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DOI:
10.3233/STAL190031

Publication date:
2019

Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190031

Soil Behaviour Under Non-Uniform and Bidirectional Cyclic Loading

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Abstract. Soil liquefaction is one of the major causes of damage due to earthquakes. Specifically in Chile, evidence of liquefaction has been observed on several sites along the country after the 2010 Mw 8.8 Maule earthquake. An ongoing research project involving the evaluation of liquefaction potential of different sites in the city of Concepción, has produced an extensive in-situ testing database. To contribute in the evaluation of liquefaction potential, a laboratory testing program is being performed through cyclic triaxial tests. The specimens tested consist of natural soils extracted at different sites from the city of Concepción. One of the objectives of this study is to evaluate the effects of non-inform cyclic loading on the threshold shear strain of natural soils. The results are compared with conventional methods to obtain the values of the cyclic shear strain amplitude. The evaluation of the dynamic properties of natural soil deposits potentially liquefiable are compared.

Keywords. Liquefaction, sand, cyclic loading.

1. Introduction

It is known that during an earthquake soil layers experience complex stress-strains histories, that involve changes in frequency and amplitude. Laboratory cyclic and dynamic tests in soils generally simplify these stress-strain histories into constant frequency and amplitude loading cycles, mostly sinusoidal loads. Much of the understanding of the liquefaction response of soils from laboratory tests has been obtained from conventional constant amplitude and frequency sinusoidal loads.

Recent advances in laboratory equipment and software control have led to the application of much more complex loading histories for soil testing, such as changes in frequency and amplitude, and non-uniform shear loads. The purpose of this work was to analyze changes in soil behavior under cyclic loading conditions different from conventional cyclic laboratory tests. The material used for this work correspond to natural soil samples extracted in the city of Concepción, Chile and from sites that evidenced liquefaction during the 8.8 Maule 2010 Earthquake. The samples were subjected to irregular cyclic triaxial tests, and bidirectional cyclic simple shear tests.

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2. Literature Review

Literature shows that if a saturated soil is subjected to undrained cyclic loading under shear strain amplitudes higher than a certain threshold, the material will experience a permanent change in volume or permanent pore water pressure change [1-3]. This cyclic threshold shear strain, usually denominated as γ_t, has been determined by many previous studies, for different materials and using different testing apparatus (e.g. drained and undrained cyclic triaxial, cyclic simple shear, resonant column), following a constant frequency and amplitude sinusoidal motion. For most clean sands the value of γ_t is close to 0.01%, and, for clayey sands around 0.1% [2]. It must be clarified that the cyclic threshold shear strain defined in this work corresponds to the denominated volumetric threshold shear strain, where shear strains higher than its value produce permanent changes to the soils microstructure [2].

The significance of γ_t lies on its representation as a boundary for which higher amplitudes produce a highly nonlinear behavior of the soil and therefore, shear stiffness degradation. Consequently, this parameter has been used to analyze the liquefaction potential of a material using a cyclic strain based method [4-5].

In terms of the influence of bidirectional cyclic loading on soils, previous studies have shown that the resulting cyclic loading resistance is lower than a unidirectional cyclic load, and generate excess pore water pressures at a higher rate [6-7].

3. Material and Testing program

3.1. Material

The tests were performed on two materials from the city of Concepción, Chile, extracted from two SPT boreholes (Table 1). The poorly graded sand (SP, Table 1), corresponds to a clean coarse sand, with N-SPT of 60, at 6 meters depth, and no evidence of liquefaction in the site after the 2010 Maule Earthquake. The clayey sand (SC, Table 1) had an SPT-N of 14, at a depth of 9 meters, and the site at which it was extracted evidenced the phenomena of liquefaction through sand boils and structure damage after the 2010 Maule Earthquake.

Table 1. Soil samples tested in the triaxial and simple shear equipment.

USCS	Depth (m)	γd (g/cm^3)	Fines (%)	IP (%)
SP	6.0	1.616	5.0	NP
SC	9.0	1.454	30.0	13

3.2. Testing program

The triaxial tests were performed on a hydraulic dynamic triaxial equipment, by VJ Tech. The 50 mm diameter samples were prepared by moist tamping with Undercompaction [8], and then saturated in order to obtain a Skempton B value higher than 0.95. The samples were then isotropically consolidated to its in situ confining pressure, and left for one hour before testing.

