Pumped HYDROelectric Storage in post MINEd areas to support regional net-zero emission energy systems development – HYDROMINE

Project ID: 101069750

D 2.3. Results of numerical modelling of reservoir slopes

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Partners:

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D.2.3. Results of numerical modelling of reservoir slopes

Numerical modelling was performed to assess slope stability at the three investigated sites: KOSD, CSA and Pesteana South. The analysis aimed to evaluate slope behavior under different geotechnical conditions and to identify the potential influence of variations in material properties on overall stability.

For numerical analysis, three different software programs were used: SILDE, SLOPE and PLAXIS 3D Advanced.

- **SLIDE – Rocscience**

SLIDE is a 2D geotechnical software used for slope stability analysis based on the Limit Equilibrium Method (LEM). It evaluates the stability of natural slopes, embankments, excavations, and earth dams by calculating the Factor of Safety (FoS) for potential slip surfaces.

Main advantages:

- Supports various limit equilibrium methods, including Bishop, Janbu, Spencer, and Morgenstern–Price.
- Automatically searches for critical slip surfaces and calculates the minimum Factor of Safety.
- Considers groundwater conditions, seismic loading, external loads, and reinforcement systems.
- Provides probabilistic and sensitivity analyses to evaluate uncertainties in soil parameters.
- Offers fast calculations, intuitive modelling, and clear graphical results.

- **SLOPE – GeoStru**

Description: SLOPE is a 2D slope stability analysis software that uses Limit Equilibrium Methods (LEM) to evaluate the stability of soil and rock slopes. It is widely applied to embankments, earth dams, open-pit mines, and natural slopes, particularly where groundwater and environmental conditions influence stability.

Main advantages:

- Supports multiple limit equilibrium methods, including Bishop, Janbu, Spencer, and Morgenstern–Price.
- Allows detailed modelling of complex slope geometries, soil layers, and loading conditions.
- Integrates with other GeoStudio tools, such as SEEP/W and SIGMA/W, to incorporate seepage and stress conditions into stability analyses.
- Supports stability assessments under changing groundwater conditions and different construction stages.
- Provides sensitivity and probabilistic analyses to assess the influence of uncertain geotechnical parameters.

3. PLAXIS – Bentley Systems

Description: PLAXIS is advanced geotechnical numerical modelling software based on the Finite Element Method (FEM). It is used to analyse soil and rock behavior, including stresses, strains, deformations, and stability under different loading and construction conditions. It is available in both 2D and 3D versions.

Main advantages:

- Provides detailed analysis of soil deformation, stress distribution, and failure mechanisms.
- Includes advanced constitutive models, such as Mohr–Coulomb, Hardening Soil, and Hardening Soil with Small-Strain Stiffness.
- Simulates staged construction, excavation, embankment development, and soil–structure interaction.
- Allows coupled groundwater flow and deformation analyses, including consolidation and pore-pressure changes.
- Evaluates slope stability using the Strength Reduction Method (SRM), while also predicting displacements and plastic deformation.

In table 1 the main capabilities of the three software are comparatively presented.

Table 1 Comparative features of geotechnical software

Feature	SLIDE	SLOPE/W	PLAXIS
Analysis method	LEM	LEM	FEM
Primary application	Slope stability	Slope stability and coupled analyses	Advanced geotechnical modelling
Factor of Safety	Yes	Yes	Yes, through strength reduction
Deformation analysis	No direct prediction	Through SIGMA/W integration	Yes
Groundwater analysis	Yes	Advanced with SEEP/W	Advanced, including coupled analysis
Calculation complexity	Low–moderate	Low–moderate	Moderate–high
Main strength	Fast and reliable stability assessment	Integration of stability, seepage, and stress analyses	Detailed simulation of soil behaviour and deformation

In conclusion, SLIDE and SLOPE are particularly efficient for conventional slope stability assessments and factor of safety calculations. PLAXIS provides a more comprehensive understanding of geotechnical behavior by modelling stresses, deformations, and progressive failure mechanisms, although it generally requires more detailed input parameters and computational effort.

1. Numerical modeling KOSD quarry

Due to the limited availability of detailed measurements and information regarding the fissure and fracture systems within the rock masses, several scenarios were defined to account for uncertainties in the geotechnical characterization. The three scenarios considered different degrees of rock mass deterioration and structural discontinuities, allowing for a comparative assessment of slope stability under varying conditions (slightly weathered basalt, weathered basalt and fractured basalt). The geotechnical model was built on the basis of information sent by partners from WUST (Figure 1).

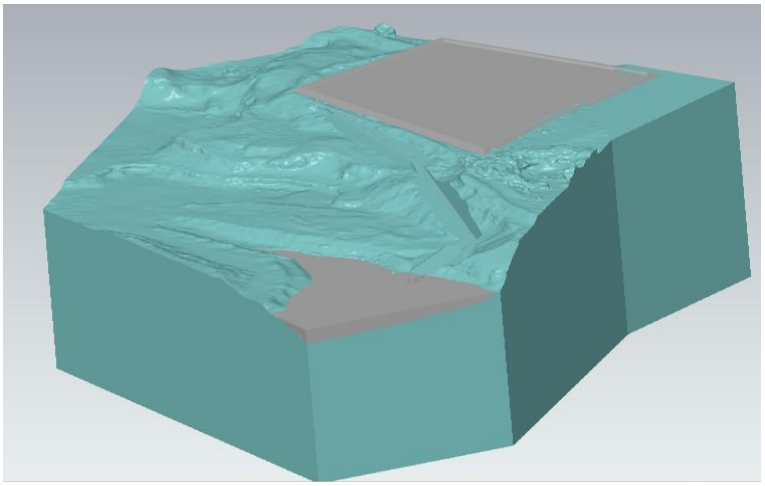


Figure 1 The demonstrator location with reservoirs and piping ramp

The geotechnical parameters used for the numerical modelling of the basalt at the KOSD site are presented in D.2.1. These parameters were used as input data for the numerical simulations and the subsequent slope stability assessment.

1.1. Stability analysis with PLAXIS LE

PLAXIS LE – stability analysis using the Limit Equilibrium Method (LEM). Potential slip surfaces are assumed, and the program searches for the critical surface and determines the factor of safety Fs based on force and/or moment equilibrium. It includes established methods such as Janbu, Bishop, Spencer, Morgenstern–Price etc.

PLAXIS LE is best used as the first-stage stability assessment tool, followed by detailed rock-mass modelling once field mapping and geomechanical investigations are completed.

The results obtained with PLAXIS LE for the three cases analyzed can be followed in figures 2, 3 and 4.

