The importance and influence of the interpretation of geological-geotechnical data on safety of earthen dams

Thalita Andrade[1], *Julliana Fernandes*[2], *Clarissa Honório*[3], *Miguel Neto*[4], *Wellison Fonseca*[5] *and Danilo Eloi*[6]

[1,4, 6]*Vale S.A, Alameda Oscar Niemeyer, 132 - Vale do Sereno, Nova Lima - MG, 34006-049, Brasil*
[2,3,5]*Walm BH Engenharia, Belo Horizonte/MG, Brasil*

ABSTRACT

The geological-geotechnical investigation campaign plays a fundamental role in dam safety by providing essential information for assessing and managing the risks associated with these structures. It also allows potential problems to be identified, such as the presence of geological faults or unstable soils. This information allows preventive actions to be taken to avoid catastrophic collapses, through additional containment measures or the revision of the dam's design.The aim of this article is therefore to present the interpretation of the geological-geotechnical data (geophysical tests, Vane Test, triaxial tests, CPTu and mixed borehole) obtained from a robust campaign to investigate the structure of a sediment containment earth dam, raised downstream, located in the state of Minas Gerais. The use of these results meant that the structure could be evaluated with the real conditions of the terrain in different situations such as seismic or hydrostatic overloads, guaranteeing the stability of the structure. In addition, it was possible to determine the soil's capacity to withstand the loads exerted by the dammed water and identify possible points of fragility.From the results obtained in the analysis and interpretation of the structure's sections, it was possible to measure the influence of the discretization of the earth dam massif through the structure's stability analysis, which also made it possible to make a comparison with the analysis sections before and after the geological-geotechnical campaign. In addition, it was possible to discuss the importance and demonstrate that it is essential to carry out comprehensive and up-to-date geological-geotechnical investigation campaigns to ensure that dams are built and operated safely.

Keywords: dam safety, geological-geotechical investigation, stability of earth dams.

1. Introduction

Dam structures constitute one of the most complex and most important engineering works for the country's economy, considering that they involve activities ranging from supply, flood control, sediment containment and others. And, regarding the issue of safety of these structures, knowledge of the geology in question is of fundamental importance.

Therefore, geological-geotechnical investigation campaigns are essential for any interpretation made by geologist and geotechnical engineers to monitor and prepare a dam project.

Geological investigation has as its main objective the delimitation of geological units and determination of geomechanical characteristics and properties through a set of investigations and targeted methods, Leinz e Amaral (1989, p.97).

Based on the results obtained in the analyzes and interpretations of the structure sections, it is possible to measure the influence of the discretization of the earth dam mass through analysis of the stability of the structures.

This article aims to demonstrate the interpretations of a robust geological-geotechnical investigation campaign of an earthen dam with a foundation in a variable layer of young residual soil on healthy, slightly fractured rock (gneiss), raised downstream (reinforcement), to contain sediments , located in Minas Gerais.

With the interpretation of the data obtained in the campaign and in the stability analyses, it is possible to mark and visualize the impacts that are generated, from the discretization of the mass of a dam, in different situations such as seismic or hydrostatic overloads, guaranteeing the stability of the structure, considering current legislation (Resolução ANM nº95/2022), published on February 7, 2022.

The analyzes and sizing were carried out using data from geotechnical investigations, methods proposed in the technical literature and computer programs Software Slide2, developed by the company Rocscience, considering the rupture criterion of Mohr-Coulomb and stability calculation by limit equilibrium theory using the Spencer Method.

2. Methodology

With the aim of supporting the development of the geological-geotechnical model characterizing the dam massif, as well as defining the spatial distribution and thickness of the residual soil, an investigation campaign was carried out with the execution of twenty-six surveys, nine of which were mixed surveys, in addition to of CPTu tests in order to evaluate the conditions of the materials present in the structure.

