Evaluation of wet front under foundation at "El Chocón dam" using electrical tomography

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ABSTRACT

El Chocón dam is located on Limay River in the province of Neuquén (Argentina) and is one of the most important in the country and in Latin America due its reservoir capacity. Currently, the dam is at full operation stage, while its structural health is monitored through a significant number of instruments installed in the dam body and its foundation. In the sector of the closure of the dam on its left margin, the measurements of some piezometers that monitor the deep rock foundation, showed some changes that gave rise to the hypothesis of the advance of wet front, despite fact that the work has practically 50 years from commissioning. To confirm or rule out this hypothesis, research work was started using the 2D electrical tomography method. The methodology was selected based on the good correlation that exists between the electrical resistivity and the volumetric content of water in a rock formation. Tomographic image obtained made it possible to determine different sectors in which wet front is detected and to define its extension, also evidencing a good correlation with what was recorded in the rock auscultation instruments, confirming the slow advance of wet front to downstream.

Keywords: Dam monitoring, electrical tomography, rock resistivity.

1. Introduction

El Chocón dam is in the north of the Northern Patagonia of Argentina, on the Limay River, which has an average annual flow of 670 m3/s and is located about 70 km upstream from the confluence with the Neuquén River (Fig. 1). The capacity of the reservoir is 20,600 hm^3, which allows seasonal adjustments, thus, the reservoir is one of the most important in the country and Latin America.

El Chocón dam is a heterogeneous loose material dam with a crest length of 2,500 m and a height of 90 m in the section of the river basin that is approximately 900 m wide. On its left bank, the dam has a curved plan and an average height of 40 m. For structural health monitoring, the dam has a significant number of instruments that allow evaluating the behaviour of the dam and its foundation. The system is basically made up of open piezometers (Casagrande type), conventional hydraulic piezometers (Bishop type), phreatic meters and flow gauges, among others (Restelli 2013).

Particularly, in the study area, the closure of the left bank (MI) is monitored by about 60 open piezometers (Casagrande type) and 5 phreatic meters, arranged at the foot of the dam and used to monitor the foundation rock in terms of levels. piezometric and phreatic metric. These devices are read every 15 days, while their response is generally correlated with variations in the reservoir level, as the main causal variable.

During the monitoring process, some pressure increases trends have been recorded in 5 (five) piezometers, which led to some investigations, among which verifications were carried out on the instruments, through field tests that confirmed the reliability of the records. Fig. 2 shows a detail of the left margin (LM) sector where the present study was focused.

Even though there are a significant number of piezometers at the foot of the dam on the left margin (LM), the information obtained is for a specific point location (piezometric capture chamber), so it is not feasible to determine the extension of the wet front. For this reason, it was decided to carry out an electrical tomography study to understand the variations recorded in some of the piezometers.

Attending two fundamental aspects that favour its implementation, the method based on electrical resistivity measurement was selected:

a) Rock foundation of the dam is found in a very homogeneous formation of sedimentary rocks known as the Chocón Formation (Rimoldi and Turazzini 1984).
b) The existence of a good correlation between electrical resistivity and moisture content for a rock formation is well known (Zhou.et al. 1997, Rinaldi 2013).

This allows us to infer that in a geological formation that is relatively homogeneous in texture, density, and mineralogical composition, resistivity variations can be attributed fundamentally to variations in the water content in the material's pores.

Figure 1. Location of El Chocón dam in the province of Neuquén, Argentina (Image Lan Sat - Copernicus)

Figure 2. Sector of study in the province of Neuquén, Argentina. The location of the completed geoelectric line is also indicated in yellow full line on the of left margin (LM).

Based on the above, the electrical tomography method was selected. By using this method, a 2D image of the variation of the electrical resistivity in a specific section is obtained (Griffiths and Barker 1993; Loke and Barker 1996). For these studies, a transverse resistive profile of 320 m length and 30 m average depth was determined. The tomographic image obtained made it possible to detect different sectors of wet fronts and their extension, linking it with the records from the dam monitoring instruments in terms of piezometric levels.

