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

doi: 10.32075/17ECSMGE-2019-0014

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

Collection of high-quality samples in liquefiable soils using new sampling techniques

Collecte d'échantillons de haute qualité dans des sols liquéfiables à l'aide de nouvelles techniques d'échantillonnage

A. Viana da Fonseca, C. Ferreira, F. Molina-Gómez & C. Ramos
CONSTRUCT-GEO, Universidade do Porto, Faculdade de Engenharia, Porto, Portugal

ABSTRACT: Due to the difficulty in collecting undisturbed samples of cohesionless loose soils, the mechanical characterisation of liquefiable soils is routinely performed in advanced laboratory tests on reconstituted specimens. Following recent advancements in sampling, namely with the development of the Dames & Moore and the Gel-Push samplers, high-quality samples of loose sands to silty sands from Benavente (Portugal) have been collected. Documents about the 1909 earthquake demonstrate the occurrence of liquefaction phenomena in these soils, which are currently being studied as part of two research projects ongoing in the CONSTRUCT-GEO centre of FEUP. This paper introduces the sampling processes in the field with both techniques, as well as the laboratory preparation and setup of the samples for element testing. Preliminary assessment of the sampling quality of the collected samples has been made through the comparison of field and laboratory measurements of shear wave velocity, obtained by SCPTu and bender-element bench tests, respectively.

RÉSUMÉ: En raison de la difficulté à collecter des échantillons de sols meubles sans cohésion et non perturbés, la caractérisation mécanique des sols liquéfiables est systématiquement effectuée lors d'essais de laboratoire avancés sur des échantillons reconstitués. Suite aux progrès récents de l'échantillonnage, notamment avec le développement des échantillonneurs Dames & Moore et Gel-Push, des échantillons de haute qualité de sables meubles à sables limoneux de Benavente (Portugal) ont été récupérés. Des documents sur le tremblement de terre de 1909 démontrent l'apparition de phénomènes de liquéfaction dans ces sols, qui sont actuellement à l'étude dans le cadre de deux projets de recherche en cours au centre CONSTRUCT-GEO de FEUP. Ce document présente les processus d'échantillonnage sur le terrain avec les deux techniques, ainsi que la préparation en laboratoire et la configuration des échantillons pour le test des éléments. L'évaluation pré-liminaire de la qualité d'échantillonnage des échantillons prélevés a été effectuée en comparant les mesures de la vitesse des ondes de cisaillement sur le terrain et en laboratoire, par des essais SCPTu et à éléments bender en banc, de manière spectrale.

Keywords: Dames and Moore sampler, Gel-push sampler, high-quality sampling, liquefiable sands, shear wave velocity.

1 INTRODUCTION

One of the most complex phenomena occurring in granular materials is liquefaction. Such phenomenon induces the loss of strength and stiffness due to the generation of excess pore water pressure. Furthermore, loose to medium sands under undrained conditions are the most susceptible for liquefaction triggering (Ramos *et al.*, 2015). The assessment of liquefaction susceptibility can be carried out by means of field and laboratory procedures. Nevertheless, there is some variability of the results obtained by different techniques, due to the soil spatial uncertainty and the disturbance of samples used for element testing in the laboratory.

Obtaining undisturbed samples of loose to medium-dense sands is a challenge, since these soils are often susceptible to experiment significant volume changes and collapse its structure during sampling. Besides, any change in relative density or fabric will affect the liquefaction resistance of the soil, as the sample becomes denser and thus less representative of the in situ conditions. Disturbance of soil samples is mainly attributed to the excessive friction generated during penetration of the sampler into the ground (Chen *et al.*, 2014). In order to solve this issue, the Dames & Moore (D&M) and the Gel-push (GP) samplers have been developed. Such samplers are known as advanced sampling devices, due to the incorporation of novel materials to reduce the friction between the sample and the walls of the liner in which the soil is collected. The D&M sampler is a hydraulic fixed-piston device, similar to the Osterberg, with a shorter length to reduce wall friction and brass tubes to generate lower friction in the interface. On the other hand, the GP sampler uses a viscous polymer gel to substantially reduce wall friction during field extraction and sample extrusion in the laboratory. Both devices allow retrieving relatively "undisturbed" samples of medium-dense sands, silty sands, silts, compressible silty sands, silty clays and clays. These samplers have already been implemented with success for laboratory characterization of liquefiable soils in Adapazari, Turkey (Bray and Sancio, 2006), Dhaka, Bangladesh (Ishihara *et al.*, 2016) and Christchurch, New Zealand (Markham *et al.*, 2016; Bray *et al.*, 2017).

