GEOTECHNICAL CHARACTERIZATION ON THE SOYO ROAD SECTION USING ELECTRICAL RESISTIVITY AND SEISMIC MEASUREMENTS

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ABSTRACT

The need for near-surface soils and rocks characterization at planned construction sites, using geophysical techniques, has grown rapidly during the last few decades to map the variations in the soil stiffness and the depth to bedrock. Although borehole data are important in geotechnical engineering, providing information on stability and strength of soils and rocks, it is limited to a few points. To take borehole data on the hole construction site becomes necessary increase the borehole density, which makes the project very expensive. Geophysical techniques have the advantage in collecting information of large volume of soils and rocks in its natural state. The Soyo Road was opened to traffic in 2017 but, due to the lack on soils and rocks physic-mechanical properties information, there is still to complete a section of about 700 meters in the mangrove zone. Geophysical techniques were applied with the main goal of providing technical information, essential for the completion of the targeted road section. Electrical resistivity data was recorded along a profile of 820m long, using forty-two electrodes20-meter spaced, under pole-dipole array. Seismic measurements were taken using twenty-four geophones, 5-meter spaced, 115-meter length spread. Five seismic spreads were connected, generating a seismic line of 575-meters long. Measured geophysical data were processed using EarthImager 2D, SeisImager/2D and SeisImager/SWpackages. Electrical resistivity section shows two zones, the first associated with unconsolidated and/or poorly consolidated soils, composed by clay, silt, sandy, carbonated rocks mixed with sloth and organic clay and, the second associated with rock, composed by clay, all them saturated with marine saltwater. Seismic refraction section shows an interface separating non-compacted soils and unconsolidated rocks to compacted soils. Multi-channel analysis of surface waves model shows an alternating sequence of horizontal horizons in the investigated first ≈25-meter depth, composed by non-compacted soils and/or unconsolidated rocks and compacted soils. Due to its shear velocity values the site is constituted by soft and stiff soils, composed by homogeneous organic matter and elements of mineral origin, responsible for the ruptures and landslides that occurred and for the sinking of the structures built on the site.

KEYWORDS

Soyo Road section, Soil and rock characterization, Electrical resistivity, Seismic refraction, Multi-channel surface wave analysis

1. INTRODUCTION

TResponding to the needs of the northern provinces of Angola and the country's development, the Government of the Republic of Angola created a vast program of rehabilitation and construction of several roads and bridges at national level. The Soyo Road and the bridge over the M'bridge River is among of them. Located along the Atlantic coast, the whole road is 150 km long, connecting Nzeto and Soyo, the main two cities of northern part of Angola. Although this road was opened to traffic in 2017, there is still to complete a section of about 700 meters long, in the mangrove zone, adjacent to the bridge over the river, north of the Nzeto city. Due to the lack on soils and rocks physic-mechanical properties information, that would allow the completion of that road, was applied geophysical survey to increase knowledge about the mechanical properties of soils and rocks in that road section [1].

The need for characterization of the near-surface materials at planned construction sites, using non-invasive geophysical techniques, has grown rapidly during the last few decades. Borehole information alone is not adequate to precisely map the variations in soil stiffness and the depth to the bedrock surface. The shear-wave velocity can indicate the soil stiffness, which can help in mapping the bedrock surface and in qualitatively describing the strength of the soil. These parameters are directly related to the ability of the soil to bear a structural load and they should be considered prior to most constructions [2]. Many structures have been building in Angola over the last 20 years but, most of them are not durable, due to the lack of engineering studies in soils and rocks characterization. This is the first time that this kind of study has been carried out, to characterize soils and rocks using geophysical methods.

In order to provide physic-mechanical information about the properties of soils and rocks of the mangrove zone, essential for the completion of the targeted road section, geophysical measurements were conducted. Electrical resistivity and seismic data were collected along the same line on the road, over profiles of 820 and 575 meters long, respectively. Electrical resistivity technique was chosen because different soils and rocks have different electrical resistivity [3]. The degree of alteration of the rocks, the presence of geological discontinuities and its water content are factors that implies in the distortion of the electric fields, created artificially by the injection of electrical current in the ground [4]. Refraction seismic has the advantage of solving certain types of problems, such as fractures and shear zones in igneous or metamorphic rocks identification, depth to water table in alluvial terrains mapping and the rippability of the bedrock, all this when the depth is less than 30 meters [5]. The rippability of rock is dependent on the geology and physical characteristics of rock. Accurate evaluation of rock rippability and prediction of the excavation effort through a better understanding of their properties will improve the preparation of both, construction schedule and cost estimation, to facilitate the selection of proper ripping equipment and maximize production [6]. In many cases, due to inaccessibility of the drill rig to some rock cuts, geophysical methods are conducted to, indirectly, predetermine the degree of rippability. Seismic refraction is the most commonly used [6]. Finally, multi-channel analysis of surface waves (MASW) technique has been frequently used in numerous studies to measure shear wave velocities. Because it responds strongly to variations in soil stiffness, the shear wave velocity becomes an extremely important parameter for surface rocks characterization [2].