According to HACHICH (1996), percussion surveying is a field geotechnical procedure, capable of sampling the soil and, when associated with the dynamic penetration test (SPT), measures the soil resistance along the drilled depth, therefore, when carrying out In this test, the aim is to know: The type of soil crossed, from the removal of a deformed soil sample, for each meter of drilling, the thickness of each layer, the resistance (N) offered by the soil to the standard sampler's insertion at each meter drilled and the position of the water level or levels, when found during drilling.

Consequently, with the information from the surveys carried out on the dam structure, it was possible to interpret the results obtained and determine the thicknesses and distribution of the existing soil layers in the region considering the separation with the Nspt's obtained in the campaign.

The results of the field tests carried out on the dam under study will be presented below.

2.1. Geotechnical Investigations

The Table 1 presents a summary of the results obtained in the SPT tests of all surveys carried out in the dam. For each of the sections tested, the minimum, maximum, average Nspt index, mode and standard deviation were calculated, as well as an indication of the average compactness/consistency for each of the reinforcement fill materials, initial fill, filter, residual soil and saprolite of gneiss.

Table 1. Summary of SPT tests obtained at the dam.

Lithological Unit	Minimum Nspt	Maximum Nspt	Mean Nspt	Consistency/ compactness
Reinforcing Embankment	7	50	17,0	Compact
Initial landfill	0	33	8,7	Moderately Compact
Filter	3	50	25,6	Compact
Residual Soil	1	32	16,8	Moderately Compact
Saprolite	25	50	42,1	Very Compact

The graphic distribution of Nspt values by lithology in relation to the tested depth is presented in Figure 1. Below are general considerations on the analysis of Nspt data for each of the materials and their correlation with the geological-geotechnical sections.

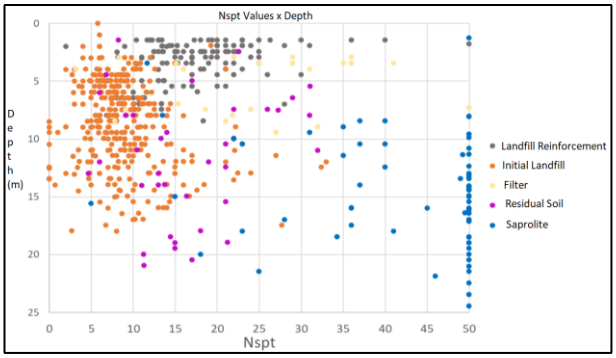

Figure 1. Graphical distribution of Nspt by depth for Dam materials.

The downstream raising (reinforcement) is characterized in surveys as clayey silty material, locally reddish brown silty sand of low plasticity, locally with roots and quartz fragments dispersed in the matrix. During the analysis of drilling cores in the field, the reinforcement fill can be distinguished from the initial fill based on its greater resistance to penetration. In general, the ATR presents Nspt ≥ 12.

The initial landfill (AI) is located underneath the reinforcement landfill (ATR) and is heterogeneous with a sand-clay-silty characteristic defined through complete characterization tests. The initial backfill has a maximum thickness of approx. of 17.0m identified in the central region of the ridge. In the drillings described there is sandy-silty, locally clayey silt, reddish brown with quartz fragments and locally scattered plant remains in the matrix.

In order to better represent the heterogeneity of the initial landfill mass, 3 regions (zones) were individualized according to the observed Nspt variation, following the standard ABNT NBR 6484 - Solo – Sondagem de simples reconhecimento com SPT. The indices were defined according to the designation for sandy soils and sandy silts in low zones, regions of Nspt ≤ 4 (soft compactness), low/intermediate regions in which 5 ≤ Nspt≤ 8 (not very compact) and intermediate/high where Nspt > 8 strokes designating moderately compact to compact regions of compactness. The individualization of Nspt levels is an attempt to correlate regions with similar penetration resistance indices and, conservatively, these regions were extrapolated to adjacent areas where no surveys are available.