2. Geological review

The area is characterized by a smooth relief, somewhat undulating, who's most outstanding positive geoforms are some isolated hills and mountains that surround the site and the reservoir. Rocky outcrops can be seen in the area, corresponding to the continental sediments of the so-called "Neuquén Group".

The dam is located at this environment of sedimentary rocks of Cretaceous age (Upper Mesozoic), in a massive and poorly differentiated succession of reddish sandstones of variable grain and predominantly calcareous matrix to clayey silt, with conspicuous levels of intercalated claystones and siltstones of approximately 70 to 80 million years old. The strata are arranged subhorizontally, with slight undulations in a slightly vaulted design, while the massif does not present important fault zones, indicating great structural tranquillity.

The outcropping rocks of the Neuquén Group (Fig. 3) make up the relief practically from the very moment of its formation, since after the Cretaceous period there was no more sedimentation or activity generating igneous rocks and with the last movement of the final phase of the Andean Orogeny the whole region took the physiognomy and height that is currently observed. A drainage network (generated at the end of the Tertiary period) with a design according to a young relief with a marked regional slope was established.

The sedimentary sequence is mainly composed of two terms: clastics (psammites and pelites) and carbonates (limestone). In the former, sandstones and sandstones predominate to a great extent, and to a lesser extent, siltstones, siltstones and claystones; while the second is frequently represented by calcarenite and limestone.

The clastic fractions are essentially siliceous, with quartz and fresh plagioclase as the main constituents of the clasts and to a lesser extent lithic clasts (fractions of other rocks) and clastic calcite; while the matrix can be both pelitic (limoclay) and carbonate (calcite); cementum, of the siliceous (opal) or zeolitic (analcime) type, is generally present but not abundant.

All the components, except for the cement, are strongly stained by a patina of iron oxides (hematite and limonite), which shows an oxidizing environment of sedimentation that gives the whole a reddish colour characteristic of continental sedimentites. Carbonates, calcarenites and limestones contain up to 90% carbonate material and generally have a lighter shade in response to less susceptibility to oxide impregnation, their coloration depending on the percentage of siliceous clasts they contain. However, the rocks of the group always present a clear appearance of sandstone.

In the regional stratigraphy it is not possible to make important differentiations since the whole group practically belongs to the same lithostratigraphic unit or formation; however, it is feasible to recognize a localized differentiation criterion that establishes Rimoldi and Turazzini (1984):

c) Upper member (upper sandstones) located above level 345 on the left bank and above level 370 on the right bank.
d) Intermediate member (El Chocón sandstone) below the previous one and up to an approximate level of 300.
e) Lower member (lower sandstones) below elevation 300 and containing layers of claystone and siltstone, characterized by its banding by stratification.

The remarkable tectonic stability of sandstone depositional environment is demonstrated by the sub-horizontal position of the strata and the absence of fault structures. The small compressive stresses that could have occurred in this eastern portion of the Neuquén geological basin, as consequence of the Andean Orogeny process during the Tertiary period, only translated into a slight vaulting of the sequence and the generation of a defined fracture design of the massif with subvertical joints grouped into two main systems.

There is another group of discontinuities that are the decompression fractures that affect the abutments and walls of the central valley, originating from the horizontal efforts of decompression towards the centre of the valley as fluvial erosion took care of eliminating an important rock cover. Thus, the formation of discontinuities in coincidence with lithological contacts was favoured.

They are of very small magnitude that are evidenced by the circumstantial presence of second-generation salts precipitated on the surface. Both groups of discontinuities, the joints in the entire area of the rock mass and the second only near the edges and bottom of the valley, constitute the runoff routes of the meteoric water and the river's filtration. The sealing of the same constituted the objective of the injection treatments carried out during the commissioning of the work.

