Characterization of a Tailings Dam Foundation in Dolomitic Rock and Soft Soils and Proposed Treatment with Stone Columns Filled with Cement Grout

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Abstract

This article details the engineering solution developed for the foundation of a tailings dam in the Iron Quadrangle region of Brazil. The dam consists of a compacted soil structure 86 m high. Along the dam slope and at the foot of the final embankment, a vertical metadolomite body occurs, with a general NW-SE trend and a dip of 70°-80° to the NW. The body is surrounded by phyllite, which confines it and thus constitutes a confined aquifer. The contact zone between the top of the metadolomite rock mass and the phyllite is marked by two low-resistance soils: loose residual metadolomite soil (adjacent to the top of the rock) and residual soft brecciated phyllite soil (up to the natural terrain). The rock in this region has high strength, generally between 50-100 MPa, but is highly fragmented and weathered parallel to the sedimentary bedding. The loose residual metadolomite soil, found at depths of less than 20 m and with thicknesses between 2 and 8 m, is sandy, of low strength, highly permeable, and exhibits drained behavior. CPTu tests (performed in accordance with ASTM D5778 and ISO 22476-1; Robertson, 2009) show metastable behavior and resistance close to zero, suggesting geotechnical stability challenges. Upward flow was observed in all boreholes carried out in the region of the soft soils and dolomitic rock.

Faced with the challenge of building a dam on low-resistance soils, an engineering solution was proposed, involving the construction of stone columns filled with cement-bentonite grout and grouting injections to fill discontinuities in the metadolomite top rock to a minimum depth of 4m. The proposed treatment aims to control deformations, improve the region's strength parameters, regulate water flow in the foundation, and prevent fine particles from being carried from the foundation into the rock fractures. To define the treatment, the main results of the geotechnical investigations, CPTU surveys, flow modeling, and stability analysis of the engineering solution were presented in this article. Preliminary results from verification of the treatment's performance indicate that this approach appears technically adequate for the

specific conditions investigated and can replace and confine part of the soft soils in the foundation. It is emphasized that these results are preliminary and specific to the geological and geotechnical context of the case study presented; generalization to other settings requires additional investigations and independent analyses.

Introduction

The tailings dam studied (hereinafter referred to as Dam A) is located in the Iron Quadrangle region (see Figure 1) in the State of Minas Gerais, Brazil. This is an important undertaking, as it will receive ultrafine tailings from several mining complexes in the region. This project began around a decade ago and has included many investigations that revealed the presence of metadolomite associated with low-strength residual soils. The starter dam was constructed to a height of 56 meters, and the upcoming downstream raising will extend the height to 86 meters, covering an area of 150 by 50 meters along the thalweg.

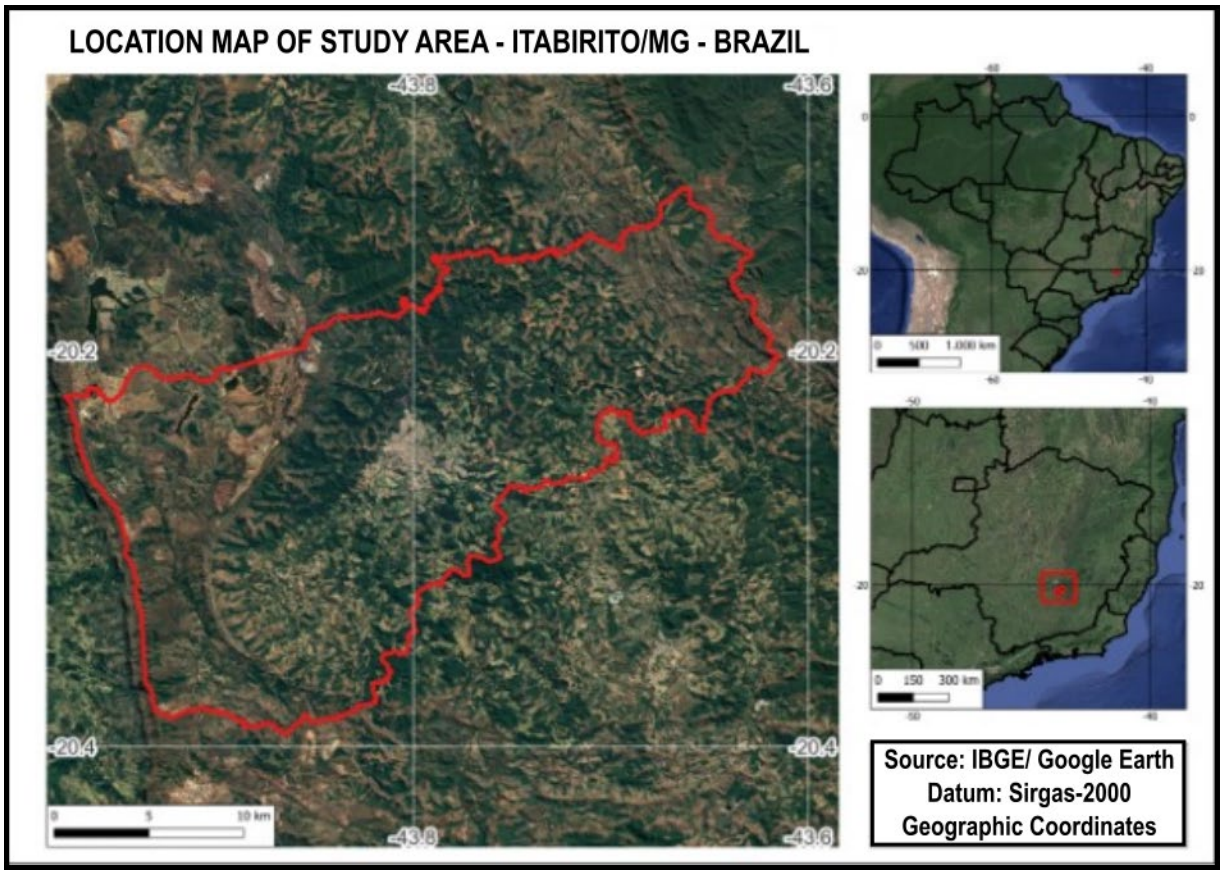


Figure 1: Map of the location of the city of Itabirito, Minas Gerais, Brazil

Regional Geological Characterization

Tailings Dam A is located near the axial zone of the Moeda Sinclinal macrostructure in the Quadrilatero

