Foreword

The academic articles here proposed concern some examples of design where the dynamic response of important structures have been analyzed through a campaign of laboratory investigation where a consistent number of cyclic simple shear tests have been carried out.
The CSS test consists in the application of a cyclic shear stress causing the angular distortion of a soil element and the continuous rotation of the principal axes of stresses and strains.
This condition of stresses simulates quite correctly the situation that occurs within the underground layers of soils when, for example, a seismic event occurs.

The paper, presented in the Proceedings of the 15th ECSMGE held in Athens in 2011, concerns the problems related to the cyclic liquefaction resistance of saturated cohesionless materials.
Liquefaction susceptibility is one of the most critical aspects of many foundation sites, where conditions of saturated subsoil layers are encountered.
The experimental program has been performed by a group of researchers of the Politecnical University of Madrid in cooperation with a design company for the geotechnical characterization of the area at the North Entrance Mouth of the Port of Barcelona.
In details the influence of the static shear stresses existing prior to the application of dynamic loads is investigated, in order to simulate as closer as possible the on-site stress conditions before a seismic event.
Liquefaction is a phenomenon in which the strength and stiffness of a saturated granular subsoil is dramatically reduced for the sudden reduction of inter granular forces, caused by the increment of pore pressure, generally due to a seismic event.
Cyclic simple shear tests, together with the traditional tests of geo mechanical characterization, allowed to investigate the influence of different conditions of initial overburden stresses and natural density on the shear strength of the subsoil.

From the documents presented herein, important indications can be drawn with reference to the design parameters, that laboratory investigations can define. Another important message is given from the awareness that it is necessary to operate with sophisticated automatic equipment with highly accurate and reliable measurement systems, that CONTROLS Group and his historical Wykeham Farrance brand can ensure.

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Cyclic behaviour of saturated sands subject to previous horizontal shear stresses

Comportement cyclique des sables saturés soumis à des contraintes précédentes de cisaillement horizontal

A. Soriano[1], H. Patiño, J. González
Universidad Politécnica de Madrid

M. Valderrama
Ingeniería del Suelo S.A.

ABSTRACT

The dynamic behaviour of saturated sands has been studied from different perspectives. However, most experimental research on this field does not take into account the shear stress conditions existing prior to the application of dynamic loads; i.e., a null initial static shear stress (o = 0) is assumed. The main objective of this work is to report on the influence that static shear stresses (o) have on the behaviour of saturated sands under cyclic shear loads. This article presents the results and analysis of part of a wider experimental programme involving 30 monotonic and 26 cyclic simple shear tests for different combinations of static shear stress (o) and cyclic shear stress (c) (all undrained), besides identification and classification tests. The tested samples have been taken from the area of the North Entrance Mouth at the Port of Barcelona (Spain).

RÉSUMÉ

Le comportement dynamique des sables saturés a été étudié sous différents angles. Cependant, la plupart des recherches expérimentales sur ce cette matière ne prennent pas en compte les conditions de contrainte de cisaillement existants avant l'application des charges cycliques, c'est á dire, on a considéré une contrainte de cisaillement statique initial nulle (o = 0). L'objectif principal de ce travail est de rapporter sur l'influence que cette contrainte de cisaillement statique a sur le comportement des sables saturés sous des charges cycliques de cisaillement. Cet article présente les résultats et l'analyse d'une partie d'un programme expérimental plus important, comprenant 30 essais monotones et 26 essais cycliques de cisaillement simple pour différentes combinaisons de contraintes de cisaillement statiques (o) et cycliques (c) (tous non drainés), en plus des essais d'identification de classification. Les échantillons testés ont été prises à l'Embouchure Nord du Port de Barcelone (Espagne).

Keywords: saturated sand, cyclic shear tests, static shear stress, cyclic stress ratio, liquefaction, harbour caissons

1 INTRODUCTION

Cyclic behaviour of granular soils has been studied for quite a long time, due to the number of foundation failures that have occurred, specially under seismic actions. Pioneering articles are, for example, those from Marsal [1], Seed and Lee [2], Seed and Idriss [3], Ross et al. [4].

This paper summarizes a research on the dynamic behaviour of granular soils under undrained conditions. This situation has predominantly been studied, for example, by Park and Silver [5], Dobry and Ladd [6], Dobry et al. [7]; whereas cyclical tests on drained sands are somewhat less frequent: Silver and Seed [8],

[1] Corresponding Author.

