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A simplified cyclic shear test for pore water pressure evolution

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Abstract. Essential for the investigation and comparison of the pore water pressure (PWP) build-up in different soils is the specimen preparation procedure and the repeatability of the testing conditions. This paper introduces a constant volume cyclic shear test for density dependent PWP build-up in coarse-grained soils. Testing procedure comprises a reproducible specimen preparation method which enables the installation of highly saturated sand specimens (without applying back pressure). Following this, a cyclic shearing of the specimen is achieved through a controlled horizontal displacement of the top cap. By measuring the evolution of the PWP during the test for different initial relative densities in case of several sands, it is possible to quantify the sensitivity of different coarse-grained soils to density dependent PWP build-up. Considering that the evolution of PWP is highly dependent on granulometric properties of soils, such sensitivity can be considered to be an index property of coarse-grained soils. The goal of this research is to establish a simple index test for comparison of density dependent PWP build-up in different coarse-grained soils.

Keywords: Cyclic shear test; PWP evolution; Coarse-grained soils; Index test; Index

1 INTRODUCTION

Due to their granular and highly permeable nature, sands are extremely susceptible to pore water pressure (PWP) accumulation during a cyclic shear loading. Mostly, the build-up of PWP in coarse-grained soils is linked to soil liquefaction which laboratory testing comprises complex cyclic triaxial and cyclic simple shear tests (Ishihara 1993, Seed and Lee 1966, Wichtmann et al. 2019, Wichtmann and Triantafyllidis 2016, Zavala et al. 2022, Tatsuoka et al. 1986). Obviously, these testing methods are neither simple nor effective in a short time. A simplified laboratory testing procedure would enable a more flexible and efficient analysis and evaluation of the PWP build-up in coarse grained soils.

In addition to the intrinsic characteristics of sands such as grain size, grain shape and surface roughness, the soil fabric also plays a significant role in the PWP build-up. Considering the same specimen installation method the role of the soil fabric can be eliminated in the first approximation. In case of the same testing conditions (stress level, loading, specimen size, etc.), the evolution of PWP for different sands with varying relative density will be different. By adopting the same installation technique and loading conditions and changing only the initial relative density, it is possible to determine the sensitivity of different sands to density changes in relation to the PWP build-up.

A comparison of the rate of PWP accumulation at a particular relative density indicates the susceptibility of different sands to PWP build-up at that relative density. A simple method presented here allows for a fast comparison of various sands and can be useful for the design of in-situ densification procedures as a countermeasure against soil liquefaction. This experiment can be considered analogously to the conventional index test, such as the determination of the loosest or densest state for coarse-grained soils or the determination of the liquid and plastic limit for fine-grained soils.

2 CYCLIC SHEAR TEST

The idea behind the cyclic shear test is based on the PWP accumulation that occurs during constant volume cyclic shearing in water-saturated coarse-grained soils (sands with a minor proportion of fines and gravel grains). The test involves a quick installation of highly saturated cylindrical sand samples without a further saturation phase. Applying a deflection of a specific amplitude and frequency to a specimen's top cap in a horizontal direction causes cyclic shearing of a soil specimen (coupled with a minor bending). Taking into account the undrained conditions during the test the PWP changes with the number of loading cycles. Under specific loading and installation conditions, the rate of PWP build-up can be used to estimate a soil's tendency to liquefy.

2.1 Experimental approach

The procedure of the suggested cyclic shear test can be divided into three principal parts. These are the installation of a highly saturated sand specimen (required for reproducible and reliable test results), consolidation of the soil specimen through suction, and, lastly, cyclic shearing under constant volume conditions. Figure 1 provides a schematic illustration of the cyclic shear test's experimental setup.

Sand is mixed with demineralized water and de-aired in a vacuum chamber prior to the specimen installation. After that, a funnel is used to pour the de-aired sand-water mixture into a supported rubber membrane, which is then sealed with a top plate. The installed sand specimen has dimensions D/H = 50/100 mm. The initial relative density of the soil D_{r0} coming from the underwater installation differs from sand to sand and ranges from a loose to a middle-dense state (in terms of a conventional density index).