Ferrifero (QF) region of Minas Gerais, Brazil. The QF consists mainly of Archean and Paleoproterozoic terrain that hosts world-class iron and gold deposits and is notable for its complex geological and structural framework. The main geological units in the QF are: Basement (Archean-Paleoproterozoic), Rio das Velhas Supergroup, and Minas Supergroup. The Minas Supergroup comprises the Caraça Group, Itabira Group, Piracicaba Group, and Itacolomi Group (Alkmim et al., 1998). The rocks beneath Tailings Dam A are chemical and clastic metasediments related to the Piracicaba Group, specifically the Cercadinho and Fecho do Funil formations (see Figure 2).

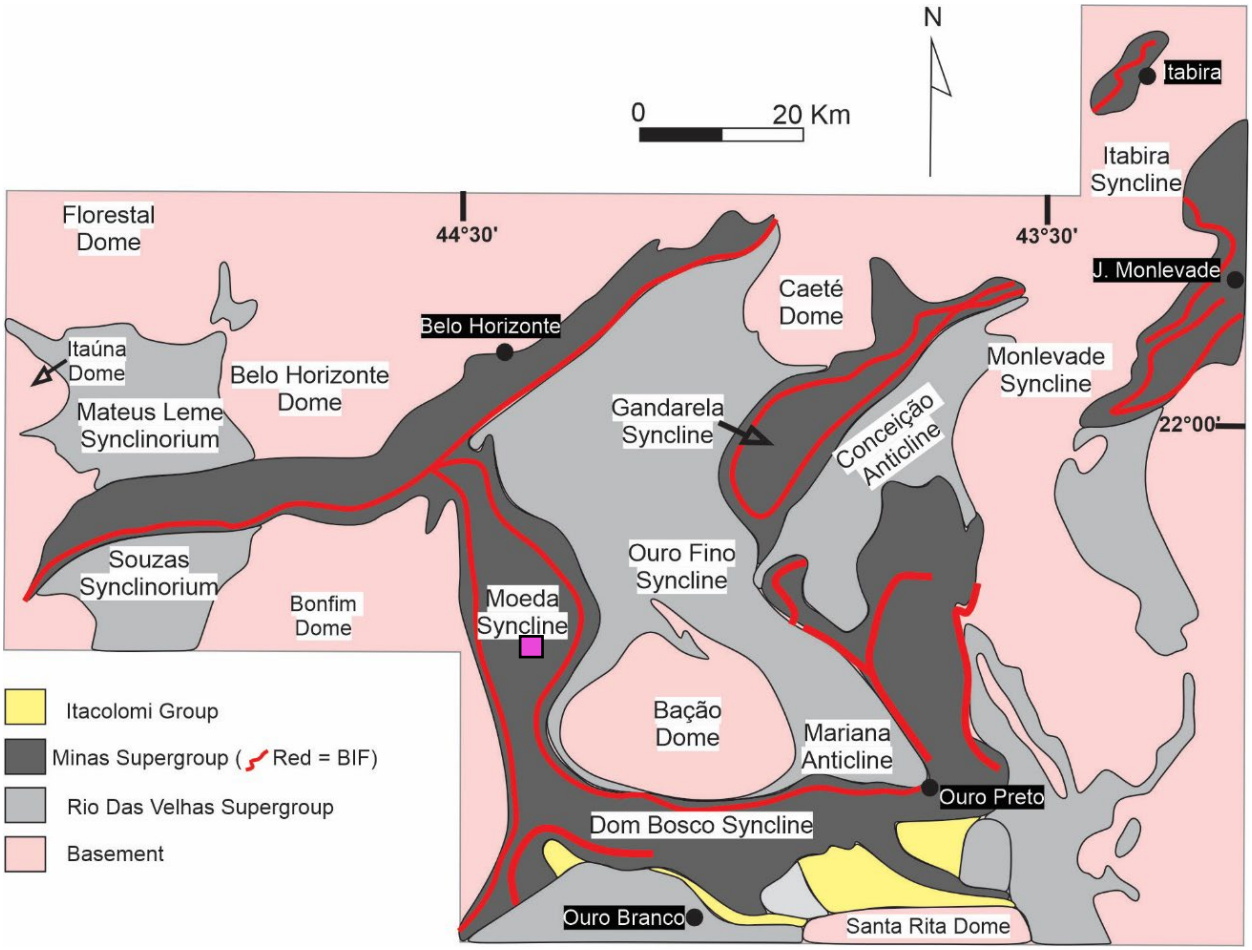


Figure 2: Geological map of the Quadrilátero Ferrífero area showing the main regional structures and geological units. The pink square indicates the approximate position of Dam A embankment

The Dam A embankment is situated along the gradational contact between the Cercadinho Formation and the Fecho do Funil Formation (Piracicaba Group – Minas Supergroup). Both units are exposed as highly weathered saprolites and residual soils, classified as R1- (< 3 MPa; Cella et al. 2019) and R0 (0.25-1 MPa), respectively, with weathering grades W5 (preserves original rock structure—saprolite) and W6 (residual soil).

