Laboratory tests and numerical simulations giving the effect of preloading on the cyclic liquefaction strength

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SUMMARY:
The effect of preloading on the liquefaction cyclic strength of sands under ground surface was investigated by cyclic shear tests where horizontal shear stress oscillated about a zero mean value on sands with varying fines content and at varying pre-stress ratios, densities and vertical stresses. Test results showed a marked increase of the cyclic soil strength with the pre-stress ratio. The effect is more pronounced for the looser specimens. In addition, the effect of preloading on the liquefaction cyclic strength of samples consolidated under isotropic conditions was investigated with cyclic triaxial tests. Again, test results showed a marked increase of the cyclic soil strength with the pre-stress ratio. Based on the test results, an emprical expression predicting the increase in cyclic strength induced by preloading was proposed. All the above tests were simulated numerically using the elastoplastic multi-mechanism model of Ecole Centrale Paris. This validated not only the laboratory tests results, but also the numerical code, especially in its ability to simulate the effect of preloading in cyclic liquefaction strength. In addition, the numerical simulation illustrated the manner that preloading affects the cyclic liquefaction strength, thru the increase of not only soil density, but also horizontal stress and soil fabric.

Keywords: preloading, sands, liquefaction, cyclic tests, numerical analysis, stress path

1. INTRODUCTION

Saturated sandy layers that are horizontal, or have a small inclination to the horizontal, run the risk of earthquake-induced liquefaction. Design codes (e.g. European Standard, 2003) demand of the practicing engineer the estimation of the liquefaction risk. The factor of safety against liquefaction, estimated versus depth, is defined as the ratio of the in-situ cyclic soil strength by the cyclic stress ratio resulting from the design earthquake (European Standard, 2003, Seed, 1979). The cyclic soil strength and cyclic stress ratio are defined hereunder. In cases where the factor of safety against liquefaction takes values close to, or less than, unity, soil improvement is an effective way to mitigate the liquefaction risk by increasing the cyclic soil strength (Committee of Earthquake Engineering et al, 1985). Preloading is a temporary loading applied at a construction site, to improve subsurface soils primarily by increasing density and horizontal stress (Stamatopoulos and Kotzias, 1985). The purpose of this work is to investigate the effect of preloading on the cyclic strength of different soils in laboratory devices both measured in the laboratory and simulated numerically.

2. THE CYCLIC STRENGTH OF SANDS

In general, prior to the application of cyclic loading, the shear stresses in the soil are zero. In addition, the effective normal vertical stress, denoted as σ'_{vo}, equals the overburden effective pressure. Furthermore, the ratio of the effective horizontal stress, denoted as σ'_{ho}, to σ'_{vo}, is given by the coefficient of earth pressure at rest, Ko. As a result of an earthquake, dynamic loading is applied primary in the horizontal direction, as shear stress τ. When harmonic shear horizontal loading is applied, a cycle of loading is defined as the complete change of the shear stress (i) from zero to τ_{cyc}, (ii) from τ_{cyc} to $-\tau_{cyc}$ and (iii) from $-\tau_{cyc}$ back to zero. Cyclic stress ratio SR is defined as:

$$SR = \tau_{cyc} / \sigma'_{vo} \tag{1}$$

In addition, cyclic shear strain during a loading cycle is defined as the maximum value of shear strain attained. Permanent strain, or permanent pore water pressure, is the part of the strain, or pore water pressure that accumulates at the end of each cycle of loading. As a result of cyclic horizontal harmonic loading on Ko-consolidated soil about a zero mean shear stress value, permanent pore pressure and cyclic shear strain build up with cycle number, while due to one-dimensional symmetry, considerable permanent horizontal movement does not accumulate (Committee of Earthquake Engineering et al, 1985). Cyclic strength for N cycles of harmonic loading, SRN, is defined as the value of the cyclic stress ratio SR causing liquefaction in N uniform cycles. Liquefaction is the state where the effective stress becomes very small and the cyclic shear strain very large. In a more functional definition this state is defined in the present work, similarly to Ishihara (1996), as when the cyclic shear strain exceeds 2.5%.

In liquefaction analyses, a reference earthquake of magnitude M=7.5, that corresponds to 15 cycles of uniform cyclic loading, is often used (European Standard, 2003, Seed, 1979). For this reason, the cyclic strength SR_{15} will be used below as an index to study the effect of preloading on the cyclic soil strength for a given ground level. Yet, it should be noted that it was observed that if the cyclic strength is taken as SR_{10} or SR_{20} instead of SR_{15}, the results presented below do not change considerably.