As expected, resistivity and seismic methods were very efficient in mapping the main the physic-mechanical characteristics of soils and rocks in the study area. Resistivity section shows two electrical resistivity zones. The investigated depth to top of the second electrical resistivity zone is ≈80 meters at South and decreases continually to North, associated with clay, silt, sandy, carbonated rocks mixed with sloth and organic clay. The second zone associated with clay, all them saturated with marine saltwater. Seismic refraction section shows, in the investigated depth of ≈25 meters, two seismic zones. The P-wave velocity of first zone is 988 m/s, associated with non-compacted soils and/or unconsolidated rocks. In the second zone P-wave value is ≈1600 m/s, associated with compacted rocks. MASW section shows an alternating sequence of horizontal horizons in the investigated ≈25-meter depth. Due to its shear velocity (Vs) values, $Vs<180$ m/s and $180 \leq Vs \leq 360$m, the site is constituted by soft and stiff soils. These soils are composed by homogeneous organic matter and elements of mineral origin. Due to its plastic nature this matter soils have been responsible for the ruptures and landslides that occurred and for the sinking of the structures built on site.

2. GEOLOGICAL SETTINGS

The study area is located in the province of Zaire, extreme northwest of Angola, with a territorial extension of 40.130 km2. This province is limited to the North by the Democratic Republic of Congo, to the West by the Atlantic Ocean and to the South by Bengo and Uíge provinces. The capital of the province is the M'Banza Kon-go city, which is also part of one of the municipalities. The other municipalities are Cuimba, Noqui, Tomboco, Soyo and Nzeto, the last being part of the study area (Figure 1). Nzeto city is the capital of the municipality with the same name, 270 kilometres away from Luanda city, the capital of the Republic of Angola.

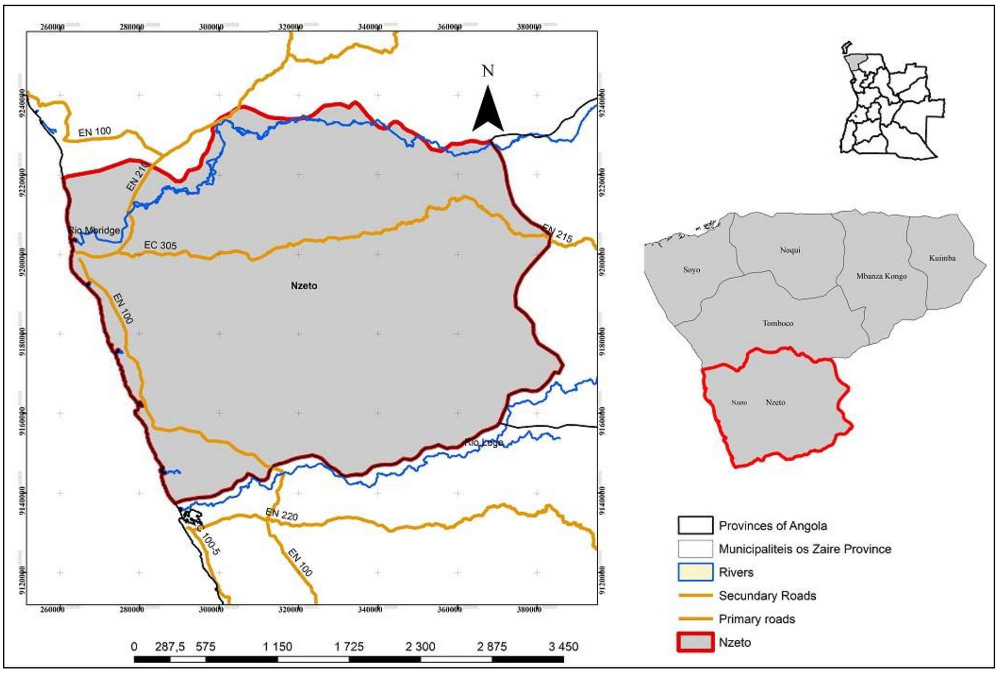

Figure 1. Localization of the study area

The Mesozoic - Cenozoic strata outcrop less and extend in an elongated and narrow pattern, forming part of the Atlantic marginal basin. Due to the plateau barrier near the of Musserra town, in the period between the Lower Cretaceous and Miocene, were formed the sedimentary basins of Congo and Kwanza, respectively, to the north and south of the of Musserra town. Thus, in the Lower Cretaceous, the Cuvo Formation was deposited in the Kwanza basin and the Ambrizete and Malembo formations were deposited in the Congo basin. From the Pliocene these two basins have the same evolution, with the Quelo Formation and other stratigraphic units being deposited in the Lower Quaternary (Pleistocene and Holocene). The Holocene deposits include, alluvium lakes and marine sediments. The deposits of lake are a set of organic dark/gray clay. The alluvium includes fluvial and alluvial sand, gravel, silty sand and a small amount of clay. The marine sediments are mainly distributed along the Atlantic coast, composed of marine terrace and littoral deposits and consist, fundamentally, of sand and clay, as well as shell debris. The Quelo Formation, of Pliocene to Pleistocene, was deposited on slopes, between rivers and coastal plains, composed of clay and red sand, sometimes fossils of freshwater organisms. Its thickness varies from tens to hundreds of meters, and it is widely distributed to the south of Nzeto. The Malembo Formation, of Eocene to Miocene, extends in a S-N direction and is distributed in a banded pattern along the south of the Zaire River, forming part of the coastal continental shelf at Mbubo and Nzeto. This formation consists of sandstones, claystones and siltstones. The upper part of the sequence is mainly composed of coarse-grained sandstones. It was formed in a delta-type environment and is an oil formation. Its thickness varies between 200 and 1000 meters in the continental area. It consists of white to grayish sandstone, grayish-yellow siltstone, silty claystone, claystone and marl intercalation. The rock composition is mainly terrigenous clastic. The yellow-grey claystone and siltstone reflect the oxidizing environment of shallow waters. The Lucula Formation (Lower Cretaceous) is composed of conglomerates, sandstones and claystones. This formation does not outcrop in the Nzeto but extends from this locality eastwards in an almost N-S direction. Its outcrops are extremely poor and mostly covered by sandy soil. The group overlain in unconformity the Precambrian and its top covered by the Quifangondo Formation. It, mainly, includes sandstones, conglomerates and gravel. The Ambrizete Formation (Upper Cretaceous to Palaeocene) is mainly composed of horizontally stratified sandstones, organic limestones, sandy limestones, marls and argillites and overly rocks of Archaic and Lucula Formation. Overlying it are the Malembo and Ambrizete formations, which outcrops are seen along the coast near Quimavenza [8].