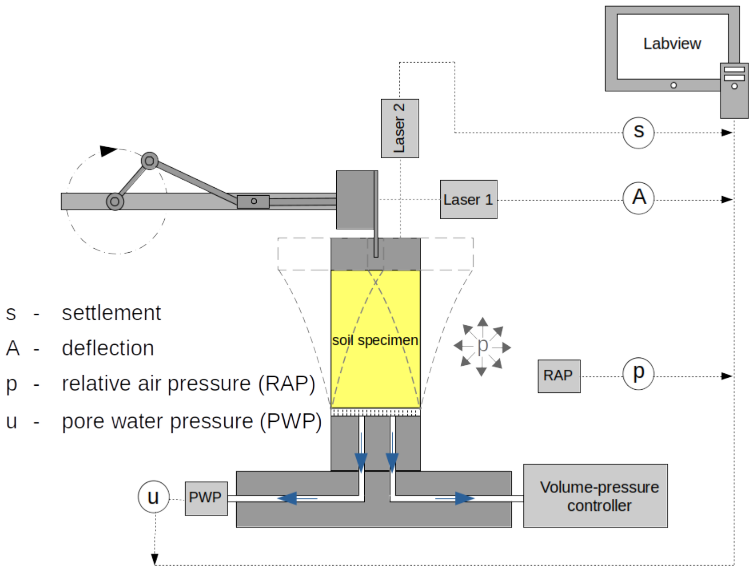


Figure 1. The cyclic shear test's experimental configuration.

After specimen installation, the effective stress in the specimen comes primarily from the specimen's own weight and is therefore insignificant. The total stress is caused by the relative air pressure acting on the rubber membrane around specimen. It remains unchanged and at zero (i. e. atmospheric pressure) during the entire test. The specimen is consolidated by applying suction (negative PWP) to the specimen's base. Considering that the total stress p is equal to zero, the effective stress p' is enhanced by the negative PWP u. This results from Eq. (1), where compression stresses are considered to be positive.

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

After specimen consolidation, the cyclic shearing of the specimen is accomplished by rigidly displacing the specimen's top cap in the horizontal direction with a specified displacement amplitude and frequency. This shearing occurs under undrained conditions due to the closure of the suction valve. As the top cap is rigidly translated, the specimen swings horizontally and a quasi-simple shearing mode is attained. Throughout the test, the relative air pressure surrounding the specimen and the excess PWP at its base are measured and assessed. Moreover, during the test, two laser distance sensors are used to monitor the top cap translation and settlement. These measurements are conducted without contact. Including specimen installation, a single test lasts about 30 minutes. The test's repeatability has been effectively evaluated, and the test has also been validated using the results of the undrained cyclic triaxial tests (Bacic and Herle 2020). Figure 2 depicts the typical evolution of the excess PWP (decrease of effective stress) with the number of cycles in this cyclic shear test.

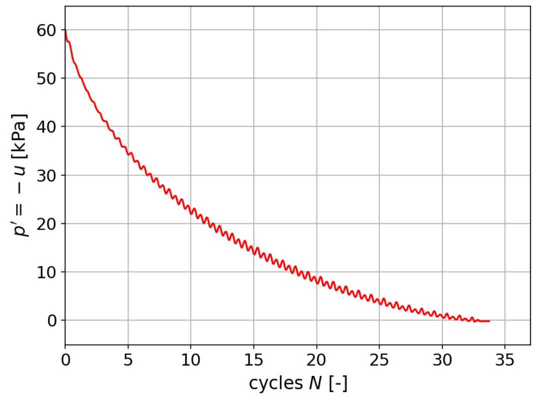


Figure 2. PWP accumulation during the cyclic shear test.

