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IDENTIFICATION AND EVALUATION OF FRACTURES USING ELECTRICAL RESISTIVITY TOMOGRAPHY IN THE VICINITY OF THE AXIS OF THE HUAMANTANGA DAM – LIMA – PERU

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ABSTRACT. Huamantanga District is located in the central highlands of Peru, in altitudes of circa 3,390 m, where an ancestral Inca water management technique that promotes the “farming” and “harvesting” of water, named “mamanteo”, is used to direct water through a ravine during the rainy season, towards places with high infiltration rates. In addition, the Huamantanga Dam was built to storage water due to the increased agricultural activities. Nevertheless, undesired leaks were observed raising the needs for an electrical resistivity tomography survey to identify the possible leakage zones. Four electric profiles parallel to the axis of the dam were surveyed, two profiles were located upstream from the axis, spaced 10 to 15 meters, and two profiles were situated downstream, being the fourth profile approximately 10 meters above the spring. The resistivity measurements were performed for each of the four electric tomography lines, in order to obtain detailed information of the stratigraphy and to identify low resistive anomalies related to geological faults. The results show the presence of considerable fractures which were recommended to be quickly impermeabilized since the risk of infiltration is latent.

Keywords: infiltration, fracture, geophysical investigation, electrical method.

RESUMO. O distrito de Huamantanga localiza-se no altiplano central do Peru, aproximadamente a 3.390 metros de altitude, onde se promove uma antiga técnica incaica de “cultivo” e “colheita” de água chamada de “mamanteo” para direcionar um fluxo de água durante a estação chuvosa, através de ravinas, para locais com alta infiltração. Além disso, a barragem de Huamantanga foi construída para armazenar água, devido ao aumento das atividades agrícolas. No entanto foram observados vazamentos preocupantes o que suscitou a realização de levantamentos de tomografia elétrica para identificação das áreas potenciais de infiltração. Foram distribuídos quatro perfis elétricos paralelos ao eixo da barragem, sendo dois perfis a montante do eixo, espaçados de10 a 15 metros entre si e dois perfis a jusante do eixo, com o quarto perfil situando-se a aproximadamente 10 metros acima da fonte de água. Assim, as medições de resistividade foram feitas para cada uma das 4 linhas de tomografia elétrica, a fim de obter informações pormenorizadas sobre a estratigrafia na área de estudo e identificar anomalias georresistivas causadas por falhas geológicas, que refletem anomalias de baixa resistividade. Os resultados indicam a presença de fraturas locais consideráveis, que foram recomendadas a ser impermeabilizadas rapidamente, face ao risco latente de infiltrações.

Palavras-chave: infiltração, fratura, investigação geofísica, método elétrico.

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INTRODUCTION

The Huamantanga Dam, located in the city of Lima, in the agricultural district of Huamantanga, is leaking water to the subsurface. According to Boneli (2013), problems of infiltration and internal erosion (tubing) are common generators of possible accidents in dams. The knowledge of stratigraphy and the identification of zones of low resistivity anomalies, can indicate the presence of faults and fractures in the subsurface, motivating an electrical tomography survey in the vicinity of the dam, to identify subsurface fractures responsible for water escape.

After field recognition, we decided to conduct electrical resistivity measurements using electrical tomography, at the edge of the geo-membrane (Fig. 1). In order to provide strong contrasts of resistivity, we dissolved 200 kilos of salt in the pool of water. The first campaign of resistivity measurements was done with natural water conditions on the first day. After dissolving the salt in the water reservoir, subsequent resistivity measurements began, tracing the salt water route. The results of the two campaigns were integrated, according to the following steps:

I. Geophysical Electrical Resistivity Tomography (ERT) survey

II. Processing and Interpretation of the resistivity values of the PDS (Pole-Dipole Soundings), and correlation with the geology of the area under investigation.

These results are presented and discussed in the following sections.

METHODOLOGY

Materials

For the present work applying the technique of electrical resistivity tomography the following equipment and geometries were used:

- 10-channel Syscal Pro Resistivity Meter – IRIS Instruments.
- Reels with 100 m of cable for vertical electrical sounding (VES).
- Cable configuration for PDS with spacing of 10 meters.
- Power supply 800 DC.
- 30 stainless steel electrodes (Dipoles) and 04 steel (AB).

Method

In groundwater exploration and mining, the geophysical prospecting generally do not exceed 100 meters in depth. In geotechnical studies, 90% of the studies do not exceed 300 meters in depth, usually less than 100 meters. For the purposes of the present study the required depth was 30 meters.

In geotechnical investigations the best results are the electrical methods in its variants Vertical Electrical Sounding (VES), Pole-Dipole Sounding (PDS) and Electrical Resistivity Tomography (ERT). Also of great importance is the refraction seismic prospection with its variants of MASW, REMI, Down Hole, H/V among others.

