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GEOPHYSICAL ANALYSES ON THE GEOMECHANICAL CHARACTERISTICS OF THE SOIL FOR CHOICES OF THE DRILLING RIG, IN THE AREA OF TÂRGU OCNA, BACĂU COUNTY, ROMANIA

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Abstract: *As part of the company Geoscan Service S.R.L., I was contacted to investigate the possibility of using resistivity, refraction seismic data and MASW seismic to identify the stratification up to 15m deep so that the client could choose the type of drilling rig for installing the conductor in order to drill two water injection wells. The main problem in the choice of geophysical methods was the lack of detailed geological data for calibrating the obtained results, as the presence of groundwater, the thicknesses of the deluvial layer and the bedrock. The choice of geophysical methods and the work procedure are carried out according to the international standards in force, ASTM D6429-99 "Standard guide for Selecting Surface Geophysical Methods", ASTM D5777-00 "Standard guide for Using the Seismic Refraction Method for Subsurface Investigation, "Standard Guide for Using the Direct Current Resistivity Method for Subsurface Site Characterization", STAS 1242/7-84 "Geophysical research of the land by seismic methods".*
Keywords: *seismic investigations, geophysics, MASW, refraction, resistivity, applied geophysics*

1. Introduction

Considering the current technical development that led to the possibility of using non-intrusive indirect measurement techniques (from the ground surface), we chose two complementary geophysical methods: seismic (refractions and MASW) and resistivity (VES vertical electrical sounding). The purpose of the investigations was to provide precise information so that the optimal technical-economic variant of the drilling rig could be chosen for drilling the conductor of the two water injection wells. The choice of the two geophysical methods was made to analyze two different sets of data: from seismic data the speeds of P and S waves that respond mainly to the density of the rocks they cross, and from VES data the resistivity which is a result of the rocks' resistance to the passage of electric current, mainly due to natural humidity.

The initial information made available consisted only of the location of the two rigs prepared for drilling. Given the confidentiality of the data, the precise position of the boreholes and the final beneficiary of the works will not be detailed in this article.

The work area is located near the city of Târgu Ocna, Bacău County, Romania, at the southern limit of Tazlău – Cașin depression with Nemira Mountains. From a geological point of view, the area is part of the Carpathian flysch unit made up of Paleogene formations arranged in Tarcău and Kliwa folds.

The choice of geophysical investigation methods took into account the following considerations:

1. The required investigation depth of 15m;

2. Estimation of existing lithological complexes in the area. For this, the 1:200000 geological maps of the Geological Institute of Romania were used, thus the study locations were included in Tarcău map composed of Paleogene formations mainly sandstones and limestones. Considering the purpose of the geophysical investigations, the results must delimit the deluvial sedimentary layer from the bedrock and the stiffness degree of the lithological complexes up to 15m deep.

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3. The landscape of the perimeters to be investigated: quasi-horizontal, considering the fact that the drilling platforms had already been set up. The two perimeters are located in a hilly area, so we considered the fact that the top of the bedrock has a slope similar to the slope of the land.

Based on this reasoning, two complementary geophysical methods were chosen so that the results of the measurements are conclusive according to the client's requirements. The two methods chosen are electrometry as the vertical electrical sounding method and seismic as the refraction method and MASW (Multi-Channels Analysis of Surface Waves Survey). *[1], [2], [3], [4]*

2. Geophysical methods

2.1 Seismic method

Geophysics studies the behavior of waves propagating inside materials. A seismic signal changes according to the characteristics of the medium it travels through. Waves can be generated artificially with a battering ram, hammer, etc. The seismic signal can be decomposed into several phases, each of which identifies the movement of particles driven by seismic waves. The phases can be:
P-Longitudinal: compression depth wave;
S-Transverse: shear depth wave;
L-Love: surface waves composed of P and S waves;
R-Rayleigh: Surface wave composed of elliptical and retrograde motion.

Rayleigh waves – "R"

In the past, studies on seismic wave propagation focused on the propagation of depth waves (P, S) considering surface waves as a "noise" of the seismic signal to be analyzed. However, recent studies have allowed the creation of advanced mathematical models for the analysis of surface waves in media with different stiffness.

