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Novel sampling techniques for collecting high-quality samples: Portuguese experience in liquefiable soils

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ABSTRACT: Innovations in the sampling techniques have been achieved in the last decade. The most relevant advanced samplers include hydraulically-activated push tubes, rotary devices and freeze sampling systems. An extensive experimental campaign for the site characterisation of recent alluvial deposits of Lower Tagus Valley, close to Lisbon, was conducted. Based on several in situ test results, thick layers of liquefiable soils were identified, in which advanced sampling techniques were implemented. This paper presents the first experience in Portugal on the collection of high-quality samples of clean sands, silty sands and sandy silts using Dames & Moore and Gel-Push samplers. An analysis of the efficiency of each sampler for collecting different types of soils is presented, highlighting the layers susceptible to trigger soil liquefaction. For this assessment, the recovery ratio of each sampler and a comparison between cone resistance profiles and sampling collection were considered. Results provide some insights on the performance of each advanced sampling technique for collecting liquefiable soils.

Keywords: Dames & Moore, Gel-Push, liquefaction, sands.

1. Introduction

Within the scope of two research projects on soil liquefaction developed in the CONSTRUCT-GEO research centre of FEUP, a series of site investigation campaigns in the Lower Tagus Valley (LVT), south of Portugal, were conducted. The research focused on the geotechnical site characterisation using Standard Penetration Tests (SPT), Piezocone Penetration Tests (CPTu), Flat-plate Dilatometer test (DMT) and geophysical tests. Based on the site characterisation results, soil samples were collected using advanced sampling techniques for element testing in the laboratory (e.g. triaxial tests, resonant column tests and simple shear tests). For the first time in Portugal, two advanced sampling techniques, namely the Gel-Push and Dames & Moore samplers, were implemented for collecting high-quality samples of liquefiable soils.

This paper addresses the most significant aspects regarding the efficiency of the Gel-Push and Dames & Moore samplers for collecting high-quality samples of liquefiable soils in the Portuguese territory. A sampling campaign was conducted at two different locations next to the Tagus River in the municipality of Benavente (near Lisbon). The soil layers suitable for sampling were identified using SCPTu tests performed in boreholes adjacent to the sampling profiles. Results of the sampling of gravely sands, clean sands, silty sands and sandy silts using both advanced techniques are presented and discussed.

2. Novel sampling techniques

The collection of high-quality samples is critical to obtain representative test results for soil characterisation in the laboratory [1]. A typical sampling campaign involves the following stages: drilling, sampler insertion, sampler retrieval, tube sealing, transport, soil extrusion, sample storage and preparation for element testing [2]. Several authors ([3, 4]) stated that all those stages are potential sources of soil disturbance. Nevertheless, some of these effects are highly dependent of the expertise of the operator, whereas a few are related with the sampling tools and methods [5].

Over the years, several progresses in the development of sampling techniques have been achieved. The advanced techniques involve hydraulically-activated push tubes, rotary devices or freeze sampling, from which the freezing method is the most expensive [6]. In this research, two sampling techniques that use hydraulically-activated push tubes were implemented, the Dames & Moore and Gel-Push samplers.

2.1. Dames & Moore

The Dames & Moore (D&M) sampler is a modified device, which uses a hydraulic activated fixed-piston and thin-walled liner. This technique follows the same principle of the Osterberg-type sampler [7]. The D&M has a brass liner with 50 cm length, which effectively minimises the friction between the tube walls and the soil [4]. The relatively short length and the low friction of the liner reduce the disturbances during sampling and extrusion of the soil sample. Viana da Fonseca *et al.* [8] stated that the main modification of D&M is the incorporation of a neoprene skirt seal in the transition of the pressure cylinder with the liner. Such improvement allows for the generation of considerable vacuum during sampler retrieval, preventing the fall of the encapsulated soil, even cohesionless and loose. In addition, this seal avoids the entrance of disturbed material into the liner. Figure 1 shows a scheme of the components of the D&M sampler.