Drnevich and Richart [9], Youd [10] and Pyke [11].

A very complex phenomenon not yet fully understood is that of “liquefaction”, thoroughly studied by Seed and Lee [2], Castro [12], Casagrande [13], Seed [14], [15], Kramer [16], Ishihara [17], Youd [18], Boulanger and Idriss [19], etc. It may affect saturated granular materials and consists in total loss of shear strength under dynamic actions, as a consequence of rapid and progressive increase of pore pressures.

A research into granular soil strength is presented here, with a view to help evaluate the safety of harbour caissons in vertical breakwaters. The foundation ground under a caisson is subject to different stress conditions, as Figure 1 shows.

However, most of the previous experimental research has been limited to simulating a material with null horizontal shear stress ($\tau_o = 0$) prior to applying the cyclic shear loads. This is but a particular case from the range shown by Fig. 1.

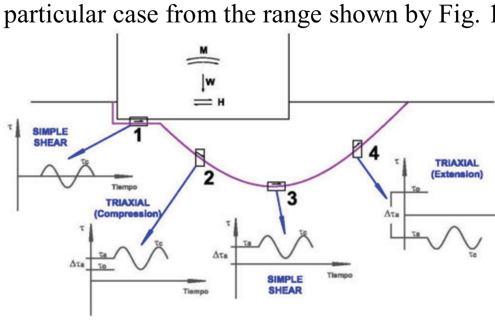

Figure 1. Idealized stress conditions along a hypothetical failure line

This articles presents results of cyclic simple-shear tests, for various combinations of initial horizontal shear stress (τ_o) and cyclic shear stress (τ_c), and analyses how this combination (τ_o - τ_c) influences sand behaviour and strength. To this end, a procedure much like the one that Patiño [20] and Patiño and Soriano [21] suggest for evaluating the cyclic behaviour of cohesive materials.

2 EMPLOYED EQUIPMENT

The apparatus for cyclic direct simple shear (DSS) tests at the Soil Mechanics Laboratory of the *Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos* (ETSICCP) of the *Universidad Politécnica de Madrid* (UPM), which was employed for this investigation, is computer-controlled and was manufactured by Wykeham Farrance, a division of Controls Group. It can be seen it Figure 2 and a full description be found in [22].

Figure 2. Cyclic DSS equipment used for the tests.

3 TESTED MATERIAL

The tested samples were taken by means of three boreholes drilled from the dyke on the North Entrance Mouth at the Port of Barcelona, Spain. The average borehole depth was 21 m under the seabed.

Table 1. Experimental programme.

Type of test	Number
Grading with sieve	12
Grading by sedimentation	5
Atterberg limits	12
Fines content	74
Natural density	73
Natural moisture content	74
Grain specific weight	6
Oedometer	5
Triaxial, CU	15
Static simple shear	30
Cyclic simple shear	26

The geological origin of the area is sedimentary: an alternation of clayey silts, silty clays and silty sands. In general, the deposits can be characterized as conchiferous and micaceous.

The total number of undisturbed samples taken for the experimental stage of this research is shown in Table 1, but this article only deals with the dynamic behaviour of silty sand samples. It was assessed by 6 monotonic and 17 cyclic simple shear tests.

Table 2 shows the index properties of silty sand samples tested with the shear apparatus. Shear strength parameters have been obtained for a limit shear deformation of 10% and assuming c = 0.

The dynamics tests, for analysing the combination of prior static shear stress (τ_o) and the cyclic shear stress applied (τ_c), were made with different ratios between these values and the in-situ effective consolidation pressure, σ'_{ov}. The following couples of (τ_o/σ'_{ov} - τ_c/σ'_{ov}), in percentage, were used: (0-5), (0-10), (0-15), (0-20), (5-15), (10-10) and (15-5).