Figure 3. View of the outcrop of the Neuquén Formation showing banding and undulations

The drill holes performed in the sector show very high core recoveries (close to 100%) and very low levels of water absorption for pressures of up to 18 kg/cm2, which would be indicating the absence of significant discontinuities and that the flow is not transmitted preferentially but through the pores of the rock.

3. Background

3.1. Electrical resistivity and water content

The influence of different parameters on electrical conductivity or its inverse (electrical resistivity) for a certain type of material has been discussed in abundant literature. (McCarter 1984; Abu-Hassanein 1996; Rinaldi and Cuestas 2001). Among the most relevant parameters are mentioned: measuring frequency (*f*), type of electrolyte and concentration (*c*), dry unit weight (γ_d), degree of saturation (*S*) and temperature (*T*). At a given temperature and constant measuring frequency, the authors showed that the influence of the different variables on the electrical conductivity of the soil can be taken into consideration by using a well-known expression, which for saturated conditions can be expressed as (Archie, 1942):

$$F = a\, n^{-m} \tag{1}$$

Where *F* is the formation factor defined as:

$$F = \frac{\rho_s}{\rho_e} \tag{2}$$

Parameters ρ_e y ρ_s are the electrical resistivity of the fluid in the pores and of the saturated soil, respectively, *n* is porosity, *a* tortuosity factor and *m* cementation factor. Values *a*, m and *p* are determined experimentally. The 1/F ratio is known as the resistivity index.

Eq. (1) for Formations in unsaturated conditions can be extended as follows:

$$F_s = a\, n^{-m}\, S^{-p} \tag{3}$$

Eq. (1) and Eq. (3) assume that in porous media particles and air are non-conducting phases and conduction takes place only through the fluid (Glover 2010).

In terms of volumetric water content (θ_v) which is defined as the ratio between the volume of water and the total volume. Thus, Eq. (3) can be rewritten as:

$$F_s = a n^{(p-m)} \theta_v^{-p} \tag{4}$$

Values ρ_e y *a* are difficult to obtain in practice, especially in fine-grained soil. Therefore, for a given Formation for which pore fluid salt concentration is approximately the same throughout the volume, from Eq. (4) it is always possible to describe the correlation between resistivity and volumetric water content as follows:

$$\rho_s = \alpha\ \theta_v^{-\beta} \tag{5}$$

Where α and β are the curve fitting parameters.

Eq. (5) shows that the electrical conductivity for a given formation depends mainly on the porosity, the volumetric water content (θ_v) and the salt concentration of the fluid in the pores (ρ_e).

The relationship between volumetric content (θ_v) and gravimetric content (w) of water can be established as:

$$\theta_v = \frac{\gamma_d}{\gamma_w} w \tag{6}$$

Where (γ_d) is unit of dry weight of the soil, (γ_w) unit weight of water and (w) gravimetric moisture content.

Eq. (5) and Eq. (6) are the basic relationship for determining water content from measured soil resistivity. From these equations, soil conductivity depends on soil density and water content (w).

3.2. Field measurement of electrical resistivity

The simplest method for measuring resistivity by obtaining an electrical profile is the vertical electric survey (VES). In this method, we work with four electrodes, as shown in Fig. 4. In the external electrodes (A y B) an electric current of known amplitude is generated (I) while at the inner electrodes (M y N) potential difference is measured (V). Thus, resistivity becomes:

$$\rho_s = K \frac{V}{I} \tag{7}$$

Where K is the geometric factor and depends on the electrode separation (Milsom J., 2003).

$$\frac{1}{K} = \frac{1}{2\pi}\left(\frac{1}{MA} - \frac{1}{MB} - \frac{1}{NA} + \frac{1}{NB}\right) \tag{8}$$

Depending on the position and separation of the electrodes, different configurations are obtained, the best known being Wenner, Schlumberger, dipole-dipole and pole-dipole. (Milson 2003). Increasing the electrode separation allows the exploration depth to be increased in any of the mentioned devices. The results obtained in field measurements are known as apparent resistivity profiles. By means of iterative programs of automatic adjustments, the thicknesses of the different traversed strata can be obtained with their resistivities on a representative vertical line of the explored site. The major disadvantage of this method is assuming that the stratification is perfectly horizontal and that there are no lateral variations, which is hardly the case.

