PANAMGEO CHILE 2024 17th PAN-AMERICAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING | 2nd LATIN-AMERICAN REGIONAL CONFERENCE OF IAEG
LA SERENA • CHILE / NOVEMBER 12 - 16, 2024

Proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE), and 2nd Latin-American Regional Conference of the International Association for Engineering Geology and the Environment (IAEG), La Serena Chile, 2024.

Proposition of a methodology for the design of a dam reinforcement using metal piles drilled by Press In

Proposição de uma metodologia para dimensionamento de um reforço de uma barragem com utilização de estacas metálicas cravadas por Press In

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ABSTRACT: Recent tailings dam accidents in Brazil have led to changes in legislation, making the criteria for tailings dam projects more stringent. This has led developers to update geological-geotechnical information, carrying out new investigations and susceptibility studies, especially considering undrained behavior. Many structures were found to be unstable, requiring reinforcements to meet the new safety standards. The short timescales for carrying out these reinforcements, along with constraints such as lack of space and concerns about possible adverse effects, meant that alternatives had to be sought. The press-in method and the rotation technique (Gyropress) stand out among the pile installation technologies already widely used in other parts of the world. This paper proposes an adaptation of these methods to Brazilian conditions and regulations, following the Japanese methodology presented in the manual "Press-in retaining structures: a handbook" (IPA, 2019), in order to minimize vibrations, noise and space occupation during installation.

KEYWORDS: Press In, Gyropress, Reinforcement, upstream dam, steel piles

1 INTRODUCTION

The recent revision of Brazilian legislation, especially after the disasters involving tailings dams, requires significant technical and regulatory deepening to ensure the safety of existing and future structures. The tragedies highlighted the urgency of reviewing design, inspection and maintenance criteria, resulting in stricter standards for the construction and management of tailings dams.

In the context of adaptations and improvements, the implementation of new techniques to assess and reinforce existing structures becomes essential. Geotechnical investigations must be more detailed, including studies of the susceptibility and behavior of materials, especially in undrained conditions, which are critical for the stability of dams.

The industry's response to these demands includes updating engineering practices and adopting new technologies. Among the techniques for pile driving, Press-in and Gyropress stand out, recognized for their applications in restrictive conditions, such as dense urban areas, and have presented themselves as viable alternatives.These methodologies stand out for their ability to install piles with minimal vibration, noise and use of space, essential characteristics for meeting the environmental and operational restrictions often found in Brazil.

Adapting these methods to Brazilian specificities, following guidelines such as those presented in the Japanese manual "Press-in retaining structures: a handbook" (IPA, 2019), is a promising path. This process involves adjusting the technologies to Brazil's geological, economic and regulatory context, ensuring that they are both efficient and compatible with local safety standards.

This methodology is widely used in the process of building walls to protect against tsunamis and in slope stabilization works in urban areas, mainly in Japan and Europe, according to Dobrisan (2018).

According to Viel (2022), the advantages of this method are related to:

- low vibration levels, so they can be installed on dams at risk and close to houses, thus minimizing impacts on adjacent structures;
- low noise levels, reducing nuisance to the surrounding population and even making it possible to carry out the work at night, optimizing construction time;
- ease of driving in almost any type of terrain;
- minimization of damage downstream, since they can be fixed to the dam structures.

In this context, the work presents discussions and analysis on the subject, starting with the presentation of the reinforcement of a structure built with metal piles. The choice of this alternative is associated with the possibility of the reinforcement being implanted on the dam massif, generating minimal vibrations and noise during installation, as well as less interference in the structure. The suggested method will be an adaptation to Brazilian conditions and legislation of the Japanese methodology for sizing these piles, presented in the manual Press-in retaining structures: a handbook (IPA, 2019).

2 METHODOLOGY

The calculation methodology presented in the document Press-in retaining structures: a handbook prepared by the International Press-in Association (IPA) will be used to design the steel piles. The stability of the retaining structure will be checked using the computer software Slide 2® and RS2®, both from Rocscience, in accordance with the IPA criteria.