The Proterozoic includes the Paleozoic, Mesozoic and Neo-Proterozoic. The Paleozoic is composed of the Lulumba and Uonde groups, constituted by tuffs, arkoses, metariolite-dacites, conglomerates and schists, alkaline and hyperalkaline granites, syenites, dolorites, gabbros and leucocratic granites, outcropping in the northeast of Nzeto. The of Schist-Gresose, Schist-Calcareous group of Congo Occidental Supergroup (Meso-Proterozoic) outcrops over a large area in the eastern part of the Nzeto municipality. The Chela group occurs in the east of the block, composed of conglomerates, quartzites, sandstones, silicalites, volcanic rocks and pyroclastic rocks. The Occidental Congo Supergroup (Neo-Proterozoic) outcrops in the northeast and is constituted of shale, quartzites, limestones, silicalites, flints, arkoses, complexes, mafic lavas and stromatolites. Paleo-Archaic and Upper-Archaic formations outcrops in the locality of Nzeto and corresponds to the Maiombe shield. Neo-Archaic has very few outcrops in the Maiombe shield.[8].

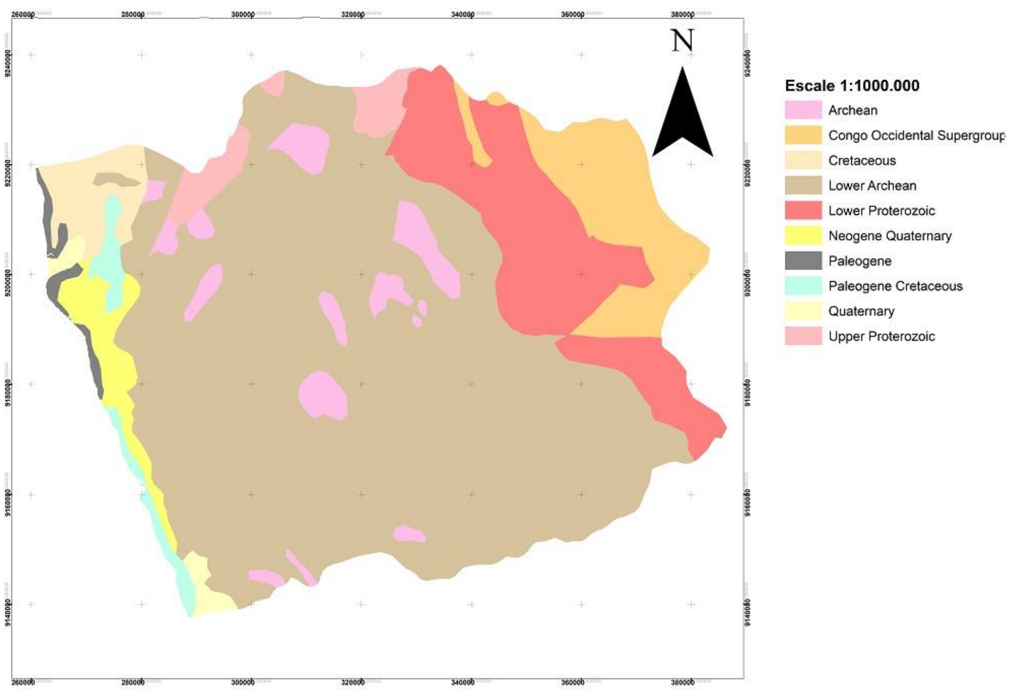

Figure 2. Map of geologic formations [9]

3. GEOPHYSICAL METHODS

3.1. Electrical Resistivity

The principles of the electrical resistivity have been presented on several books on the subject of [10], [11], [4], [12]. Therefore, only a few details will be discussed here. In an electrical resistivity survey, a direct current or a very low frequency alternating current is passed into the ground through a pair of current electrodes, A and B, and the resulting potential drop is measured across a pair of potential electrodes, M and N. Figure 3 shows a source of electric current, electric current and potential difference measuring devices.

