Offshore Shear Wave Velocity Measurements for the Assessment of Soil Sampling Quality

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ABSTRACT

Shear wave velocity Vs is a critical soil parameter for several geotechnical and geophysical engineering applications including seismic site response analysis, liquefaction risk assessment and design of shallow and deep foundations. Moreover, the comparison of shear wave velocity between laboratory and in situ measurements has become a standard acceptance criterion for the assessment of sampling quality.

Offshore in situ shear wave velocity testing is considerably more challenging than onshore, due to the difficulties in the correct deployment of the instrumentation as well as of the wave source, in absence of direct visibility of the ground level below water. This paper describes the methodology employed for offshore shear wave velocities (Vs) measurements in the harbour of Barcelona in September 2022. Medusa SDMT tests were performed in sea depths ranging between 15-17 m from a jackup and employing a drill rig to penetrate the probe down to 40 m below the seafloor. The paper includes examples of recorded S-wave seismograms, analyses of Vs repeatability for the same depth measurements and Vs profiles with depth.

In the same test locations, carefully prepared specimens of undisturbed samples were tested after reconsolidation to the estimated in situ stress states in stress path triaxial cells with bender elements transducers. The obtained lab shear wave velocities were compared with the in situ values obtained with the Medusa SDMT tests to assess sample quality.

Keywords: offshore Vs, offshore shear wave velocity, offshore seismic, offshore shear wave source, SDMT, seismic dilatometer, Medusa, sample quality assessment

1. Shear Wave Velocity for design

Shear wave velocity Vs plays a key role in modern site characterization both onshore and offshore. International standards require this parameter for most geotechnical and geophysical engineering applications, in terms of both design and monitoring in construction projects. In addition to seismic site response analysis, Vs and G_0 are commonly employed for liquefaction risk assessment and for the design of shallow and deep foundations. The comparison of shear wave velocity between laboratory and in situ measurements has become a standard acceptance criterion for the assessment of sample quality, required to reduce the uncertainty in using soil parameters obtained in laboratory (Viana da Fonseca and Pineda, 2017).

2. Onshore Vs measurements

Today shear wave velocity measurements are routine practice in onshore soil characterization projects, usually in combination with other soil investigations such as laboratory or in situ testing. Non-invasive seismic instrumentation may be positioned at ground level, to record surface waves and provide estimates also of shear wave velocity. Examples of this type of equipment are MASW, SASW and Tromino®.

On the other hand, invasive probes containing seismic receivers are inserted into the ground at depth, either within a pre-drilled borehole (downhole and crosshole) or pushed with a static penetrometer in virgin soil (SDMT and SCPT). Seismic waves, in particular S-waves and P-waves, are artificially generated at ground level using wave sources generally supplied with the seismic probe.

Downhole and crosshole tests require to drill one or more boreholes, installing tubes that must first be cemented. These operations may require considerable time – typically between 1 and 3 weeks – before allowing seismic test execution. The wave source is placed either at the surface (Downhole) or lowered inside one of the holes (Crosshole). One or more sensors are lowered into the other drill(s) and measurements are performed at each test depth, generally with a depth step of 1.0 m.

This paper will address seismic measurements combining a seismic add-on module with direct push invasive probes such as DMT and CPT. The SCPT is the combination of the cone penetration test (CPT) with a seismic module supplied by cone manufacturers. The SDMT is the combination of the Flat Dilatometer with the seismic module specifically designed for combination with the blade (Fig. 1).

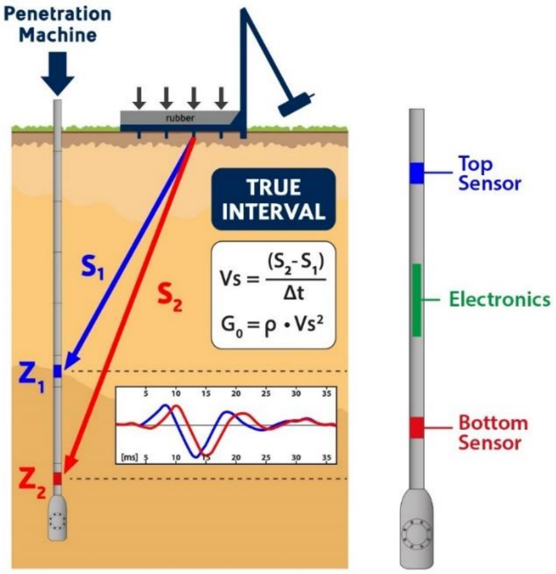


Figure 1. SDMT test layout for shear wave velocity measurements

Since 2015, the seismic module of the SDMT was combined also with the CPT of different cone manufacturers and the corresponding probe has been named SDMT Cone. In 2021 the SDMT was integrated in the fully automated dilatometer probe (Medusa DMT) for providing in addition to DMT results also shear wave velocity (Medusa SDMT), as shown in Fig. 2.