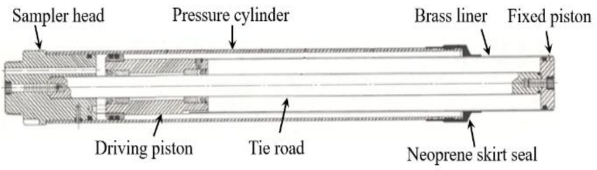


Figure 1. Schematic of D&M sampler components [8].

This advanced sampling technique has been used to obtain samples for liquefaction characterisation in Turkey [9], New Zealand [10] and Portugal [4]. D&M sampler allows collecting relatively "undisturbed" samples of sands (medium-dense) and silty sands [11]. Besides, at maximum performance, this sampler is able to recover samples with 45 - 50 cm length [6]. The D&M sampler uses thin-walled brass tubes (1.15 mm wall thickness) of constant internal diameter, $d_{int} = 61.2$ mm, and outer diameter, $d_{out} = 63.5$ mm. The area ratio, defined by Hvorslev [12] as $C_a = (d^2{}_{out} - d^2{}_{int})/d^2{}_{int}$, is 7.6 % for the D&M brass liners.

As the Osterberg sampler [7], the D&M sampler is inserted into a borehole, previously drilled, to a specific depth. The equipment must be connected to a water pump, in order to apply 1400 kPa of hydraulic pressure for pushing the brass liner into the soil, at constant penetration rate. The sample is collected inside the brass liner. At the completion of liner advancement (50 cm), the tube remains stationary for a minimum of 1 min. The sampler is extracted from the borehole and the liner is removed from the sampler. The ends of the liner must be closed and sealed to prevent changes in the soil state (e.g. moisture content changes and densification) and material losses. Finally, the soil sample is transported and stored, for testing in the laboratory.

2.2. Gel-push

The Gel-Push (GP) is an advanced sampling technique, which uses a viscous polymer gel as its drilling fluid. The name of this technique was attributed due to this non-Newtonian fluid function and its influence in the high performance operation. The purpose of using gel is to significantly reduce the friction between the sample and the liner [13]. This innovation allows minimising the disturbance of the soil samples not only during sampling but also during extrusion in the laboratory [14]. In addition, the rheological properties of the polymer gel play a key role in obtaining high-quality samples as it allows the preservation of soil structure from the sampler shoe to the top of the sample [6].

This advanced sampling technique was developed by the Japanese geotechnical company Kiso-Jiban Consultants. They designed four different variations of GP: GP-Rotary, GP-Drilling, GP-Triple, and GP-Static, in order to develop a method able to replace freezing techniques, which is an expensive and time consuming procedure. In this study, the GP-Static (GP-S) was implemented, as it is the most adequate for sampling loose granular soils. This sampler follows the concepts of fixed-piston sampling, similar to the D&M.

Unlike conventional hydraulic activated fixed-piston, GP-S has a triple core barrel, that is, it includes three pistons: the stationary piston, the sampling tube-advancing piston, and the core-catcher activating piston.

Viana da Fonseca *et al.* [4] described the purpose of the three pistons as follows. 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 very smooth surface metallic liner tube. Besides, the "Chinese lantern" core-catcher, which is smoothly rotated and partially closed by a short increase of the fluid pressure, prevents the fall of the sample during the device retrieval. Figure 2 shows a scheme of the components of the GP-S sampler.

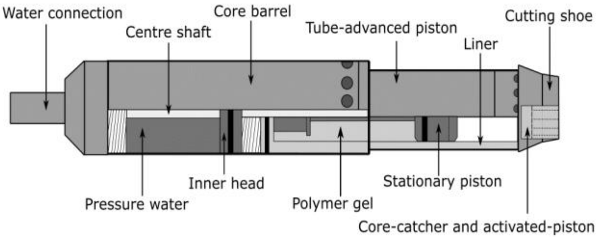


Figure 2. Schematic of GP-S sampler components [15].

