ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

*Northeast Geosciences Journal*

v. 11, nº 1 (2025)

https://doi.org/10.21680/2447-3359.2025v11n1ID37824

# Geotechnical treatment analysis for headrace tunnel in gneissic rock mass

## *Análise geotécnica de tratamento para túnel de adução em maciço rochoso gnáissico*

**Soraia Bastos Katereniuk[1]; Alessander C. M. Kormann[2]; Vítor Pereira Faro[3]; Pedro de Carvalho Thá[4]**

[1] Federal University of Paraná (UFPR), Civil Engineering Graduate Program, Curitiba/PR, Brazil. Email: eng.sbk@gmail.com
**ORCID:** https://orcid.org/0009-0007-1019-3829

[2] Federal University of Paraná (UFPR), Civil Engineering Graduate Program, Curitiba/PR, Brazil. Email: alessander@ufpr.br
**ORCID:** https://orcid.org/0000-0002-4512-3763

[3] Federal University of Paraná (UFPR), Civil Engineering Graduate Program, Curitiba/PR, Brazil. Email: vitorpereirafaro@gmail.com
**ORCID:** https://orcid.org/0000-0003-0001-5459

[4] Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Civil Engineering Graduate Program, Rio de Janeiro/RJ, Brazil. Email: pedro.tha@gmail.com
**ORCID:** https://orcid.org/0006-1274-1502

**Abstract:** This article presents the methodology adopted for the geotechnical design of the support applied to the headrace tunnels of the Laúca Hydropower Plant (AHE Laúca), located in Angola. The plant's headrace system consists of six parallel tunnels, each with an average length of 1900 meters, excavated in a gneissic rock mass. To determine the supports required to maintain excavation stability during the construction phase and the plant's operation, geological and geotechnical tests and investigations were conducted. The results of these investigations supported the studies presented here, providing parameters such as compressive strength and deformability of the rock mass, as well as shear strength of the rock mass discontinuities. The definition of appropriate support to ensure excavation stability was based on the Q-system rock mass classification. After the preliminary design of the support for excavations in competent rock mass, classified as Classes I to III, the proposed support was subjected to verification and validation through local stability analyses. These analyses were performed using the Unwedge software for the End of Construction load case, and a combined approach of local stability and coupled flow analysis using the Unwedge and Phase software for the operational phase load condition. The results highlighted the necessity of a drainage system consisting of perforated drains in the rock mass, in addition to the standard treatment comprising anchors and shotcrete. This system was crucial for reducing pore pressures acting on potentially unstable wedges around the excavations, particularly in scenarios where one tunnel remained empty while the others were in operation. Currently, all tunnels in the project are in operation and have undergone emptying processes due to operational demands. On none of these occasions were issues observed with the tunnel floor, nor were there any reports of block falls from the walls or crown.

**Keywords:** Tunnel; Rock Mass; Geotechnical Treatment.

**Resumo:** Este artigo apresenta a metodologia adotada para o dimensionamento do tratamento geotécnico dos túneis de adução do Aproveitamento Hidroelétrico (AHE) Laúca, localizado em Angola. O circuito de adução da usina compreende seis túneis paralelos, com extensão média de 1900 metros cada, escavados em um maciço gnáissico. Para determinar os suportes necessários à manutenção da estabilidade das escavações durante a fase construtiva e a operação da usina, foram realizados ensaios e investigações geológico-geotécnicas. Os resultados dessas investigações fundamentaram os estudos apresentados, fornecendo parâmetros como resistência à compressão e deformabilidade do maciço rochoso, além da resistência ao cisalhamento das descontinuidades. A definição do suporte adequado para garantir a estabilidade das escavações foi baseada no sistema de classificação de maciços rochosos Q-system. Após o pré-dimensionamento do suporte para as escavações em maciço rochoso competente, classificado como Classe I a III, o tratamento proposto foi submetido a verificações e validações por meio de análises de estabilidade local. Essas análises foram realizadas utilizando o software Unwedge para condições de carregamento de final da construção, e uma abordagem combinada de estabilidade local e fluxo acoplado, com os softwares Unwedge e Phase, para o carregamento correspondente à fase de operação. Os resultados demonstraram a necessidade de um sistema de drenagem composto por drenos perfurados no maciço rochoso, associado ao tratamento padrão composto por ancoragens e concreto projetado. Esse sistema foi essencial para reduzir as poropressões atuantes em possíveis cunhas instáveis ao redor das escavações, especialmente em cenários nos quais um túnel permanecesse vazio enquanto os demais estivessem em operação. Atualmente, todos os túneis do empreendimento encontram-se em operação e já foram submetidos ao processo de esvaziamento em função de demandas operacionais. Em nenhuma dessas ocasiões foram observados problemas no piso, tampouco houve registro de queda de blocos nas paredes ou abóbada.

**Palavras-chave:** Túnel; Maciço rochoso; Tratamento.

Recebido: 30/09/2024; Aceito: 14/02/2025; Publicado: 07/03/2025.

## 1. Introduction

In large-scale projects, such as hydroelectric power plants, it is sometimes necessary to excavate tunnels, either during the river diversion phase or to configure the hydraulic circuit. Different types of support are commonly requested for the excavation of tunnels to stabilize the excavations during construction and project operation.

Tunnel excavation engineering has evolved due to the growing understanding of rock mass behavior and its interaction with structures. The development of rock mass classification methods, such as the Q-System proposed by Barton *et al.* in 1974, has contributed to the rational design of support systems for underground excavations (ALEJANO, 2024).

Furthermore, advancements in computing and numerical methods now enable more precise modeling of rock mass behavior and the interactions between support systems and tunnels. Methods such as the Finite Element Method (FEM) and the Distinct Element Method (DEM), described by authors like Zienkiewicz *et al.* (2005) and Cundall & Hart (1992), provide detailed analyses, allowing the prediction of structural performance under various loading conditions. These tools have been fundamental in developing optimized geotechnical solutions and mitigating risks associated with excavations.

The present article focuses on the design of the geotechnical treatment required for stabilizing tunnel excavations in competent gneissic rock masses at the Laúca Hydroelectric Plant. In the context of this study, competent rock masses are understood as those in which failure occurs along planes of weakness, also known as discontinuities (KATERENIUK, 2022; WYLLIE; MAH, 2004).

The Laúca Hydroelectric Plant, whose data were used in the present case study, is located at Malange Province in Angola and its generation circuit is configured with six water intakes, circular shafts, headrace tunnels averaging 1900 meters in length each, and a powerhouse cavern housing six generating units (THÁ, *et al*., 2017).

The headrace tunnels are 11.33 m high and 10.10 m width and have a 20 m rock pillar between them. The tunnels, in its majority extension, do not have a concrete lining, even submitted to an external pressure of 240 m.wg of the reservoir. The reinforced concrete lining was only necessary in sections where the gneiss excavations crossed fault zones, where the rock mass was in poorer condition.

In 2017, year of operation of its first unit, the Laúca project installed capacity represented more than 30% of the entire Angolan electrical system (MINEA, 2014). Given its high importance, ensuring a robust generation system and safe construction works was essential for the project's success.