The Cercadinho Formation occurs along the left abutment and consists of quartzite and sericitic phyllite. It makes a gradational contact with the Fecho do Funil Formation, marked by an increase in carbonate content in the phyllites, culminating in a metadolomite body along the talweg that records the beginning of the Fecho do Funil Formation. Dolomitic phyllite occurs along the right abutment.

The Paleoproterozoic structural framework records parallel structural and metamorphic foliation, with bedding dipping SE along the right abutment, NW along the left abutment, and vertically in the talweg zone. This pattern, together with data from local parasitic folds, is interpreted as an antiform structure with a low-angle NE-dipping hinge. A younger Cenozoic tectonic event appears at the site as normal faults with NW-SE and NE-SW strikes and as highly brittle zones recognized in the metadolomite rock mass. The NE-SW normal faults formed grabens that were filled with transported immature sediments, whereas the NW-SE normal faults are mainly detected by the down-dip displacement of the metadolomite body and its physiographic expression (see Figure 3).

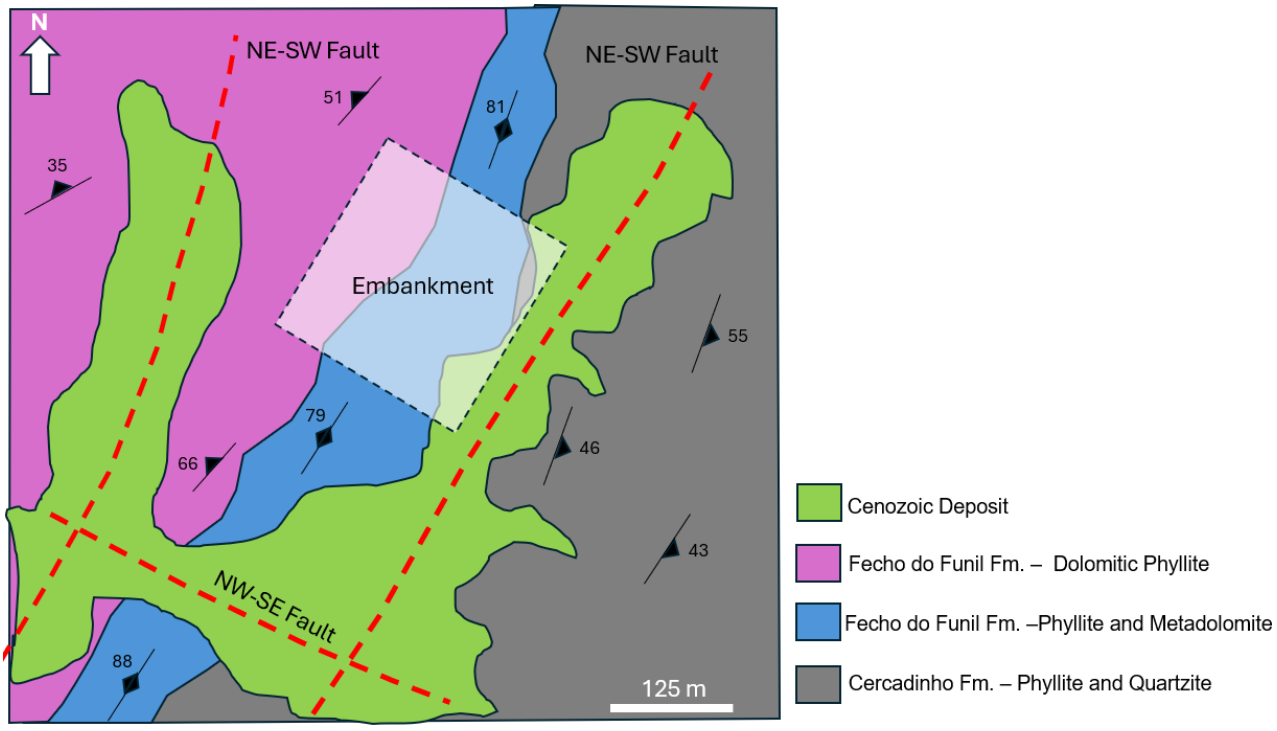


Figure 3: Simplified geological map of the Dam A area

Geological-Geotechnical Framework

The geological-geotechnical framework along the thalweg is characterized by a vertical metadolomite body, laterally enveloped by a saprolite of brecciated phyllite and overlain by two low-strength soils, both formed by the weathering of the phyllite and metadolomite. The permeability contrast between the rocks makes the metadolomite a confined aquifer and the phyllite an aquitard.

The metadolomite consists of a vertical body with variable thickness, around 40 m near the surface, exhibiting a fine-grained granoblastic texture with stromatolitic structures and reworking features recorded by the presence of oolite. The intact rock typically has a UCS greater than 30 MPa, but the rock mass is highly fragmented, which favors rock dissolution, mostly along the rock top and discontinuities. The karstification process at the site is a kind of "unique" environment, considering that the product of dissolution remained in situ and gave rise to loose soils formed by the association of endogenous and predominantly exogenous processes (fluvial and rainfall waters).