For the objectives of the present project, an electrical resistivity survey, applying the Pole-Dipole Sounding (PDS) electrode distribution was adopted. The earth is a good conductor of electric current, due to its content of metallic minerals, degree of humidity and mineralization of the water that occupy the interstitial spaces of the rocks and sedimentary formations. The temperature also influences the electrical conductivity of the rocks. These are the most important characteristics that define the resistivity of the physical environment. In geological formations such as those observed in the investigated area, the resistivities vary from Ω-meter units for wet to saturated soils, with different degrees of mineralization and humidity. Higher mineralization and humidity, generates lower resistivity and vice versa.

The electrical resistivity method applies double electrode dipole. The first dipole is the electric current transmitting circuit, from a source of direct current that can be a current accumulator, current generator, solar panel or other sources, by means of electrodes (AB) made of resistant metals to penetrate hard floors. This circuit measures the electric current (I) that is sent to earth. The second dipole is the receiver or potential circuit formed by electrodes MN, where the potential or fall of electric voltage (DV), created by the flow of the electric current, is measured.

For the distribution of the AB and MN electrodes there are several arrangements, such as those devised by Wenner, Lee and Schlumberger (can be symmetrical or asymmetrical) among others. In Peru the Schlumberger arrangement gives better results in soils with strong lateral anisotropy and/or rugged topography.

The electrolytic distribution of Schlumberger is characterized by being linear, symmetrical and/or asymmetric, which allows investigating the depth in the central part of the electrode distribution.

There are other distributions such as Dipole-Dipole, Pole-Pole, and Pole-Dipole. For this distribution of electrodes, equipment with 10 to more simultaneous measuring electrodes is used. They are characterized by providing horizontal and vertical information.

Figure 1 – Photograph of the filtered water pond.

Pole-Dipole or Electrical Resistivity Tomography

According to Keller & Frischknecht (1966) the pole-dipole electrical resistivity tomography allows investigating in horizontal and vertical directions, giving important information to define the geotechnical characteristics of the area under study. The configuration and distribution of electrodes used with the Pole-Dipole method is shown in Figure 2. These measurements were made with a 10-channel Syscal Pro Resistivity Meter, which allows to perform 10 continuous readings in less than 30 seconds, and the data is stored or recorded by the equipment, and then downloaded in a CPU and proceed to processing.

The lateral and vertical resistivity variations of the subsoil, are presented in 2D pseudo-section models, as seen in Figure 3. The resolution of the models are dependent on the density of the data, especially for imaging narrow structures (Dahlin & Loke, 1998).

To begin the readings the current electrodes were positioned in positions 1-2 (Fig. 3), while the potential electrodes occupy positions 3-4, so that the separation factor of the device dipoles will be $n = 1$. The intensity (I), electrode spacing (a), and potential (ΔU) are measured and introduced in the Eq. (1) to calculate the electrical resistivity:

$$\rho_a = \pi * n(n+1)(n+2) * a\frac{\Delta U}{I}\,. \qquad (1)$$

This gives the value of ρa corresponding to the pair of positions 1-2 and 3-4. From the center of these positions are drawn lines at 45°, so that at the point where they intersect, the value of the measured apparent resistivity is assigned.

Then the measurement is performed for the pair of positions 1-2 and 4-5, plotting the corresponding point. Following this process a pseudo-resistivity of the whole subsurface is drawn, the representation of which is generally in the form of a trapezoid.

It is very important to emphasize that this pseudosection procedure is only a graphic convention, and in any case implies that the depth of investigation of the device is given by the intersection of the two lines at 45°.

The pseudo-section gives a very approximate image of the distribution of resistivities in the subsoil. However, the image they provide is distorted.

RESULTS

The present item corresponds to the measurement phase of the geo-resistive parameters, such as the current sent to earth and the difference of potentials created by it, work done in the field and pre-processing of the data. A 5 meters spacing between electrodes was adopted, which will allows a penetration depth of 25 to 30 m, appropriate for the project objectives.

For an adequate identification of the areas of fractured rock, a first campaign of resistivity measurements in natural conditions was carried out, resulting in profiles ERT-01 A, 02 A and 03 A. At the end of these measurements, 200 kilos of salt were dissolved in the water reservoir. The readings were repeated in each electrical resistivity profile in the following day, resulting in the geoelectric profiles ERT-01 B, 02 B, 03 B and additionally ERT-04 B. The data

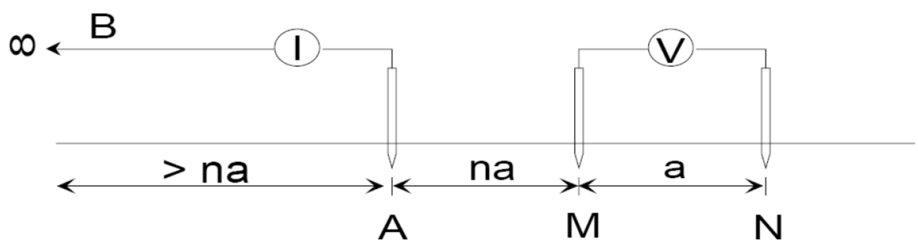

Figure 2 – Pole-Dipole Array.