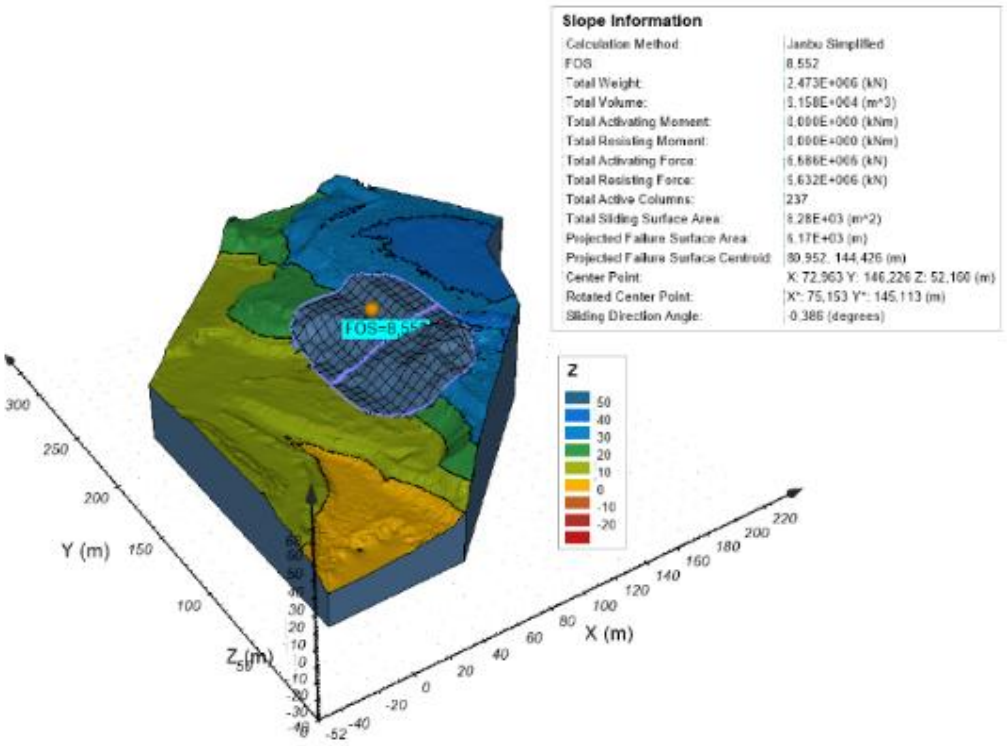


Figure 2 Case 1 - Slightly weathered basalt – Fs = 8,552

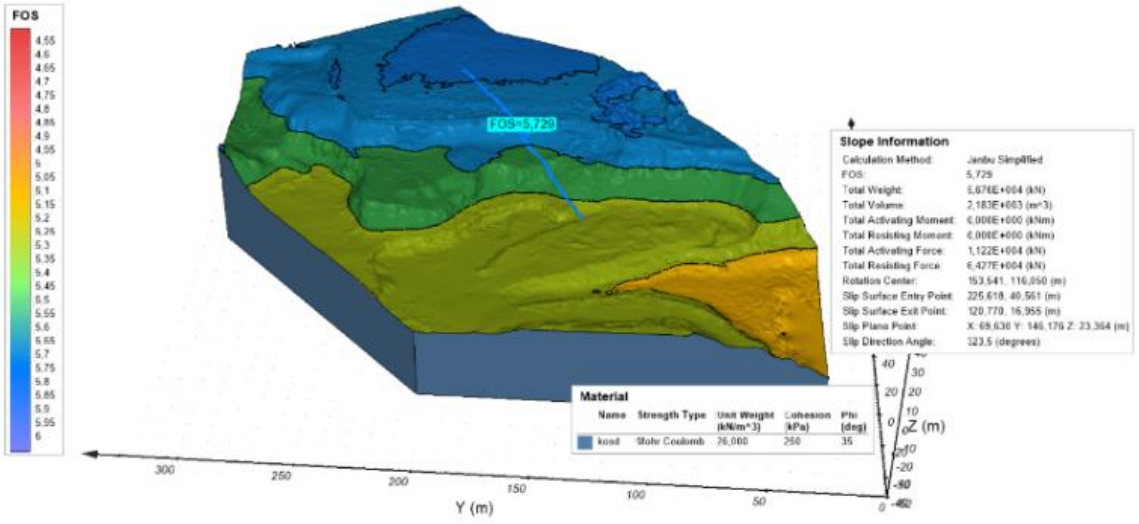


Figure 3 Case 2 - Weathered basalt – Fs = 5,729

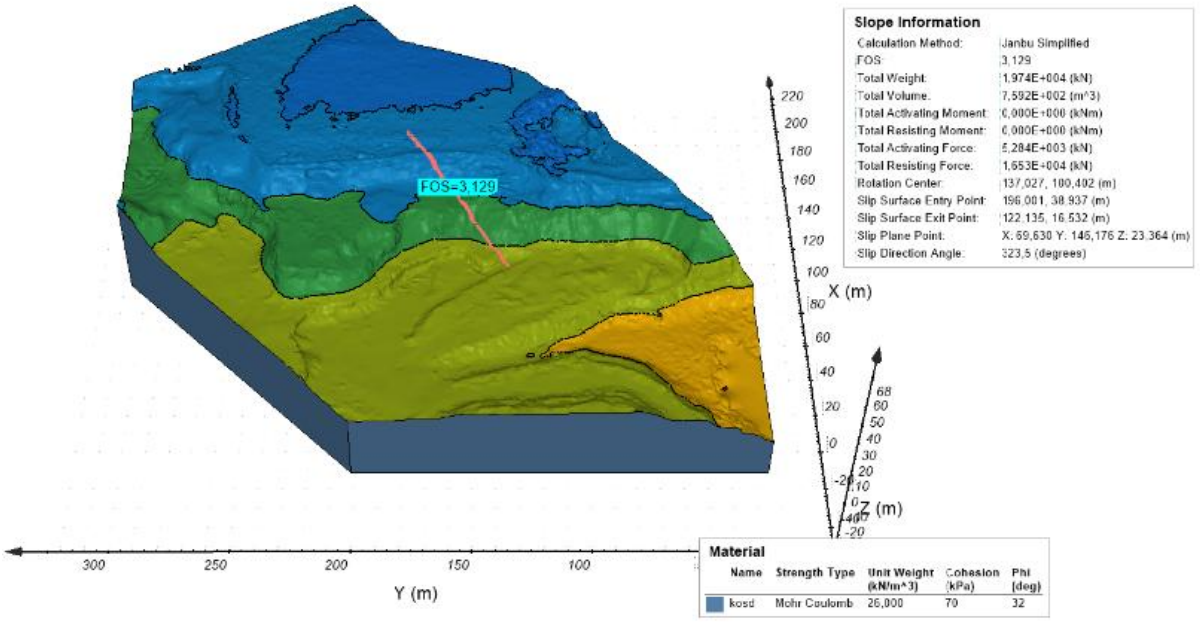


Figure 4 Case 3 - Fractured basalt – Fs = 3,129

1.2. Stability analysis with SLOPE by GEOSTRU

GeoStru Slope – also based on Limit Equilibrium Methods (LEM), primarily focused on slope stability. It analyzes failure surfaces and calculates the factor of safety Fs using limit equilibrium methods; it allows for the consideration of soil stratification, water, seismic effects, external loads, and stabilization measures.

Figures 5, 6 and 7 present the analyzed cross section and the results for the three cases considered.