The loose residual soil of metadolomite consists of fine dolomitic sand associated with a silt fraction and rock fragments (metadolomite) (see particle size distribution curve in Figure 4). It covers the rock top and extends into discontinuities to depths of around 30 m. During the geological-geotechnical investigation campaign carried out at the site, the loose soil was characterized by: i) low Nspt blow counts, with many tests marked by advancement under the hammer weight; ii) artesian conditions transporting sand to the surface; iii) CPTu tests recorded drained behavior and Qt values (point strength) lower than 0,5 MPa; iv) the material was recovered only by sonic drilling, and during part of the project its existence was presumed. The permeability of the carbonate soil is around 10-3 cm/s.

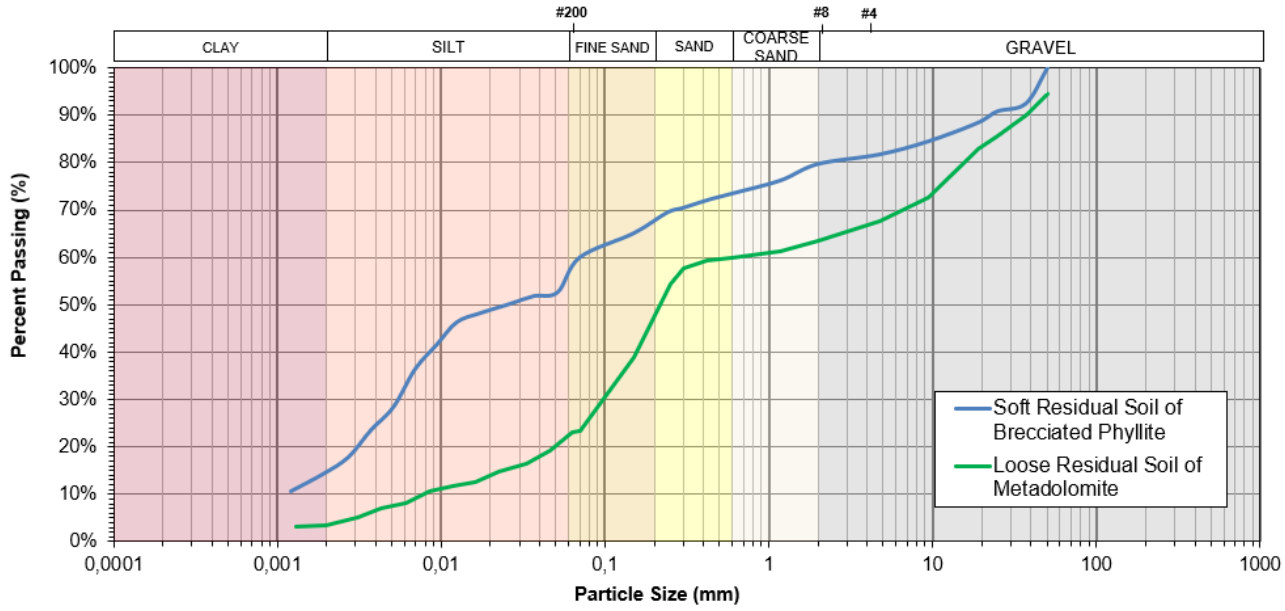


Figure 4: Particle size distribution curve

The soft residual soil of brecciated phyllite consists of silt (see the particle size distribution curve in Figure 4) that overlies the loose dolomitic soil and the metadolomite rock mass. It is characterized by: i) low Nspt blow counts, with higher values (approximately 5 blows) compared with the loose soil; ii) being recoverable during diamond drilling; and iii) exhibiting permeabilities around 10-6 cm/s.

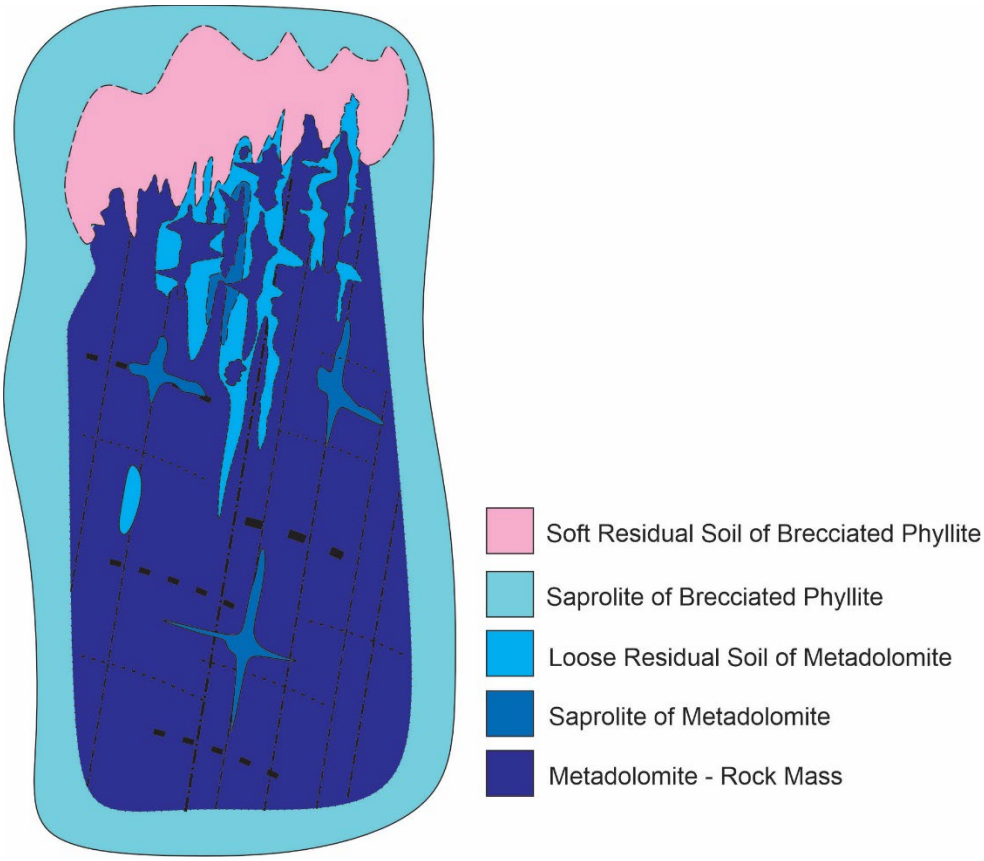


Figure 5: Geological-geotechnical cross-section along the thalweg of the Dam A embankment. Note the soft, loose soil at the site