2.2 Materials tested in cyclic shear test

In this experimental study, three different sands were used. Figure 3 shows the grain size distribution curves of these sands, while Table 1 lists their classification properties. Each of the three sands contains a small amount of fines and a few fine gravel grains.

Table 1. Index properties of the tested sands.

Sand	φ_c	e_{min}	e_{max}	C_U
	°	-	-	-
W1	32.5	0.556	0.892	1.8
W4	31.4	0.372	0.813	3.0
W7	33.4	0.395	0.851	2.8

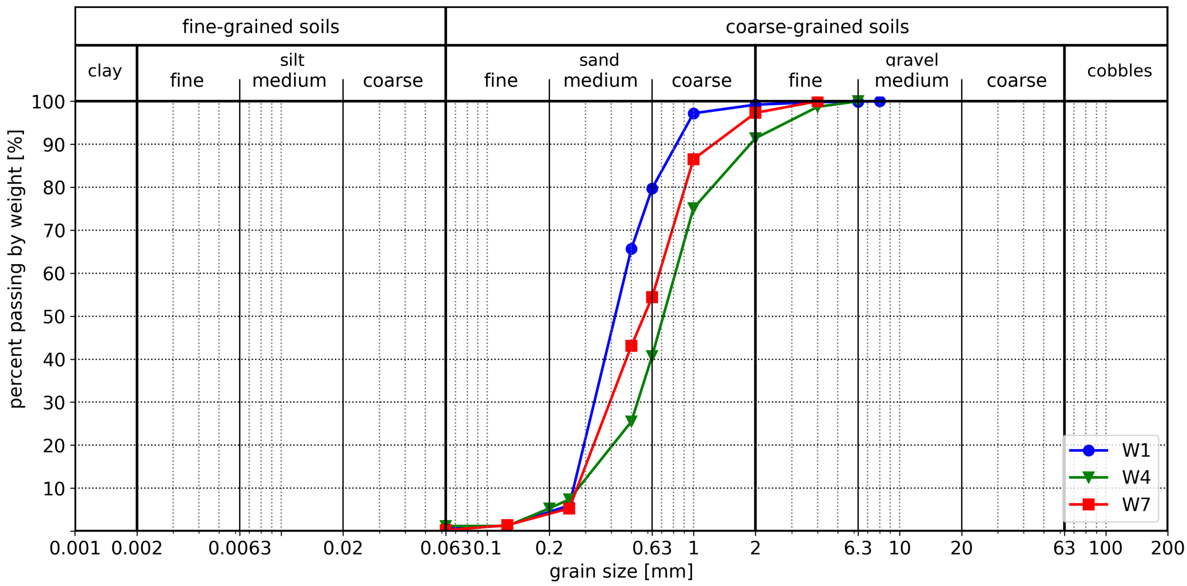


Figure 3. Grain size distribution curves of tested materials.

2.3 Single test evaluation

Even though the PWP build-up is measured and evaluated at a single point at the specimen's base during the cyclic shear test, this test is not a perfect element test. It can be regarded as an index test in which specimen installation, soil consolidation, and cyclic loading are carried out in accordance with a prescribed procedure. Thus, regardless of the granulometric composition of the tested soils, the soil initial fabric and stress level are always the same. Depending on the granulometric properties of the soil, the initial relative density of the specimen after installation differs for various sands. Still, the initial relative density represents the minimum density possible in water.

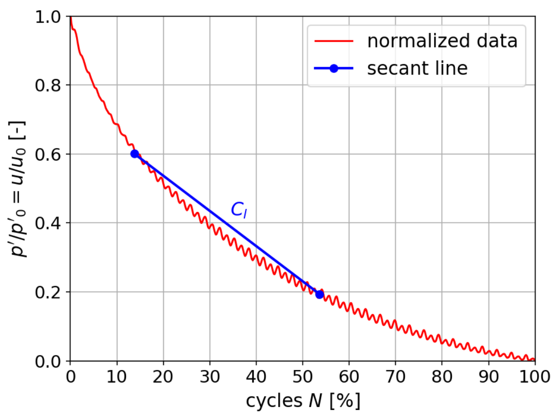


Figure 4. A single cyclic shear test evaluation.