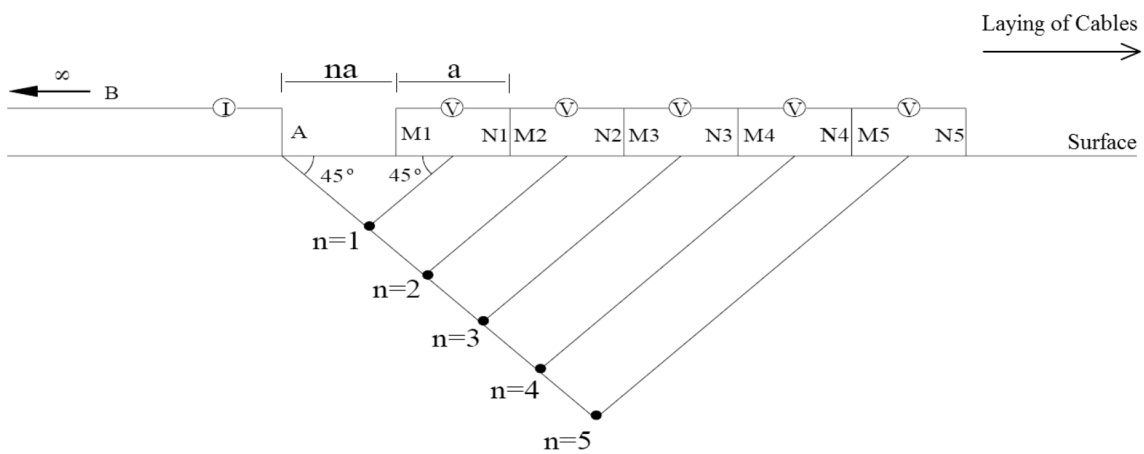

Figure 3 – Representation of the pseudo-domains with arrangement Pole-Dipole.

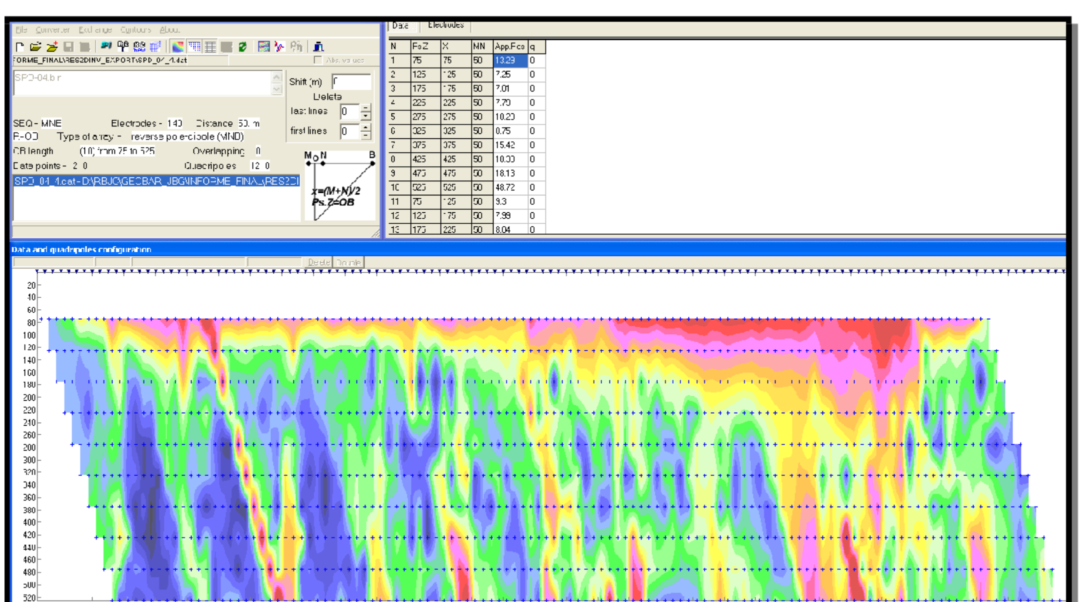

Figure 4 – Data Visualization X2IPI (Moscow University & IRD).

was processed and visualized using the X2IPI software as shown in the Figure 4 example.

After verifying the information as well as its data, we exported the information to the Res2dinv software to observe the block diagram for the three lines as shown in Figure 5.