The knowledge regarding the rock mass behavior where the construction will be implemented plays the main role in the success of a geotechnical project. Thus, the characterization of the rock mass and the existing discontinuities is a fundamental step during the design of an underground excavation.

In competent rock masses, the discontinuity planes are the major elements that may cause instability in excavations. In these type of rock masses, the shear strength of the discontinuities is the parameter to be considered in analyses (KATERENIUK, 2022; WYLLIE; MAH, 2004). Discontinuities are defined as planes within the rock mass that separate the blocks of the rock matrix (VALLEJO *et al.*, 2002). Based on the characteristics of these planes, discontinuities can be classified into faults, joints, bedding planes, or foliation (FIORI; CARMIGNANI, 2015).

The characterization of the shear strength of rock mass discontinuities is typically carried out through geological field mapping and/or laboratory tests. Field mapping, conducted by geologists, involves the identification, orientation, and characterization of discontinuities, as well as the evaluation of their geometry and filling conditions, parameters used to estimate shear strength (BARTON *et al.*, 1974; HOEK; MARSHALL, 1976). In parallel, laboratory tests, such as direct shear tests or triaxial shear tests, allow for the quantification of the mechanical properties of the discontinuities (BARTON; CHOU, 1979; GRAY; PARRY, 1999).

The characterization of shear strength parameters of rock mass discontinuities serves as input for engineering analyses and the design of underground structures. This is relevant in tunnel projects, where the stability and support requirements are influenced by the mechanical behavior of the surrounding rock mass (HOEK *et al.*, 1995; WITTKE, 1990). In the case of the Laúca Hydroelectric Plant, the design of its tunnels relied on the Q-system.

The Q-system is a rock mass classification method widely used internationally. This system integrates geological and geotechnical data, including the properties of discontinuities, to provide a guide for excavation design and support specification to ensure the stability of underground works (HOEK, 2007; ALEJANO, 2024). The system was developed at the Norwegian Geotechnical Institute (NGI) and was first published in 1974 by Barton, Lien, and Lunde.

In this article, the authors present the design methodology used to define the necessary support systems for the headrace tunnels of the Laúca Hydroelectric Plant, as/ well as the basic information supporting these evaluations, obtained through field mapping and laboratory tests. The authors also highlight what they considered the most critical aspects to be addressed in the project to ensure the satisfactory performance of the structure.

## 2. Metodology

The following sections will provide an overview of the Laúca Hydroelectric Plant, focusing on the key aspects of rock mass characterization for the design of the headrace tunnels support. Additionally, the methodology employed in the pre-dimensioning and validation of the recommended geotechnical treatment for excavations in gneissic rock masses of classes II and III, where the behavior is primarily governed by discontinuities, will be discussed.

### 2.1 Asset Description

Laúca Hydroelectric Plant is in the Kwanza River, at Malange Province in Angola. The project comprises a 156 m high rolled compacted concrete dam and a hydraulic circuit composed of six water intakes, circular shafts, headrace tunnels with an average length of 1900 m each, and a powerhouse cavern with six generating units. Figure 1 illustrates the project's hydraulic circuit and the position of the headrace tunnels.

The total installed capacity is 2070 MW, from which 2004 MW generated at the main powerhouse and 70 MW at the ecological powerhouse, located at the dam's toe.

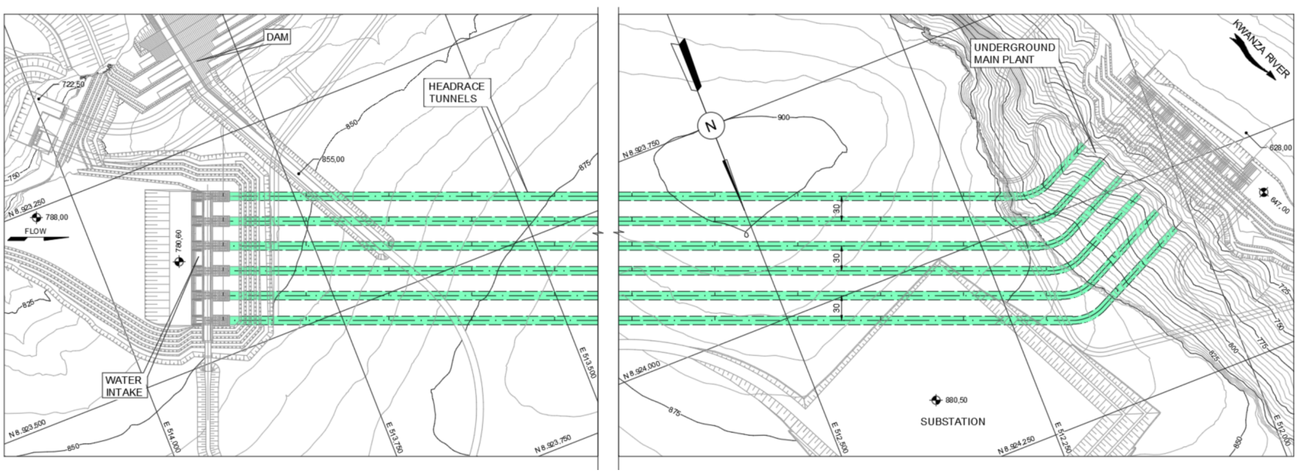


*Figure 1 – Headrace Tunnels of Laúca HEP.*
*Source: Modified from Intertechne (2014).*

The regional geology is formed by a package of metasedimentary rocks, approximately 100 m thick, deposited in sub-horizontal contact formed by an unconformity on a Precambrian gneiss base. The metassedimentary sequence is composed of metasandstones, metalimestones and conglomeratic breccia. In the dam region, on both riverbanks, there are cliffs of metasedimentary rocks forming subvertical walls up to 100 m high. At the foot of the escarpments, there are deposits of talus and colluviums of decametric thickness. A few meters above the riverbed, approximately at EL. 750 m, the gneisses of the Precambrian basement emerge. The contact between the gneiss and the overlying metasedimentary package gradually rises towards the main plant area, where it emerges approximately at EL. 800 m. The entire tunnel and cave complex of the main plant is positioned in a gneiss massif.

The headrace tunnels had its geotechnical support and lining defined according to the rock mass classes. For classes I, II, and III, the treatment consists of shotcrete reinforced with steel fibers, passive bolts, and radial drains. At class IV rock masses, it is foreseen, in addition to the geotechnical treatment with shotcrete and bolts, a reinforced concrete lining with 98 cm thick. The geometry of the excavation cross section is shown in Figure 2. The tunnels are 11.33 m high and 10.10 m width.

