An Electrical Resistivity Survey on Tunnel Rock Mass. Statistical Validation of Rocks Classification

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Abstract: In the civil construction, the significance of underground information is known for developing a good project. However, the Construction of Small Hydroelectric Power Plants is considered to be different. Studies of construction sites are vital to the development of a good project. In addition, an effective geophysical study can deliver more detailed information about the work site. With the improvement of the basic data quality, it is possible to mitigate investment risks and develop projects that are more detailed. This paper aims to present the validation of a methodology for forecasting the rock mass quality, and the construction of an adduction tunnel of Dores de Guanhaes Small Power Plant is the analysis object with the assistance of geophysics. The result will be a statistical comparison between the percentages of rock mass qualities that were estimated in the basic Project found in field measurement during the tunnel excavation and what was estimated through the interpretation of the results of the geological and geotechnical studies complemented with geophysics investigations.
Keywords: geophysics; investigations, rock mass class; statistic; etc.

1. Introduction

The construction of big engineering works has always demonstrated enormous challenges due to its technical complexity, environmental and social impacts and its implantation costs. For these reasons, in order to avoid majors unforeseen during the construction, it is necessary to make detailed studies on the construction site and its natural characteristics in all engineering knowledge areas for the sake of subsidizing the development of a good engineering project. Furthermore, it is possible to study the economic viability of a venture through this project.

The Construction of Small Hydroelectric Power Plants is no different. Studies on constructions sites are vital to the development of a good project that includes its actual characteristics, and thus provides trustworthy information properly for the development of a feasibility technical-economic study. Although it has been verified that entrepreneurs have invested less and less in local characterization studies during the last few years. This has generated little reliability in the projects developed, and consequently reduced the certainties in economic studies, thus increasing the costs envisaged for the implementation of the work.

In the civil construction, information about underground conditions is important to a project development, planning and constructive methodologies determination. Sites investigations are a process in which geological, geotechnical and other relevant data that may affect the construction are acquired. From a geotechnical point of view, an enormous amount of information obtained through various methods of exploratory boreholes and field investigations is necessary to make it possible to elaborate projects, previsions that approach to the field reality, and enable the development of more accurate budgets for improving these ventures economic-financial viability.

However, works of Small Hydroelectric Power Plants generally do not have detailed geological investigations before the commencement of their construction. A geologic field mapping and a few exploratory boreholes are usually conducted, and that is not sufficient in the development of a reliable geological and geotechnical model. For that reason, the uncertainties are big anda there is a massive range of possible variations of subsurface features that can be predicted through the data obtained. Therefore, the best projects normally are not developed and their costs may be extrapolated. Thus, the uncertainties during the elaboration of geological models and projects that will base on work budgets are shrunken and associates risks of the venture and consequently the contingencies costs are increased. To avoid such problems, it is necessary to make more detailed studies in the interest areas (including geophysics surveys).

One of the biggest challenges observed during preliminary projects elaboration is how to define mass rocks classes, because once they come from natural sources, their properties are irregular and difficult to be identified in many cases. This factor may imply in technical, economic and environmental consequences. Based on this information, the significance of geological, geochemical and geotechnical studies are emphasized. For this reason, methods to mitigate investments risks and develop more detailed projects that based on more robust data are studied. Besides, the assistance of geophysics investigation is evaluated, coupled with investigations usually performed in this type of venture, which can deliver more detailed information about the work site. A responsible professional who is in charge of the project clarifies relevant matters and provides solutions to geological and geotechnical problems that are raised following these studies.

Results of such investigations, as well as obtained characteristics and geotechnical data seeking to characterize rock mass properties, must be subjected to a rigorous analysis. All that with the final goal to define if the quantities of witch rock mass class from the geotechnical characterization are suitable for the predicted geological conditions. With the aim to reduce uncertainties, a detailed analysis of all geological information generated through preliminary studies should be made searching all the data obtained from the various investigations (exploratory boreholes and geophysics), so a conceptual model that represents the morphology and rock mass classification can be made. In that way, to Small Hydroelectric Power Plants, with interpreted results and geological models generated through data analysis from investigations, it is possible for a Power Plant work to estimate more precisely the quality and position of the rock in several structures of this type of venture contains.

These are important information in the elaboration of predictions to treatments of several embankments, foundations and tunnels. These studies would improve the quality of the projects for this kind of works, once they would be grounded in data that are more reliable. In that way, risks and implantations costs could be reduced. To tunnel works, it is also extremely important to estimate the rock mass quality that could be found over the tunnel excavation, and treatment quantities that include the preliminary budget of a work are predicted through the information. Thus, the more accurate the forecast of rock mass quantities of the tunnel is, the more accurate the prediction of treatments to be applied will be, and consequently the budget will be more precise.

