INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0429

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Characterisation of liquefiable sands using the hollow cylinder apparatus

Caractérisation de sables liquéfiables à l‘aide de l‘appareil à cylindre creux

L.M. Araújo Santos
Polytechnic Institute of Coimbra, Coimbra, Portugal

P.A.L.F. Coelho, R.C. Ramos
University of Coimbra, Coimbra, Portugal

D.M.G. Taborda
Imperial College London, London, United Kingdom

ABSTRACT: Liquefaction-related phenomena due to earthquake events are a serious threat to modern societies. Most of the main frameworks used are based on triaxial test results, which do not reproduce in a realistic way the field conditions and seismic loading. To overcome these limitations, the University of Coimbra uses its hollow cylinder apparatus to investigate sand behaviour under generalised loading conditions. Two sands of different origins were used to carry out this study: Coimbra sand (Portugal) and Hostun sand (France). Based on the results of monotonic and cyclic torsional tests, several features of the behaviour of saturated sands are identified and discussed, reinforcing the applicability of this tool to the prediction of the response of sands when subjected to generalised cyclic loading.

RÉSUMÉ: Les phénomènes liés à la liquéfaction dus aux séismes constituent une menace sérieuse pour les sociétés modernes. La plupart des principaux outils utilisés sont basés sur des résultats de tests triaxiaux, qui ne reproduisent pas de façon réaliste les conditions de terrain et les charges sismiques. Pour surmonter ces limitations, l'Université de Coimbra a commencé à utiliser son appareil à cylindre creux pour étudier le comportement du sable sous des conditions de chargement généralisées. Deux sables d'origine différente ont été utilisés pour réaliser cette étude: le sable de Coimbra (Portugal) et le sable de Hostun (France). Ayant comme base des résultats d'essais de torsion monotones et cycliques, plusieurs caractéristiques du comportement des sables saturés sont identifiées, renforçant l'applicabilité de cet outil même quand les sables sont soumis à des chargements cycliques généralisés.

Keywords: Sand liquefaction, hollow cylinder apparatus, phase transformation state, cyclic loading.

1 INTRODUCTION

Liquefaction-related phenomena due to earthquake events are a serious threat to modern societies in seismic active zones due to the damage they can produce. In order to implement the concept of performance-based design and to allow the use of advanced design tools in current design practice in the field of geotechnical earthquake engineering, fundamental characterisation of sands is extremely important.

Most of the main frameworks used are based on triaxial compression and extension test results, which do not reproduce in a realistic way neither the field conditions nor the characteristics of seismic loading. To overcome these limitations, the University of Coimbra uses its hollow cylinder apparatus (HCA) to investigate sand behaviour under generalised loading conditions. The versatility of this equipment enables the application of more realistic testing conditions in the context of sand liquefaction (Ishihara, 1996). In addition, the sets of global and local instrumentation allow the characterisation of the mechanical behaviour of sands under a wide range of strain levels, enabling critical state conditions to be reached.

The correct understanding of the behaviour of sands requires the knowledge of several special states, among them the Phase Transformation State. This state, in which the soil passes from a contractive behaviour to a dilatant behaviour, is usually defined in monotonic loading tests with stress path cells, such as the one illustrated in Figure 1. These findings are then applied in the study of different scenarios involving cyclic loading, in order to determine the stress-strain-strength behaviour of sands during seismic events.

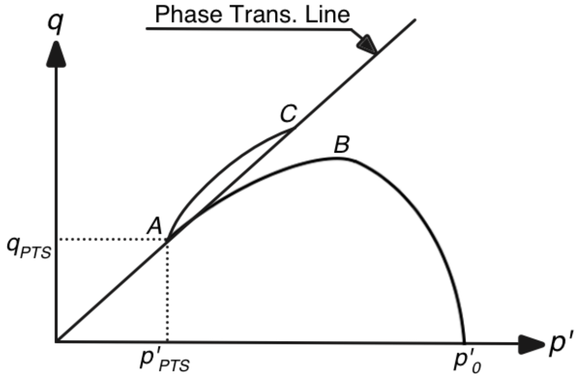

Figure 1. Schematic representation of the behaviour of a loose sand (adapted from Ishihara, 1996).