The data inversion and modeling used the method of finite

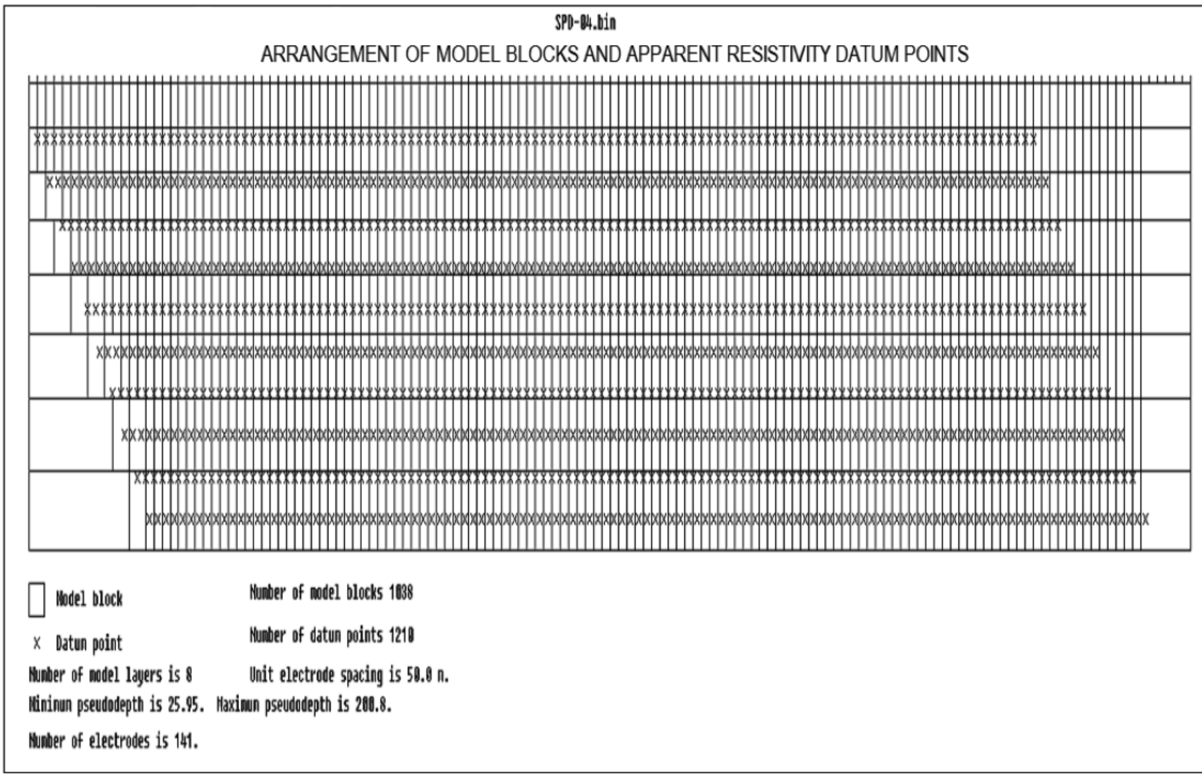

Figure 5 – Block diagram.

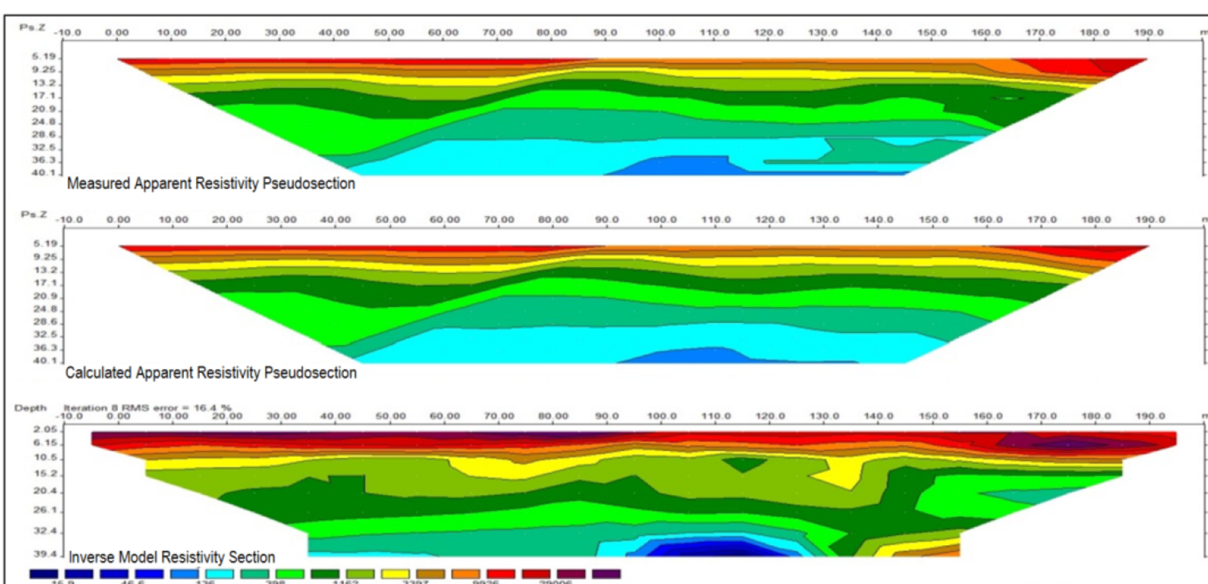

Figure 6 – Inversion model for line 1.