2. Study objectives

The study aims to validate a methodology for forecasting the rock mass quality, and the construction of an adduction tunnel of Dores de Guanhaes Small Power Plant is the analysis object with the help of geophysics. The result will be a comparison between the percentages of rock mass qualities that were estimated in the basic Project, the one collected through field measurement during the tunnel excavation and what was estimated through the interpretation of the results of the geological and geotechnical studies complemented with geophysics investigations. The geophysical investigation applied on the tunnel axis has an electric resistivity section of the shaft of this tunnel as final result. Allying to exploratory boreholes and field mapping information, with this section it is possible for to elaborate previsions of general rock mass conditions of the tunnel following Barton`s classification.

3. Methodology

The research was carried out according to the following descriptions:

Firstly, the data obtained through the electrical resistivity survey was analyzed and interpreted. The information from previous investigations that are carried out during the Basic Project development is employed to do this. These are the geological and geotechnical information from exploratory boreholes and a field mapping held in the previous stage. According to the simple fact that a mesh covers the studied area allowing an analysis of the whole and resulting in a better area coverage, the method of this investigation makes it possible to obtain more information about the studied site than the regular method that only counts on small number of boreholes and a simple field mapping. Interpretation of the results will be used as a base to predict the rock mass quality along the studied tunnel according to Barton's parameters.

Percentage predictions of each rock mass class originated from a compilation of data from the Basic Project, according to Barton's parameters, expected to be found during the tunnel excavation were predicted, at the second stage. At the third stage, the field mapping information that were collected during the tunnel execution when the rock masses were ranked as the excavation advanced was organized. These data were recorded in a spreadsheet and later the Executive Project is integrated as Built.

All these data complied will enable the elaboration of a table with the estimated values from the geophysical study, the Basic Project and the field measures during the tunnel excavation. On the basis of this definition, a statistical study with the goal to check possible gains brought by the use of this proposed methodology was done at the last stage of this paper. The statistical analyses were elaborated through the chi-squared ($\chi2$) test. For such a study, it was conducted two distinct calculations. In the first calculation, the Basic Project estimates were compared with the field measures. In the second one, estimates obtained from the geophysics interpretation were compared with the field measures as well.

Finally, with the completion of this analysis, it was possible to evaluate the gains from more detailed investigations at the implantation site.

4. Geophysics Studies

In order to conduct an effective geophysical study, it is important to determine which data is expected to be obtained and what local conditions of the site must be investigated. Then it is possible to choose which geophysics methodology is more appropriate to be used in a specific situation.

In this studied case, it was concluded that the electrical resistivity method is more appropriate in getting the desired data along the tunnel axis. This type of investigation once was very common in civil engineering ventures, because it is very useful in complementing the geological information obtained through methods that are more conventional. The information obtained helps to predict the characteristics of the rock mass and generate the data of the optimum quality.

Another determinant factor in choosing the electrical resistivity method was the fact that it is possible to discriminate eventual geological fractures that conducts water, once this specific method generates good image of fractured system. And, if water conducts occur, it is also possible to map these anomalies.

After the campaign, it generates a subtract profile with the results of the electrical resistivity investigation. The analysis of this profile, allied to other information obtained through other studies performed in the area, allows a good interpretation of the geophysics data. The following image which presents a result of the investigation along the tunnel axis.

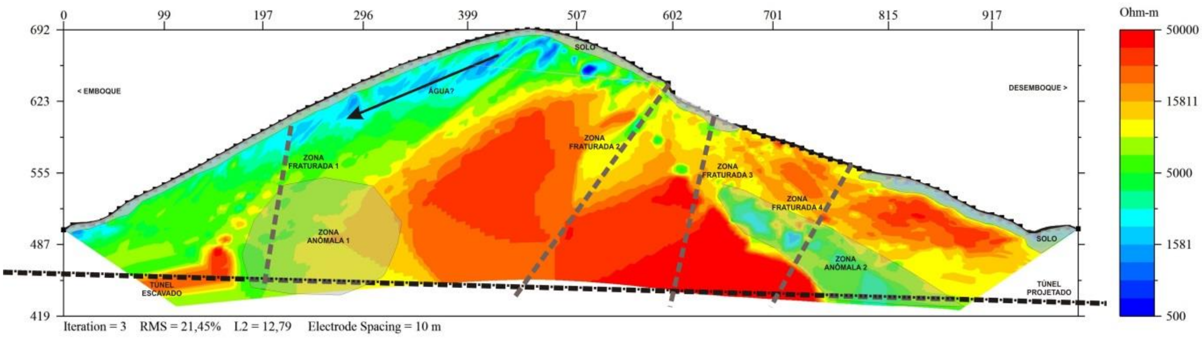

Figure 1. Result of the Geophysics performed and tunnel axis (dashed line)

As it can be observed, there is a great range of variation in resistivity values. It is known that in general, the soil and regolith part present resistivity lower than 5,000 ohms/m. Above the values rock is found, that can get to resistivity values over 50,000 ohms/m. In the shallow section (initial 10m), it is possible to visualize some sections with more humidity through the color scale varying from 500 to 1,500 ohms/m. Even though, this resistivity values are very high, and show little presence of water.