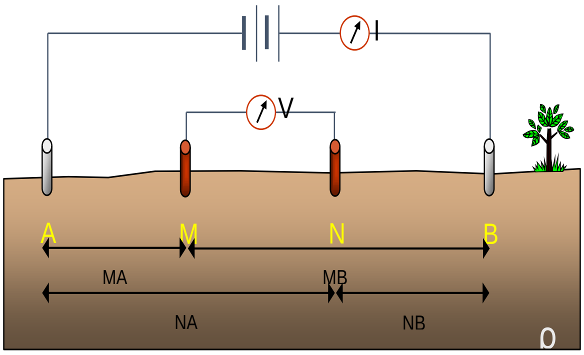

Figure 4. Tetra-electrode device for electrical resistivity measurement in a semi-infinite medium

To overcome the VES limitation, Electrical Tomography is developed where a significant number of electrodes (usually between 24 and 100) are used, and are switched from four electrodes simultaneously, using all possible combinations for a configuration defined, usually Wenner, Schlumberger or Dipole-Dipole (Griffith and Baker 1993).

The mentioned switching can be done manually using a switch box or automatically, through an electronic switching system (switch box). Electrical tomography is a two or three-dimensional image of the distribution of electrical resistivity measured in the subsoil, which is obtained from mathematical models;(inverse problem).

The inverse problem is simply the set of methods (single step algorithms, iterative algorithms based on the least squares criterion, elements of algebra and numerical computation as regularization techniques that include prior information in the algorithms) used to extract useful information of the environment from physical measurements or data.

The useful information will be specified as numerical values of some property of this environment. These properties will also be referred to as model parameters. These specific methods or models will relate the parameters to the data. The inverse problem contrasts with the forward problem, where the data is predicted from the parameters and from a model.

The theory of the inverse problem in its broadest sense has been developed in the field of geophysics. The reason is that this science tries to understand the interior of the earth only from data obtained from the surface. However, the reverse problem appears in many other branches of the physical sciences and engineering, such as medical tomography, image processing or curve fitting (Loke 1996; Santamarina and Fratta 1998).

4. Piezometer Readings

The sector under analysis is monitored with a significant density of Casagrande-type piezometers (some installed when the facilities were commissioned in 1971 and others during the treatment tasks in 1984). Fig. 5 shows the location and density of the monitoring points in the MI sector. Fig. 6 shows the response of some instruments indicated in Fig. 5 where the results obtained from the monitoring of these piezometers for the last 10 years and for the last 2 years have been separated as a function of the reservoir level. Note the increasing response of piezometers C125 and C127 with respect to the rest (C110, C111, C112 and C118).

Fig. 7 shows a rebutted cross-section of the sector involved where the location of the piezometers and phreatic meters with their designation are indicated. The piezometric level readings recorded during the execution of the geophysical studies are indicated with a solid line, while the sectors enclosed in dotted lines indicate the areas of potential wet front.

The sectors in which higher readings are observed in correspondence with potential advances of the wet front are indicated in dotted lines. A first sector, is comprised of piezometer C110, a second by piezometers C112 to C116 and phreatic meter F26, a third by piezometer C124, and a fourth sector by piezometers C26, C126 and phreatic meters F27 and F28, and finally a fifth sector in piezometer C128.

