Challenges to the laboratory evaluation of field liquefaction resistance

Les défis de l'évaluation en laboratoire de la résistance à la liquéfaction de terrain

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ABSTRACT: Soil liquefaction is one of the most feared phenomena in Geotechnical Earthquake Engineering, due to the serious damage it can cause to modern societies in seismically active regions. Even if significant progress has been achieved in the laboratory evaluation of liquefaction resistance of sandy soils, considerable challenges still remain. These mostly result from the complex and variable nature of earthquakes, which apply non-uniform and multidirectional cyclic loading to soils and is therefore difficult to reproduce in laboratory testing. This paper aims at discussing the impact of the loading conditions imposed during soil testing. In particular, the effects of using uniform, axial and unidirectional cyclic loading are considered. The results show that the existence of a singular peak load of larger amplitude considerably affects the number of cycles required to liquefy the soil, with the location of that peak being of upmost importance for the evaluation of liquefaction resistance. Also, it was found that the loading mode affects the cyclic response of the soil, with fewer cycles being necessary to liquefy the soil under radial cyclic loading. Moreover, the liquefaction resistance of sand is substantially reduced when multidirectional loading is used.

RÉSUMÉ: La liquéfaction de sols est un des phénomènes les plus redoutés en Génie Parasismique Géotechnique à cause des graves dommages qu'il peut causer aux sociétés modernes dans des régions sismiquement actives. Même si d'importants progrès ont été réalisés dans l'évaluation en laboratoire de la résistance à la liquéfaction de sols sablonneux, des défis considérables demeurent. Ceux-ci adviennent principalement de la nature complexe et variable des tremblements de terre, lesquels appliquent des chargements cycliques non uniformes et multidirectionnels sur les sols qui sont très difficiles à estimer à partir des données de laboratoire. Cet article vise à présenter l'impact des conditions de chargements appliqués durant des essais sur sols, en considérant en particulier les effets de l'usage de chargements cycliques uniformes, axiaux et unidirectionnels. Les résultats démontrent que l'existence d'un pic de charge singulier de plus grande amplitude affecte considérablement le numéro de cycles nécessaires à la liquéfaction d'un sol, ainsi comme son emplacement est d'extrême importance pour l'évaluation da résistance à la liquéfaction. En outre, il a été constaté que le mode de chargement affecte aussi la réponse cyclique des sols, en étant nécessaire moins de cycles pour liquéfier un sol sous un chargement cyclique radial. De plus, la résistance à la liquéfaction de sables est considérablement réduite lors de chargements multidirectionnels.

KEYWORDS: liquefaction; non-uniform cyclic loading; loading mode; multidirectional cyclic loading.

1 INTRODUCTION

The shear stresses induced on an element of soil in level ground during earthquakes are mainly irregular and multidirectional. Due to the difficulty in the application of such complex patterns of stress changes in laboratory testing, it has been current practice to use uniform and unidirectional loading conditions in laboratory testing. The cyclic strength of soil obtained under such conditions is then corrected in order to account for the effect of load irregularity and multidirectionality (e.g. Ishihara & Nagase 1988).

In this paper, laboratory test data obtained with a stress path cell is used to point out the consequences of using different loading conditions in the assessment of liquefaction resistance of a sandy soil. In particular, it is shown that the occurrence of singular peaks in uniform cyclic loading, as well as using different loading modes, clearly affect the cyclic response of the soil. This suggests that some challenges concerning laboratory evaluation of liquefaction resistance still remain.

2 IRREGULAR LOADING

2.1 *Motivation*

In general, the evaluation of liquefaction potential of an element of soil is based on the comparison of the cyclic shear stresses induced in the field by the earthquake motion with the shear stresses required to liquefy representative samples in the laboratory. This comparison is hampered by the erratic nature of seismic loading, varying, in general, in amplitude in each cycle. The current methodology adopted to overcome this problem consists of converting the random stress history of earthquake motion into an equivalent uniform cyclic stress history, which is expected to cause a similar effect on the soil (e.g., Seed et al. 1975). According to this methodology, the damage induced in the material is proportional to the stress level and independent of the location of the stress cycle in the loading history (Shen et al. 1978).

In order to investigate the effect of the largest stress cycle on the resistance of soil, as well as the importance of its location in the overall load pattern, undrained cyclic triaxial tests having a singular loading cycle with much larger amplitude were carried out. The amplitude of the singular peak load and its location in the time history of the uniform loading were defined in accordance with the analyses of real seismic records (Azeiteiro et al. 2012). Namely, the results of those analyses suggest that largest peaks usually occur between 0.1 and 0.7 of the total number of representative cycles, close to the middle cycle of the earthquake. Furthermore, the authors concluded that maximum and average accelerations of a given earthquake are approximately directly proportional. Thus, a singular peak with double amplitude of the remaining uniform loading was considered in laboratory testing. In order to study the influence of the time instant at which the maximum peak load occurs, its location in uniform loading was varied in each test.