A conventional index test yields an index value related to a particular soil property. This cyclic test delivers a dimensionless value that indicates the average rate of PWP accumulation in relation to the soil's relative density. To generate a dimensionless quantity, the measured evolution of PWP during the test is normalised with the initial value of PWP u_0. As depicted in Fig. 4, the rate of PWP accumulation C_l is represented by the gradient of a secant line to a normalised data curve in the N vs $p'/p'_0 = u/u_0$ graph. This secant line is defined between the excess PWPs corresponding to 40 percent and 80 percent of the initial PWP, i.e. $u_{0.4}$ and $u_{0.8}$. The determination of C_l is derived from Eq. (2). The minus sign in the equation results in positive C_l values.

$$C_l = -\frac{\Delta u / u_0}{\Delta N} \tag{2}$$

2.4 Density-dependent rate of PWP accumulation

The relative density of the soil is one of the most significant factors affecting the evolution of excess PWP (Belkhatir et al. 2013, Ishihara 1993, Seed and Idriss 1971, Wichtmann et al. 2019).
Using Sand W4, the influence of relative soil density on the evolution of PWP in the cyclic shear test will be demonstrated. Seven tests were conducted on specimens with different initial relative densities. All specimens were installed according to the installation procedure described earlier (see section 2.1) i. e. with the minimum density possible at water pluviation. To create denser specimens, varying durations of tapping were applied to the wall of the installation mould. Table 2 contains further testing conditions, such as consolidation stress p'_0, loading amplitude A, and loading frequency f.

Table 2. Testing conditions in cyclic shear tests.

Condition	p'_0	A	f
	kPa	mm	Hz
Value	60	4.79	1

Figure 5 depicts the evolution of PWP with loading cycles for this sand. The x-axis is scaled logarithmically to better demonstrate the evolution of PWP for specimens with lower relative densities. It is evident that specimens with a greater initial relative density are less prone to PWP build-up, as a greater number of loading cycles are required to completely reduce the effective stress in the specimen.

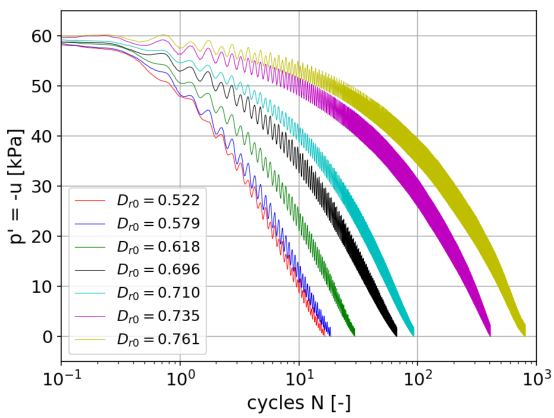


Figure 5. PWP accumulation in Sand 1 at various initial relative densities.

Each test was evaluated using the procedure outlined in section 2.3, and the rate of PWP accumulation depending on the initial relative density was estimated. Figure 6 shows this dependence. Obviously, the relationship between the initial relative density of the soil and the rate of PWP accumulation (represented by the factor C_l) is exponentially decreasing. In case of the here depicted Sand W4, the initial relative density ranges from a middle dense ($D_{r0} = 0.5$) to a dense ($D_{r0} = 0.76$) state, while the C_l

value ranges from a maximum of around 0.07 (for the loosest soil state) to a minimum of nearly 0.0002 (for the greatest relative density tested).