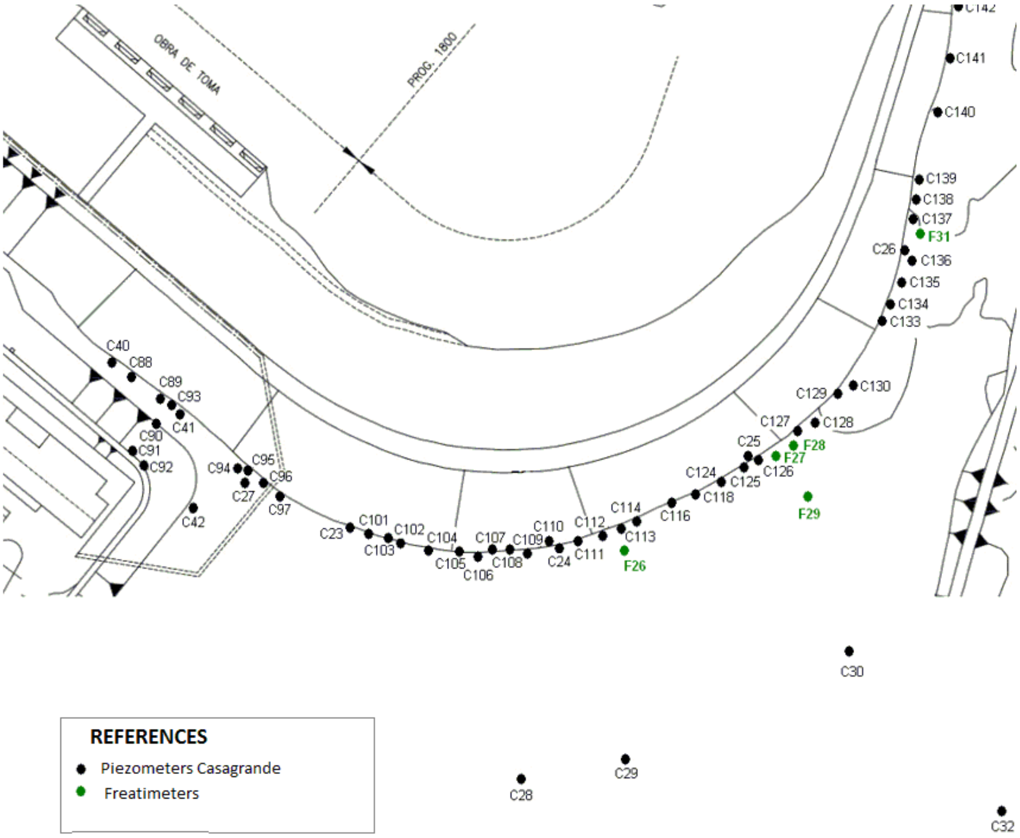

Figure 5. Plant of the sector under analysis, with location and density of instruments for monitoring.