This advanced sampling technique has been used to obtain samples for liquefaction characterisation in Taiwan and Japan [16], Bangladesh [17], Poland [18] New Zealand [14, 19] and Portugal [4]. The GP sampler allows the collection of high-quality samples in very contractive liquefiable soils, in reliable undisturbed conditions to performed representative tests in the laboratory [15]. Besides, at maximum performance, this sampler is able to recover samples with 71 mm diameter and 1 m length.

Before sampling, the gel is prepared at a 1 vol% concentration ratio of the viscous polymer in clean water and is immediately inserted into the device. The sampler is assembled and inserted into the borehole. The system is connected to a water pump, which injects 5 l/min of clean water in the sampler and then guarantees a constant pressure of 50 MPa. Thanks to the pressure in the system, the core barrel advances and the cutting shoe penetrates into the soil at a constant rate of 1 m/min. Simultaneously, the hydraulic piston closes a bypass valve and the fixed piston squeezes the gel into the core-catcher, lubricating the inside interface of the tube liner through its bottom end in the exact position where the soil is inserted into. When the core barrel reaches the maximum liner length (1 m), the remnant gel flows through the liner, creating a smooth gel layer at the soil-liner interface. The piston remains in such position during 3-5 minutes at a pressure of 50 MPa, to ensure that the catcher closes completely. The sampler is then extracted from the borehole and the GP-S is dissembled to remove the liner with the collected sample. When removing the liner from the sampler device, the soil at the bottom is levelled, eliminating effect of the area ratio of cutting shoe. Finally, the liner is hermetically closed for trasnporting and storing.

3. Site description

Portugal is a country located in the South-West of the Iberian Peninsula with an extensive Atlantic Ocean coast, where the seismicity increases in intensity from North to South and is concentrated in the South and the Atlantic margins [20]. The seismicity in the adjacent Atlantic region is very intense due to the proximity to the boundary between the African and Eurasian plates.

The south of Portugal is probably the zone, in this country, with greater seismic risk and it is affected by the occurrence of large magnitude (>8) distant earthquakes and medium magnitude (>6) near earthquakes [21]. There is historical evidence of soil liquefaction phenomena after the last large earthquake that occurred in the Lower Tagus region. Reports about the seismic event in 23rd April 1909 (moment magnitude scale, $Mw = 6.0$ and with epicentre near Benavente) indicated that there was significant damage and destruction in several small towns located in the valley [22].

The sample collection presented in this study was conducted in two different investigation points, which are part of an experimental site next to the Tagus River in the north of Benavente municipality (Portugal). Such investigation points were named NB1 and NB2. The position coordinates are 39°1'15.37"N-8°49'51.47"W and 39°1'0.77"N-8°50'25.89"W for NB1 and NB2, respectively. Figure 3 shows the location of the experimental site and the two investigation points.

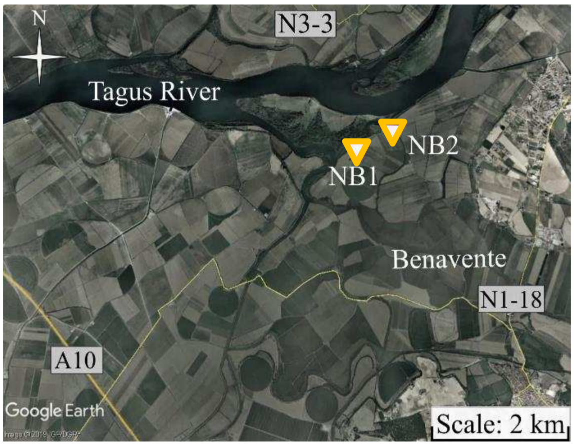


Figure 3. Map of the experimental site and location of NB1 and NB2 investigation points.

Prior to sampling, an extensive geotechnical site characterisation including seismic piezocone tests (SCPTu) was performed. The measurement of seismic wave velocities (Vs) was carried out during the extraction of the piezocone at each 1 m depth. Figure 4 presents the SCPTu test results in terms of cone resistance (q_c), sleeve friction (f_s) pore-water pressure generated during cone penetration (u_2) and shear wave velocity (Vs).