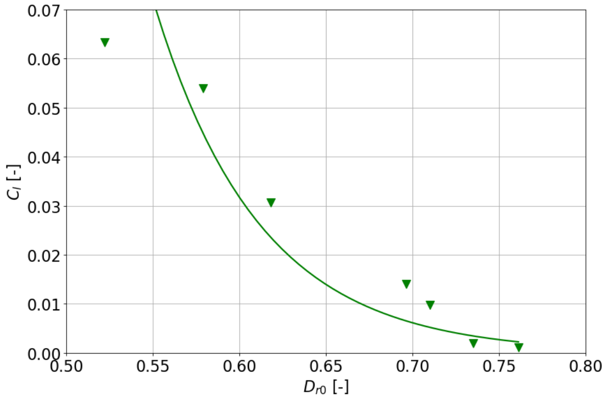


Figure 6. Exponential relationship between the D_{r0} and the C_l for Sand W4.

As shown in Fig. 7, in order to quantify the relationship between D_{r0} and C_l, the C_l values are plotted in a logarithmic scale. Assuming a linear regression between $\ln(C_l)$ and D_{r0}, the regression coefficient k_l can be derived as a sand-specific parameter. The calculation of k_l follows from Eq. (3):

$$k_l = -\frac{\Delta \ln(C_l)}{\Delta I_{D0}} \tag{3}$$

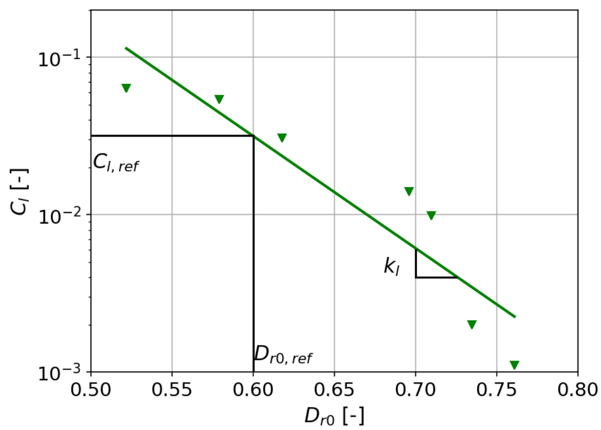


Figure 7. Linearization of the relationship between the C_l and the D_{r0} for Sand W4.

By selecting a reference value of the initial relative density $D_{r0,ref}$ (here set to 0.6), the reference rate of the PWP build-up $C_{l,ref}$ may be defined. For any relative soil density, the rate of PWP accumulation can be determined by using k_l and $C_{l,ref}$. Equation (4) proposes the following relationship for the density-dependent rate of PWP accumulation:

$$C_l = C_{l,\,ref} * e^{-k_l * (I_{D0} - I_{D0,ref})} \tag{4}$$

This type of test interpretation and evaluation enables a comparison of the rate of PWP accumulation for various sands at different relative densities.

3 COMPARISON OF DIFFERENT SANDS

The sands introduced in section 2.2 were tested at different initial relative densities (installation method from sections 2.1 and 2.4) and evaluated according to the procedures from sections 2.3 and 2.4. Table 2 summarizes the testing conditions. The linearized dependence between C_l and D_{r0} for these sands is shown in Fig. 8.

