]	A [mm]	f[Hz]
60	2.4	1

Totally 11 tests with different initial relative densities were performed with Sand 1. The evolution of PWP with the loading cycles for this sand is shown in Fig. 5. Logarithmic scaling of x-axis is used to better illustrate the evolution of PWP for tests in case of lower relative densities. It is noticeable that specimens with higher initial relative density are less susceptible to PWP build-up, since more loading cycles are needed for a complete reduction of the effective stress.

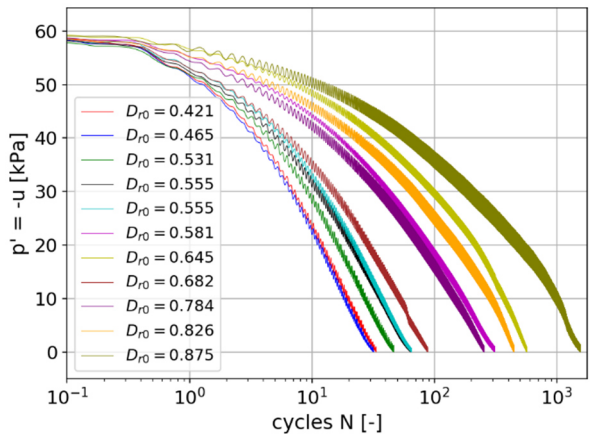

Figure 5. Build-up of PWP in Sand 1 for different initial relative densities.

Each test was evaluated according to the evaluation procedure described in section 2.3 and the rate of PWP build-up depending on the initial relative density was determined. This dependence can be taken from Fig. 6. It can be seen, there is an exponential decay between the initial relative density of the soil and the rate of PWP build-up. In case of Sand 1, the initial relative density is ranging from loose (D_{r0}=0.4) to dense state (D_{r0}=0.9), while the C_l value is ranging between its maximum at approximately 0.035 (for the loosest soil state) and its minimum at almost 0 (for the highest tested relative density).

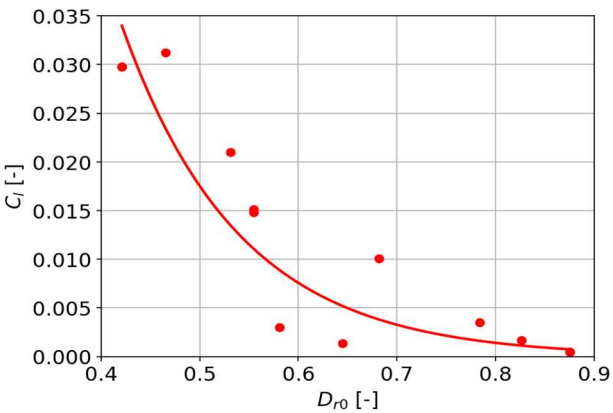

Figure 6. Exponential dependence between the initial relative density and the rate of PWP build-up for Sand 1.

In order to quantify the relation between D_{r0} and C_l, the C_l values are transformed to the logarithmic scale, as illustrated in Fig. 7. Assuming a linear regression between $ln(C_l)$ and D_{r0}, a regression coefficient k_l can be determined as a characteristic parameter for sand. The calculation of k_l follows from Eq. (3):

$$k_l = -\frac{\Delta \ln(C_l)}{\Delta D_{r0}} \tag{3}$$

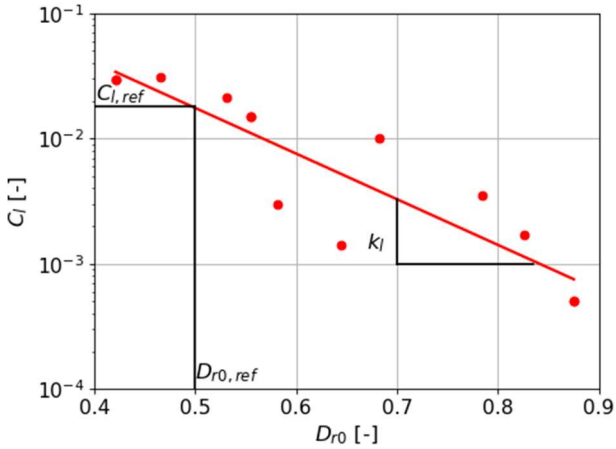

Figure 7. Linearization of the dependence between the rate of PWP build-up and the initial relative density for Sand 1.

Choosing a reference value of the initial relative density $D_{r0,ref}$ (here set to 0.5), the reference rate of the PWP build-up $C_{l,ref}$, corresponding to this relative density, can be determined. Under consideration of k_l and $C_{l,ref}$, the rate of PWP build-up can be calculated for any relative density of the soil. A proposed relation for the density dependent rate of PWP build-up follows from Eq. (4):

$$C_l = C_{l,ref} \cdot e^{-k_l \cdot D_{r0}} \tag{4}$$

This kind of test interpretation and evaluation enables a comparison of the rate of PWP build-up for different soils at various relative densities.