For this project, a SYSMATRACK Seismograph equipment with 2 channels and 24 4.5Hz geophones and 10Hz trigger was used. The seismic source used was an 8kg seismic hammer.

Signal analysis using the MASW technique

According to the fundamental hypothesis of linear physics (Fourier's Theorem) signals can be represented as the sum of independent signals, called harmonics of the signal. These harmonics, for one-dimensional analyses, are sine and cosine trigonometric functions, and behave independently without interacting with each other. Focusing our attention on each harmonic component, the final result in the linear analysis is equivalent to the sum of the partial behaviors corresponding to the individual harmonics. Fourier analysis (FFT spectral analysis) is the fundamental tool for spectral characterization of the signal. The analysis of Rayleigh waves, by means of the MASW method, is carried out by the spectral processing of the signal in the transformed domain where it is possible, in an easy way, to identify the signal relative to Rayleigh waves compared to other types of signals, noting, moreover, that the speed with which Rayleigh waves propagate is a function of frequency. The speed-frequency relationship is given by the dispersion spectrum. The dispersion curve identified in the f-k domain is called the experimental dispersion curve and represents the maximum amplitudes of the spectrum in the given domain.

Data processing

Starting from a synthetic geotechnical model characterized by thickness, density, Poisson's ratio, S-wave speed and P-wave speed, it is possible to simulate the theoretical dispersion curve that connects speed and wave length according to the relationship:

$$v = \lambda \times v$$

By changing the parameters of the synthetic geotechnical model, an overlap of the theoretical dispersion curve with the experimental one can be obtained: this phase, called inversion, allows the determination of the velocity profile in environments with different stiffness.

Modes of vibration

Both in the theoretical and in the experimental inversion curve, the various configurations of ground vibrations can be identified. The modes for Rayleigh waves can be: deformations in contact with air, nearly zero deformations at mid-wavelength, and zero deformations at high depths.

Depth of investigation

Rayleigh waves decay at a depth approximately equal to the wavelength. Short wavelengths (high frequencies) allow the survey of shallow areas, while long wavelengths (low frequencies) allow surveys at great depths.

Table 1. Vp-Vs velocities of the main sedimentary rock types
according to Geol 615: Geostatistics – University of Mississippi

Type of rock	P waves velocity (Vp) – m/sec	S waves velocity (Vs) – m/sec
limestones	2500 - 6000	3100
sandstones	1400 - 4000	2400
gravel, sand	400 - 2300	80 - 880
clay	200 - 2200	100 - 1500
soil	100 - 500	50 - 180

Seismic refraction studies allow the interpretation of the subsurface stratigraphy through the physical principle of the refraction of the incident seismic wave on a discontinuity, detected between two bodies with different mechanical properties (refraction horizon).

The basic requirement for conducting seismic refraction studies is one for which the succession of layers to be investigated is characterized by an increase in seismic velocity with increasing depth. In this way, up to 4 or 5 different refraction horizons can be analyzed. The processed seismic data resulting from the survey, it will be compared with Vp-Vs velocities of the main sedimentary rock types according to the Geostatistics – University of Mississippi (Table 1) and with regional or local geological data.

Surveys are based on the measurement of elastic wave travel times for which, assuming extended discontinuity surfaces compared to the wavelength or, at any rate, with weak curvature; the wave fronts are represented by relative seismic waves. The analysis is based on Fermat's principle and Snell's law.

Fermat's principle states that the wave travels the distance between the seismic source and the receiver following the minimum propagation time. Given a plane separating two media with different elastic properties, the seismic wave is the one that propagates along a plane perpendicular to the discontinuity containing both source and receiver.

Snell's law is a formula that describes the refraction modes of a seismic wave in the transition between two media characterized by different wave speeds or, equivalently, by different refractive indices. The angle formed between the surface of the discontinuity and the seismic ray is called the angle of incidence θi while that formed between the refracted ray and the surface normal is called the angle of refraction θr. The mathematical formula is:

$$v_2 \sin \theta_i = v_1 \sin \theta_r$$

where v1 and v2 are the velocities of the two media separated by the surface of the discontinuity.

