

Prediction on thickness and compressibility of saturated soils by the interpretation of multi-spectral analysis (MASW) and seismic refraction method

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ABSTRACT: Settlement of compressible soils by loading or natural consolidation processes depends mainly on thickness, soil stiffness and degree of saturation. Those input parameters are measured directly by standard field and laboratory test (SPT, CPTu and consolidation test as well). On several projects, according to cover wide areas or design a preliminary engineering with a lack of information or economic resources, the geophysical methods are reliable tools to describe a brief geotechnical description of ground profile. This article shows the determination of the thickness of compressible and saturated soils from Postpampeano Formation inside a coastal area close to Ensenada city, Buenos Aires province (Argentina). The assessment of MASW & seismic refraction techniques was carried out and compared with SPT results and laboratory routine tests. Finally, results showed that these techniques are very important to consider during preliminary geotechnical campaigns or as a complementary tool on typical campaigns with boreholes or penetrometer testing.

KEYWORDS: Soft soil – Postpampeano – MASW – Seismic refraction - Settlement

1 INTRODUCTION

1.1 Geophysical methods in geotechnical site characterization

Over the past few decades, geophysical methods have been increasingly incorporated as complementary tools in standard geotechnical investigations. In these campaigns, traditional boreholes with penetration testing such as SPT are combined with geophysical techniques to provide additional insights not only enhancing the understanding of soil parameters but also expanding the volume of soil mass being investigated. In that way, boreholes give information on a 1-D (depth) while geophysical techniques such as MASW, seismic refraction or another give 2-D (depth-horizontal) information.

1.2 Multi-spectral analysis of surface waves (MASW) and seismic refraction methods.

MASW and seismic refraction methods (Park 1998a, 1998b, 1999; ASTM D5777) are capable of determining shear (S-wave) and compressional (P-wave) velocities, respectively.

Data acquisition consists of i) placing geophones (4.5 Hz) towards a straight line and equidistant, ii) checking hard-shot communications with all the geophones, iii) making a hard shot in the ground level by 5 – 8 kg sledgehammer or heavy death weight falling a fix height, iv) data acquisition of the entire wave frame on different positions along the main line, v) repeat those steps until obtain good data quality. Figure 1 shows a typical layout during seismic fieldwork.

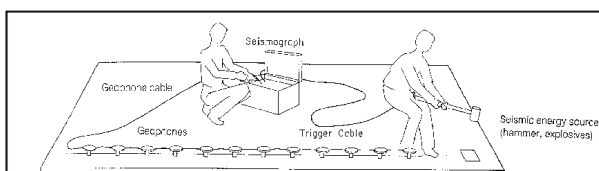


Figure 1. Seismic methods (ASTM D 5777, D 6429).

1.3 Limitations of geophysical techniques

It is important to acknowledge the limitations of these techniques for geotechnical applications. The very low strain levels do not allow the prediction of shear strength or stiffness parameters required for foundation design, for example.

Table 1 of ASTM D6429 offers a standardized guide for selecting the most appropriate geophysical methods for various geotechnical objectives, such as identifying the water table, detecting voids and sinkholes, locating bedrock, and characterizing soil or unconsolidated layers. In several cases, MASW and seismic refraction are classified as “B” or “-” in this standard, indicating that they are either secondary choices or not recommended. Additionally, natural limitations—such as wind, machinery interference, and the presence of voids—can commonly affect the reliability of these methods.

2 CASE OF STUDY

2.1 Brief description of the CTEB Project

The Combined Cycle Thermoelectric Plant of Ensenada de Barragán (CTEB) is located at the metropolitan area of Gran La Plata, Buenos Aires Province, Argentina. This major infrastructure project began in 2011, and its energy generation capacity is expected to reach 847 MW upon completion of the final construction works.

A key component of the project was the construction of a 20-inch diameter, 3,000-meter-long aqueduct connecting the CTEB plant to the water treatment facility near coastline. Figure 2 shows an aerial view of the key facilities.



Figure 2. CTEB location and aqueduct 20” (red line).