On the basis of this conclusion and the resistivity profile, it was possible to identify some important characteristics of the investigated underground such as the rock type and humidity according to resistivity values found in a field and bibliography. The fractures observed in the rock, mapped in the field and lately located in the profile also present high resistivity. It indicates that this section probably had dried or almost dried fractures during the electrical resistivity study. The next image presents the profile with the fractures indicated on it.

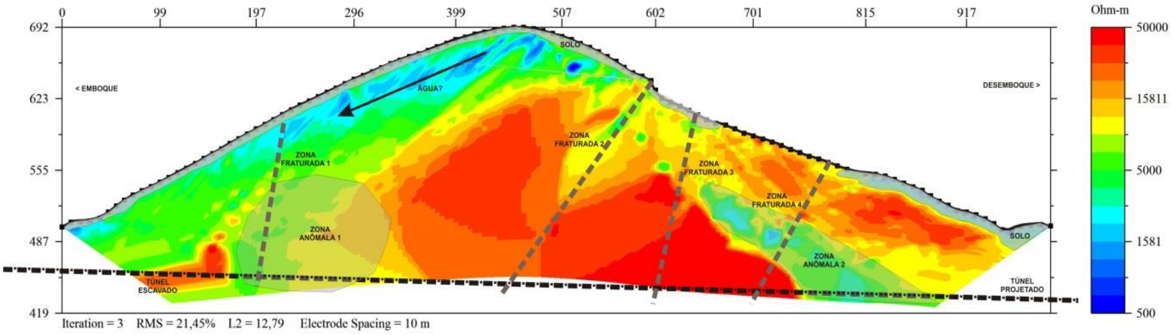

Figure 2. Interpreted Geophysics

It can be observed in the tunnel profile that in the initial section of it (left hillside on the image) the electrical investigation made it clear that lower resistivity and humidity occurred in the initial 10 meters of soil / regolith (figure 3). In addition, in the opposite hillside it illustrated that various rock outcrops occurred in a section with a high resistivity.

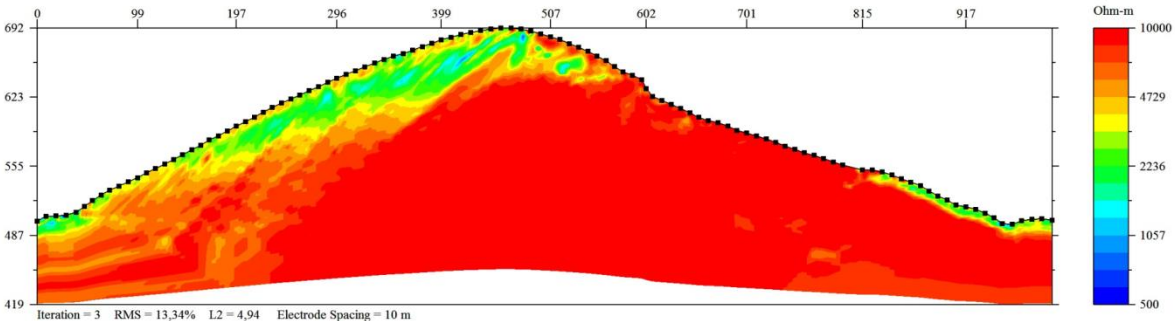

Figure 3. Color scale highlighting discontinuity in the initial hillside

From the space distribution analyses, it is possible to visualize an interaction between rock dips mapped in the field with the electrical resistivity survey (figure 4).

