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Geophysical and geotechnical characterization of soft marine soils in port infrastructures

Caractérisation géophysique et géotechnique des sols marins tendres dans les infrastructures portuaires

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ABSTRACT: This paper presents the results of a research project focused on the application of different geophysical and geotechnical in situ techniques to characterize the mechanical properties of soft materials present in port infrastructures. The goal of the study is to determine which combination of methods is more convenient for its geotechnical characterization.

The study was carried out in the reclamation land of a shipping terminal recently built in the South of Spain, where sandy hydraulic fills were poured over natural soft clays. After the consolidation of the fills, two boreholes were drilled to collect samples and to perform pressumetric tests. The following seismic methods were applied: P-S suspension logging, down-hole and spectral analysis of surface waves (SASW). In addition to the seismic methods, an electromagnetic probe and a spectral gamma probe were used to determine the conductivity and natural gamma content of the different materials involved.

To demonstrate their effectiveness, the results obtained by the different geophysical techniques are compared with conventional geotechnical methods such as pressuremeters and penetration tests.

RÉSUMÉ: Cet article présente les résultats d'une recherche centrée sur l'application de différentes techniques géophysiques et géotechniques in situ pour caractériser les propriétés mécaniques des matériaux souples présents dans les infrastructures portuaires. Le but de cette étude est de déterminer quelle combinaison des méthodes est la plus pratique pour cette caractérisation.

L'étude a été réalisée sur l'esplanade d'un terminal maritime récemment construit dans le sud de l'Espagne, où des remblais hydrauliques sableux ont été déversés sur des argiles molles naturelles. Après la consolidation des remblais, deux forages ont été réalisés afin de collecter des échantillons et de exécuter des essais pressimétriques. Les méthodes sismiques suivantes ont été appliquées: diagraphie en suspension P-S, analyse spectrale des ondes de surface (SASW). En outre les méthodes sismiques, ont été utilisées une sonde électromagnétique et une sonde gamma spectrale pour déterminer la conductivité et le contenu gamma naturel des différents matériaux impliquées.

Pour démontrer leur efficacité, les résultats obtenus par les différentes techniques géophysiques sont comparés aux méthodes géotechniques courantes telles que les pressiomètres et les essais de pénétration.

Keywords: Geophysical methods; soft soils; dynamic properties.

1 INTODUCTION

The Geotechnical Laboratory of CEDEX (Spanish Centre for Public Works Studies and Experimentation) is carrying out a research project which aim is to characterize the filling materials of port infrastructures and the soft natural soil of the seabed. To determine the dynamic properties of these soft materials, different geophysical methods have been applied. The goal of this study is to find out which combination of geophysical methods is more convenient for this characterization. In order to demonstrate their effectiveness the results obtained by the different geophysical techniques are compared with other geotechnical tests such as pressuremeters and cone penetration tests.

A proper in situ characterization is crucial to understand the performance of these soft materials under static and cyclic loads and also to generate time dependent models.

The study was carried out in the reclamation land of a shipping terminal recently built in the Port of Cadiz, in the South of Spain, where sandy hydraulic fills were poured over natural soft clays. After the consolidation of the fills, two boreholes were drilled to collect samples and to perform pressumetric tests.

The field campaigns were performed over 2016 when the upper layers of the subgrade were still being built. Besides, in 2017 when the construction works had been finished, an additional in situ test campaign were carried out.

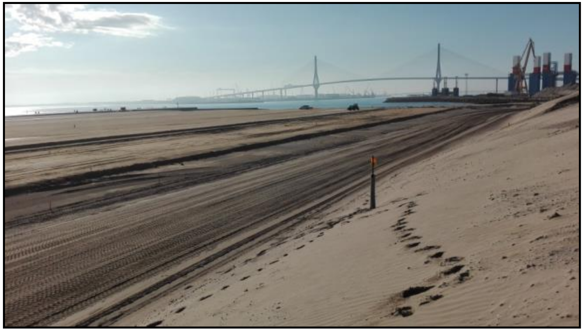

Figure 1. General view of the new shipping terminal during its construction.