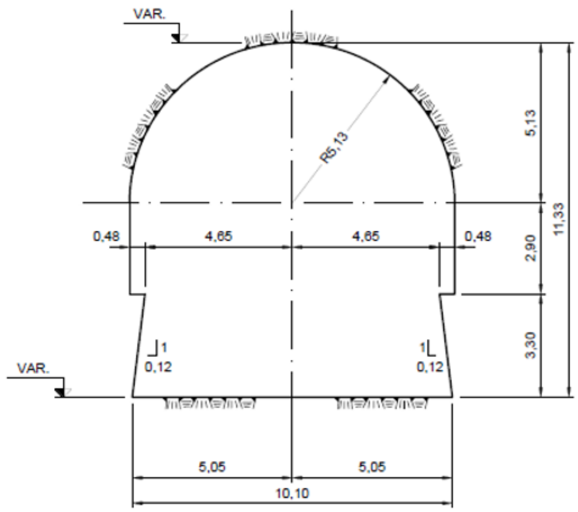


*Figure 2 – Excavation cross section.*
*Source: Intertechne (2014).*

Close to the powerhouse cavern, the headrace tunnels have a 40 m long steel lining followed by a 20 m long concrete lining 80 cm thick, regardless of the rock mass classification.

The headrace tunnels are integrally inserted in a gneiss rock mass. In the water intake region, the tunnels have the lowest coverage, which is about 140 m. In the powerhouse cavern area, the most extensive coverage occurs, which is approximately 240 m.

### 2.2 Rock Mass Characterization

For the present study, the results of laboratory tests and information collected during field mapping conducted on rock outcrops as well as on the excavation of the headrace tunnels were considered.

The information collected from the mappings was processed using the Dips 6.0 software (ROCSCIENCE, 2025a), which generated a stereogram and identified the discontinuity sets to be considered in the design. The resulting stereogram is presented in Figure 3.

The most frequently mapped sets in the excavations, J1 and J1’, correspond to the gneissic foliation and regional faulting. These sets exhibit similar orientations but have steep dips in opposite quadrants. Below are presented the attitudes (dip and dip direction) of the main discontinuity sets identified during mapping:

- J1: 021/78 – subvertical fracturing dipping NE, sometimes associated with gneissic foliation and regional faulting;
- J1’: 218/81 – subvertical fracturing dipping SW, sometimes associated with gneissic foliation and regional faulting;
- J2: 132/75 – subvertical fracturing dipping SE;
- J3: 307/73 – subvertical fracturing dipping NW;
- J4: 080/76 – subvertical fracturing dipping NE;
- J5: 116/17 – subhorizontal fracturing dipping SE.

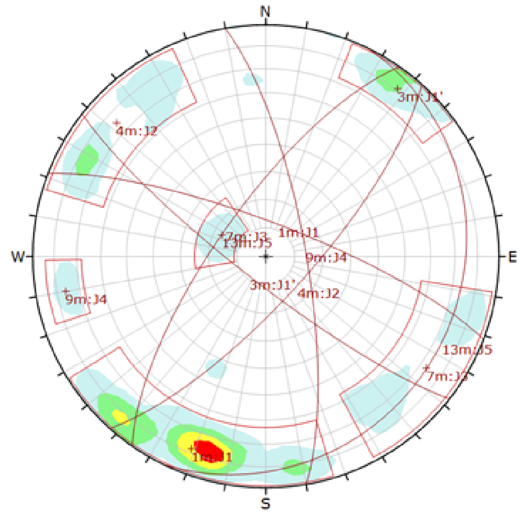


*Figure 3 – Joint discontinuities stereonet.*
*Source: Intertechne (2014).*

To enable tunnels without reinforced concrete lining, for most of its length it is necessary to have a rock mass with adequate properties. To prevent hydraulic fracturing the rock mass cannot be subjected to dissolution processes, and needs to have an appropriate mechanical resistance, an adequate state of tension, and low permeability.

Rock permeability and resistance to hydraulic fracturing were determined based on the results of 256 Lugeon tests and 149 tests of hydro-jacking performed on existing fractures, in some stretches of the six tunnels. The maximum pressure applied in the Lugeon tests was 2.4 MPa, which is the operational maximum internal pressure for the tunnels. Of the tests performed, only 26 had water absorption, with very low values (less than 1 Lugeon in most cases). In the other 230 tests, the absorption was zero. The permeability defined for the gneissic rock mass was $3.10^{-8}$ m/s.

The rock mass mechanical characterization was made through simple compression tests, triaxial and direct shear tests in drilling cores and dilatometer tests performed *in situ*. Measures of the roughness of the excavation discontinuities were also made. The summary of the mechanical characteristics of the rock mass is shown in Table 1.

*Table 1 – Summary of the rock mass properties.*

| **Discontinuities** | | | **UCS (MPa)** | **Young's Modulus (GPa)** |
|---|---|---|---|---|
| **$\phi_r$ (°)** | **JRC** | **JCS (MPa)** | | |
| 30 | 8,7 | 105 | 105 | 28 |

*Source: Intertechne (2014).*

In the analyses conducted in this study, for Class II rock masses, the friction angle of discontinuities was assumed to be 30°. For the discontinuities related to faults, the range of friction angle values corresponding to the observed conditions, according to the proposal by Barton *et al.* (1974), lies between 14° and 27°. Thus, an intermediate friction angle value of 21° was adopted for the project analyses for Class III rock masses, where the influence of a fault zone was considered.

Regarding the geological-geotechnical mapping, in all the excavation advances, mapping and classification of the rock mass were carried out according to the Q-system (NGI, 2022). The percentage of each rock mass class that effectively occurred during the excavations is shown in Table 2 as well as the range of the Q-value that represents each rock mass class in the project.

*Table 2 – Rock mass classes – Headrace Tunnels.*

| **Class** | **%** | **Q** |
|---|---|---|
| I | 0,04 | $> 20$ |
| II | 71,03 | $3 < Q < 20$ |

| Class | % | Q |
|---|---|---|
| III | 28,30 | 0,3 < Q < 3 |
| IV | 0,63 | 0,01 < Q < 0,3 |
| V | 0,00 | < 0,01 |

*Source: Intertechne (2014).*

### 2.3 Geotechnical Support Design

The required support to ensure the stability of an underground excavation, such as tunnels, can be preliminarily defined based on rock mass classification systems. These rock mass classification systems are empirical methods, based on an extensive database of existing projects, that correlate rock mass conditions with the required support. Among the various existing methods, the most widely used are: RQD (Rock Quality Designation), RMR (Rock Mass Rating), and the Q-system (A'ssim; Xing, 2010).

For the executive design of the Laúca Hydropower Plant, the Q-system classification method was employed, which will be briefly presented in this chapter.

The Q-system classification method, also known as the NGI system, was originally proposed in 1974 by N. Barton, R. Lien, and J. Lunde. This classification methodology considered six parameters that could be obtained from field mapping and the evaluation of a geologist regarding the rock mass conditions (Barton *et al.*, 1974). Since its creation, the system has undergone two major revisions (1993 and 2002) aimed at incorporating new types of support as well as data from more than 1950 underground works (NGI, 2022).

The Q-system classification provides a description of the stability of a rock mass in an underground excavation. High values indicate good stability, while low values suggest poor stability. The equation defining the Q-value is presented below (NGI, 2022):

$$Q = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF}$$

The parameters that constitute the equation above are:

- RQD – Degree of jointing (Rock Quality Designation);
- $J_n$ – Joint set number;
- $J_r$ – Joint roughness number;
- $J_a$ – Joint alteration number;
- $J_w$ – Joint water reduction

The design of the necessary geotechnical treatment for the Laúca Hydropower Plant tunnels considered, for the different rock classes, the logic of the expected geomechanical behavior.