The shear wave source plays a key role for successful Vs measurements, onshore and offshore. The equipment manufacturer generally designs the wave source, to maximise the signal to noise ratio (SNR) and the quality of the generated wave, according to the type of sensors and to the specifically suggested test layout.

Today onshore seismic testing is standard practice, in particular employing true interval digital seismic invasive probes with digital data communication, such as the SDMT and SCPT described in this manuscript.

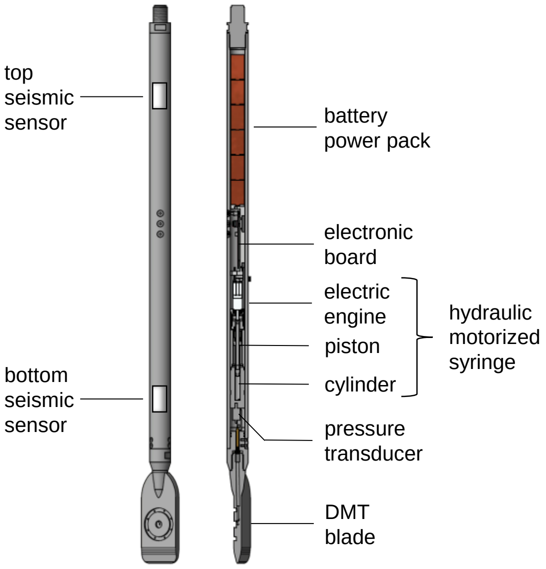


Figure 2. Medusa SDMT probe components, combining S-wave seismic sensors with the automation of Medusa DMT

3. Offshore shear wave velocity

In onshore seismic testing both the probe and the wave source may be visually inspected just before the probe starts the penetration into the ground. In case of improper deployment, the wave source configuration may be amended at any time, even during test execution.

Offshore seismic testing is considerably more challenging than onshore. The reason is that the probe and the wave source are lowered from the surface to the seafloor, without the possibility of inspecting if their deployment occurred as expected nor the possibility of amending it during the test. No specific standard is available for offshore seismic testing and the know-how is mostly based on previous experiences of single operators. It is not unusual that inexperienced operators return from offshore test sites with waveforms that are very complex to process, without considerable difficulties in evaluating a reliable shear wave velocity profile. In this respect, the feature of automated seismic data processing, providing real time Vs evaluations, is a fundamental feedback available on site for the quality assessment of the acquired waveforms during test execution.

4. The Llobregat delta campaigns

The Llobregat delta is located south of the Barcelona city and has been the focus of extensive research in the last two decades due to the construction of various infrastructures in Barcelona's southwestern region. Specifically, the construction of the wastewater treatment plant, the new T1 terminal at El Prat airport, and multiple extensive geotechnical campaigns conducted by the Port

Authority of Barcelona as part of its strategic expansion efforts. These campaigns aimed to analyze the seafloor and quaternary soft soils present in the delta sediments.

For all these campaigns, both onshore and nearshore utilising jack-up platforms, core boreholes with rotary drilling rigs (BH) collecting high quality undisturbed samples and SPT tests, Cone Penetration Testing (CPT) & Piezocone Penetration Testing (CPTu), Dilatometer Testing (DMT), as well as seismic tests, Vane tests, Ménard pressuremeter tests, laboratory analyses, and moreover, geotechnical monitoring of certain infrastructures were conducted.

In the geotechnical research campaigns in the area of the Llobregat delta, especially in the port of Barcelona, in addition to boreholes and laboratory tests, in situ geotechnical tests have been invaluable in providing knowledge of the stratigraphy, geotechnics, and even sedimentology (Fig. 3).

This extensive endeavour (more than 1.000 CPTUs executed) culminated in the creation of a vast database, which has been the foundation for numerous studies (e.g. Devincenzi et al., (2004), Lafuerza et al., (2005), Madrid et al., (2012, 2021), Tarragó et al., (2012, 2021), Deu et al., (2021), among them) and will undoubtedly continue to be a highly valuable resource for future research.