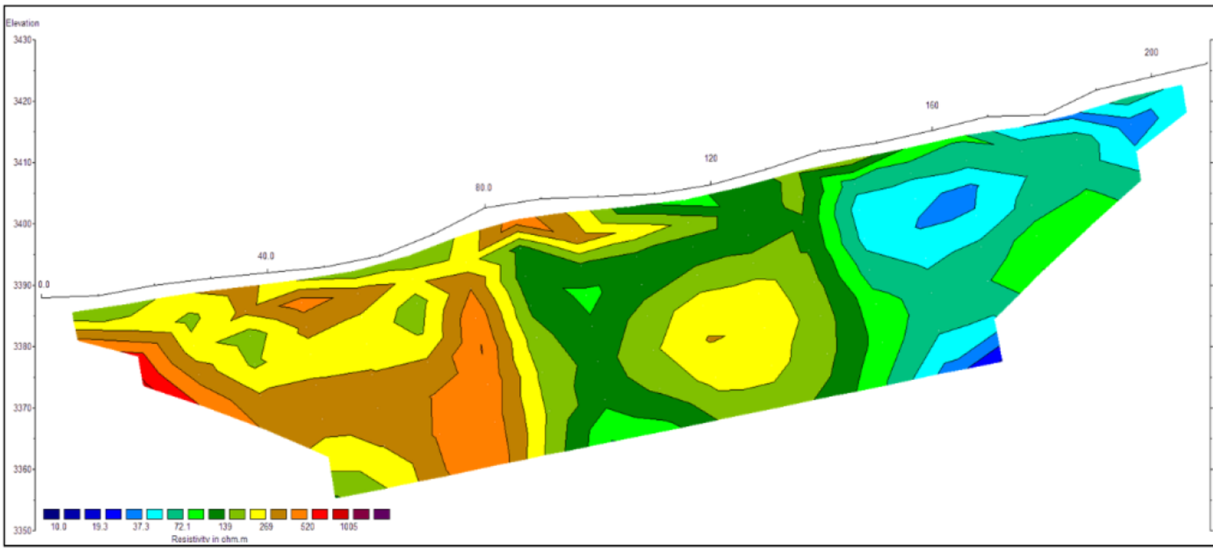

Figure 7 – Topography inversion model for line 1.

elements for the solution of equations and the inversion by least squares, resulting in images such as that shown in Figure 6.

The topography inversion model was applied to the three tomographic lines, using the software Res2dinv, using the method of finite elements for the approximation of the observed and inverted data. Figure 7 shows the topography inversion model applied to profile 1.

DISCUSSION

The information of the PDS or ERT lines made in the probable zones of the water leaks were distributed as shown in Figure 8.

The readings were made to adequately contrast resistivities before and after salting the water reservoir. pH measurements of the water before salting were taken, giving values from 7.2 to 7.4 in the reservoir and in the spring source. Electrical conductivity values before salting are 90 mmΩ at the reservoir and 100 mmΩ at the source.

After salting the water, electrical conductivity values of 180 mmΩ in the reservoir and 180 to 190 mmΩ in the spring were registered.

The information obtained from the ERT lines represent changes in the physical and chemical characteristics of the hydrogeological medium. The range of resistivity values were classified as follows (Fig. 9):

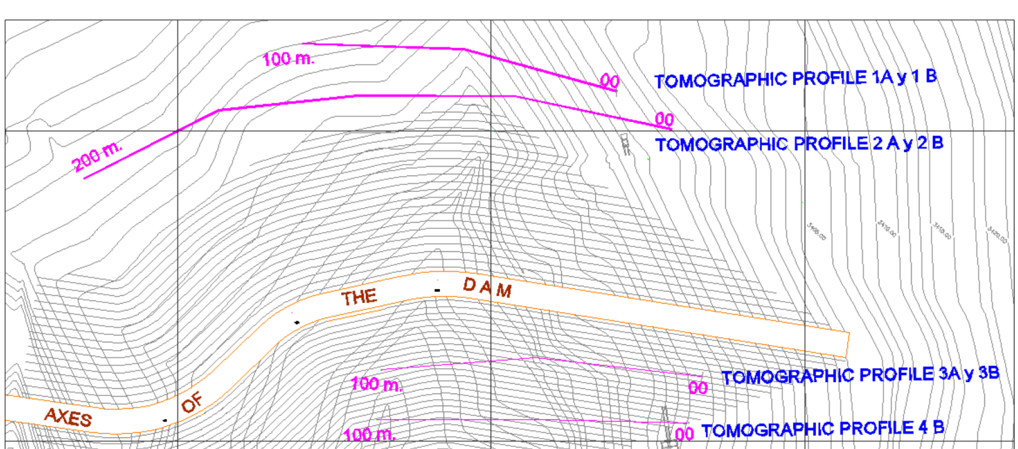

Figure 8 – Location of the tomographic profiles.

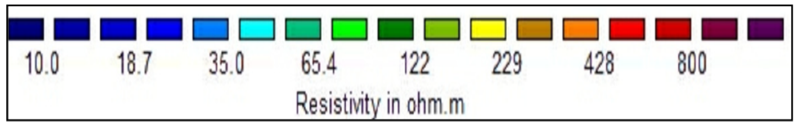

Figure 9 – Color for range of resistivity.

- Resistivities from 10 to 30 Ω-meters in shades from dark to light blue, correspond to fractured and saturated rocks.
- Resistivities from 30 to 300 Ω-meters in green and yellow colors correspond to the clay formations with little content of fine and slightly compact sands.
- Resistivities greater than 300 Ω-meters in colors red, orange to dark purple represent very compact sediments or non-weathered rocks.