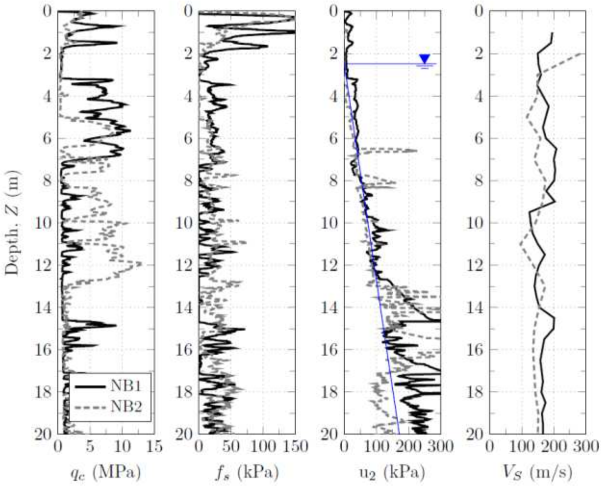
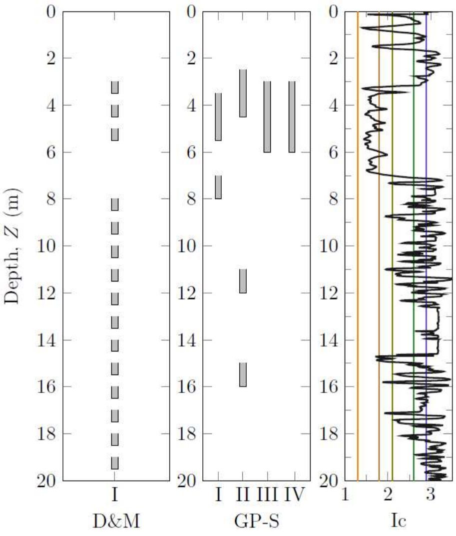


Figure 4. SCPTu results.

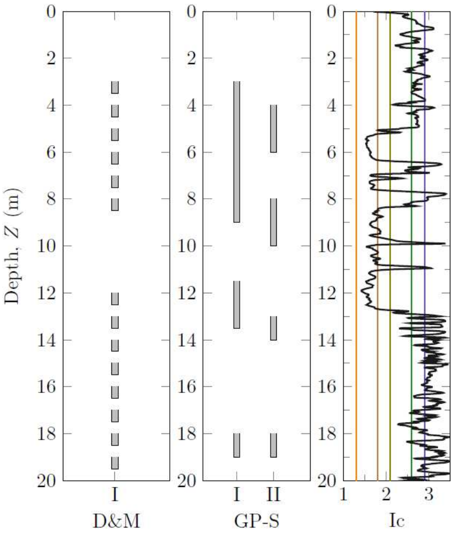
By comparing the SCPTu results, similarities were observed between both profiles. Analysing these results, the sites were characterised and liquefiable layers were identified in both profiles, for future sample collection. The liquefiable layers are composed of recent alluvial material, which were transported along the Tagus River. Besides, such alluvial deposits are formed by interstratified layers composed of sand and clays with origin in the Holocene [23, 24].

4. Obtaining high-quality undisturbed samples

During the experimental campaign, a total of 32 D&M and 29 GP-S samples were collected. At NB1, five locations were selected for soil sampling, one for D&M and four for GP-S; in turn, at NB2, three different locations were selected for soil sampling, one for D&M and two for GP-S. Samples were collected in adjacent boreholes at about 5 m distance to the respective SCPTu. The sampling depths were selected by interpreting the SCPTu data in terms of the soil behaviour type (SBT) criterion proposed by Robertson [25]. Figure 5 schematises the sampling depths for each technique in each investigation site, chosen based on the soil behaviour type profile.