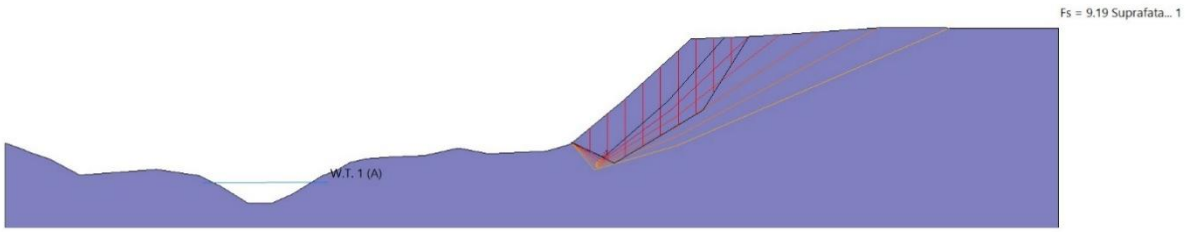


***Figure 5 Case 1* - Slightly weathered basalt, Fs = 9,19**

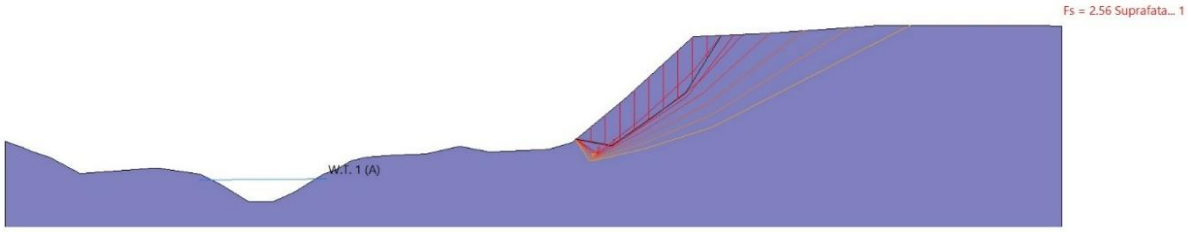


***Figure 6 Case 2 - Weathered basalt*, Fs = 2,56**

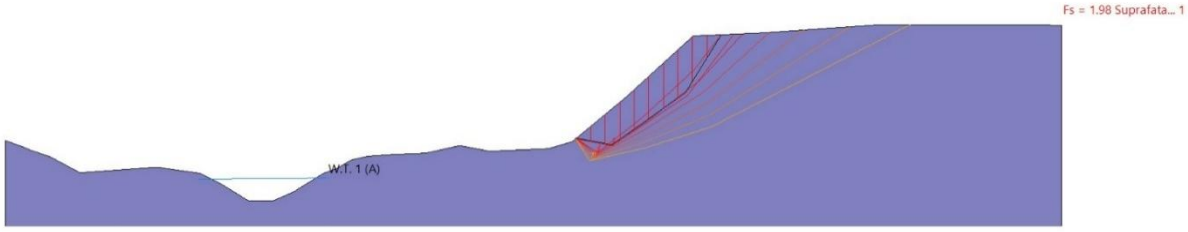


***Figure 7 Case 3 - Fractured basalt*, Fs = 1,98**

1.3. Stability analysis with SLIDE by ROCSCIENCE

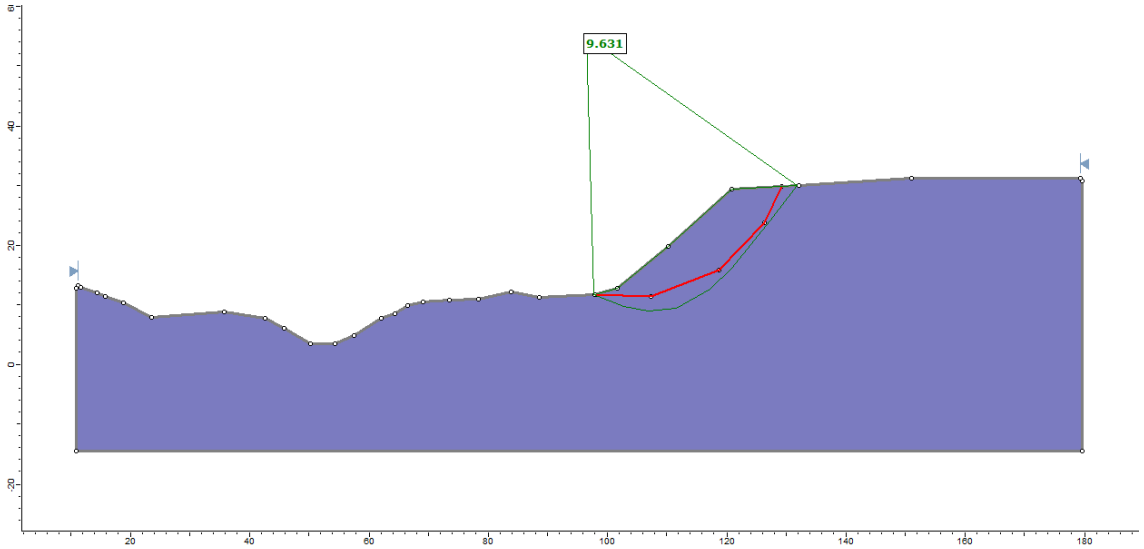


Figure 8 *Slightly weathered basalt*, Fs = 9.63

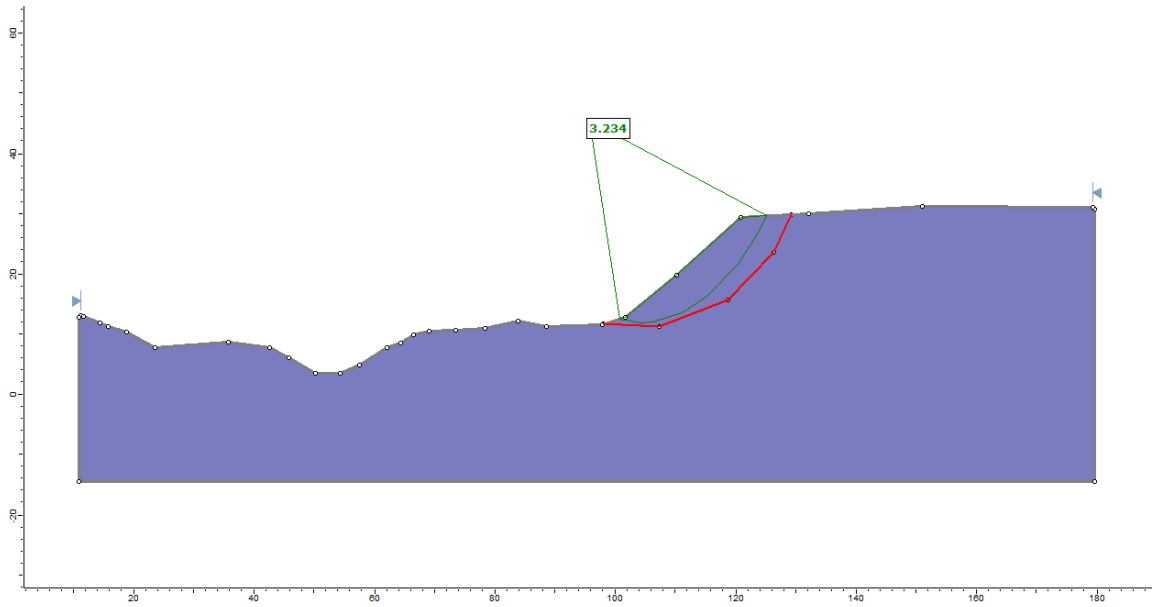


***Figure 9 Weathered basalt*, Fs = 3.23**

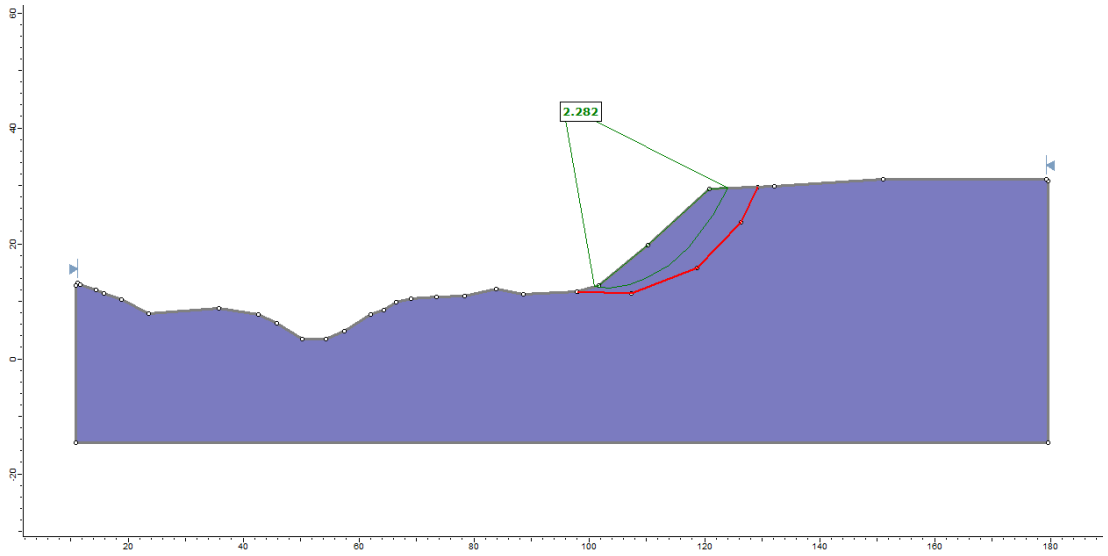
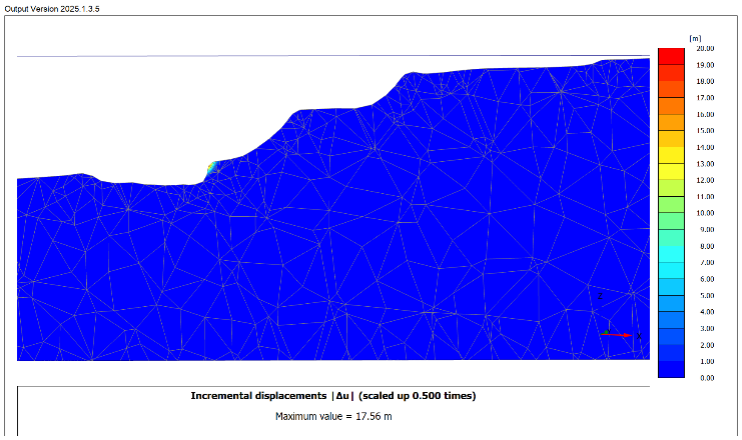


***Figure 10 Fractured basalt*, Fs = 2.28**

1.4. Stability analysis with PLAXIS 3D ADVANCED



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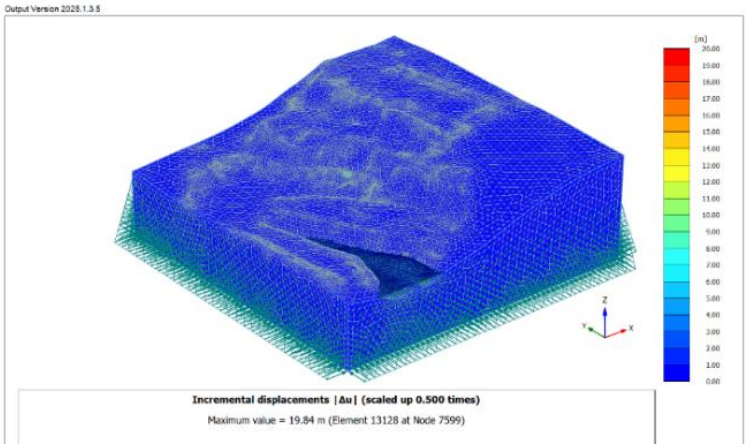

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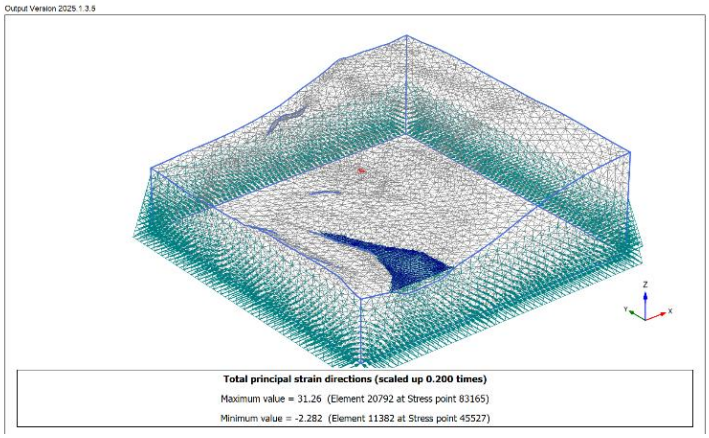
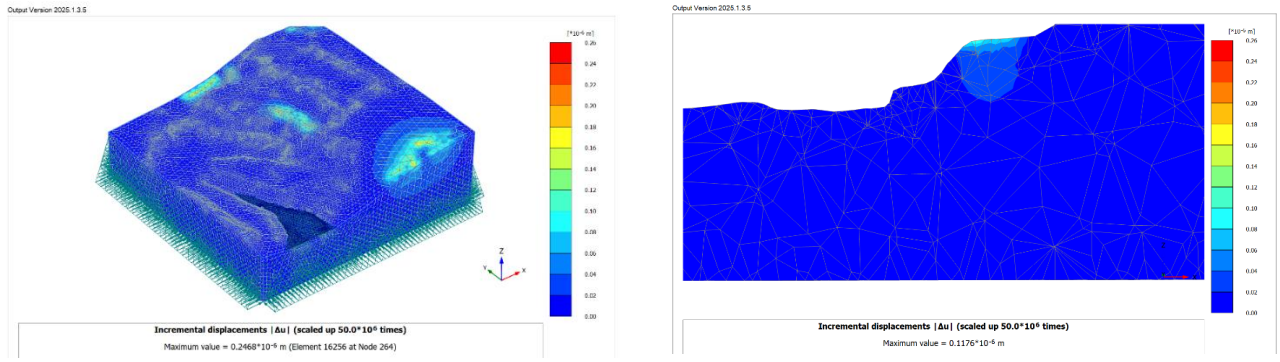


c.

Figure 11 *Case 1 - Slightly weathered basalt, F*s = 6.198

a. Incremental displacements; b. Incremental displacements for a section; c. Total principal strain direction



a. b.

