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# A simple method for the determination of sensitivity to density changes in sand liquefaction

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**Abstract.** Fully saturated loose coarse-grained soils are known to be prone to liquefaction. Conventional laboratory tests for soil liquefaction include usually cyclic testing in triaxial apparatus. However, such investigations are complicated and time-consuming. The objective of the outlined work is to evaluate the sensitivity of different sands to density change with respect to liquefaction using a relatively 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. The results have confirmed a good repeatability of the new method as well as an expected dependence of the pore pressure build-up on initial density. Validation of the method was performed using the results of cyclic triaxial tests. A good agreement between both methods was observed regarding the rate of the pore pressure increase with initial density. Furthermore, it was shown that the initial fabric of soil has a larger impact on the pore pressure build-up during cyclic loading than the relative density.

**Keywords.** Liquefaction, laboratory tests, cyclic shear test, cyclic triaxial test, soil fabric

# 1. Introduction

Since the 1964 earthquakes in Niigata and Alaska, the research on the phenomenon of soil liquefaction has been gradually intensified. A methodology termed as a *simplified procedure* [Seed and Idriss, 1971] has evolved over several past decades into a standard of practice for evaluating the liquefaction potential of soils. The procedure is based on empirical correlations of the soil liquefaction resistance and the SPT or CPT test data [Robertson and Wride, 1998, Tokimatsu and Yoshiaki, 1983]. Since the establishment of this globally recognised liquefaction evaluation technique in 1971, many modifications and improvements usually considering different correction factors for SPT or CPT penetration resistance were made [Youd et al., 2001]. It is important to note that the simplified procedure is linked to liquefaction triggering only. Other issues like deformation, strength and stability of the ground and the consequences of liquefaction on nearby structures can be found elsewhere [Dobry and Abdoun, 2015, Ishihara and Yoshimine, 1992, Kokusho, 2016, Martin et al., 2002, Maurer et al., 2015, Youd et al., 2002].

In order to quantify the soil liquefaction resistance in the laboratory, undrained cyclic triaxial tests on specimens with different initial densities, stress levels and loading amplitudes are usually conducted [Castro, 1969, Ishihara, 1993, Ishihara and Yasuda, 1972, Kramer, 1996, Seed and Lee, 1966, Wichtmann et al., 2019]. Two different criteria are adopted by the researchers for the determination of the onset of liquefaction in triaxial tests. While [Ishihara, 1993] took into account that the specimen liquefies after reaching the 5 % double amplitude axial strain (± 2,5 % axial strain), [Seed and Lee, 1966] considered the number of cycles at which the excess pore water pressure reaches the value of the initial effective confining pressure as the liquefaction criterion.

Obviously, the above mentioned approaches are far from being easy and effective in short-time. A simplified procedure for laboratory investigations would increase the accessibility and flexibility in the evaluation of the liquefaction potential. This can be useful especially in regions with a high variability in the soil properties, like flooded man-made landfills as products of the open pit mining, e.g. in Lusatia, Germany [Kudla, 2012].

It has been acknowledged that sands have the highest tendency to liquefaction. The granulometric properties (grain size distribution, grain shape, roundness and roughness) are the major but not sufficient controlling factors. The sand grains within the soil skeleton can be ordered in various configurations which can be characterised through density and fabric. The soil fabric is controlled mainly by the method of the specimen preparation and can be understood as a spatial arrangement of solid particles and associated voids [Oda, 1972]. The main focus is put on the spatial arrangement of solid particles. This includes the orientation of individual particles and the interparticle relations (space distribution of the particle contact orientations and/or distribution of the interparticle forces).

The role of stress-dependent relative density and fabric for soil liquefaction is indisputable [Hleibieh and Herle, 2019, Ishihara, 1993, Miura and Toki, 1982, Mulilis et al., 1977, Seed and Idriss, 1971, Silver and Park, 1976, Sze and Yang, 2013, Tatsuoka et al., 1986a,b, Thomson and Wong, 2008, Yamashita and Toki, 1993, Yang et al., 2008]. However, it is extremely difficult to describe the soil fabric in situ. Thus, it would be advantageous to eliminate the role of the fabric in the first approximation and to identify the impact of relative density in a fast simple procedure.