The Table 2 The reference is presented for the subdivision of the Nspt value ranges according to the predominance of clayey to clayey silt textures (consistency) and sandy to sandy silt textures (compactness) according to the standard ABNT NBR 6484 (2021- Solo – Sondagem de simples reconhecimento com SPT.

Table 2. Summary of SPT tests obtained at the Dam.

Clay and Clayey Silt		Sand and Sandy Silt	
SPT	**Classification**	**SPT**	**Classification**
≤ 2	Too Soft	**≤ 4**	Soft
3 a 5	Soft	**5 a 8**	Not very Compact
6 a 10	Medium	**9 a 18**	Moderately Compact
11 a 19	Rigid	**19 a 40**	Compact
> 19	Stiff	**> 40**	Very Compact

The dam foundation materials are divided into residual soil and gneiss saprolite. In general, residual soil and saprolite have similar granulometric characteristics, consisting of clayey silty to silty sandy material, dark reddish brown in color with white, beige and yellowish spots. Residual gneiss soils were differentiated from gneiss saprolite through penetration resistance tests (SPT), so that gneiss saprolites are characterized with Nspt equal to or greater than 30 strokes.

The granite-gneiss lithotype is predominantly resistant to very resistant (R4-R5), slightly altered (W1/W2) and slightly fractured with extremely fractured portions (F2/F5). When they are, they exhibit a whitish gray color while it transitions to yellowish tones and when altered, it is made up of quartz, feldspar, biotite and amphibole and exhibits a granolepidoblastic texture, in addition to a millimeter to centimeter gneiss banding. It sometimes presents veins of poorly fractured milky quartz, which can locally be interpreted as granite due to the absence of banding and the presence of mineral flow.

The geological-geotechnical section presents a geotechnical profile made up from top to bottom by downstream elevation (reinforcement embankment), inclined filter, initial embankment, residual soil and gneiss saprolite and healthy granite-gneiss rock. In general, in the upstream region, the dam crest area, the materials exhibit predominantly slightly compact to moderately compact Nspt values (5 ≤ Nspt ≤ 18 blows), interspersed throughout the development of the soundings. In the area of the intermediate berm and the region downstream of the dam, there are more expressive values of stretches of soft consistency (Nsp ≤ 4 strokes), however, there is still a predominance of slightly compact to moderately compact stretches (5 ≤ Nspt ≤ 18 strokes).

2.2. CPTus Results

In order to corroborate the information on the characteristics and behavior of the landfill material that presents low resistance to penetration by the SPT test, CPTus tests were carried out and analyzed on the dam. A presents the geological-geotechnical section A-A' with the projection of the CPTu tests carried out close to the existing drillings.

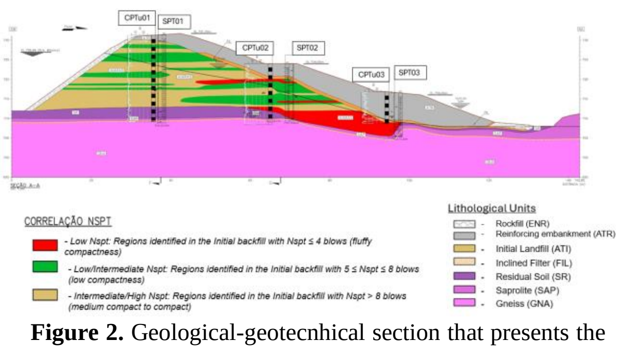

Figure 2. Geological-geotecnhical section that presents the results of the CPTu campaign.

At the crest of the dam, a correlation was made between CPTu-01 and the SPT-01 survey, as can be seen there is a convergence between their results. At the approximately 2.0m depth mark, an anomaly of an increase in the tip resistance value (Qc) is observed in the same region where the highest Nspt values occur in the SPW-2 survey, which reaches 50 blows/30cm, characterizing the embankment of the downstream heightening (reinforcement) compacted. In the remainder of the CPTu-01 hole, a variation in Qc values is observed, which can be related to the variation in consistency throughout the massif, with areas of low Nspt at moderate values, continuing up to the limit with the gneiss saprolite, where the probe reaches the impenetrable and SCPTu trial is stopped.