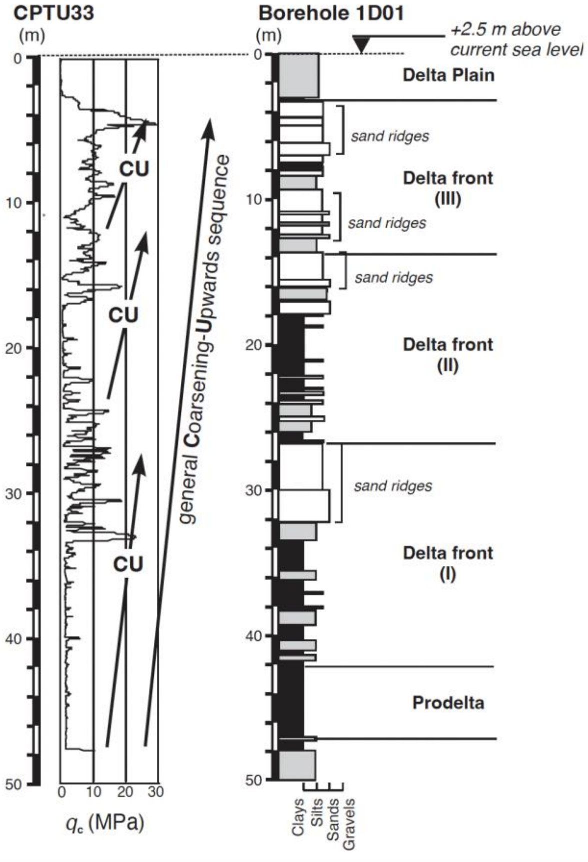


Figure 3. Correlation between a qc profile from a CPTU test and a borehole in the right bank of Llobregat river near the shoreline (Lafuerza et al., 2005).

5. Geological framework

The general architecture of the Llobregat delta consists of five main units, whose from base to top are: (1) a lower unit of Pliocene blue clays and shales with fragments of shells (bedrock), (2) fluvial gravels that form the lower aquifer probably younger than 18.000-15.000 y B.P., (3) prodelta deposits made of clayey silts, (4) the upper aquifer unit made of gravels, sands and some silts from delta front and delta plain and (5) the superficial level with flood plain fine sands, silts and clays and marsh clays (Marqués, 1974; Bayó, 1985). Fig. 4, adapted from Lafuerza et al. (2005), shows a general cross section of the delta sediments.

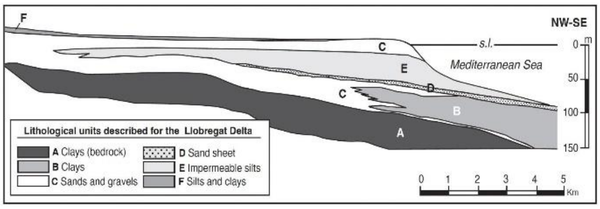


Figure 4. NW-SE geological cross-section showing the general architecture of the Llobregat delta (Lafuerza et al., 2005).

Obtaining an undisturbed sample from the prodelta's fine soils, which constitute the widespread and homogeneous environment of the delta, presents a significant challenge, not only due to the inherent nature of the terrain and the mechanics of sampling itself, but also because pockets of gas may be encountered. Verifying the quality of undisturbed samples is therefore of the utmost importance for the correct geotechnical characterization of the terrain.

6. Barcelona harbour case history

Within the project of the expansion of the Barcelona harbour, a large offshore test campaign was carried out for soil characterization in September 2022. In addition to laboratory, CPT and DMT tests, shear wave velocity measurements were also requested for the in situ measurement of G_0 and for the quality assessment of undisturbed samples. The fully automated seismic version of the Flat Dilatometer (Medusa SDMT) was employed for performing DMT tests and Vs measurements in the same offshore sounding.

Fig. 5 shows the jack-up employed for the extensive test campaign in Barcelona harbour, provided with two circular moonpool holes spaced 1.5 m and a drill rig machine. One of the holes was used to install a seabed shear source. Since such a source could not pass through the moonpool hole of the jack-up, it had to initially be placed on a boat and carried below the jack-up structure. It was then connected to rods of the drill rig passing through the moonpool hole. After the secure connection between the wave source and the rods, the drill rig lowered the source down to the seafloor. Fig. 6 shows the details of the shear wave source employed for the project. The hinged pendulum hammer was charged by an operator on deck pulling a rope. When the rope was released, the hammer striked in the horizontal direction the tube connected to the rectangular base placed on the seabed. The horizontal acceleration of the base generated high quality shear waves required for Vs evaluation.