2 METHODS AND IN SITU TEST CAMPAINGS

2.1 Methods used

Among the techniques that will be described next, the seismic methods are the most interesting for dynamic studies. The goal of these techniques is to obtain the propagation velocity of the compressional waves (V_P) and shear waves (V_S). These body waves travel through the different ground layers after the application of an impact or cyclic perturbation in the surface or inside the ground.

The propagation velocity of the waves only depend on the physical properties of the medium through which they travel and do not depend on the source, so propagation velocity is a useful indicator of the aggregation state of the particles in the soil (Kramer, 1996) .

The great potential of seismic methods lies in the fact that once V_P and V_S are known it is possible to calculate the dynamic moduli of the studied materials (Kramer, 1996):

Poisson ratio *ν*
$$\nu = \frac{\frac{1}{2}\left(\frac{V_P}{V_S}\right)^2 - 1}{\left(\frac{V_P}{V_S}\right)^2 - 1} \qquad (1)$$

Shear modulus *G*
$$G = \rho {V_S}^2 \qquad (2)$$

Young´s modulus *E*
$$E = 2(1 + \nu)G \qquad (3)$$

The abovementioned moduli allow to determine the strain response of soils under the application of stresses or loads. Equation 2 shows that once V_S is obtained only the density of the material (ρ)is required to calculate the Shear modulus G, a physical magnitude that is essential for the mechanical characterization of the site (Jamiolkowski, 2012). Therefore, most of the techniques used on this work are focused on the determination of V_P and V_S and their variation with depth, paying special attention to V_S.

2.1.1 P-S suspension logging

The P-S suspension logging probe is meant to determine V_P and V_S at different depths in the surroundings of a borehole (Kitsunezaki, 1980). Only one borehole is required, which in this study was also needed for the pressumetric test. Obviously, the preparation for suspension logging is by far cheaper than the cross-hole which needs at least two near boreholes. Although it can be used to characterize soft rocks, this probe is especially designed for soils, and yields fairly good results in soft soils, so it seems to be an ideal technique to fulfill the aim of this study. P-S suspension logging can be applied in boreholes protected with casing tubes, as it happened in this case.

2.1.2 Spectral analysis of surface waves (SASW)

This method provides a V_S profile from the study of the dispersion curve of the Rayleigh-type surface waves propagating through a layered material (Foti, 2015) Signals are generated and recorded at the ground surface around a central test point and results are presented over its vertical. Therefore, if this particular point is chosen near a borehole top, it appears to be a very convenient technique to complement P-S suspension logging. Although it is a test performed at the surface, results obtained are reliable. (Stokoe, 1994).

2.1.3 Down-Hole

This seismic tests provides the V_P and V_S distribution with depth. The interval velocities are calculated from arrival times of seismic waves which are generated in the surface and travel all the way down to an array of vertically installed seismic sensors inside a borehole (ASTM D7400-17).

2.1.4 Well logging

In addition to the seismic tests and to make the most of the existing boreholes, some geophysical probes capable of logging data in casing wells were used.

Specifically, an electromagnetic induction probe and a spectral gamma probe were chosen.

The lectromagnetic probe can measure the conductivity within the surroundings of the borehole by means of two couples of coils that induce two currents, one near the borehole and other further away (Ellis, 2007).

The spectral gamma probe detects the presence of some elements such as potassium, thorium and uranium, as well as the total counts of natural gamma of the soil. (Ellis, 2007).

2.1.5 CPTU and pressumeter

Some widely used geotechnical tests were also performed to contrast the results provided by the geophysical tests. A set of Cone penetration tests (CPTU) were carried out to measure, among other parameters, point and shaft resistance (ASTM D-5778-12). Besides, a self-boring pressumeter was used to measure the strength and the static stiffness parameters at different depths inside the boreholes (Belloti, 1989).