The rock discontinuities control the wedge stability at excavations of rock classes I, II and III. For those cases, the support was defined by empirical methods, based on Barton's geomechanical classification system using the Q-system and the ESR (Excavation Support Ratio) (NGI, 2022). The ESR (Excavation Support Ratio) factor depends on the type of excavation, ranging from 0.9 to 1.1 for underground power plants, main highway tunnels, underground civil defense shelters, tunnel junctions, and intersections (VALLEJO, 2002). For the Laúca tunnels, a value of 1.0 was adopted.

For rock masses class IV, the geomechanical behavior is not determined by discontinuities orientation but instead by the rock mass resistance. The support validation was made using numerical analysis with the software Phase (ROCSCIENCE, 2025b). However, the design of the support required for this class of rock mass is not within the scope of the present paper.

The support design for excavations on rock masses class V was not foreseen, as this class was not expected and effectively did not occur during construction.

Besides the different classes of rock mass, the necessary support must guarantee the safety of the excavation for the different load cases expected for the tunnels. The load cases considered in this project were:

- Load Case I: End of construction;
- Load Case II: Steady Seepage, considering Tunnel 4 empty and the other tunnels operating;

In the first case, the tunnels are empty, and the potential wedges formed at the excavation are submitted only to its self-weight. It was not considered the presence of water because all the excavations opened during construction were dry.

The second load case corresponds to the most critical for the tunnels. In this scenario, when one of the tunnels is empty and the others are operating, the pore-pressures acting on the rock mass around the empty tunnel will generate a load acting on the wedges and causing instability. For this case, the performed analyses were made for Tunnel 4, for a section just upstream the steel-lined tunnel (Figure 4), where the static hydraulic load reaches its maximum value. This tunnel was chosen because Tunnels 3 and 4, if empty, are the ones in which the pore-pressures are higher because they are the internal tunnels.

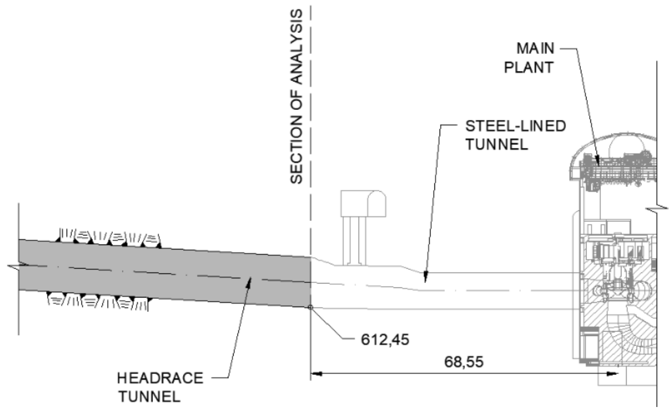


*Figure 4 – Indication of analysis section.*
*Source: Modified from Intertechne (2014).*

### 2.3.1 Support design for rock massif classes I, II and III

The preliminary design of the treatments for the tunnel sections excavated in rock mass classes I, II, and III was carried out using the support chart shown in Figure 5. The support chart is part of the Q-system and allows to determine, based on the rock mass quality, the required support detailing the bolt length, bolt spacing and thickness of shotcrete.

The resultant support for the headrace tunnels is indicated below:

- Class I ($Q > 20$): no support required except spot bolting.
- Class II ($3.0 < Q < 20$): Systematic 8 cm thick of shotcrete reinforced with fibers + bolts, 4 m long, Ø25 mm, and spacing of 2.3 m.
- Class III ($0.3 < Q < 3.0$): Systematic 8 cm thick of shotcrete reinforced with fibers + Ø25 mm bolts, 4 m long, Ø25 mm, and spacing of 1.7 m.

The validation of the support mentioned above was made through wedge stability analyses using the software Unwedge (ROCSCIENCE, 2025c). Unwedge is a software developed by Rocscience that allows underground tunnel excavations analysis with intersecting discontinuities and determines the stability of tetrahedral wedges formed along the tunnel perimeter. The software also permits the user to calculate the support requirements to achieve the factor of safety desired.

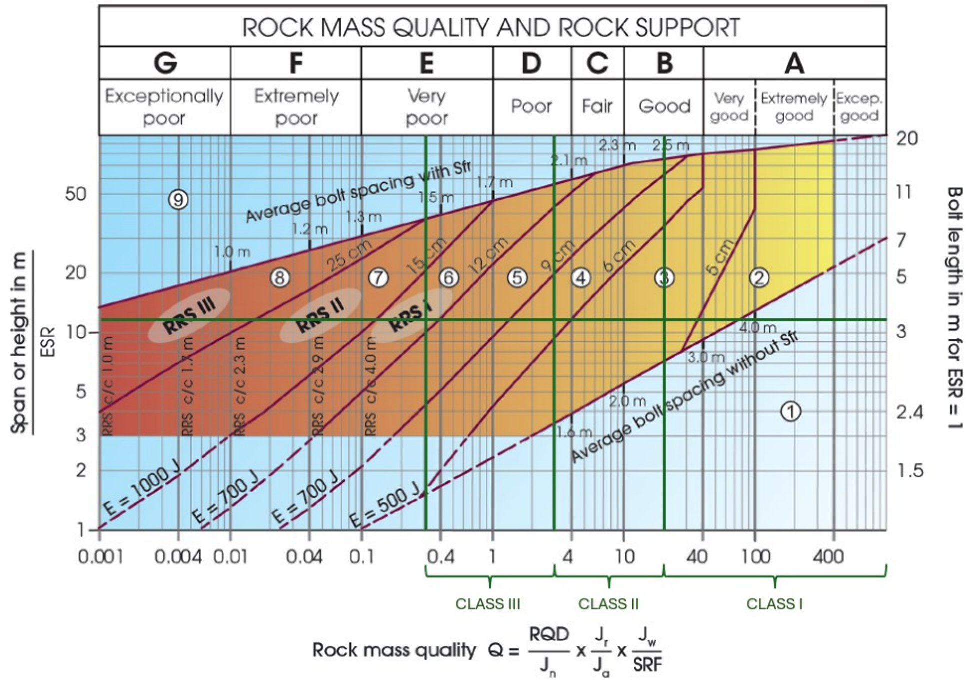


*Figure 5 – Support chart of the Q-system with estimative of the treatment required for the headrace tunnels with an equivalent diameter of 10.10 m for rock mass classes I to III.*
*Source: Modified from NGI (2022).*

The stability analysis of potential wedges was made considering the discontinuities' orientation, presented at Figure 3, and the headrace tunnels orientations (N291º and N244º).

For the Load Case I - End of construction, the potential wedges that may form around the tunnel excavations were analyzed, considering only the action of their own weight. In this loading case, the objective was to verify whether the pre-established treatment would provide a minimum acceptable safety factor of 1.50.

There will be a certain moment during the service life of the headrace tunnels when maintenance of one of them will be required. This operational condition will result in a special loading case, and the most unfavorable situation for this loading case will occur when Tunnel 3 or Tunnel 4 is under maintenance while the other tunnels are in operation. This situation will lead to the development of pore pressures around the tunnel under maintenance and, consequently, an increase in the load on potentially unstable wedges. This situation was considered as Load Case II. As this is an operational loading of an exceptional nature, the minimum acceptable safety factor is 1.30.