2.2 *Experimental procedures*

2.2.1 *Material and specimen preparation*

All tests were performed on an artificial sand, named Coimbra Sand, which represents the soil conditions of Quaternary deposits located along the banks of Mondego River. The sand was graded between no. 40 (0.425 mm) and no. 100 (0.150 mm) sieves of ASTM series. The mean grain size is about 0.28 mm, while the minimum and maximum void ratios are about 0.48 and 0.81, respectively. Due to the susceptibility of these deposits to liquefaction, as observed during past earthquakes (e.g., Coelho et al. 2007), this sand has been tested in different Portuguese research institutions (Santos et al. 2012).

Air-pluviation of dry sand was used to prepare 38 mm diameter samples with height/diameter ratio close to 2 and a relative density close to 40 %. All samples were saturated by flowing de-aired water through the bottom to its top (using a small differential pressure of about 10 kPa), at low and high back-pressures, until a Skempton's B-value close to 0.99 was measured in all tests. Moreover, in order to ensure saturation during the whole experiment, the samples were tested using a back-pressure of 450 kPa. All samples were isotropically consolidated to an effective pressure of 100 kPa before shearing.

It is also noteworthy that the extension load was applied by means of a flexible sleeve sealing a plane top cap to an adjustable reaction head, in order to control radial and axial stresses independently.

2.2.2 *Testing program*

Three undrained cyclic triaxial (UCT) tests were carried out on samples of Coimbra sand. In two of them, a singular loading cyclic with a deviatoric peak stress amplitude of about $|q_p| = 60$ kPa was applied, which corresponds to double the amplitude of the remaining uniform loading $|q_{unif}| = 30$ kPa. As referred to earlier, the position of the singular loading cycle was varied in each test. Namely, it was applied at a mean effective stress, p'_p, of about 80 and 50 kPa, as detailed in Table 1. In the last test, a constant deviatoric stress oscillation of 40 kPa (corresponding approximately to $0.65\,|q_p|$) was used. All samples were tested until large strains and excess pore water pressure were observed.

Table 1. Characteristics of undrained cyclic triaxial tests performed to study sand liquefaction under irregular loading conditions.

Test ID	$\|q_{unif}\|$ *(kPa)*	$\|q_p\|$ *(kPa)*	p'_p *(kPa)*
UCT/30/60/50	30	60	50
UCT/30/60/80	30	60	80
UCT/40	40	–	–

2.3 *Effect of a singular peak load on the liquefaction resistance of a sand*

Figure 1 compares the behaviour of identical samples when subjected to non-uniform (UCT/30/60/50 and UCT/30/60/80) and uniform (UCT40) loading. It can be seen that, in all tests, the stress paths become temporarily close to zero (Figure 1a), i.e. cyclic softening occurred, confirming the liquefaction susceptibility of those samples.