This paper deals with the description of the collection of high-quality samples of liquefiable soils from a pilot site in Benavente (south of Portugal) by means of D&M and GP sampling. The selection of the depths to retrieve the samples was based on SCPTu test results, as these provide valuable information regarding soil behaviour type and the location in depth of the sandy layers. In addition, shear wave velocity (V_S) values obtained from in situ and bender-element (BE) bench tests in the laboratory were used to evaluate the quality of the samples. Finally, a comparative analysis is presented regarding the quality of the samples retrieved by both samplers.

2 MATERIALS AND METHODS

2.1 Site description

An experimental campaign to retrieve high-quality samples of liquefiable soils was carried out in a pilot site located in the municipality of Benavente, in Lower Tagus River Valley (LTV) region, south of Portugal. According to Eurocode 8, the South of Portugal is the region with the highest seismic risk of the country due to the proximity of the boundary of African and Eurasian plates. Besides, such area is affected by the occurrence of large magnitude (>8) distant earthquakes and of medium magnitude (>6) near earthquakes (Azevedo et al., 2010).

The selection of the location of the pilot site was based on historical records of liquefaction during the earthquake of 23rd April 1909 in Benavente (Teves-Costa and Batlló, 2011; Cabral *et al.*, 2013). In addition, from extensive geological and geotechnical data reported by Saldanha *et al.* (2018), the presence of thick profiles of recent alluvial sandy deposits was identified in this region. The selected site is located near the shore of the Tagus River and its position coordinates are 39°1'0.77"N, 8°50'25.89"W (Figure 1). Prior to sampling, the site was investigated with SCPTu in order to identify consistent soil layers suitable for sampling. V_S values were measured at each 1 m depth. Figure 2 presents the SCPTu test results, which were interpreted according to Robertson (2009). Based on site characterisation, sandy layers were identified at 5 to 12 m depth. This work focuses on the study of the soil samples collected at such depths.

Figure 1. Pilot site location (adapt Google Earth®).

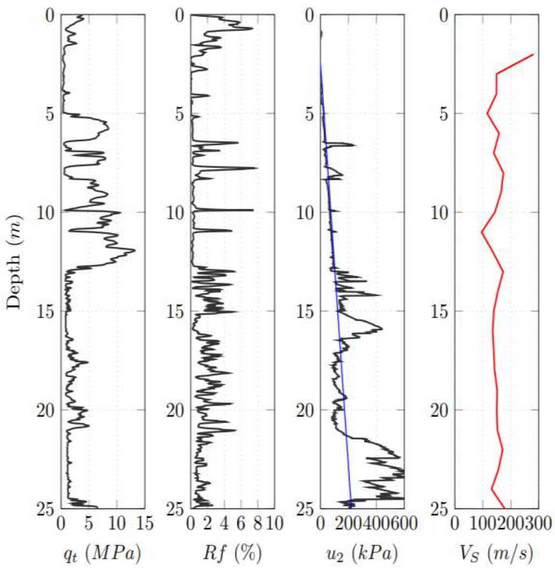

Figure 2. SCPTu results

2.2 *Dames and Moore sampler*

Dames and Moore (D&M) sampler is an advanced sampler used to collect mainly fine sands and silty soils (Bray and Sancio, 2006). This device consists of an Osterberg-type hydraulic activated fixed-piston sampler, that can retrieve relatively "undisturbed" soil samples (Markham *et al.*, 2016). D&M sampler has a 50 cm long liner, made of smooth brass that effectively minimizes the friction between the tube walls and the soil.

On the other hand, the D&M sampler presents an innovation related to its sealing system. This system keeps the sample inside the liner during the retrieval due to the vacuum generated during insertion, which allows recovering samples with 45-50cm length, preventing sample from falling inside the borehole (Viana da Fonseca and Pineda, 2017). The key component to ensure the vacuum is a neoprene skirt seal, located in the transition of the pressure cylinder and the liner. This seal prevents the entrance of disturbed soil into the liner from the bottom of the borehole and also acts as a check valve for the driving pressure. Figure 3 shows a scheme of the components of the D&M sampler.