(a)

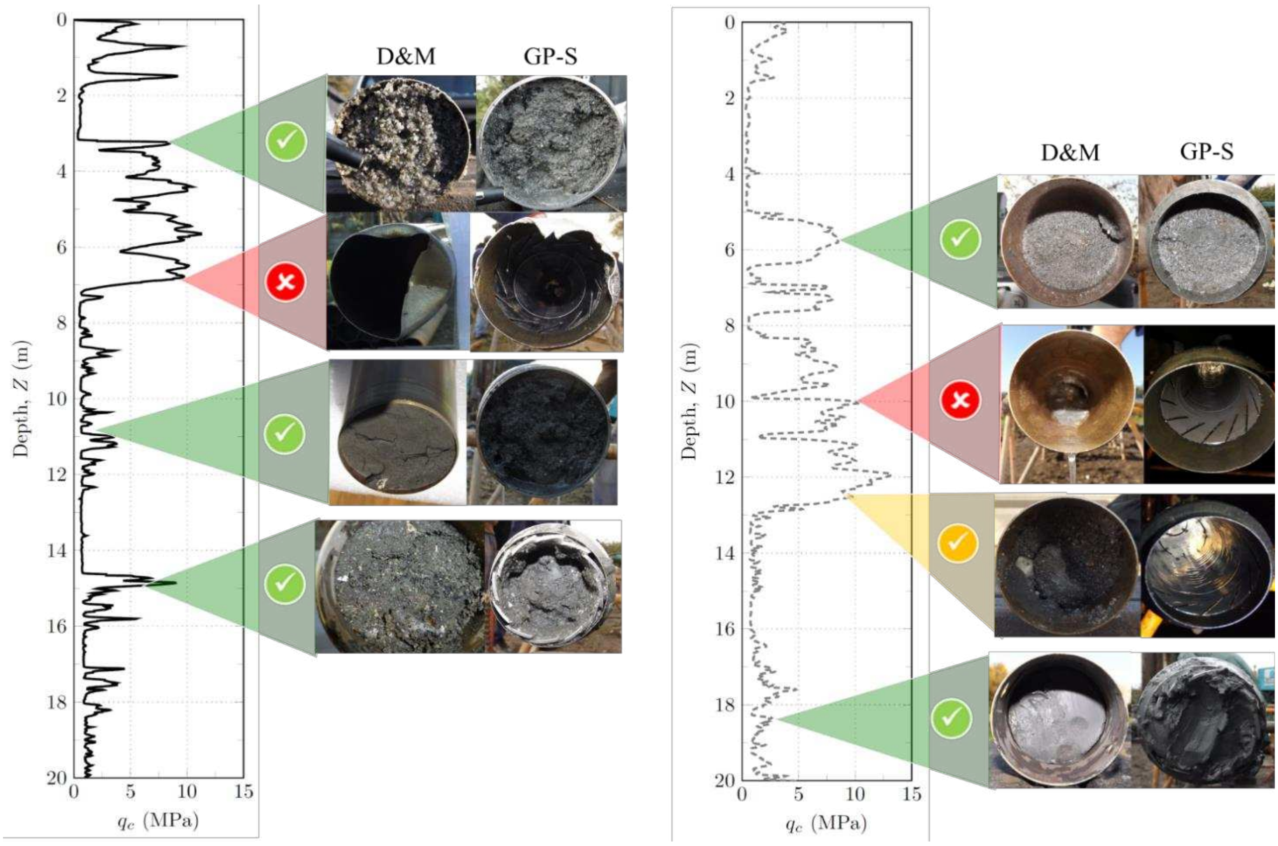


(b)

Figure 5. Samples retrieved using advanced sampling techniques and soil behaviour type profile: (a) NB1; (b) NB2.

The recovery ratio of D&M ranged between 80% and 94%, whereas for GP-S such ratio ranged between 43% and 88%. The differences in recovering efficiency can be related, mainly, with the length of the liner, which is lower for D&M sampler. Furthermore, the vacuum generated during the sampler insertion by the neoprene skirt seal, in the D&M, secures the sample and prevents the loss of material during the device retrieval.