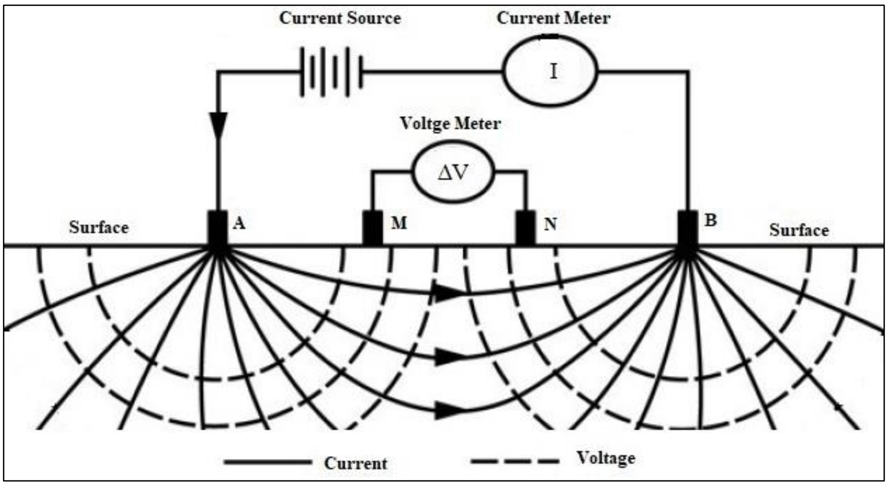

Figure 3. Basic concept of resistivity measurement

Knowing the injected electric current (I) and the measured potential difference (ΔV) the resistivity (ρ) can be computed from the Equation (1);

$$\rho = \frac{\Delta V}{I} k. \qquad (1)$$

Where k is a geometric factor, that is determined by the geometry and spacing of the electrode array. If the ground is composed of an infinity-thick, homogeneous, and isotropic medium, then the resistivity calculated from the above equation will be the true resistivity of that medium; otherwise, the calculated resistivity is called an apparent resistivity (ρa) [14]. In general, for a heterogeneous medium, the apparent resistivity depends on the geometry, the spacing, and the orientation of the electrode array with respect to lateral in homogeneities, and it depends on the spatial distribution of materials with different electrical resistivities [14].

To investigate changes in resistivity with depth, the size of the electrode array is varied. For small electrode spacing, the apparent resistivity is close to the surface layer resistivity, whereas at large electrode spacing, it approaches the resistivity of the basement layer. Usually, the electrodes are arranged in a collinear array in one of several fixed geometries. Several standard electrode geometries have been developed for various applications. For engineering, environmental, and groundwater studies, the Wenner, Schlumberger and dipole-dipole arrays are the most commonly used [15].

Resistivity surveys are made to satisfy the needs of two distinctly different kinds of interpretation problems: (1) the variation of resistivity with depth, reflecting more or less horizontal stratification of earth materials and (2) lateral variations in resistivity that may indicate soil lenses, isolated ore bodies, faults, or cavities. For the first kind of problem, measurements of apparent resistivity are made at a single location (or around a single centre point) with systematically varying electrode spacing. This procedure is sometimes called vertical electrical sounding, or vertical profiling. Surveys of lateral variations may be made along definite lines of traverse, a procedure sometimes called horizontal profiling [15]. During horizontal profiling surveys, when several electrodes are used to take measurements, with fixed electrode spacing along stations in the profile line, to assess lateral changes in subsurface conditions at a given depth, the procedure is sometimes called continuous vertical electrical sounding or electrical resistivity tomography.

The interpretation problem for vertical electrical sounding data is to use the curve of apparent resistivity versus electrode spacing, plotted from field measurements, to obtain the parameters of the geoelectrical section, the layer resistivities and thicknesses. Data obtained from horizontal profiling are normally interpreted qualitatively. Apparent resistivity values are plotted as profiles, and areas displaying anomalously high or low values or anomalous patterns are identified. Interpretation of the data, as well as the planning of the survey, must be guided by the available knowledge of the local geology. The interpreter normally knows what he is looking for in terms of geological features and their expected influence on apparent resistivity, because the resistivity survey is motivated by geological evidence of a particular kind of exploration problem [15].

3.2. Seismic Refraction

Theoretical fundaments of the seismic refraction method are well documented in [16], [17], [18], [19], [20], therefore, only a few details will be discussed. Refraction and reflection seismic methods are named for a key element of the geometry of the ray paths in each method, respectively. Both methods are affected by the refraction of seismic rays at velocity contrast boundaries. However, the key geometrical element in the reflection method is that the incident rays on a target boundary are reflected back to the surface. In refraction surveying, the incident ray is critically refracted along the target boundary before it returns to the surface [5].

The physical property of earth materials, which is measured in seismic studies, is the rate at which acoustic wave energy propagates through the various units of the subsurface. Of most importance in the refraction seismic method is the primary waves (p-wave) energy. P-waves are compressional body waves that have the highest rate of propagation of any seismic waves. As a p-wave travels through the earth, it moves each particle it traverses in a direction collinear with the direction of propagation. The rate of propagation in a specific medium is generally called the velocity of the medium. Velocity is the rate at which p-wave energy is propagated through the respective subsurface media, assumed to be isotropic with respect to velocity. The velocity of a particular earth material can vary over a wide range as a function of its age, depth of burial, degree of fracturing or porosity, and whether water or air fills the voids [5].