Tomographic Profile ERT-02 A and B

This profile has a length of 200 linear meters in an E-W direction (Fig. 8). In Figures 10 and 11, we observe two low resistivity zones where the rocks are fractured. In the following descriptions the distances are referred in meters from the beginning of the profiles, from E to W (Fig. 8):

ZONE I – corresponds to the main fractured zone, from 53 to 67 m. It is a vertical zone, where the water presently infiltrates giving rise to the water spring downstream of the dam.

The profile ERT-02 B was made 12 hours after salting the water (Fig. 11). The main fractured zone is still identified between 52 to 60 m, and a second one is seen from 75 to 90 m distance (green to light blue in Fig. 11). The main fractured zone from 52 to 60 m, must have a special impermeabilization treatment.

ZONE II – corresponds to the low resistivity anomaly identified by the ERT-02 A, from 160 to 200 m at the end of the profile. For security, we suggest applying to this zone the same impermeabilization treatment given to the first zone.

Tomographic Profile ERT-01 A and B

This section has a length of 100 linear meters in the E-W direction (Fig. 8), distanced nearly 10 to 20 m from ERT-01 section. The ERT-01 A and ERT-01 B are very similar (Figs. 12 and 13), indicating non-weathered rock layers with contrasting resistivity values parallel to the surface (colors orange to brown). The anomaly or fracture occurs only in the vicinity of the geo-membrane placed in eastern side of the dam.

Tomographic Profile ERT-03 A and B

Section ERT-03A has a length of 100 m in a E-W direction (Fig. 8). ERT-03 A and ERT-03 B are similar, (Figs. 14 and 15) without marked resistivity anomalies, also suggesting very homogeneous geological formations up to 25 m in depth. This homogeneous stratification in ERT-03, suggest that the water leaks are passing through very fine cracks, which are not resolved with the present method. In Figure 15, after salting the water, a light blue spot anomaly is observed in ERT3-B, near to 13 m, where some water leakage may occur.

Tomographic Profile ERT-04 B

Section ERT-04B has a length of 100 meters in a E-W direction (Fig. 8). This profile is very close to the spring originated by the waters that infiltrate the dam. This section was surveyed only after

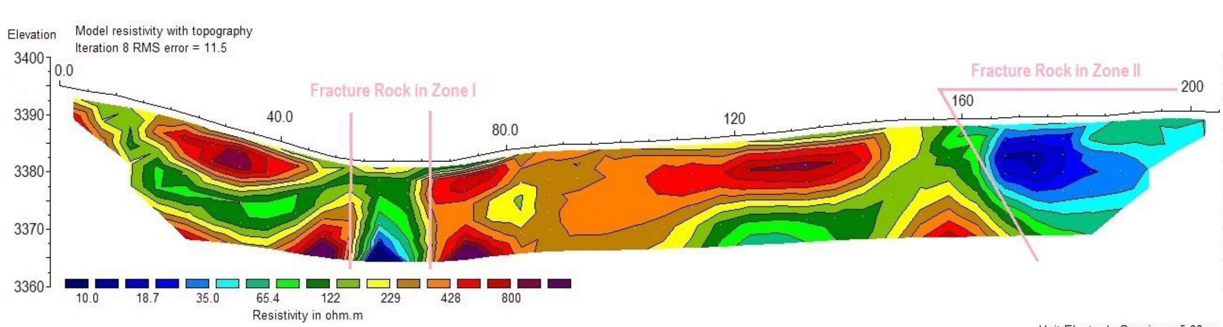

Figure 10 – Tomographic Profile without Salt, ERT-02 A.

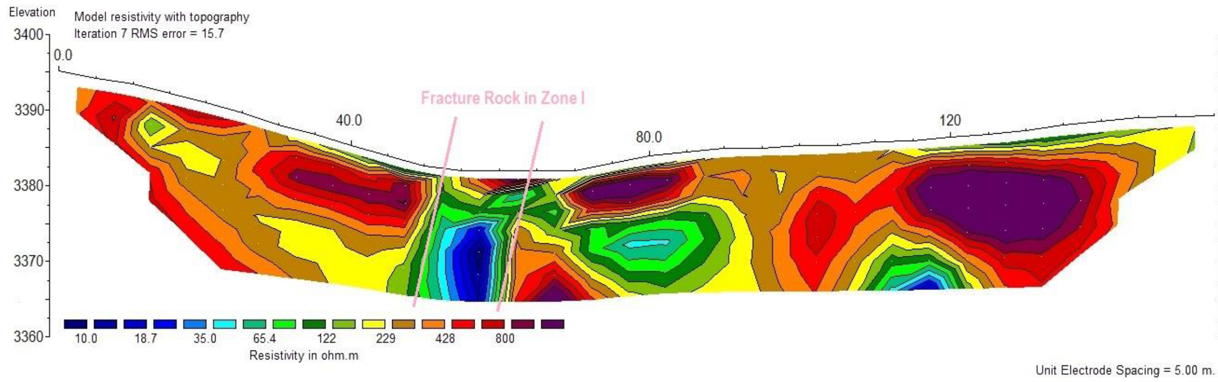

Figure 11 – Tomographic Profile with Salt, ERT-02 B.