The cyclic strength is measured in the laboratory by cyclic undrained or constant-volume tests using devices which can be classified into three types: (a) Tests on the triaxial device with isotropic consolidation at stress $\sigma'_{co}=\sigma'_{vo}$ and then oscillation of the vertical stress between $(\sigma'_{co} + 2\tau_{cyc})$ and $(\sigma'_{co} - 2\tau_{cyc})$, (b) tests on the direct-shear or the simple-shear device where samples are subjected to one-dimensional consolidation at vertical stress σ'_{vo} and then to horizontal oscillation of the shear stress σ_{zx} between τ_{cyc} and $-\tau_{cyc}$ and (c) tests on the torsional-shear device where samples are subjected in the triaxial chamber to consolidation at vertical stress σ'_{vo} and any horizontal stress and then to horizontal angular oscillation of the shear stress $\sigma_{r\theta}$ between τ_{cyc} and $-\tau_{cyc}$ (Seed and Peacock, 1971, Ishihara and Takatsu, 1979). In test (b) the ratio of the effective horizontal to the effective vertical stress prior to the application of cyclic loading is the coefficient Ko.

As will be described below, in all these devices the effect of pre-stressing has been studied. The cyclic strength is correlated to the Pre-stress Ratio, PR, defined as

$$PR = \sigma'_{v\text{-}c} / \sigma'_{vo} \tag{2}$$

where $\sigma'_{v\text{-}c}$ is the maximum effective vertical stress exerted during consolidation and σ'_{vo} is the effective vertical stress just prior to the application of cyclic loading. Compared to tests under Ko consolidation, at tests under isotropic consolidation, pre-stress is performed under different horizontal stress, and thus cyclic soil strength takes a different value. Thus, SR_{15} and PR under isotropic consolidation will be denoted differently, as $SR_{15\text{-}iso}$ and PR_{iso} respectively. Furthermore, to differentiate the cyclic strength without and with preloading at similar (initial) density and confining stress, the cyclic strength at PR=1 is denoted as $SR_{15\text{-}1}$ and $SR_{15\text{-}iso\text{-}1}$ under Ko and isotropic consolidation respectively. Preloading affects the cyclic soil strength due to (a) the increased density under Ko conditions, (b) the increased horizontal stress and (c) changes in the sand fabric (Stamatopoulos and Stamatopoulos, 2007). Cyclic direct-shear and simple-shear tests performed at different PR ratios can simulate all the above effects. Cyclic triaxial tests cannot simulate effect (b), but models adequately all other effects. For these reasons both types of devices will be considered in the present study.

3. EFFECT OF PRELOADING IN THE CYCLIC STRENGTH MEASURED IN THE LABORATORY

3.1 Previous work

A number of cyclic triaxial and shear tests have been performed studying the effect of preloading on cyclic soil strength and based on the analyses of these tests empirical expressions have been proposed in the literature. The most complete study is given by Stamatopoulos and Stamatopoulos (2007). Stamatopoulos and Stamatopoulos (2007) proposed the following equations predicting the increase in cyclic strength induced by preloading in triaxial and shear tests:

$$SR_{15\text{-}iso}/SR_{15\text{-}iso\text{-}1} = PR_{iso}^{0.91-3.08SR_{15-iso-1}} \tag{3a}$$

$$SR_{15}/SR_{15\text{-}1} = PR^{0.92-2.02SR_{15-1}} \tag{3b}$$

where all the above factors have been defined above.

3.2 Present work

In the current laboratory program, the materials used to prepare the mixtures tested were (a) a clean sand and (b) a non-plastic silt. The first material is a subwhite natural sand of quartz from the Egyptian desert. Its quartzy grains are not lustrous but are well rounded, transparent and colorless. There are very few black grains of iron oxides or magnetic oxides of unknown provenance (less than 0.1%), whose existence could be due to manmade contamination. The non-plastic silt was obtained by grinding natural deposits of quartz from the area of Assirou near Thessaloniki, Greece. The materials were provided by Prof. Tika of Aristotle University of Thessaloniki (AUTH). Fig. 1 gives the grain size distribution of the sand and silt materials. The measured specific gravity of grains was 2.65 for the sand and 2.64 for the silt. Sand-silt mixtures with different fines contents were prepared. A program of cyclic shear tests and triaxial tests investigating the effect of pre-stress on cyclic behaviour was performed on specimens from mixtures with different fines contents at different densities and different consolidation stresses (50 and 150kPa). Two different PR values will be tested: 1 and 3.

