Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-362

Use of steel piles in the de-characterization process of tailings dams in Brazil

Utilisation de pieux métalliques pour la décaractérisation des digues à stériles au Brésil

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ABSTRACT: The recent accidents involving tailings dams in Brazil have promoted significant changes in the current legislation and, consequently, have made the criteria and assumptions in projects related to mining tailings dams more restrictive. The short deadlines set by the inspection agents, the unavailability of areas, constructive restrictions and, mainly, the need for systematic operational controls during construction to eliminate possible triggers for the liquefaction process to which such structures are susceptible, made the application of steel pile walls as a reinforcement/containment element in dams to become technically feasible in comparison with conventional alternatives. The pile driving method associates the pressing method (Press in) to the rotation technique (Gyropress) and presents, among other advantages, low vibration levels, low noise levels, easy driving in different types of foundations and minimization of downstream damage. This paper presents the results of the application of the pile driving using the press in method to reinforcement as part of the process that dam decharacterization projects developed in Brazil by the applications of criteria and premises established by the International Press-in Association (IPA, 2019).

RÉSUMÉ: Les récents accidents impliquant des digues à stériles au Brésil ont entraîné des changements significatifs dans la législation actuelle et, par conséquent, ont rendu plus restrictifs les critères et les hypothèses dans les projets liés aux digues à stériles minières. Les délais courts fixés par les agents d'inspection, l'indisponibilité des zones, les restrictions constructives et, principalement, la nécessité de contrôles opérationnels systématiques pendant la construction afin d'éliminer les déclencheurs possibles du processus de liquéfaction auquel ces structures sont sensibles, ont fait que l'application de murs de pieux en acier en tant qu'élément de renforcement/confinement dans les barrages est devenue techniquement réalisable par rapport aux solutions de rechange conventionnelles. La méthode de battage des pieux associe la méthode de pressage (Press in) à la technique de rotation (Gyropress) et présente, entre autres avantages, de faibles niveaux de vibration et de bruit, un battage facile dans différents types de fondations et une minimisation des dommages en aval. Cet article présente les résultats de l'application du battage de pieux à l'aide de la méthode de pressage pour le renforcement dans le cadre du processus des projets de décaractérisation des barrages développés au Brésil par l'application des critères et des prémisses établis par l'Association internationale de pressage (IPA, 2019).

Keywords: Steel piles; dam, tailings, decharacterization.

1 INTRODUCTION

The last decade was marked by two accidents involving mining dam collapses in Brazil, which prompted significant changes in state and federal legislation, as well as in techniques for disposing of mining tailings. In this context, at the federal level, the National Mining Agency (ANM) published Resolution No. 95 of 2022, which covers the entire country and establishes precautionary regulatory measures to ensure the stability of mining dams.

In response to the new guidelines and criteria, the entrepreneurs had to update their geological-geotechnical information bases and gain a better understanding of the boundary conditions that control the geotechnical and hydraulic behavior of the structures, in operation or not. As part of this process, new field investigations and susceptibility studies of the materials that make up the dams (embankment, tailings, and foundation) were initiated, to evaluate of the undrained behavior of these materials. As a result, several structures were declared unstable, with safety factors below the requirements, resulting in the need to reinforce the structures.

The short deadlines established in the legislation for reinforcing the structures, as well as factors such as the unavailability of areas and construction restrictions, such as the generation of vibration and noise that could be triggers for the process of liquefaction and cause instability dams, required the search for new alternatives to implement the reinforcements.

As a technically feasible alternative, studies using steel piles as a construction element and reinforcement have shown advantages over conventional solutions. Among the different technologies for driving piles, the press-in method stands out. This method is widely used in the construction of walls to protect against tsunamis in Japan, and in slope stabilization works in urban areas, mainly in Japan and Europe, according Dobrisan (2018). The Press in method consists of using hydraulic jacks attached to the pile installation equipment to press the piles into the ground. When compared to the other driving techniques used, the press in method stands out due to its fast execution and low noise and vibrations. This technique also determines the load capacity of the piles, since this driving is like a static load test (Tehrani et al., 2016). Installation by pressing uses static loading for its execution. Its design is based on using the tensile strength of piles previously installed in the ground to obtain the reaction force to press, with a static load, the new piles that will be driven into the ground. Depending on the resistance penetration of the foundation soil, it may be necessary to combine the Press in method with the Gyropress technique. In this case, the Gyropress method combines driving by pressing with the rotational movement of the pile, which results in the cutting of the ground by means of a cutting tool (drill) welded to the tip of the pile. Therefore, this combination allows them to be driven piles into resistant materials such as rocks or concrete structures (Ishihara, 2018) (Randolph, 2021).