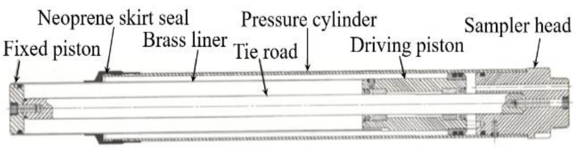

Figure 3. Schematic of D&M sampler components

The operation principle of this sampler is based on the fixed hydraulic piston sampler proposed by Osterberg (1973), which consists of three different stages. The first stage refers to the drilling of an external hole to stabilize the excavation and prevent the groundwater seepage through the borehole. In the second stage, the sampler is inserted in the borehole to a specific depth. A thin-walled tube or liner is then pushed into the ground at constant pressure until its maximum length is reached, by means of the injection of a fluid (usually water) at 1400 kPa minimum pressure, in order to achieve a constant penetration rate. The soil sample is collected inside the brass liner. At the completion of liner advancement, the tube remains stationary for a minimum of 1 min. The third stage corresponds to the sample recovery. The sampler is retracted to the surface and the liner is extracted and prepared for transport and storage. Figure 4 illustrates the operation phases of a fixed hydraulic piston sampler, which is the same principle of the D&M.

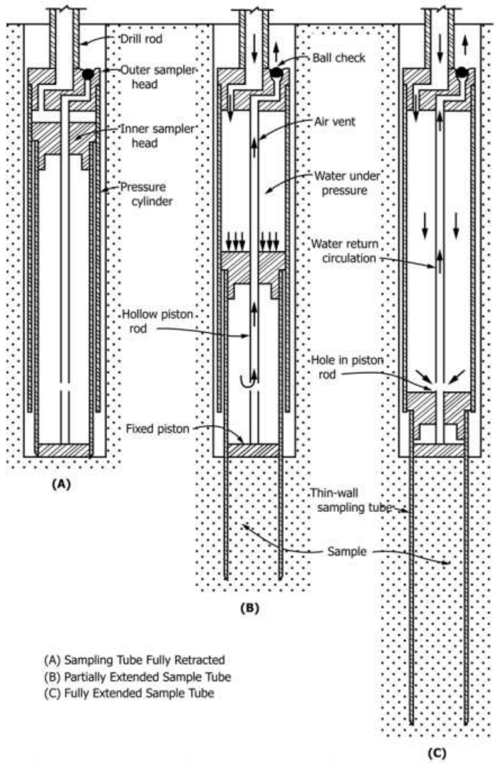

Figure 4. Fixed hydraulic piston sampler operation (ASTM International, 2015)

2.3 Gel-push sampler

The Gel-push sampler is an advanced device capable of recovering high-quality undisturbed samples of granular soils, developed by the Japanese geotechnical consulting company Kiso-Jiban Consultants. This sampler is composed by a triple core barrel and uses a viscous polymer gel as its drilling fluid, hence the name Gel-push (GP). Its name is a reference to the operating principle and the viscous polymer gel which is used for soil collecting (Mori and Sakai, 2016). The gel lubricates and reduces friction between the cut sample and the tube, both during sampling as well as during extrusion in the laboratory (Taylor et al, 2012). Such innovation is a key factor in liquefaction assessment since the rheological properties of the polymer allows preserving the soil structure (Viana da Fonseca and Pineda, 2017).

In this study, the GP-Static (GP-S) was implemented. This sampler follows the concepts of fixed-piston sampling (Osterberg, 1973) with triple core barrel, but makes use of a viscous polymer gel during drilling. The main components of the GP-S sampler, which differentiate this equipment from conventional Osterberg and D&M samplers, are a cutting shoe and its three pistons: the stationary piston, the sampling tube advancing piston, and the core-catcher activating piston. The first piston is fixed and the other two are travelling pistons. The outer tube secures the borehole and keeps the penetration rod and piston fixed in alignment during penetration. The advancing piston contains the gel, ensures the downward movement of the system and activates the catcher while it is inserted into the soil. The core-catcher piston captures the sample inside a metallic liner tube, with approximate inner/outer diameters of 71/76 mm and 1 m length (Taylor, 2015).