Considering the same soil fabric, stress level, loading amplitude, etc., the liquefaction response of different sands to variations of relative density will be different. An analogy to classification tests (e.g. plastic or liquid limit for fine grained soils) can be seen. Changing only one factor while keeping all other unchanged, it is possible to determine a sensitivity of soil to the relevant factor and attribute an index value to it. In case of liquefaction, the aim is to change only the relative density. If the installation procedure and loading conditions remain the same, a sensitivity of different sands to density changes with respect to liquefaction can be obtained.

Obviously, such a method deals only with intrinsic soil behaviour and requires reconstituted (disturbed) specimens. It does not provide a direct evaluation of the in situ state. However, it enables a comparison of different sands among each other and can be useful for the design of densification procedures in situ.

# 2. Liquefaction test

The principle of the proposed liquefaction test is based on the evolution of excess pore water pressure (PWP) during cyclic shearing of a water saturated sand. A fast installation of a cylindrical specimen is possible and the test provides results in a short time. A cyclic loading in the horizontal direction is applied to the top of the specimen, which induces a quasi simple shear deformation (combined with a slight bending of the specimen). Undrained conditions during the test allow for a build-up of excess PWP. Measuring its evolution in a certain number of cycles and at different initial densities, a liquefaction sensitivity of the tested soil to the density changes can be determined.

The fast test procedure facilitates a comparison of the liquefaction sensitivity to density changes for different sands. The crucial factor for such a comparison is a standardised and well reproducible experimental procedure for the preparation of the soil specimens.

## 2.1. Experimental procedure

The experimental procedure can be divided into three steps: specimen installation, consolidation of the soil and cyclic shearing in undrained conditions. The test set-up is schematically presented in Figure 1. The installation procedure ensuring a very high initial saturation of differently graded sands is essential for the repeatable initial state of the soil and outcome of this test.

At the beginning of the test, the specimen ($D/H \approx 50/100$ mm) is installed by pouring a de-aired sand-water mixture through a funnel into a supported rubber membrane filled with water (1). Contrary to cyclic simple shear and cyclic triaxial test, the specimen is not surrounded by a cell filled with water. Also, no lateral confinement with a series of thin and evenly spaced rings is necessary (as for testing in simple shear aparatus).

The described installation method resulted in a very high saturation ($S_r \approx 99\,\%$) of the soil. Saturation is controlled by mixing of sand with water under vacuum prior to the installation of the specimen. Degree of saturation is determined by measuring the mass of the water in the specimen at the end of the test. These measurements yielded fluctuations up to $\pm 2\,\%$.

After installing the specimen into the installation mould, the PWP and the effective stress are equal to zero corresponding to the atmospheric pressure (neglecting the self-weight stresses coming from the very small height of the specimen). The total stress corresponds to the relative air pressure (atmospheric pressure) acting on the rubber membrane from outside (2). Small oscillations of the relative air pressure during the test can be considered negligible. It remains unchanged and equal to zero during the entire test.

In order to consolidate the specimen, a negative PWP $u_0$ is applied to the bottom of the specimen (3) using a volume pressure controller. Figure 2 shows that the reduction of negative PWP for the duration of the test on Sand 1 (for the lowest initial relative density) without application of cyclic loading lies below 1 kPa and can be considered negligible. Taking into account the zero total stress $p$, the effective stress $p'_0$ increases to the magnitude of $u_0$:

$$p = p'_0 + u_0 = 0 \rightarrow p'_0 = -u_0 > 0\,\text{kPa} \qquad (1)$$

Herein, the stresses are considered positive in case of compression.