Figure 2.Performance of SASW test near borehole S1

2.2 In situ test campaigns

The wharf of the new shipping terminal has been constructed using concrete caissons and sandy hydraulic fills were poured in the inner side to build the esplanade. Consolidation of the hydraulic fills was accelerated using preloading and vertical prefabricated vertical drains. In April 2016, shortly after the preloading was moved away, two boreholes of 22 m depth were drilled. Figure 3 shows their location on the reclamation land. In these boreholes pressumetric tests were performed at different depths. Once these tests were finished, the boreholes were protected using casing tubes to, afterwards (when casing tube is perfectly coupled to the ground), introduce different geophysical probes. From the retrieved material some representative samples of each level were chosen to perform additional laboratory tests. The tests executed in the boreholes were: Down-hole, P-S suspension logging, natural gamma and conductivity.

In addition to the tests executed on the boreholes, other techniques were implemented from the surface. In this regard, two SASW tests were performed, the center of each spread is near the borehole top, as shown in Figure 3.

Furthermore, a set of CPTU were carried out, two of which were performed close to the boreholes.

All the referred tests were executed during Springtime 2016. One year later, another suspension logging test were performed in each borehole.

A new P-S suspension logging campaign is programmed to be developed in 2019.

Figure 3. General view of the reclamation land and a sketch of the boreholes location and SASW spreads.

The chronology of the works is summaraized next:

- April 2016. Pressumetric, SASW tests and Down-Hole.
- May 2016. CPTU´s, spectral gamma and electromagnetic probes.
- June 2016. P-S suspension logging.
- May 2017. P-S suspension logging.

3 RESULTS

The values of the different parameters measured versus depth are presented. In order to simplify the interpretation of the results, depths are referred to the zero port sea level, due to the fact that the height of the surface was changing as top layers of the subgrade were being built.

Table 1 shows the heights of each borehole at the different moments of the construction when measures were carried out. In addition, the depths of the sea floor in the vertical of each borehole are included. This last information was obtained from the last bathymetry performed before the beginning of the works, at the end of 2013.

Table 1. Heights of the surface at the dates of the different campaigns and original Sea floor level.

Date	**S1** Z (m)	**S2** Z (m)
Original Seafloor	-6.0	-3.5
2016 April	5.71	5.27
2016 May	5.71	5.27
2016 June	5.71	5.70
2017 May	6.19	6.31

The results obtained from the different methods are presented separatedly for each borehole.

3.1 Borehole S1

Figure 4 shows the distribution of body waves propagation velocities obtained with the different methods applied in borehole S1.