Figure 5. Gemigeo Jackup Barge in Barcelona harbour

Figure 6. Details of the seabed shear wave source employed in Barcelona harbour

The second jack-up moonpool hole was used to deploy the Medusa SDMT equipment. As a first step, a large and robust metal tube was employed to guide the casing rods lowered by the drill rig vertically down to the seabed. The sequential procedure for performing the tests consisted in drilling the soil, advancing the casing to the drilled depth and then pushing the penetration rods with the Medusa SDMT probe, starting from the bottom of the cased hole. DMT measurements were taken with 0.20 m depth intervals, seismic S-wave measurements with 0.50 m intervals.

The shear wave was generated with the seabed wave source described above. Each wave source energisation provides a shear wave that is recorded by the Medusa SDMT probe at depth. The electronic board embedded in the device amplifies and digitises receivers' signals at depth. Data is transmitted via digital communication cable to the acquisition unit on the platform deck. The waveforms, displayed on the screen of the laptop computer, are processed instantly by the SDMT Pro software and a real time evaluation of Vs is displayed to the operator. Multiple strikes with the seabed wave source at the same test depth enable to check the quality and repeatability of the measurements before proceeding to the next test depth.

Results are shown for test location MED-SDMT-179, with a water depth of 17.20 m and with a final test depth of 40 m below the seafloor. Fig. 7 illustrates examples of the deepest seismograms, recorded at 38.5-40.0 m below the seafloor. The blue and the red colour lines pertain to the trace of the top and of the lower sensor respectively. The 'Recorded Signals' seismograms on the left display an initial low noise for both traces, followed by a powerful shear wave exhibiting a clear delay between the top and the lower sensor trace, finally terminating with wavelets of low amplitude. The real time automated processing of the seismic waveforms evaluates the delay Dt of each seismogram and the 'Rephased Signals' replicate the 'Recorded Signals', with the difference that the red trace is shifted backwards in the time domain of the evaluated delay Dt, to provide a visual inspection of the correct wave superposition.

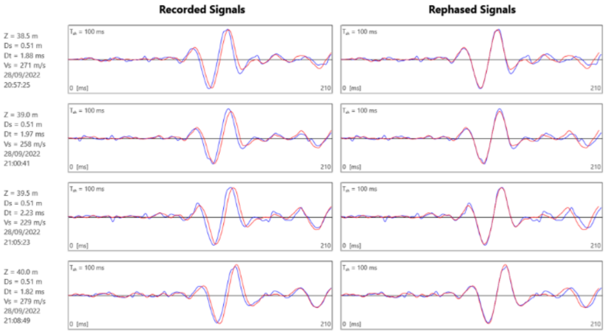
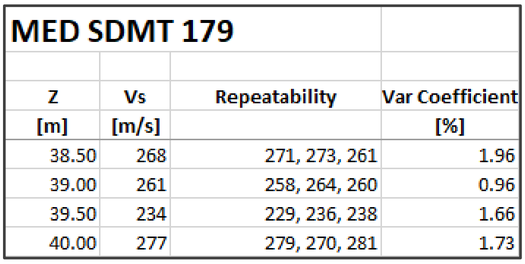


Figure 7. Examples of S-wave recorded seismograms in MED-SDMT-179 at depth 38.5 m to 40.0 m, as recorded and rephased according to the evaluated delay



MED SDMT 179			
Z [m]	Vs [m/s]	Repeatability	Var Coefficient [%]
38.50	268	271, 273, 261	1.96
39.00	261	258, 264, 260	0.96
39.50	234	229, 236, 238	1.66
40.00	277	279, 270, 281	1.73

Table 1. Vs results in test location MED-SDMT-179 between depths 38.50 m to 40.0 m

For each test depth, three distinct energizations of the seabed hammer enabled to evaluate the repeatability of the obtained Vs results, determined with the variation coefficient statistical parameter. Table 1 displays Vs evaluated as the algebric average of the repeated shear wave velocity measurements obtained at each depth between 38.5-40.0 m below the seafloor. The variation coefficient was always within 2.0 %.