The determination of the pore pressures increasing around the tunnel under maintenance was made using a numerical model at Phase software. The analysis begins with the determination of pore-pressures acting around the excavation, for a cross-section just upstream the steel-lined tunnel, in which the floor of all the tunnels is at the elevation 612.45 m, as shown in Figure 6.

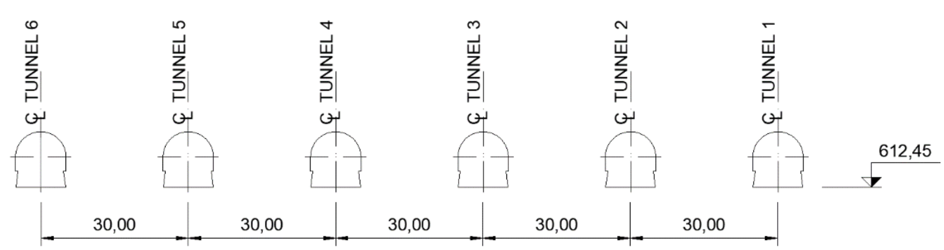


*Figure 6 – Steady seepage analysis section.*
*Source: Modified from Intertechne (2014b).*

As boundary conditions, Tunnel 4 had the condition of zero pressure applied at its excavation contour. At the other tunnels, a head of the reservoir at EL. 850 m was applied, which corresponds to the normal operational level.

The numerical model of the headrace tunnels, created in the Phase software, including the generated finite element mesh and applied boundary conditions, is shown in Figure 7. The obtained pore pressures at this model were directly imported into the Unwedge program, where the stability analyses were conducted.

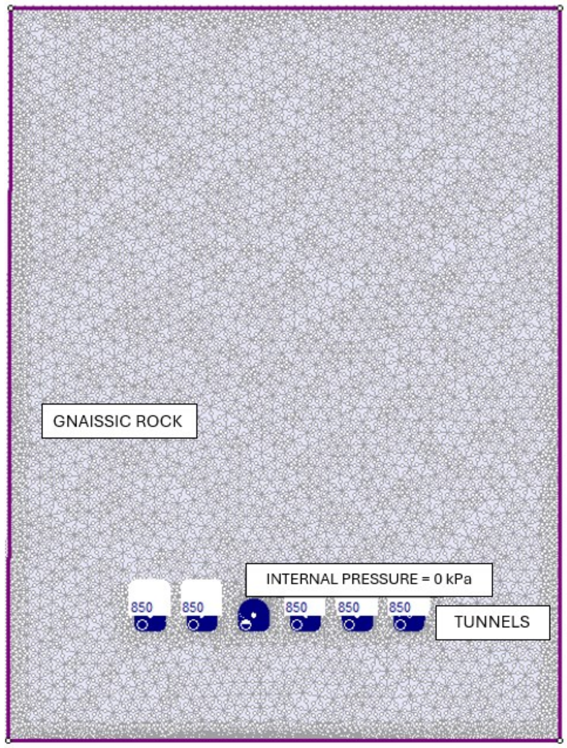


*Figure 7 – Finite element mesh and boundary conditions.*
*Source: Modified from Intertechne (2014).*

**2.3.2 Support design for rock massif classes IV and V**

The preliminary design of the treatments for the tunnel sections excavated in rock mass classes IV and V was carried out using the support chart shown in Figure 5 presented before. Class IV massif is characterized, at this specific project, by values of Q varying from 0,01 to 0,3 and corresponds to the masses in fault zones. A massif of class V presents a Q value lower than 0,01.

The resultant support for the headrace tunnels is indicated below:

- Class IV ($0{,}01 < Q < 0{,}3$): Systematic 15 cm thick of shotcrete reinforced wire mesh + Ø25 mm bolts, 4 m long, Ø25 mm, and spacing of 1,4 m.

The support design for excavations on rock masses class V was not foreseen, as this class was not expected and effectively did not occur during construction.

It is important to highlight that the pre-dimensioned treatment is intended to ensure the stability of the excavations during the construction phase. For the operational phase, the sections of the tunnels excavated in Class IV rock mass have been designed to receive a structural lining composed of reinforced concrete. The detailed design of the structural lining, however, falls outside the scope of this study as well as the verification of the adequacy of the pre-dimensioned support for construction phase.

## 3. Results and discussion

The analyses indicated that the foreseen support for rock classes II and III is sufficient to stabilize all the potential wedges, for the end of construction case, achieving safety factors higher than 1.50, minimum safety factor required for Load Case I. The analysis was carried out using the software Unwedge previously mentioned.

The Unwedge program performs wedge stability analyses for all possible combinations of discontinuities. In the case study, considering the discontinuities shown in the stereonet of Figure 3, a total of 20 combinations were obtained.

Each combination, consisting of three discontinuity sets, generates one or more potential wedges formed on the tunnel walls, crown, or floor. The wedge position depends on the orientation of the discontinuities and the tunnel's trend and plunge. An example of the wedge formation provided by the Unwedge software is shown in Figure 7. The presented analysis refers to the wedges formed by the combination of the discontinuity sets J1', J1, and J4, for the tunnel section oriented at N291°.

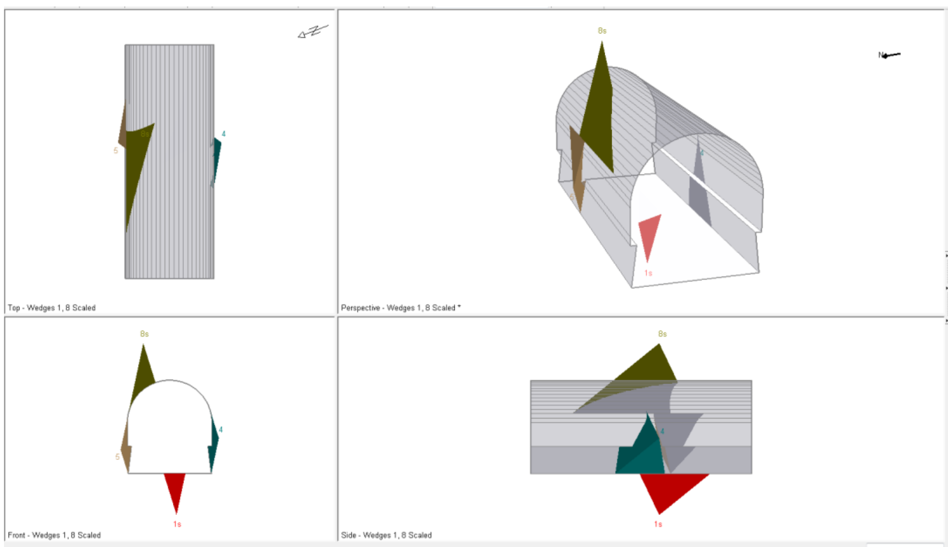


*Figure 7 – Unwedge analysis - discontinuity sets J1', J1, and J4 – tunnel N291°.*
*Source: Intertechne (2014).*

For each combination of discontinuities sets there is a critical wedge that, depending on its size and position along the excavation perimeter, requires the highest support pressure to be stabilized. These wedges are the ones formed in the crown and the upper portions of the tunnel walls.