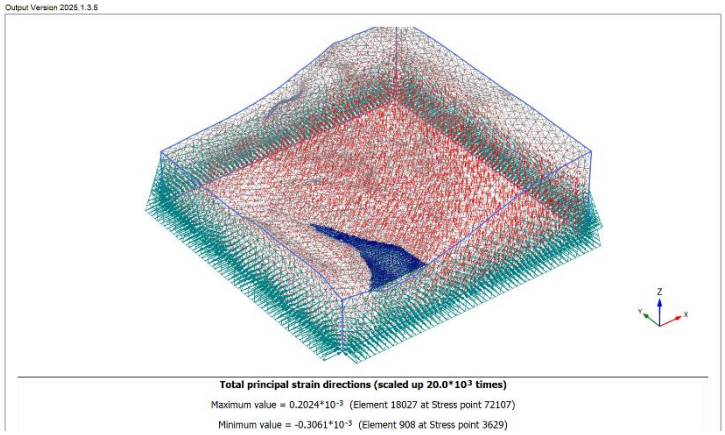


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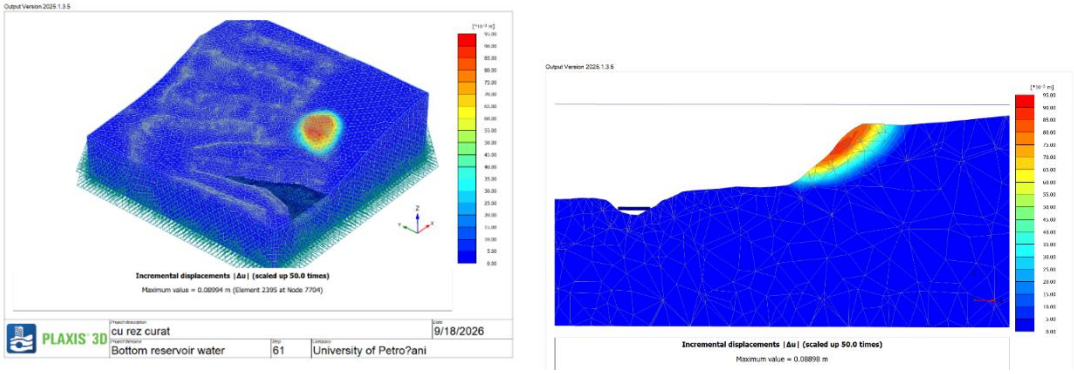
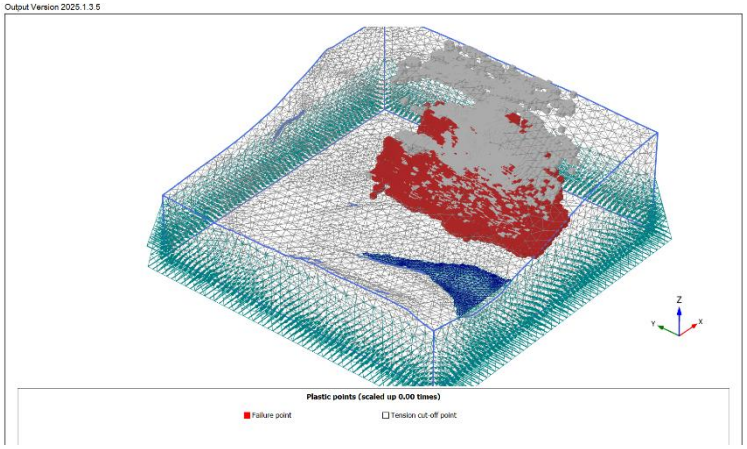
Figure 12 *Case 2 - Weathered basalt*, Fs = 2.605

a. Incremental displacements; b. Incremental displacements for a section; c. Total principal strain direction



a. b.



c.

Figure 13 Case 3 - Fractured basalt, Fs = 2.393

a. Incremental displacements; b. Incremental displacements for a section; c. Total principal strain direction

Three-dimensional analysis using the strength reduction method yields the following global factor of safety:

- Fs = 6.198 for the case of slightly weathered basalt - the analysis provides a strong resistance to shear deformation, with no indication of a continuous critical failure surface developing through the rock mass. The high Fs suggests a substantial stability margin for this modeled case.
- Fs = 2.605 for the case of weathered basalt - the slope remains stable, but with a considerably reduced stability margin and the displacement contours show localized deformation concentrations near the upper slope/bench and along parts of the slope face, reflecting the reduced strength and stiffness associated with weathering.
- Fs = 2.393 for the case of fractured basalt - the slope remains stable under the modeled conditions, the incremental displacement field indicates the development of a critical mechanism localized predominantly in the upper part of the slope, and the distribution of plastic points is consistent with the progressive mobilization of the soil mass strength during the safety analysis.

Table 2 Summary of stability analyses

Software	Slightly weathered basalt	Weathered basalt	Fractured basalt
PLAXIS 3D	6.19	2.60	2.39
PLAXIS LE	8.55	5.73	3.12
SLOPE	9.19	2.56	1.98
SLIDE	9.63	3.23	2.28

The results indicate that the geotechnical condition of the basalt rock mass significantly influences overall slope stability. The factor of safety progressively decreases as the rock mass deteriorates from slightly weathered to weathered and fractured basalt. PLAXIS 3D provides additional insight into deformation, stress redistribution, plastic yielding, and the development of potential failure mechanisms, while SLOPE, SLIDE, and PLAXIS LE provide independent limit-equilibrium assessments.

The generally comparable results obtained using PLAXIS 3D, SLOPE, and SLIDE, particularly for the weathered and fractured basalt conditions, strengthen confidence in the overall interpretation. In conclusion, the slope is predicted to remain globally stable under all three basalt conditions investigated, considering the modeled geometry, material properties, groundwater conditions, and loading assumptions.

1.5. Bearing capacity of soil cover

The bearing capacity of the foundation soil is the maximum pressure that the soil can withstand beneath a foundation without losing stability due to shear failure and without causing deformations (settlements) that would affect the normal functioning of the structure.

Types of bearing capacity:

• Ultimate bearing capacity (q_u) is the pressure at which the soil reaches the state of shear failure.

• Allowable bearing capacity (q_{adm}) is the maximum pressure permitted during service, obtained by applying a safety factor to the ultimate bearing capacity:

$$q_{adm} = \frac{q_u}{F_s}$$

where:

qu - ultimate load-bearing capacity;

Fs - safety factor (typically 2,5–3).

Determining the bearing capacity is one of the most important steps in a geotechnical study, as it allows foundations to be designed so that the loads transmitted to the structure are safely supported. Insufficient bearing capacity can lead to excessive settlement, tilting of the structure, or even failure of the foundation soil.

Considering Terzaghi's classic formula for a continuous foundation, with:

• foundation width: B = 1.0 m;

• foundation depth: Df = 1.0 m;

• ultimate bearing capacity qu;

• safety factor F_s = 3,

for determining the allowable bearing capacity, the calculation equation is:

$$q_u = c \cdot N_c + \gamma \cdot D_f \cdot N_q + 1/2 \cdot \gamma \cdot B \cdot N_\gamma$$

where the load-bearing capacity factors are calculated using:

$$N_q = e^{\pi \cdot tan\varphi} tan^2(45^o + \frac{\varphi}{2})$$

$$N_c = \frac{N_q - 1}{tan\varphi}$$

$$N_\gamma = 2(N_q + 1)tan\varphi$$

Table 3 Determination of Load-Bearing Capacity Factors

φ [°]	N_q	N_c	N_γ
16.57	4.48	11.80	3.27
18.13	5.18	13.09	4.05

Table 4 Calculation of load-bearing capacity

Sample	*c [kPa]*	*φ [°]*	*γ [kN/m³]*	*q_u [kPa]*	*$q_{adm} = q_u/3$ [kPa]*
Hydromine 1	57.54	16.57	19.975	804.95	268.32
Hydromine 2	37.70	18.13	18.358	641.78	213.93
Hydromine 3	39.68	16.57	18.178	591.58	197.93
Hydromine 4	41.67	16.57	18.934	616.61	205.54
Hydromine 5	29.76	18.13	19.044	551.24	183.75
Average	41.27	17.19	18.89	641.23	213.89

Sample 1 exhibits the highest bearing capacity due to its high cohesion (57.54 kPa). Sample 5 has the lowest bearing capacity, as it has the lowest cohesion value (29.76 kPa).

The differences between the samples are primarily influenced by cohesion, and secondarily by the angle of internal friction and bulk density.

Discussions regarding the pressure exerted by the pipeline on the ground

Based on the available data, the bedrock is basalt and impermeable. The pipeline will be laid freely on the surface, without support, on levelled ground and/or in an open trench. Beneath the pipeline: solid rock and compacted rock fragments or gravel.

Maximum ground gradient: 20°.

The weight of the water in the pipe

Area	962,11 cm²	350 mm diameter
Weight of water per m	96,21kg	1m pipe
Total mass of water	19.242,26 kg	pipework system 200 m
The weight of the pipe		
Outer diameter	400 mm	
Inner diameter	350 mm	
Density of HDPE	0,92 g/cm³	
Weight of the pipe per metre	27,10 kg	1000 mm
Total mass of the pipe	5.419,25 kg	200 m total length

For a pipe laid directly on the ground, the maximum pressure exerted is much lower than the bearing capacity of the ground, qadm = 213.894 kPa, which means that the ground (particularly as it consists of solid rock and compacted gravel) will support the pipe safely, with no risk of structural failure of the ground.