In test location MED-SDMT-179, DMT and S-wave measurements were performed starting from the depth of 2.0 m below the seafloor down to the depth of 40.0 m. Fig. 8 displays the most relevant soil parameters obtained from both tests.

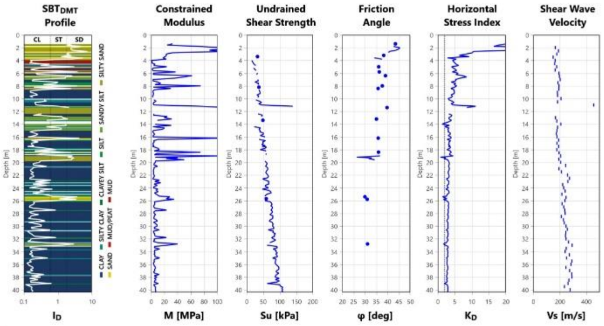


Figure 8. Offshore DMT and SDMT results in location MED-SDMT-179 in Barcelona harbour on 27-28/9/2022

The SBT_{DMT} profile highlights many thin interbedded layers of clays, silts, sands and their mixtures, whereas below 20 m the stratigraphy is mostly classified as clay. The shear wave velocity is the right-most plot of Fig. 8, showing a gradual Vs increase from a minimum of 150 m/s in the shallow layers to about 280 m/s at the deeper clay layer.

7. Sampling procedure

The sampling, handling, storage and transport methodology was focused on minimizing the disturbance induced in every stage of the soil sampling process described by Ladd and DeGroot (2003). Undisturbed samples of silty clay and clayey silt from the Llobregat delta were collected using a fixed hydraulic piston sampler of 80 mm external diameter. It was assembled on the drill rods and was lowered to the bottom of a cleaned and stable borehole. The walls of the borehole were cased down to the sampling depth. A water pressure between 70 and 80 bar was applied to force the thin wall tube to penetrate into the ground until it reached the maximum travel. Although the penetration rate was not measured, the water pressure was applied consistently, ensuring that the operation was conducted at a constant rate. Once achieved the maximum length, the liner containing the soil sample was kept stationary for at least a minute. Then, the sampler and rods were carefully pulled out in 6-meter sections, avoiding impacts or vibrations, with the only interruptions being to unscrew each section. Once the sampler was on deck, the inner tube containing the sample was carefully extracted from the outer sampler tube. A preliminary soil description on top and bottom was done. Then, samples were promptly hermetically sealed and stored vertically on board in a reefer with controlled temperature and relative humidity conditions until testing. Wooden boxes specifically designed for this purpose were used with an isolation to avoid vibration or shakes during transport. Each set of samples from a specific borehole were disembarked with care using an auxiliary boat and transported to the onshore laboratory before a new positioning of the jack-up.

A qualitative sample assessment analysis was done using a micro-CT scanner. This X-ray technique enables the selection of the less disturbed samples in a non-destructive and simple procedure. The focus of this selection was to avoid non-natural heterogeneities such as cavities, holes or discontinuities that may have occurred during sampling. Special attention was paid to the potential presence of natural gas bubbles. Fig. 9 shows a longitudinal and some transversal sections of a selected sample for further analysis. Although some fractures were observed at the top and bottom of the sample, the central part was qualitatively suitable and apparently undisturbed.

Selected samples were finally transported to the geotechnical laboratory of the Department of Civil Engineering in FEUP (UPorto) for further analysis. A target of three specimens for each stress path triaxial test was set, although the final number of specimens was defined once the sample was carefully opened and analysed by the laboratory technicians. Fig. 10 shows a set of samples in the wooden boxes in the laboratory.