3. Influence of the internal soil structure

Even though the density of soil is recognised as one of the governing factors influencing the build-up of PWP, many studies have shown that differently prepared samples with the same density generate different PWP and have different liquefaction potential (Mitchell et al. 1976, Mulilis et al. 2005, Sze and Yang 2013, Tatsuoka et al. 1986). Investigations of the soil structure have shown that the soil fabric changes in dependence of the specimen preparation method. Also, depending on the installation method, the stress leading to soil liquefaction can vary up to 100% (Mulilis et al. 2005).

All specimens of the five sands in this study were prepared under the same procedure, described in section 2.1. After pouring the de-aired sand-water mixture through a funnel into the supported rubber membrane, the density of the soil is the lowest possible in case of the described preparation method. For this reason, it is fair to assume that the internal structure of the specimens (soil fabric) at the initial state is the same for all of them.

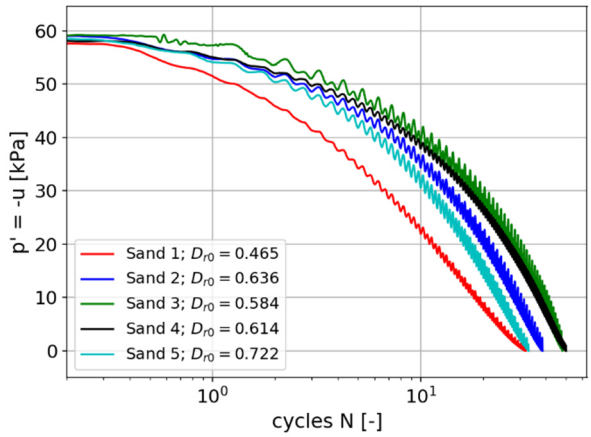

Figure 8. Build-up of PWP in the cyclic shear test for different sands under same installation and loading conditions.

The evolution of the excess PWP during the cyclic shearing at this loosest possible state (for the given specimen preparation method) is presented in Fig. 8. Significant differences are noticeable between D_{r0}, ranging from middle-dense to dense state, although the specimen preparation method was the same in case of all sands. It can be assumed, that these variations of D_{r0} reflect the differences in the granulometric properties of the tested soils. It is also recognisable from Fig. 8 that the number of cycles necessary for the complete reduction of effective stress is very similar for all sands, despite the large differences in D_{r0}.

The rate of PWP build-up for each of these sands in the loosest state can be taken from Fig. 9. It is obvious, that in spite of the large differences in D_{r0}, the C_l values are very similar and lie in a narrow range from 0.017 to 0.034. Comparing these results with the C_l values in case of similarly dense specimens of Sand 1 from Fig. 6 it can be seen that the C_l values lie in a much wider range, namely from 0.001 to 0.035. Therefore, it seems that the same soil internal structure (soil fabric) prescribed by the same installation method has a stronger impact on the build-up of the pore water pressure than different relative densities. Note that the vertical axis range is kept the same in both figures for better comparison and illustration of the results.

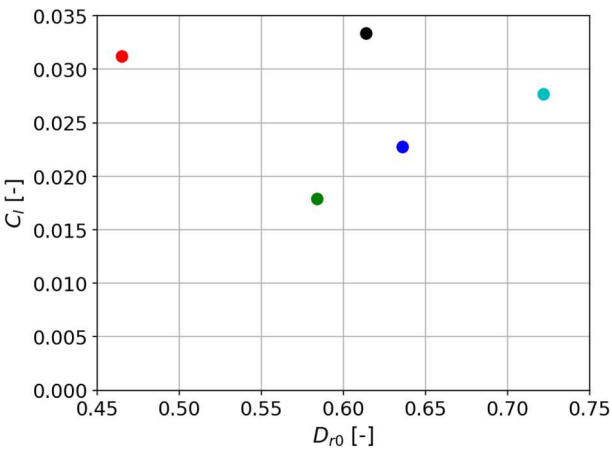

Figure 9. Rate of PWP build-up for five tested sands in the loosest state obtained via described installation method.

4. Conclusions

The presented simple cyclic shear test and the results proved that this method can successfully be used for fast and systematic investigation of the PWP evolution and its comparison for different coarse-grained soils. As seen, the test is applicable to clean sands as well as sands with low amount of fines or gravely grains.

The test evaluation yields a C_l parameter which represents the average rate of the PWP build-up linked to an initial relative density of the soil. This parameter is defined as a slope of a secant line to the normalised PWP evolution and it can be regarded as a suitable parameter for the classification of the soil sensitivity to the PWP build-up at a particular relative density.

Another parameter following from the test evaluation is the regression coefficient k_l which quantifies the dependency between the C_l and D_{r0}. This parameter classifies the soil sensitivity with respect to the dependence between the PWP increase and the relative density.

The dependence of the PWP evolution on the initial relative density was confirmed. An exponential relationship can be recognised between these two values.

Testing of five different sands under the same specimen installation procedure and the same loading conditions, it was observed that the soil fabric induced by the specimen preparation method has a stronger influence on the PWP build-up than the initial relative density.

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