As the pipe is circular and rests on a flat surface, the theoretical contact between the cylinder and the ground is a line. In reality, however, under the weight of the pipe and due to the granular nature of the compacted gravel, the material will settle slightly, creating an actual contact width (a support footprint).

The pressure calculation is carried out for the worst-case scenario (the pipe filled with water):

Calculation of the force (weight) per linear metre

Weight of the full pipe: m = 119.31 kg/m

Acceleration due to gravity: g = 9.81 m/s²

Force exerted: F = m g = 119.31 × 9.81 = 1,170.43 N/m = 1.17 kN/m².

Determination of ground pressure as a function of contact width.

- ***First case***

Minimum/point contact on hard rock, very narrow contact patch of b = 5 cm.

$$\sigma = \frac{F}{b} = \frac{1{,}17}{0{,}05} = 23{,}41\ kPa$$

- ***Second case***

Standard angle of support in the trench, estimated footprint of b = 10 cm.

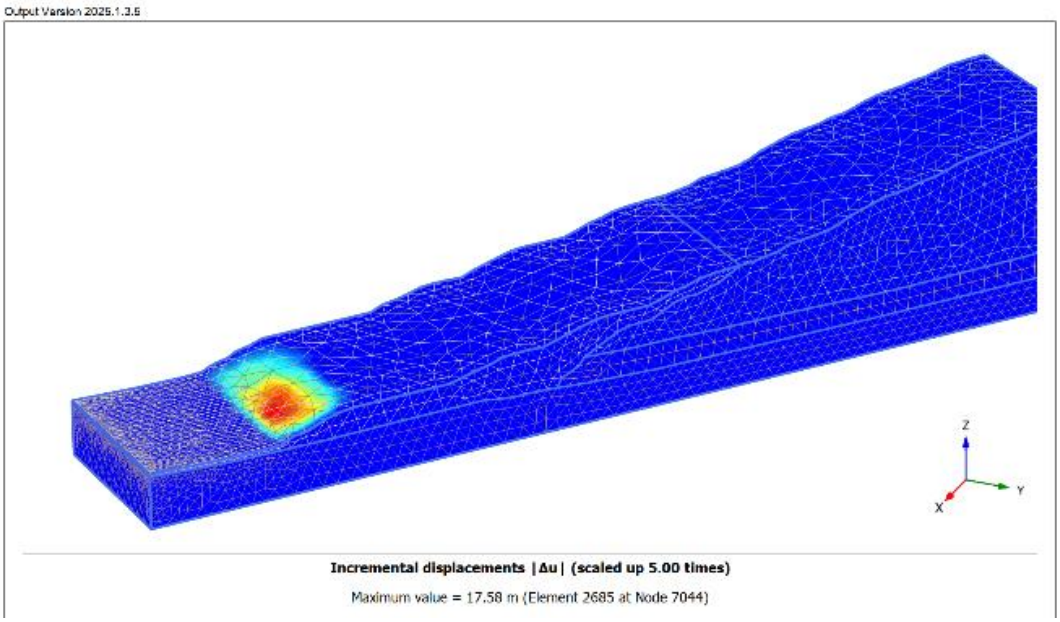
$$\sigma = \frac{F}{b} = \frac{1{,}17}{0{,}1} = 11{,}7\ kPa$$

Conclusion

Even in the worst-case scenario of extremely rigid contact (σ = 23.41 kPa), the pressure exerted by the pipeline is almost 10 times less than the soil's permissible bearing capacity of 213.894 kPa.

2. CSA - Open Cast

The numerical analyses were performed using three-dimensional finite element modelling in PLAXIS 3D Advanced. The analyzed sections were selected as representative cross-sections of the mining area and were modelled considering the identified geological and geotechnical units. The geometry of the models was defined based on the available topographic and geological information, including the existing excavated slopes and the water body formed within the former mining area.



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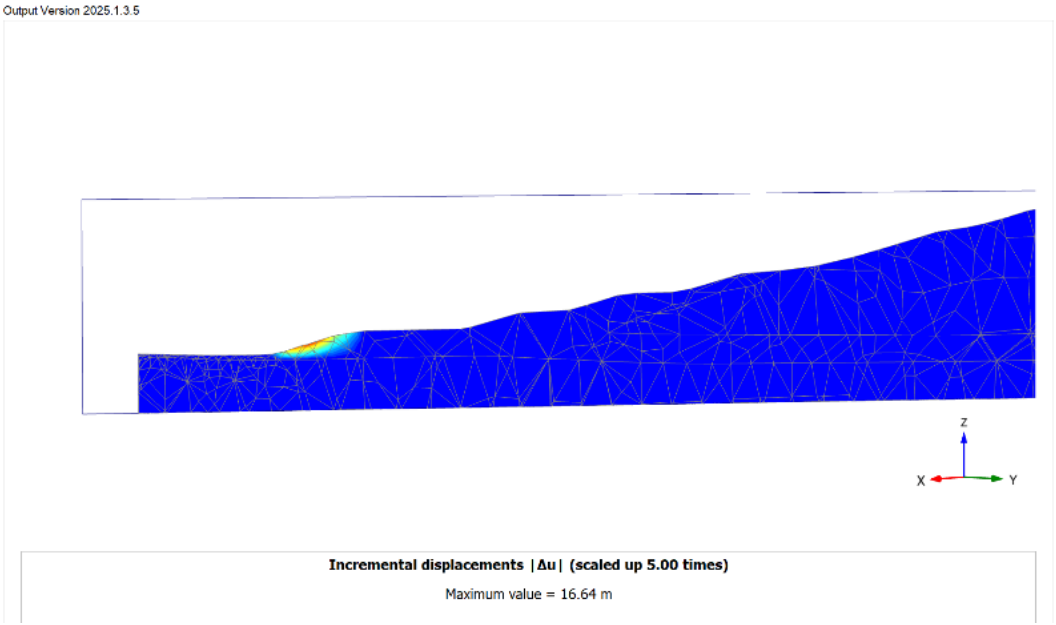

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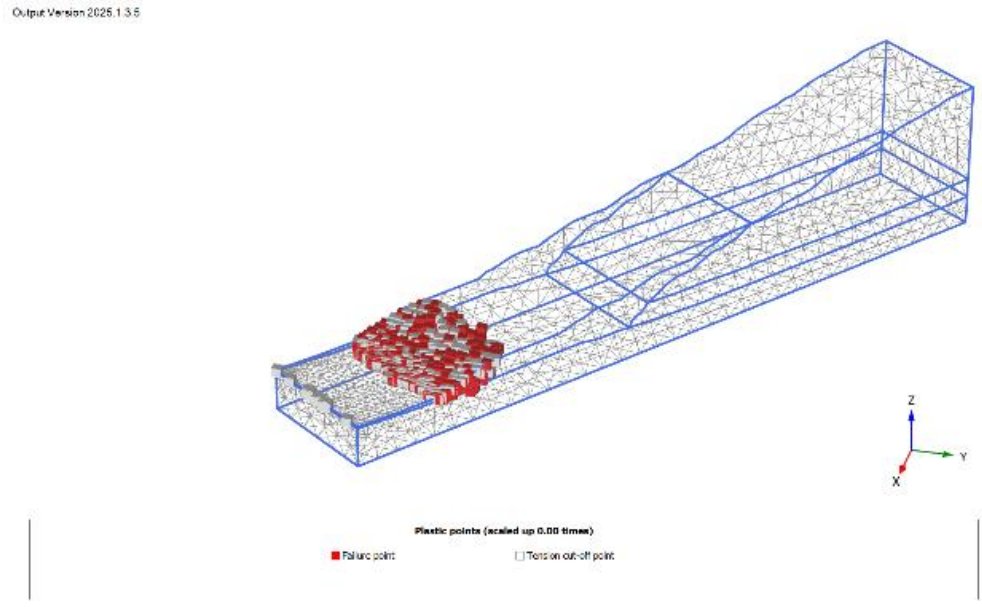

c.

Figure 14 CSA Open Cast - stability analysis results

a. Incremental displacements; b. Incremental displacements for a section; c. Total principal strain direction

Table 5 CSA Open Cast - stability analysis results

HL	Plaxis	Slope	
	Undrained	Morgenstern–Price	Janbu
180	1.223	1.23	1.14
170	1.225	1.28	1.20
160	1.227	1.34	1.25
150	1.229	1.41	1.31
140	1.231	1.40	1.39
130	1.234	1.41	1.26

The analyses indicate that the calculated factor of safety (FS) is influenced by the hydrostatic level (HL), although the magnitude of this influence varies depending on the method applied. In the PLAXIS analysis using the Undrained B material model, the factor of safety remains almost constant, ranging from 1.223 to 1.234. This limited variation indicates that, under the assumptions adopted in the numerical model, changes in the hydrostatic level have a relatively small effect on the calculated stability. However, this result must be interpreted in relation to the selected constitutive model, geotechnical parameters, hydraulic conditions, and numerical modelling assumptions.

In contrast, the Morgenstern - Price method shows a more pronounced decrease in the factor of safety, from 1.41 at HL = 130 m to 1.23 at HL = 180 m. The Janbu method exhibits a similar overall trend, with FS values ranging from 1.39 to 1.14, the lowest value also occurring at HL = 180 m. These results demonstrate the sensitivity of limit equilibrium analyses to variations in the hydrostatic level. As the lake level rises, changes in water pressure can reduce the effective stresses within the slope and consequently decrease the available shear resistance, leading to a reduction in the calculated factor of safety.

