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Application of half Schlumberger configuration for detecting karstic cavities and voids for a wind farm site in Greece

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Abstract

At the preliminary site investigation stage for a wind farm in Central Continental Greece, the half Schlumberger configuration was selected before using direct investigation methods. The purpose of this geophysical investigation was to measure earth resistivity for detecting karstic cavities and voids beneath the foundations of wind turbines. The half Schlumberger method is more rapid than the typical Wenner method but also proved to work efficiently for the difficult task of cavity detection. The wind turbines are very sensitive structures that need careful design for their site investigation and it was proved that when geophysical surveys precede drilling, unforeseen foundation costs can be predicted and in parallel the site investigation is optimized in quality, cost and time. The results of 42 depth probe profiles that were performed on the site are analyzed and shortly presented in this paper.

Keywords: half Schlumberger configuration, resistivity, limestone, karstic, void, wind farm, geophysical interpretation

1 Introduction

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Geophysical survey methods for measuring electrical properties of soils and rocks are using artificially generated electrical currents that are imported into the ground and measure the potential difference generated on the free surface. The current input and the voltage measurements are obtained using stainless steel electrodes. Resistance of a material is defined as the Ohmic resistance between two surfaces of the same material with a prescribed boundary. Resistance in Ohms is a physical property that can vary from material to material but can also vary in the same material from point to point (Kearey and Brooks, 1994).

At the preliminary site investigation stage for a wind farm in Continental Central Greece, earth resistivity methods were applied. The main scope of the geophysical investigation was to delineate the resistivity profile of the area and to investigate the presence of cavities below the foundations of the wind turbines.

At the axis of each wind turbine (W/T), two soundings were executed with their survey lines normal to each other. For obtaining the resistance profile below each W/T, vertical electrical sounding (VES or depth soundings or profiles) were performed. The purpose of this type of geoelectrical investigation is to determine the vertical variation of electrical resistance, ie the variation of apparent resistivity ρ_α with depth d. The data collected from the execution of the depth soundings was the voltage drop (mV) between the electrodes and current intensity (mA).

This pair of values was recorded during the development of the electrodes.

It is customary to develop a number of electrodes during such surveys that are configured according to a specific array. There are a number of different arrays that are well known to geologists and geotechnical engineers. The development methodology of electrodes applied for the project was half Schlumberger.

2 Description of Half Schlumberger methodology

The earth resistivity methods are usually applied by using a number of steel electrodes which are nailed in to the ground for some distance of a few centimeters (Figure 1).

The electrodes are usually divided in two teams; one team is for measuring the voltage drop and the other for applying the current. A closed circuit is formed between the ground and the electrodes through which current and voltage drop applies. The current intensity and the voltage drop of this circuit are measured by using a resistivity meter.

The number of electrodes varies between instruments. Some DC source is used for generating the input current.

For half Schlumberger method the potential (voltage drop) electrodes M and N (Figure 1) are placed in a fixed distance l (= one meter) from the center of the array which is less than 1 / 3 of the distance of the current dipole distance AB/2. If the potential (mV) drops to very low values (<3mV) the potential electrodes are further opened to a new distance l_1 (=10m.)> l until the completion of the profile.

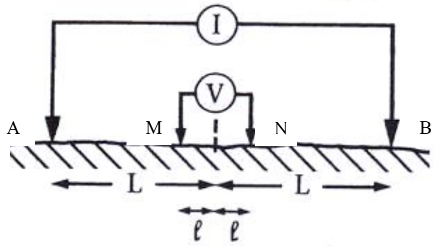

Figure 1: Schematic arrangement for half Schlumberger electrode configuration. The electrode A is progressively moved while B is steadily positioned at an infinite distance three times the distance AB/2.

The current electrode A opens progressively with specific steps (3.2m, 5m etc.) while the electrode B is placed at such distance L that represents infinity. Practically the electrode B is always at a distance L greater than 3(AB/2) in order to satisfy the condition for half Schlumberger. For example, for an investigation depth of 50m, the distance AB/2 should be 50 meters.