The key geometrical element of ray-paths in the refraction seismic method is critical refraction of the ray at some velocity contrast boundary in the subsurface. If a p-wave seismic ray is incident on a velocity contrast boundary, some of the p-wave energy is converted to s-wave (secondary wave) energy and some remains as p-wave energy. Some of the p-wave and s-wave energy is reflected back into the medium from which the ray was initially incident. Some of the energy is transmitted below the boundary. Snell's Law defines the relationship between the angle that the incident ray and the angle that the transmitted (refracted) p-wave make with the normal to the boundary (Figure 4a), computed from Equation (2);

$$\frac{\sin i}{r} = \frac{V_1}{V_2} \quad (2)$$

Critical refraction is the condition in which the refracted angle is 90 degrees (Figure 4b). After being critically refracted the signal travels in the lower medium at the velocity of the lower medium but, essentially, along the boundary between the two media. Snell's Law indicates that critical refraction can occur only at a boundary that shows an increase in velocity with depth across it [5].

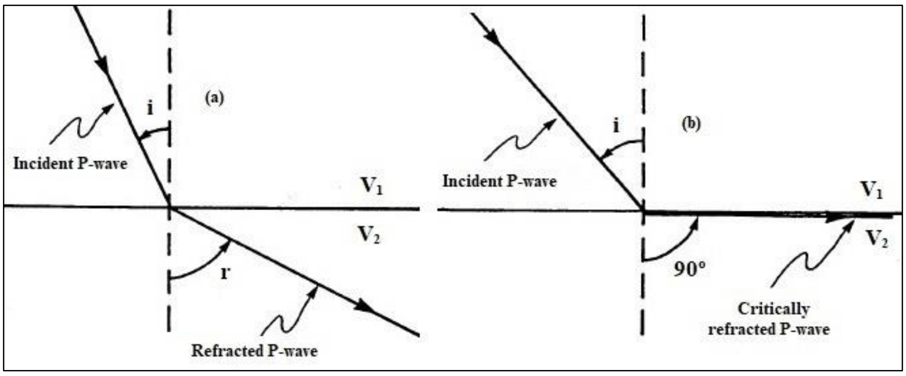

Figure 4. Diagram illustrating the Snell's Law: (a) incident and refracted rays (b) critical refraction [5]

3.3. Surface Wave

In a bounded elastic solid seismic wave, known as surface waves, can propagate along the boundary of the solid. Rayleigh waves propagate along a free surface or along the boundary between two solid media, the associated particle motions being elliptical in a plane perpendicular to the surface and containing the direction of propagation. The orbital particle motion is in the opposite sense to the circular particle motion associated with an oscillatory water wave and is, therefore, sometimes described as retrograde. A further major difference between Rayleigh waves and oscillatory water waves is that the first involve a shear strain and are thus restricted to solid media.

The amplitude of Rayleigh waves decreases exponentially with distance below the surface. They have a propagation velocity lower than that of shear body waves and in a homogeneous half-space they would be non-dispersive. In practice, Rayleigh waves travelling round the surface of the Earth are observed to be dispersive, their waveform undergoing progressive change during propagation as a result of the different frequency components travelling at different velocities. This dispersion is directly attributable to velocity variation with depth in the Earth [21].

In most surface seismic surveysthat use a vertical seismic source, like sledge-hammer, more than two-thirds of total seismic energy generated is imparted into Rayleigh-type surface waves, the principal component of ground roll. Assuming vertical velocity variation, each frequency component (f) of the surface waves has different propagation velocity or phase velocity (Cf), providing a different wave-length (λf) for each frequency propagated. This property is called dispersion, used to infer near-surface elastic properties. One of the most common ways to use the dispersive properties of surface waves is the construction of a shear (s)-wave velocity (Vs) profile through the analysis of plane-wave, fundamental mode Rayleigh waves. The entire process classically used to produce a Vs profile involves three steps: acquisition of ground roll, construction of dispersion curve and inversion of the Vs profile from the calculated dispersion curve. The inversion of the Vs profile is accomplished iteratively, using the measured dispersion curve as a reference for either forward modelling or a least-squares approach [22].

Conventional surface wave method analyses Rayleigh waves, recorded at two separate surface locations, treating the recorded data being dominated by that specific type. The multi-channel analysis of surface waves (MASW) method uses multiple receivers deployed in a linear pattern of equal receiver spacing with each receiver connected to an individual recording channel. One measurement (record) consists of multiple recordings (traces) of seismic wave fields made at different distances (offsets) from the source.

Surface waves measurements are used for geotechnical characterization of near-surface materials [22]. For more detailed information on the surface wave method numerous papers covering engineering aspects are available in the several journals, more detailed investigation on the theoretical background can be found in [23]; [24]; [25]; [26]; [27].

4. FIELD PROCEDURE AND RESULTS

4.1. Field Procedures and Data Acquisition

Resistivity data measurements were performed using two-dimensional multi-electrode arrays, providing a two-dimensional vertical picture of the sounding medium. Figure 5 shows a two-dimensional multi-electrode array procedure with dipole-dipole array, illustrating the current transmitter (AB) and potential receiver (MN) electrodes, lines of current and potential distributions within homogeneous and isotropic ground and theoretical investigation levels.