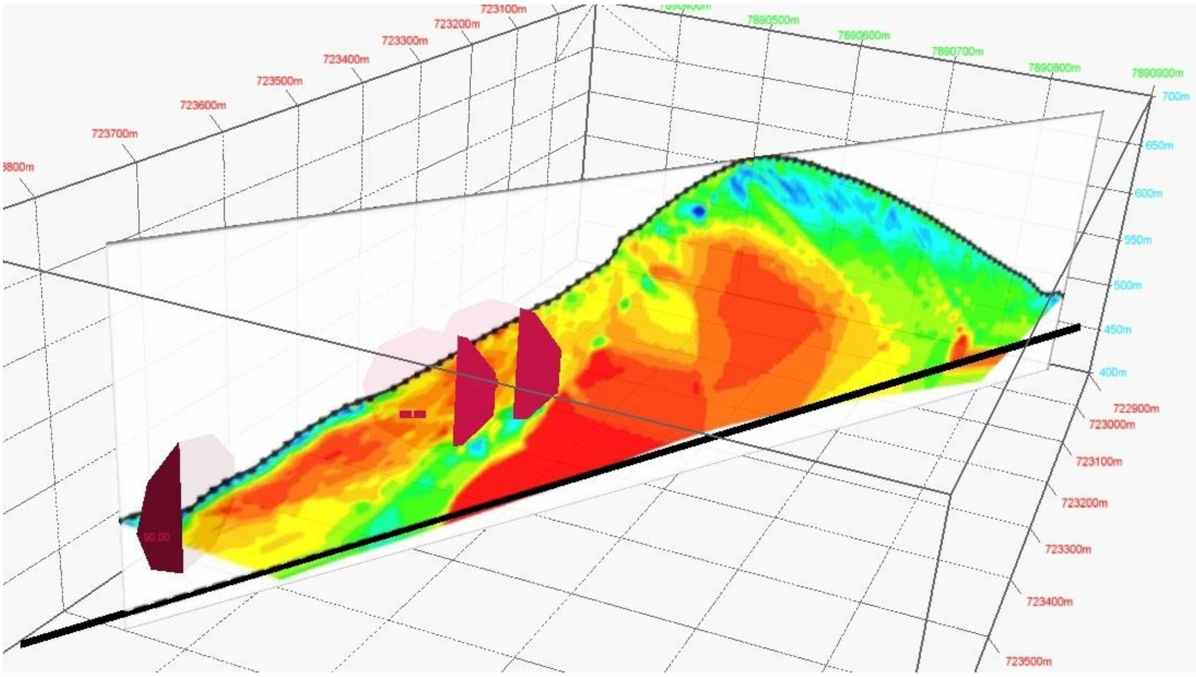

Figure 4. Dips direction mapped in field located in electrical resistivity profile

It can be observed that the erosion faces at the end of the tunnel present good correlation with the tow resistivity breaks. In addition, there is a possibility that these fractures are guided to superficial water to penetrate the rock mass enabling it to get to the tunnel. This fact may be relevant to geotechnical questions. In the interior tunnel, parallel layers were identified rich in biotitic. It is possible that more water is conducted when these features are intersecting the pegmatite rocks, and then weathering is pronounced more frequently.

The main results of this survey are:

1) An electrical resistivity profile along the tunnel axis.

2) The profile indicated few water conductive fractures.

3) In the initial section of the tunnel a discontinuity probably related to the biotitic dam occurs.

4) In the final section of the tunnel a water inflow beneath the rocks maybe related to a geological contact or a water conductive fracture.

5) In the final section a discontinuity nest to a culminating point occurs. This discontinuity presents a projection to the middle of the tunnel. However, high values of resistivity indicate that if there are fractures they will be dry or with little water.

6) The floor thicknesses are generally shallow with higher values on the initial face of the tunnel

