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Liquefaction resistance of TP-Lisbon sand: A comparison between cyclic triaxial and cyclic direct simple shear tests

Résistance à la liquéfaction du sable TP-Lisbon: Une comparaison entre les essais triaxiaux cycliques et cisaillement simple direct cycliques.

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ABSTRACT: Soil liquefaction is one of the most complex phenomena characterised by the rapid loss of the strength and stiffness of soil. In the laboratory, the liquefaction resistance can be assessed by different testing procedures, involving axisymmetric and plain strain conditions. This paper addresses an experimental comparison between the results of cyclic triaxial and cyclic direct simple shear testing. The tests were conducted using a historically liquefiable sand from the city centre of Lisbon, denominated as TP-Lisbon sand. Findings showed a higher liquefaction resistance for axisymmetric conditions (cyclic triaxial tests) than plane strain conditions (direct simple shear tests). Therefore, a method to transform the results derived from either cyclic triaxial or direct simple shear is proposed. This method provides a reliable prediction of liquefaction resistance derived inversion and rotation of principal stresses in a single approach.

RÉSUMÉ: La liquéfaction des sols est l'un des phénomènes les plus complexes et instables, se caractérisant par une perte rapide de la résistance et de la rigidité du sol. En laboratoire, la résistance à la liquéfaction peut être évaluée par différentes procédures d'essai, impliquant des conditions axiales symétriques et de déformation simple. Cet article aborde une comparaison expérimentale entre les résultats des essais triaxiaux cycliques et des essais de cisaillement simple direct cycliques. Les essais ont été réalisés avec un sable historiquement liquéfiable du centre-ville de Lisbonne, sable TP-Lisbon. Les résultats ont montré une plus grande résistance à la liquéfaction dans des conditions axysy axisymétriques métriques (essais triaxiaux cycliques) par rapport aux conditions de contrainte pure (essais de cisaillement simple). Par conséquent, une méthode de transformation des résultats obtenus par des essais triaxiaux cycliques ou de cisaillement simple est proposée. Cette méthode permet de prédire la résistance à la liquéfaction en prenant en compte l'inversion et la rotation des contraintes principales au sein d'une seule approche.

Keywords: Liquefaction; laboratory testing; cyclic characterisation; sands.

1 INTRODUCTION

Liquefaction phenomena is characterised by the rapid loss of the strength and stiffness of soil due to the pore pressure build-up during cyclic or monotonic loading. Effective stress tends to zero during liquefaction due to the generation of pore pressure build-up (Ishihara, 1993). Around the world, liquefaction has seriously damaged a number of infrastructures. In Portugal, local liquefaction-induced damage dates from 1344, 1531, 1755 and 1909 when distant and local intraplate earthquakes (with a magnitude between 6.0 and 8.5) struck the Portuguese onshore mainland, mainly affecting the greater Lisbon area (Jorge, 1993). Therefore, the characterisation of the cyclic behaviour of liquefiable soils of Lisbon centre is essential to prevent damage and possible collapse of buildings and infrastructure in this region due to earthquake-induced liquefaction.

This paper presents the results of the liquefaction resistance characterisation of TP-Lisbon sand using cyclic triaxial tests (CTx) and cyclic direct simple shear tests (CDSS). TP-Lisbon sand was collected in a site locally denominated as 'Terreiro do Paço', located in the historical centre of Lisbon (Molina-Gómez & Viana da Fonseca, 2021). The experimental program focuses on the assessment of the effects of the inversion and rotation of principal stresses. A method to assess and compare these effects is proposed herein, proposing an estimation from a single approach. This method provides a reliable unification of both CTx and CDSS results to characterise the liquefaction resistance of TP-Lisbon sand.

2 MATERIALS AND METHODS

2.1 Description of TP-Lisbon sand

TP-Lisbon sand is an alluvial granular soil with origin in the late Quaternary, which has sedimented next to the Tagus River in the historical centre of Lisbon. This site is named by locals as 'Terreiro do Paço', (that in English means courtyard palace). The buildings surrounding this relevant historical spot correspond to old heritage Pombalino masonry buildings (Couto et al., 2020). The samples of TP-Lisbon sand were collected within the scope of geotechnical exploration for the construction of the Lisbon blue line tunnel of 'Metropolitano de Lisboa'. These samples were collected in a site investigation located into the 'Praça do Comércio', specifically at the coordinates 38º42'26.6"N–9º8'13.4"W (Molina-Gómez & Viana da Fonseca, 2021).

The specific gravity of solid particles (G_s), the minimum void ratio (e_{min}) and the maximum void ratio (e_{max}) are shown in Table 1. The parameters of the particle size distribution are also exposed in Table 2, including the mean diameter (D_{50}), the coefficient of curvature (Cc), the coefficient of uniformity (Cu) and the fines content (FC). The particle size distribution of TP-Lisbon sand is depicted in Figure 1. The unified soil classification system (USCS) classifies the TP-Lisbon sand as poorly graded (SP), with low values for Cu and Cc.