Figure 6 presents the performance of both advanced sampling techniques in the two investigation sites. In this Figure, it is shown with green colour the depths where both samplers were successful in collecting soil samples, red colour indicates the depths where none of the technique collected samples and orange colour specifies the depths where only one of the samplers collected samples. Moreover, the performance is evaluated using the evidence obtained in the field during sampling and the profiles of cone resistance.



(a) (b)

Figure 6. Performance of the advanced sampling techniques: (a) NB1; (b) NB2.

As Figures 5 and 6 show, both samplers were successful when sampling in soil layers with medium dense sands, fine sands, silty sands, silts and clays. However, it was found that D&M and GP-S were not able to collect coarse-grained soils. By comparing results, it can be observed that at the depths where the cone resistance, q_c, was higher than 8 MPa, the D&M and GP-S techniques failed to successfully collect soil samples. Besides, both samplers suffered some damage in the cutting shoe when penetrating those gravelly layers (see Figure 6a, NB1 at 7 m depth). This issue can be overcome by using rotating devices (e.g. GP-Rotary), which allow drilling coarse materials [13]. On the other hand, in some cases, both samplers did not recover samples of clean sands due to the very loose conditions of this type of materials in saturated conditions (see Figure 6b, NB2 at 10 m depth). Nevertheless, such performance was not detected in both sampling techniques in all layers with clean loose sands, as the neoprene skirt seal of D&M generates a partial suction during sampling, which allowed recovering some clean loose sand samples (see Figure 6b, NB2 at 12.5 m depth). Therefore, from this sampling experience, it was found that both samplers are able to collect soils with mean size less than 2.0 mm. This diameter satisfies the concept of Representative Elementary Volume proposed by Holtz and Gibbs [26], which states the test specimens must be six to ten times bigger than the particle maximum size.

5. Handling high-quality undisturbed samples in the field and laboratory

After retrieving the D&M and GP-S samplers from the borehole, the devices were carefully laid out horizontally and the liner was removed from the equipment with the least vibration possible. The liners with the samples inside were hermetically sealed and transported about 300 km distance to the laboratory at FEUP. For this purpose, specifically designed wooden boxes were used [8]. All samples were transported in the vertical position inside the box. The box featured a built-in vibration isolation system, which effectively reduced sample vibration during transport and transit. Figure 7 shows the extraction of the samples in both devices and one box in which the samples were transported from the experimental site to the laboratory.


(a) (b) (c)

Figure 7. Sample handling in the field: (a) disassembling of the GP-S sampler; (b) extraction of the D&M liner; (c) transportation box.

In the laboratory, the samples were extruded using a vertical hydraulic piston and individual specimens were immediately prepared. A large number of specimens (more than 100) was extruded from the liners, ready for element testing. The small specimens were conditioned in PVC tubes and stored vertically in a curing room under controlled temperature conditions until testing [4]. These PVC tubes effectively preserved the soil fabric, while allowing sample handling during its setup in the testing apparatus [15].

During extrusion, it was evidenced that the samples of granular soils were easier to remove from the D&M liner than from the GP-S liner. This was probably due to the different length of the liners, which is lower for the D&M sampler. On the other hand, the GP-S samples with clayey soils presented gel in their perimeter, which reduced the friction in the soil-liner interface and allowed extruding the samples easily. This effect was attributed to the low permeability of such type of soils. Sample extrusion is a key issue, since this process can densify or compact the soil when applying significant pressure with the vertical piston. Figure 8 shows the extrusion process of the samples from the liners using the vertical piston and the conditioning in the PVC tubes.


(a) (b) (c)

Figure 8. Sample extrusion in the vertical piston: (a) positioning of the liner; (b) GP-S sample of clayey soil (gel remains around the sample); (c) D&M sample of sandy soil inside a small PVC tube.