In the present study, results of monotonic and cyclic tests carried out using two sands – Coimbra sand, a Portuguese sand extracted on the banks of Mondego River that flows through the city of Coimbra in the centre of Portugal, and Hostun sand, a well-known reference sand for international liquefaction studies – are presented. Firstly, the behaviour of the two sands is presented and compared. Secondly, the Phase Transformation Line established based on undrained monotonic tests is compared to that obtained in cyclic torsional tests, in order to confirm if the conclusions typically drawn from cyclic triaxial tests remain valid.

2 EXPERIMENTAL PROGRAMME

The laboratory testing programme comprises the realisation of monotonic and cyclic torsional tests in two sands: Coimbra sand and Hostun sand. All the tests were carried out in the University of Coimbra's HCA. The following sections present a description of the laboratory equipment, the investigated materials and the testing procedures.

2.1 Studied materials

Coimbra sand is an artificial sand, obtained by sieving alluvial deposits collected along the banks of the Mondego River, the largest Portuguese river flowing through the centre of the country. Its principal properties are summarised in Table 1.

Table 1 – Physical properties of the sands tested

	Coimbra sand	**Hostun RF sand**
D_{min} (mm)	0.125	0.075
D_{max} (mm)	0.425	0.850
D_{50} (mm)	0.290	0.330
C_U (-)	1.789	1.400
C_C (-)	1.000	-
G (-)	2.640	2.640
e_{min} (-)	0.55^*	0.660
e_{max} (-)	0.96^+	1.000

* determined according to ASTM 4253-00
$^+$ determined according to ASTM 4254-00

Hostun RF sand is a fine-grained, sub-angular to angular, siliceous sand (Flavigny et al., 1990), which comes from SIKA industries, located near Hostun, in the South-East of France, between Valence and Grenôble. Throughout the past decades, it has been used as a reference soil to study sand behaviour and liquefaction-related phenomena and different values of physical characteristics have been proposed by different authors. The present study adopts the values established in previous research work carried out at the University of Coimbra (Azeiteiro et al., 2017)

Figure 2 shows the grain size distribution of both sands and, as it can be seen, both curves lie within the limits established by Tsuchida (1970) to define soils which are susceptible to liquefaction.

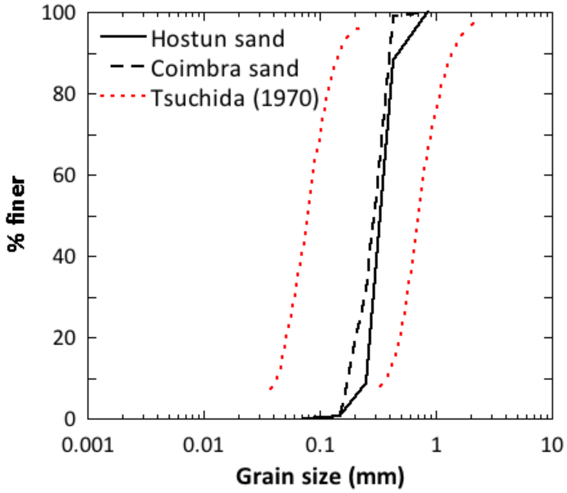

Figure 2. Grain size distribution of Coimbra and Hostun sands.

2.2 Hollow cylinder apparatus

The University of Coimbra's equipment is a HCA Mark II (Jardine, 1996) and was developed at Imperial College London. The adopted design enables the control of the axial load, the torque, the inner cell pressure, the outer cell pressure and the backpressure. By controlling and monitoring these five variables, one may impose more realistic stress state conditions to the soil sample, as well as control the direction of the principal stress.

The HCA is equipped with two sets of instrumentation: four global instruments and seven local devices, in addition to a combined load cell and four pressure transducers. The latter transducers control the inner and outer cell pressures, as well as the backpressure. It should be noted that, while both top and bottom backpressures readings can be acquired, it is only possible to control one of them (typically the bottom one). The global instrumentation consists of two strain displacement transducers, which are connected to the HCA pedestal and measure the axial and angular displacements of the sample, and two volume gauges to control and register volume variations of the inner cell and the sample.