A summary of the results obtained for the end-of-construction loading case, presenting the percentage of wedge formation at each portion of the tunnel cross section, is presented in Figure 8.

As can be seen at the results presented at Figure 8, for the headrace tunnels of Laúca, the major number of critical wedges are formed at the crown and highest part of the walls. For the tunnel oriented at N 291°, the upper left region of the cross section is the critical zone. Once the tunnel is oriented at N 244°, the critical zone is concentrated at the crown area and the upper right wall.

For the portion of the tunnels oriented at N 291°, regardless of the rock mass class, the wedge that determined the geotechnical treatment, due to requiring the highest support pressure to stabilize the rock block, was the one formed by the J1'-J3-J4 discontinuities, located in the crown. For the tunnel sections oriented at N 244°, the critical wedge was formed by the J1-J4-J2 discontinuities, located in the upper right portion of the cross-section.

As can be observed, the location with the highest number of wedge formations does not necessarily correspond to the location where the most critical wedge occurs.

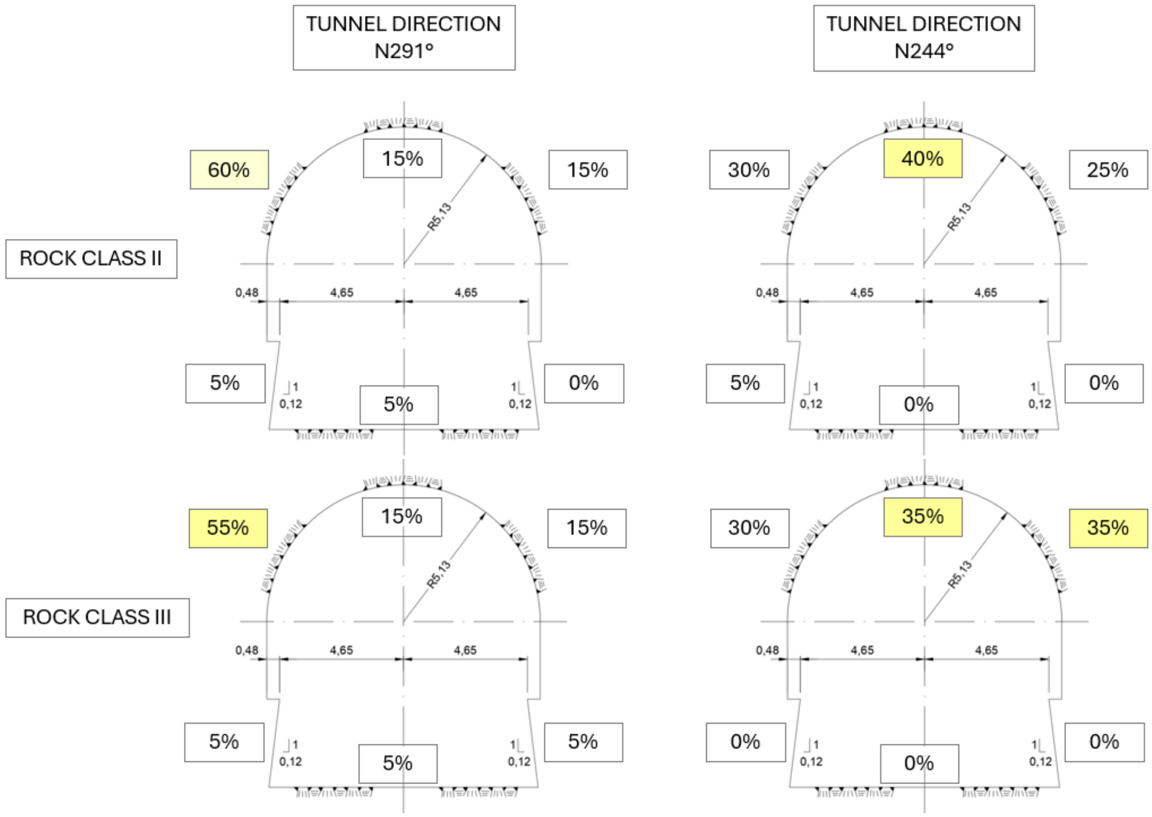


*Figure 8 – Wedge analysis for Load Case I – Summary of results – Local of unstable wedges formation. Source: Authors (2024).*

For Load Case II, the finite element model indicated that the pore-pressures are elevated, reaching 500 kPa at 3.5 m from the tunnel excavation face (Figure 9). These values of pore-pressures were imported directly into the Unwedge program, where a stability analysis was performed.

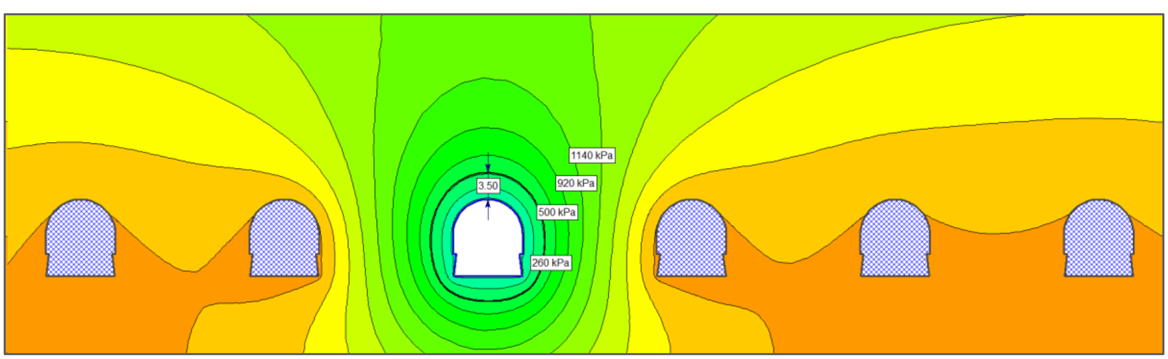


*Figure 9 – Pore-pressure iso-lines considering tunnels with no drainage system. Source: Intertechne (2014a).*

It was concluded that to guarantee the minimum safety factor required for this exceptional case, only reducing bolt spacing would not be sufficient. The solution for stabilizing the wedges then consisted of reducing pore-pressures.

The reduction of pore-pressures was achieved with the use of a drainage system around the tunnels excavations. By default, the drainage system consisted of 2 m long drains, drilled in a 2.0 x 2.0 pattern in rock masses class III. For rock masses class II, the spacing indicated was 2.5 x 2.5 m. The drainage system ensured a minimum safety factor of 1.30 at the wedge analyses.

The analysis considering the action of the drains involved modeling a 2-meter-thick region around the excavations where the permeability was increased from $3.10^{-8}$ m/s to $1.10^{-3}$ to simulate the effect of the drains. Details of the revised numerical model incorporating the effect of the drains, as well as the results obtained from the new analysis, are presented in Figure 10.