All specimens were weighed and measured for bulk density estimation. In addition, the specimens were tested using the bender element bench test, which allowed to obtain the shear wave velocity before element testing in the triaxial chamber. The shear wave velocity measured in the laboratory was compared against its corresponding field value for assessing the sample quality. Viana da Fonseca *et al.* [4, 8] and Molina-Gómez *et al.* [15] presented the results of such quality assessment, using the criterion proposed by Ferreira *et al.* [1]. These authors established that the advanced sampling techniques implemented in this study collect samples of very good to high-quality samples in liquefiable soils. Furthermore, these authors found that the GP-S provides, in general, higher values of sampling quality than the D&M.

For element testing, the specimens were positioned in the bottom pedestal of the triaxial chamber. An acrylic plate was placed on the top of the specimen to prevent damage in the edges during the installation of the latex membrane. The PVC tube was carefully removed and the latex membrane was inserted. After that, the testing procedures were conducted. Figure 9 shows the preparation for triaxial testing of a soil specimen.

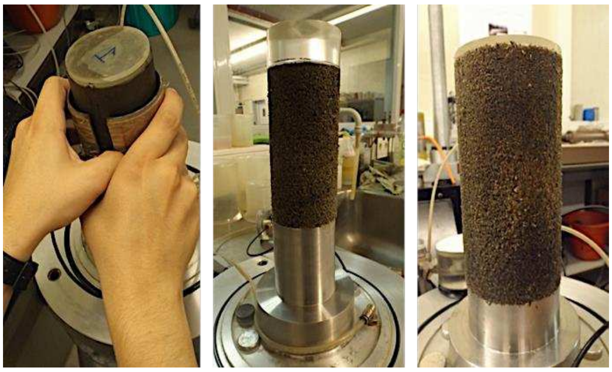

(a) (b) (c)

Figure 9. Specimen preparation for element testing: (a) positioning of the specimen and PVC tube removal; (b) D&M specimen of sandy soil; (c) GP-S specimen of sandy soil.

Moreover, during the specimen preparation for triaxial testing, a visual inspection of the samples was performed. Observations showed that the samples have a very good structure and integrity and apparently minimal disturbance. Besides, the visual inspection revealed that both advanced techniques allowed the preservation of soil fabric. Such a condition can be observed by the cylindrical geometry and the slight variability of the natural colour of the specimens, as shown in Figures 9b and 9c. The high-quality of the samples is a clear joint result between the technology of both advanced techniques and the good practices for handling, transport, extrusion and storage implemented during this study.

6. Summary and concluding remarks

This paper presented the first Portuguese experience collecting liquefiable soils using Dames & Moore and Gel-Push samplers, which presently may be considered two of the most advanced sampling techniques. High-quality samples were collected in an experimental site next to the Tagus River located in the municipality of Benavente, near Lisbon. Moreover, this paper describes key issues to ensure adequate preservation of the high-quality of the samples after sampling, including handling, transportation, extrusion and storage, as well as a good practice to set up the specimens for testing in a triaxial chamber. The main aspects to preserve the quality of the samples are the use of specifically designed boxes during transport, which keep samples positioned vertically and properly insulated from vibrations, and the extrusion of the samples in the laboratory in the vertical position.

The Portuguese experience showed that D&M and GP-S samplers are able to collect liquefiable soils, such as medium-coarse sands, fine sands, silty sands and silts, as well as clayey soils. In addition, it was observed that both advanced techniques are not appropriate for collecting gravels or soils with cone resistance higher than 8 MPa. When sampling soils in such layers, the devices cannot collect samples and can suffer some damage in the cutting shoe.

Sampling results showed that the D&M has a better repeatability than the GP-S during all the sampling and preparation processes (in the field and in the laboratory). The above is due to its shorter liner (50 cm length) and the generation of vacuum during the sampler extraction by the neoprene skirt seal the stationary pushing, which allowed obtaining a recovering ratio of 80%-94% and easier retrieval of the samples. Although the sample quality, evaluated by the shear wave criterion (as referenced in the text), was superior in the specimens obtained by GP-S, this sampler presented different performance according to the soil type, e.g. clear friction reduction during sample extruding in clayey soils. Such performance depends on the rheological properties of the gel, which is related to soil permeability. This issue might be studied in the future to obtain higher recovering ratios in GP-S.

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