According to Santos and Futai (2021), for a structure in which one of the dimensions extends indefinitely in relation to the others, the consideration of a pile element in a Plane State of Deformation is plausible. The beam element developed in the Timoshenko methodology, as pointed out in the work by Cheng et. al. (1997), adequately correlates principles of stress distribution in beams according to the mechanics of deformable solids and displacement behavior associated with shear forces, using geometric and deformability parameters of the retaining wall and boundary elements of the soil medium itself.

Considering the guidelines contained in the IPA manual, the analysis of tubular piles to be adopted in this study will take into account equation (1) to define the maximum admissible stress.

$$\sigma_{max} = \frac{M_{max}}{Z} \tag{1}$$

Where M_max is the maximum moment that occurs in the pile (kNm) and Z is the moment resistance of the area (m³).

It is important to note that the IPA recommends that σ_max be lower than the admissible stress of the steel, so a safety factor of 1.50 will be used over the yield strength.

Equations (2) and (3) show the calculations developed to measure the area resistant moment, and there is a correction for the resistant moment per meter, dividing it by the diameter of the pipe added to the spacing between them.

$$Z_i = \frac{\pi\,({R_{ext}}^4 - {R_{int}}^4)}{4 * R_{ext}} \tag{2}$$

$$Z = \frac{Zi}{Dext + e} \tag{3}$$

For the maximum shear force developed in the pile, referring to the Plane State of Deformation, the Tresca quoted by Beer (2011) failure criterion will be used in which, in the direction of the shear stress, the shear stress developed is equal to half the maximum normal stress. Equations (4) and (5) express the equations evaluated.

$$\tau_{xy} = \frac{\sigma_e}{2} \tag{4}$$

$$F_{máx} = \tau_{xy} * A \tag{5}$$

Where σ_e= yield stress adopted for the material (MPa); τ_xy= shear stress developed on impact (MPa); A= effective area of the section (m²).

The pile embedment length required to guarantee the stability of the system will be obtained using the manual developed by the IPA. First, the initial horizontal reaction coefficient of the pile with the soil is obtained, according to Equation (6) derived from Yoshida and Adachi (1970).

$$k_{HO} = \frac{1}{B_{ref}}\,\alpha\,E_o \tag{6}$$

Where B_ref = length of the plate from the horizontal thrust coefficient test carried out in Japan, with a value of 0.3 m; α = correction coefficient for the modulus of elasticity value according to the test (for correlation with NSPT it has a value of 1, according to the IPA manual); E_o= modulus of elasticity of the soil (kPa);

The horizontal reaction coefficient of the pile is obtained according to Equation (7) from the research by Okahara and Takagi (1990).

$$k_H = k_{HO}\left(\frac{B_H}{B_{ref}}\right)^{-3/4} \tag{7}$$

Where = equivalent length of the load (understood as 10 m by the IPA methodology).

The necessary horizontal reaction coefficient developed by Broms and Francis (1968) quoted by Ananthanathan et al (2000) is also evaluated to check the methodology, presented in Equation (8).

$$k_H = 0{,}65 * \frac{(E_o)}{(1-\upsilon^2)}\sqrt[12]{\frac{E_o * B^4}{E\,I}} \tag{8}$$

Where B= foundation width, or pile diameter (m); E= modulus of elasticity of the pile material (kPa); I= moment of inertia of the pile section (m^4).

Equations (9) to (11) are used to obtain the pile embedment length.

$$\beta = \sqrt[4]{\frac{k_H\,B}{4\,E\,I}} \tag{9}$$

$L_o \geq \frac{3}{\beta}$ for permanent structures or $L_o \geq \frac{2{,}5}{\beta}$ for temporary structures (10)

$$I_i = \frac{\pi\,({R_{ext}}^4 - {R_{int}}^4)}{4} \tag{11}$$

Where L_o= pile embedment length (m).

Using the above methodology and taking into account the fact that the pile can only be embedded in high-strength materials, it is possible to determine the minimum embedment length in a competent material, varying according to the thickness and diameter of the pile.

Although studies in Brazil take into account the determination of reference Safety Factors (SF) for stability studies, in this study, due to the use of the Press-in method, the criteria defined in Japan will be used, which prioritize the limit state of use according to the guidelines of the Japan Road Association (2009). Therefore, the maximum horizontal displacement is used as a design criterion:

- Less than 1% of the pile, and no more than 300mm in the case of normal works;

In addition to the displacement criterion presented, the pile's resistance to bending and shearing forces will also be checked. To this end, the maximum bending moment found in the piles in the simulations carried out must be less than the admissible moment calculated for each pile or set of piles.