In the CPTU-02 and CPTU-03 tests, contact between the embankments is also shown, with the reinforcing embankment showing high tip resistance at depths of approx. of 4.0m (CPTU-02) and 7.0m (CPTU-03). It is also possible to recognize the influence of internal drainage devices (inclined filter), the sand filters exhibit a relative increase in Qc values, which contrasts with the low values observed for the initial landfill.

2.3. Definition of Parameters

In the investigation campaign, CIU triaxial tests were carried out taking into account the heterogeneity of the initial landfill. 9 samples were collected and distributed according to the Nspt results obtained in the surveys. Of these, 3 samples were taken in the zone of Nspt ≤ 4, 3 samples in the zone of 5 ≤ Nspt≤ 8 and 3 samples in the region of Nspt > 8 strokes.

In order to determine the resistance parameters, 35 tests were considered in total, representing approximately 33 undrained resistance envelopes. For the analysis of triaxial tests, the following input variables were considered: load/loading, minor tension (σ3), generation of pore pressure throughout the test (U), axial deformation (εa) and volumetric deformation (εv). From them, the deviation stress (q), pore pressure variation throughout the test (ΔU), average effective stress (p'), stiffness (Young's Modulus - E) and undrained shear strength (Su) of the structures were determined. samples.

Therefore, in Figure 3, get that parameters are determined considering the maximum deviation voltage obtained in each test. In no test was a loss of post-peak resistance observed, that is, a reduction in the maximum deviation stress with an increase in deformation in order to determine residual parameters.

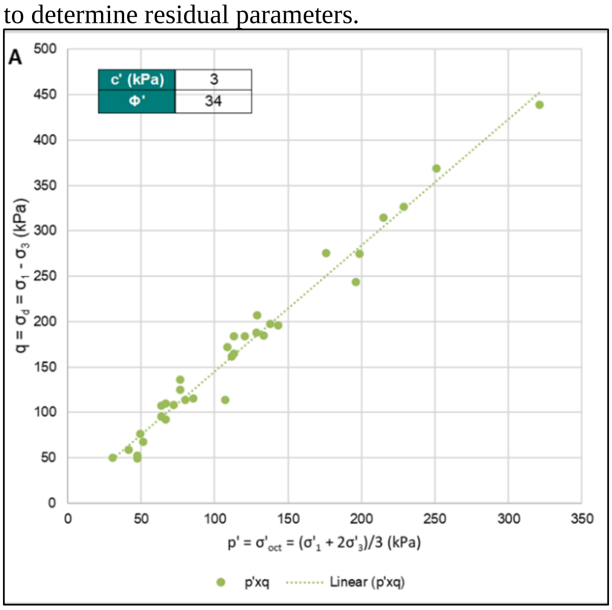

Figure 3. Compilation of effective stress trajectories from CIU tests of the dam's initial embankment.

The parameters established for the Initial Landfill for zones of Nspt > 8 blows were c’ = 3 kPa and ϕ’ = 34°. For the region of Nspt ≤ 4, conservatively, we chose to adopt the lowest values of cohesion and friction angle found in the tests carried out, that is, c’ = 0 kPa and ϕ’ = 30°. For the zone of 5 ≤ Nspt ≤ 8, the average values between those defined were adopted, c’ = 1.5 kPa and ϕ’ = 32°, in Table 3.

Table 3. Summary of resistance values (c‘ e ϕ’) from triaxial tests of the dam‘s initial embankment.

Initial landfill zones	γ (kN/m³)	ϕ’ (°)	C’ (kPa)	Su/σ´v
NSPT≤4	19,3	30	0	0,34
5<NSPT≤8	19,3	32	1,5	0,41
NSPT>8	19,3	34	3	0,48

For the analysis carried out considering the homogeneous bus, the values of average undrained resistance parameters were adopted, with Su/σ´v = 0,41.