Table 1 gives the states studied in triaxial and shear devices and cyclic soil strength for PR=1 and PR=3. Fig. 2 and 3 give typical results of a shear test and a triaxial test. Fig. 4 gives typical liquefaction curves for (a) triaxial tests and (b) shear tests. Fig. 3 gives the ratio of cyclic liquefaction strength at PR=1 and 3 in terms of SR_{15}-PR=1 for both the shear and the triaxial tests. The previous proposed equations (3) are given for comparison. It can be observed that the previous equations (a) overpredict the increase of cyclic strength with preloading and (b) predict that the ratio $SR/SR_{PR=1}$ takes values less than unity at large values of SR_{15}-PR=1, that is not reasonable and not according to the observed data. Based on the results of the current laboratory program and the above discussion, in place of equations (3), the following equations can be proposed to predict the effect of preloading on the cyclic stress:

$$SR_{15\text{-}iso}/SR_{15\text{-}iso\text{-}1} = PR_{iso}^{a1/SR_{15-iso-1}} \tag{4a}$$

$$SR_{15}/SR_{15\text{-}1} = PR^{a2/SR_{15}} \tag{4b}$$

where a1=0.05 and a2=0.04.

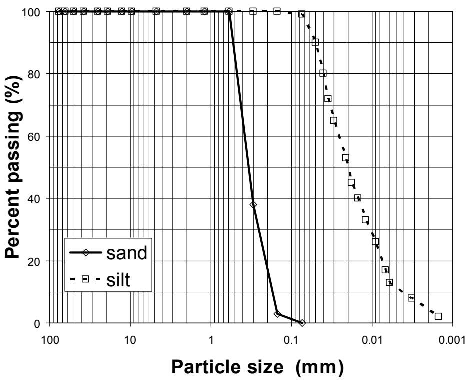
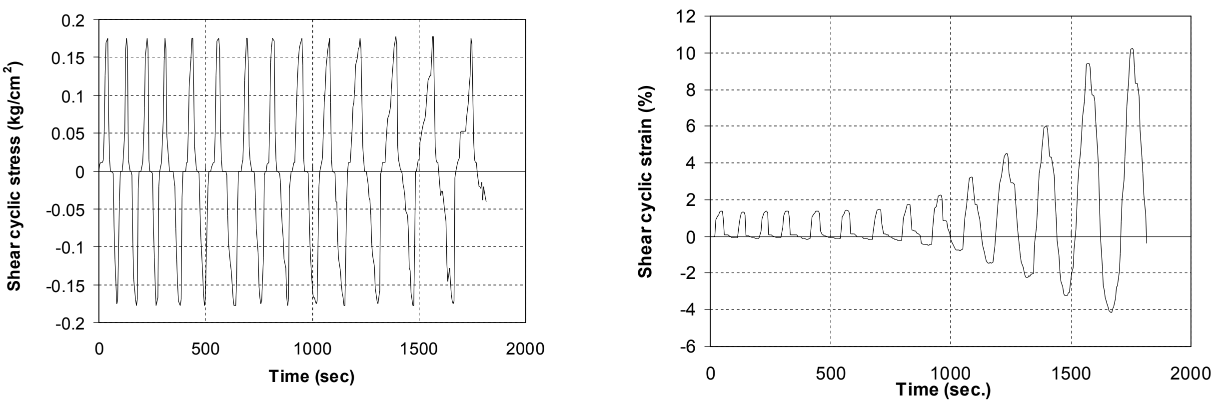


Figure 1. Grain size distribution of the sand and silt used to form the mixtures of the present study.

