



GEOTECHNICAL EVALUATION OF QUARRY-TO-LAKE CONVERSION USING NUMERICAL MODELLING

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Abstract: The conversion of exhausted sand and gravel quarries into artificial lakes represents an increasingly adopted post-mining land-use strategy, particularly in alluvial environments where excavations intersect shallow groundwater systems. However, the long-term stability of quarry slopes under changing hydrogeological conditions remains a critical geotechnical challenge. This study presents a numerical investigation of slope stability for the planned quarry-to-lake conversion of the Simeria Veche-2 perimeter (Hunedoara County, Romania), located within the Strei River floodplain. The site is characterised by thick gravel-sand alluvial deposits overlying compact marly clay, with excavation extending below the natural groundwater table. Slope stability analyses were performed using both limit-equilibrium (SLIDE2) and finite-element (RS2) modelling approaches under multiple hydrogeological scenarios, including dry conditions, a natural groundwater regime, partial filling, and full-lake development, using a drained analysis. The results indicate that groundwater conditions represent the dominant controlling factor affecting long-term slope stability. While the proposed 45° slopes remain stable under dry conditions, safety margins decrease significantly when pore-water pressure is considered. The study highlights the importance of integrating hydrogeological processes into post-mining geotechnical design and proposes practical measures, including slope optimisation, staged filling strategies and groundwater monitoring. The proposed methodology provides a useful framework for the safe rehabilitation and long-term management of quarry lakes developed in highly permeable alluvial deposits [1], [2], [3].

Keywords: geotechnical assessment, slope stability, numerical modelling, post-mining, quarry-to-lake, safe rehabilitation

1. Introduction

The rehabilitation of open-pit aggregate quarries by forming permanent lakes is widely adopted in Europe as a means of landscape restoration, biodiversity enhancement and recreational development. However, when excavations intersect shallow aquifers in granular deposits, slope behaviour is strongly controlled by groundwater conditions, and the transition from a dry quarry to a flooded basin can critically modify stability.

The Simeria Veche-2 quarry is permitted for sand and gravel extraction, followed by the creation of a fish-farming lake.

The concept design assumes 45° slopes in dense alluvial gravels and sands, intersected by groundwater at about mid-height, with water levels governed by the regional phreatic surface and precipitation. Existing hydrogeological and geotechnical studies provide detailed information on stratigraphy and groundwater regime, but only schematic stability considerations.

To support a risk-informed design for the final lake geometry, a more rigorous numerical assessment is needed.

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The objectives of this paper are therefore to:

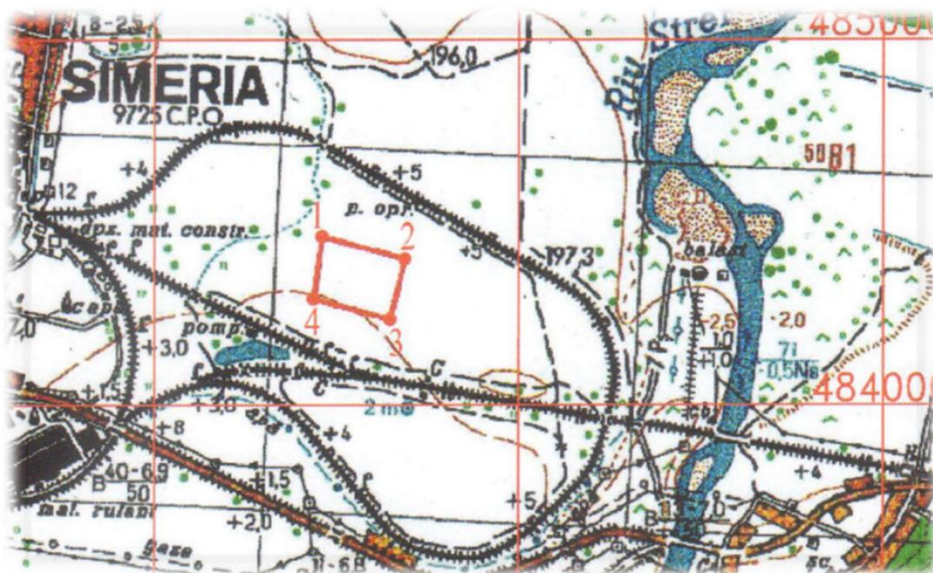
- synthesise the geotechnical and hydrogeological model of Simeria Veche-2;
- formulate material parameters and scenarios for slope stability analysis;
- apply SLIDE2 and RS2 to quantify the effect of groundwater on slope stability for the planned geometry, and
- derive practical recommendations for safe quarry-to-lake conversion in similar alluvial settings [4].

2. Site Description

2.1 Location and Perimeter

The Simeria Veche-2 perimeter lies in Simeria, Hunedoara County, in the Orăștie Corridor at the south-eastern margin of the Transylvanian Basin. It is situated on the left bank of the Strei River, approximately 1.0 km from the river and 1.3 km from the Mureș River, near their confluence. The exploitation perimeter, defined in Stereo 1970 coordinates, encloses about 39,900 m², of which 37,500 m² are designated for excavation, leaving a 3 m protection pillar along the boundaries.

Ground elevations across the site range from 196.1 to 196.5 m a.s.l., with planned excavation down to 188.5 m a.s.l., yielding a maximum pit depth of about 8.0 m. The topography is almost flat, characteristic for the floodplain, and no existing slope instabilities are reported within the perimeter.