Table 2. Index properties of tested samples

Index property	Value range
Natural density, gr/cm^3	1.90 – 2.05
Natural water content, %	21.6 – 27.6
Grain specific weight, gr/cm^3	2.73
Fraction passing #200 sieve, %	12.7 – 36.6
Plasticity index, %	NP
Fraction with size < 2μ, %	10
Internal friction angle	39º ± 3º
Dimensionless shear strength, s_u/σ'_v	0.46 ± 0.10

To make all tests consistent, they were performed under these conditions:

- Undisturbed samples.
- Specimens were 70 mm in diameter and 19 mm in height.
- The test effective consolidation pressure was the same as the in-situ vertical effective stress (σ'_{ov}). As sampling was done from boreholes drilled through the caissons of the already-existing dyke, the increase in effective pressure due to the caisson weight was added to that from the soil own weight.
- Undrained conditions with evaluation of generated pore pressure. According to Bjerrum and Landva [23], constant-volume simple shear tests are equivalent to undrained tests and the change in vertical pressure applied on the specimen is equal to the change in pore pressure that would undergo a specimen under an undrained simple shear test with constant axial stress.
- Controlled stress, during the cyclical loading stage. Sine wave with an amplitude equal to the cyclic shear stress (± τ_c) and a period of 15 seconds.
- Controlled strain rate, during the monotonic loading. The shear deformation rate was 0.015 mm per minute, which equates 4% per hour.

4 ANALYSIS OF RESULTS

4.1 *Number of cycles to failure*

Cyclic simple shear tests have stopped when liquefaction occurred (condition A), when angular deformation reaches 15 % (condition B) or the number of cycles reached 1300 (condition C).

Figure 3 shows the type of condition motivating the end of tests. It seems that the value of prior shear stress has an influence on this matter. For the same value of maximum shear stress ($\tau_{máx} = \tau_o + \tau_c$), liquefaction has only occurred in tests with low values of τ_o.

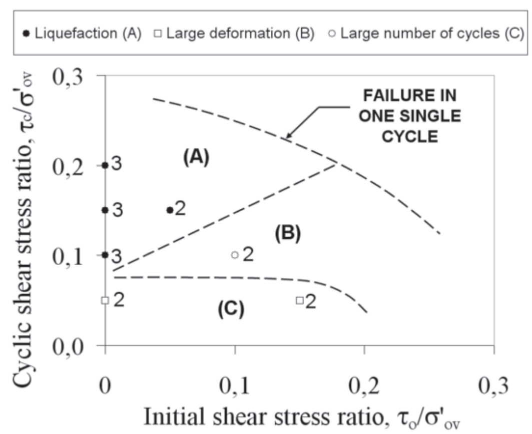

Figure 3. Type of condition that led to stopping the test and number of tests done.

For small cyclic stresses and within the range of initial stresses being explored, no liquefaction or excessive strain occur; the end of tests is controlled by the maximum number of cycles.

In the diagram of Figure 3, it seems that some borderlines may exist, which would indicate the regions for each condition. The lower region, C, could be considered stable; the intermediate region, B, could correspond to failure due to large strain; only in region A, sudden liquefaction would happen at a certain moment. For the condition of τ_o = 0, when liquefaction occurs, the ratio between the number of cycles and the cyclic stress (τ_c) is shown in Figure 4.

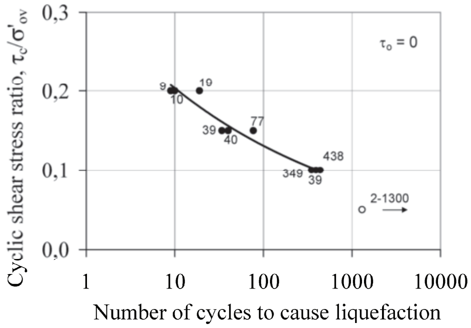

Figure 4. Number of cycles needed to cause failure for different stress conditions

4.2 *Stress-strain behaviour*

Figure 5 shows the typical stress-strain behaviour for the different combinations of (τ_o/σ'_{ov} - τ_c/σ'_{ov}).

In all included graphs, the horizontal axis corresponds to unitary cyclic strains (γ_c) and the vertical axis to cyclic stress (τ_c).

In Figure 5, it can be clearly observed how the combination (τ_o/σ'_{ov} - τ_c/σ'_{ov}) influences the stress-strain behaviour of the studied soil.

For the same τ_o and different τ_c values, a small increase of τ_c significantly reduces the number of cycles needed to reach the same cyclic strain (γ_c).