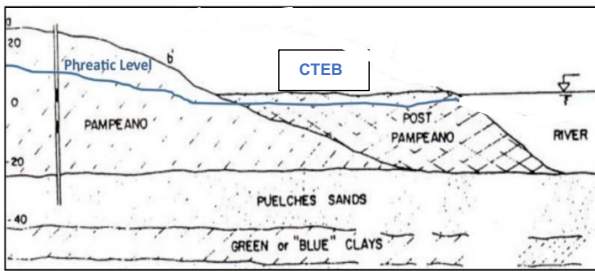


Figure 3. A-A section and CTEB location. Typical geotechnical ground profile from Buenos Aires, right margin of Rio de La Plata (Núñez 1986).

At this specific site, the upper 4–5 meters below ground level (bgl), which corresponds to the exact depth of construction for the aqueduct line, are primarily composed of soils from the Postpampeano Formation. This geotechnical unit consists of soft, grey clays with high plasticity, interbedded with low-density silty and sandy layers. At the project site, the groundwater table is typically found at a depth of 1–2 meters bgl.

2.2 Field works across the aqueduct line

The main field geotechnical works carried out are listed below and identified in Figure 4:

- 25 machine boreholes (S1321 to S1325) between 10.0 to 25.0 m depth, with SPT every single meter.
- 14 MASW 2-D lines (LS 1301 to LS 1314), 60.0 m length.
- 6 Seismic refraction 2-D lines (LS 1303, 1305, 1307, 1309, 1311, 1313), 60.0 m length.
- 8 Dynamic Probing Super Heavy (DPSH) cone penetration until 12.0 m depth.
- 13 geoelectrical resistivity 1-D surveys (Wenner method).

Figure 4 illustrates the locations of several boreholes with SPT, which were used to confirm the presence of Postpampeano soils through routine laboratory tests, including Atterberg limits, moisture content, unit weight, and fines content (passing sieve #200). Given the 3,000-meter length of the aqueduct line, geophysical surveys were essential to assess the lateral continuity of the Postpampeano unit and to identify any changes in geotechnical stratigraphy at depth, based on the interpretation of shear wave velocity (Vs) profiles. This methodology was carried out by the authors in other circumstances (Codevilla, Covassi & Homenec, 2024).

Geophysical 2-D lines were carried out by a hard-soft unit (seismograph) with 16 channels, 16-bit A/D converter, 12.5 kHz sampling rate per channel and 200 kHz channel sweep provided by INETEK, a local Argentinian company.

DPSH and resistivity tests were carried out at additional and specific locations to enhance the density of field data along the aqueduct alignment. However, to narrow the scope of this paper, those results are not presented.

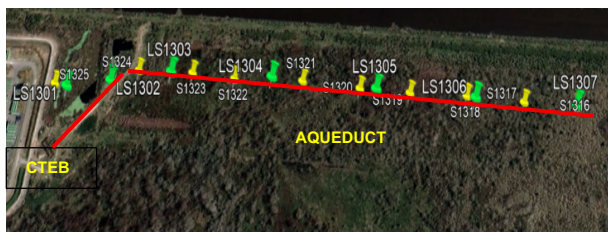


Figure 4. Boreholes + SPT (S1301 – S1325) and geophysical survey lines (LS 1301 – LS1314) following the aqueduct path (red line).



Figure 5. Typical layout for geophysical test (tape 100 m, cables, geophones 4.5 Hz, hard-soft unit and 6 kg sledgehammer).

3 GENERAL RESULTS

3.1 Boreholes with SPT

Field and lab test confirmed the geotechnical unit sequence at the site, basically:

- Topsoil (TS): man-made fill, soft to compact, $2 < N_{SPT} < 7$.
- Postpampeano (PP): soft clays with erratic low-density, low to high plasticity sandy silts, $N_{SPT} < 3$.
- Pampeano (PA): clays and silts stiff to very stiff to hard, $12 < N_{SPT} < 40$.