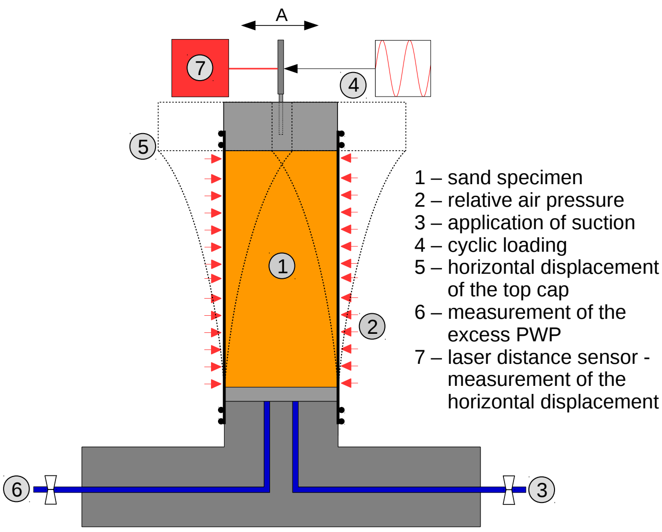


**Figure 1.** Experimental set-up.

Subsequently, the drainage is disabled and the specimen is cyclically loaded (4) in globally undrained conditions (no possibility for external drainage). The loading is imposed by a cyclic horizontal displacement of the top cap of the specimen (5). This induces a deformation mode similar to cyclic simple shear (combined with a slight bending of the soil specimen). The displacement amplitude $A$ and frequency $f$ are kept constant during the entire test.

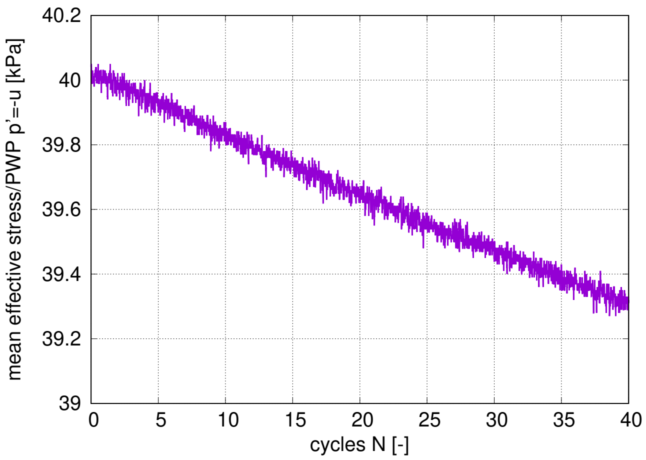


**Figure 2.** Decrease of negative PWP without applying cyclic loading for the duration of the test on Sand 1 in case of the lowest relative density.

During the test, the air pressure around the specimen and the excess PWP $u$ within the soil are measured using two independent pore pressure transducers. The measurement of the excess PWP takes place at the bottom of the specimen (6). Analogously to other undrained cyclic shear tests, one representative PWP for the whole specimen is assumed. The horizontal displacement of the top plate is measured without contact using a laser distance sensor (7). The test is terminated when the PWP increases to a certain value, e.g. 50 % of its initial value $u_0$. The limit value at full soil liquefaction corresponds to $u = 0$, see Figure 3. The duration of one entire test is approximately 30 minutes, including the specimen installation.

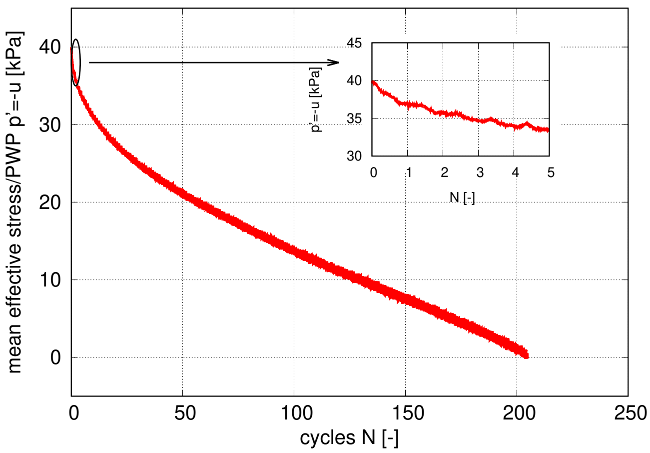


**Figure 3.** Build-up of PWP in a test with full soil liquefaction.

This cyclic shear test is, strictly considered, not representing an element test, even though it is being evaluated as such. It can be treated as an index test where the specimen installation and loading take place through a clearly defined and reproducible procedure. In this manner, the 'disturbed' soil state (fabric, stress level) is always the same although different than in situ. The initial relative density depends on the granulometric properties of the tested soil. Such methodology enables a comparison of the results for different sands and can be understood as an analogy to the conventional index tests, e.g. determination of $\rho_{min}$ and $\rho_{max}$.