A



Figure 6: A) The loose residual soil of metadolomite recovery with sonic drilling



Figure 6: B) The soft residual soil of brecciated phyllite

Proposal for Foundation Treatment

Before the solution definition process began, several project constraints were imposed. For instance, the low-strength materials detected in the dam's talweg region (loose residual soil of metadolomite and soft residual soil of brecciated phyllite) could not be excavated. This limitation arose because the initial embankment (starting dike) was already constructed and operational, and environmental licensing restrictions prevented extensive excavations for material removal.

In this context, the evaluation of the proposed engineering solution for foundation treatment consisted of three stages: qualitative analysis of solutions, trade-off studies among alternatives, and final solution selection.

During the initial phase, multiple engineering solutions were explored and qualitatively assessed. The four main lines of study focused on gravel columns, jet grouting, rigid inclusions, and hybrid solutions combining jet grouting and gravel columns. For each of these alternatives, a table was created detailing risks, failure modes, analyses, and mitigation strategies (see Figure 7).

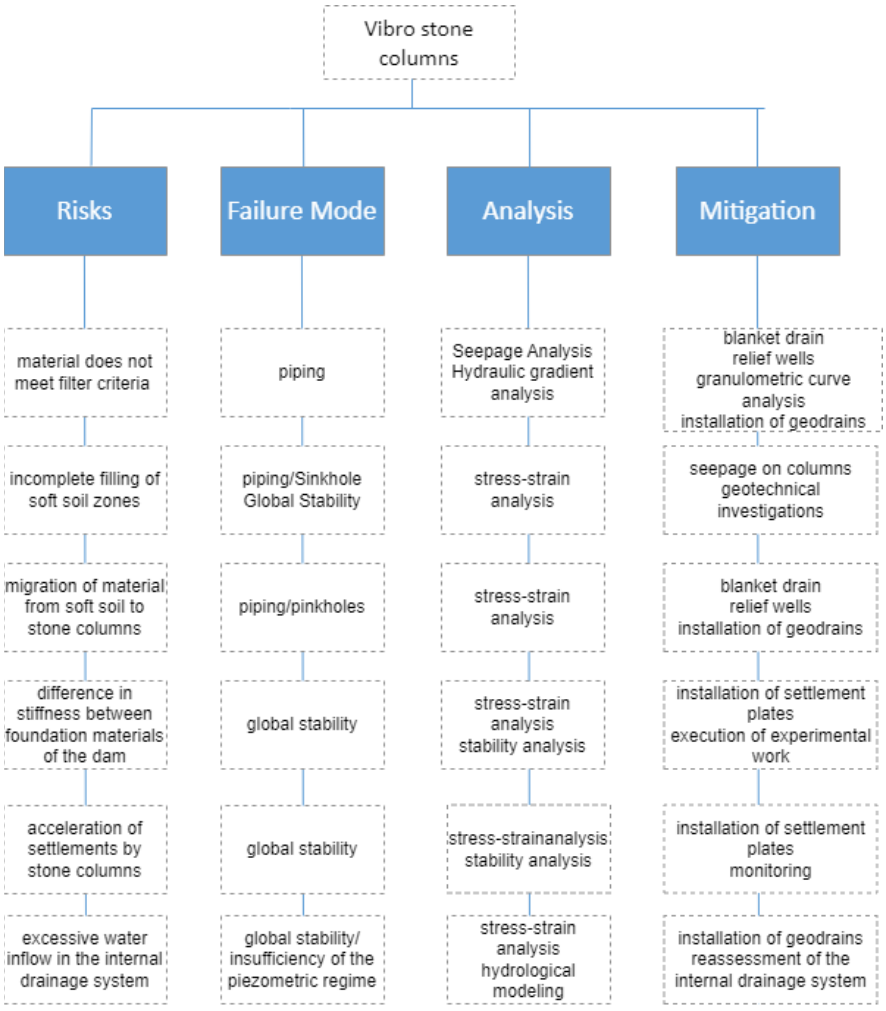


Figure 7: Example of risk matrix and failure modes developed for the stone columns solution

In the second phase of the studies, following the initial qualitative assessment, a detailed study was conducted on the evaluated solutions, which were refined after the discussions held during the first-phase qualitative study. In this context, two-dimensional seepage analyses, stability analyses, and stress/strain analyses (for the selected one) were conducted for four individual and mixed solutions: gravel columns; gravel columns with jet grouting; gravel columns for the soft residual soil of brecciated phyllite; jet grouting for the loose residual soil of metadolomite; jet grouting columns for the soft residual soil of brecciated phyllite; and low-mobility jet grouting for the loose residual soil of metadolomite. The analyses provided the following understanding:

- For loose residual metadolomite soil: Given that the soft soil collapses under small changes in applied stresses, the proposed solutions aim to increase confinement stress through soil displacement (vibrocompacted grouted gravel) and to increase relative density (cavity expansion). The transport of solid particles from the soft soil should be prevented in two ways: reduce vertical

flow by injecting dolomitic rock and by vibrocompacting the gravel columns with a binder mixture (traditionally, cement/bentonite). In detailing the solution, sensitivity studies of the loss of stiffness and resistance of this layer (between injection points) resulting from increased void ratio should be deepened. The grout used in the vibrocompacted columns needs to be weak (1,5 MPa) to avoid excessive column stiffness and pile behavior.