3 IMPUTS

3.1 *Definition of boundary conditions for structural design*

The location of the retaining wall must take into account the subsoil conditions and the geomorphology of the terrain. To better understand the subsoil, a campaign of geotechnical investigations should be carried out, including field and laboratory tests that will help validate the geotechnical parameters of the area, define the stratigraphic profile of the subsoil and identify the water level. In order to define the specifications of the drive system required, it is important to check the resistance parameters. For this study, a geotechnical profile of a fictitious foundation was proposed. The geotechnical parameters of the foundation and materials were defined using values from the literature and are shown in Table 1.

Table 1. Material strength and deformability parameters.

MATERIAL	ENVOLTÓRIA RESISTÊNCIA	E [Mpa]	E_u [Mpa]	ν	$ν_u$	γ (kN/m³)	c' (kN/m³)	ϕ' (°)	Su/σ'v (Pico)
Tailings I	Mohr-Coulomb	16000	19333	0.2	0.45	21	2	26	0,2
Tailings II	Mohr-Coulomb	16000	19333	0.2	0.45	23	0	29	0,25
Foundation 1	Mohr-Coulomb	9000	10875	0.2	0.45	21	3	22	0,29
Foundation 2	Mohr-Coulomb	50000	-	0.3	-	21	11	28	-
Foundation 3	Mohr-Coulomb	60000	-	0.3	-	22	15	42	-
Foundation 4	Mohr-Coulomb	75000	-	0.3	-	20	27	36	-
Foundation 5	Mohr-Coulomb	70000	-	0.3	-	22	24	34	-
Foundation 6	Mohr-Coulomb	100000	-	0.3	-	24	41	40	-
Foundation 7	Mohr-Coulomb	65000	-	0.3	-	22	17	33	-
Foundation 8	Mohr-Coulomb	100000	-	0.3	-	22	21	36	-
Foundation 9	Mohr-Coulomb	90000	-	0.3	-	19	1	23	0,2
Foundation 10	Mohr-Coulomb	100000	-	0.3	-	22	22	35	-
Rockfill	Leps superior	150000	-	0.3	-	Envoltória de Leps (Superior)			-

4 RESULTADOS

4.1 *Design of pile resistance forces*

The piles used will be made of ASTM A572 - Gr. 50 steel with a minimum yield strength of 345 MPa, and a safety factor of 1.50 has been adopted over the yield strength. Table 2 shows the values of area, inertia and admissible moments for the simple resistant line for the stress-strain analysis in the plane strain state of maximum pile forces.

Table 2. Characteristics of piles for foundation reinforcement.

Pile	Inertia (m⁴)	Area (m²)	Admissible Bending Moment (kN/m)	Admissible Shear Stress (kN/m)
1 pile -diameter 1.200 mm – steel Gr 50, thickness 21mm	5.3E-03	3.0E-02	2030.00	2106.00

4.2 *Estimating pile embedment*

To define the pile embedment length, the initial horizontal reaction of the pile was calculated according to Yoshida and Adachi (1970), Okahara and Takagi (1990) and Broms and Francis (1968) quoted by Ananthanathan et al (2000). The input data for calculating the embedment is detailed in Table 3.

Table 3. Calculation of the embedment length.

Inputs required for calculating inlays	**Value**
E (Pa)	1.8E+07
V (m/m)	0.2
Diameter (m)	1.2
Spacing between piles (m)	1.2
Thickness (m)	0.021
Inertia (m^4)	5.1E-03
Elasticity of the pile (Pa)	2.0E+11
Kh (Broms and Francis, 1968)	9.4E+06
Kh (Yoshida and Adachi, 1970)	6.8E+07
Kh (Okahara and Takagi, 1990)	4.9E+06
B (m/m)	1.9E-01
Bh (m/m)	10
L (m) – Permanent Structure	**15.00**

The IPA criterion is being considered as a benchmark and starting point for sizing the pile embedment length. Structural and stress-strain checks will lead to a more appropriate pile length and type.