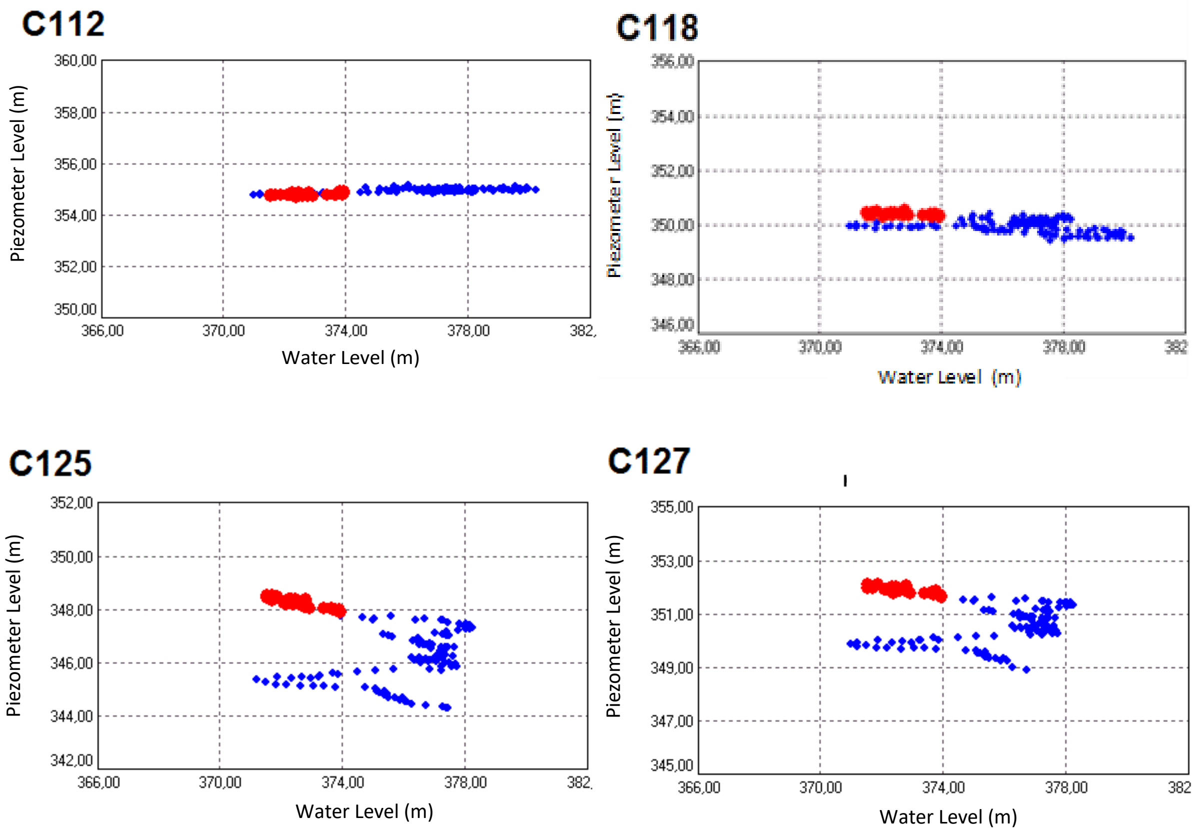

Figure 6. Records in terms of piezometric levels Blue points last 10 years - Red points last two *years*

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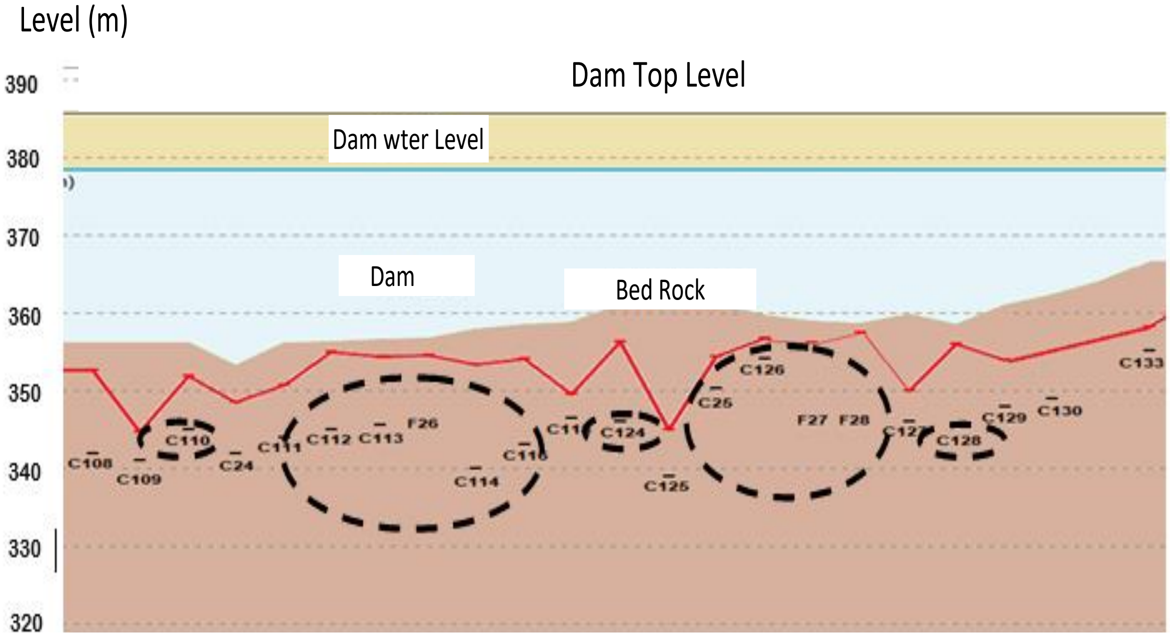