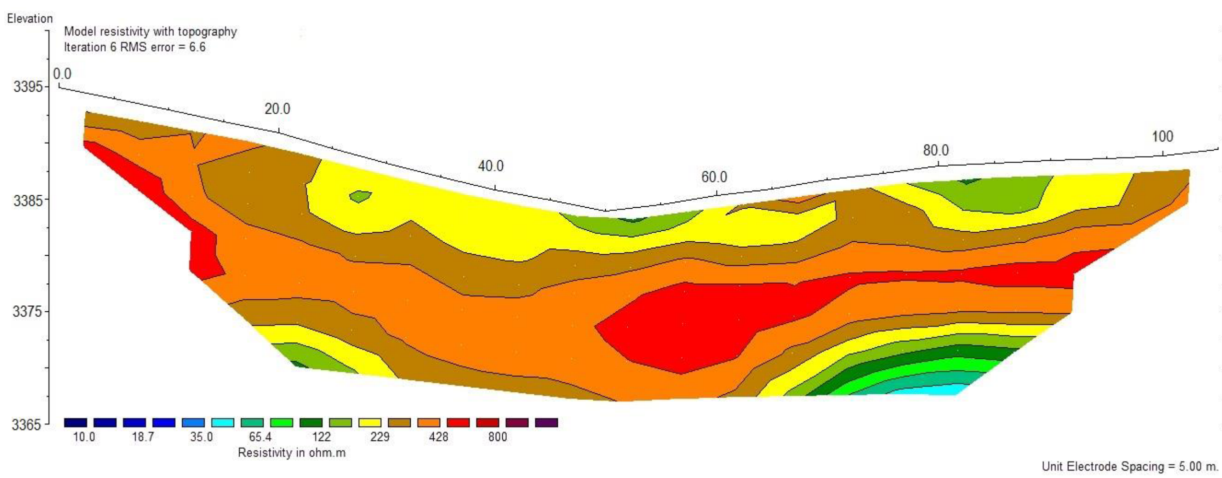

Figure 12 – Tomographic Profile without Salt, ERT-01 A.

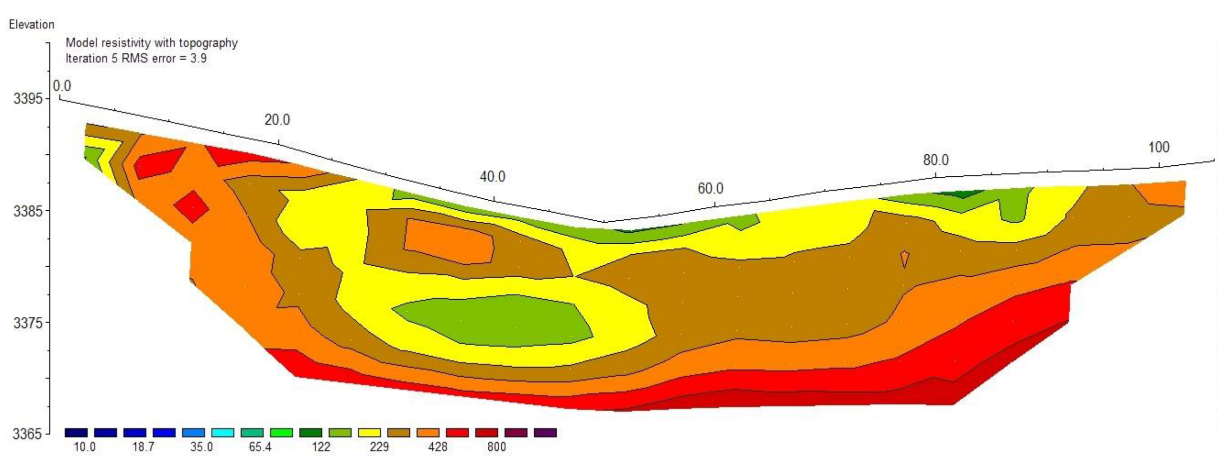

Figure 13 – Tomographic Profile with Salt, ERT-01 B.

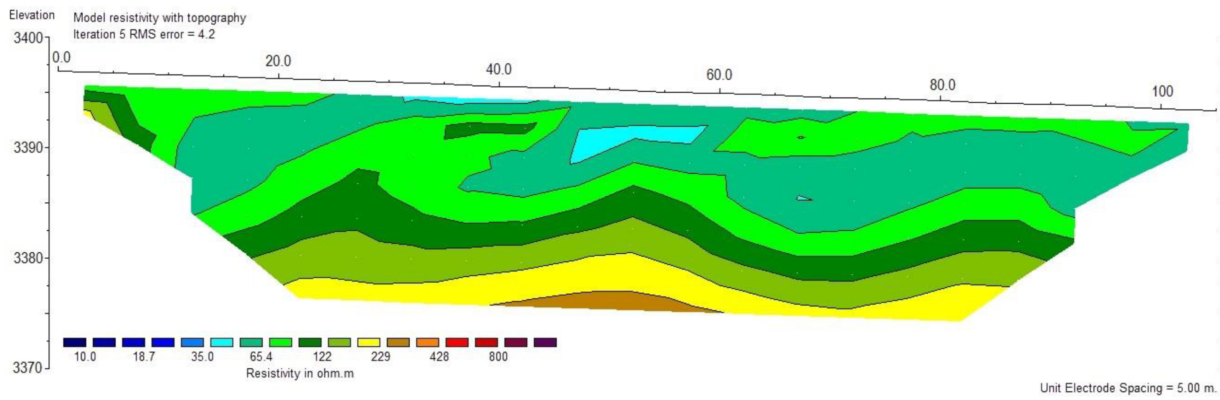

Figure 14 – Tomographic Profile without Salt, ERT-03 A.