The differences between the results obtained using PLAXIS Undrained B and the limit equilibrium methods can be attributed to their different theoretical approaches and modelling assumptions. PLAXIS evaluates slope stability through finite element strength reduction analysis, whereas the Morgenstern - Price and Janbu methods determine the factor of safety based on limit equilibrium conditions. Consequently, the methods may respond differently to variations in hydraulic conditions, stress distribution, material behavior, and the geometry of the potential failure surface. The results should therefore be interpreted comparatively, taking into account the limitations and assumptions associated with each method.

Although all calculated factors of safety remain greater than 1.0, indicating that the analyzed slopes do not reach the theoretical limiting equilibrium condition under the simulated scenarios, this does not necessarily demonstrate that the slopes satisfy the applicable stability requirements. At the maximum analyzed hydrostatic level of 180 m, the Morgenstern - Price method yields an FS of 1.23, while the Janbu method gives an FS of 1.14. These values indicate a reduced stability margin under elevated lake-level conditions, particularly according to the Janbu analysis.

Overall, the results confirm that increasing the hydrostatic level is generally associated with a decrease in the calculated factor of safety, although the extent of this reduction differs between the numerical and limit equilibrium methods. The findings highlight the importance of considering variations in lake level when evaluating slope stability, as changes in hydraulic conditions may influence the stress state and shear resistance of the materials. The interpretation of the results should also consider the applicable stability criteria, the reliability of the geotechnical parameters, and the assumptions used in the numerical and limit equilibrium models.

3. Pesteana South – open pit

Three-dimensional numerical analyses were conducted using PLAXIS 3D to investigate the hydro-mechanical response of the rock mass during operation of the Pumped Hydroelectric Energy Storage (PHES) system. The numerical model was developed to simulate the interaction between the reservoirs, the surrounding slopes, and the geological formations under cyclic loading conditions associated with repeated reservoir filling and drawdown.

The three-dimensional geometry was generated based on the topographic configuration of the study area and the proposed reservoir layout. The model included

the rock mass surrounding the reservoirs as well as the main geological units identified during the site characterization. The model boundaries were positioned sufficiently far from the area of interest to minimize boundary effects on the numerical results. Horizontal displacements were restrained along the vertical boundaries, while the base of the model was fixed in all translational directions.

The rock mass was discretized using ten-node tetrahedral finite elements available in PLAXIS 3D. A medium-to-fine mesh was adopted, with local mesh refinement implemented around the reservoir slopes and in areas characterized by significant geological discontinuities, where higher stress gradients and deformation concentrations were expected. Mesh sensitivity analyses were performed to ensure that the calculated displacements and stress distributions were independent of the element size.

The mechanical behavior of the rock mass was represented using the Mohr - Coulomb constitutive model, which assumes linear elastic behavior before yielding and perfectly plastic behavior after the failure criterion is reached. The model parameters included Young's modulus (E), Poisson's ratio (v), cohesion (c), friction angle (φ), dilatancy angle (ψ), and unit weight (γ). Material properties were assigned according to the lithological units identified during the geological investigations and calibrated using available laboratory and field test data.

Groundwater conditions were incorporated through the groundwater flow module available in PLAXIS 3D. Initial pore-water pressures were established according to the natural groundwater regime, while transient hydraulic conditions were introduced to simulate reservoir impoundment and drawdown. Variations in hydraulic head generated corresponding changes in pore-water pressure, allowing the coupled hydro-mechanical analysis to evaluate their influence on effective stresses and rock mass deformation.

The construction and operational sequence were simulated using staged construction analysis. The initial stress state was generated using the gravity loading procedure, followed by the excavation and reservoir formation stages. Reservoir operation was then represented through successive loading and unloading phases corresponding to cyclic changes in water level. Different operational scenarios, including rapid drawdown and prolonged impoundment, were analyzed to assess their influence on stress redistribution and slope stability.

The numerical simulations provided spatial distributions of total and effective stresses, displacements, plastic zones, and pore-water pressures. These results formed the basis for the subsequent evaluation of ground deformation and slope stability under both normal operating conditions and extreme loading scenarios.

3.1. Excavated Slope

A numerical stability analysis was performed to evaluate the response of the excavated slope under varying lake water levels. The results include displacement, stress distribution, and factor of safety, allowing the influence of changing hydraulic conditions on slope stability to be assessed. The representative model used in the analysis is shown in figure 15 (PLAXIS) and 16 (SLOPE).

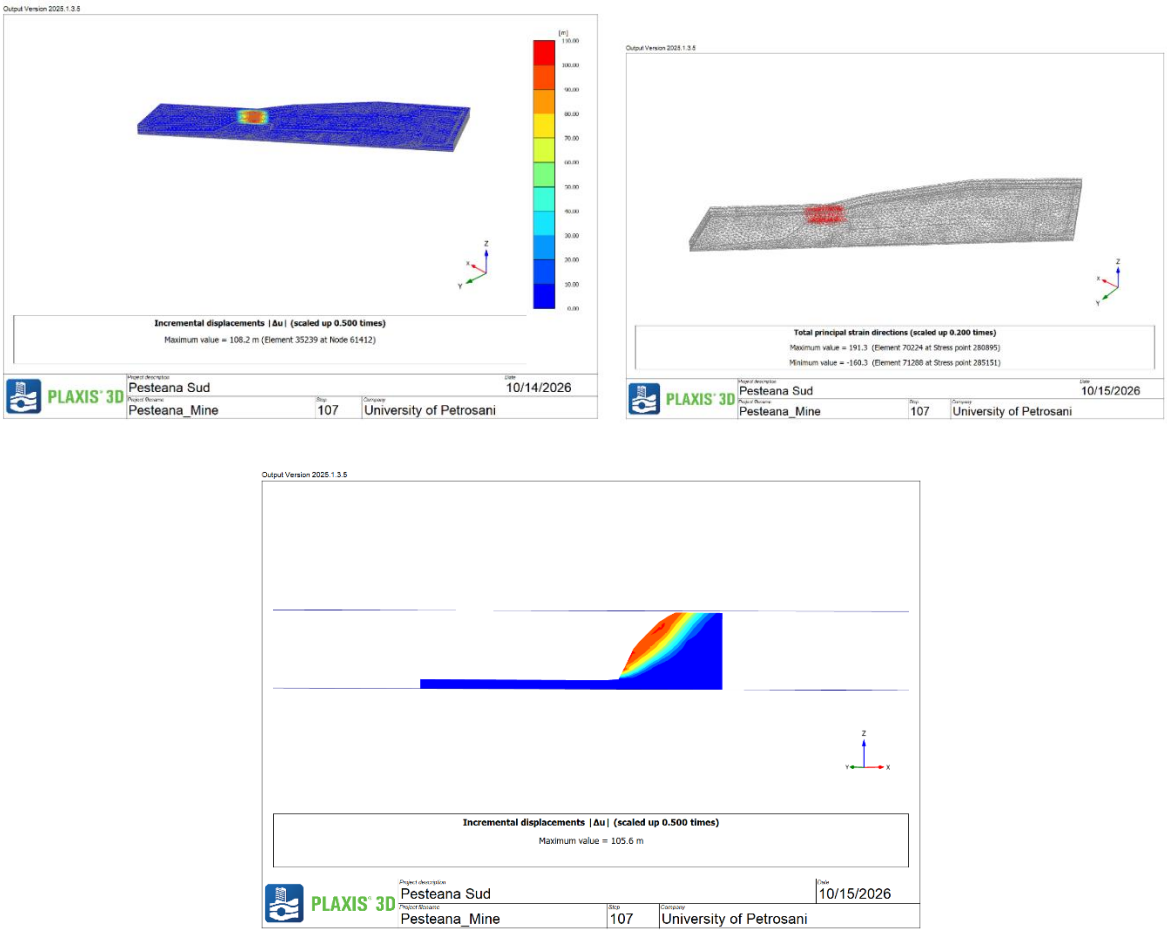

Figure 15 Pesteana South - stability analysis results (Excavated slopes – PLAXIS 3D)

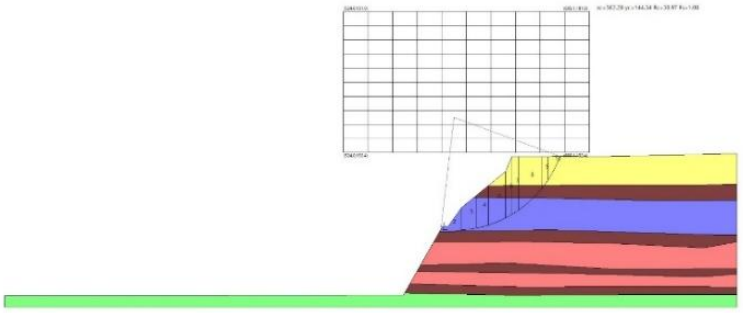

Figure 16 Representative cross section for the excavated slope side (SLOPE)

Figure 15 illustrates the total displacement contours, the plastic points and and the failure surface in the most critical cross section of the excavated slope obtained from the PLAXIS 3D analysis. The largest displacements are concentrated near the slope crest and along the upper excavated face, while the remaining area exhibits only minor movements. The localized deformation pattern indicates stable behavior under the analyzed conditions.

To further assess the stability of the excavated slope, the factor of safety (Fs) was evaluated for different lake water levels (NH). The calculated values obtained from the PLAXIS 3D and SLOPE analyses are summarized in Table 6.