2.2 Geo-electrical method

The geo-electrical measurements were carried out by the method of resistivity, using the procedure of vertical electrical sounding (VES), according to the standards in force.

The principle of the method used consists in injecting into the basement a current of known intensity (I) by means of two current electrodes (A, B) and measuring the potential difference (ΔV) with the help of another pair of potential electrodes (M, N).

Apparent resistivity is calculated using the relationship:

$$\rho a = k\Delta V/I \quad [\Omega m]$$

where k is a constant that depends on the geometry of the device and is obtained using the expression:

$$k = 2\prod a$$

For the execution of vertical electrical sounding, Schlumberger-type symmetrical quadripole devices were used, with a maximum emission line of 40m for investigation depths of maximum 20m considering a device constant AB/2.

The resistivity processed data will be compared with the values of the resistivity of the main types of sedimentary rocks according to the Geostatistics – University of Mississippi (Table 2) and with regional or local geological data.

Table 2. Resistivity of the main types of sedimentary rocks
according to Geol 615: Geostatistics – University of Mississippi

Type of rock	Resistivity (ohmmeters)	Type of rock	Resistivity (ohmmeters)
limestone	100 - 10 000	drilling fluid	4.5
sandstones	100 - 1 000	marl	100 - 1 000
compact sandstone	1000 - 10000	salt	1012 - 1014
Gravel, sand	100 - 10 000	oil	109 - 1016
clay, silty clay	1 - 100	sweet water	10 - 100
wet plastic clay	20	Sea water	0.1 - 1
soil	1 - 10		

3. Field data acquisition

We carried out the three geophysical investigations: refraction and MASW seismic profiling, and vertical electrical sounding (VES) for both locations required for investigation. The field acquisition was done as presented in figures 1 – 3.

Figure 1. Seismic profile PS1

Figure 2. Seismic profile PS2

Figure 3. Vertical electrical sounding

Seismic data acquisition was done using the following configuration:
Number of geophones: 24 (fixed range)
Distance between geophones: 2.5m
Investigation depth: 15m
Orientation: SW-NE
Number of Stations: 1 (24 geophones/Station)
Source type: hammer, 8kg
Distance between sources: variable
Number of sources: 3
Sampling interval: 0.000133 s
Recording length: 0.681s

In order to acquire geo-electrical data, a rectilinear device was drawn with the distance between the A-B electrodes increasing, every 5m (increasing equidistance 10 - 15 - 20 - 25 - 30 - 35 - 40m), and the distance between the M-N electrodes was kept fixed at 0, 70m.

4. Geophysical data processing

4.1 Raylaigh (MASW) surface waves processing

Data processing was performed using the EasyMASW software.

Data loading - Recordings (fig. 4)

No. records	24
Total recording sampling time [msec]	681.0
Spacing of geophones [m]	2.5
Recording sampling time [msec]	133.0

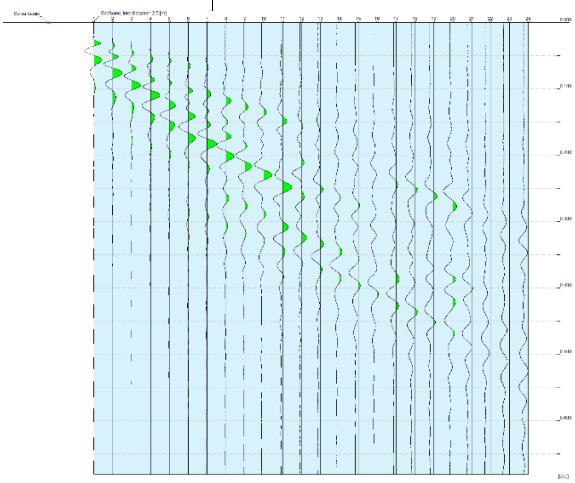

Figure 4. Seismic recording

Spectral analysis - The spectral analysis phase is necessary to determine the experimental dispersion curve.