## 2.2. Tested materials

Figure 4 shows the grain size distribution curves of the sands used in this study. All tested sands have narrow grain size distribution curves. Sand 1 is coarse-grained and very uniform in the grain size. Sand 2 contains medium-coarse and coarse grains while Sand 3 consists of mostly fine grains. The classification properties of the sands are summarised in Table 1. By visual inspection the particle shape is similar for all three tested sands.

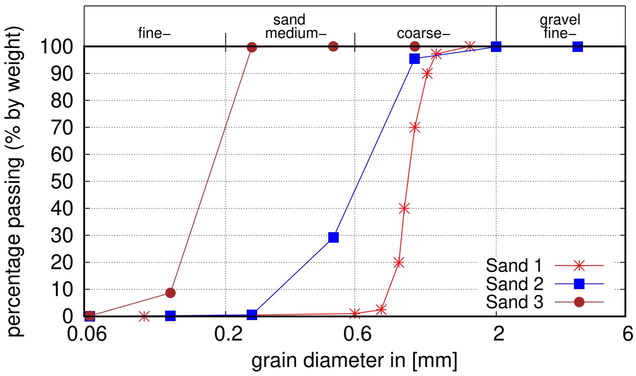


**Figure 4.** Grain size distribution curves of the tested sands.

**Table 1.** Classification properties of the tested sands.

| Soil | $\varphi_c$ | $e_{min}$ | $e_{max}$ | $C_u$ |
|---|---|---|---|---|
| Sand 1 | 30° | 0.579 | 0.865 | 1.20 |
| Sand 2 | 34° | 0.546 | 0.846 | 2.20 |
| Sand 3 | 30° | 0.674 | 1.105 | 1.46 |

## 2.3. Test repeatability

The repeatability of the presented experimental method was studied using Sand 1 (reference sand in this study). All specimens were prepared with the same procedure (described in 2.1) resulting in similar values of the initial relative density. The consolidation pressure corresponded to $p'_0 = 40$ kPa. The loading conditions (frequency, top cap displacement) were also kept unchanged, see Table 2. The tests were terminated when the PWP increased to 50 % of its initial value (in this case, 20 kPa).

The results are depicted in Figure 5 showing the decrease of PWP $u$ with number of cycles $N$. It is obvious that very

**Table 2.** Initial and boundary conditions in the experiments.

| $p'_0$ | $\Delta u$ | $f$ | $A$ |
|---|---|---|---|
| 40 kPa | 20 kPa | 1 Hz | 2.5 cm ± 2 % |

consistent results for similar initial states (initial relative density and degree of saturation) are achieved. The number of cycles corresponding to $\Delta u = 0.5u_0$ varies between 57 and 61 which proves a correspondence of the test results to a great extent. Thus, the repeatability of the installation procedure and the test results can be confirmed.

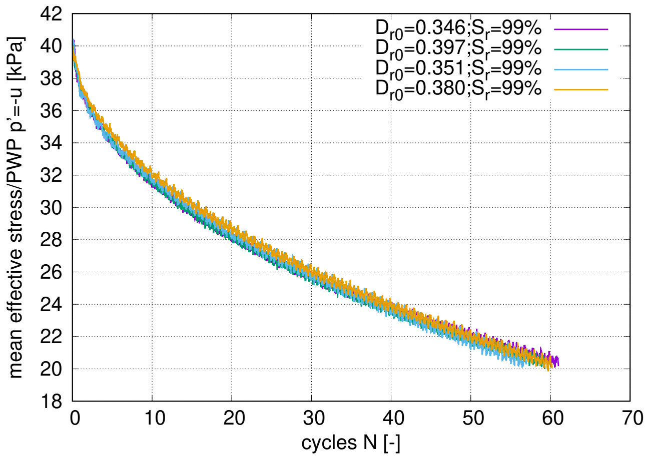


**Figure 5.** Build-up of PWP in the repeatability tests on Sand 1.

It should be remarked that the specimen saturation has a strong impact on the reproducibility of the test results. The dependence between the saturation and the grain size distribution has been discussed for 14 different sands in [Bacic and Herle, 2019].