When τ_o = 0, cyclic (γ_c) and permanent (γ_p) strains are comparable in magnitude; the comparison of combinations (0-15) and (5-15) shows that a small increase in τ_o restricts the generation of permanent strain (γ_p) and, therefore, cyclic strains (γ_c) are prevalent; when (τ_o/σ'_{ov}) > 5%, soil behaviour changes radically and permanent strains (γ_p) are larger than cyclic ones (γ_c).

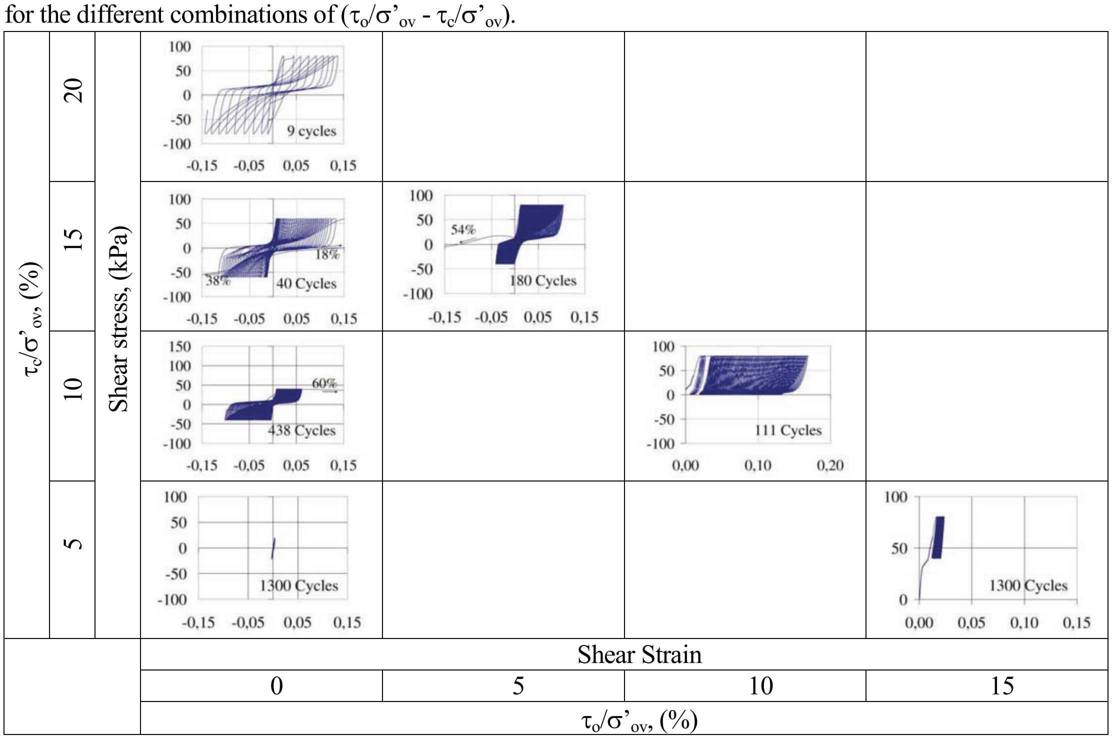

Figure 5. Typical stress-strain curves for different combinations of (τ_o/σ'_{ov} - τ_c/σ'_{ov}).

The shear modulus (G) corresponding to each cycle varies along the test, as Figure 6 shows. It can be seen that this modulus is a function not only of the number of cycles (N) but also of the combination (τ_o/σ'_{ov} - τ_c/σ'_{ov}). For the same (N) and (τ_o/σ'_{ov}), (G) decreases when (τ_c/σ'_{ov}) grows. Apparently, a prior static stress (τ_o/σ'_{ov}) induces a certain stiffening in the soil, and can even modify its behaviour. The clearest proof of the influence of the combination (τ_o/σ'_{ov} - τ_c/σ'_{ov}) arises when comparing the pairs (0-20) y (15-5), for both of which (τ_o/σ'_{ov}) + (τ_c/σ'_{ov}) = 20%. For the pair (0-20), (G) decreases from 4 to 1 MPa in 9 cycles, whereas (G) increases from 9 to 12 MPa in 1300 cycles for the combination (15-5).