4.3 *Geotechnical evaluation*

The geotechnical evaluation of the stresses in Section A-A was carried out by evaluating the displacements, deformations, maximum shear stress, limit equilibrium analyses and Shear Strength Reduction (SSR) analyses. All the geotechnical analyses are aimed at evaluating the behavior of the pile together with the

Dam massif for the most critical scenario (peak undrained condition).

With regard to displacements, for the hypothetical scenario of mobilizing the peak undrained resistance of the structure's constituent materials, the pile shows a total displacement of 51 cm, as shown in Figure 1. It should be noted that the displacement obtained in the finite element analysis refers to the pile and dam masses as a whole. The displacement/torsion absorbed by the structural element will be evaluated in section 4.4.

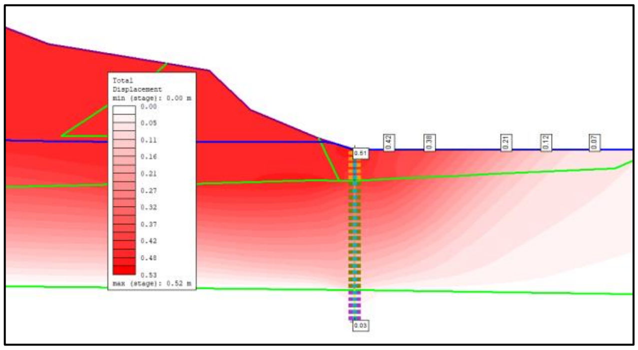

Figure 1. Total Displacement - Geotechnical Evaluation

One of the evaluations to be carried out on the pile and mass set concerns the deformations and maximum shear strain. Taking into account the displacement and length of the piles, they show deformations of 3.92%. Figure 2 illustrates the maximum shear stress obtained. It should be noted that the maximum shear strains only occur near the piles and do not propagate.

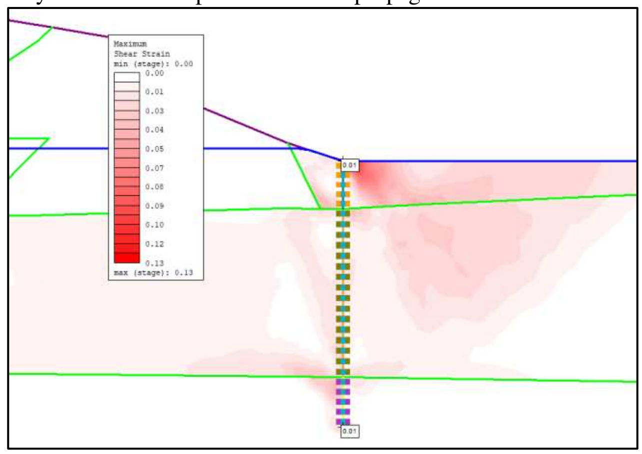

Figure 2. Maximum Shear Strain – Geotechnical Evaluation

With regard to stress-strain analysis, one of the checks is carried out using the Shear Strength Reduction (SRR) technique. This method consists of the systematic use of finite element analysis to determine a Strength Reduction Factor (SRF) that brings the slope to failure. In addition, the Mohr Coulomb strength of materials model was used to calculate the SRF, which in addition to the angle of friction and cohesion, also takes into account the modulus of elasticity and poison coefficient.