Figure 7. Piezometric line distribution in the foundation of the dam and areas of increased pressure

As shown in Fig. 7, the piezometric values corresponding to the precise location of the phreatic meters (fundamentally between elevations 340 m and elevation 350 m) indicate higher readings than the average. This can only be attributed to the measurement point and does not allow us to assume whether these values are due to a preferential runoff point or to a broader sector in extension.

On the other hand, it can be investigated how other sectors of greater or lesser height not affected by the presence of piezometers are found. These questions motivated the execution of this geophysical study.

5. Field work

The geophysical study was carried out in the MI of the dam along about 320 m at the foot of the dam. The covered study front extends between the location of piezometers C108 and C132 approximately. The prospecting direction was towards the left margin (LM).

To carry out the measurements, an ARES I digital resistivity meter from GF Instruments with a maximum power of 850 W was used (Fig. 8). A total of 32 electrodes separated by 10 m from each other connected to a multifilament cable with intelligent terminals were used. The change between electrodes is done automatically through the previous programming of the resistivimeter. The prospecting method used was the dipole-dipole since it allows a greater number of apparent resistivity values to be measured in each section, generating a better resolution in the tomographic image.
To reduce contact resistance, the electrodes were placed in pre-wells with abundant saline irrigation. The measurement procedure used was the dipole-dipole, reaching an approximate of 96 resistivity readings.
The processing of the images was carried out using the Computer Program Res2inv (Loke, 2002). This software allows graphing both the apparent resistivity profiles and the real resistivity distribution of the subsoil through an inversion algorithm based on the least square's technique. The topography of the site was surveyed using GPS and entered the image processing profile. The depth reached in all cases was approximately 30 m. The order of precision error in the inversion of the measurements to obtain the geoelectric profile was approximately 2.2%, which can be considered satisfactory.


(a)


(b)

Figure 8. a) Electrical tomographic equipment used, b) Measurement electrode in working position.

6. Results and Interpretation

Fig. 9 shows the geoelectric profile surveyed in this work. The profile shows the scale of maximum and minimum resistivity values determined. In general, values between 6 Ohm-m and 22 Ohm-m were obtained. The lowest values are associated with the material of the Chocón Formation in natural humidity conditions and the highest values to the same formation in the saturated condition. For the purposes of a better visual location of the different sectors of the profile, the positions of some of the piezometers used for monitoring were included as a reference. From the profile of Figure 9 in comparison with the interpretation of the readings of the piezometers and phreatic meters of Figure 7, it is observed:

- 4 sectors with resistivities markedly lower than the average (7 Ohm-m) that are attributed to wet fronts with clearly defined extensions were identified. These sectors have been indicated by ellipses in the same figure. The upper part of these sectors is approximately between 7 m and 10 m deep (elevations +340 m to +350 m).
- Between piezometers C110 and C111, a first wet front is located between 10 m and 20 m deep and longitudinal extension approximately 30 m displaced to what was assumed in the interpretation of the piezometric readings.
- A second sector is the most important due to its extension and is located between phreatic meters C112 and C118, which covers an average width of 70 m and goes deeper than the 30 m recorded in the geoelectric profile. This sector is coincident with that interpreted from the piezometric readings, although its extension was unknown.
- A third sector is located between piezometers C118 and C 125. Its center of influence is coincident with piezometer C124, which registered a load jump. Its extension is more significant than expected from the interpretation of the piezometer readings.
- A fourth sector is located between piezometers C125 and C127, coincident with the sector indicated in the interpretation of the piezometric readings and of similar magnitude to that expected.
- No wet front is recorded in the geoelectric image in correspondence with the location of piezometer C128 that would explain the high reading of this piezometer. This case would require a more detailed survey, using smaller electrode spacing.
- In the second sector, the moisture front is not uniformly distributed around a radial focus as might be expected from a preferential infiltration point, but rather appears to come from a massive and homogeneous moisture front with some more superficial ramifications, probably due to the decompression of rock formation planes.
- The wet front in the first, second and third sectors, on the other hand, seem to have a more focused preferential location, which radiates in the vicinity with relative uniformity.