Table 1. Physical properties of TP-Lisbon sand.

Parameter	Value
Gs	2.66
e_{min}	0.64
e_{max}	1.01
D_{50} (mm)	0.21
Cu	1.69
Cc	1.13
FC (%)	2.21

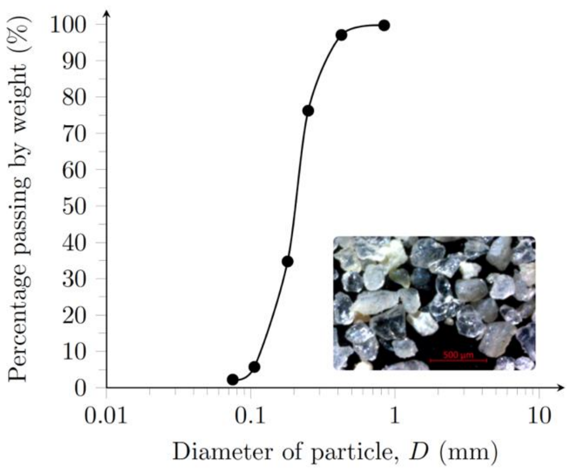

Figure 1. Particle size distribution of TP-Lisbon sand.

2.2 Testing devices and experimentation

The experimental programme for assessing the liquefaction resistance of TP-Lisbon sand involved an advanced testing programme in the laboratory involving cyclic triaxial (CTx) and cyclic direct simple shear (CDSS) tests. CTx and CDSS apparatuses allowed for the inversion and rotation of principal stresses, respectively. Therefore, the comparison between the results of both types of tests provided a comprehensive characterisation of cyclic behaviour and liquefaction resistance of TP-Lisbon sand.

The CTx apparatus featured a traditional triaxial cell equipped with a submersible load cell with a capacity of 1 kN. Cyclic loading was applied using a servo-actuator, consisting of a hydraulic piston for displacement or load control, with a frequency ranging between 0.001 and 2 Hz. A precise regulation of cell pressure and back-pressure was achieved using a pair of Pressure/Volume Controllers manufactured by Global Digital Systems (GDS). These controllers allowed for the automated increment of both pressures during the saturation and consolidation phases. To ensure reliable contact between the top cap and the hydraulic piston during cyclic loading, a rubber V-ring was employed to guarantee the inversion of principal stresses during the cyclic testing (Cordeiro et al., 2022; Molina-Gómez et al., 2023).

An advanced and fully automatic simple shear apparatus manufactured by Willie Geotechnik was employed. The equipment features two high-quality servomotors for vertical and horizontal loading, two local LVDT transducers to measure vertical and horizontal displacements and a multi-axis load cell. It enables static and cyclic tests under both strain and stress control by a SGI configuration. The SGI configuration comprises a series of stacked copper rings to maintain a constant cross-sectional area while allowing for shear distortion of the specimen. The cyclic loading was applied under constant volume conditions, ensuring an invariant height of the specimen through active control based on the vertical displacement reported by local LVDT. Constant volume tests are equivalent to undrained shear tests (Dyvik et al., 1987).

In this study, the following testing procedures were implemented for both CTx and CDSS tests. All samples were reconstituted to achieve a Dr of 50% using the dry pluviation method. This method was adopted due to its capability to replicate the initial fabric of alluvial soil deposits (Quinteros & Carraro, 2023). The samples were saturated by flushing carbon monoxide and de-aired water (Viana da Fonseca et al., 2021). The full saturation condition was confirmed through bender element tests by reporting P-wave velocity values higher than 1482 m/s are needed to ensure the full saturation of the soil (Astuto et al., 2023). After saturation confirmation, the samples were consolidated for a mean effective stress (p'_0) of 50 kPa and effective vertical stress (σ'_0) of 80 kPa for CTx and CDSS tests, respectively. The soil samples were sheared using different cyclic stress ratio (CSR) combinations at a frequency of 0.1 Hz.

3 RESULTS AND DISCUSSION

3.1 Description of TP-Lisbon sand

Figure 2 shows the liquefaction resistance curves for TP-Lisbon sand derived from the results obtained from 5 CTx and 5 CDSS tests. These curves were derived by a power law that correlates the number of cycles liquefaction onset (N_L) for each CSR. N_L was identified when double axial strain exceeding 5.0% for CTx tests and double shear strain exceeding 7.5%.