The measurements are taken by progressively moving electrode A from the center of the array towards 50meters distance. Electrode B should be located at 3X(AB/2)=150meters away from the center before the initiation of the survey.
By using half Schlumberger configuration, only one electrode is moved and the other three remain in their initial position. By this technique a lot of time can be saved on site which can be used for taking more measurements. During the development of the array the change of apparent resistivity reflects the distribution of resistivity with depth causing deeper layers to affect the value of resistivity.
Whenever the distance AB/2 increases, the current intensity bulb penetrates deeper than the previous one (Beck, 1991).
The apparent resistivity ρ_a for the half-Schlumberger configuration is calculated with the formula:

$$\rho_a = 2\,K\,\frac{\Delta V}{\Delta I} \qquad (1)$$

where ρ_a= apparent resistivity on Ohm m

K=geometrical factor for the half Schlumberger configuration given from equation (2) below

$$K = \frac{\left[\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2\right]}{(2\,MN)}\ X\,\pi \qquad (2)$$

where AB and MN are shown in Figure 1 and π=3.14

3 Methodology for the interpretation of results

The in situ measurements were taken with a digital self calibrated earth resistivity meter GEOTRON-CX. The readings of the instrument are in milliamperes (mA) for the current electrodes AB and in millivolts (mV) for the potential electrodes MN. Each measurement was taken at least three (3) times (or more) until equilibrium was reached in the closed circuit for obtaining consistent results. When the above values were variable, their average was used.

The interpretation of measurements was performed with the use of RIA software (RESISTIVITY INVERSION ALGORITHM). By using a logarithmic graph the variation in resistivity with depth can be presented. The geoelectric interpretation with RIA gives the distribution of electrical resistivity versus depth as well as the thickness in meters and the specific resistance in OHM M for each discrete layer determined. These layers are finally converted in to real geological formations taking into account the geological setting of the area under investigation.

The interpretation of resistivity measurements with RIA is performed by using the following steps:

1. The recorded in situ data pairs for voltage and current are introduced in the program. The software responds during input of values with messages related to the data accuracy of field measurements.

2. A random value for the parameters of the layers (ρ_i, h_i) are introduced in the program where ρ_i = apparent resistivity for the layer i and h_i=layer thickness for the same layer i. The values for i, hi and ρi are introduced in to the software based on geological data of the site under investigation rather than any random insertion.

3. The curve of apparent resistivity versus depth d (which is essentially equal to the length AB/2) is formed according to the geological model adopted in the

previous step 2. The curve is formed by using forward calculations algorithms of the Ghosh type (Ghosh, 1971).

4. Adjustments for the ρi and hi values with trial and error until the RIA computational theoretical curve matches the curve for actual in situ measurements of step 1. The theoretical curves have been calculated previously by various researchers (Ghos, 1971; Kumar and Das, 1977; Koefoed, 1979). RIA at the fourth step uses the method of least squares (iterative least squares procedure). The method was introduced in 1973 by Inman (Inman, 1973) and completed in 1977 by Johansen (Johansen, 1975; Johansen, 1977).

The method of least squares is applied by using the formula:

$$x = \sqrt{\frac{\left(\Sigma\left(\left(\ln Rhoam\right) - \ln\left(Rhoac\right)\right) * weight\right)^2}{ND}} \qquad (3)$$

where R_{hoam} = apparent resistivity measured at the site (Ohm m)

R_{hoac} = calculated apparent resistivity from theoretical models with the aid of RIA (Ohm m)

ND = number of measurements

The geological model is closer to the theoretical model as the value of x above becomes smaller. A few geological models with trial and error (typically between 5 and 10) have to be tested before adopting the final one.