The local instrumentation comprises a LVDT to measure the radial deformation of the inner sample wall and three proximity sensors to measure that of the outer sample wall. The axial and shear strains are computed based on the measurements of two dual-axis electrolevels and on single-axis electrolevel. These last two devices were also developed at Imperial College London (Burland and Symes, 1982; Shibuya, 1985). The location of the local instrumentation is illustrated in Figure 3. With the exception of the proximity sensors, all local devices are glued to the membrane of the sample. All the instruments must be installed at the mid-height of the sample, thus avoiding stress non-uniformities associated with end effects (Hight *et al.*, 1983).

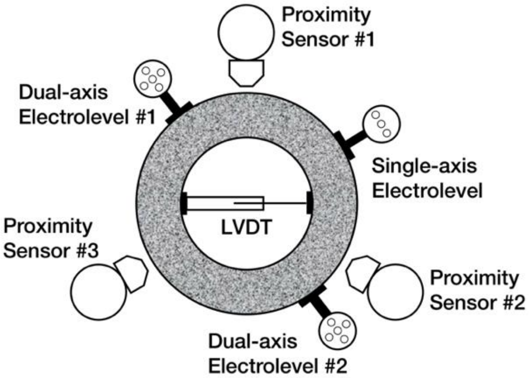

Figure 3. Positioning of the local instrumentation

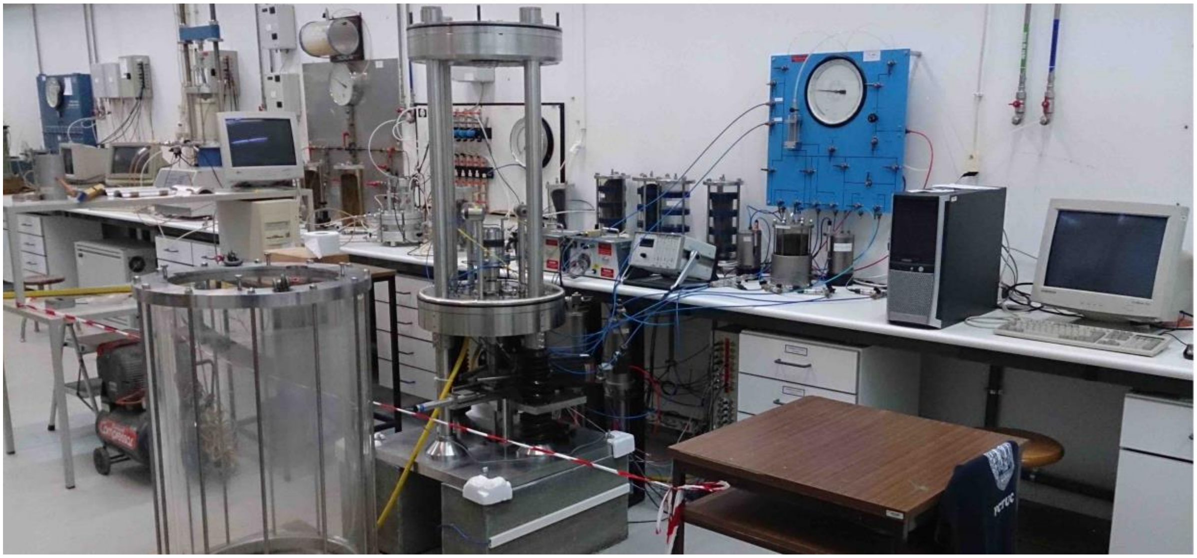

Figure 4. Coimbra's hollow cylinder apparatus

The operation of the HCA requires a 1MPa compressed air network and all the pressure and measurement devices are remotely operated via computer software. The axial load and torque may be applied by air/water interfaces or by controlled rate stress pumps (CRSP), while the inner and outer cell pressures are applied via air/water interfaces or, as it currently stands for the inner cell pressure, by volume gauges. Lastly, all the hydraulic lines are connected to a control panel, which enables the control of the pressures inside the HCA, as well as the application of suction within the sample during its preparation. Figure 4 shows a global overview of the HCA and its components.