The cyclic simple shear tests (CSS) were performed on the University of Dundee bidirectional dynamic simple shear device VDDCSS by GDS Instruments Ltd. The equipment is capable of controlling cyclic horizontal shear stresses or deformations in two directions, as well as the vertical direction allows the control of stresses and displacements. All samples have 70 mm diameter and 20 mm height. Figure 1 shows the sample installed in the equipment. Samples were prepared by dry deposition [3] and then subjected to their corresponding in-situ vertical confining pressure σ'_v. The tests were performed by the constant volume approach to simulate undrained conditions, and subjected to cyclic shearing at a frequency of 1 Hz.

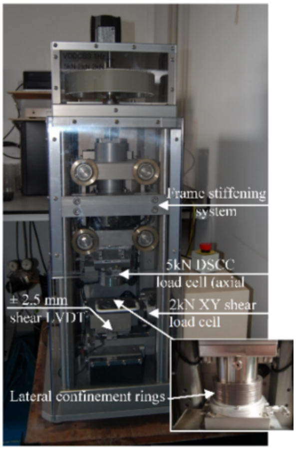

Figure 1. University of Dundee Bidirectional cyclic simple shear apparatus.

The methodology used to evaluate γ_t was that proposed by [4], using both, the triaxial and the simple shear apparatus. Initially, each sample was subjected to a series of undrained cyclic strain controlled loading conditions, with a total of 10 cycles each, and sinusoidal loading. The magnitude of shear strain amplitude applied ranged from 0.005% to 0.05%. The residual pore water pressure obtained after each stage was recorded. After each stage was finished, the resulting excess pore water pressure was dissipated.

In order to study the influence of an irregular or variable cyclic load on the measured threshold shear strain γ_t, the same procedure previously described to obtain γ_t was then applied to triaxial samples, using an irregular cyclic load (Figure 2), with decreasing amplitude and frequency.

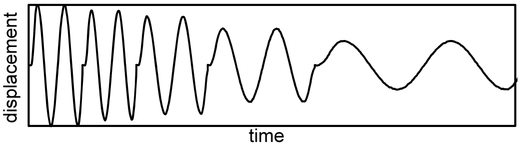

Figure 2. Irregular cyclic displacement applied to triaxial samples.

Subsequently, only the samples tested on the bidirectional cyclic simple shear apparatus were then subjected to an amplitude higher than γ_t in order to obtain significant excess pore water pressures and analyse the application of shear strain amplitudes in two directions (Alternated loading, Figure 3a), and differences in frequency (Eight loading, Figure 3b). The tests performed in the simple shear apparatus are given in Table 2.

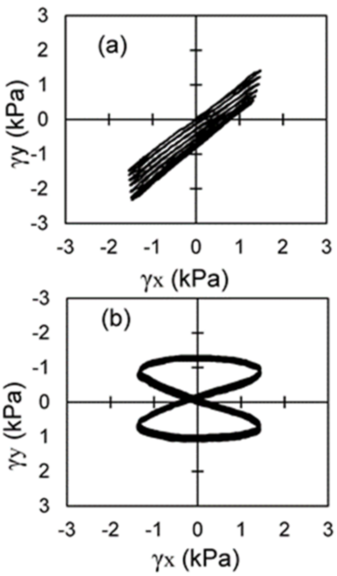

Figure 3. Bidirectional cyclic shear strain motions: (a) alternated; (b) eight.

Table 2. Testing program in the cyclic simple shear device.

Test	**Amplitude**	**Frequency (Hz)**
Unidirectional (Uni)	$\Delta\tau x \neq 0$ $\Delta\tau y = 0$	$fx \neq 0$ $fy = 0$
Alternated (Alt)	$\Delta\tau x = \Delta\tau y$	$fx = fy$
Eight (8)	$\Delta\tau x = \Delta\tau y$	$fx = 2fy$

4. Results

4.1. Threshold shear strain

Figure 4 shows the curves of excess pore water pressure at the end of each stage versus the applied cyclic shear strain amplitude. The results indicate that for all samples, the value of γ_t decreases from a conventional undrained cyclic triaxial test as the loading condition is changed to bidirectional. For both triaxial testing conditions and unidirectional CSS, γ_t is close to 0.01% for both materials. A significant reduction in γ_t is observed when a bidirectional loading with different frequencies is applied (CSS.8, Figure 4), with $\gamma_t \approx 0.006\%$ for SP samples, and $\gamma_t \approx 0.003\%$ for SC samples. The *CSS.Alt* loading results were not included as, in this case, they gave similar results than *CSS.Uni* results.