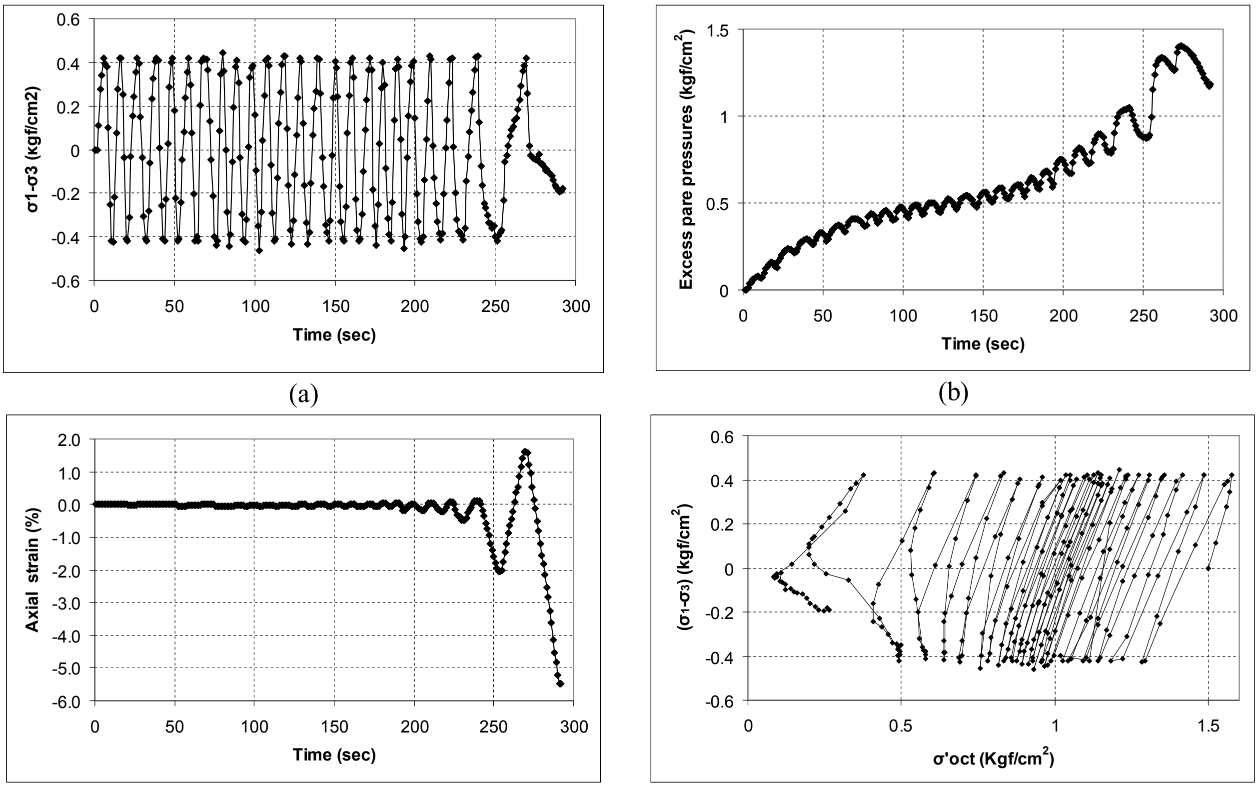
Table 1. Current laboratory program. States studied and cyclic soil strength measured in shear and triaxial tests for PR=1 and PR=3.

f	σ'_{vo} (kPa)	eo	Shear tests		Triaxial tests	
			SR_{15}-PR=1	SR_{15}-PR=3	$SR_{15\text{-}iso}$-PR=1	$SR_{15\text{-}iso}$- PR=3
0	150	0.79	0.15	0.21	0.36	0.43
0	150	0.67	0.17	0.25	-	-
0	150	0.58	0.19	0.24	0.45	0.49
0	50	0.79	0.2	0.26	-	-
0	50	0.67	0.2	0.32	-	-
0	50	0.58	0.24	0.33	0.7	0.79
0.25	150	0.72	0.08	0.13	0.11	0.18
0.25	150	0.67	0.09	0.13	0.12	0.17
0.25	150	0.53	-	-	0.33	0.43
0.25	150	0.36	0.12	0.17	-	-
0.25	50	0.72	0.14	0.18	-	-
0.25	50	0.67	0.16	0.21	-	-
0.4	150	0.77	0.11	0.15	0.1	0.15
0.4	150	0.39	-	-	0.3	0.36
0.4	50	0.77	0.18	0.23	-	-
0.6	150	0.77	0.08	0.13	-	-
1.0	150	1.04	0.07	0.12	-	-



(a) (b)