4 Results of half Schlumberger surveys

The project was consisting of 21 wind turbines. For each one, two (2) soundings were executed with a total of 42 soundings. The investigation depth for each one was 50 meters. The two typical configurations followed for each W/T were: 3.2, 5, 6.4, 10, 25, 32, 50m and 3.2, 6.4, 10, 16, 25, 32 and 50m. The general result after RIA interpretations for all 42 soundings was that the geological profile consisted of a two layered medium.

The prevailing geoelectrical condition determined was:

$\rho_2 > \rho_1$

where ρ_1= resistivity of first upper layer (Ohm m)

ρ_2 = resistivity of second deeper layer (Ohm m).

The best average geological model that fitted all the collected data had a first upper conductive layer ($\rho1$) with thickness between 0.1 and 6.5m and resistivity between 100 and 260 Ohm m. The second layer was having a higher resistivity ($\rho2$) between 613 and 5788Ohm m. The first layer was conductive enough to be interpreted as clay (terra rosa) that has resulted from weathering of the second deeper layer of limestone. The second layer was detected at very shallow depths down to 6.5 meters deep from the free surface and it was interpreted as the limestone bedrock of the site. In figures 2 and 3 are shown two typical examples for raw data curves of soundings 5 and 6 and in figures 4 and 5 their resulting geoelectrical and geological models after the interpretation with RIA.