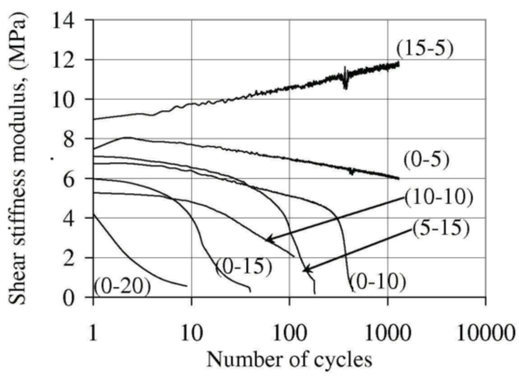

Figure 6. Typical trends of variation of the shear modulus (G) with the number of cycles (N).

4.3 Damping (ζ)

The range of variation of damping (ζ) is influenced by the number of cycles (N) and the combination (τ_o/σ'_{ov} - τ_c/σ'_{ov}) - see Figure 7. For the pairs (0-5) and (15-5), i.e., for low values of (τ_c/σ'_{ov}) and irrespective of (τ_o/σ'_{ov}), damping decreases slowly until cycle number 10; afterwards, it tends to remain constant, with average values around 10% for combination (0-5) and 5% for combination (15-0).

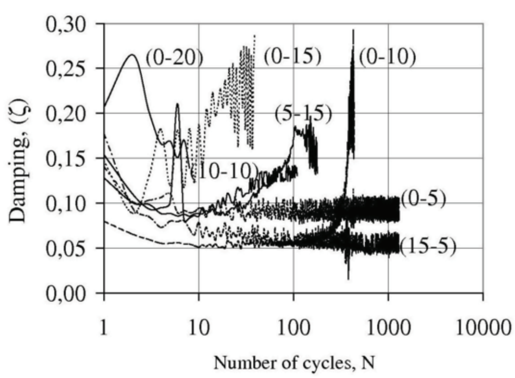

Figure 7. Typical trends of variation of damping (ζ) as a function of the cycle number (N).

4.4 Pore pressure (u)

Figure 8 represents the trends of variation or the pore pressure generated during the dynamic loading. Besides combinations (0-5) and (15-0), in the remaining cases the ratio ($\Delta u/\sigma'_{ov}$) was larger than 85%, which led to degradation of the soil stiffness and therefore to large cyclic and/or permanent strains. In cases (0-5) and (15-5), this ratio was 50% at most, after 1300 cycles.

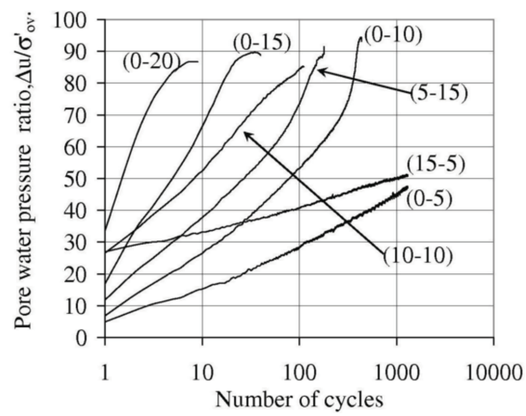

Figure 8. Typical trends of variation of generated pore pressure (u) with the cycle number (N).

5 CONCLUSIONS

It is well known that the cyclic stress ratio (τ_c/σ'_{ov}) is a governing factor in dynamic behaviour of soils. However, on the basis of this research results, it can be stated that soil behaviour is also controlled by the ratio (τ_o/σ'_{ov}).

The value of initial shear stress (τ_o) significantly influences the type of failure that takes place in tests. It affects the ranges of variation of shear modulus (G) and damping (ζ), the development of cyclic (γ_c) and permanent (γ_p) strains and pore pressure generation.

Taking into account that the combination (τ_o/σ'_{ov} - τ_c/σ'_{ov}) governs the development of cyclic and permanent strains, some soil regions under a structure would tend to reach failure due to cyclic deformation and other regions due to permanent strain. However, the needed compatibility of strains along a failure line prevents these two regions to be adjacent. Therefore, a re-distribution of stress must occur, also controlled by the combination (τ_o/σ'_{ov} - τ_c/σ'_{ov}).

For the particular material tested, small cyclic strains are developed while the ratio ($\Delta u/\sigma'_{ov}$) is < 80%; for larger values, the generation of cyclic strains accelerates – they even can go from 14% to 60% in a single cycle.

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