Table 6 Results and Fs variation depending of water level in the lake – dump slope side

NH level	Stability factor Fs	
	PLAXIS 3D	SLOPE
118	1.29	1.16
115	1.25	1.12
112	1.20	1.09
109	1.17	1.06
106	1.15	1.04
103	1.13	1.05
100	1.10	1.05

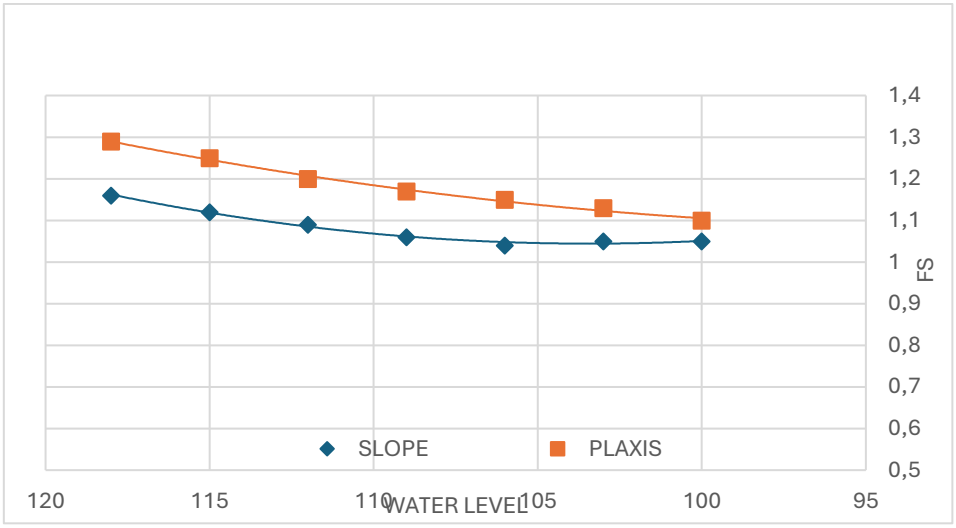

Figure 17 Results and Fs variation depending of water level in the lake – excavated side

Analyses carried out with PLAXIS 3D and SLOPE highlight the same general trend of reducing the stability factor as the water level in the lake drops. In the three-dimensional analysis, the stability factor decreases from 1.29 at an altitude of 118 m to 1.10 at an altitude of 100 m. In two-dimensional analysis by the limit equilibrium method, the factor decreases from 1,16 to 1,05.

The values obtained with PLAXIS 3D are approximately 5–12% higher than those resulting from SLOPE. The difference can be attributed to the three-dimensional effect, the mobilization of lateral resistance and the redistribution of tensions in the massif. The relatively low amplitude and the regular evolution of the differences indicate a satisfactory agreement between the two methods.

However, the SLOPE analysis indicates stability factors of only 1,04–1,06 for levels between approximately 109 m and 100 m. These values show a low stability reserve and a high sensitivity to changes in interstitial pressures, the rate of emptying of the lake and the uncertainty of geotechnical parameters.

For the conservative assessment and the establishment of operating conditions, it is recommended to adopt the values resulting from the SLOPE analysis. The PLAXIS 3D results should be used complementarily, to highlight the three-dimensional effect, the distribution of deformations and the potential failure mechanism. Based on the available results, the lowering of the water level below 109–

106 m should be treated as a critical situation and analyzed in a transitional regime, with monitoring of the interstitial pressures and slope displacements.

3.2. Dump slopes side

The stability of the dump slope was evaluated using numerical analyses under different lake water levels. The obtained results provide information on the deformation pattern and the corresponding factors of safety, allowing the influence of reservoir drawdown on slope stability to be assessed. The representative model adopted for the analysis is presented in Figure 18.

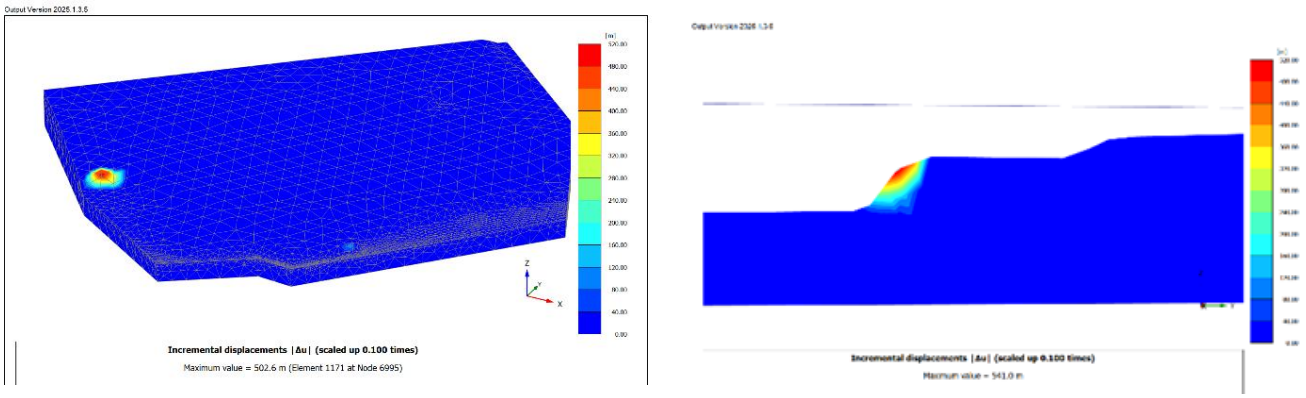

Figure 18 Pesteana South - stability analysis results (Dump slopes side)

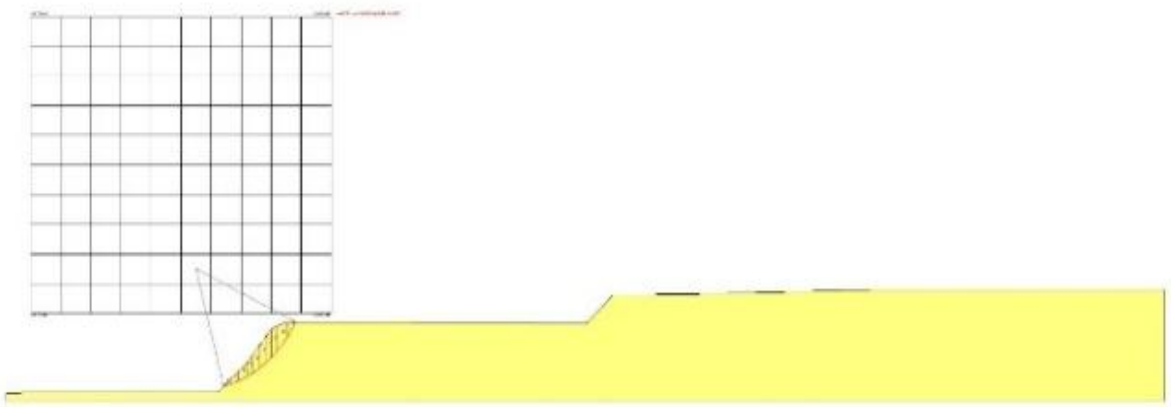

Figure 19 Representative cross section for the dump slope side

To evaluate the stability of the dump slope under different hydraulic conditions, the factor of safety (Fs) was calculated for a range of lake water levels. The results obtained from the PLAXIS 3D and SLOPE analyses are summarized in Table 7.

Table 7. Stability analysis results

NH level	Stability factor Fs	
	PLAXIS 3D	SLOPE
118	1.20	1.01
115	1.14	0.92
112	1.11	0.82
109	1.09	0.82
106	1.05	0.85
103	1.03	0.88
100	1.00	0.88

The variation of the factor of safety with lake water level is presented in Figure 7, providing a graphical comparison of the results obtained from the PLAXIS 3D and SLOPE analyses.

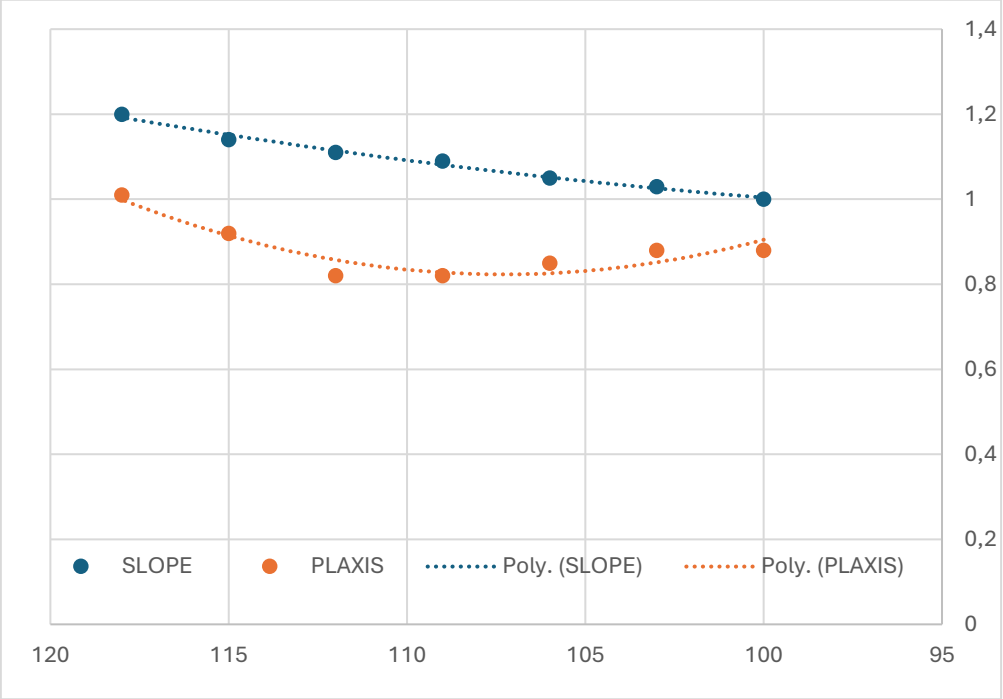

Figure 20 Fs variation depending of water level in the lake - dump side

The results obtained from the stability analyses of the dump slopes highlight a general trend of a reduction in the stability factor with decreasing water level in the lake. In the case of analyses performed with PLAXIS 3D, the stability factor progressively decreases from Fs = 1.20, for the NH = 118 m level to Fs = 1.00, for the NH = 100 m level. This evolution indicates the reduction of the support effect exerted by the water from the lake on the slopes and the approach of the system to the limit state of equilibrium at the lower levels.