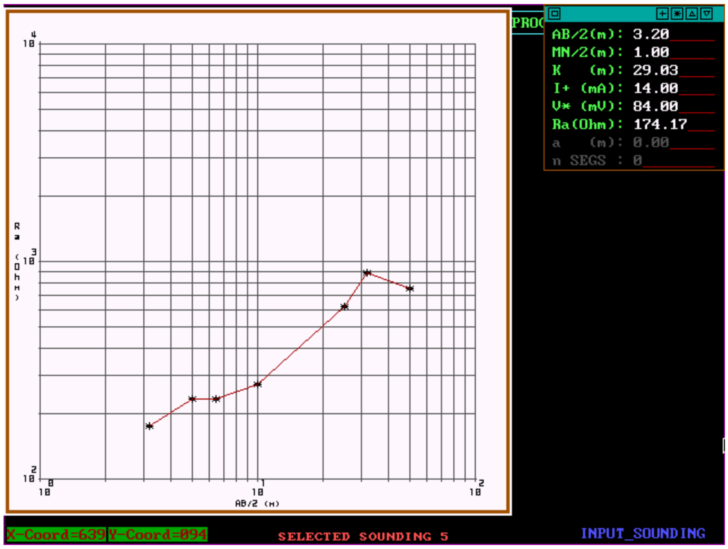

Figure 2: Raw data curve for sounding 5 with a discrete peak at 32m depth -W/T 3

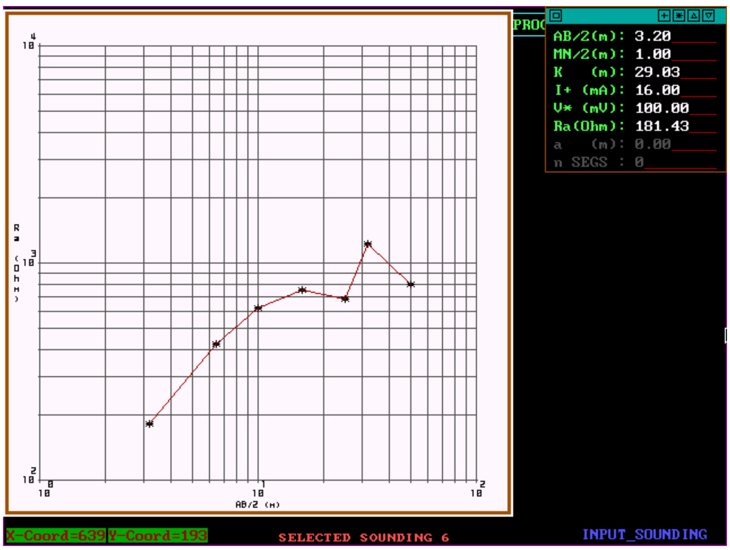

Figure 3: Raw data for sounding 6 with a discrete peak at 32m depth for -W/T 3

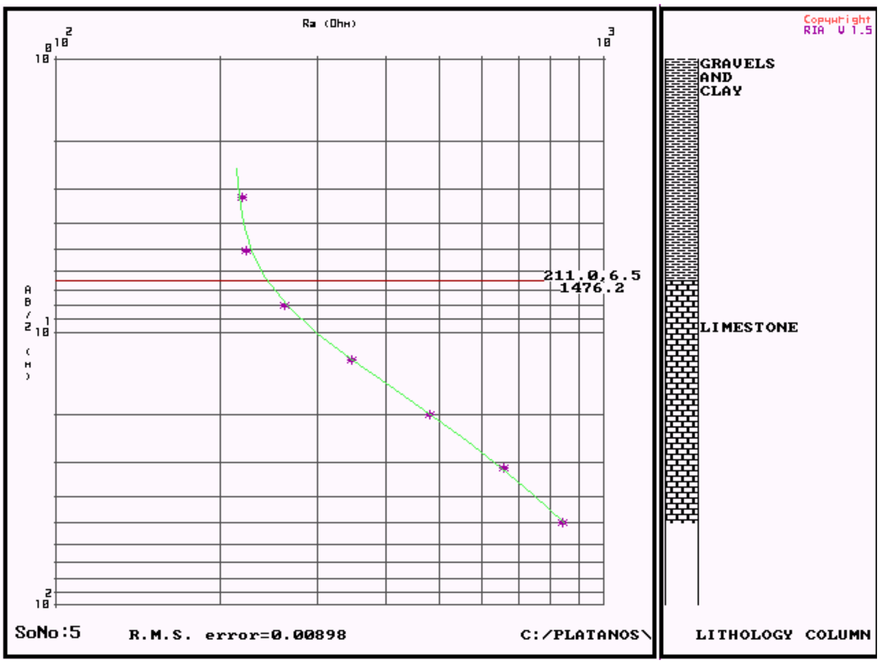

Figure 4: Resulting interpretation with RIA for raw data curve of figure 2
(ρ_1=211Ohm m- h_1=6.5m and ρ_2=1476.2Ohm m)