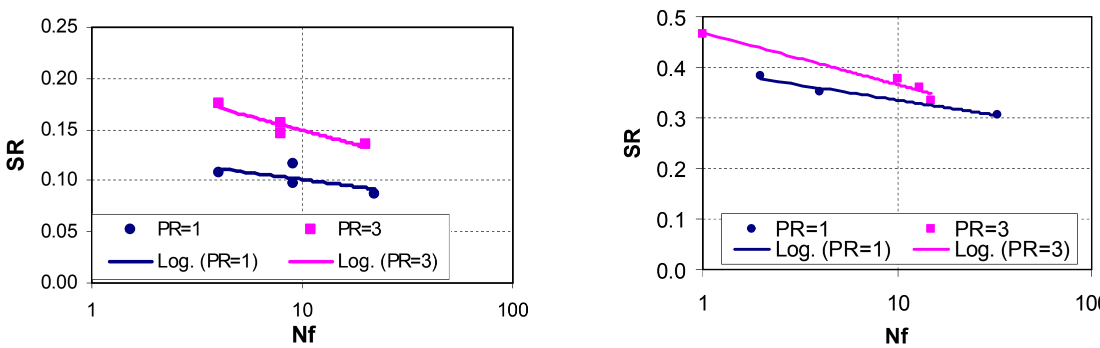
Figure 2. Typical results of a shear test (f=0, eo=0.67, σ'_v=150kPa, PR=3).



(a) (b)

(c) (d)

Figure 3. Typical results of triaxial test (f=0.25, eo=0.68, σ'_v=150kPa, PR=1)



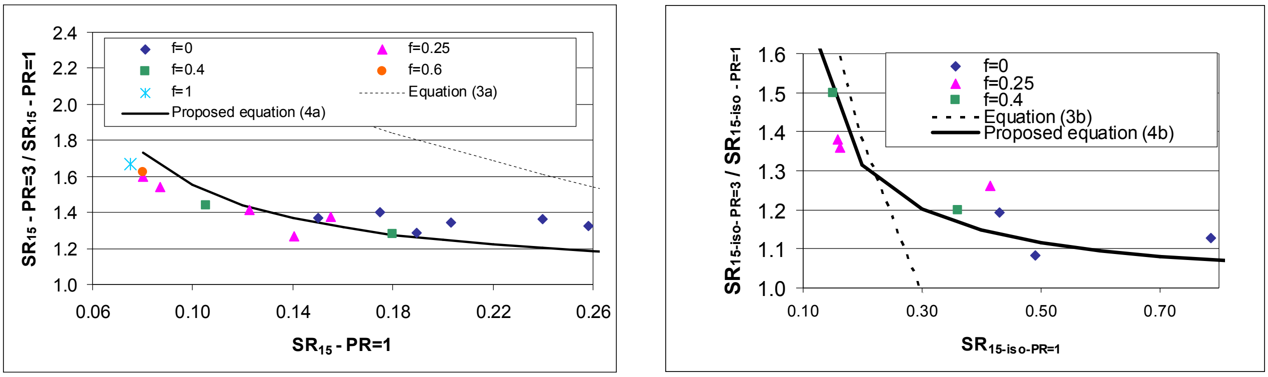
(a) (b)

Figure 4. Typical liquefaction curves for (a) shear tests and (b) triaxial tests. In (a) the case with fc=0.6, eo=0.77, σ'_v=150kPa is given. In (b) the case with fc=0.4, eo=0.39, σ'_v=150kPa is given.

4. NUMERICAL MODEL

In order to assess the ability of the soil behavior model to simulate the effects of the preloading in cyclic liquefaction strength, several liquefaction laboratory tests models were done. Three sets of model parameters which represent three kinds of sandy soil with different relative density (Dr) were used.

The elastoplastic multi-mechanism model developed at Ecole Centrale Paris, known as ECP model is used to represent the soil behaviour. This model can take into account the soil behaviour in a large range of deformations. The model is written in terms of effective stress. The representation of all irreversible phenomena is made by four coupled elementary plastic mechanisms: three plane-strain deviatoric plastic deformation mechanisms in three orthogonal planes and an isotropic one. The model uses a Coulomb type failure criterion and the critical state concept. The evolution of hardening is based on the plastic strain (deviatoric and volumetric strain for the deviatoric mechanisms and volumetric strain for the isotropic one). To take into account the cyclic behaviour a kinematical hardening based on the state variables at the last load reversal is used. The soil behaviour is decomposed into pseudo-elastic, hysteretic and mobilized domains. Refer to Aubry et al. (1982), Hujeux, (1985) among others for further details about the ECP model.