The current configuration of the University of Coimbra's HCA enables the testing of samples with two different dimensions: 60ID:100OD:200H and 150ID:200OD:300H (ID – internal diameter; OD – outer diameter; H – height of sample; all in mm). The axial load is limited to 8 kN while a maximum torque of 400 Nm can be applied. The maximum pressure allowed inside the chamber is 850 kPa.

Fundamentally, the HCA allows the characterisation of several features of sand behaviour that are difficult or impossible to study in conventional triaxials, e.g. i) the effect of induced or inherent anisotropy; ii) the impact of principal stress rotation; iii) the influence of the intermediate principal stress. In addition to these, the HCA is a powerful and versatile equipment, providing insight into the cyclic behaviour of sands in general and liquefaction-related phenomena in particular. Indeed, it is possible to simulate green-field conditions, studying, for example, the influence of different lateral restraint conditions (Araújo Santos, 2015), as well as applying multi-directional loadings in order to simulate, for example, the behaviour of foundations under seismic loading (e,g. Jin *et al.*, 2008).

2.3 Testing procedures

Running laboratory tests on the HCA requires methodical and systematic procedures for sample and equipment preparation. The following sections provide a brief overview of the employed methodologies, as well as the main characteristics and initial conditions of the tested samples, the results of which are presented in this paper.

2.3.1 Sample preparation and mounting

All the tested samples were reconstituted samples prepared by pluviation through air. With this technique, the sand is rained through a surface which covers the entire cross-sectional area of the sample. This procedure is commonly accepted as being the most adequate to simulate the natural sand deposition process as well as the soil structure observed in a natural alluvial environment (Oda *et al.*, 1978).

This preparation technique depends essentially on four factors: i) the medium through which the sand is poured; ii) the height from which the sand is dropped; iii) the deposition flow and iv) the deposition mode. As previously mentioned, all the samples were poured through air from a height of about 200 mm, with deposition flow being controlled by the number of holes (and their diameter) on a plate through which the sand was rained. There was no need of using sieves to ensure an effective spreading of sand particles.

With this methodology, relatively loose samples (D_R=40%) of the two different sands were prepared by two different researchers, obtaining very consistent values of initial relative density (standard deviation below 3%). The standard deviation observed in the relative density of denser samples (D_R=70%) of Coimbra sand was slightly higher, of about 3.8% (Araújo Santos, 2015).

2.3.2 Description of tests and initial conditions

The results presented are part of extensive characterisation studies on both sands, covering a wide range of relative densities, loading conditions and drainage characteristics. In this study, only the results obtained for loose samples (relative density, D_R, of 40%) are discussed. This value of D_R corresponds to initial void ratios of 0.864 and 0.796 for Hostun and Coimbra sands, respectively.

After sample preparation and the installation of all the measurement devices, samples were subjected to two saturation processes (Araújo Santos, 2015). The first process starts immediately after having filled the outer cell and enough pressure is applied to safely remove the suction from within the sample. By keeping a small pressure differential between the bottom and top of the sample, water is allowed to flow upwards and the air trapped in the sample and hydraulic pipes is collected in the air/water interface.

The pressures are then increased until pressures for which the consolidation stage begins are reached. At this point, and keeping once again a small pressure differential between the bottom and the top of the sample, water is allowed to percolate upwards. This second saturation process ensures the removal of the air within the sample and hydraulic pipes that has not been dissolved when pressure was being increased. This double saturation process ensures a value for Skempton's pore water pressure parameter (B) greater than 0.97. Higher values are difficult to obtain because all the HCA's hydraulic system is not fully saturated when the sample preparation begins.