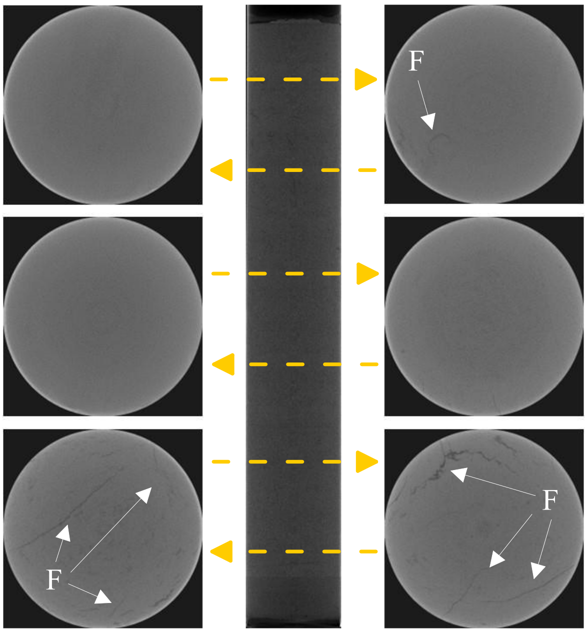


Figure 9. Longitudinal and transversal sections of a piston sample analyzed by X-ray analysis in a micro-CT scanner. F: fractures

Figure 10. Samples in the wooden boxes in the laboratory before testing.

To minimise as much as possible the sample disturbance during extrusion, a gentle longitudinal cutting along the liner was done with a very precise milling cutter in the mechanics workshop of FEUP in a gentle procedure (high frequency with low vibration amplitudes – Fig. 11). Specimens were carefully prepared into the triaxial cell for testing immediately after extrusion from the tube.

8. Vs for Sample Quality Assessment

Sample quality assessment is very important in any geotechnical campaign. The laboratory tests, and especially those used for strength characterization, should be carried out on representative high-quality samples. It must be considered not only the disturbance induced during the sampling process but also the natural variability of soil along the tube. This was of relevance on soils from the Llobregat delta, where thin fine sand layers were very commonly interbedded in the silty clay. These intercalations caused transverse discontinuities in some samples that were discarded for further advanced tests. Moreover, the gas presence was also reported in several boreholes, CPTu and SDMT (Tarragó et al. 2024). It might cause damages and porosity due to the effect of the exsolution and expansion of the gas when removing the soil sample (Sultan et al. 2012).

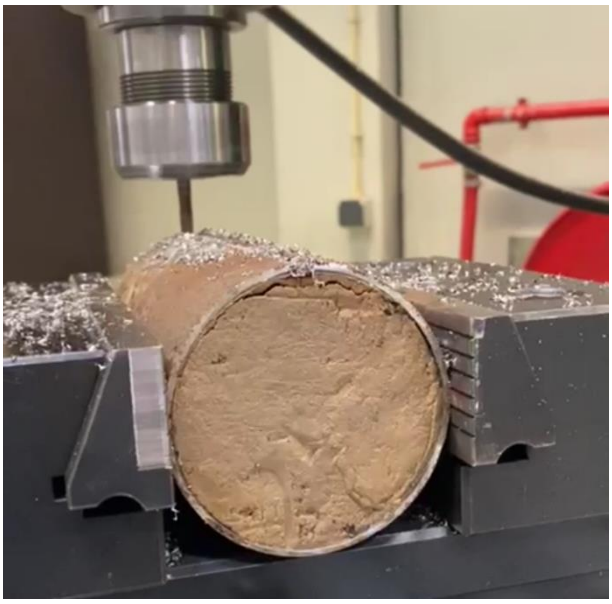


Figure 11. Opening the sample by gentle longitudinal cutting

There are different methodologies proposed over the years to assess sample quality based on non-destructive techniques and on laboratory tests. Among them, the comparison between in situ and laboratory measurements of seismic shear wave velocity and shear modulus is one of the most reliable. While P-waves propagate through both solids and fluids, S-waves can only travel through along the contacts of the particles. Okumura (1971) and Jamiolkowski et al. (1995), among others, demonstrated that S-waves are sensitive to void ratio, effective stress state and grain-to-grain contacts. Therefore, changes in these aspects during sampling might be captured through comparison between in-situ and laboratory S-wave measurements. Several authors have used this comparison to assess sample disturbance. Shiwakoti et al. (2000) compared the in situ G_{max} measured by seismic CPTU and by bender elements on laboratory reconsolidated Japanese piston samples of naturally sedimented soft clay. Tan et al. (2002) analysed the effects of different tube sampling methods and equipment for Singapore lower marine clay. Other outstanding works were presented by Landon et al. (2007), Sukolrat et al. (2008), Donohue & Long (2010), Ferreira et al. (2011), Arroyo et al. (2015) and Pineda et al. (2016), among others. Generally, it is observed a good relationship between the sample quality assessed by shear wave velocity measurements ($V_{s\text{-(LAB)}}/V_{s\text{-(IN-SITU)}}$) and by the criteria from volumetric strain proposed by Lunne et al. (1997) ($\Delta e/e_0$).