The sampling methodology of the GP-S includes three operation phases. The first phase covers the sampler assembly and preparation of the gel, to a concentration ratio of 1% of polymer in clean water, which is immediately inserted into the device. At this phase, a borehole of 150 mm diameter must be drilled, as in the D&M operation procedure. In the second phase, the sampler is lowered into the borehole and the GP-S is connected to a water pump. Afterwards, clean water is pumped to the sampler at a constant pressure of 50 MPa or a penetration rate of 1 m/min. The core barrel starts to advance and the cutting shoe penetrates the soil. Simultaneously, the hydraulic piston closes a bypass valve and the fixed piston enables to squeeze gel in the core catcher lubricating the end of the collected soil. In the third phase, the core barrel advances downward into the soil until 1 m depth (liner length). The remnant gel flows through the liner, allowing the sliding of the sample and the blades of the catcher close, holding the soil. Figure 5 displays the operation phases of the sampler.

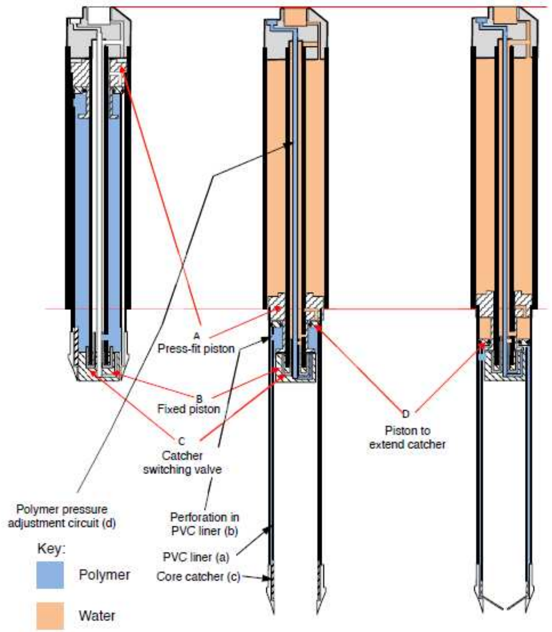

Figure 5. GP-S operation (Taylor, 2015)

3 EXPERIENCE WITH THE NEW SAMPLING TECHNIQUES

Three different boreholes separated by 2 m distance were drilled, with the purpose of retrieving soil samples with the minimum spatial variability between investigation points. The sampling techniques were implemented as follows: two boreholes with the GP-S and one with the D&M. In total, 29 samples (17 GP-S and 12 D&M) were collected. This paper focuses on the performance of both sampling techniques in collecting liquefiable soils and only the samples retrieved at 5 to 12 m depth will be analysed. Figure 6 illustrates the sampling profile.

During the experimental campaign, it was recognised that both samplers were successful in sampling silty sands (5 and 8 m) and silts (9 - 10 m). However, clean medium sands (7 and 11 m) were not collected, since the sample dropped during lifting with both samplers. The recovery ratio of GP-S ranged between 43% and 88% and between 80% and 94% for the D&M. Figures 7 and 8 show the operation of both samplers.

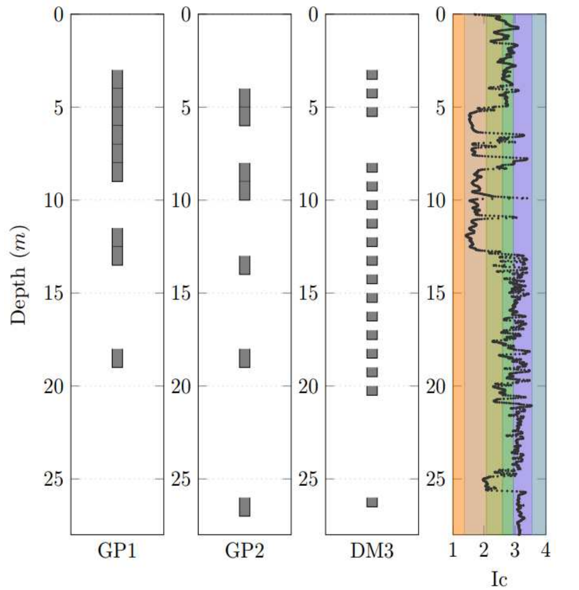

Figure 6. Samples collected by GP-S and D&M, and I_c from CPTu data

Figure 7. D&M operation: (a) key components; (b) device assembled; (c) liner after sampling.