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

- low vibration levels, making possible the application in restricted areas like dams at risk or near homes,
- low noise levels;
- ease of driving in almost any type of terrain;
- minimizing damage downstream;
- reduced construction time
- facility with transportation and handling of construction materials;
- the possibility to vary the pile lengths;
- high resistance to compression, bending and cutting;
- high quality control during the construction stages.

In the case of a project using tubular piles installed by the press-in method, it is recommended to adopt the premises and criteria consolidated by the International Press-in Association (IPA), in the document Press-in retaining structures: a handbook (IPA, 2019).

In view of the advantages of using steel piles and the pressing method, the aim of this work is to present a technical feasibility analysis of the use of tubular steel piles to reinforce dams, enabling stabilization and reinforcement processes prior to the dam decommissioning process. A methodological proposal for sizing this type of structure in Brazil will be presented, addressing the particularities and adaptations required, and finally the application of the sizing of a fictitious reinforcement structure, designed according to the proposed methodology.

In order to design these reinforcements, some items deserve special attention, including the calculation of the forces on the pile, the moments and displacements acting on the piles, as well as the evaluation of the behavior of the foundation materials in the face of the demands imposed, and it is also important to note that the behavior of the groundwater after the piles are installed must be analyzed.

2 METHODOLOGY

The design of the steel piles will be based on the calculation methodology presented in the document Press-in retaining structures: a handbook prepared by the International Press-in Association (IPA). The stability of the retaining structure will be checked using the computer software Slide 2® and RS2®.

According to Santos and Futai (2021), for a structure in which one of the dimensions extends indefinitely in relation to the others the assumption of plane state of deformation of the reinforced soil is realistic. 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 consider equation (1) to define the tension yield stress adopted for the material:

$$\sigma_e = \frac{M_{max}}{Z} \qquad (1)$$

where Mmax is the maximum moment in the pile (kNm) and Z is the resistant moment area (m³).

It is important to note that the IPA recommends that σ_max should be lower than the steel's admissible stress, 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 plus the spacing between them:

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

$$Z = \frac{Zi}{Dext+e} \quad (3)$$

For the maximum shear force developed in the pile, referring to the Plane State of Deformation, the Tresca failure criterion will be used in which, in the direction of the shear stress. Equations (4) and (5) express the equations evaluated:

$$\tau_{xy} = \frac{\sigma_e}{2} \quad (4)$$

$$F_{máx} = \tau_{xy} * A \quad (5)$$

where σ_e= tension yield stress adopted for the material (MPa); τ_xy= yield shear stress (MPa); A= effective area of the section (m²).

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, in addition to the SF, 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 pile displacement is used as a design criterion:

- Less than 1% of the length the pile in the case of normal works;
- Less than 3% of the length the pile in the case of temporary works;

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

The piles are first inserted into the model embedded in competent material, and then the number of pile rows and embedment length are adjusted to meet the criteria for relative displacement, bending stresses, and safety factors. First, the maximum bending moment in the pile is observed to determine which pile configuration (number of rows, type of steel, and pile thickness) has a higher allowable moment and is closest to the maximum achieved. The analysis is then conducted for the most suitable configuration from the point of view of bending stresses. If necessary, the pile length is adjusted by increasing the embedment to reduce the relative displacement at the top of the pile until the relative displacement criterion is met, and then the pile length is adjusted if it is necessary to embed more than required to reduce the relative displacement at the top of the pile until the relative displacement criterion is met in the most optimized way. This length adjustment will be reflected in the bending moments generated, so it should be re-evaluated with respect to the allowable moments of the proposed pile configuration. It should be noted that this process can be repeated several times until the most optimized result is obtained, with relative displacements and maximum moments below and closer to the allowable ones.

In addition to the bending stresses and relative displacements, the yielding of the foundation materials and the shear deformations associated with yielding will also be observed, looking for the formation of a failure mechanism that could lead to the pile collapse. After this stage, the solution is validated using the safety factors obtained by limit equilibrium, according to Brazilian and international standards, demonstrating the effectiveness of the solution.

3 RESULTS

3.1 Definition of the boundary conditions for the design of the structure

This stage of the project consists of defining the position and alignment of the pile rows and checking the conditions of the containment structure's foundation.