Figures 6 and 7 present typical field and laboratory spreadsheets that clearly illustrate the transition between the geotechnical units: Topsoil (TS), Postpampeano (PP), and Pampeano (PA). In some cases, topsoil was not encountered. Table 1 summarizes the range of geotechnical and physical parameters measured from samples obtained via SPT, using standard laboratory testing procedures. As is well known, disturbed samples from SPTs are suitable for these types of tests. Table 1 presents the range of physical parameters obtained by laboratory routine and the experience of the authors at the site.

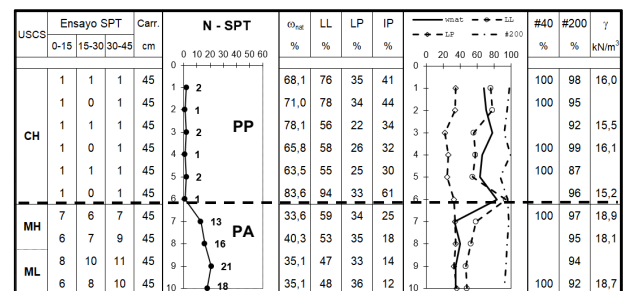


Figure 6. S1307 site. SPT - lab test and PP-PA transitions.

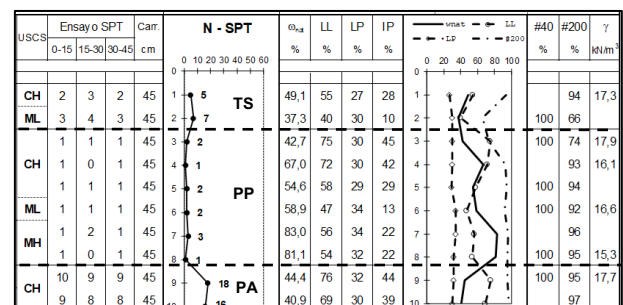


Figure 7. S1314 site. SPT - lab test and TS-PP-PA transitions.

Table 1. Physical parameters from SPT boreholes (S1301 to S1325).

Parameter	Symbol	TS	PP	PA	Unit
Unit weight	γ	17-19	15-18	18-19	MN/m ³
Moisture content	ω_{nat}	20-48	40-100	25-50	%
Liquid limit	LL	30-50	30-90	35-60	%
Plastic index	IP	5-20	5-50	10-30	%
Fine content	#200	85-100	60-100	85-100	%
USCS	-	CH, CL, ML	CH, MH, ML, SM	MH, CL, ML	-

3.2 MASW interpretation (V_s tomography)

Post-processing of data acquisition was carried out to obtain dispersion curves (frequency vs. phase velocity) at various positions along the survey line during fieldwork. Subsequently, an inversion algorithm was applied to generate a 2-D tomography of the shear wave velocity (V_s) profile (m/s vs. x-z coordinates).

Figures 8 and 9 present the results for sites LS1303 and LS1307, respectively. Over a span of 60 meters along the aqueduct alignment and to a depth of 26 meters, shear wave velocities ranged from 50 to 320 m/s on both sides. Regarding the relationship between shear wave velocity and shear modulus at very low strain, this is expressed by equation 1:

$$G_0 = V_s^2 \cdot \rho \quad (1)$$

where ρ is the soil mass density. In general, “soft” soils have shear wave velocity values less than 200 m/s (Milsom & Eriksen, 2011). As the V_s value increases, the soil profile becomes progressively stiffer. In Figure 9 it can be seen near the first 2 m a transition between “soft” to “firm” soil instead of Figure 8.

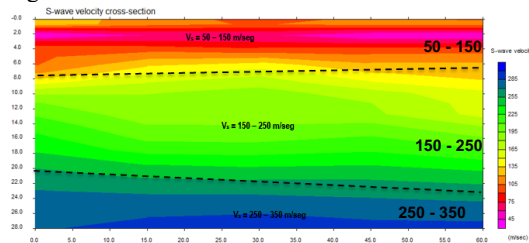


Figure 8. LS1303 site. MASW - V_s profile.