Spectral analysis (fig. 5)

Minimum processing frequency [Hz]	4.5
Maximum processing frequency [Hz]	30
Minimum processing speed [m/sec]	1
Maximum processing speed [m/sec]	800
Speed range [m/sec]	1

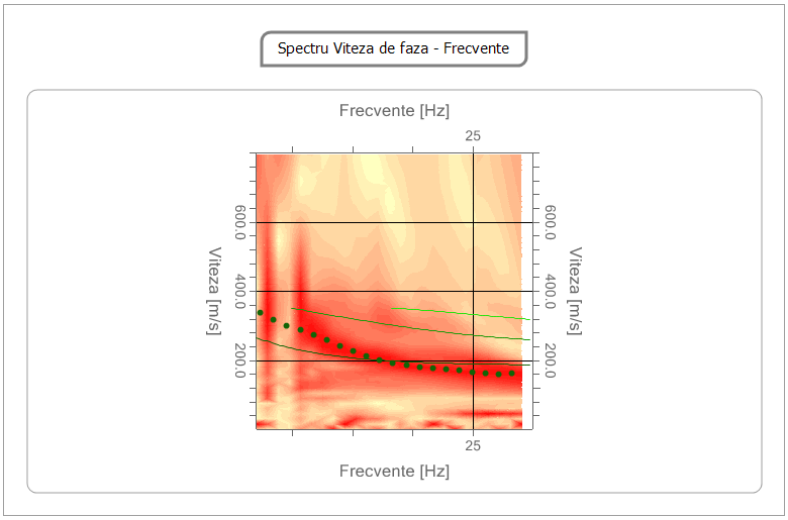

Figure 5. Example of synthetic model curves

In this phase, it is necessary to define a synthetic model of the terrain on which the subsequent processing will be based. The parameters to be defined are:

- number of layers;
- minimum research thickness;
- initial research thickness;
- maximum research thickness;
- volumetric weight;
- volumetric weight in saturated state;
- the presence of water;
- Poisson's ratio;
- minimum admissible wave speed for the layer;
- wave speed for the first attempt;
- maximum admissible wave speed for the layer.

4.2 Compressional waves – P – processing

The data processing was carried out with the help of EasyRefract software:

Data import (fig. 6)

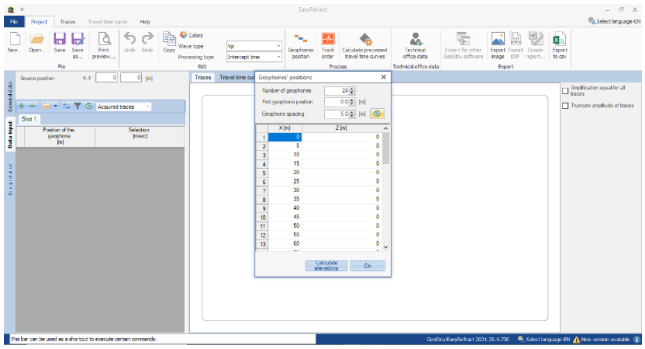

Figure 6. Loading recordings

Data filtration (fig. 7)

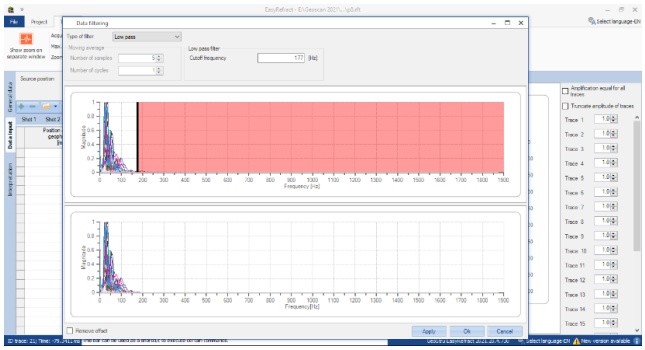

Figure 7. Filtration process

Choosing the first arrivals (fig. 8)

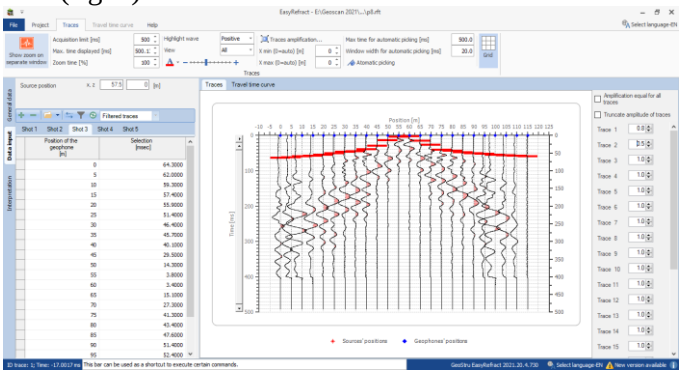

Figure 8. Choosing the time for the first arrival

Calculation of speed curves (fig. 9)