## 2.4. Influence of relative density

The relative density of soil is without doubt one of the most important factors influencing the liquefaction susceptibility. While loose saturated sands are known to be prone to liquefaction, dense sands tend to dilatancy linked with a reduction of excess pore water pressure.

Figure 6 demonstrates the behaviour of Sand 1 in the presented cyclic test under different initial relative densities $D_{r0}$. All specimens were first installed under the same conditions described before. Their densification was achieved through a tapping on the wall of the installation mould. Changing the tapping duration, different initial densities could be obtained. Other test conditions can be taken from Table 2.

The results confirm an expected dependence of the PWP build-up on the soil density. Considering a particular change of the PWP ($\Delta u = 0.5u_0$), the lowest number of cycles $N_{50}$ corresponds to the specimen with the lowest initial relative density. It can be recognised in Figure 7 that the number of loading cycles needed for $\Delta u = 0.5u_0$ increases almost exponentially with the increase of the initial relative density.

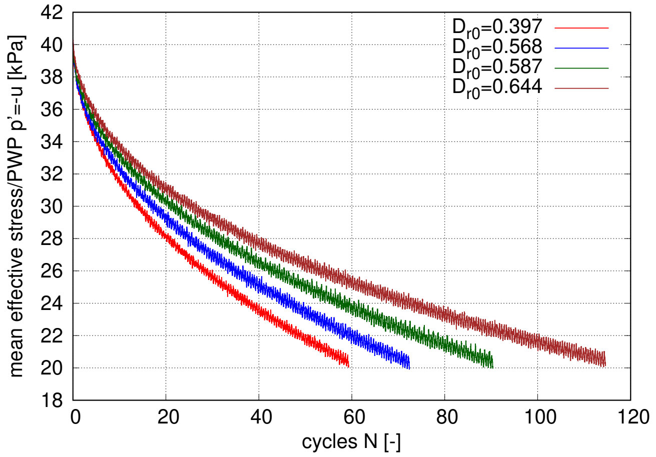


**Figure 6.** Build-up of PWP in Sand 1 at different initial relative densities.

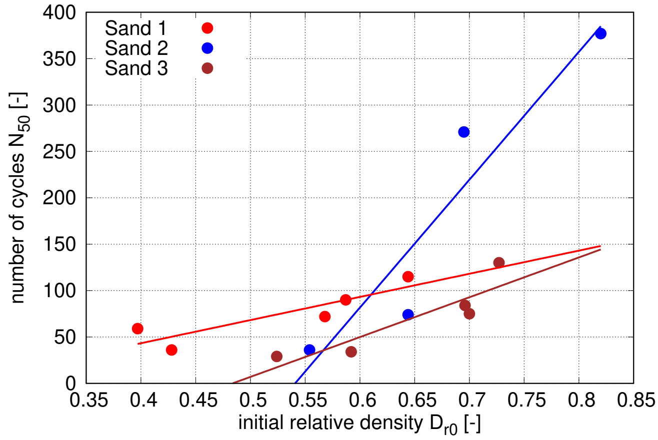


**Figure 8.** Dependence between the number of cycles $N_{50}$ and the initial relative density for all tested sands.

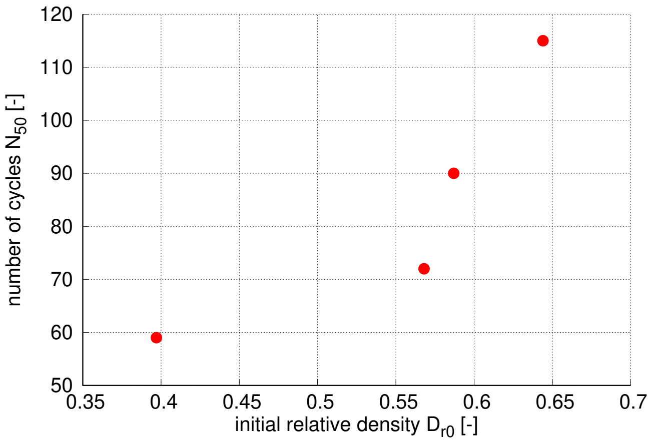


**Figure 7.** Dependence between the number of cycles $N_{50}$ and the initial relative density for Sand 1.

## 3. Sensitivity of different sands to initial relative density

As shown in the previous section, the proposed experiment can successfully reproduce the dependence of the PWP build-up on the initial soil density. To compare the change of the $N_{50}$-value with the density increase for different sands, Sand 2 and Sand 3 (Figure 4) were also included in this study. Analogously to Sand 1, specimens of both new sands were investigated at different initial relative densities. All other test conditions remained the same (Table 2).