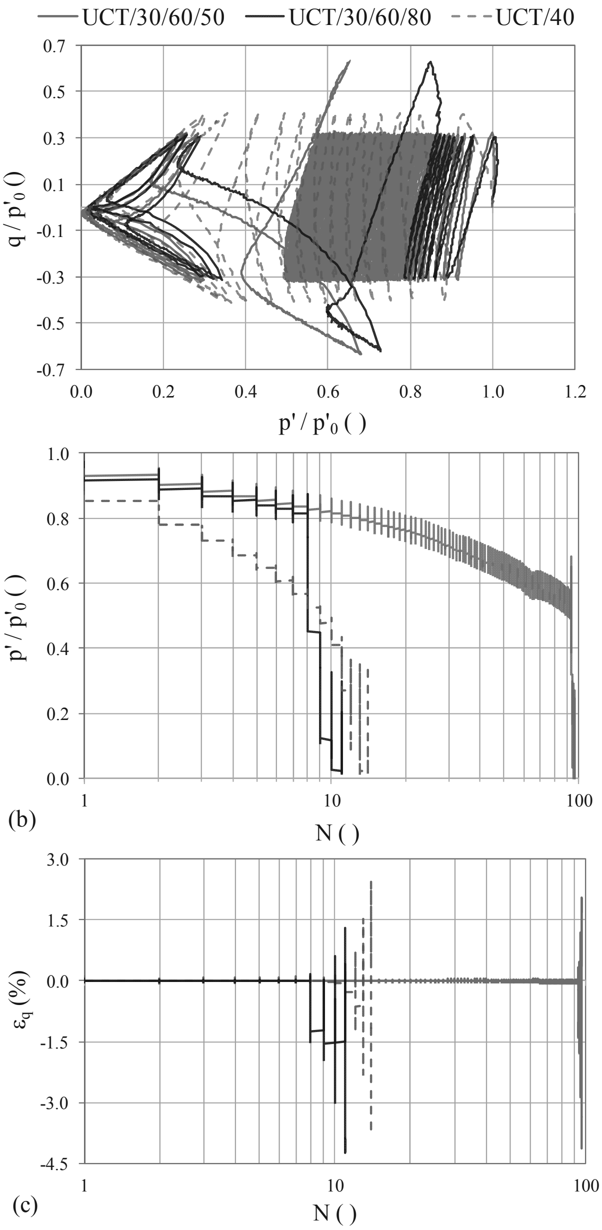

Figure 1. Comparison between the behaviour of similar samples subjected to non-uniform and uniform loading: (a) stress path; (b) mean effective stress degradation with the number of cycles and (c) deviatoric strain variation with the number of cycles.

The main difference in the response of the samples is related to the effect of the peak load on its resistance. In fact, in test UCT40 the rate of mean effective stress degradation is initially slightly faster but remains fairly constant until p' / p'_0 is close to 0.3 (Figure 1b), while in the non-uniform tests that rate suddenly increases as the singular peak occurs, leading to a very rapid degradation of the mean effective stress after that moment. As a consequence, the number of cycles, N, required to obtain a double amplitude of deviatoric strain, ε_q, of 5 % is significantly greater when the peak load is applied at p' / p'_0 of 0.5 (UCT/30/60/50) than when it occurs at p' / p'_0 of 0.8 (UCT/30/60/80) (Figure 1c). This suggests that the location of the peak load plays an important role in sand liquefaction, in opposition to what is assumed in the current methodology used to convert the random stress history of earthquake motion into an equivalent uniform cyclic stress history (as mentioned in Section 2.1). More specifically, when the singular load peak is applied later, either a greater number of cycles is required for the onset of liquefaction or the stress level needed is higher, in accordance with Shen et al. (1978).

Furthermore, it can be observed that the number of cycles required to obtain a double amplitude of ε_q of 5 % is smaller in the case of UCT/30/60/80 test (N = 11) than in the UCT/40 test (N = 14), while it is substantially greater in the case of UCT/30/60/50 test (N = 96). This suggests that the consideration of only uniform loading to evaluate liquefaction potential may not be suitable, namely when the singular peak load occurs in the first cycles, as previously concluded by Azeiteiro et al. (2012).

3 EFFECT OF LOADING MODE ON THE UNDRAINED CYCLIC BEHAVIOUR OF A SAND

3.1 *Load patterns*

Two different tests were carried out in order to study the effect of loading direction on the behaviour of Coimbra sand: axial and radial cyclic triaxial loading. In the first test (UCT/V), which is the most common in laboratory testing, the radial stress was kept constant while the axial stress was varied in order to reach an oscillation of the deviatoric stress of about ±40 kPa (Figure 2a). A similar oscillation of deviatoric stress was imposed in the second test (UCT/H), but by varying only the radial stress, as shown in Figure 2b. It can be observed that the loading frequency used in the latter test had to be reduced, in order to keep the variation of axial stress (which was controlled by a Constant Rate of Strain Pump – CRSP, instead of an air/water interface) close to zero. However, it is commonly accepted that the influence of the loading frequency on the results of these tests is negligible (e.g. Liu et al., 2001).