The results obtained with the SLOPE program are more conservative. The stability factors calculated are subunit for all levels analyzed, with values ranging from Fs = 0.82 to Fs = 1.01. The minimum value, Fs = 0.82, was obtained for the NH = 112 m and NH = 109 m level. According to the assumptions used in the SLOPE model, these values indicate the possibility of developing failure mechanisms and the failure of the static stability condition.

The differences between the results of the two methods can be attributed to the distinct calculation formulations, the three-dimensional character of the PLAXIS 3D model, the geometry of the potential slip surfaces, the way interstitial pressures are

represented, and the drainage conditions adopted. In PLAXIS, the yield surface results from the progressive redistribution of stresses and the reduction of resistance parameters, while in SLOPE, stability is evaluated for slip surfaces assumed or identified by a search algorithm.

The results of the analyses indicated that the stability of the slopes, especially in the area of the tailings heap, is extremely sensitive to the water level in the lake. The lower dimensions are associated with a reduction in the stability factor, the values obtained with PLAXIS 3D approaching the equilibrium limit, and those obtained with SLOPE being subunit for all the analyzed situations.

In its current form, the results do not demonstrate the existence of a sufficient stability reserve in the case of South Pesteana for the safe operation of the remaining gap as the lower or upper reservoir of a pumped-storage hydropower plant. The situation shall be assessed in relation to the minimum safety factors required for normal, transient, accidental and seismic conditions.

4. Geotechnical and Hydrogeological Suitability Assessment Matrix

The development of a **Geotechnical and Hydrogeological Suitability Assessment Matrix** responds to this need by integrating the main factors controlling reservoir stability and hydraulic containment into a structured multi-criteria assessment framework. By assigning standardised suitability scores and weights of relative importance to the selected parameters, the matrix allows for a consistent preliminary assessment of the different open quarry configurations and geological context. This approach facilitates the identification of favourable conditions, the recognition of potentially critical limitations and the prioritisation of sites requiring further investigation.

The geotechnical conditions in the case of the conversion of a former quarry into the PHES system are represented by several factors, including the height and inclination of the slopes, the configuration of the steps, the quality of the rock mass, the strength of the intact rock, the degree of alteration and the characteristics of the geological discontinuities. The hydrogeological conditions are determined by the hydraulic conductivity of the surrounding formations, the levels and gradients of groundwater, as well as the hydraulic properties and connectivity of the fracture networks. These factors are interdependent, as fractures can simultaneously

constitute preferential pathways for groundwater flow and surfaces of mechanical weakness along which slope instability can be triggered.

Assessing these conditions typically requires detailed geological investigations, field and laboratory trials, hydrogeological characterization, and numerical modeling. While these approaches are essential for advanced feasibility studies and engineering design, their application in the preliminary selection stage of a large number of abandoned mine sites may be limited by the availability of data, the costs of investigations, and the time required for analysis.

Therefore, a rapid and systematic assessment methodology to support the preliminary identification of former quarries with favorable geotechnical and hydrogeological characteristics for the development of reservoirs for pumped hydropower plants (PHES) can be extremely useful. Such a methodology should integrate the main determinants into a transparent assessment framework, distinguishing between conditions that can be managed by engineering measures and those that may constitute critical constraints.

Multi-criteria decision analysis provides a practical basis for the development of such a selection methodology. By assigning standardized scores and relative weights to the selected parameters, multi-criteria approaches allow the integration of heterogeneous geological and engineering information into comparable suitability indices.

The most appropriate tool for this purpose is a rapid geotechnical and hydrogeological suitability assessment matrix, intended to analyze the potential for transformation of former quarries into reservoirs for pumped hydroelectric power plants (PHES). The proposed methodology integrates the geometric, geotechnical, hydraulic and fracture system characteristics into a geotechnical and hydrogeological suitability indicator.

The proposed methodology is intended to support initial selection and prioritisation, and in no way replaces detailed geotechnical and hydrogeological investigations. Its application can facilitate site comparisons, improve the transparency of preliminary assessments and provide a structured basis for identifying the investigations needed in the subsequent feasibility stages.

Geotechnical suitability refers to the ability of the slopes of the excavation and the surrounding massif to maintain their stability under the operating conditions of the

reservoir, including during repeated filling and emptying cycles. Hydrogeological suitability refers to the ability of geological formations to maintain groundwater exchange and hydraulic responses that can be managed, without generating unacceptable effects on the surrounding groundwater system.

These requirements shall be assessed separately to avoid excessive compensation between mechanically favorable and hydraulically unfavorable conditions.

The proposed evaluation matrix involves the use of 10 parameters, grouped into four categories, and with its help it can estimate the suitability of a remaining gap of the quarries from a geotechnical point of view to conversion to a PHES system. For each parameter considered, an initial weight is proposed for screening, but this is not empirically validated (table 8).

Table 8 Proposed suitability matrix

Category	Parameter	Weight
A. Geotechnical conditions	Rock-mass quality (RMR/GSI)	10%
	Existing slope stability	15%
	Weathering and weak materials	5%
B. Geometrical conditions	Overall slope angle and bench geometry	10%
	Pit depth/slope height	5%
C. Hydrogeological conditions	Rock-mass hydraulic conductivity	15%
	Groundwater hydraulic conditions	10%
	Rapid drawdown susceptibility	10%
D. Fracture system	Fracture aperture and connectivity	10%
	Discontinuity orientation and persistence	10%
Total	10 parameters	100%

The rapid scoring criteria are presented in the table 9. Each parameter receives a score from 1 (very unfavorable) to 5 (very favorable).

Table 9 Scoring criteria

Parameter	1 (Very poor)	3 (Moderate)	5 (Very good)
Rock-mass quality	RMR <40	RMR 40–60	RMR >60
Existing slope stability	Active or significant instability	Local instability / uncertain	Stable with supporting evidence
Weathering	Highly weathered, weak material	Moderately weathered	Fresh, competent rock
Slope geometry	Steep, adverse geometry	Moderate slope configuration	Favourable, stable geometry
Pit depth / slope height	High slopes with major stability concerns	Manageable slope heights	Heights demonstrated stable
Hydraulic conductivity	High, uncontrolled seepage	Moderate, potentially manageable	Low, controllable seepage
Groundwater conditions	Strong adverse gradients	Moderate groundwater interaction	Limited adverse interaction
Rapid drawdown	High instability susceptibility	Uncertain / moderate	Stable under expected cycling
Fracture aperture/connectivity	Open, connected fractures	Partly connected	Tight, poorly connected
Orientation/persistence	Major potential failure planes	Some adverse discontinuities	No significant kinematic mechanism

Note: Scores 2 and 4 are assigned between the corresponding descriptions.

From the methodological point of view, it is important to know that the same rock-mass properties influence multiple criteria. For example, fracture orientation affects slope stability, and fracture connectivity affects hydraulic conductivity. To limit double counting, the scoring criteria should distinguish measured rock properties from the consequences predicted by stability and seepage analyses.

The suitability index SI could be calculated by using the formula:

$$SI = \frac{\sum_1^{10} w_i \cdot S_i}{100}$$

where w_i is the percentage weight and S_i is the score from 1 to 5.

The preliminary classification of suitability to convert former open pits/quarries to PHES systems can be seen in the table 10.

Table 10 Preliminary classification of suitability

SI	Preliminary classification
4.20–5.00	Very high suitability
3.40–4.19	High suitability
2.60–3.39	Moderate suitability
1.80–2.59	Low suitability
1.00–1.79	Very low suitability

The application of the proposed methodology to the three careers analyzed from the point of view of stability can be followed in the table 11 and 12.

Table 11 Suitability analysis of the three open pits

Parameter	KOSD	CSA	South Pesteana
Rock-mass quality	4	3	2
Existing slope stability	4	2	3
Weathering	4	3	3
Slope geometry	5	2	3
Pit depth / slope height	5	3	4
Hydraulic conductivity	4	3	3
Groundwater conditions	4	3	3
Rapid drawdown	5	3	3
Fracture aperture/connectivity	2	4	4
Orientation/persistence	2	4	4

Open pit	SI	Suitability
KOSD	3,85	High suitability
CSA	2,95	Moderate suitability
South Pesteana	3,15	Moderate suitability

This methodology can facilitate the identification of potentially favorable sites, highlight geological and hydraulic limitations and guide the prioritization of more detailed investigations.

Focusing specifically on the geotechnical and hydrogeological requirements of reservoir exploitation – rather than on the overall energy or economic feasibility of PHES systems – the proposed approach aims at a distinct preliminary step in the assessment of the reuse of post-exploitation mining infrastructures.

Note:

“This research was funded by the CETPartnership, under the Joint Call 2023. The CETPartnership’ s research projects are co-funded by the European Commission (Grant Agreement No. 101069750) and the national funding organizations listed on the CETPartnership website.”