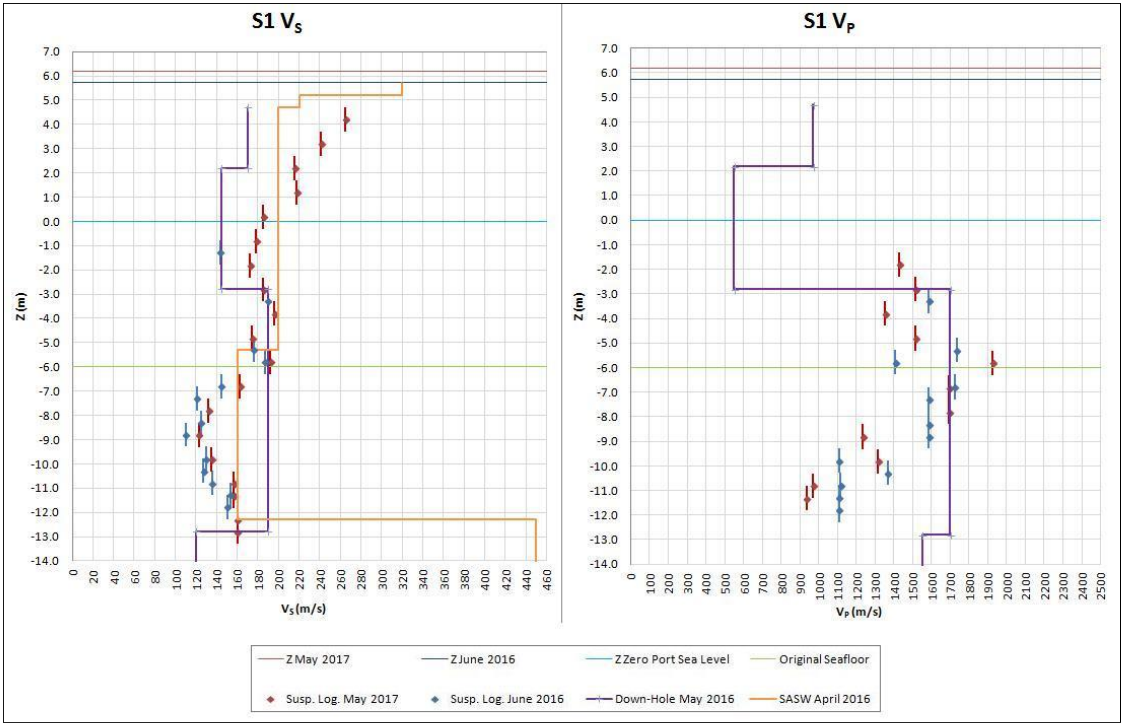

Figure 4. Propagation velocitiesof body waves in borehole S1. V_S on the left and V_P on the right.

3.1.1 *Shear wave velocity, V_S*

As it can be observed on left side of Figure 4 the results provided by the P-S suspension logging fit fairly well with the layer distribution. The highest values were found in the upper layers presumably because the materials there were heavily compacted so the stiffness there is high. The velocities in the sand fill decrease until reaching the sea level and from there to the natural soil is almost constant. Below there, velocities decrease because the material there is the natural soft clay. The minimum was found at a depth of -9 m and the velocity there is 110 m/s, which indicates the low stiffness of this material. From there to the end of the borehole, the velocity increases slowly. All these results agree perfectly with the samples extracted.

Results obtained with SASW and with P-S suspension logging are similar. The main differences between them are due to SASW is performed from the surface so a larger amount of material is involved, and of course, the deeper the larger. The large difference between both methods in the bottom layers can be attributed to the fact that SASW test reaches the bed rock and it was needed to place it above of its true depth in order to fit the experimental dispersion curve to the model.

Down-hole results do not adjust the layer distribution. The mean value are similar to those obtained with the other methods but without any correlation at the different depths.

3.1.2 *Compressional wave velocity, V_P*

The results that best adjust the material distribution are those of P-S suspension logging, but the poor quality of the signals in the upper layers did not allow to calculate the velocities above -2 m.

Results yielded by down-hole in the upper layers of the sandy fills are higher than those underneath, which is an expected behavior. Below -2.5 m, V_P has a constant value of 1700 m/s which is not far from the propagation velocity of water. See right side of Figure 4.

3.1.3 *Conductivity and natural gamma*

On the left side of Figure 5 the results provided by the electromagnetic probe are shown. It can be observed that conductivity increases in the sandy fill from the surface to the sea level due to the increasing water content and from there to the natural ground the value is constant. Below there, conductivity is almost constant presenting a sligth decrease. The spike at -7 m must be caused by the presence of a small ferromagnetic material because it is much higher for the short coil separation than for the longer one.

On the right side of Figure 5 the contents of potassium and natural gamma radiation arround borehole S1 are presented. At a depth of -7 m, corresponding to the clays presence, there is an increase in both values, much more evident in the natural gamma.

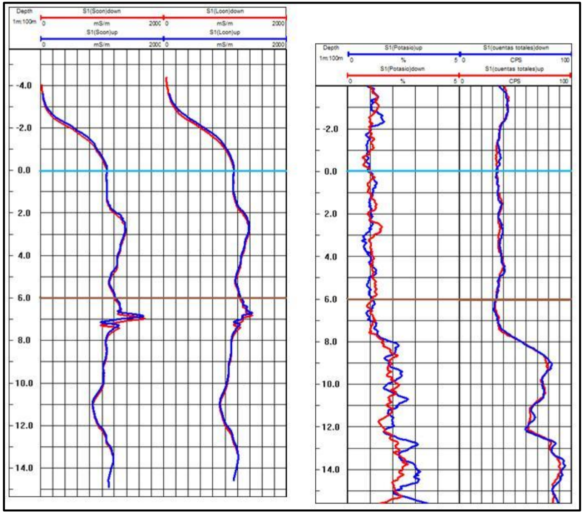

Figure 5. Left: Conductivity obtained for the short and far field. Right: Potassiumand Natural gamma content nearby borehole S1. Blue and red lines are data collected in up and down direction respectively.