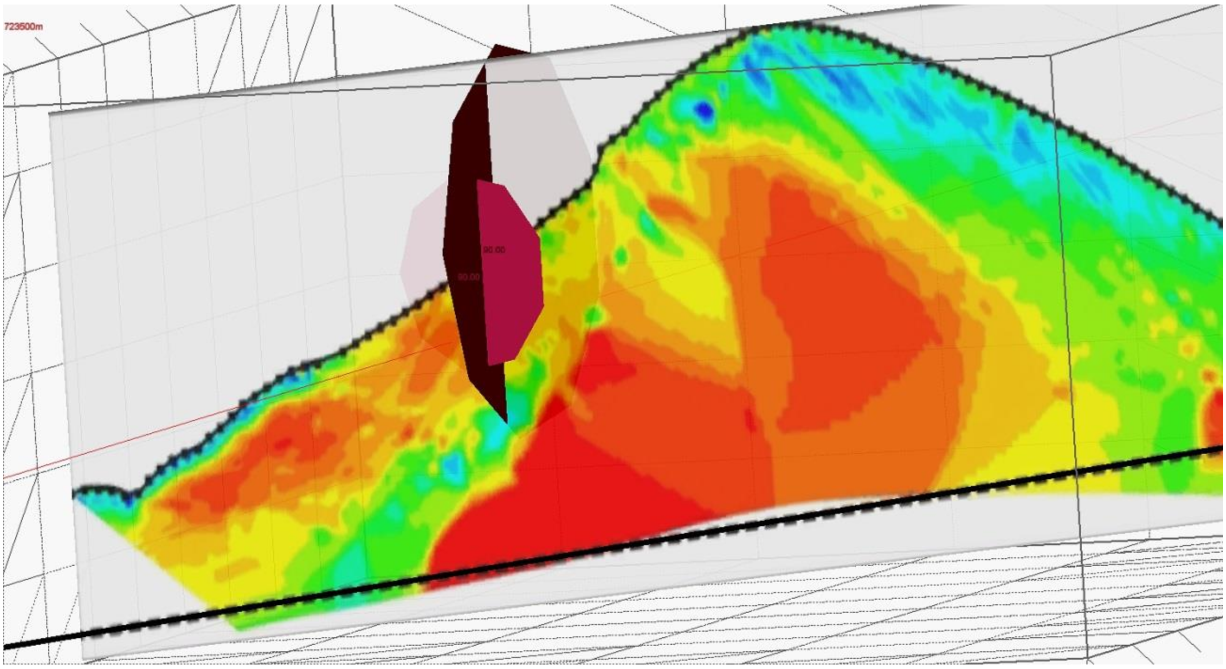

Figure 5. In brown the disposal of foliation with the erosive feature in rose

5. Rock Mass Classification

5.1 Geophysics

With information obtained through field studies including the geophysics survey of the tunnel axis, it was estimated that the rock mass quality of the tunnel could generate an estimate of quantities of each rock class that can be found during its excavation.

During the development of the Basic Project, every study composed a range of data to the analyses of the rock mass of the tunnel that helped posterior classification.

When the geophysics survey was conducted, parts of the tunnel had already been excavated, which compromised the results obtained by the electrical resistivity campaign. The figure below presents the demarcation of the regions mentioned.

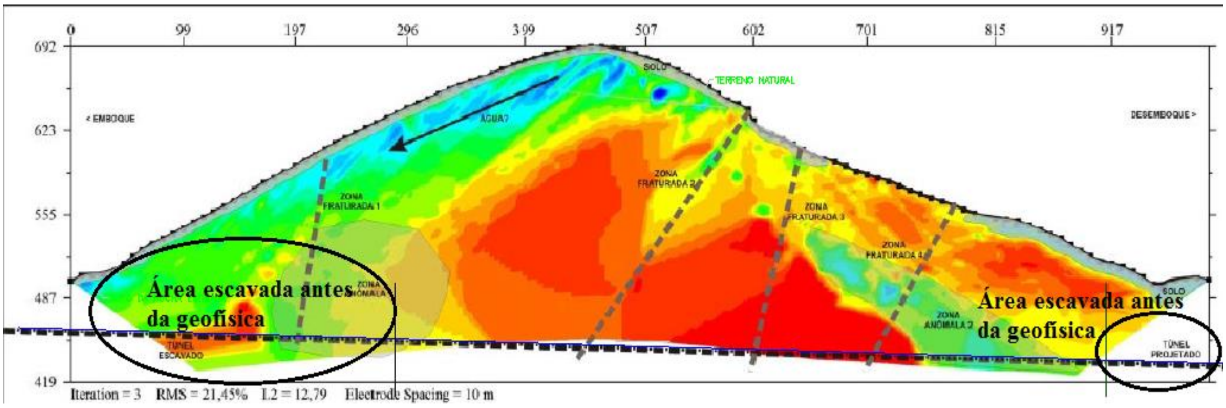

Figure 6. The demarcated areas indicate the extent of the tunnel that had already been excavated when the electric resistivity campaign was carried out

This evaluation generated a table with the summary of results and the percentages that each of them represents in total.

To execute this evaluation, the tunnel was divided in different sections. The following figure demonstrates how this division was.

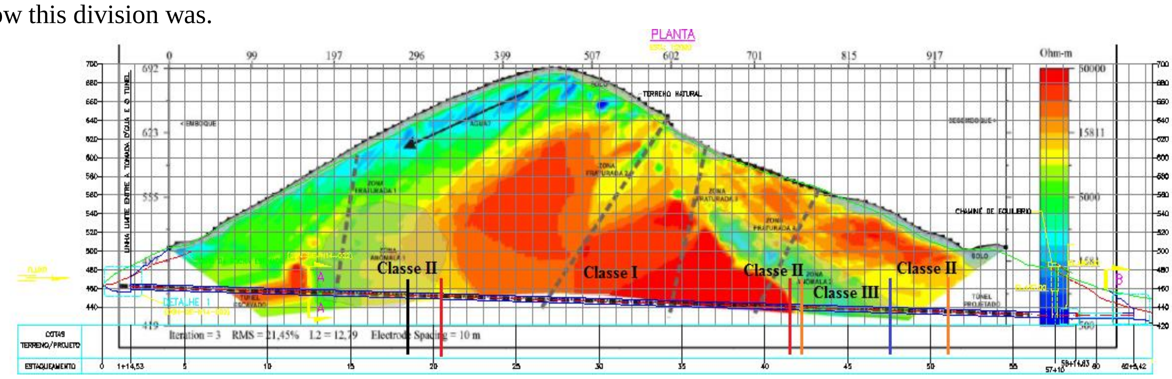

Figure 7. Tunnel sections division

After the conclusion of this analysis, a table was elaborated with the results, and then this analysis could be posteriorly compared with the field mapping and the Basic Project estimative in this way.