- For the soft residual soil of brecciated phyllite: The soft phyllite soil is the region where, in a more straightforward and versatile way, different techniques can be applied to improve its stiffness and resistance properties. It should promote an increase in its stiffness to values close to 30 MPa in order to reduce its contrast (differential settlements—cracks) with the door frames.

In the third phase, after defining the proposed foundation treatment (gravel columns filled with cement/bentonite poor grout), validation of the engineering solution involved two-dimensional and three-dimensional analyses of seepage and stability. These analyses assessed hydraulic gradients within the foundation and their impact on overall structural stability. In addition, computational stress-strain analyses were conducted, followed by stability analysis using strength reduction. These analyses aimed to verify the solution with respect to the ultimate global stability limit state. The foundation treatment region was modeled using geotechnical parameters for an equivalent material that combined in situ soil properties with reinforcement elements. Furthermore, analyses were performed to assess the ultimate bearing capacity of the foundation soil. These analyses also evaluated potential stress concentrations within the columns due to their greater stiffness compared to the surrounding low-strength soil. Additionally, serviceability limit state analyses evaluated vertical displacements and deformations for both short-term conditions (immediately after the construction of the second stage of the dam—final raising) and long-term conditions (during dam operation).

Evidence of the Treatment Performance

The treatment performance was assessed using three main investigation methods and tools: i) diamond boreholes with percussion and permeability tests along the axes of the grouted stone columns; ii) CPTU tests in the soil between stone columns; iii) Vs values obtained from the geophysical method MASW (Park et al., 1999) (multichannel analysis of surface waves) before and after the stone column treatment. In this paper, the focus was on the diamond boreholes that recovered the stone columns and the Vs values because of their effectiveness in showing the increase in soil strength.

The grouted stone columns were recovered through diamond boreholes drilled along their axes. It was possible to identify and describe the ratios of stone, grout, and associated soils, and to confirm that the stone columns reached the rock top, as shown in Figure 8. Permeability tests were conducted, and the recorded

values ranged from 10-3 cm/s to 10-4 cm/s along the columns, while most of the percussions tests exhibited values over 30 blows, confirming improved soil behavior inside the columns.

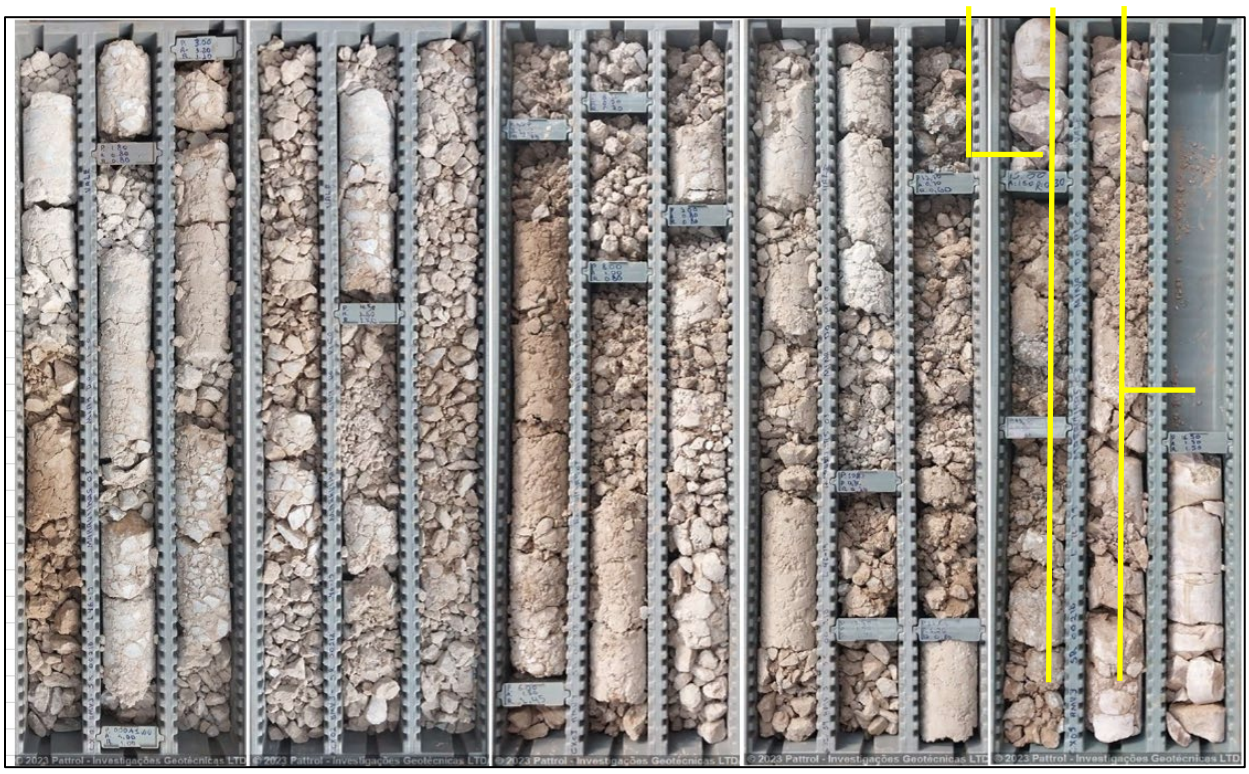


Figure 8: Grouted stone column supported by the metadolomite rock top at its base (yellow limit)

The MASW survey conducted across the treatment area enabled the construction of a 3D Voxel model, which was imported into the Leapfrog software alongside the geological-geotechnical model. Figure 9 shows a cross-section through the treatment area, including the geological-geotechnical model, stone columns, and injections along the alignment. It is important to note that the injections are not treated in this paper. Figures 10 and 11 present the same cross-section as Figure 9, but with data from the Voxel model derived from the MASW geophysical survey in 2022 (pre-treatment) and 2024 (post-treatment). The Voxel models consist of interpolations of Vs values acquired in the foundation.