Figure 8 depicts the obtained dependence between the number of cycles $N_{50}$ needed for $\Delta u = 0.5u_0$ and the initial relative densities $D_{r0}$. It is clear that the tested sands respond differently to the density change. Assuming in a first approximation a linear regression between $N_{50}$ and $D_{r0}$, a regression coefficient $k_{cs}$ can be determined as a characteristic parameter for each sand. To ensure the comparison with already published results from the undrained cyclic triaxial test (see section 4), a linear dependence between $N_{50}$ and $D_{r0}$ was kept. The steeper the slope, the stronger is an impact of the relative density change on the tendency to liquefaction (rate of the PWP increase). For high values of the parameter $k_{cs}$, a small densification can already significantly increase the liquefaction resistance of the considered soil.

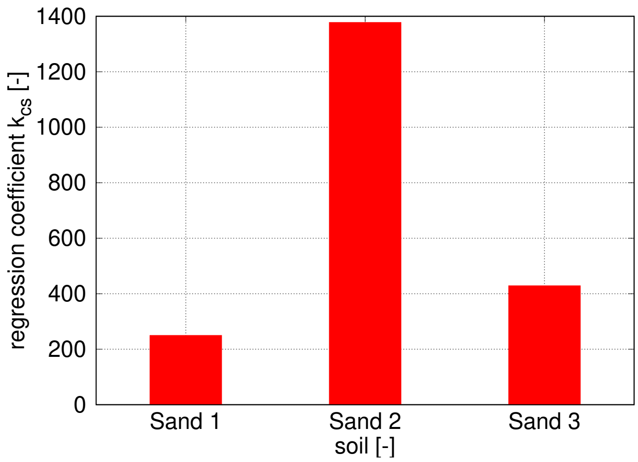


**Figure 9.** Comparison of the $k_{cs}$ parameters from the proposed cyclic shear test for all tested sands.

A comparison of the $k_{cs}$ values in Figure 9 quantifies the sensitivity of the tested sands to density changes. Obviously, Sand 2 exhibits the highest $k_{cs}$ value, being thus the most sensitive. Applying a densification from a comparable soil state, it should be easier to increase the liquefaction resistance of Sand 2 than of Sand 1 and Sand 3.

## 4. Comparison with cyclic triaxial test

A further validation of the cyclic shear test was performed using the results of cyclic triaxial tests. For this purpose, Sand 2 and Sand 3 were used. Figure 10 depicts the results of cyclic triaxial tests on these sands considering the data from [Wichtmann et al., 2019]. Instead of $N_{50}$, cyclic resistance ratio (CRR) is used for the characterisation of the triaxial test results. It is defined as the cyclic stress ratio (CSR) causing failure of the soil specimen in $N_f = 10$ cycles [Wichtmann et al., 2019]. CSR is calculated as a ratio of the cyclic shear stress ($q^{ampl}$) and the mean effective stress ($2p'_0$). Assuming in a first approximation a linear regression between CRR and $D_{r0}$, a regression coefficient can be again determined as a characteristic parameter for each sand.