Table 1. Rock mass class estimative (Geophysics)

Rock Mass Class		Q (Barton)	Extension	
			(m)	(%)
I / IA	VERY GOOD	> 10	420,00	64,02
II	GOOD	4 a 10	136,00	20,73
III	FAIR ROCK	1 a 4	100,00	15,24
IV	POOR ROCK	0,1 a 1	0,00	0,00
V	VERY POOR	< 0, 1	0,00	0,00
Total			656,00	100,00

5.2 Basic Project

The tunnel rock mass class estimative based on the Basic Project data, is presented according to the table below (Table 2).

Table 2. Rock mass class estimative (Basic Project)

Rock Mass Class	Q (Barton)	Extension

			(m)	(%)
I / IA	**VERY GOOD**	> 10	726,60	60,00
II	**GOOD**	4 a 10	302,75	25,00
III	**FAIR ROCK**	1 a 4	145,32	12,00
IV	**POOR ROCK**	0,1 a 1	24,22	2,00
V	**VERY POOR**	< 0, 1	12,11	1,00
Total			**656,00**	**100,00**

5.3 Field Measurements results

During the tunnel excavation, the walls were systematically mapped and evaluated in a field by a trained geologist. In addition, the collected data were registered in order to compose the tunnel as built project. In order to compare the initial estimative with what was found after the excavation, the information collected in the field were organized in a way that was possible to compose a table similar to the one proposed by the Basic Project.

Table 3. Rock mass class estimative (Field Mapping)

Rock Mass Class		Q (Barton)	Extension	
			(m)	(%)
I / IA	**VERY GOOD**	> 10	750,37	62,02
II	**GOOD**	4 a 10	215,00	17,77
III	**FAIR ROCK**	1 a 4	244,43	20,20
IV	**POOR ROCK**	0,1 a 1	0,00	0,00
V	**VERY POOR**	< 0, 1	0,00	0,00
Total			1.209,80	100,00

6. Statistical Analysis

After these three estimates were made, a statistical study is carried out by comparing these results to evaluate if there was any benefit from the additional data obtained through the geophysical survey. The chi-square test was executed twice. The first test was done to compare Basic Project estimative with field measurements results. The second one was an analysis between the estimative based on geophysical, borehole exploration and preliminary field mapping data and field measurements results.

6.1 Chi-square test – Basic Project x Field Measurements results

Based on the chi-square methodology, the data obtained through studies that are elaborated during the Basic Project development were compared with the data obtained through field measurements as the tunnel was excavated. The following table demonstrates the considered data in this test.

Table 4. Basic Project x Field Measurements

Rock Mass Class	Observed (Field Measurements)		Expected (Basic Project)	
	Extension (m)	%	Extension (m)	%
I	750.37	62.02%	726.6	60.00%
II	215.00	17.77%	302.75	25.00%
III	244.43	20.20%	145.32	12.00%
IV	0.00	0.00%	24.22	2.00%
V	0.00	0.00%	12.11	1.00%
TOTAL	**1,209.80**	**100%**	**1,211.00**	**100%**

Following the chi-square steps, the test will be executed with the relevant data. The table below presents the frequency obtained through the Basic Project prediction.

Table 5. Expected frequency for each rock mass class (Basic Project)

Rock Mass Class	I	II	III	IV	V
F Expected	60.00	25.00	12.00	2.00	1.00

Step 1

The following two hypotheses will be tested.

Null Hypothesis - H_0: $F_{BP} = F_{FM}$

For this hypothesis, the occurrence frequency verified for each of the rock class is equal to the field measurement.

Alternative hypothesis - H_1: $F_{BP} \neq F_{FM}$

For this hypothesis, it is stated that a frequency is inequality.

Step 2

The degree of freedom (ϕ) is equal to – $\phi = K - 1$

Where K is the number of events

The number of possible events is equal to five in this case, because there are five different rock classes (I, II, III, IV and V). In that way:

$\phi = K - 1 = 5 - 1 = 4$

Step 3

For this analysis, the significance level is 0.05.

According to the standard $\chi 2$ value table, the value of $\chi c2$ is 9.49 as it can be seen in the following table.

Table 6. Standard Chi-Square data. Degree of Freedom 4 and significance level of 10%

Alfa / Fi	0.05
4	9.49

$\chi_c^2 = 9.49$

Step 4

Table 7. Expected and observed frequencies

Rock Mass Class	I	II	III	IV	V
F observed	62.02	17.77	20.02	0.00	0.00
F expected	60.00	25.00	12.00	2.00	1.00

The statistical calculus of the χ_t^2 was executed through an application of the following equation:

$$\chi_t^2 = \sum_{i=1}^{k} \frac{(F_{oi} - F_{ei})}{F_{ei}} =$$

$$\frac{(62.02 - 60)^2}{60} + \frac{(20.02 - 25)^2}{25} + \frac{(20.02 - 12)^2}{12} + \frac{(0 - 2)^2}{2} + \frac{(0 - 1)^2}{1} =$$

$$\chi_t^2 = 10.762$$

Step 5

Comparing the calculated values of $\chi_t^2 = 10.762$ with $\chi_c^2 = 9.49$, it is possible to conclude that χ_t^2 calculated > χ_c^2 tabulated. Therefore, the null hypothesis, H_0, is rejected. That fact leads to the conclusion that frequencies observed and expected are discrepant. In this case, the hypothesis not adjusting is accepted.