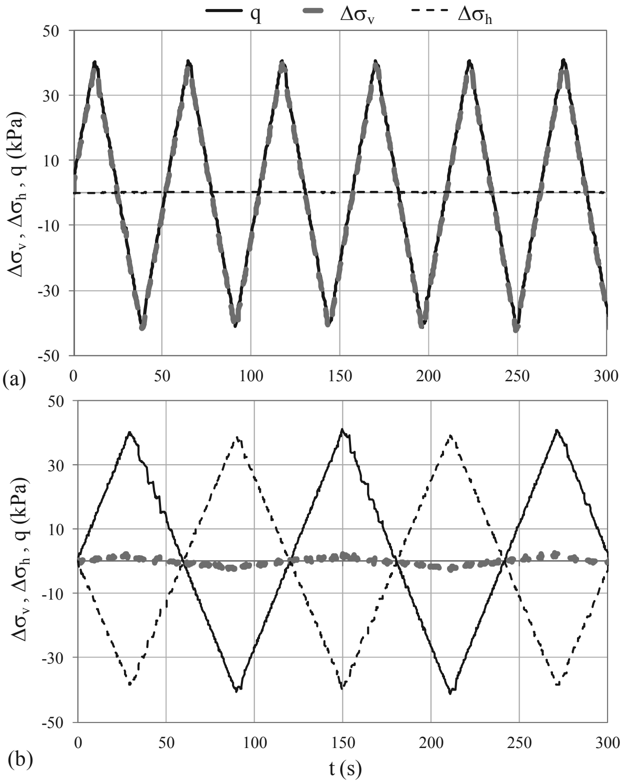

Figure 2. Unidirectional load pattern: (a) vertical and (b) horizontal cyclic triaxial loading.

In addition, to study the effect of multidirectional loading, an undrained cyclic triaxial test with simultaneous variation of the axial stress, σ_v, and the radial stress, σ_h, was performed (UCT/HV test). These stresses were varied 90 º out of phase, in such a way that for a complete cycle the average value of p was kept constant and the maximum oscillation of the deviatoric stress was ±40 kPa (Figure 3). Thus, the imposed load can be considered similar to those used in the other tests, where only the axial or radial stress was varied in each cycle.

Although the same oscillation of deviatoric stress is being applied, the loading mode used in each test was different. While in axial loading only one of the principal stresses (specifically, σ_v) was varied during the whole test, in radial loading two of the principal stresses (i.e. those in the radial direction, σ_{h1} and σ_{h2}) were changed. Finally, in the case of multidirectional loading, the three principal stresses were varied. This implies that the direction of the total stress path is different in each test. As shown in Figure 4, when only axial loading is applied (UCT/V test) the ratio between the variation of the deviatoric stress, q, and the variation of the mean total stress, p, is 3, while for radial loading (UCT/H test) this ratio is 1.5. In the case of multidirectional loading (UCT/HV test), it can be seen that a closed total stress path connecting the extreme points of the previously described tests was used.

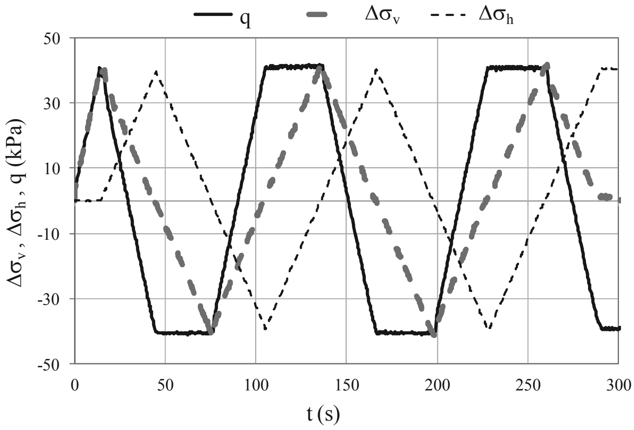

Figure 3. Multidirectional load pattern (approximately first 2.5 cycles).

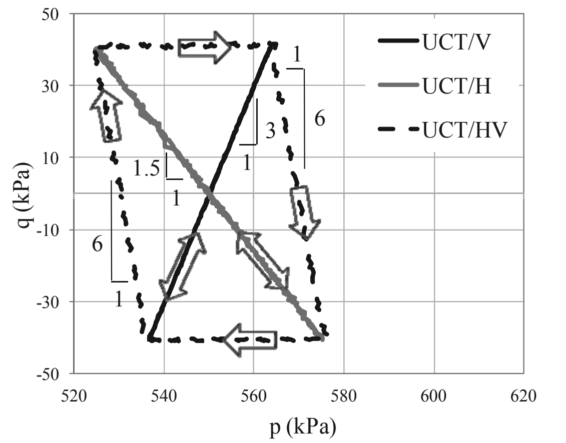

Figure 4. Total stress paths (one cycle).

3.2 *Comparison of axial and radial cyclic triaxial loading*

The stress paths of similarly prepared samples subjected to axial (UCT/V) and radial (UCT/H) loading are presented in Figure 5. It can be observed that a faster degradation of the mean effective stress occurred for radial loading. As clearly shown in Figure 6, the average excess pore water pressure generated in each cycle is greater in UCT/H test, with fewer number of cycles being required for the onset of liquefaction (i.e. to obtain 5 % double amplitude of shear strain). In part, this can be justified by the different loading direction applied to the sample in these tests. As it can be seen in Figure 4, for the same deviatoric stress, q, the range of variation of the mean total stress, p, is greater for the UCT/H test than for the UCT/V test. Thus, for a given variation of pore water pressure in both tests, the variation of the mean effective stress, p’, would be greater in UCT/H test.