Based on the Vs values from the pre-treatment MASW campaign (Figure 10), blue and green colors indicate that Vs values between elevations of 1,220 m and 1,208 m are mostly below 200 m/s, reflecting soft, loose residual soils. In the post-treatment data (Figure 11), Vs values are generally above 300 m/s (yellow), indicating a substantial increase compared with the pre-treatment data.

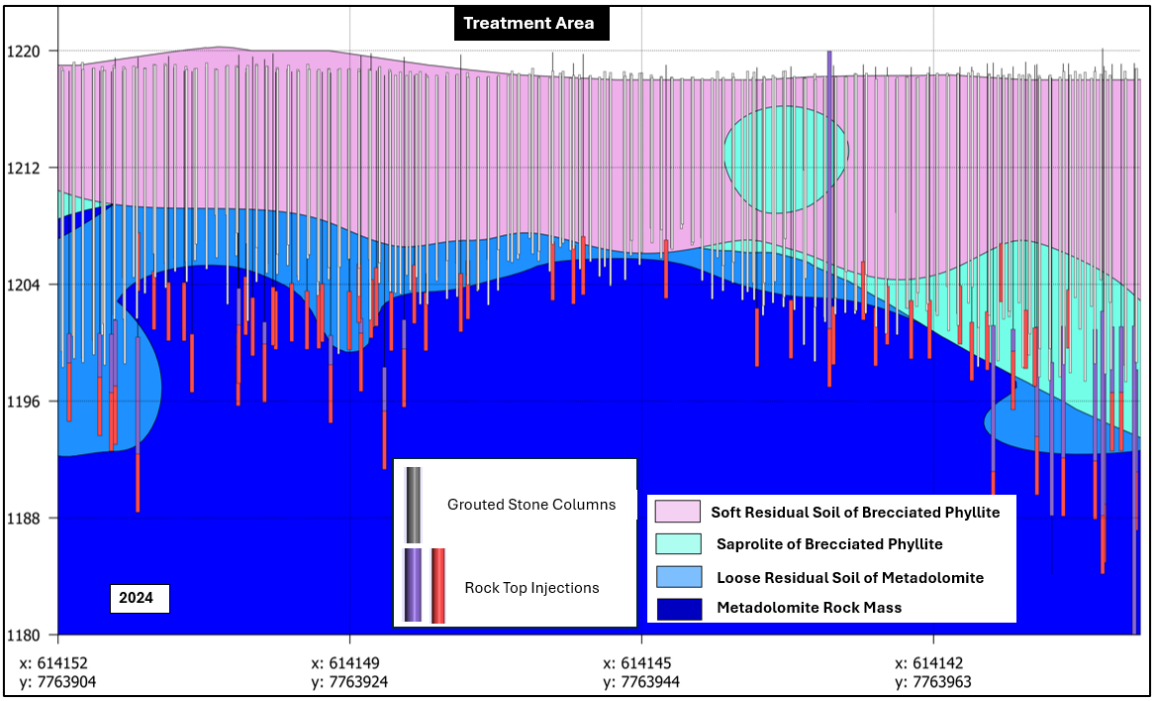


Figure 9: Cross-section along the treatment area exhibiting the geological-geotechnical units as long as the grouted stone columns executed