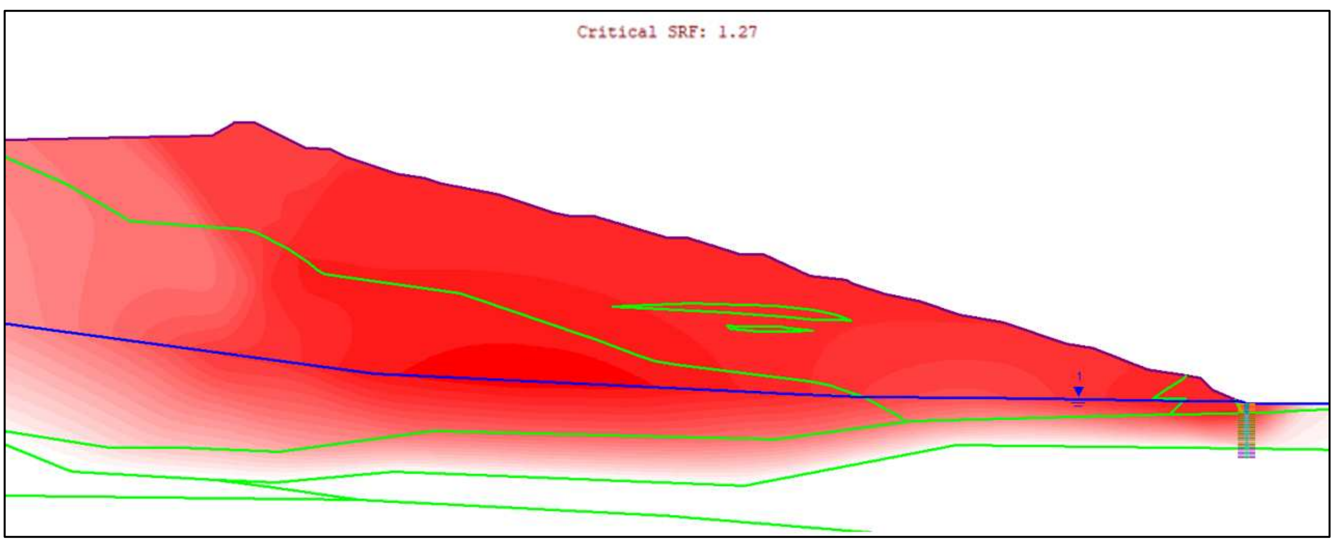

Figure 3. SSR – Critical SRF – Geotechnical Evaluation

In general, after checking displacement, deformation and stress-strain states, it can be seen that the structure together with the foundation reinforcement piles behaves well even in hypothetical and critical scenarios of peak undrained mobilization. These checks are crucial to understanding how the dam structure, together with the reinforcement piles, behaves under various conditions. The good behaviour observed even in hypothetical scenarios of peak undrained mobilization is an indication that the reinforcement measures are effectively improving the stability and safety of the dam.

The Shear Strength Reduction (SSR) analysis shows that by progressively reducing the shear strength of the soil, it is possible to determine the safety factor of the structure. The fact that a 27% degradation of the parameters would be required to bring the dam to failure in an undrained mobilization scenario indicates a significant safety margin. This means that the structure, with the reinforcement piles, is considered safe up to a considerable level of loss of resistance.

In addition to assessing the structure as a whole, it is also important to carry out a specific structural analysis of the reinforcement piles. This process will be detailed in section 4.4, which involves checking the load capacity, shear strength and other mechanical properties of the piles themselves. This ensures that each component of the reinforcement solution is properly sized and capable of fulfilling its function without compromising the overall integrity of the dam.

4.4 *Structural evaluation*

Structural analysis is necessary to verify the stresses acting on the pile. The structural analysis was carried out using SAP2000 software and stress-strain analysis using Rocscience RS2 software. Figure 4 and Figure 5 illustrate the diagram of moments and shear forces obtained.