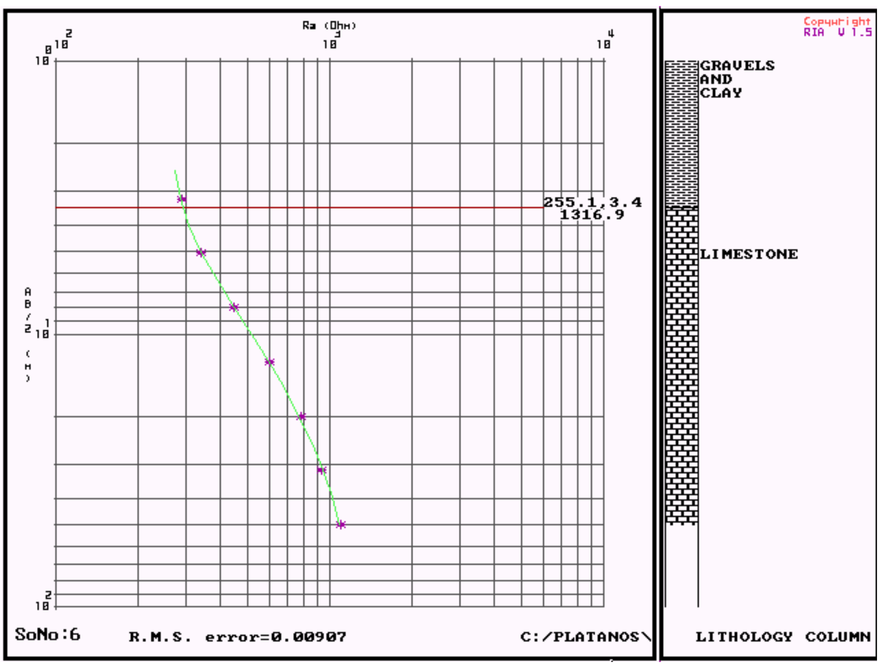

Figure 5: Resulting interpretation with RIA for raw data curve of figure 3
(ρ_1=255.1Ohm m- h1=3.4m and ρ_2=1316.9Ohm m)

The collected raw data from the geophysical site investigation have also been evaluated and interpreted. During this stage it was noted that many measurements were producing peak resistivity values at a certain depth and then the next measurements were normal as the ones before this peak. Examples of this behavior are shown in figures 6,7,8,9.

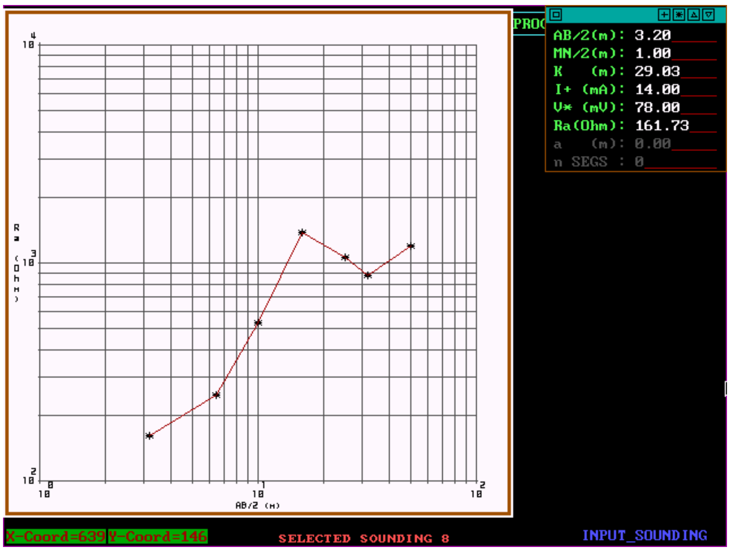

Figure 6: Raw data curve (W/T 4, profile 8) with peak at 16m and rebound at 50m (possible void filled with clay between 16 and 50m)

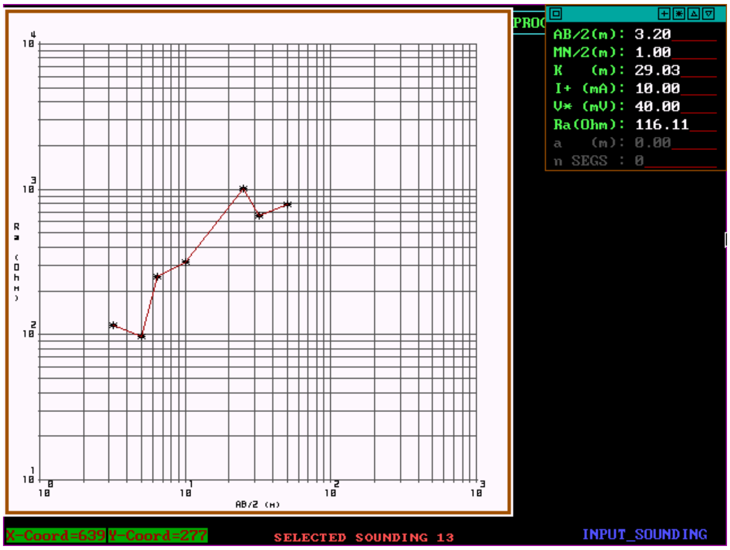

Figure 7: Raw data curve (W/T 7, profile 13) with peak at 25m and partial rebound at 50m (possible void filled with clay between 25 and 50m)