Lastly, samples are consolidated. In the present study, all samples were consolidated to an initial isotropic effective stress state of 200 kPa. This stress state is kept for twelve hours to allow for creep phenomena, with the shearing stage starting as soon as creep rates are deemed to be sufficiently low. The results of two monotonic torsional tests (**MT**) and one cyclic torsional test (**CT**) performed are discussed in the following sections. It should be noted that all the tests were carried out under undrained conditions (**U**). Table 2 summaries the main characteristics of these tests and their initial conditions.

Table 2. Tests designation and initial conditions

Test designation	**Sand**	p'_0 **(kPa)**	e_0 **(-)**
CbrUMT$^+$	Coimbra	200	0.787
HosUMT*	Hostun	200	0.880
HosUCT*	Hostun	200	0.870

$^+$ (Araújo Santos, 2015); * (Ramos, 2018)

3 SOIL BEHAVIOUR

The presentation and discussion of the test results follow the sequence of tests on which this article is based: monotonic tests results are first introduced, followed by those of the cyclic test.

3.1 Monotonic behaviour of Hostun and Coimbra sands

The stress-strain behaviour of both sands is represented in Figure 5. Clearly, both sands exhibit the expected behaviour for fully saturated loose granular materials under undrained conditions. After an initial contractive stage, the samples start dilating until the end of test. As it can be seen, both sands present identical behaviour during the early stages of the test, where their stress-strain curves are coincident. Subsequently, given the more contractive behaviour of Coimbra sand, the stress-strain curves diverge. However, once Coimbra sand starts dilating, it is characterised by a slightly stiffer response than Hostun sand. It should be noted that the maximum shear strain reached in the CbrUMT test is only about half of that registered in the HosUMT test, due to the use in the former test of the original 50 mm displacement transducer. This device was subsequently replaced by a new one with a 100 mm capacity, an improvement which was crucial in order to allow greater deformation, namely in cyclic tests (Araújo Santos, 2015).

The contractive and dilatant behaviour of both sands is more visible when plotting their stress paths in p'-q space, as shown in Figure 6. Additionally, this representation allows the identification of the Phase Transformation State (PTS) for both sands, which corresponds to the point where samples stop contracting and start dilating. The Phase Transformation Line (PTL) for Hostun sand is also represented in Figure 6. Despite having an identical initial state (D_R= 40% and p'_0= 200 kPa) as well as some similarities in their stress-strain behaviours, the switch from a contractive to a dilatant behaviour occurs in different states. A closer look at the PTS of Coimbra sand reveals another interesting feature of sands, the Quasi-Steady State (QSS). This state, which coincides with the PTS can be seen as a special case of the latter. Indeed, while the PTS is defined as the point at which the minimum mean effective stress (p') is reached in a contractive-dilating behaviour, the QSS corresponds to minimum values of both mean effective stress and deviatoric stress (q) (Ishihara, 1996).

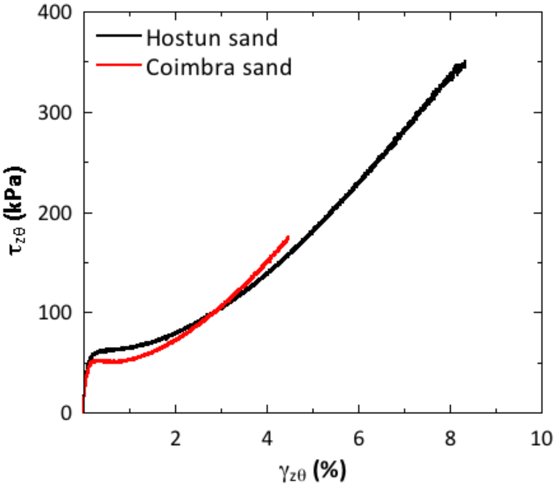

Figure 5. Stress-strain behaviour under monotonic torsion of Hostun and Coimbra sands (D_R=40 %).