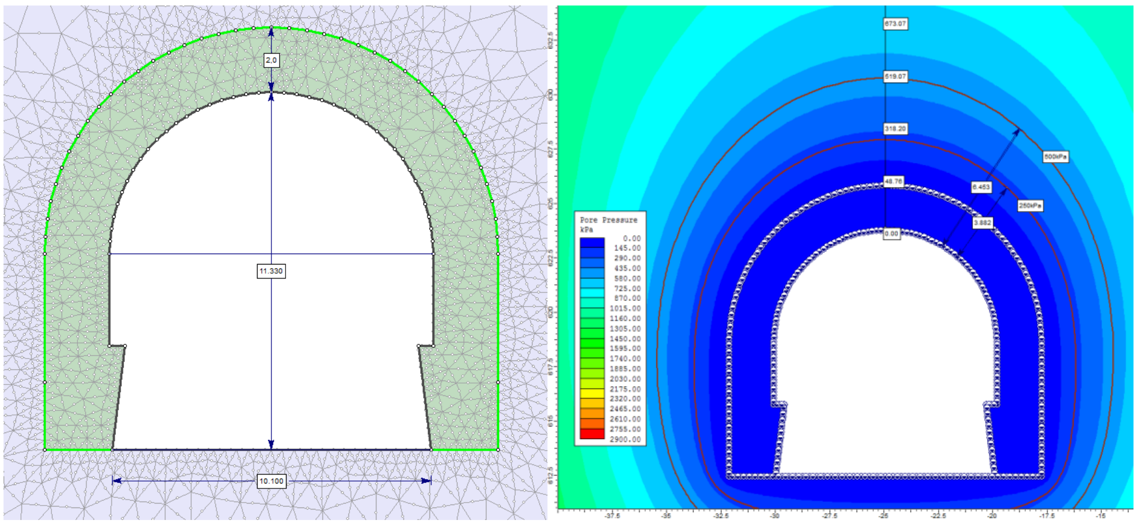


*Figure 10 – Numeric model detail and pore-pressure iso-lines considering tunnels with drainage system. Source: Intertechne (2014).*

The pore pressure results around the empty tunnel excavations indicated lower values when compared to those obtained without the implementation of the drainage system. With the inclusion of drains, a pore pressure of 500 kPa is reached at 6.45 m from the excavation face, whereas previously, this value was achieved at only 3.5 m away.

With the updated pore pressure distribution, a wedge stability analysis was conducted around the excavated section of the tunnels. An example of a wedge analysis performed in Unwedge, incorporating the imported pore pressure data, is shown in Figure 11. The presented analysis refers to the wedges formed by the combination of the discontinuity sets J1', J3, and J4, for the tunnel section oriented at N291°, excavated in a class II rock mass.

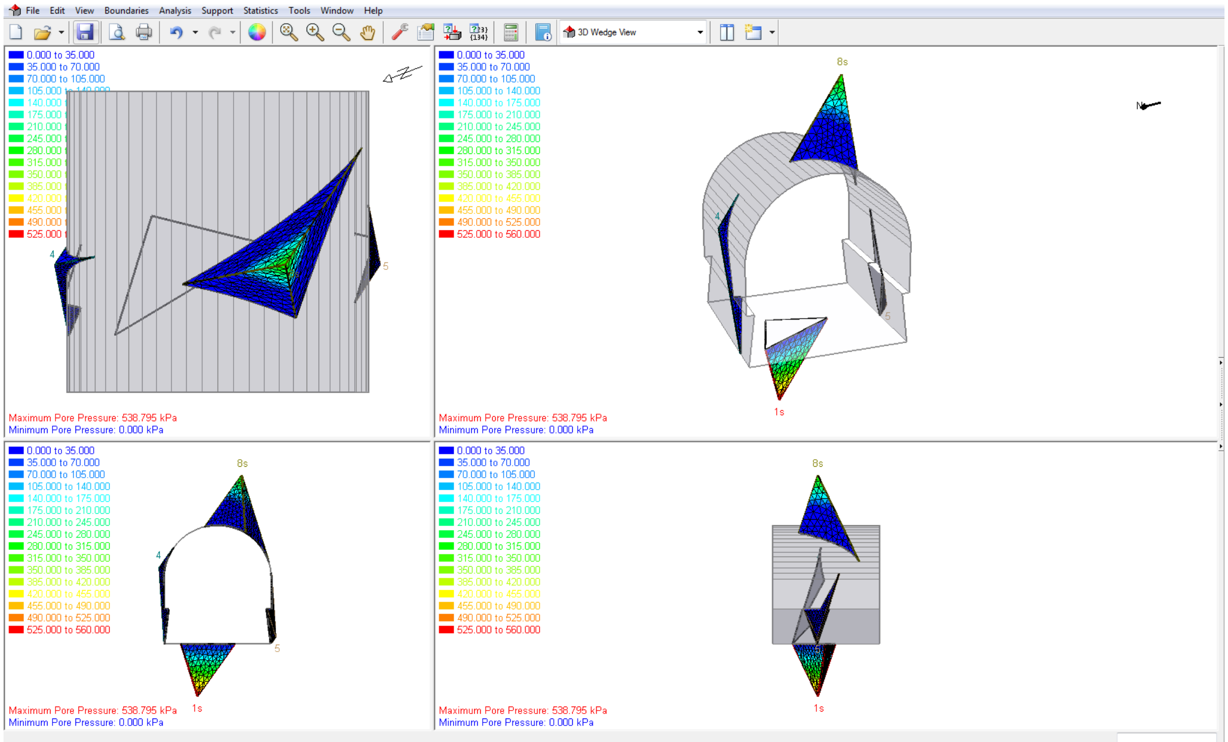


*Figure 11 – Unwedge analysis - Load Case II -* Steady seepage.
*Source: Intertechne (2014a).*

The proposed drainage system proved effective in the analyses, ensuring high safety factors for most discontinuity combinations. However, two wedges formed by the discontinuity sets J1'-J3-J4 (Tunnel N291°) and J3-J5-J4 (Tunnel N244°), in class II rock mass, required reinforcement in the previously estimated geotechnical treatment. Note that the combination J1'-J3-J4 (Tunnel N291°) was also critical for the design of geotechnical support for the Load Case I.

The necessary reinforcement involved increasing the shotcrete thickness from 8 cm to 15 cm for the discontinuity set J1'-J3-J4. For the wedge formed by the J3-J5-J4 combination, instead of implementing the treatment recommended for class II rock mass, it was necessary to apply the treatment specified for class IV rock mass.

## 4. Final Considerations

This paper covered the main design aspects of the geotechnical support of the headrace tunnels of Laúca Hydroelectric Plant.

Laúca Hydroelectric Plant is located at Malange Province in Angola. The total installed capacity is 2070 MW, from which 2004 MW generated at the main powerhouse and 70 MW at the ecological powerhouse, located at the dam's toe. In 2017, the year when the first generating unit began operation, the total installed capacity of the Angolan electrical system was 3,925 MW. In other words, the Laúca power plant alone would account for more than 30% of the country's total installed capacity.

Given its high importance, ensuring a robust generation system and safe construction works was essential for the project's success.