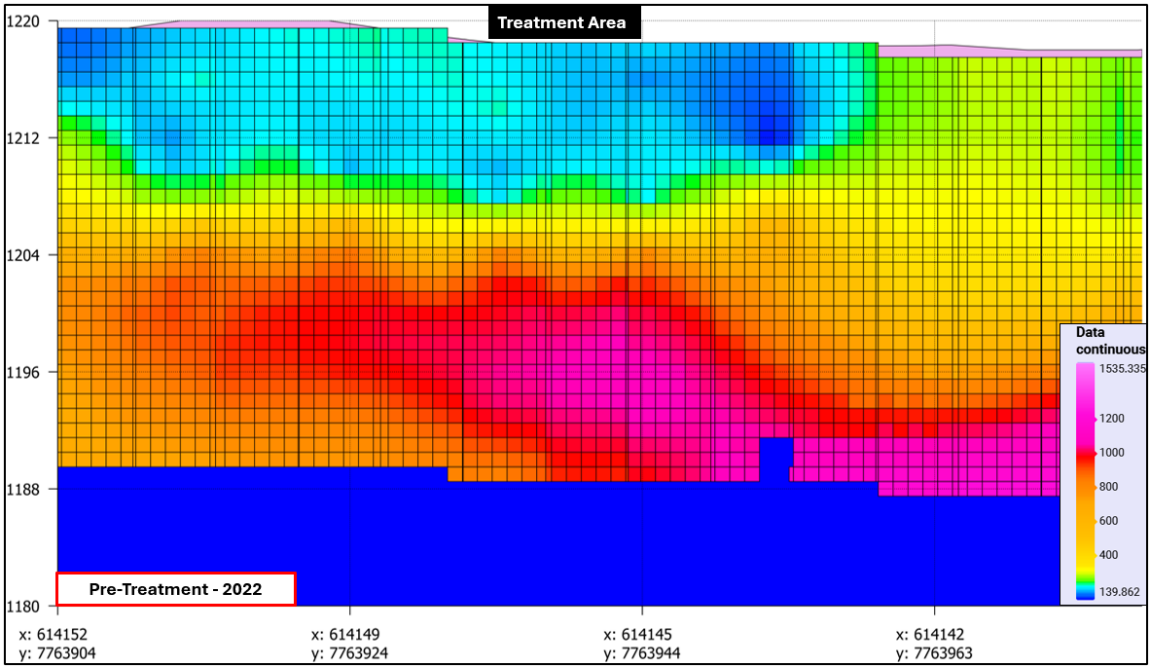


Figure 10: Cross-section along the treatment area exhibiting the voxel model based on Vs values from the pre-treatment survey campaign (2022)

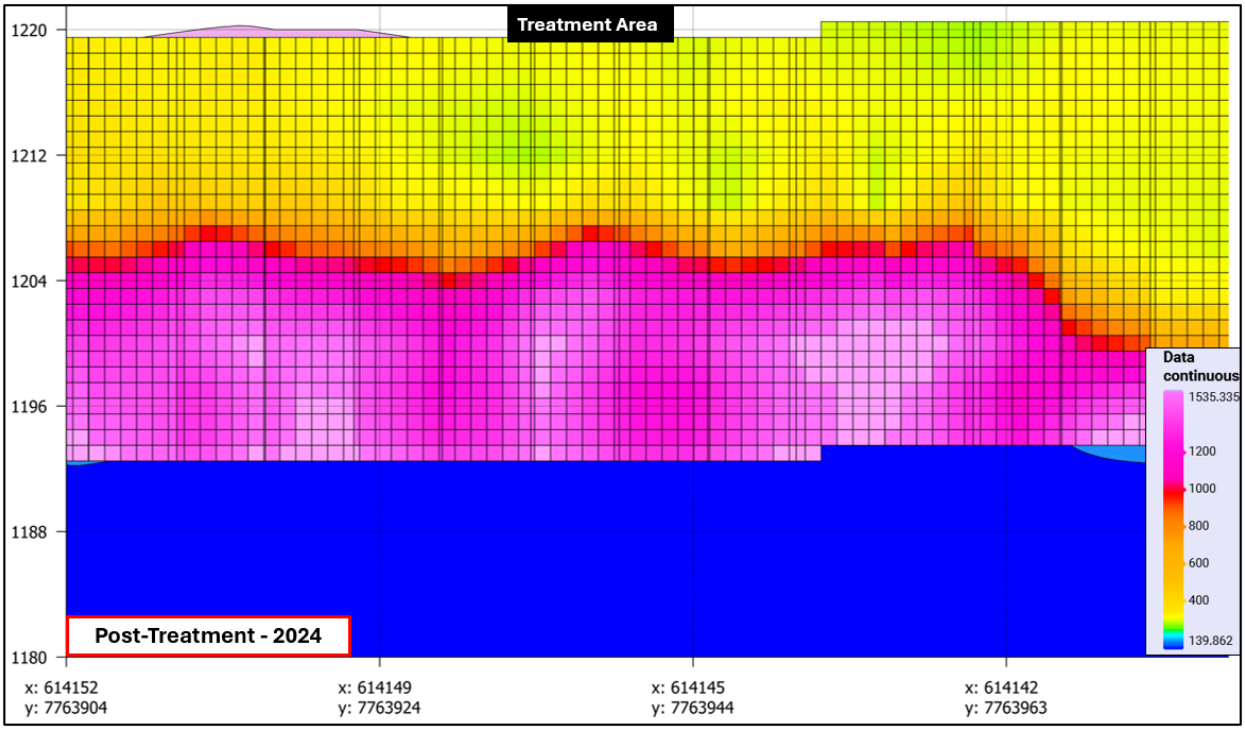


Figure 11: Cross-section along the treatment area exhibiting the voxel model based on Vs values from the post-treatment survey campaign (2024)

Conclusion

The proposed foundation treatment, involving the construction of stone columns filled with cement-bentonite grout, was technically adequate for addressing the challenges posed by low-strength residual soils and a confined aquifer. The comprehensive geotechnical investigations, including CPTu tests (conducted in accordance with ASTM D5778 and ISO 22476-1), flow modeling, and stability analysis, provided critical insights into the behavior of the foundation materials. The treatment aims to control deformations, enhance strength parameters, regulate water flow, and prevent the migration of fine particles, thereby contributing to the structural stability and operational safety of the dam, consistent with good geotechnical engineering practices and dam safety requirements.

The three-phase evaluation process, comprising qualitative analysis of solutions, trade-off studies, and final solution selection, underscored the importance of a systematic, thorough approach to foundation treatment design. The detailed two- and three-dimensional analyses of seepage and stability, combined with computational stress-strain assessments, validated the effectiveness of the engineering solution in enhancing the foundation's performance. The use of geophysical methods, such as MASW, further corroborated the success of the treatment, with significant post-treatment improvements in soil strength parameters.

The integration of grouted stone columns showed promising results in addressing the geotechnical challenges associated with the construction of the dam under study. This case study underscores the importance of tailored engineering solutions in complex geological settings. However, the results are considered preliminary and site-specific, and broader applicability should be assessed through further monitoring, independent analyses, and adherence to established geotechnical engineering standards and dam safety best practices.

Acknowledgements

The authors would like to thank the miner and the engineering company responsible for the project for their support in the development of the present study.

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