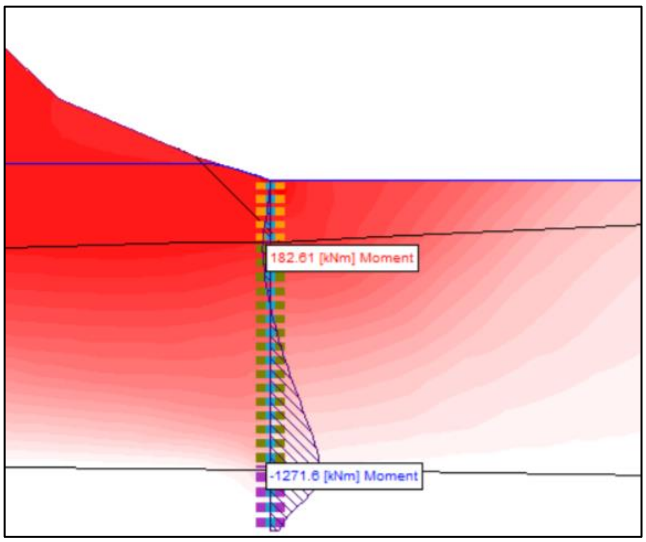

Figure 4. Moment diagram - Structural evaluation

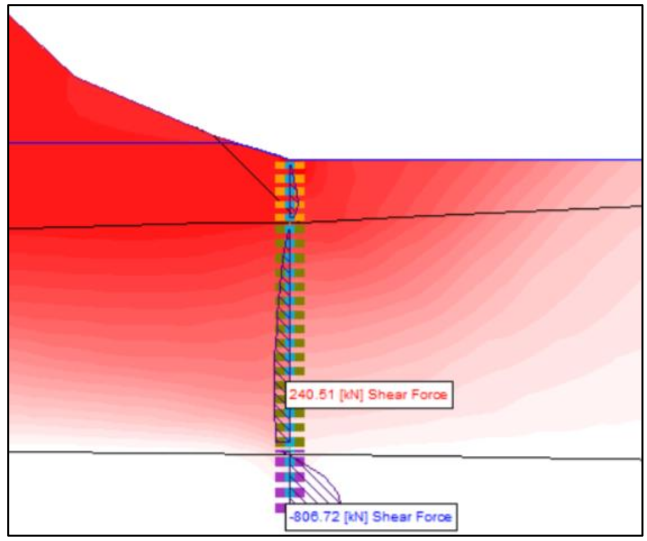

Figure 5. Shearing force diagram – Structural evaluation

When comparing the stresses exerted by the pile with the stresses resisted by the pile, as detailed in Table 6.3, it can be seen that all the stresses exerted by the pile are lower than those admissible by the pile. However, it is necessary to carry out a complementary assessment of the relative displacement/torsion exerted only by the steel piles.

The evaluation of the relative displacement/torsion of the structural element was carried out using SAP2000 software, considering all the thrust, moment and shear forces obtained from the geotechnical analysis. As a result, it was observed that the pile presents a relative displacement/torsion of 5 cm in the hypothetical scenario of undrained mobilization (most critical), with the ultimate limit state being 27 cm. Figure 6 shows the values obtained for the current request condition and the ultimate request condition.

Having said this, it can be seen that the steel piles are being stressed by around 18% of their relative displacement/torsion capacity. It should be noted that the 51 cm displacement obtained in the geotechnical assessment differs from the 5 cm relative displacement observed in the structural assessment.

Thus, the geotechnical and structural assessment of the stresses on the structure and on the dam and foundation elements as a whole shows that the structure is functioning well.