3.1.4 *CPTU´s and pressumetric tests*

CPTU tests are the most suitable to asses changes in litologhy, even in the range of centimeters. Point and shaft resistance fluctuates around a constant value during the first 12 meters, and underneath that depth, both resistances decrease. In addition, at 12 m from the surface, interstitial pressure and temperature rise sharply. All these features suggest that at 12 m from the surface, that is -6m from sea level, the transition between sandy fills and clays take place.

The static moduli obtained with pressumetric tests at several depths correlates well with P-S suspension logging velocities, with higher values in the sandy fills than in the clays.

3.2 *Borehole S2*

3.2.1 *Shear wave velocity, V_S*

Results obtained for V_S are shown on the left side of Figure 6. Again, the results that better adjust the material litologhy are those provided by P-S suspension logging.

Velocities obtained with SASW and down-hole, despite not being equal, follow a similar pattern between them and similar to P-S suspension logging.

3.2.2 *Compressional wave velocity, V_P*

Results obtained for V_P are shown on the right side of Figure 6. P-S suspension logging measurements of 2016 failed to provide the velocities in the shallower layers.

Down-hole was carried out at that time, so comparison of the results is not possible in the shallower layers given by the two methods at that time. Conditions in the upper layers were not the same in 2016 and 2017. So it is not accurate to compare results from P-S suspension logging May 2017 with those obtained from down-hole May 2016. The stiffness of the shallower layers near borehole S2 were different in those dates because the upper layers in that area were compacted during the Summer of 2016. So that might explain the low velocity provided by down-hole in the upper layers.

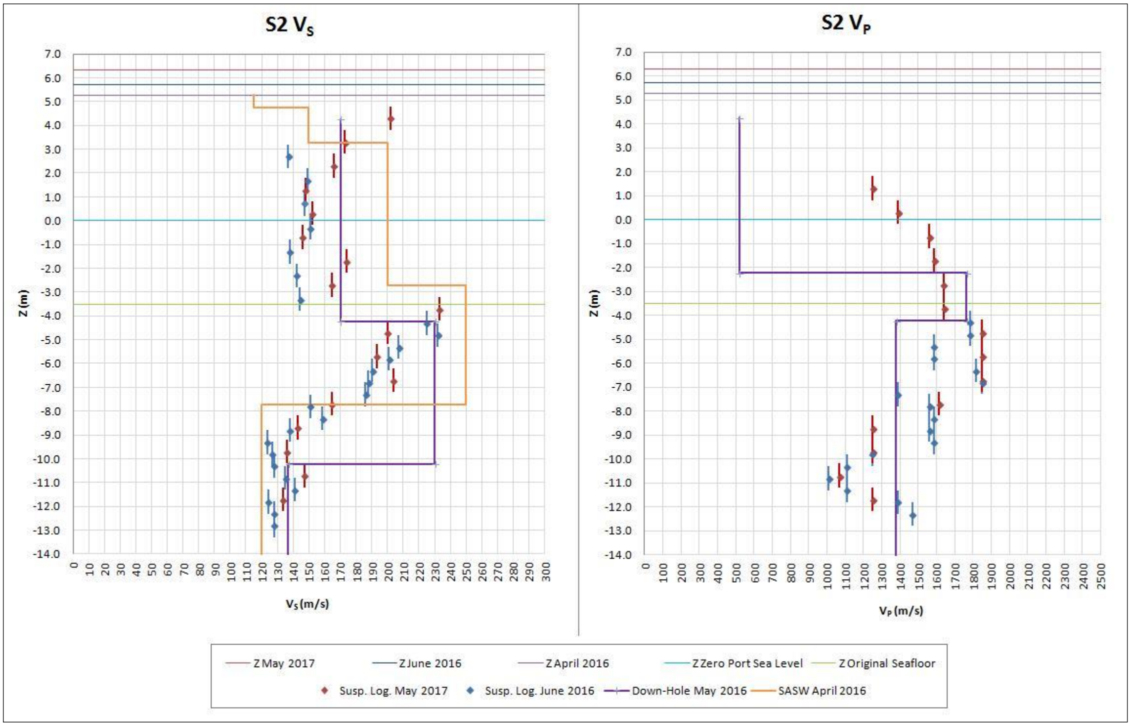

Figure 6. Propagation velocities of body waves in borehole S2. V_S on the left and V_P on the right.