Figure 8. GP-S operation: (a) key components; (b) device assembled; (c) activated core catcher.

After sampling, the samples (inside the liners) were hermetically sealed and transported to the laboratory, in the vertical position inside a wooden box, specifically designed for these liners. Each box includes two horizontal sections to ensure the vertical alignment of the liners. With the purpose of minimising the lateral movement of the liners, foam was placed around the tubes inside the box. The foam laminae were also placed at the top and bottom of the boxes in an effort to isolate the samples from vibrations. Figure 9 shows one box, used for transporting the samples from the site to the laboratory.

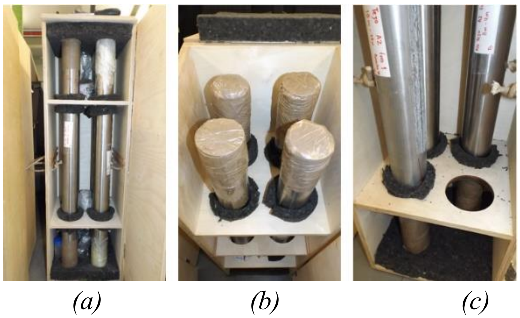

Figure 9. Transportation box: (a) ready for transport; (b) detail of liner confinement using foam; (c) foam isolation at the sides and the base.

4 SAMPLING QUALITY ASSESSMENT

In the laboratory, each sample was unsealed and the total weight and effective length were measured, in order to estimate its unit weight (γ). Such values were compared against the in situ γ obtained by means of the CPTu correlation proposed by Robertson and Cabal (2010). This quick comparison allowed for a preliminary assessment of the density variation due to the sampling process. This revealed a good fitting between the results, which is indicative of low compression during sampling. Figure 10 presents the γ comparison between lab and in situ values.

The extrusion of samples from the liner was performed using a vertical hydraulic piston. Subsequently, samples were divided into smaller specimens for element testing (three specimens per liner on average). After extrusion, each specimen was transferred into a PVC tube, carefully sealed and stored in a wet room under controlled temperature and humidity until testing.

The assessment of sampling quality was made, based on the comparison of field and laboratory shear wave velocities, as proposed by Ferreira *et al.* (2011). Such assessment compares the normalized shear wave velocity (Vs^*) measured in the laboratory with the corresponding normalized in situ values, at the same depth. In this work, V_S data were obtained in the field by SCPTu and in the laboratory by means of bender-element (BE) bench tests.

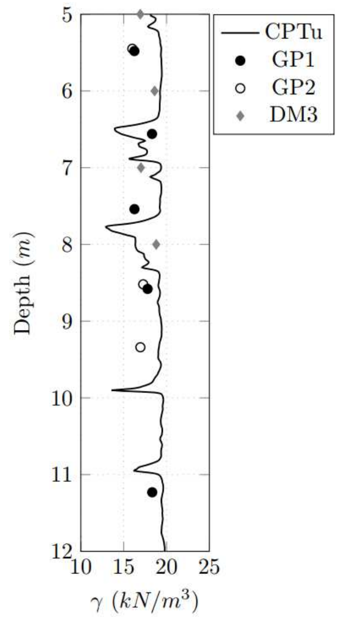

Figure 10. Comparison between the unit weight of the samples collected by GP-S and D&M and the estimated unit weight in depth (from CPTu data)

In addition, Ferreira *et al.* (2011) suggested a classification based on five different quality zones (Table 1).

Table 1. Sample quality classification based on Vs normalised ratio (Ferreira et al., 2011)

Quality zone	Vs^* ratio	Sample quality	Sample condition
A	≥ 85%	Excellent	Perfect
B	85% - 70%	Very good	Undisturbed
C	70% - 60%	Good	Fairly undisturbed
D	60% - 50%	Fair	Fairly disturbed
E	< 50%	Poor	Disturbed

Normalisation with respect to soil state was done using the empirical void ratio function $F(e) = e^{-1.3}$ (Lo Presti et al., 1997) and assuming $p'_{lab} = 1\ kPa$. Moreover, BE results were interpreted according to the procedure presented in Viana da Fonseca et al. (2009). Figure 11 shows the summary of the sampling quality assessment results.