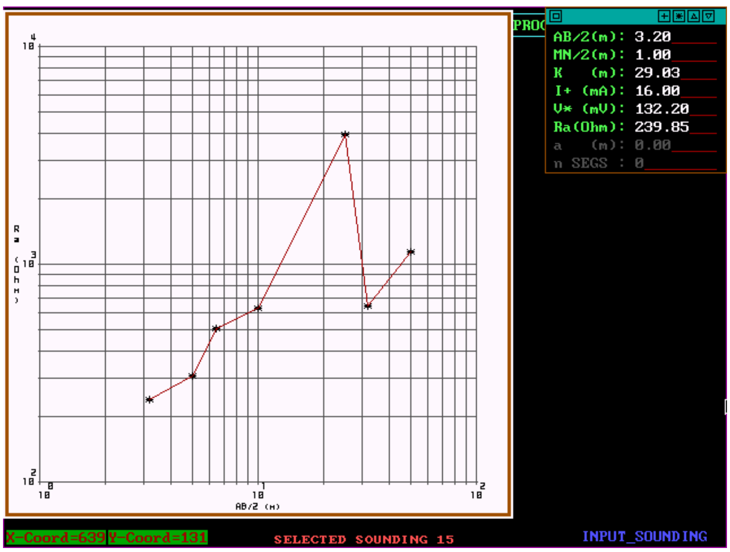

Figure 8: Raw data curve (W/T 8, profile 15) with peak at 25m and sudden drop at 32m (possible void between 10 and 32m)

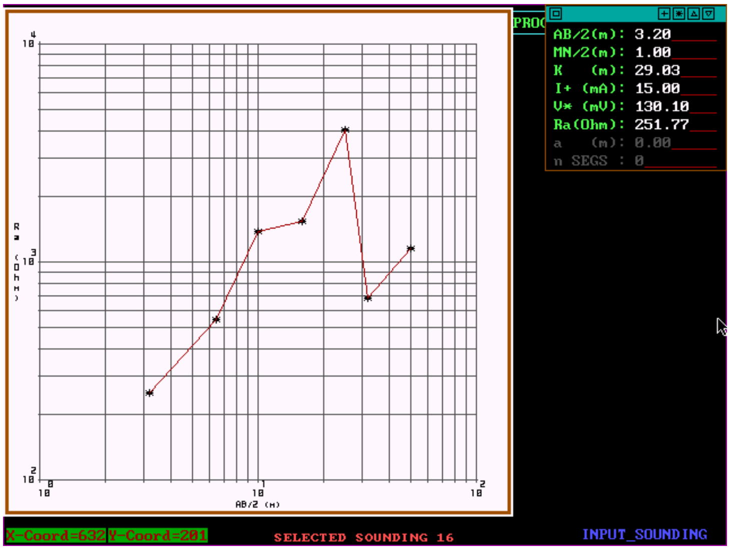

Figure 9: Raw data curve (W/T 8, profile 16) with peak at 25m and sudden drop at 32m matching the curve in figure 9 for the same W/T