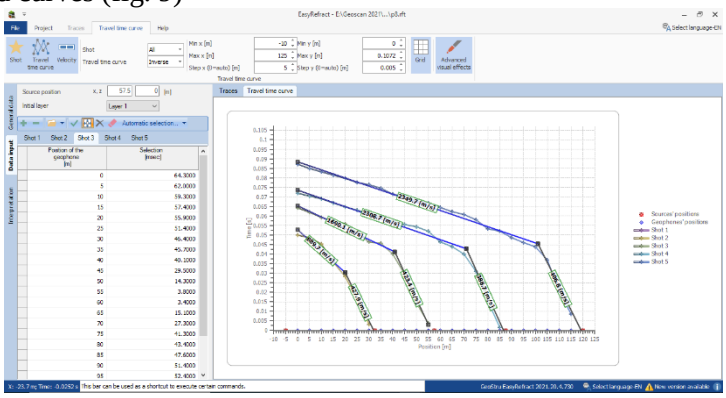

Figure 9. Calculation of speed curves

5. Geophysical data interpretation

5.1 Surface waves Rayleigh interpretation (MASW)

The MASW data have been represented in two different ways:

- Depth (m) vs. Vs (m/s) according to fig. 10 and 11;
- Tables containing dynamic parameters for every seismic complex (tables 3 and 4).