The location of the containment must take into account the conditions of the subsoil and the geomorphology of the terrain. In order 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 for the necessary driving system, it is important to check the resistance parameters. For this study, a geotechnical profile of a fictitious foundation was proposed.The geotechnical parameters for the foundation and materials were defined using values from the literature and are shown in Table 1.

3.2 Taling Dam without reinforcement

Based on the resistance and deformability parameters established above, the structure was checked for the current condition, without the implementation of reinforcement. In this condition, it was found that the dam does not present favorable safety conditions for the liquefied (Figure 1) and pseudo-static (Figure 2), scenarios, thus justifying the implementation of reinforcement works for these conditions.

Table 1. Material strength and deformability parameters.

Material Name	Unit Weight (kN/m3)	Poisson's Ratio	Young's Modulus (kPa)	Failure Criterion	Material Type	Peak Friction Angle ( )	Peak Cohesion (kPa)	Vertical Stress Ratio	Minimum Shear Strength (kPa)
Sterile	21	0.25	50000	Mohr-Coulomb	Plastic	36	0		
Landfill - silty sand	20	0.4	30000	Mohr-Coulomb	Plastic	36	5		
Granodiorite A4/R1+	20	0.25	500000	Mohr-Coulomb	Elastic	35	105		
Granodiorite A4/R1-	20	0.25	300000	Mohr-Coulomb	Elastic	35	10.5		
Calcilutite A4/R1-	20	0.27	200000	Mohr-Coulomb	Elastic	35	10.5		
Tailings - clayey	19	0.33	8000	Vertical Stress Ratio	Plastic			0.3	5
Tailings - sandy silt with clay	19	0.3	160000	Vertical Stress Ratio	Plastic			0.25	5
Tailings - silty sand	19	0.35	25000	Mohr-Coulomb	Plastic	34	0		
Tailings - clayey silt	19	0.35	16000	Mohr-Coulomb	Plastic	24	0		
Compacted silty sand embankment	20	0.4	40000	Mohr-Coulomb	Plastic	35	0		
Peak tailings - clay	27	0.3	8000	Vertical Stress Ratio	Plastic			0.3	5
Peak tailings - sandy silt with clay	19	0.3	16000	Vertical Stress Ratio	Plastic			0.25	5
Peak tailings - silty sand	19	0.35	8000	Vertical Stress Ratio	Plastic			0.3	5
Peak tailings - clayey silt	27	0.3	20000	Mohr-Coulomb	Elastic	35	10.5		

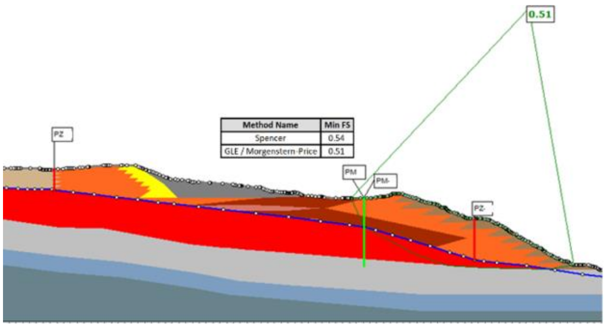

Figure 1. Stability analysis for the dam's base scenario - liquefied scenario.

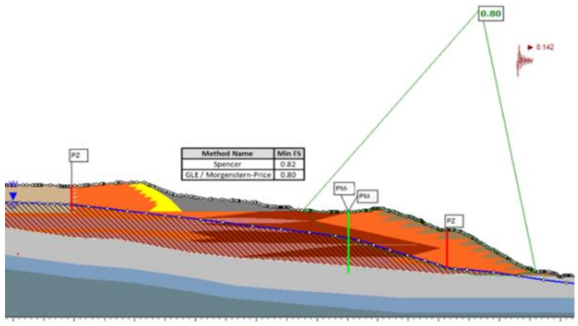

Figure 2. Stability analysis for the dam's base scenario - pseudo-static scenario.