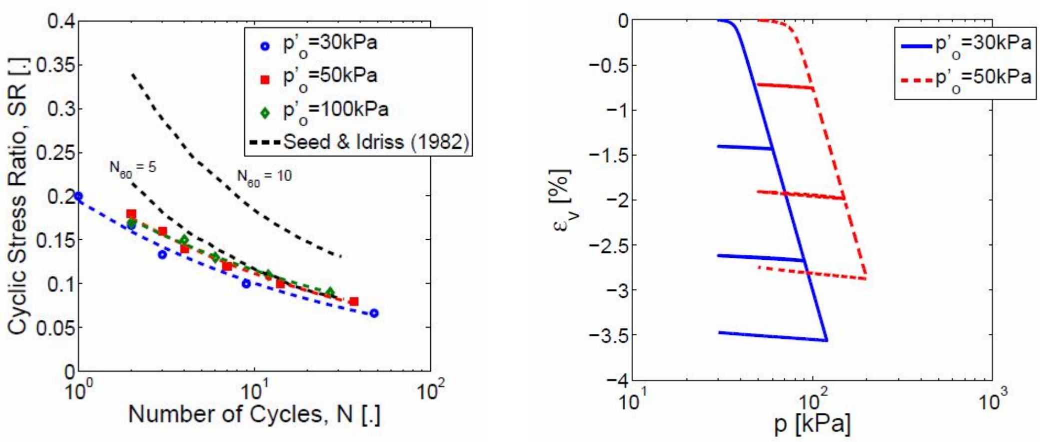


(a) (b)

Figure 5 Ratio of cyclic liquefaction strength at PR=1 and 3 for both triaxial and shear tests in terms of SR_{15}-PR=1. The previous proposed equations (3) and (4) are given for comparison.

The model's parameters of three soils are obtained using the methodology suggested by Lopez-Caballero et al. (2007). Fig. 6a shows the obtained curves of cyclic stress ratio (SR) in triaxial paths with isotropic consolidation as a function of the number of loading cycles to produce liquefaction (N) at p'_o=30, 50 and 100kPa. The modeled test results are compared with the reference curves given by Seed and Idriss (1982) for sands at different densities (i.e. SPT values).

So as to study the effect of pre-stressing on the cyclic strength some isotropic consolidation tests were simulated at p'_o = 30 and 50kPa (Fig. 6b). Three levels of pre-stress ratio (PR) were studied (i.e. 2, 3 and 4). The pre-stress ratio (PR) is defined as in equation 2. Fig. 7 shows the model prediction for the variation of τ-σ'_v and ΔU during the test simulation for one of the set parameters.



(a) (b)

Figure 6. Simulated a) liquefaction curves obtained in triaxial path for the sand model and b) Simulated isotropic consolidation test.

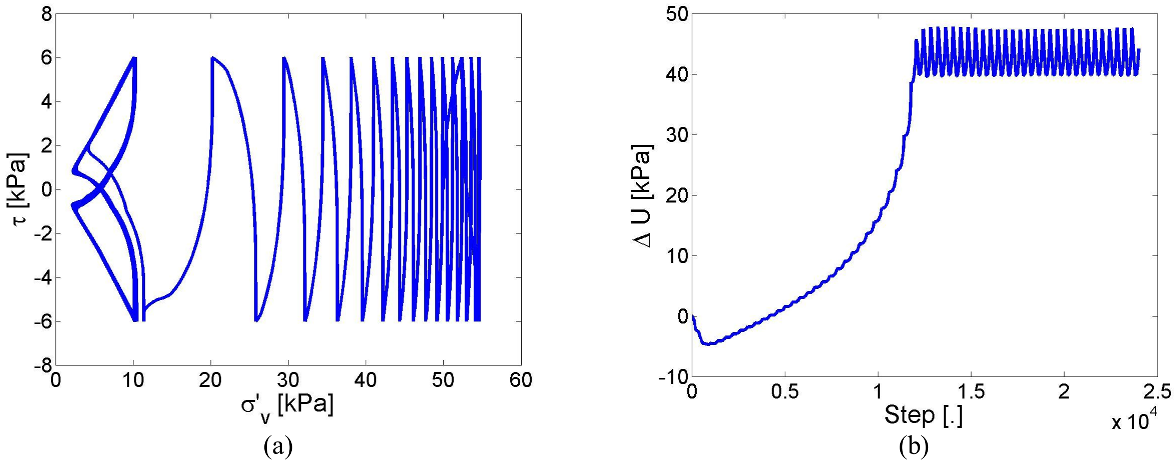


Figure 7. Simulated undrained stress controlled cyclic shear tests (a) τ-σ'_v curve and (b) evolution of ΔU with computation step.