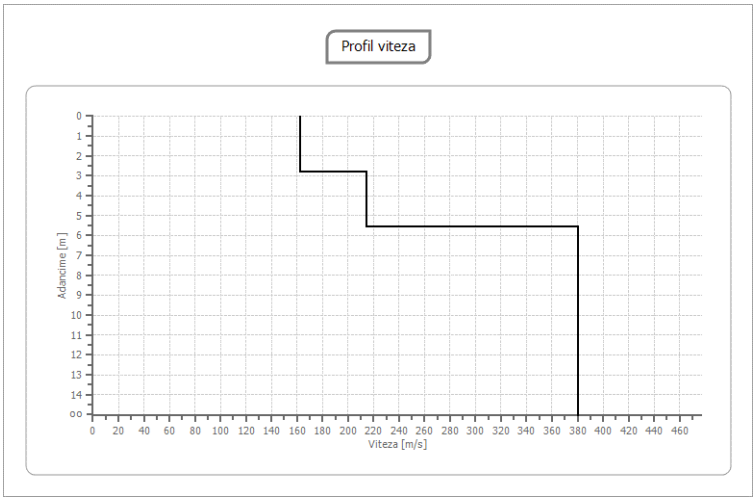

Figure 10. Vs velocity model–PS1 profile

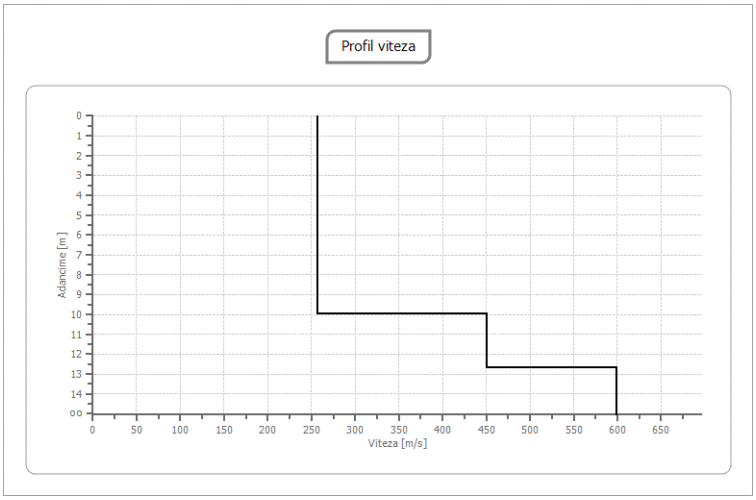

Figure 11. Vs velocity model–PS2 profile

Table 3. Seismic data MASW interpretation

Profile	Description	Depth [m]	Thickness [m]	Volumetric weight [kg/mc]	Poisson's coefficient	Water table presence	Vp [m/sec]	Vs [m/sec]
PS1	Complex 1	2.81	2.81	2000.0	0.25	No	281.6	162.6
	Complex 2	5.55	2.74	2100.0	0.25	No	371.6	214.5
	Complex 3	15.55	10.00	2200.0	0.25	No	658.2	380.0
PS2	Complex1	9.99	9.99	2000.0	0.25	No	444.1	256.4
	Complex 2	12.66	2.67	2100.0	0.25	No	780.4	450.6
	Complex 3	15.59	2.93	2200.0	0.25	No	1036.8	598.6

Table 4. Other geotechnical parameters

Profile	Depth [m]	Thickness [m]	Vs [m/s]	Vp [m/s]	Density [kg/mc]	Poisson's coefficient	G0 [MPa]	Ed [MPa]	M0 [MPa]	Ey [MPa]	NSPT	Qc [kPa]
PS1	2.81	2.81	162.60	281.63	2000.00	0.25	52.88	158.64	88.13	132.20	22	268.72
	5.55	2.74	214.54	371.59	2100.00	0.25	96.65	289.96	161.09	241.64	32	1081.94
	15.55	10.00	379.99	658.17	2200.00	0.25	317.67	953.01	529.45	794.17	N/A	N/A
PS2	9.99	9.99	256.37	444.05	2000.00	0.25	131.46	394.37	219.09	328.64	75	2648.60
	12.66	2.67	450.56	780.40	2100.00	0.25	426.31	1278.94	710.52	1065.79	N/A	N/A
	15.59	2.93	598.62	1036.84	2200.00	0.25	788.35	2365.06	1313.92	1970.88	N/A	N/A

Description of the parameters used in tables 3 and 4:

Vs: S waves velocity;
Vp: P waves velocity;
G0: Shear deformation module;
Ed: Edometric module;
M0: Volumetric compressibility module;
Ey: Young module;
Ey: Young module;
NSPT: normal standard penetration test;
Qc: conventional pressure

Results - PS1

Depth [m]	15.00
Vs,30 [m/sec]	475.47
Soil category	B

Type B soil: Soft rocks or very dense large-grained soil deposits or very consistent small-grained soils with thicknesses greater than 30 m, characterized by a gradual improvement in mechanical properties with depth and values of Vs,30 between 360 m/s and 800 m/s (NSPT,30 > 50 in large-grained soils and with,30 > 250 kPa in small-grained soils).

Results - PS2

Depth [m]	15.00
Vs,30 [m/sec]	695.09
Soil category	B

Type B soil: Soft rocks or very dense large-grained soil deposits or very consistent small-grained soils with thicknesses greater than 30 m, characterized by a gradual improvement in mechanical properties with depth and values of Vs,30 between 360 m/s and 800 m/s (NSPT,30 > 50 in large-grained soils and with,30 > 250 kPa in small-grained soils).

5.2 Compressional waves – P - interpretation

Following the processing of the frontal wave data using the previously presented steps, we made velocity maps of the P - Vp frontal wave variations for the two profiles PS1, PS2 (seismic vertical sections) presented in fig. 12 and 13.