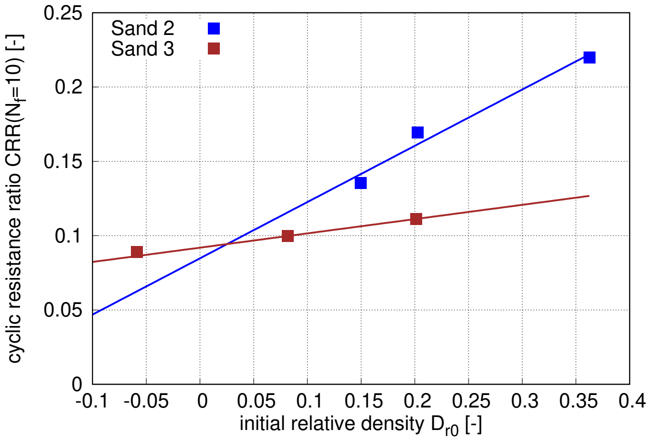


**Figure 10.** Cyclic resistance ratio (CRR) from cyclic triaxial tests (data from [Wichtmann et al., 2019]).

There are striking differences in initial relative densities in the cyclic shear and triaxial tests, respectively. Using a conventional description, the states of the triaxial specimens vary between loose and medium dense, while the specimens of the cyclic shear tests from this study are all in the medium dense state. This difference emphasises a strong influence of the specimen installation methods used in the considered tests. The sand in the cyclic shear tests was installed as a saturated suspension under water using a funnel, whereas a free fall method was applied for the wet sand in triaxial tests [Wichtmann et al., 2019].

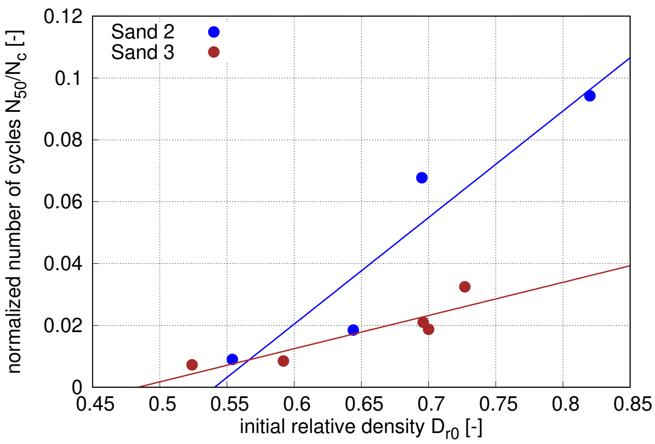


**Figure 11.** Normalised $N_{50}$ in cyclic shear tests, both for Sand 2 and Sand 3 at different initial relative densities.

Comparing Figures 8 and 10, qualitatively similar inclinations of the regression lines can be recognised for Sand 2 and Sand 3. Obviously, both independent test procedures produce qualitatively similar outputs, in spite of the differences in the range of initial densities. In order to make a basis for a quantitative comparison of the results, the $N_{50}$-values were divided by a scaling factor $N_c$. With $N_c = 4000$, values of $N_{50}/N_c$ are transformed to a similar range like CRR values from the triaxial tests (Figure 11).

The correspondence between the outputs of both testing procedures becomes even more obvious when comparing the slopes of the regression lines from the diagrams in Figure 10 and 11. With the normalised values, the slope of the regression lines can be denoted with $k_{cn}$ for the cyclic shear tests and $k_{tx}$ for the triaxial tests, respectively. Figure 12 confirms a very good correspondence between the $k$-parameters from both tests. It can be postulated that the sensitivity of PWP increase as function of the density changes does not substantially depend on the relative density itself.