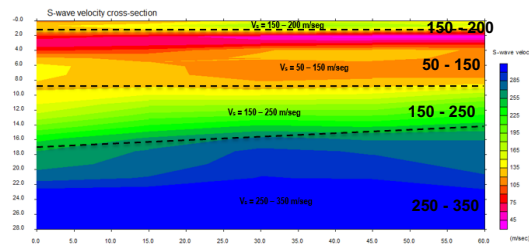


Figure 9. LS1307 site. MASW - V_s profile.

3.3 Seismic refraction interpretation (V_p tomography)

Using the same field data acquisition applied in the MASW method, time-distance curves were obtained for each site. Subsequently, an inversion algorithm was used to generate 2-D tomography of the P-wave velocity (V_p) profile (m/s vs. x-z coordinates).

Figures 10 and 11 show the results of LS1303 and LS1307 sites, respectively. Along 60 m towards the aqueduct line and

26 m in depth, compressional wave velocities were 200 – 1650 m/sec on both sides.

Considering the reference values for compressional wave velocities in surface materials ($V_p \approx 240-610$ m/s) and water ($V_p \approx 1450-1660$ m/s) as suggested by ASTM D5777, it is possible to interpret these characteristics within the V_p profiles. For that reason, Figures 12 and 13 show V_p profiles with just 2 soil layers, unsaturated soil and saturated soil, respectively.

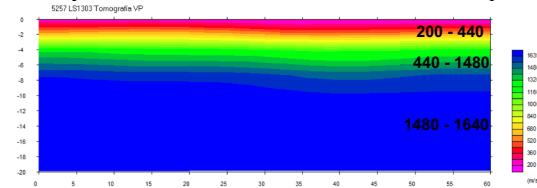


Figure 10. LS1303 site. Seismic refraction - V_p profile.

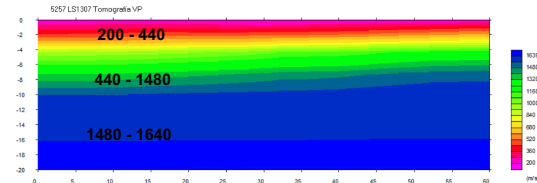


Figure 11. LS1307 site. Seismic refraction - V_p profile.

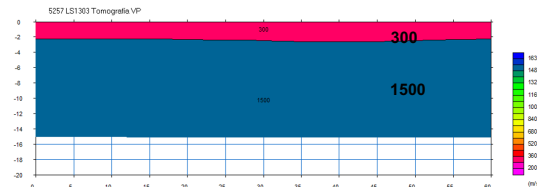


Figure 12. LS1303 site. V_p profile with 2 layers.

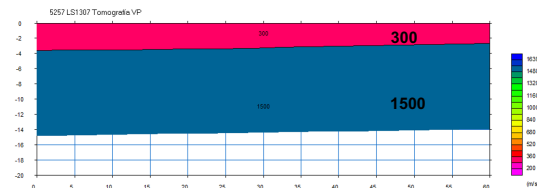


Figure 13. LS1307 site. V_p profile with 2 layers.

3.4 Comparison between SPT and seismic methods to predict soil transitions, thickness of soft soils and saturated zones

SPT results from the boreholes confirm the actual transitions between the TP, PP, and PA geotechnical units, as well as the thickness of soft soils and the groundwater level. These findings are based on precise field locations and direct measurements obtained through both field and laboratory testing.

Using the MASW and seismic refraction data, Table 2 summarizes the range of shear wave velocity values for each geotechnical unit, as well as groundwater levels at various locations, assuming a $V_p \approx 1500$ m/s. Table 3 summarizes the Postpampeano soil thickness derived from both SPT and MASW methods, along with groundwater levels determined from borehole groundwater screening. Several important observations are provided below these results:

1. Topsoil (TS) shows shear wave velocities values between 50 – 200 m/sec, which may show the typical erratic and heterogeneous soil conformation in the site.
2. Postpampeano soil (PP) shows shear wave velocities values between 50 – 200 m/sec, which is reasonable for soft soils.
3. Postpampeano-Pampeano transition (PP-PA) predicted by MASW was close to 130 – 200 m/sec, which is reasonable for a transition of soft medium soils.