6.2 Chi-square test – Complete data x Field Measurements results

In this item, a test will also be done with the chi-square methodology. Although at this stage the comparison will be performed among the results obtained through the analysis of the Basic Projects and geophysics investigation data done along the tunnel axis and what was measured in a field while the tunnel was excavated.

Table 8. Geophysics study data x Field Measurements

Rock Mass Class	Observed (Field Measurements)		Expected (Basic Project)	
	Extension (m)	%	Extension (m)	%
I	445	67.84	420	64.02
II	135	20.58	136	20.73
III	76	11.59	100	15.24
TOTAL	656	100	656	100

Following the chi-square steps, the test will be executed with the relevant data. The table below shows the frequency obtained through the Basic Project and geophysics data.

Table 9. Expected frequency for each rock mass class (Geophysics data)

Rock Mass Class	I	II	III
F Expected	64,02	20,73	15,24

Step 1

The following two hypotheses will be tested.

Null Hypothesis - H_0: $F_{BP} = F_{FM}$

For this hypothesis, the occurrence frequency verified for each of the rock class is equal to the field measurement.

Alternative hypothesis - H_1: $F_{BP} \neq F_{FM}$

For this hypothesis, it is stated that there is a frequency which is unequal.

Step 2

The degree of freedom (ϕ) is equal to – $\phi = K - 1$

Where K is the number of events

The number of possible events is equal to three in this case, because through the analysis of the collected data, it was considered that only three different classes for the rock mass analyzed, the Class I, II and III would possibly occurred. Therefore:

$\phi = K - 1 = 3 - 1 = 2$

Step 3

For this analysis, the significance level is 0.05.

According to the standard $\chi 2$ value table, the value of χ_c^2 is 5.99 and it can be seen in the following table.

Table 10. Standard Chi-Square data. Degree of Freedom 4 and significance level of 10%

Fi \ Alfa	0.05
2	5.99

$\chi_c^2 = 5.99$

Step 4

Table 11. Expected and observed frequencies

Rock Mass Class	I	II	III
F observed	67.84	20.58	11.59
F expected	64.02	20.73	15.24

The statistical calculus of the χ_t^2 was executed through an application of the following equation:

$$\chi_t^2 = \sum_{i=1}^{k} \frac{(F_{oi} - F_{ei})}{F_{ei}} =$$

$$\frac{(67.84 - 64.02)^2}{64.02} + \frac{(20.58 - 22.10)^2}{22.10} + \frac{(11.59 - 13.87)^2}{13.87} =$$

$$\chi_t^2 = 1.103$$

Step 5

After the calculus were completed, it is concluded that $\chi_t^2 = 1.103$ é $\leq \chi_c^2 = 5.99$ according to the comparison between the values of χ_t^2 and χ_c^2. It is possible to suppose that the null hypothesis, H_0, is valid. In other words, the frequencies observed and expected were not discrepant. In this case, the adjustment adequacy of this hypothesis is accepted.

6.3 Results analysis

With the accomplishment of the appropriate statistical analyzes for each proposed situation, it is possible to compare them qualitatively in order to evaluate the main differences among them. The same statistical test was applied for the two proposed cases and the values considered for the "F observed", both are originated from the same field measurements, it is reasonable to conclude that the differences in results are due to the differences in the considered values of expected frequency ("F expected"). Thus, the statistical tests were able to clearly illustrate that if there was real gain with the advent of geophysics to the preliminary studies that are carried out during the study phase for developing a Basic Project.

The non-parametric chi-square test was carried out with the Basic Project estimates and with the values defined by the field measurement, it was possible to verify that there was a large discrepancy in the expected frequencies (estimated in the Basic Project) and observed (field measurements). Therefore, the hypothesis proposed, $H_{0,}$ in which it would not be verified a large discrepancy between the frequencies observed and expected, was not confirmed by the calculations performed in this test.

On the other hand, the same test carried out with the estimates calculated with the aid of the information provided by the electrical resistivity campaign, it was verified that the expected frequencies (estimated using all studies, including geophysics) and observed frequencies (Field measurements) did not present considerable discrepancies in this case. Once the proposed hypothesis, H_0, in which a large discrepancy between observed and expected frequencies would not be verified, was confirmed by the calculations performed in this test.

The following table summarizes the statistical tests performed with two different parameters.