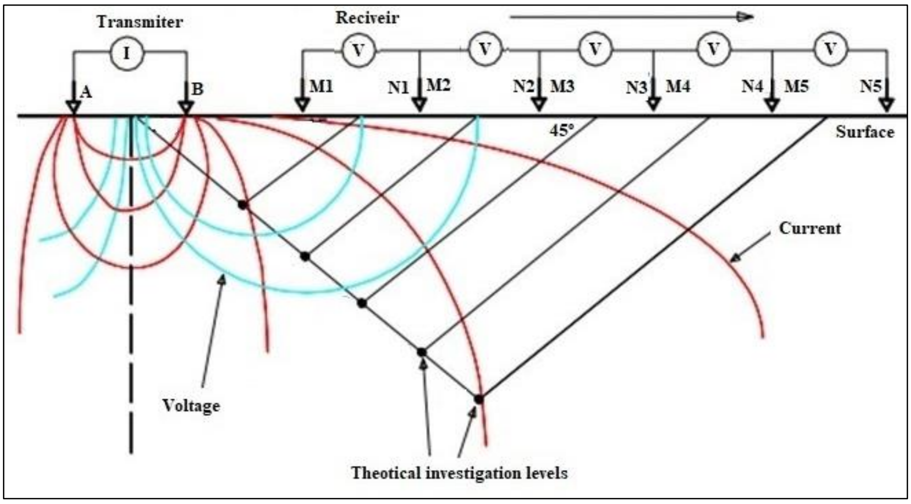

Figure 5. Schematic showing electrical procedure with dipole-dipole array [28]

In this procedure the current and potential electrodes are maintained at a regular fixed distance from each other and are progressively moved along a line at the soil surface. At each step, one measurement is recorded. The set of all these measurements at this first inter-electrode spacing gives a profile of resistivity values. The inter-electrode spacing is increased and a second measurement line is done. This process is repeated until the maximum spacing between electrodes is reached. Can be noticed that the larger the n-values, the greater the depths of investigation. As the distribution of the current also depends on the resistivity contrasts of the medium, the depth of investigation deduced from the spacing is called the “pseudo-depth”. The data are then arranged in a 2D “pseudo-section” plot that gives a simultaneous display of both horizontal and vertical variations in resistivity. Conventional graphic puts each measured value at the intersection of two 45-degree lines through the centres of the quadripole. Each horizontal line is then associated with a specific value of n, and gives a pseudo-depth of investigation [29].

Data measurements were recorded using the pole-dipole array with 20-meter maximum electrode spacing. Fourth two electrodes were used and a profile of 820-meter length covered. The SuperSting R8/IP/SP Resistivity Meter was used to measure the data. This instrument is an electrical resistivity meter, induced polarisation (IP) and self-potential (SP) system measurement, used to scan and image the subsurface of the earth and visualize the results in 2D slices or 3D volumes [30].

Figure 6 shows the used geometry of seismic refraction wave measurements. The spread has one long offset shot and one short offset shot at each end of the spread and one mid spread shot. Geophone spacing of 5m were selected and used twenty-four geophones, covering 115-meter length for each spread.

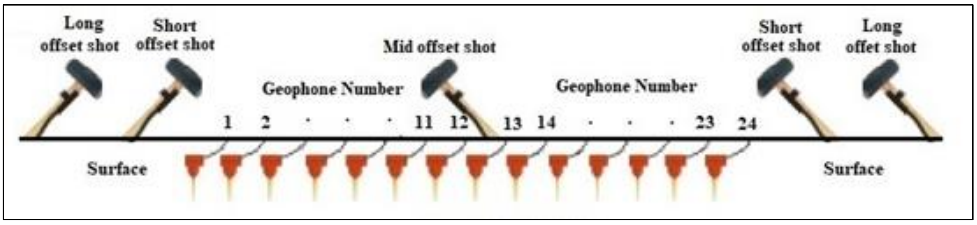

Figure 6. Geophone spread of 115-meter length for seismic recordings

The geometry of the overlapped five spreads, along of seismic line, is illustrated in Figure 7. Each spread overlapped the next one by a geophone (Figure 7a), covering a seismic line of 575 meters long (Figure 7b). The same geophone array was used for surface waves measurements records, according to the 2DMASW technique [31], however, additional shots were established at intervals between all the geophones, in order to produce a 2D section of shear wave velocities. Was used, for field measurements, the Geode, a versatile and flexible seismograph for reflection, refraction, MASW or tomography surveys, as well as for more niche use cases such as earthquake, quarry blasts, or heavy equipment monitoring [32].