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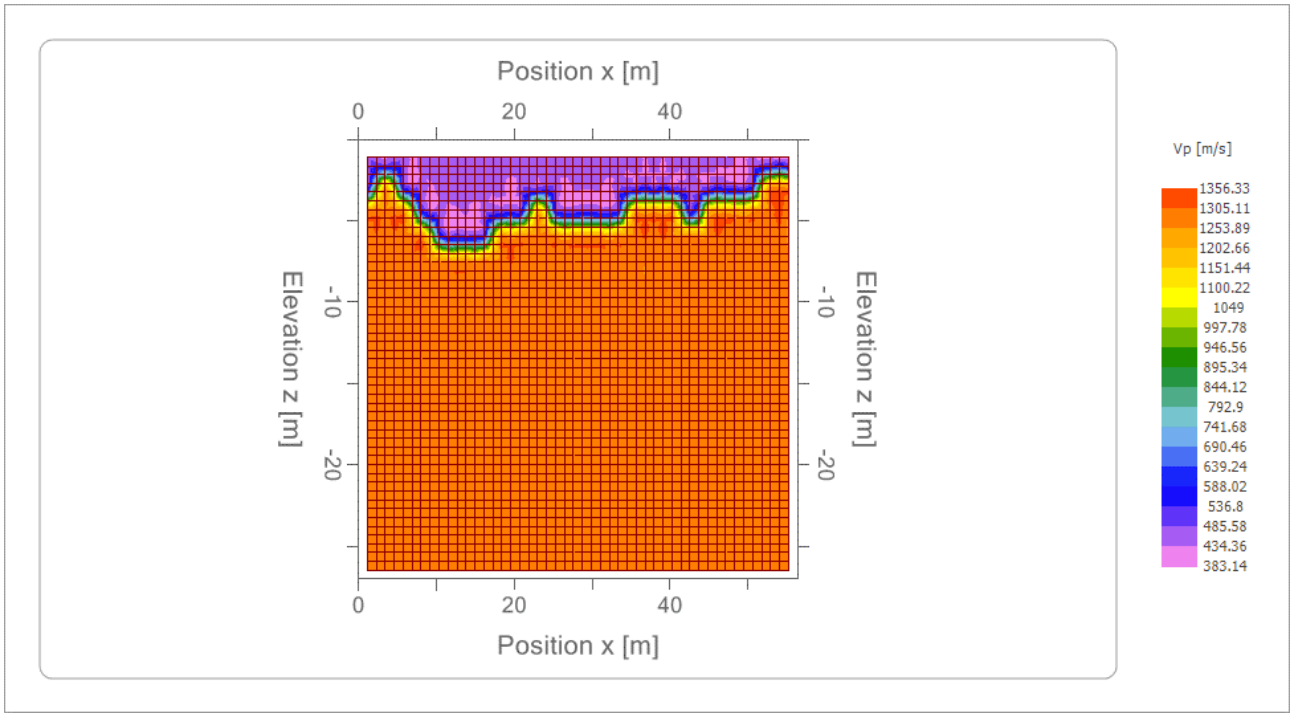