Table 12. Chi-Square Test Summary

Chi-Square Test						
	Hypotheses			χ_c^2	χ_t^2	**Result**
Basic Project x Field Measurements	Null – H_0	Observed frequencies (F_{FM}) are not different from expected frequencies (F_{BP})	$F_{BP} = F_{FM}$	7.779	10.762	$\chi_t^2 > \chi_c^2$ Alternative Hypothesis – H_1 valid
	Alternative – H_1	Observed frequencies (F_{FM}) are different from expected frequencies (F_{BP})	$F_{BP} \neq F_{FM}$			
Complete Data x Field Measurements	Null – H_0	Observed frequencies (F_{FM}) are not different from expected frequencies (F_{CD})	$F_{CD} = F_{FM}$	4.605	1.103	$\chi_t^2 \leq \chi_c^2$ Null Hypothesis – H_0 valid
	Alternative – H_1	Observed frequencies (F_{FM}) are different from expected frequencies (F_{FM})	$F_{CD} \neq F_{FM}$			

On the basis of these analyses, it is concluded that the additional information from the geophysical studies, in this case represented by the electrical resistivity survey executed along the tunnel axis, , displayed a significant gain in the reliability for the estimation of quantitative rock mass.

7. Conclusions

The lack of preliminary studies on the site of implantation has generated little reliability in the developed projects, and consequently reduced the certainties in economic studies, thus increasing the predicted costs for this kind of venture. Therefore, the certainties at the time of elaborating geological models of the studied area and projects that will be the basis for budgets of the work are diminished. Moreover, risks associated with the venture increase and consequently so do the cost contingencies as well. To avoid this problem, more detailed studies of the area of interest (including geophysics) are required.

The geophysics usage as another investigation tool, together with other investigations that are traditionally carried out, can be an effective way improving the quality of the data obtained in this phase without an excessive cost increase of geological investigation.

Using the appropriate method for geological investigations, geophysics is capable of delivering useful results for projects and implementation of works. That is why it is extremely important that the data which is expected to be obtained is known before the beginning of the geophysical campaigns, what can be facilitated with the aid of a subject specialist. Therefore, it is necessary to determine in advance which subsoil physical parameters are desired to be obtained through geophysical campaigns so that the correct investigation method enabling the achievement of parameters meet the needs of the enterprise is selected.

The implementation of geophysics in the research of the site of implantation does not represent a great increase at investigation costs, and this methodology is considered to be able to study a large area in a relatively short time. Besides, at the beginning of the site investigation, it is advantageous to carry out the geophysical survey aiming to identify areas that should be investigated by exploratory boreholes, places where anomalous data were obtained. In the case under analyses, it would be advisable to conduct probes in the anomalous areas which are indicated in the figure below.

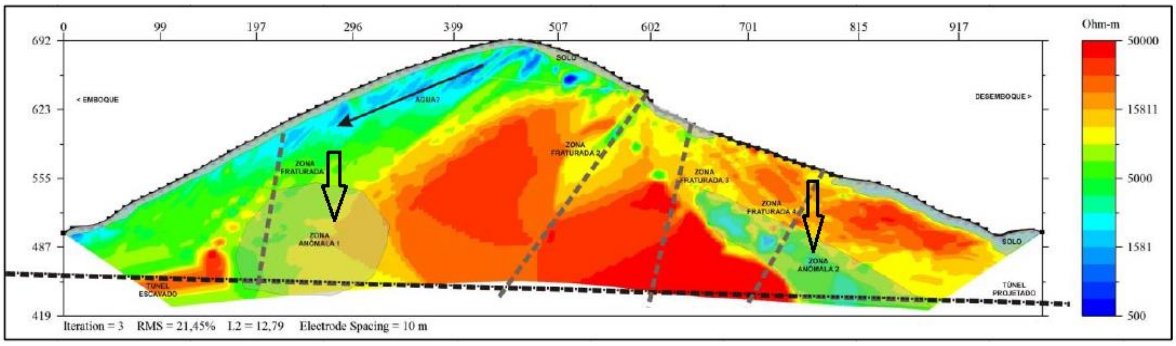

Figure 8. The arrows indicate the anomalous zones where drilling would be indicated

During the survey campaigns, geophysics can be used to check the interpretation of the geological structure between the drill holes. Other geophysical campaigns between drill holes and surface can be used to determine the geological, hydrogeological and geotechnical properties of the geological-geotechnical horizon in which the construction would be carried out. It is also an effective tool for determining the rocky top, mainly in the regions where the different structures of the enterprise will be implanted.

The results obtained in this work demonstrate that the gains which the geophysics representing for geological investigation allow quantitative estimates be more precise than that realized without geophysical data.

All this leads to the conclusion that, in addition to the observed gain for the quantitative estimates of rock along the adduction tunnel, geophysical investigation performed at all points of interest of a site of implantation could bring more gains for the implantation.

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