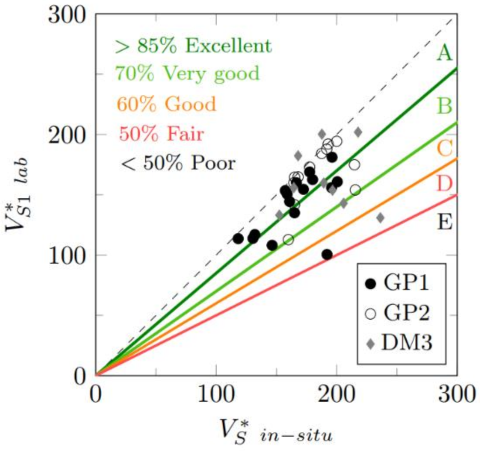

Figure 11. Results of sampling quality assessment.

From the sampling quality assessment, it can be observed that only two samples were categorized as fair, one retrieved with the GP-S and the other with the D&M. Furthermore, two D&M samples presented *Vs* ratios higher than 100%. Nevertheless, such values are acceptable since they are attributed to the uncertainties associated with direct field measurements in terms of resolution (spaced 1.0 m into the downhole). Both samplers presented a good performance in collecting liquefiable soils as almost all samples were categorized as excellent to very good, which indicates a high-quality sample condition.

5 CONCLUSIONS

This paper described a sampling campaign on liquefiable soils by means of two advanced sampling techniques, GP-S and D&M. High-quality samples were collected in a pilot site located in Benavente, near Lisbon. Sampling quality was assessed using a comparison between normalized *Vs* values measured in the field and in the laboratory. A preliminary assessment of the quality of each sample indicated close results between both samplers. In addition, more than 90% of samples studied in this work were classified, based on the *Vs* criteria, as excellent or very good quality. The following conclusions can be drawn:

- The results demonstrate that the GP-S and D&M samplers induce minimal to low disturbance in the fabric and structure in silts to silty sands. The low friction of these samplers introduces low compression of the soil during sampling, providing representative soil samples.
- Key issues, which require specific attention to preserve the high quality of the samples, also include transport, handling and storage before element testing. It is then necessary to consider specific measures for minimising vibrations during transport of the samples, namely using specifically designed boxes, with the samples positioned vertically and properly insulated.
- The comparison between seismic wave velocities measured in situ and in the laboratory is an excellent method to estimate the quality of soil samples. However, for the comparison to be valid, it is necessary to normalise the respective void ratio function and mean effective stress. This method allowed estimating the effect of changes in the fabric and structure of the soil during the sampling process.

6 ACKNOWLEDGEMENTS

LIQUEFACT project (Assessment and mitigation of liquefaction potential across Europe: a holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters) has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement GAP-700748. The authors also acknowledge the Portuguese Foundation for Science and Technology (FCT) for the support of the PTDC/ECM/GEO/1780/2014 project "Liquefaction Assessment Protocols to Protect Critical Infrastructures against Earthquake Damage: LIQ2PROEARTH". The second and fourth authors also acknowledge the support of FCT through grants SFRH/BPD/120470/2016 and SFRH/BD/120035/2016, respectively.

7 REFERENCES

ASTM International 2015. *D6519 - Standard Practice for Sampling of Soil Using the Hydraulically Operated Stationary Piston Sampler*.

Azevedo, J. Guerreiro, L., Bento, R., Lopes, M., Proença, J. 2010. Seismic vulnerability of lifelines in the greater Lisbon area, *Bulletin of Earthquake Engineering*. Springer Netherlands, **8**(1), pp. 157–180. doi: 10.1007/s10518-009-9124-7.

Bray, J.D., Markham, C.S., Cubrinovski, M. 2017. Liquefaction assessments at shallow foundation building sites in the Central Business District of Christchurch, New Zealand, *Soil Dynamics and Earthquake Engineering*. Elsevier, **92**, pp. 153–164. doi: 10.1016/J.SOILDYN.2016.09.049.

Bray, J.D., Sancio, R.B. 2006. Assessment of the Liquefaction Susceptibility of Fine-Grained Soils, *J. Geotechnical and Geoenvironmental Engineering*, **132**(9), pp. 1165–1177. doi: 10.1061/(ASCE)1090-0241(2006)132:9(1165).