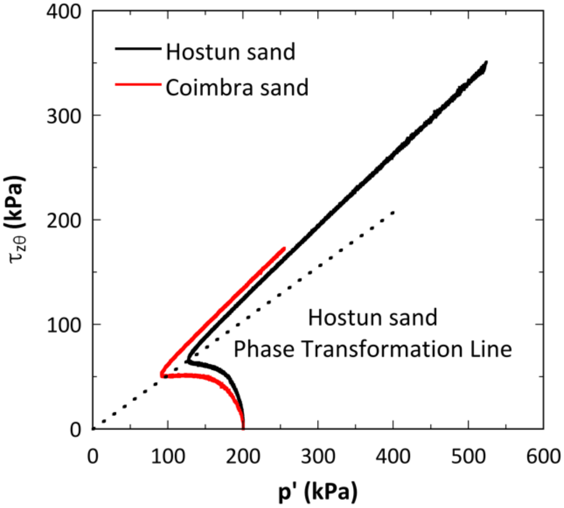

Figure 6. Monotonic torsion tests stress paths of Hostun sand (D_R=40%).

The analysis of these two monotonic tests allowed the identification of some of the key features of the behaviour of sands, confirming that the conclusions drawn based on the results of triaxial tests are also verified for non-triaxial loading conditions. Unfortunately, it was not possible to reach the critical state due to limitations in the applicable strain range.

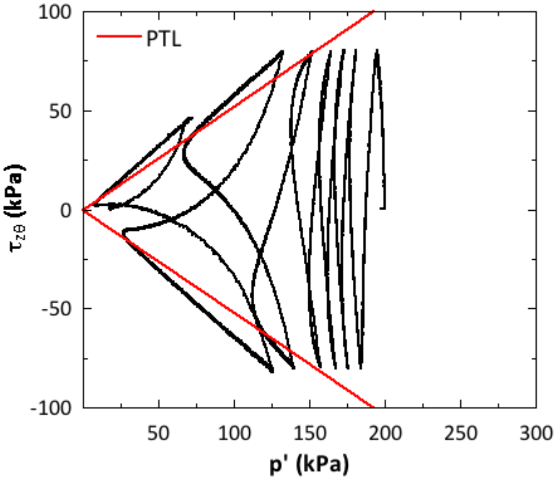

Figure 7. Hostun sand response under cyclic torsional loading at 40 % relative density.

3.2 Cyclic behaviour of Hostun sand

Under cyclic loading, the behaviour of saturated sands behaviour is characterised by progressive softening (cyclic mobility) due to generation of excess pore pressures (Kramer, 1996). It should also be noted that shear strains tend to increase due to the dilatant behaviour as soon as the PTL is crossed, after which an unloading stage generates additional excess pore pressures (Chern, 1985).

To verify the previous statement for torsional loading conditions, a cyclic torsional test was carried out on a sample of Hostun sand characterised by the same initial conditions as those of the sample tested under monotonic loading. The stress path of this third test is shown in Figure 7. The Phase Transformation Line obtained in the monotonic test is also represented. As expected, Hostun sand exhibits a cyclic mobility behaviour when subjected to undrained cyclic loading. It is also clearly visible that in the first cycles, the generated excess of pore pressures is low, becoming more significant when the PTL is crossed.

Examining the stress state when the sand behaviour switch from a contractive to a dilatant behaviour, it can be seen that it occurs slightly below the Phase Transformation Line resulting from the analysis of the monotonic test results. Two reasons may be appointed for this result. Firstly, despite the initial void ratio (after pluviation) of both cyclic and monotonic sample being very similar (see Table 2), a slight densification of the cyclic test sample may have occurred. Thus, and since the Phase Transformation Line depends on the relative density (Zhang et al., 1997), monotonic and cyclic results cannot be compared.

The second reason is due to the fact that a unique Phase Transformation Line may not be sufficient to fully predict the cyclic behaviour of sands. Indeed, some authors, among them Zhang *et al*. (1997) and Nakata *el al*. (1998) postulate that the Phase Transformation Line moves during the cyclic loading.

4 CONCLUSIONS

The comprehensive understanding of the behaviour of saturated sands when subjected to cyclic loading is required to establish appropriate safety criteria in the design of (infra)structures to avoid both social and economic losses due to liquefaction-related phenomena. This can only be achieved through the application of competent frameworks established based on laboratory testing which replicate *in situ* conditions.