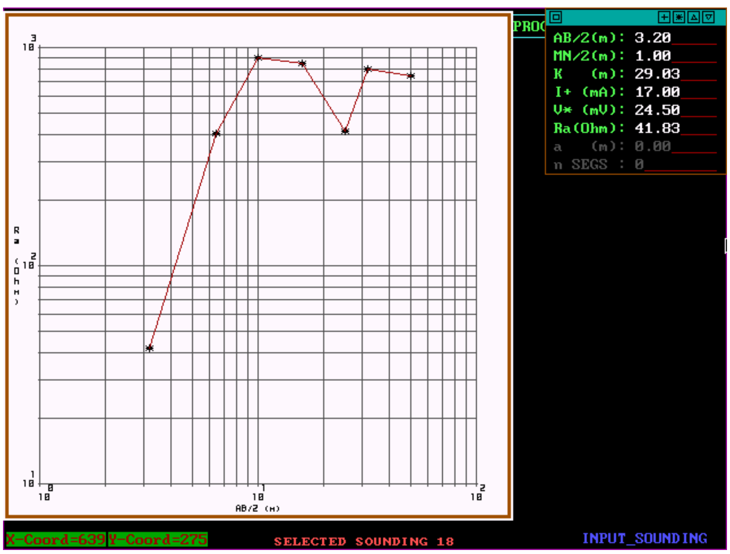

Figure 10: Raw data curve (W/T 9, profile 18) with sudden drop at 25m and rebound at 32m (possible void filled with clay between 16 and 32m)

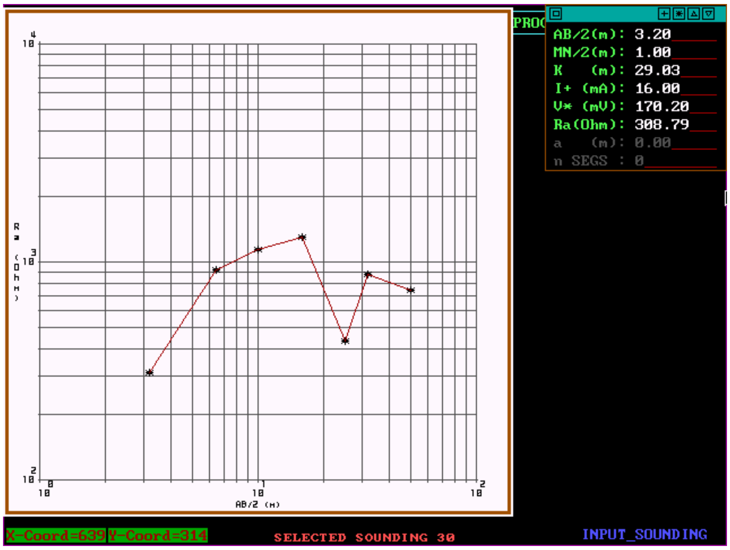

Figure 11: Raw data curve (W/T 15, profile 30) with sudden drop at 25m and rebound at 32m (possible void filled with clay between 16 and 32m)

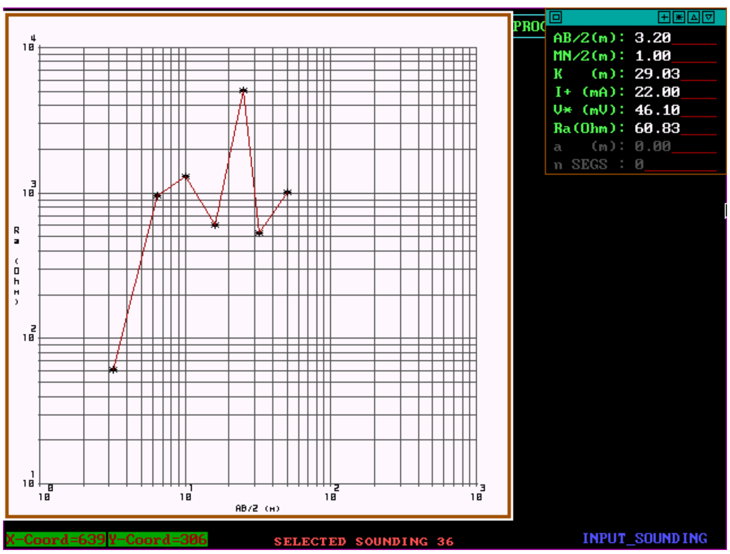

Figure 12: Raw data curve (W/T 18, profile 36) with sudden drop at 16m, peak at 25m and drop at 32m (possible void filled with clay between 10 and 16m and karstic void between 16 and 32m)