4. Postpampeano thickness estimated using the MASW method gives more value than SPT information. Lateral soil profile variation could be the reason but still we cannot confirm this.
5. A saturated zone was detected by the seismic refraction method in all the seismic lines, which was confirmed by SPT information.
6. The water table depth estimated by the seismic refraction method was higher than that obtained from SPT borings.

Table 2. V_s (m/sec) values for TP, PP and PA units by MASW and $V_p = 1450$ m/sec value for water table depth by seismic refraction.

Site	TS (m/sec)	PP (m/sec)	PA (m/sec)	Water table (m)
LS 1301	-	50 - 150	150 - 320	-
LS 1302	-	50 - 200	200 - 320	-
LS 1303	-	50 - 130	130 - 320	2.0
LS 1304	-	50 - 150	150 - 320	-
LS 1305	-	50 - 150	150 - 320	3.0 - 4.0
LS 1306	-	50 - 200	200 - 320	-
LS 1307	50 - 200	70 - 150	150 - 320	2.5 - 3.5
LS 1308	70 - 200	70 - 150	150 - 320	-
LS 1309	70 - 150	70 - 150	150 - 320	4.0
LS 1310	50 - 200	50 - 130	130 - 320	-
LS 1311	70 - 200	70 - 130	130 - 320	0.5 - 2.0
LS 1312	70 - 200	70 - 130	130 - 320	-
LS 1313	100 - 200	70 - 180	180 - 320	2.0
LS 1314	130 - 200	50 - 150	150 - 320	-

Table 3. Determination on Postpampeano (PA) soil thickness by SPT borings and MASW method and water table by SPT borings.

Site	PA thickness (SPT borings)	PA thickness (MASW)	Water table (SPT borings)
LS 1301-S1325	5.5 - 6.0	8 - 9	-
LS 1302-S1324	4.5 - 5.0	7 - 8	2.8
LS 1303-S1323	4.5 - 5.0	8 - 9	2.8
LS 1304-S1321	5.5 - 6.0	7 - 10	2.3 - 2.6
LS 1305-S1320	5.5 - 6.0	8 - 13	1.6 - 2.2
LS 1306-S1318	6.5 - 7.0	8 - 11	1.4 - 1.5
LS 1307-S1316	6.0 - 7.0	9 - 10	1.4 - 1.5
LS 1308-S1314	6.5 - 7.0	8 - 9	1.1 - 1.4
LS 1309-S1312	6.5 - 7.0	7 - 10	1.1 - 1.2
LS 1310-S1307	4.0 - 4.5	7 - 8	1.4 - 1.6
LS 1311-S1308	3.0 - 4.5	7	1.3 - 1.6
LS 1312-S1307B	4.0 - 4.5	7 - 9	1.1
LS 1313-S1306	5.5 - 6.5	7 - 8	1.3
LS 1314-S1304	6.0 - 6.5	6 - 7	1.2 - 1.3

4 CONCLUDING REMARKS

Geophysical methods are highly effective tools for enhancing the geotechnical characterization of a site. Today, many infrastructure and architectural projects integrate both geotechnical and geophysical techniques as part of optimized site investigation campaigns. These approaches are increasingly aligned with national and international standards that actively promote their combined use. In some cases, such as in modern seismic standards, the use of geophysical methods

is even encouraged to better determine the site's subsoil class and to more accurately define the response spectra to be applied during structural design.

Particularly in the CTEB project, the MASW method provided reliable results that helped to show the Postpampeano-Pampeano sequence and identify soft soil deposits through interpretation of the V_s profile, offering valuable insights along the aqueduct alignment. Additionally, the seismic refraction method, based on V_p profile interpretation, indicated the presence of the water table—though with certain limitations according to the exact depth, possibly due to stiffness inversion effects caused by the topsoil layer.

Given these complexities, such geophysical techniques should be applied by experienced geotechnical engineers, capable of making informed judgments. In many cases, proper interpretation may lead to discarding misleading results, ensuring that conclusions are based on sound engineering reasoning.

5 ACKNOWLEDGEMENTS

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