Ferreira et al. (2011) proposed a sample quality and sample condition classification based on the normalised shear wave velocities in the field and in the laboratory for residual soils (Table 1), which can allow a clear evaluation of the quality of the specimen interior body reconditioned to the stress state under the assumed natural conditions prior to shearing.

Table 1. Proposed classification of sampling quality by Ferreira et al. (2011)

Quality zone	$V_{s\,(LAB)}/V_{s\,(IN\ SITU)}$	Sample quality	Sample condition
A	≤0.85	Excellent	Perfect
B	0.85-0.70	Very good	Undisturbed
C	0.70-0.60	Good	Fairly undisturbed
D	0.60-0.50	Fair	Fairly disturbed
E	>0.50	Poor	Disturbed

As summarized by Viana da Fonseca & Pineda (2017), despite the simplicity and cost-effective nature of the shear wave propagation technique as a tool to assess sample quality, it is important to recognize the fact that sampling may affect the soil stiffness in two opposite ways. On the one hand, soil stiffness may decrease due to soil destructuration. On the other hand, it may increase if soil destructuration causes a reduction in porosity (soil compression).

9. Results

In geotechnical marine surveys, generating and measuring seismic waves is not trivial. Both the equipment and the testing methodology must be thoroughly analysed and executed. Small variations from the optimal conditions may produce inadequate waves that might be difficult to interpret, inducing unreliable and unrealistic results. The repeatability and variation coefficient of shear waves throughout the SDMT tests were carefully analysed. At least 3 measurements were taken at each depth.

To measure shear wave velocities in the laboratory, samples were restored to their in-situ stress. Bender elements (BE) are embeded in the bases and tops where the secimenn is positioned in the triaxial chamber, working as a wave transmitter and receiver, respectively. Several stress path triaxial cells were performed at different vertical effective stresses.

In this paper, the results of 5 triaxial tests are presented in which the shear wave velocity in the laboratory was measured at the in situ vertical stress of the sample. The Vs measurements were compared with the in-situ shear wave measurements from SDMT in the same location.

The soil analysed is described as low-plasticity (5 < PI < 15 %) clayey silt to silty clay with thin millimetric to centimetric intercalations of fine to very fine silty sands interbedded. These facies are interpreted as the prodelta sediments of the Llobregat delta. Although the laboratory tests for the identification and classification of these soils are still undergoing, soils recovered from nearby geotechnical investigations and from the same geological unit were described in detail and reported by Deu et al. (2018).

The three intermediate DMT parameters and the shear wave velocity measured in situ by 4 SDMT offshore tests and in the laboratory in 5 samples by bender elements are shown in Fig. 12. The velocities measured in the laboratory are lower than in the field as it would be expected considering the possible soil disturbance during sampling. Nevertheless, values are in a very good agreement. The $V_{s\text{-(LAB)}}/V_{s\text{-(IN-SITU)}}$ ratio is between 0.80 and 0.99.

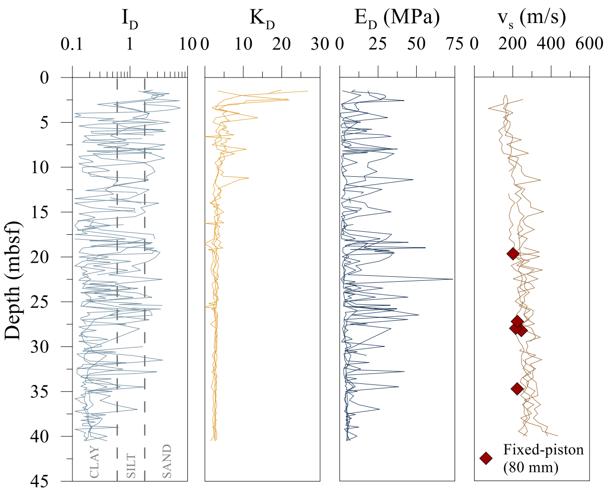


Figure 12. Intermediate parameters and shear wave velocities from 4 offshore SDMT and from BE in the laboratory.