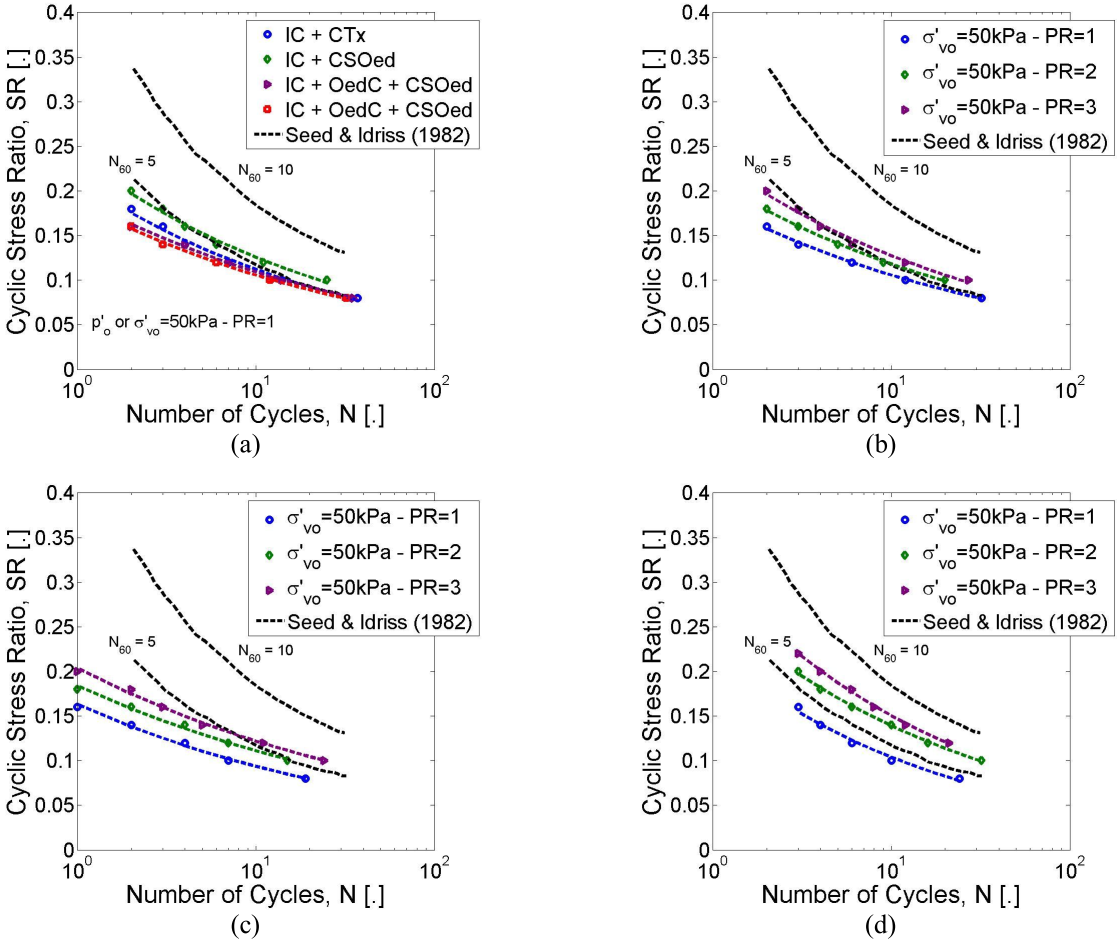


Figure 8. Simulated liquefaction curves, (a) effect of the loading path (b) to (d) effect of prestress ratio (PR) on the three sands for loading path (iv)