2.4. Results

The stability analyzes of the Dam described in this article were carried out using the Software Slide2, developed by the company Rocscience, considering the rupture criterion of Mohr-Coulomb and stability calculation by limit equilibrium theory using the Spencer Method.

The water table adopted was represented for the condition of a heterogeneous dam with little compaction, that is, considering the highest level.

Such as NBR 13.028 (2017) does not establish reference safety factors for undrained requests, the guidelines of the Canadian Dam Association were used as acceptance criteria (for reference only) for the request conditions (CDA, 2013), he Safety Factors FS>1.3 for peak resistance parameters and FS>1.2 for residual resistance parameters were adopted as a reference.

Regarding the value of the Probabilistic Seismic Threat acceleration, the methodology presented in “Critérios de Projeto Civil” of ELETROBRÁS October 2003 version, used for hydroelectric dams and for purposes other than mining, which recommends pseudo-static analysis adopting seismic loads corresponding to accelerations of 0.05g in the horizontal direction and 0.03 in the vertical direction.

Therefore, based on the results obtained through this robust geological-geotechnical investigation campaign, it is possible to compare the Safety Factors obtained in the stability analyzes carried out in the current geological-geotechnical section and the one used prior to conducting the campaign.

The Figure 4 presents the result obtained for the section after an investigation campaign, for the drained pseudo-static condition, with a non-circular rupture surface, in order to represent a more conservative Safety Factor. The Figure 5 presents the result obtained, for the same conditions, for the section analyzed without discretization of the dam massif (homogeneous mass).

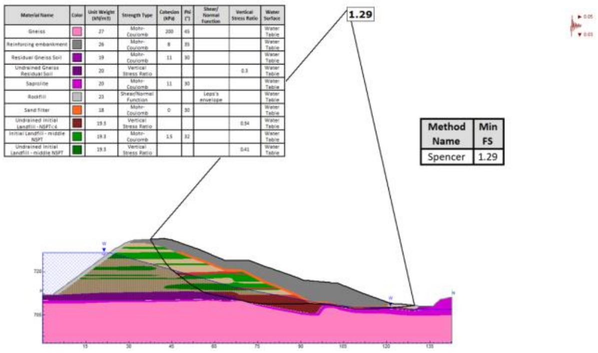

Figure 4. Non-Circular pseudo-static stability analysis performed using the Spencer Method – Heterogeneous Initial Dam.

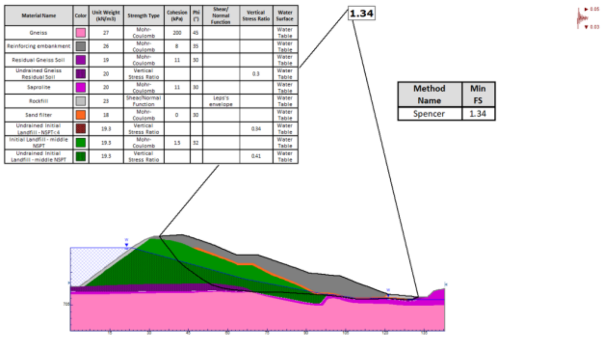

Figure 5. Non-Circular pseudo-static stability analysis performed using the Spencer Method – Homogeneous Initial Dam.

3. Conclusions

A distinction can be observed in the section used prior to the implementation of the proposed research campaign compared to the section adopted after the new definitions. This discrepancy occurred due to the geological investigations carried out, which allowed the identification of the materials and the subsequent adaptation of the section geometry.

In this context, it appears that the Safety Factors achieved for the section after the campaign and for the old section are equivalent to 1.29 and 1.34, respectively. This data highlights the relevance of conducting a comprehensive geological-geotechnical investigation campaign in dams, since the scarcity of information and the inadequate determination of the cross-section of the structure can contribute to the determination of an increased Safety Factor, resulting in an assessment which does not match the reality and safety of the structure.

4. References

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