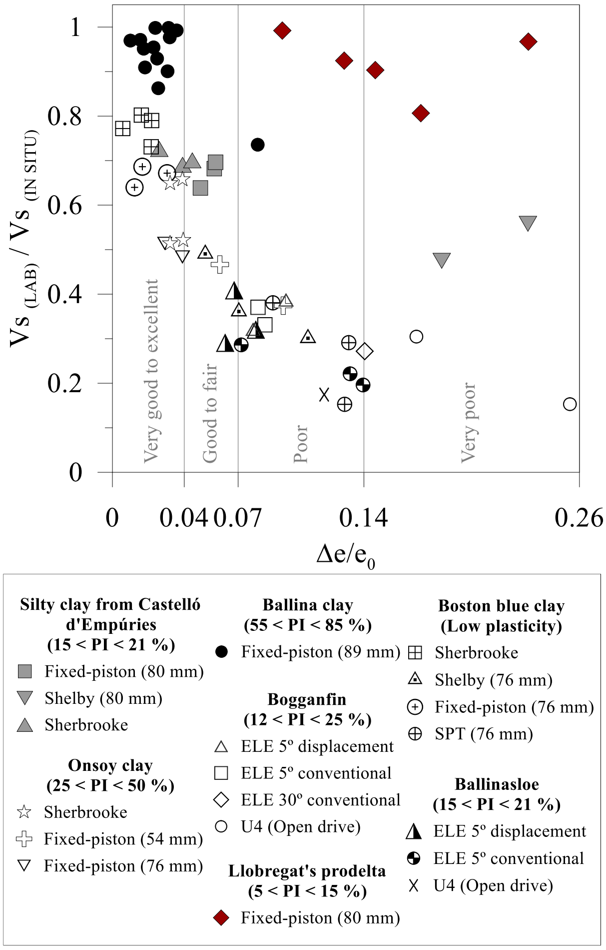


Figure 13. Shear wave velocities vs sample quality criteria by Lunne et al. (1997). Extracted from Landon et al. (2007), Donohue & Long (2010), Arroyo et al. (2015) and Pineda et al. (2016)

The sample quality was also estimated using the criteria from volumetric strain ($\Delta e/e_0$). Contrary to the previous cited references, there is no observed correlation between the results using both criteria. While the criteria from shear wave velocity measurements suggest a very good sample quality, the criteria proposed by Lunne et al. (1997) indicates a poor to very poor sample quality. Fig. 13 shows the sample quality for a wide variety of soils using both criteria. Different authors published these results: Boston blue clay (USA) (Landon et al. 2007), Bogganfin and Ballinasloe (Ireland) and Onsoy clay (Norway) (Donohue & Long 2010), silty clay deposits from Castelló d'Empúries (Spain) (Arroyo et al. 2015) and Ballina clay (Australia) (Pineda et al. 2016). The quality level for slightly overconsolidated soils (1 < OCR < 2) is used for the comparison. The sampler used in each set and the Plasticity Index (PI) range for each soil are also indicated.

During the opening of the liners in the geotechnical laboratory, despite the effort to keep the samples under tensional conditions, they may experience decompression in a thin anular cylindrical priphery, where some soil chips stood out and were repositioned, before starting the triaxial tests procedures. This could be the main reason for the divergence in the sample quality criteria, due to the recamporessiona of that relieved marginla zone.

10. Conclusions

Shear wave velocity plays a key role in engineering design parameters and is increasingly requested in small to large scale projects. Onshore Vs measurements are relatively straightforward, when employing high quality seismic probes with true interval configuration and digital data communication.

Offshore shear wave velocity measurements are considerably more challenging, due to physical constraints of the employed barge/jack-up/vessel and pushing machine, in addition to the difficulties of monitoring the state of the wave source at depth.

This manuscript describes successful shear wave velocity measurements performed in the harbour of Barcelona in September 2022 employing a drill rig placed on a jack-up, a custom designed seabed shear wave source and using the Medusa SDMT probe. The obtained high-quality seismograms provided a consistent and repeatable evaluation of Vs up to 40 m depth, with a water depth of 15-17 m.

The comparison between in situ and laboratory measurements of seismic shear wave velocity was adopted as a criterion for sample quality assessment. Results in 5 samples of low plasticity clayey silt to silty clay suggest a very good sample quality with $V_{s\text{-(LAB)}}/V_{s\text{-(IN-SITU)}}$ ratio between 0.80 and 0.99.

It is observed a discrepancy between this methodology and the criteria from volumetric strain proposed ($\Delta e/e_0$) which might be due to sample decompression of a mraginal peripherical zone during laboratory tests preparation.

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