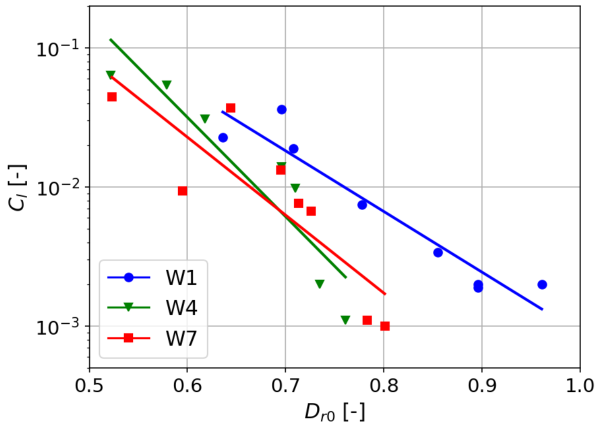
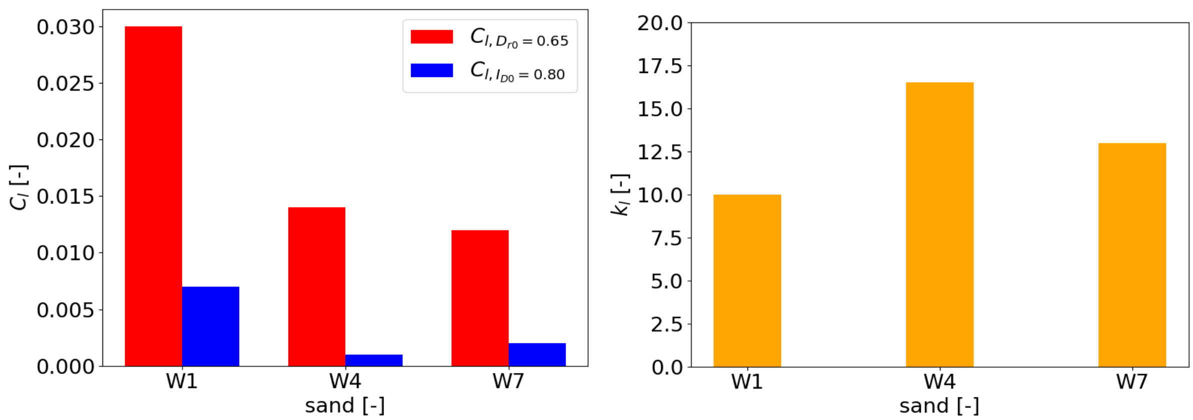


Figure 8. Linearized dependence between the rate of PWP build-up and the initial relative density for sands in this study.

In order to compare the sands among themselves, the C_l values were determined at the initial relative density D_{r0} = 0.65. It can be seen that the W1 sand has the highest tendency to PWP build-up at the given relative density. This tendency decreases over sand W4 to sand W7, which is the least sensitive to the accumulation of the PWP (see Fig. 9a)).



a) b)

Figure 9. a) Comparison of the C_l values for all sands at D_{r0} = 0.65 and D_{r0} = 0.80, b) Comparison of the k_l values for all sands.

Figure 9a) also shows that all tested sands are relatively insensitive to the development of the PWP at the relative density D_{r0} = 0.8, since the C_l values in case of all sands are very low. As expected, the compaction of these sands leads to a reduction of the rate of PWP build-up. This reduction is most noticeable for the sand W4 and is reflected in the largest k_l parameter (see Fig. 9b)). Therefore, the liquefaction resistance of this sand can be increased strongly by compaction. In contrast, the reduction of the rate of PWP build-up in sand W1 is smaller, which corresponds to the lowest k_l parameter of this sand. Similar to sand W4, this means that the compaction of sand W1 leads to a lower increase in liquefaction resistance. The sand W7 lies between these two sands.

4 CONCLUSIONS

The simple cyclic shear test and its results show that this method can be used to quickly and systematically investigate PWP development and compare it for different coarse-grained soils.

It was shown that the PWP build-up depends on the relative density of the soil. An exponential relationship between these two quantities was observed.

The evaluation of the outlined cyclic shear test yields the C_l parameter, which indicates the average rate of the PWP build-up in relation to the particular relative density of a soil. This parameter, which is defined as the slope of a secant to the normalised PWP build-up, can be used for the evaluation of a soil's sensitivity to the PWP build-up at a specific relative density. At the same relative density, a soil with high C_l is more susceptible to the PWP build-up than a soil with low C_l.

Another parameter derived from the evaluation of the test is the regression coefficient k_l, which quantifies the relationship between C_l and D_{r0}. This parameter categorises the sensitivity of the soil based on the dependence between the PWP build-up and the relative density.

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