Cabral, J., Moniz, C., Batlló, J., Figueiredo, P., Carvalho, J., Matias, L., Teves-Costa, P., Dias, R., Simão, N. 2013. The 1909 Benavente (Portugal) earthquake: search for the source, *Natural Hazards*, **69**(2), pp. 1211–1227. doi: 10.1007/s11069-011-0062-8.

Chen, C.-C., Lee, W.F., Chen, J.-W., Ishihara, K. 2014. Liquefaction potential of non-plastic silty sand, *J. Marine Science and Technology*, **22**(2), pp. 137–145. doi: 10.6119/JMST-013-0117-3.

Eurocode 8 2005. *Design of structures for earthquake resistance*, *European Committee for Standardization*.

Ferreira, C., Viana da Fonseca, A., Nash, D. 2011. Shear wave velocities for sample quality assessment on a residual soil, *Soils and Foundations*, **51**(4), pp. 683–692. doi: 10.3208/sandf.51.683.

Ishihara, K., Harada, K. Lee, W.F., Chan, C.C., Safiullah, A.M.M. 2016. Post-liquefaction settlement analyses based on the volume change characteristics of undisturbed and reconstituted samples, *Soils and Foundations*. Elsevier, **56**(3), pp. 533–546. doi: 10.1016/J.SANDF.2016.04.019.

Markham, C.S., Bray J., Riemer M., Cubrinovski M. 2016. Characterization of Shallow Soils in the Central Business District of Christchurch, New Zealand, *Geotechnical Testing Journal*. ASTM International, **39**(6), p. 20150244. doi: 10.1520/GTJ20150244.

Mori, K., Sakai, K. 2016. The GP sampler: a new innovation in core sampling. *Geotechnical and Geophysical Site Characterisation 5*. Sydney, Australia: AGS, pp. 99–124.

Osterberg, J.O. 1973. An improved hydraulic piston sampler, *8th ICSMFE*. Moscow, pp. 317–321.

Lo Presti, D.C.F., Jamiolkowski, M., Pallara, O., Cavallaro, A., Pedroni, S. 1997. Shear modulus and damping of soils, *Géotechnique*, **47**(3), pp. 603–617. doi: 10.1680/geot.1997.47.3.603.

Ramos, C., Viana da Fonseca, A., Vaunat, J. 2015. Modeling flow instability of an Algerian sand with the dilatancy rule in CASM, *Geomechanics and Engineering*. Techno-Press, **9**(6), pp. 729–742. doi: 10.12989/gae.2015.9.6.729.

Robertson, P.K. 2009. Interpretation of cone penetration tests - a unified approach, *Canadian geotechnical journal*. NRC Research Press, 46(11), pp. 1337–1355. doi: 10.1139/T09-065.

Robertson, P.K., Cabal, K.L. 2010. Estimating soil unit weight from CPT, in *2nd International Symposium on Cone Penetration Testing*. CA, USA.

Saldanha, A.S., Viana da Fonseca, A., Ferreira, C. 2018. Microzonation of the liquefaction susceptibility: case study in the lower Tagus valley, *Geotecnia*, **142**, pp. 7-34. doi: 10.24849/j.geot.2018.142.01.

Taylor, M.L. 2015. *The geotechnical characterisation of Christchurch sands for advanced soil modelling.* University of Canterbury.

Taylor, M.L., Cubrinovski, M., Haycock, I. 2012. Application of new “Gel-push” sampling procedure to obtain high quality laboratory test data for advanced geotechnical analyses, in *2012 NZSEE Conference*. Christchurch, New Zeland, pp. 1–8.

Teves-Costa, P., Batlló, J. 2011. The 23 April 1909 Benavente earthquake (Portugal): macroseismic field revision, *J.Seismology*, **15**(1), pp. 59–70. doi: 10.1007/s10950-010-9207-6.

Viana da Fonseca, A., Ferreira, C., Fahey, M. 2009. A Framework Interpreting Bender Element Tests, Combining Time-Domain and Frequency-Domain Methods, *Geotechnical Testing Journal*, **32**(2), p. 100974. doi: 10.1520/GTJ100974.

Viana da Fonseca, A., Pineda, J. 2017. Getting high-quality samples in “sensitive” soils for advanced laboratory tests, *Innovative Infrastructure Solutions*. Springer International Publishing, **2**(1), p. 34. doi: 10.1007/s41062-017-0086-3.