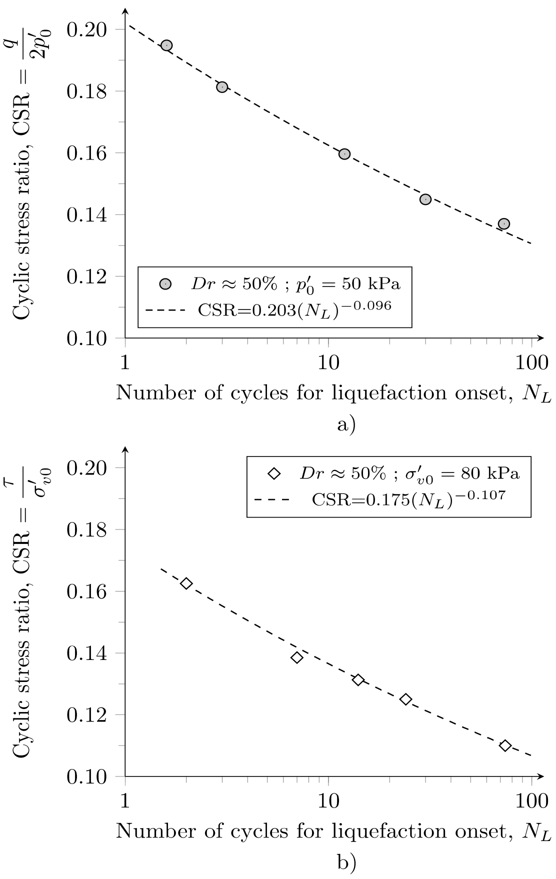

Figure 2. Liquefaction resistance curves: a) CTx results; b) CDSS results.

Experimental results in Figure 2 revealed that inversion of principal stresses (i.e. CTx tests) leads to a higher liquefaction resistance than rotation of principal stresses (i.e. CDSS tests). However, Figure 2 shows that the liquefaction resistance curves for TP-Lisbon sand are parallel, independently of the testing condition. The CTx and CDSS results have been contrasted (Giretti et al., 2018; Nong et al., 2021). Although the loading differences, these results can be correlated using a correction coefficient (*Cr*), which transforms liquefaction resistance from isotropic triaxial testing into liquefaction resistance in simple shear conditions:

$$CSR_{SS} = Cr \cdot CSR_{CTx} \tag{1}$$

Diverse authors (Castro & Poulos, 1977; Finn et al., 1971; Ishihara et al., 1985) demonstrated that *Cr* is a function of the lateral earth pressure coefficient at rest (K_0). Equation 2 presents a *Cr* correlation for TP-Lisbon sand.

$$Cr = \frac{2 + 3K_0}{4} \tag{2}$$

This correlation was obtained by adjusting the experimental results by the least-square method, obtaining a correlation coefficient R^2 = 0.92. For normally consolidated sands, K_0 is reasonably estimated by the approximation $K_0 = 1\text{-}\sin\phi_{cv}$ (Jaky, 1944). Molina-Gómez & Viana da Fonseca (2021) found that the friction angle at constant volume (ϕ_{cv}) of TP-Lisbon sand is 34º. Hence, *Cr* is equal to 0.83. Figure 3 demonstrates that the results obtained from both test types are associated since they fall into a single liquefaction resistance curve after applying the *Cr* transformation.

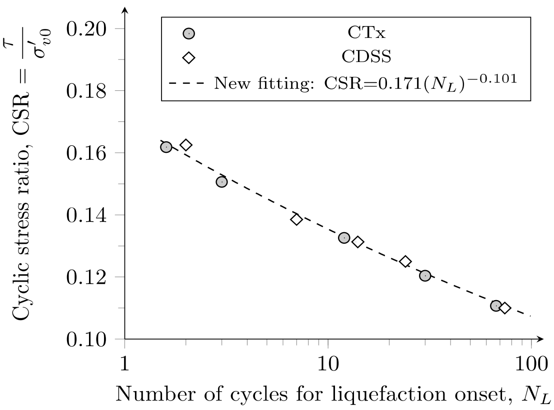

Figure 3. Transformed liquefaction resistance curve.

Figure 3 shows a good agreement between CTx and CDSS after results transformation. Hence, by using the *Cr* transformation, it is possible to compare the liquefaction resistance estimated by both testing procedures, providing a robust basis for cross-referencing their results and facilitating a more comprehensive understanding of cyclic behaviour of TP-Lisbon sand.

4 CONCLUSION

This paper has presented a comprehensive characterisation of the liquefaction resistance of the TP-Lisbon sand using CTx and CDSS testing. Experimental results showed that the inversion of principal stresses leads to higher resistance than the rotation of principal stresses. This disparity between the two testing conditions can be overcome by introducing the correction coefficient, *Cr*. The transformation provided by *Cr* allows for a reliable approach, which provides a valuable approach to compare and understand the liquefaction resistance of TP-Lisbon sand under different stress paths.

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