The hollow cylinder apparatus is, currently, the most complete and versatile element testing apparatus. In this study, torsional tests employing the University of Coimbra's HCA were used to verify the applicability for other loading directions of the main features of sand behaviour, initially proposed based on triaxial compression/extension conditions tests.

The analysis of monotonic tests carried out on two different sands, Hostun sand (France) and Coimbra sand (Portugal), clearly demonstrates that some of the features of the behaviour of sands remain valid. Both Phase Transformation and Quasi-Steady states may be identified as well as the strain softening and strain hardening behaviours of loose sands. Lastly, a cyclic torsional test was performed, reinforcing the importance of knowing the Phase Transformation Line in order to better predict the generation of excess pore pressures and how it affects the stress state during the loading.

5 REFERENCES

ATSM 2000. D 4253 – Standard test methods: maximum index density and unit weight of soils using a vibratory table. American Society for Testing Materials. West Conshohocken, USA.

ATSM 2000. D 4254 – Standard test methods: minimum index density and unit weight of soils and calculation of relative density. American Society for Testing Materials. West Conshohocken, USA.

Araújo Santos, L.M. 2015. Characterization of the mechanical behaviour of Coimbra sand under generalised loading conditions, *PhD thesis*. Coimbra: University of Coimbra, Portugal (in Portuguese).

Azeiteiro, R.J.N., Coelho, P.A.L.F., Taborda, D.M.G., Grazina, J.C.D. 2017. Critical state-based interpretation of the monotonic behavior of Hostun sand, *Journal of Geotechnical and Geoenvironmental Engineering*, **143** (5).

Burland, J.B., Symes, M. 1982. A simple axial displacement gauge for use in the triaxial apparatus, *Géotechnique*, **32** (1): 62-65.

Chern, J.C. 1985. Undrained response of saturated sands with emphasis on liquefaction and cyclic mobility, *PhD Thesis*. Vancouver: University of British Columbia, Canada.

Flavigny, E., Desrues, J., Palayer, B. 1990. Le sable d'Hostun «RF», *Revue Française de Géotechnique*, **53**: 67-69.

Hight, D.W., Gens, A., Symes, M.J. 1983. The development of a new hollow cylinder apparatus for investigating the effects of principal stress rotation in soils, *Géotechnique*, **33** (4): 355-383.

Ishihara, K. 1996. Soil behaviour in earthquake geotechnics. New York: Oxford Science Publications.

Jardine, R. 1996. Preliminary report on the design and manufacture of equipments. Imperial College London, London. *Internal Report*.

Jin, D., Luan, M.-T., Li, C. 2008. Liquefaction and cyclic failure of sand under bidirectional cyclic loading, *Electronic Journal of Geotechnical Engineering*, **13** (G).

Kramer, S.L. 1996. Geotechnical Earthquake Engineering. New Jersey: Prentice Hall.

Nakata Y., Hyodo M., Murata, H., Yasufuku, N. 1998. Flow deformation of sands subjected to principal stress rotation, *Soils and Foundations*, **38** (2): 115-128.

Oda, M., Koishikawa, I. Higuchi, T. 1978. Experimental study of anisotropic shear strength of sand by plane strain tests, *Soils and Foundations*, **18** (1): 25-38

Ramos, R.C. 2018. Characterization of the cyclic behaviour of Hostun sand using the hollow cylinder apparatus. *MSc dissertation*. Coimbra: University of Coimbra, Coimbra (in Portuguese).

Shibuya, S. 1985. Undrained behaviour of granular materials under principal stress rotation, *PhD thesis*. London: Imperial College London, UK.

Tsuchida, H. 1970. Prediction and countermeasure against liquefaction in sand deposits, *Proceedings of the Seminar of the Port and Harbour Research Institute*: 3.1-3.33.

Zhang, J.-M., Shamoto, Y., Tokimatsu, K. 1997. Moving critical and phase transformation stress state lines of saturated sand during undrained cyclic shear, *Soils and Foundations*, **37** (2): 51-59.