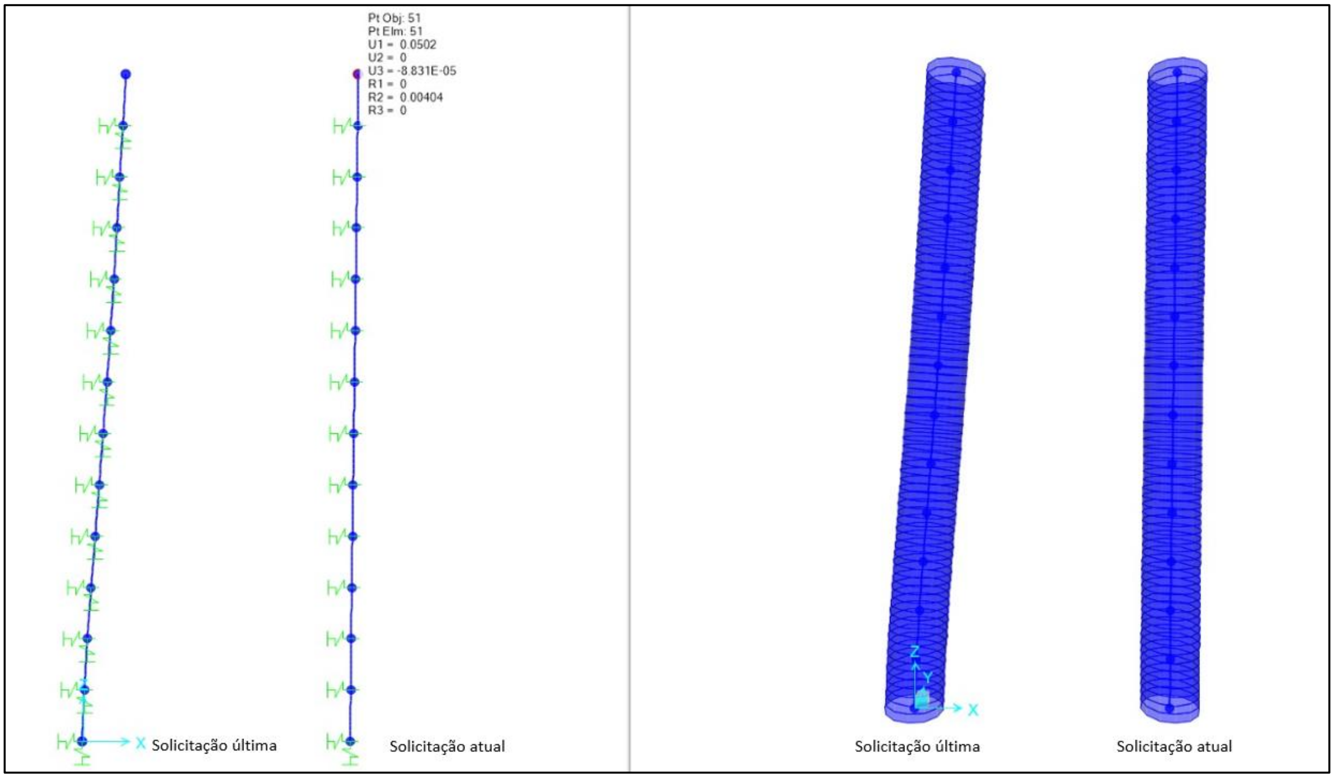

Figure 6. Relative displacement/admissible torsion - Structural evaluation

5 CONCLUSIONS

In summary, the analyses described provide a comprehensive understanding of the performance of the dam structure following reinforcement interventions. The combination of a global assessment with detailed testing of individual elements, such as the piles, provides a solid basis for confidence in the stability and safety of the dam under various operational and geotechnical conditions. Following an analysis of the current conditions and the reinforcement needs of the dam foundation, it is possible to state that the proposed solution, which involves driving metal piles into the foot of the slope, appears to be an appropriate and effective approach to guaranteeing the stability and safety of the structure.

Due to the fact that the driving and design method was developed for slope and tsunami containment, in order to bring the design to Brazilian needs, such as in this case a dam reinforcement, the pile length of the piles was determined based on the embedment criteria (Yoshida and Adachi/1970, Okahara and Takagi/1990 and Broms and Francis/1968 quoted by Ananthanathan et al/2000) in accordance with the IPA (International Press-in Association) manual and on stress-strain analyses in order to validate the necessary embedment of the piles. This increase is justified by the fact that the piles intersect the failure surfaces in the foundation, providing greater structural stability.

The stress-strain analyses also showed favorable results, with displacements and deformations within the admissible limits for the structure. In addition, using the finite element method, it was possible to calculate the displacements, deformations, bending moments and shear forces in the piles. A comparison of the shear force diagrams obtained between the SAP 2000 structural software and the RS2 geotechnical software showed that the results converged, all of which were below the admissible values for the designed conditions.

It is also worth mentioning that the geotechnical finite element analyses were necessary to assess the behavior of the reinforcement elements in conjunction with the dam. The structural analysis refers to the absorbed forces and deformations observed in the steel piles. The two analyses proved to be consistent and demonstrate adequate structural and geotechnical behavior of the reinforcement proposal. It is therefore concluded that the proposed reinforcement solution meets the dam's safety requirements.

It is suggested that future work assess the impacts of installing the piles in a limit equilibrium analysis to meet the regulatory safety factors. In addition, it should be noted that percolation should be assessed after the piles are driven (spaced 1.2 m apart in this case) to ensure that the water table does not rise in such a way as to jeopardize the stability of the structure. It is also recommended that a test area be set up to check the vibrations and piezometry increments generated during the pile driving process.

3 ACKNOWLEDGEMENTS

The authors are grateful to Fonntes Geotécnica for having provided an environment that supports us in overcoming challenges, with the opportunity and incentive to develop innovative projects to serve our clients and to disseminate the results in scientific circles to promote knowledge in the geotechnical community.

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