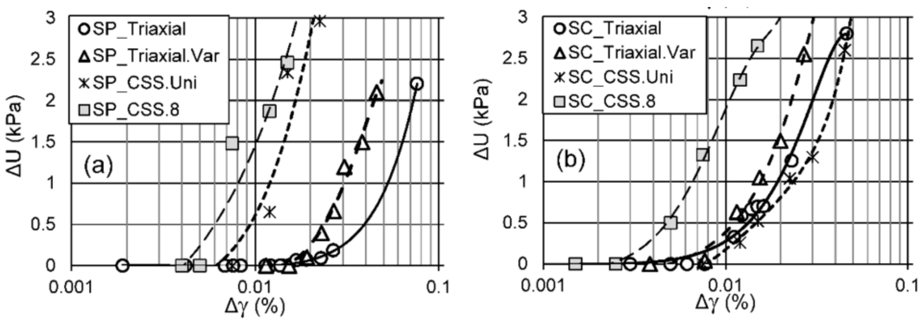

Figure 4. Cyclic shear strain amplitude versus Excess pore water pressure for a conventional triaxial test, triaxial tests an irregular load (Var), unidirectional CSS test (CSS.Uni), and CSS test with an eight loading pattern (CSS.8).

4.2. Pore water pressure for shear strains above γ_t

From the CSS tests, the excess pore water pressures curves generated after 200 loading cycles are exposed in Figure 5. For both materials, the most detrimental loading condition is that given by a bidirectional eight loading, followed by an alternate motion. The SP samples generate higher excess pore water pressures, compared with SC samples, and they even reach full liquefaction as the soil is tested under CSS eight loading conditions. These findings are important for the analysis of the shear stiffness degradation that could occur under seismic action.

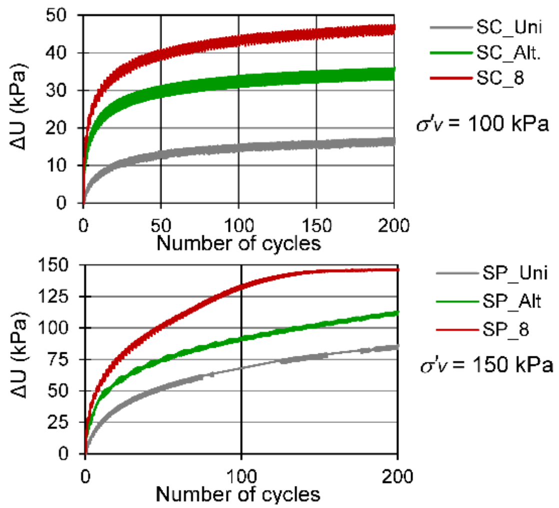

Figure 5. Excess pore water pressure versus number of cycles: (a) SC tests, (b) SP tests.

5. Conclusions

- The cyclic threshold shear strain γ_t is reduced when the loading is applied in two directions and with differences in their frequencies. Although the magnitude changes of γ_t may seem subtle, they represent significant changes in terms of the shear strain limits that represent a linear elastic soil behavior and nonlinear behavior. The effects of bidirectional loading on γ_t were higher on a clean sand, compared with a clayey sand.

- An irregular or variable cyclic load applied in the triaxial samples did not produce changes in γ_t but produced a steeper excess pore water pressure increase with increasing shear strain amplitude. It is expected that the influence of an irregular loading condition will have higher effects as an amplitude higher than γ_t is applied.
- Bidirectional loading had a considerable influence on the excess pore water pressure generation, on the materials tested. Specifically, clean sands reached liquefaction condition under *CSS_eight* loading (Figure 5b).
- From the value of SPT-N and in-situ evidence, it is known that the SC material is potentially liquefiable. However, by the results, this material presented lower excess pore water pressure generation with the number of cycles, compared to the SP material. Yet, its γ_t was far more affected, and therefore decreased, when a cyclic loading history similar than a seismic load was applied.
- Future work considers the study of different bidirectional loading histories, with changes in amplitude and phase angle, in potentially liquefiable natural soils.

Acknowledgements

The authors would like to acknowledge the CONICYT PAI/ACADEMIA 79150011 program, and FONDEF ID16I10157 for supporting this work.

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