3.3 Tailing dam with reinforcement

Bearing in mind that the project is presented as a definitive solution, the evaluation criterion for relative displacements is that they must be less than or equal to 1% of the total length of the pile. In this context, the section meets the established criterion with the greatest displacement occurring in axis 5 of the solution, at 0.94%. (Figure 3). As for the bending stresses, in the configuration defined for this section, in axes 1, 2 and 3, there is a solution with a 1200 mm pile, 21 mm thick and grade 50 steel, in which the maximum bending moment of 1926.8 kNm was verified in axis 2, which is lower than the 3516 kNm admissible for this configuration. For axes 4, 5 and 6, the solution is a 1500 mm pile, 25 mm thick and grade 50 steel, in which the maximum bending moment of 2171.9 kNm was verified. (Figure 4) in axis 6, which was lower than the 5446 kNm admissible for this configuration. Finally, as for the other evaluations, yielding and shear deformation, the section behaved satisfactorily and within expectations during the scenarios evaluated, undergoing yielding in some regions of the tailings. (Figure 5), with a maximum shear deformation of less than 5% near the piles (Figure 6), indicating that these regions where yielding occurs are not representative of a rupture wedge that could lead to the collapse of the structure. The results of the stress-strain study and the behavior of the piles in terms of permissible and acting moments are shown in Table 2. This fact was proven in the limit equilibrium analyses, which in the liquefied scenario the solution presents FS of 1.24 (Figure 7 higher than FS>1.1 and FS of 1.23 (Figure 8) for the pseudo-static scenario, higher than FS>1.1, both stipulated by the CDA (2019).

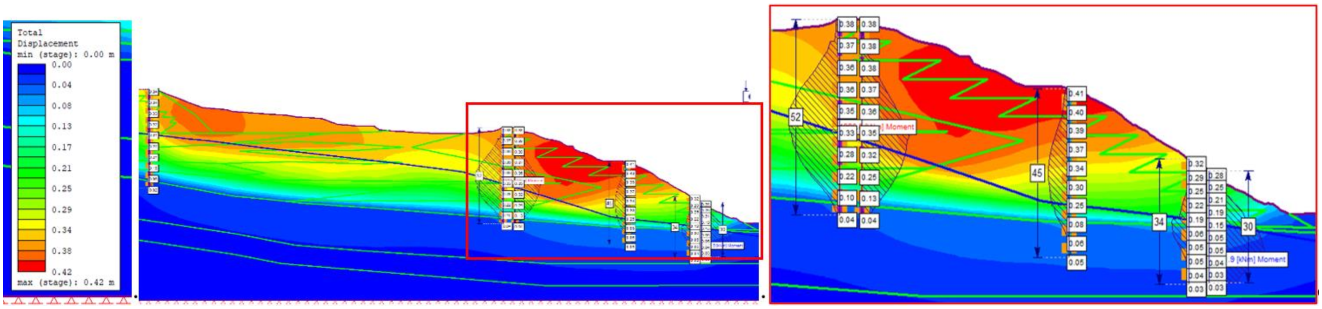

Figure 3. Total Displacement.

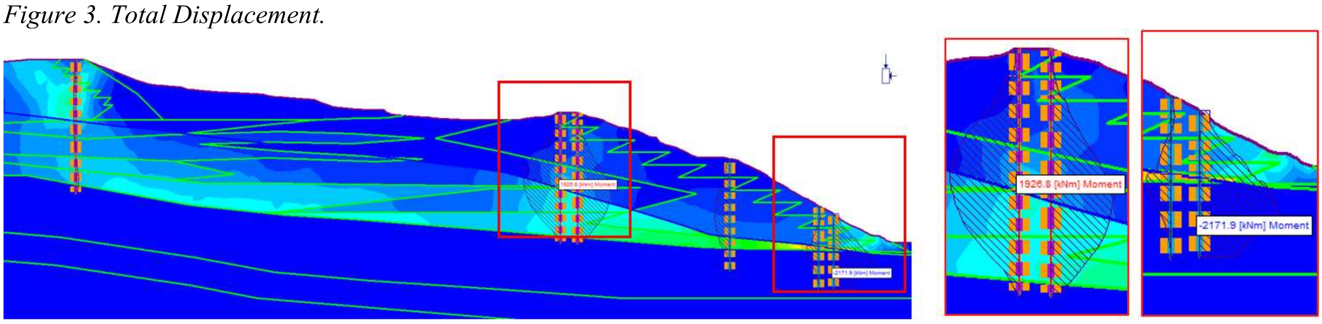

Figure 4. Bending Moment.

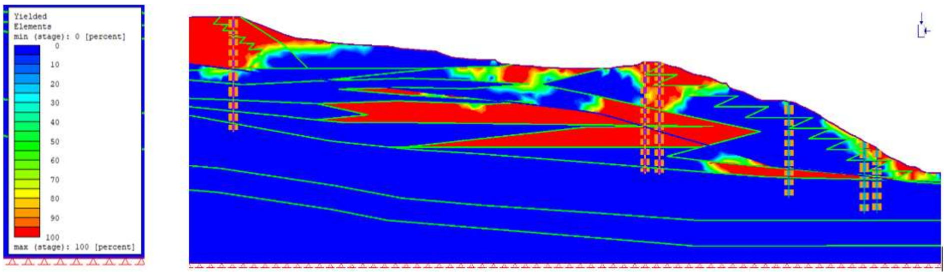

Figure 5. Yielded Elements.