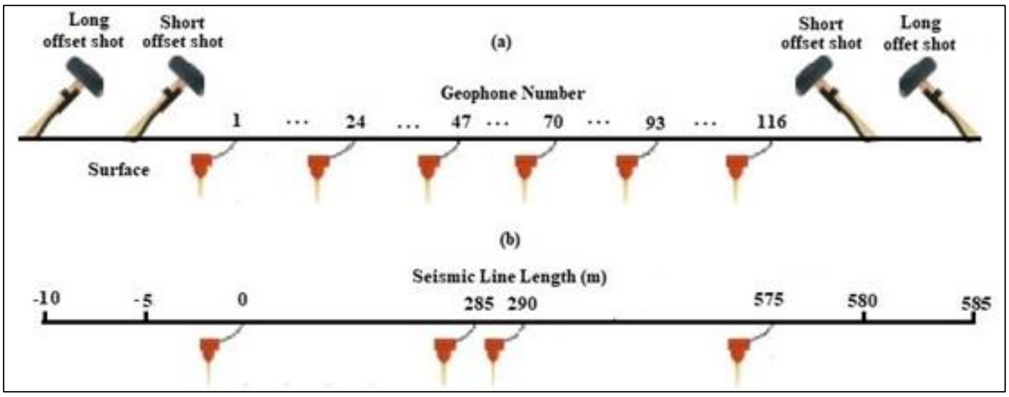

Figure 7. Overlapped five spreads of 575-meter length for seismic recordings

4.2. Results and Discussion

Inversion of the measured apparent electrical resistivity were carried out using the AGI EarthImager 2D. This software interprets two dimensional (2D) electrical resistivity data and produces inverted resistivity section. Based on the smoothed least squares algorithm this software requires a synthetic model (number of layers, its thickness and resistivity) to calculate synthetic data. The software adjusts synthetic data to that measured in such a way that the synthetic model converges, being the best adaptation to the subsurface resistivity distribution of the measured data [33]. Before performing the inversion processes, measured data were edited for noisy suppression and to remove erroneous data points. Data misfit was tested several times during inversion process. If calculated data fits corresponding measured data exactly, the process is stopped. Several attempts were made to obtain the final acceptable fit between calculated and measured data. The criterion for accepting results was the visualization and analysis of the histogram of convergence and adjustment of the data on the computer screen, considering a minimum RMS (root mean square) [33].

The resulted resistivity section (Figure 8) shows two resistivity zones. The resistivity intervals between first and second zone are 0.35≥ρ≤0.93 Ω-m and 0.9>ρ≤2.4 Ω-m. The investigated depth to top of second is zone is ≈23 meter (North) and ≈80 meter (South). Information from drilled boreholes in the study area describes that this zone is composed by a sedimentary sequence constituted by silts, clays, sands, limestones, sometimes mixed with sludge and organic matter. Lower resistivities values, from 0.35 Ω-m to 0.75 Ω-m, are associated with clay concentration and/or saltwater saturated zones. The second zone is associated with clays.

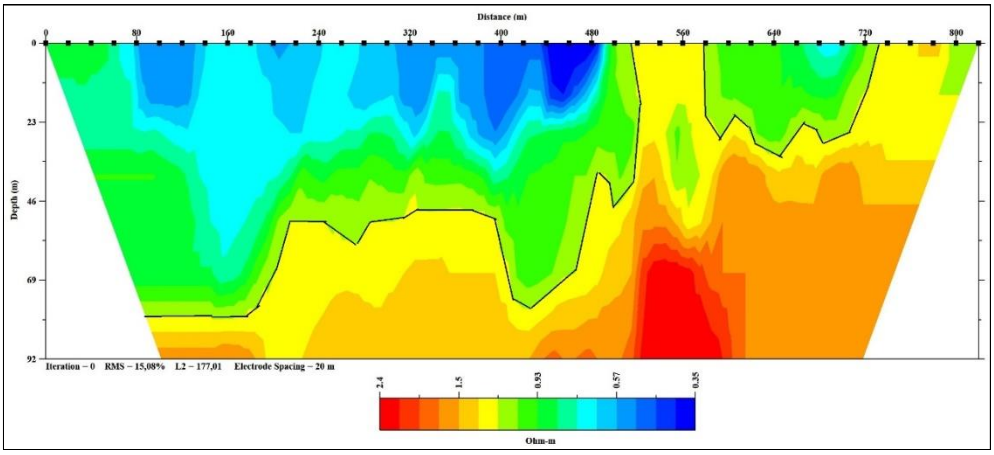

Figure 8. Resistivity section

Seismic refraction data were processed using SeisImager/2D. This software allows reading and displaying refraction data, making corrections, picking first breaks and inverting data for a velocity section. Allows output travel-time, velocity sections and other graphics plot. It offers three separate inversion techniques, as time-term method, reciprocal method, and tomography. Both, the time-term and reciprocal methods are based on “delay times”. The main difference between the two is the method by which the delay times are calculated. In the time-term method, the delay times are calculated automatically (via a linear least-squares inversion technique). In the reciprocal time method, the delay times are calculated manually [34].

Data processing follow tree steps: first arrival times picking, time-distance graph plot and P-wave velocity model plot. The resulted seismic refraction section (Figure 9) shows two seismic zones.

For a better understanding, it is importance to point out that zero-meter position, in Figure 9, matches position 160 meters in Figure 8. P-wave velocity value of first seismic zones, ≈23-meter of investigated depth to top of second is zone, is 988 m/s, associated with non-compacted soils and unconsolidated rocks. The second zone is associated to consolidated clays.