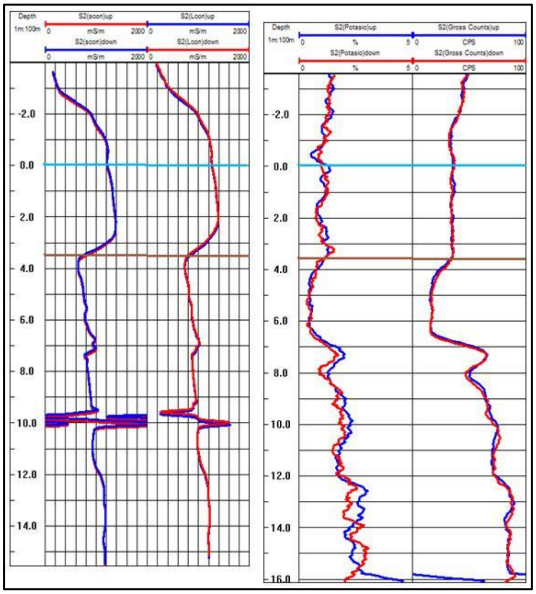

Figure 7. Left: Conductivity obtained for the short and far field. Right: Potassium and Natural gamma content nearby borehole S2. Blue and red lines are data collected in up and down direction respectively.

3.2.3 *Conductivity and natural gamma*

Left side of Figure 7 displays the results of the electromagnetic probe in borehole S2. The transition between the sandy fill and the sea subsoil materials is clearly detected. Furthermore, as it happened in borehole S1, in borehole S2 conductivity also increases in the sandy fill from the surface to the sea level.

The presence of active clays is detected at -7 m, as it is inferred from the observation of right side of Figure 7.

3.2.4 *CPTU´s and pressumetric tests*

All the comments included in section 3.1.4 for borehole S1 are hold for borehole S2. The only difference is that despite the fact that clay also appears at 12 m from the surface, in this borehole S2 this depth corresponds to 3 m below the original sea floor. This feature is also observed with the other geophysical methods and in the extracted samples.

4 CONCLUSIONS

Among the different seismic methods, P-S suspension logging seems to be the most reliable. Velocity variations with depth provided by this technique fit properly to the material distribution. Furthermore, V_S and V_P values given by this method are expected in the existing materials under the current conditions. Therefore, it is a suitable technique for the dynamic characterization of the materials around the borehole.

P-S suspension logging is very sensitive to surface noise and sometimes it is difficult to calculate propagation velocities at shallower layers, especially in the case of P waves.

Down-hole accuracy is lower than that of the P-S suspension logging, but velocities are similar at the depths at which reliable data are available to compare both methods. Down-hole tests appear to be a good complement to P-S suspension logging in the shallower layers, especially bellow the first three meters.

The results provided by SASW tests do not always agree well with P-S suspension logging. However, the mean velocity values of each layer and the depths at which they appear are rather similar.

These two methods enhance each other due to the fact that the material involved in P-S suspension logging is limited to the surrounding of the borehole and SASW test cover bigger masses of soil, especially for large sensor separation, that is, for big depths.

Due to the fine correlation between P-S suspension logging and SASW tests, the usage of the latter is recommended where it is not possible to drill a borehole.

Results obtained with electromagnetic and natural gamma probes are really successful. Electromagnetic probe allows to clearly identify the transition between the sandy fills and the natural soil. Besides, it is possible to set the depth where sandy fills are water saturated.

Gamma natural probe can identify the presence of active clay with high accuracy.

All the provided results for the pressumetric and CPTU tests agree with the velocity distribution given by P-S suspension logging and the litologhy deduced from the other probes.

5 ACKNOWLEDGEMENTS

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