7. Conclusions

With the purpose of evaluating the existence and extension of the humidity fronts that propagate below the dam body of the left margin sector of the El Chocón foundation was presented. The equipment used was adjusted and calibrated considering the characteristics of the rock mass of the foundation, considering the piezometric records. From this work it can be derived the following conclusions:

a) The results obtained allowed validating the geoelectric method used during the investigations, since a good precision detail was achieved in the mapping the humidity fronts that propagate in sectors where the piezometers indicated values of increasing trends.

b) All the identified fronts occur at a height level between +340 m and +350 m approximately, except in sector 2, where it extends deeper. A plausible explanation could be the existence of an unconfined zone, however, for a better definition, a specific investigation with direct intervention through drilling and specific tests would be required in which geophysical tools for well logging could be included, such as resistivity, natural gamma, and images with televiewers.

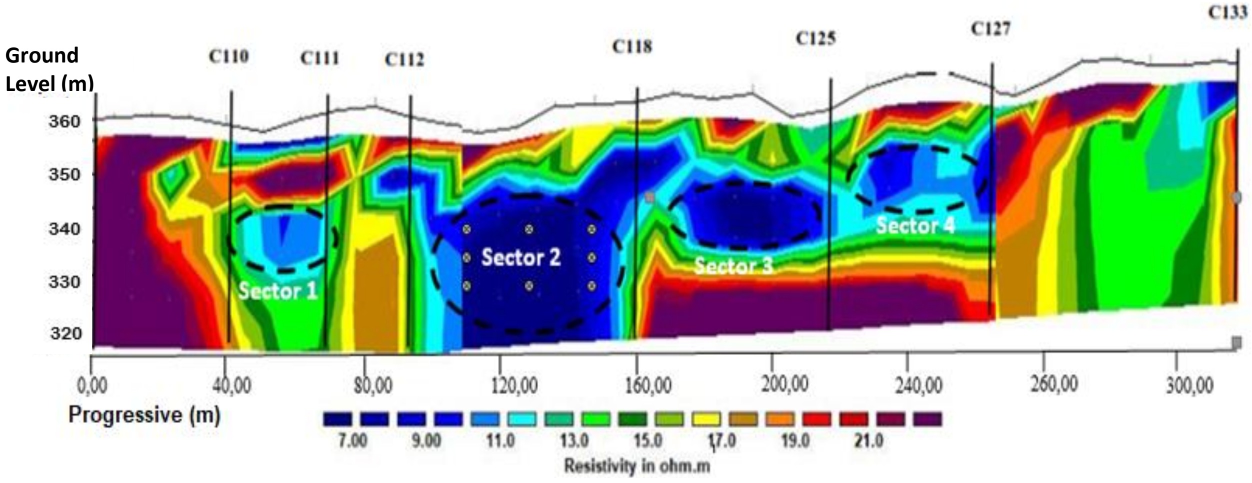

Figure 9. Resistivity profile obtained at the foot of the dam on the LM- El Chocón dam.

c) Working hypotheses regarding the expected correlation between resistivity and volumetric water content for a given formation were very helpful in mapping subsurface moisture distribution.
d) The separation used for the electrodes (10 m) resulted in sufficient precision for the development of the investigations; however, if greater definition is required, it would be convenient to reduce separation, increasing the number of electrodes and maintaining the length of the device in order not to sacrifice prospection depth.
e) The results obtained are consistent with the records monitored from the auscultation and provide a significant added value to the interpretation of the measurements, confirming in principle the fact that the increases and changes recorded in the sector correspond to a very slow saturation process of the rock mass.

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