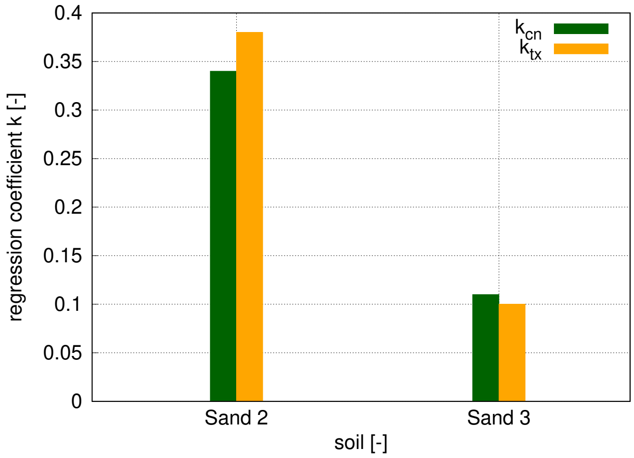


**Figure 12.** Comparison of the $k$-parameters from cyclic shear and cyclic triaxial tests.

## 5. Role of the soil fabric

Many studies have demonstrated a strong influence of the soil fabric on the tendency to liquefaction [Mitchell et al., 1976, Mulilis et al., 2005, Sze and Yang, 2013, Tatsuoka et al., 1986a]. All sands in this study were installed with the same procedure. Therefore, it is reasonable to assume that all specimens have the same soil fabric in the initial state. Without a densification by tapping, the relative density after the mould filling by the described preparation method is the lowest possible. Table 3 summarises these values. It can be recognised that, although the preparation method was identical for all specimens, significant differences between $D_{r0}$ can be observed. These variations of $D_{r0}$ reflect the differences in the granulometric properties of the tested soils. The uncertainties in $D_{r0}$ values (derived from the repeatability tests) lie in range of ±2 %.

Additionally, a number of cycles $N_{50}$ from the cyclic shear tests is included in Table 3. In spite of the significant differences in $D_{r0}$, the values of $N_{50}$ are very similar. Obviously, the same initial fabric induced by the installation method has a more dominant effect than the magnitude of the relative density.

**Table 3.** Initial relative densities and the corresponding values of $N_{50}$ for all tested sands.

| Soil | $D_{r0}$ | $N_{50}$ |
|---|---|---|
| Sand 1 | 0.428 | 36 |
| Sand 2 | 0.554 | 36 |
| Sand 3 | 0.592 | 34 |

The evolution of the pore water pressure during cycling for the tests in Table 3 is presented in Figure 13. Here, it is even more visible that the response of all specimens is almost identical. Thus, it seems that the same soil fabric prescribed by the same installation method has a stronger impact on the build-up of the pore water pressures than the (different) relative density.

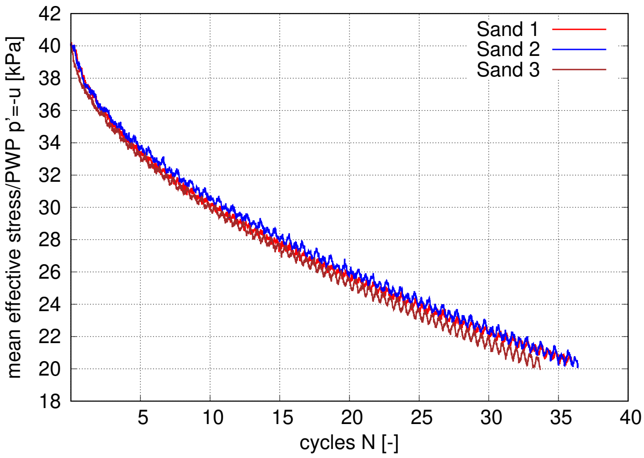


**Figure 13.** Build-up of PWP in the cyclic shear tests for different sands under same installation and loading conditions.

# 6. Conclusions

The results of the newly developed simple procedure for laboratory testing of the PWP evolution in undrained conditions have demonstrated that the presented cyclic shear test can be used for a fast and systematic investigation of the tendency of coarse-grained soils to liquefaction. The paper deals with the application of the test to clean sands.

Repeatability of the specimen installation and testing procedure were successfully demonstrated by performing several tests on one soil under the same initial and loading conditions. The dependence of the PWP build-up on the soil relative density was confirmed. Furthermore, it was shown that the regression coefficient $k_{cs}$ of the dependence between $N_{50}$ and $D_{r0}$ can be considered as a suitable parameter for the classification of the soil sensitivity with respect to the dependence between PWP increase and relative density.

A comparison between the results of the proposed cyclic shear tests and cyclic triaxial tests revealed a very good agreement. Looking at the evolution of the pore water pressure during undrained cycling, both (independent) testing procedures showed a higher sensitivity of Sand 2 than Sand 3 to the relative density.

Testing different sands under the same preparation and loading conditions in the new cyclic shear test, it could be observed that the soil fabric induced by the preparation method has a more pronounced effect on the PWP build-up than the initial relative density.

# Conflicts of Interest

There are no potential conflicts of interest.


# Acknowledgements

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