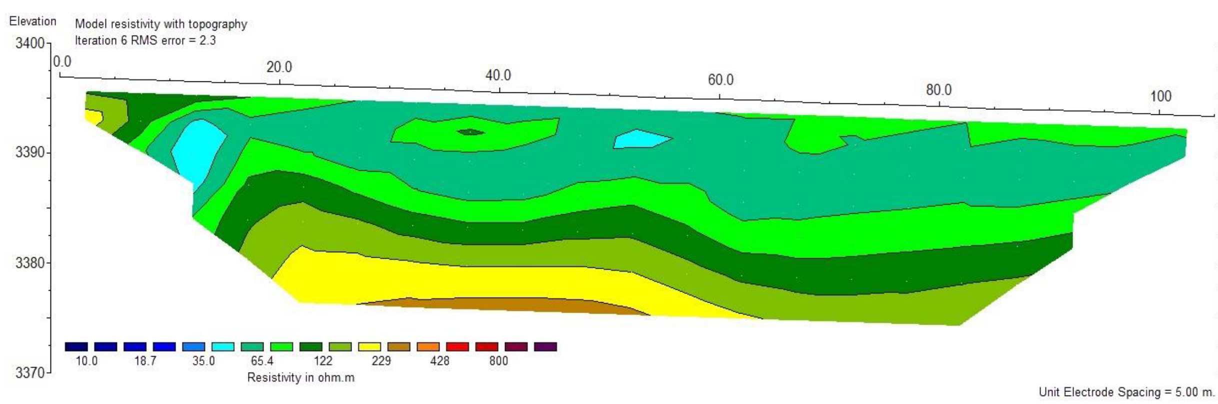

Figure 15 – Tomographic Profile with Salt, ERT-03 B.

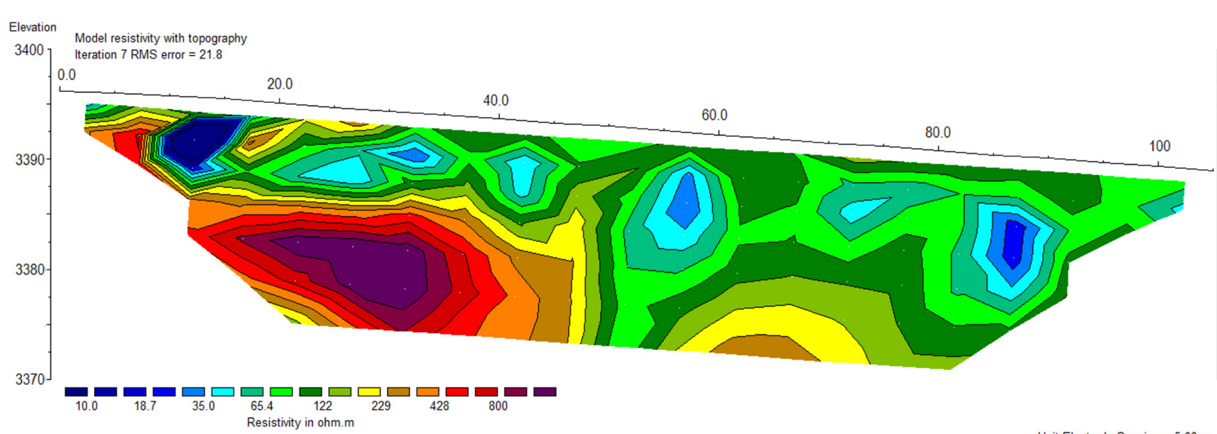

Figure 16 – Tomographic Profile ERT-04 B.

Figure 17 – Limit above the geomembrane and the pool of filtered water.

salting the water. The tomographic profile shows a low resistivity, saturated layer along most of the section, cropping out between distances from 84 to 94 m, which would be related to the water leak that needs impermeabilization. This feature is 3 m wide and the central water spring is nearly 1 m wide (Figs. 16 and 17).

CONCLUSIONS

By means of the present study two zones of weakening or fracturing of the rocks have been identified:

ZONE I – It corresponds to the most important, vertical fractured zone in the section ERT-01 between distances 53 to 67 m. These fractures originate the water spring downstream of the dam. In this same section, another low resistivity zone is observed nearby, from distances 75 to 90 m. These are the main areas deserving greatest care for impermeabilization.

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ZONE II – corresponds to the fractured zone identified in section ERT-01, between distances 160 m to the end of the section. This fractured zone is not as deep as in Zone I. For security, we suggest applying to this zone the same impermeabilization procedures.

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