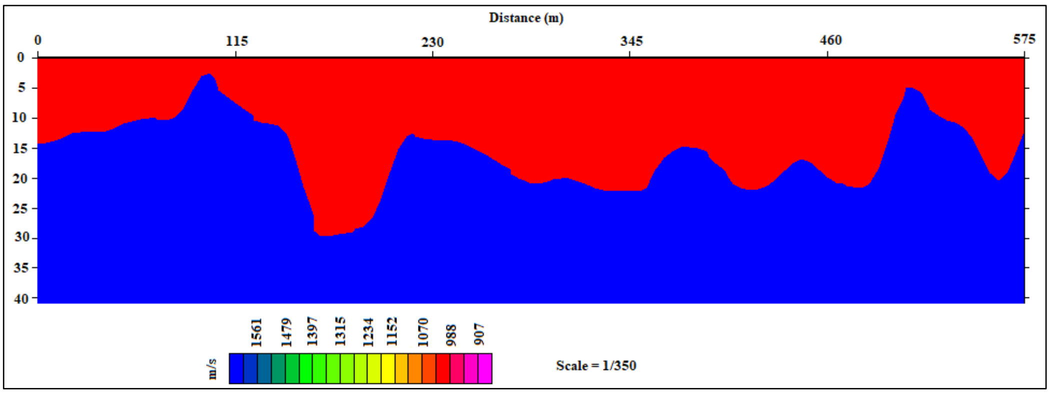

Figure 9. Seismic refraction section

Surface waves technique data were interpreted using SeisImager/SW. The software allows the extraction of Rayleigh wave phase velocities as a function of frequency, resulting in a dispersion image [34]. From the dispersion image a dispersion curve is extracted using the maxima of the energy. After extracting the dispersion curve, the inversion process is executed. In the inversion process the dispersion curve is analysed being compared, iteratively, with stratigraphic models of thickness, velocity and densities [25]; [24]. The result of the inversion is a model of the variation of the wave velocity Vs in the subsurface due to its most significant contribution with the variation of the Rayleigh wave.

MASW section shows an alternating sequence of horizontal horizons in the first ≈25 meter investigated. The S-wave velocity values of these horizons are ≈100 m/s, ≈220 m/s and ≈360 m/s. According to site classification [7] Vs<180 m/s and 180≤Vs≤360m/s conditions are related to type soils of classes E and D, associated to soft and rigid soils, respectively. These soils are, certainly sludge and clayey silt with organic matter, intercepted by the boreholes drilled at the site. Boreholes results describe this material as composed by organic soils, formed by the homogeneous mixture of decomposed organic matter and mineral elements, generally, having black or dark grey colour, sometimes called sludge.

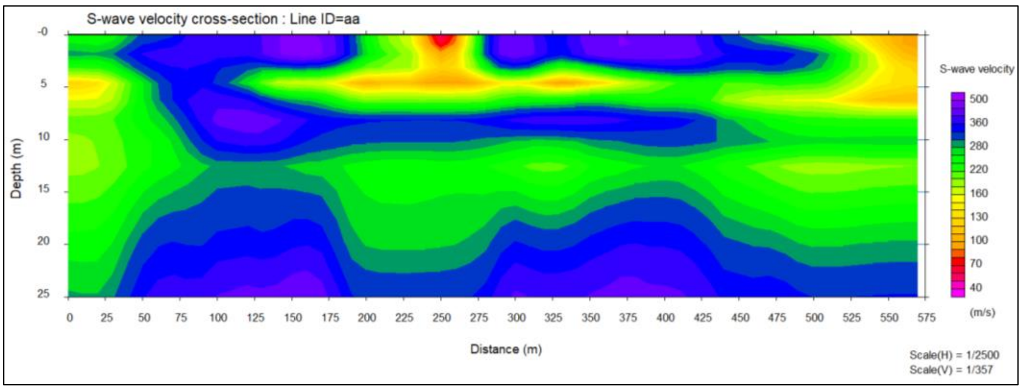

Figure 10. MASW velocity section

5. CONCLUSIONS RECOMMENDATIONS

The applied geophysical techniques were very efficient in mapping the main physic-mechanical properties of soils and rocks. The resulted resistivity section shows two electrical resistivity zones. From top to bottom, electrical resistivity of the first zone is $0.35 \geq \rho \leq 1.0$ Ω-m, associated with clay, silt, sandy, carbonated rocks mixed with sloth and organic clay. The investigated depth to top of second is zone is ≈23 meter (North) and ≈80 meter (South). The lower resistivity values in this zone may be associated with the concentration of clays highly saturated with marine saltwater. The slight increase in the resistivity value can be associated with the decrease in the presence of saltwater. The resistivity of second zone is, $1.0 > \rho < 2.4$ Ω-m, is associated with clays, with the presence of some marine saltwater content. The geological material associated with the resistivity values of these two geoelectric zones were described in the lithological collum from boreholes drilled in the study area, as constituted by silts, clays, sands, limestones sometimes mixed with sludge and organic matter.

Seismic refraction section shows an interface separating two seismic zones. The first presents P-wave velocity of 988 m/s, associated with non-compacted soils and unconsolidated rocks. The investigated depth to top of second seismic zone is ≈25 meters. The P-wave velocity of second seismic zone is ≈1600 m/s, associated with compacted soils. P-wave velocity values of these two seismic zones are associated with silts, clays, sands, limestones sometimes mixed with sludge and organic matter, described in the lithological collum from boreholes drilled in the study area. MASW section shows an alternating sequence of horizontal horizons in the investigated first ≈25-meter depth. Due to its shear velocity (Vs) values, $V_s < 180$ m/s and $180 \leq V_s \leq 360$m, the site is constituted by soft and stiff soils. These soils are composed by homogeneous organic matter and elements of mineral origin. Due to its plastic nature this matter soils have been responsible for the ruptures and landslides that occurred and for the sinking of the structures built on the site.

Geophysical results presented were collected along a single alignment along the road. It is very important that more detailed geophysical studies, using MASW technique, must be carried out in order to cover the hole mangrove zone and surroundings, along the road. The knowledge of the characteristic of the physic-mechanical property of the first 25-meter depth will allow selecting the best option to finish building the target road section.

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