First of all, it is important to study the effect of the loading path, both in consolidation phase and the cyclic loading, on the response of the laboratory test simulation. To this intent, four loading paths were tested i) isotropic consolidation and cyclic triaxial loading (IC+CTx), ii) isotropic consolidation and cyclic 1D (no lateral strain) simple shear loading (IC+COed), iii) isotropic consolidation till 20% of total load then oedometric consolidation till total load and cyclic 1D shear loading (IC+OedC+COed),

iv) isotropic consolidation till 10% of total load then oedometric consolidation till total load and cyclic 1D shear loading (IC+OedC+COed). According to our results (Fig. 8a), for PR=1, a higher liquefaction curve (i.e. cyclic strength) is found when the loading path (ii) is used. However, by comparing the path (i) and (iii) a difference in the cyclic strength values for high SP (low N values) was found. Finally, no difference was found between path (iii) and (iv). In the next, the loading path (iv) will be used.

Fig. 8b to 8d display the liquefaction curves obtained for the three soils at one initial stress and three PR values. It is noted that for similar confining stresses, the SR value increases as PR increases, as shown in the laboratory tests (section 3). According to Stamatopoulos et al., (1999), the effect of PR on the SR value could be approximated by the following relationship:

$$SR_{15}/SR_{15\text{-}1} = PR^{\Lambda} \tag{5}$$

with $\Lambda = 0.65$. According to our computations (Fig. 9a) for the simulated soil a similar trend but with a $\Lambda = 0.34$ was found. Now, based on the results of the current work, a comparison between the SR15/SR15-1 ratio obtained by simulations and the one estimated with the equation 4b is provided in Fig. 9b. It is interesting to note that all computed values are found in a range of 20% of the predicted value.

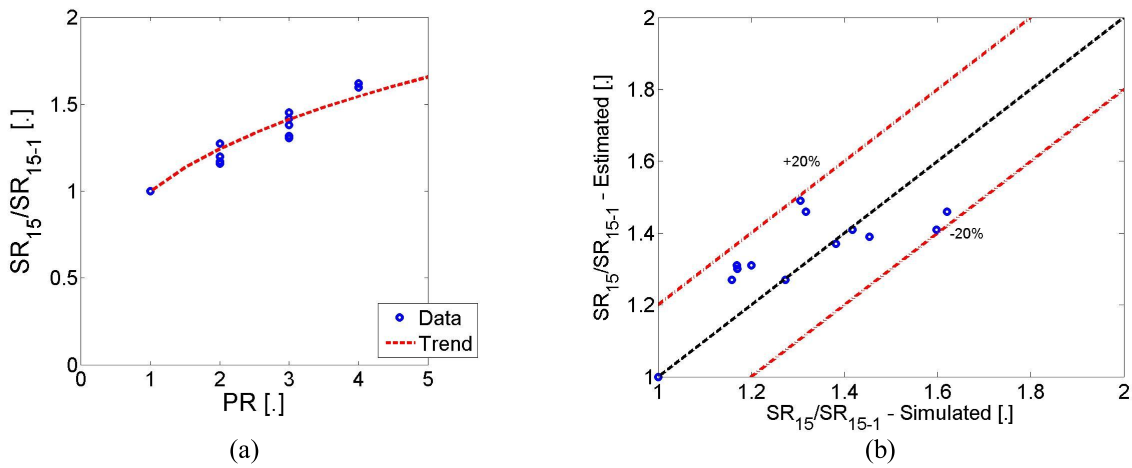


Figure 9. (a) Ratio SR_{15}/SR_{15-1} in terms of prestress ratio (PR). and (b) Comparison between simulated and estimated by equation (4b) SR_{15}/SR_{15-1} ratio.

5. CONCLUSIONS

A series of laboratory tests and numerical simulations are performed to investigate the effect of pre-loadings on the cyclic strength of liquefiable soils. Based on the test results, the emprical expression (4b) predicting the increase in cyclic strength induced by preloading was proposed. Several issues have been addressed. On one hand the soil composition by testing several mixtures, and on the other hand the soil state expressed not only by the density and applied stresses but also the stress path the soil sample has undergone or/and the fabric it has resulted to. Hence, if the choice of experimental device is not very important in normally consolidated soil, for pre-stressed conditions it becomes an important factor and the state of the test sample should be as similar as possible to the one in the field. The comparison of the laboratory test results and the numerical simulation responses is a practical cross verification of the hypotheses on which the constitutive model of the soil is based and the coherence of the experimental results.

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