The generation circuit of the project is configured with six water intakes, circular shafts, headrace tunnels averaging 1,900 meters in length each, and a powerhouse cavern housing six generating units.

The tunnels have a cross-section of approximately 103 m² and a 20 m rock pillar between then and do not have a concrete lining in most of its extension, even been submitted to an external pressure of 240 m.wg of the reservoir. The reinforced concrete lining was only necessary in sections where the gneiss excavations crossed fault zones, where the rock mass was in poorer condition.

For the remaining sections, excavated in competent gneissic rock mass, where the behavior and safety of the excavations are governed by the discontinuities within the rock mass, treatments with rock bolts and shotcrete alone were sufficient to achieve the safety factors required for this type of work.

The geotechnical support design was made for two analyses cases: End of Construction and Steady Seepage, considering one tunnel empty and the other tunnels in operation.

A drainage system was also foreseen to allow pore-pressure reduction around the excavation cross-section and ensure a satisfactory performance during the tunnels emptying.

Despite the high quality of the rock mass, the incorporation of a drainage system around the tunnel excavations proved to be of great importance in reducing the need for geotechnical treatment. Although the condition of tunnel emptying does not occur frequently, accounting for this possibility during the design phase proved crucial, as some tunnels have already been emptied due to construction and operational needs.

The headrace Tunnel 1 went into operation in July 2017, the Tunnel 2 in October 2017 and the Tunnel 3 in February 2018. During the operation of tunnels 1 to 3, seepage into the empty tunnels was low. Although, at the stretches where faults were detected at the geological mapping, convergence pins and piezometers were installed for deformation monitoring around the empty tunnels' excavation. The installed piezometers were dry during the monitoring period and the convergence measures showed no variation.

The Tunnel 4 went into operation later in 2018, in November. In the next year, 2019, the Tunnel 05 had its first filling in May and in November 2020 the last tunnel, Tunnel 6, went into operation.

Some tunnels had to be emptied due to operational reasons. After these occurrences, tunnels' inspections showed no damage to the floor or failure of rock wedges. The emptied tunnels were inspected and there was no damage to the excavated section or to the floor covering, which indicates that the design considerations are valid.

**Acknowledgments**

The authors would like to thank Intertechne Consultores and the Graduate Program in Civil Engineering – PPGEC/UFPR – for supporting the completion of this study.

**References**

A’ssim, A.; Xing, Z. Y. Most Used Rock Mass Classifications for Underground Opening. *American J. of Engineering and Applied Sciences 3*: 403-411, 2010. Available at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=b5dd72bfbc4a1e9c5db4a681af64bb27380fba64#:~:text=The%20Excavation%20Support%20Ratio%20(ESR,10%20years. Accessed on 02/01/2025.

Alejano, L.R. Rock Mass Classification Systems: A Useful Rock Mechanics Tool, Often Misused. *Rock Mech Rock Eng*, 2024. https://doi.org/10.1007/s00603-024-04087-y

Barton, N., Chou, D. The Shear Strength of Jointed Rock Masses. *Rock Mechanics*, 12(3), 183–202, 1979.

Barton, N.; Lien, R.; Lunde, J. Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics 6*, 189–236, 1974. https://doi.org/10.1007/BF01239496

Cundall, P. A.; Hart, R. D. Numerical Modelling of Discontinuous Rock. *Proceedings of the 33rd U.S. Symposium on Rock Mechanics (USRMS)*. American Rock Mechanics Association, 1992.

Fiori, A. P.; Carmignani, L. *Fundamentos de mecânica dos solos e das rochas: aplicações na estabilidade de taludes*. São Paulo, 2015. 576 p.

Gray, D. H.; Parry, R. *Geotechnical Engineering for Mine Waste Storage Facilities*. AK Leiden, The Netherlands: CRC Press, 1999.

Hoek, E. *Practical Rock Engineering*. 2007. Available at: https://www.rocscience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf. Accessed on 02/01/2025.

Hoek, E.; Kaiser, P. K.; Bawden, W. F. *Support of Underground Excavations in Hard Rock*. Rotterdam: Balkema, 1995. 228 p.

Hoek, E.; Marshall, J. The effect of Discontinuities on the Stability of Underground Excavations in Rock. *Geotechnical Engineering*, 27(4), 87–108, 1976.

Intertechne. Circuitos de geração – Túneis de Adução – Geral – Tratamentos Geotécnicos – Memória de Cálculo. AHL-MC4-07B08-0001, 2014a.

Intertechne. Projeto executivo – Circuito de geração principal – Túnel de adução – Geral – Escavações – AHL-DE4-07B07-0012, 2014b.

Katereniuk, S. B. *Avaliação da resistência ao cisalhamento de descontinuidades em metarenito, metasiltito e gnaisse e aplicação de método probabilístico à estabilidade de taludes.* Dissertação (mestrado) – Universidade Federal do Paraná, Setor de Tecnologia, Programa de Pós-Graduação em Engenharia Civil – Curitiba, 2022.

MINEA. Ministério da Energia e Águas. *Angola Energia 2025 – Visão de Longo Prazo para o Sector Eléctrico*. Supervisão: Joaquim Ventura. MINEA, 2014. Available at: https://angolaenergia2025.gestoenergy.com/sites/default/files/editor/livro_angola_energia_2025_baixa.pdf. Accessed on 02/01/2025.

NGI. The Norwegian Geotechnical Institute. *Using the Q-system – Rock mass classification and support design*. Oslo, 2022. Available at: https://www.ngi.no/globalassets/bilder/forskning-og-radgivning/bygg-og-anlegg/handbook-the-q-system-may-2015-nettutg_update-june-2022.pdf. Accessed on 02/01/2025.

Rocscience. *DIPS – Graphical and Statistical Analysis Software for Orientation Data*. 2025. Available at: https://www.rocscience.com/software/dips. Accessed on 02/01/2025a.

Rocscience. *RS2 – 2D Finite Element Analysis Software*. 2025. Available at: https://www.rocscience.com/software/rs2. Accessed on 02/01/2025b.

Rocscience. *UnWedge – Underground 3D Wedge Stability Analysis Software*. 2025. Available at: https://www.rocscience.com/software/unwedge. Accessed on 02/01/2025c.

Thá, P.C.; Katereniuk, S.B.; Kraemer, S.M.; Kenzo, P.; Estevão, E.D. Projeto geotécnico da encosta do pátio dos transformadores e comportas – Aproveitamento Hidrelétrico de Laúca. *VII Conferência Brasileira sobre Estabilidade de Encostas – COBRAE 2017*. Florianópolis, 2017.

Vallejo, L.I.G.; Ferrer, M.; Ortuño, L.; Oteo, C. *Ingeniería Geológica*. Madrid: Pearson Educación, 2002.

Wittke, W. *Rock Mechanics: Theory and Applications with Case Histories*. Berlin: Springer-Verlag, 1990.

Wyllie, D. C.; Mah, C. W. *Rock Slope Engineering - Civil and Mining*. London and New York: Spon Press, 2004.

Zienkiewicz, O. C.; Taylor, R. L.; Zhu, J. Z. *The Finite Element Method: Its Basis and Fundamentals*. Elsevier, 2005.