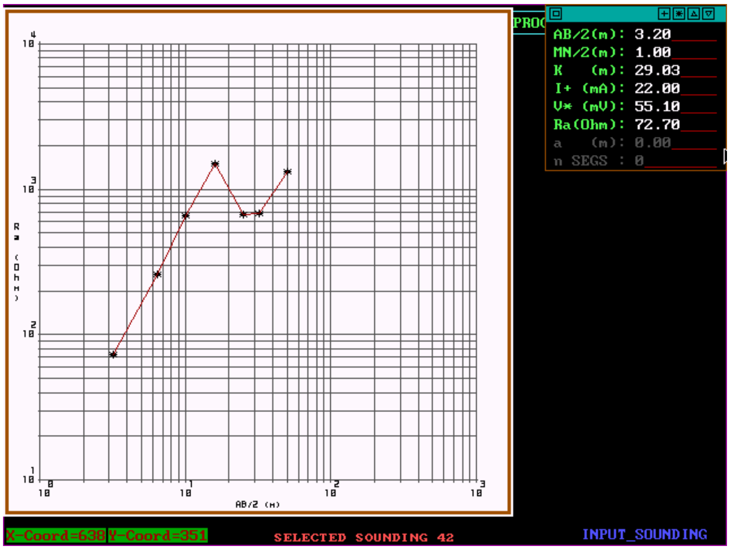

Figure 13: Raw data curve (W/T 21, profile 42) with sudden drop at 25 and rebound at 50m (possible void filled with clay between 16 and 50m)

The important information was revealed not only from the interpretation of the measurements, but from the raw curves. It is evident from the pattern of these curves shown above that these peaks or sudden drops could be associated with the presence of cavities of karstic origin. This sounded very heretic because it is very rare the case for karstic voids in Triassic and Cretaceous Limestone at the top of a mountain which is badly sheared, faulted and folded and at the same time there are no signs of karstic processes on the ground surface. The suspicions were stronger when one observes that the raw curves present very sudden resistivity decreases and after a few measurements the resistivity increases abruptly by taking into account the 1900m altitude and the massive limestone thickness. This could be associated with the presence of karstic voids that has been filled with clay (tera rosa) from the weathering of limestone and water action. Below the void the limestone is intact and compared to the filled with clay void, it has greater resistivity. Thus the resistivity increases again as the electrodes are further deployed.

The half Schlumberger configuration thus proved to be sensitive enough for locating probable void locations or voids that have been filled with some form of conductive material like clay.

5 Conclusions

Geophysical site investigation was applied at a very early stage for the construction of a wind farm at Central Continental Greece. The wind farm was consisting of 21 wind turbines developing on the crest of a mountain. The site was mainly consisted of massive limestone and the scope of the geophysical survey was to detect the presence of voids or filled cavities that could put in risk the project.

The half Schlumberger configuration was proposed for detecting such voids and it proved to be efficient. The sensitivity of half Schlumberger configuration could be attributed to the interval between successive measurements. In contrast to Schlumberger, Wenner configuration collects data usually every meter and thus the raw data curve it is continuous between 1 and 50 meters. The discontinuity of half Schlumberger configuration (for example from 16m to 25m depth leaves a gap of 9m) gives a better pronounce to the peaks and drops of resistivity. But on the other hand the collected data leave a big gap between the upper and the lower elevation of the probable void.

A detected void between 16 and 50m depth for example (W/T 21, profile 42) can be of no engineering use since such a void could impose a high risk with its exact dimensions unknown. Optimization of the site investigation can be achieved only by applying direct methods like drilling boreholes and sampling at the suspect locations (hot spots) beneath the wind turbines. In this way the interpretation with half Schlumberger configuration becomes a tool for designing the next step of the site investigation scheme by executing boreholes and in situ testing. In this way qualitative and quantitative methods are linked with resulting reduction for the site investigation cost from deep boreholes. Such boreholes could also prove to be unnecessary when direct methods are only used without applying geophysical investigations at an earlier stage.

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