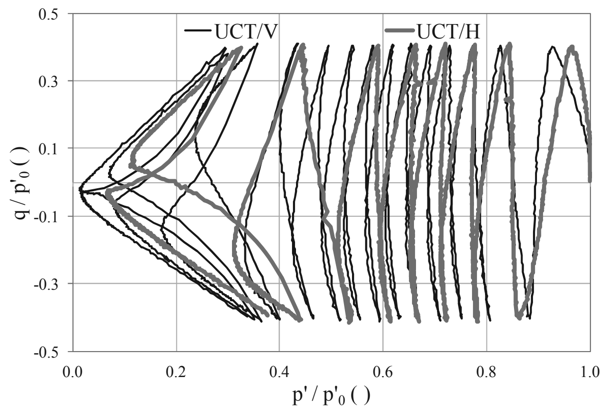

Figure 5. Effective stress paths of axially and radially loaded samples.

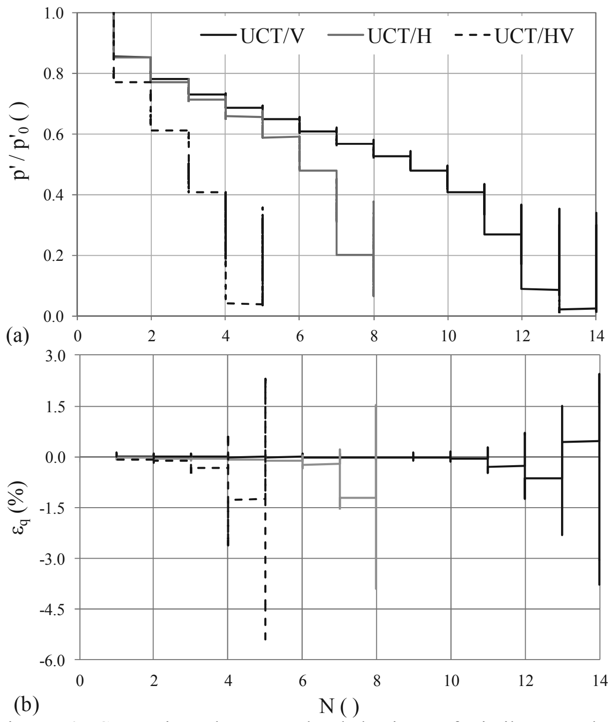

Figure 6. Comparison between the behaviour of similar samples subjected to unidirectional and multidirectional loading: (a) mean effective stress degradation and (b) deviatoric strain variation with the number of cycles.

3.3 *Effect of multidirectional loading on the liquefaction resistance*

Figure 6 compares the response of similar samples of Coimbra sand subjected to unidirectional (UCT/V and UCT/H) and multidirectional loading (UCT/HV). It can be observed that the degradation of the mean effective stress is considerably faster in the case of the sample subjected to multidirectional loading. In particular, the number of cycles required to achieve 5 % double amplitude of shear strain under multidirectional loading is about 65 % and 38 % less than those required under axial and radial loading conditions, respectively.

4 CONCLUSIONS

The results presented herein show that the behaviour of sand is highly dependent on the loading conditions. As suggested by previous studies (e.g. Ishihara & Yasuda 1975), the pore water pressure (pwp) build-up in tests where non-uniform cyclic loading is applied differs from that observed in tests using uniform loading conditions. In the former, a dramatic increase of pwp occurs when the largest load peaks are applied, while, in the latter, an almost constant rate of pwp generation is observed. Consequently, the location of these large peaks clearly affects the number of cycles required for the onset of liquefaction.

Furthermore, even when the variation of deviatoric stress imposed to similarly prepared samples during testing is identical, different loading directions lead to different cyclic responses. Indeed, the results show that liquefaction resistance is greater under axial loading than under radial loading conditions.

Lastly, the application of a multidirectional loading pattern leads to a faster degradation of the mean effective stress than that observed in unidirectional cyclic loading tests.

Due to the random nature of earthquakes, significant uncertainty exists regarding the characteristics of the loading conditions to which soil deposits are subjected during seismic events. Therefore, the evaluation of the impact of the loading mode on liquefaction resistance presents a significant challenge in Geotechnical Earthquake Engineering. This is particularly important when designing laboratory testing programmes, where simplifications are obviously necessary. This paper offers insight into this topic by demonstrating that both non-uniform cyclic loading and the application of relatively simple total stress paths have a considerable effect on the number of cycles required for the onset of liquefaction.

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