Figure 12. P waves velocity model – PS1

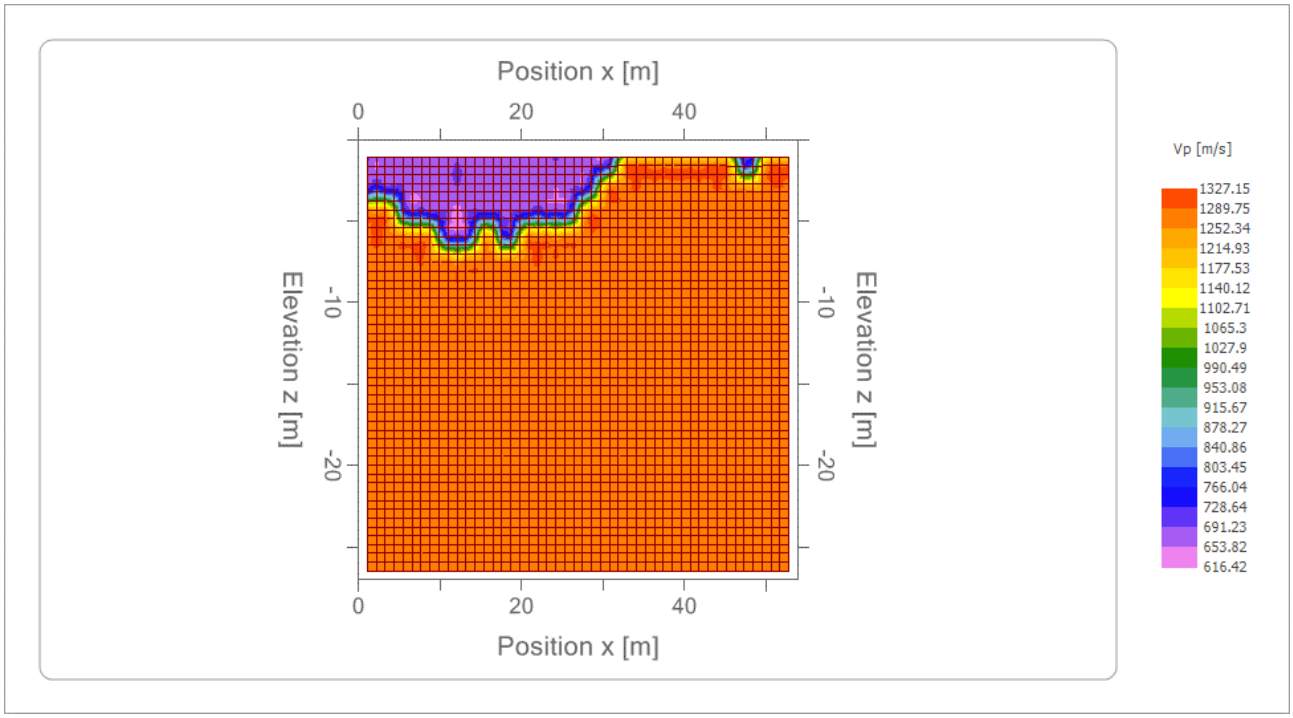

Figure 13. P waves velocity model – PS2

5.3 Interpretation of geo-electric data

After processing the geo-electric resistivity data, we obtained tables of values of the resistivity variation with depth, shown in the tables 5, 6 and 7.

Table 5. SEV1 values

No.	ρ (ohmm)	Thickness (m)	Depth (m)
1	20.5	1.99	1.99
2	3.64	1.73	3.72
3	82.1	3.18	6.90
4	36.4	10.8	17.7
5	10587		

Table 6. SEV2 values

No.	ρ (ohmm)	Thickness (m)	Depth (m)
1	10.7	1.52	1.52
2	150	1.71	3.23
3	2.25	3.69	7.19
4	3.59	2.64	9.83
5	2964		

Table 7. SEV3 values

No.	ρ (ohmm)	Thickness (m)	Depth (m)
1	96.1	1.34	1.34
2	6.25	0.89	2.23
3	38.3	3.70	5.93
4	2.91	5.04	11
5	12671		

We choose a resistivity model made by 4 resistivity complexes with different values (according to tables 5, 6 and 7). Analyzing the resistivity values, we considered that the lithology up to 15m depth has a high-water content with high porosity and/or permeability specific to soft to medium rocks.

6. Conclusions

Following the interpretation of the seismic and resistivity data, two important lithological complexes resulted, as follows:

- the complex located up to 5-6m deep with the speed of p waves between 500 – 600 m/s, of s waves between 160 – 260 m/s and resistivity variations between 3.60 – 6.25 ohmm.
- The complex located below 5-6m depth with the speed of p waves between 1327 – 1356 m/s, of s waves between 658 – 1036 m/s and resistivity variations between 2.90 – 36.4 ohmm.

For the S-wave application plan according to Eurocode 8, the lithological complex below 5-6m depth is described as soil type B: soft rocks or very dense large-grained soil deposits or very consistent small-grained soils with thicknesses greater than 30 m, characterized by a gradual improvement of mechanical properties with depth and values of Vs,30 between 360 m/s and 800 m/s (NSPT,30 > 50 in large-grained soils and with,30 > 250 kPa in small-grained soils).

By analyzing the entire set of geophysical data, without having access to direct data, it was concluded that up to 15m depth there are two complexes characterized both seismically and by resistivity as having high porosity, with a relatively high content of bound water, with relatively low seismic wave velocities Vs and Vp. So a low-density geological material that can be penetrated by percussion drilling methods, without more costly mud circulation drilling rigs that involves higher mobilization and execution costs.

Consequently, the client for whom the works described above were carried out made the decision to drill with a percussion hydraulic installation, the method with minimal drilling costs.

As a final conclusion, the seismic and resistivity geophysical methods used together give conclusive results for the analysis of the lithology and geo-mechanical parameters of the strata through which direct investigations are requested.

Acknowledgements

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