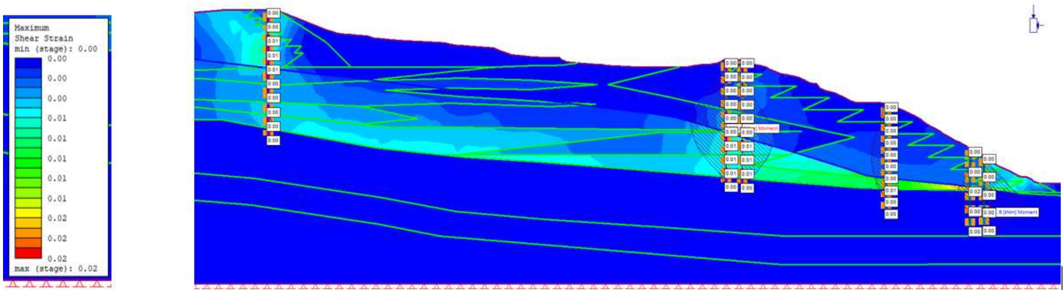

Figure 6. Maximum Shear Strain.

Table 2. Summary of the results of the stress-strain study.

Section	Maximum moment		Allowable moment (kNm)	Maximum deformation				Permissible deformation (%)	Piles
	Axis	Value (kNm)		Length	Displacement		%		
Section AA	1	166,7	**3516**	54	Top	0,34	0,63%	**1,00% of the length the pile (Japan Road Association, 2009)**	1200mm thickness 21mm and GRADE 50 STEEL
	2	1926,8		52	Top	0,38	0,73%		
	3	1806,2		52	Top	0,38	0,73%		
	4	797,56	**5446**	45	Top	0,41	0,91%		1500mm thickness 25mm and GRADE 50 STEEL
	5	668,27		34	Top	0,32	0,94%		
	6	2171,9		30	Top	0,28	0,93%		

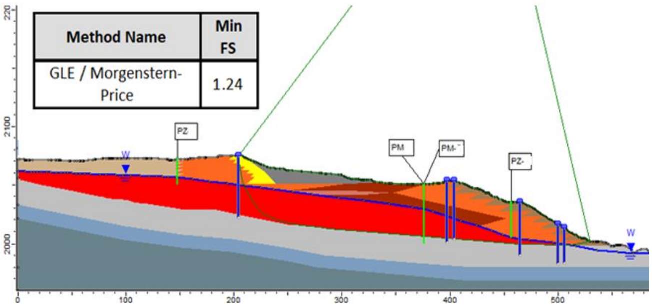

Figure 7 – Stability analysis for the dam's base case - liquefied scenario.

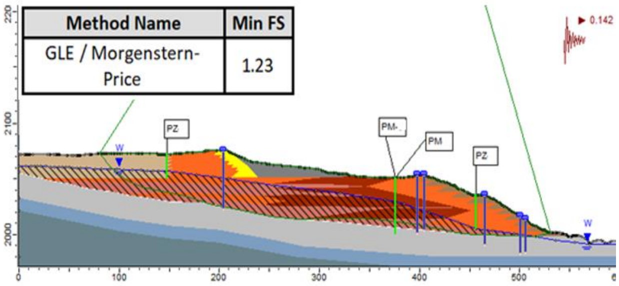

Figure 8 – Stability analysis for the dam's base scenario - pseudo-static scenario

4 CONCLUSIONS

As presented, there are technologies available that can promote the geotechnical improvement of upstream dams, to increase the safety conditions of the structure and carry out its de-characterization process. The innovative nature of using the press-in method to reinforce these structures susceptible to liquefaction stands out. In this application context, this methodology becomes viable due to the low levels of vibrations during driving, which, through full-time control and monitoring, can avoid triggering liquefaction during the construction of the reinforcement. Therefore, given the relevance and risk levels associated with such geotechnical structures, to conduct the reinforcement, a monitoring plan must be implemented with the installation of quick response piezometers associated with geophones. It is worth mentioning that control levels must be previously defined through the execution of tested areas.

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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