Permeability coefficients derived from regional data and typical ranges for similar deposits indicate that the gravel-sand unit is highly permeable (k on the order of 10^{-3} - 10^{-1} m/s), while the underlying marly clays are of low permeability.

Seasonal groundwater fluctuations are expected, but systematic monitoring data are not yet available. Importantly, the planned base of excavation is at 188.5 m a.s.l. lies about 3 - 3.5 m below the current phreatic level, meaning that the lake will be formed by intersecting the aquifer.

3. Materials and Methods

3.1 Geotechnical Characterisation and Design Parameters

The geotechnical characterisation of the Simeria Veche-2 perimeter was based on borehole investigations, dynamic penetration tests and laboratory analyses performed during the feasibility and permitting stages of the project. The investigations identified two principal engineering units controlling slope behaviour and groundwater interaction within the future quarry lake: a thick gravel-sand alluvial sequence (Unit G) and an underlying marly clay formation (Unit M).

The gravel-sand alluvium represents the main material involved in the excavation slopes and therefore governs the overall stability of the quarry-to-lake conversion. The deposit is characterised by medium- to high-density conditions, high permeability and predominantly frictional mechanical behaviour, typical for coarse alluvial sediments developed within river floodplain environments. Due to its high hydraulic conductivity, rapid pore-pressure variations and strong groundwater interaction are expected during both the excavation and lake-formation stages.

The underlying marly clay unit forms a stiff, low-permeability foundation beneath the alluvial deposits. Although this unit is not expected to control shallow failure mechanisms directly, it may significantly influence deep-seated rotational behaviour and stress concentration near the gravel-clay interface under saturated conditions.

The representative geotechnical parameters adopted in the numerical analyses were derived from the available site investigation data, engineering judgement, and reference ranges commonly reported for similar geomaterials.

The representative geotechnical parameters adopted for the gravel-sand alluvial deposits (Unit G) are summarised in Table 1. These parameters were selected based on the available geotechnical investigations and are considered representative for the granular materials forming the excavation slopes and controlling groundwater interaction within the future quarry lake.

Table 1. Representative geotechnical parameters for gravel-sand alluvium (Unit G – G1, G2)

Parameter	Symbol	Adopted Range	Engineering Interpretation
Unit weight	γ	18 - 20 kN/m ³	Typical for medium-dense to dense saturated alluvial deposits
Relative density	-	Medium to high	Indicates favourable shear resistance under drained conditions
Drained friction angle	ϕ	32 - 38°	Governs frictional slope resistance in granular material
Drained cohesion	c	≈10 kPa	Represents minor apparent cohesion due to fines and partial cementation
Hydraulic conductivity	k	10^{-3} - 10^{-1} m/s	Indicates highly permeable material with rapid groundwater response

The representative engineering properties assigned to the underlying marly clay formation (Unit M) are presented in Table 2. This unit acts as a stiff and low-permeability foundation layer beneath the alluvial sequence and plays an important role in controlling deep-seated stability behaviour under saturated conditions.

Table 2. Representative geotechnical parameters for marly clay (Unit M – MC1)

Parameter	Symbol	Adopted Range	Engineering Interpretation
Unit weight	γ	20 - 22 kN/m ³	Characteristic for compact cohesive formations
Consistency	-	Stiff to very stiff	Suggests reduced deformability and increased bearing capacity
Drained friction angle	ϕ	30 - 35°	Contributes to deep rotational stability
Effective cohesion	c	50 - 100 kPa	Reflects cohesive resistance of compact marly deposits
Hydraulic conductivity	k	10^{-7} - 10^{-9} m/s	Indicates very low permeability and limited groundwater flow

The adopted parameter ranges were subsequently implemented in both the SLIDE2 and RS2 numerical models to evaluate slope stability under different hydrogeological scenarios, including dry conditions, the natural groundwater regime, partial filling, and full-lake development.

3.2 Final Lake Geometry

The final geometry of the proposed quarry lake was established based on the approved exploitation and rehabilitation design developed for the Simeria Veche-2 perimeter. The selected configuration reflects both the operational requirements associated with aggregate extraction and the intended long-term post-mining land use as a permanent fish-farming lake. Particular attention was given to excavation depth, slope inclination and groundwater interaction, as these parameters directly influence the stability behaviour of the future lake slopes.

The excavation is planned within a relatively flat alluvial floodplain environment, with ground elevations varying only slightly across the site. The final pit geometry consists of a large open excavation extending below the natural groundwater table, resulting in the formation of a permanent water body hydraulically connected to the surrounding alluvial aquifer. The proposed slope configuration adopts relatively steep inclinations for both above-water and underwater sections, which represents one of the critical aspects evaluated in the numerical stability analyses.

The principal geometric parameters adopted in the modelling programme are summarised in Table 3.

Table 3. Final lake geometry and excavation characteristics

Parameter	Symbol Adopted Range	Engineering Interpretation
Total perimeter area	39,900 m ²	Defines the overall project boundary
Excavation footprint	37,500 m ²	Represents the effective excavation area used in modelling
Maximum excavation depth	8.0 m	Controls slope height and groundwater interaction
Planned excavation level	188.5 m a.s.l.	Located below the natural phreatic level
Ground elevation range	196.1–196.5 m a.s.l.	Indicates very low-relief floodplain topography
Lake water depth	Approx. 4m (maximum 8m)	Defines long-term hydraulic loading conditions
Slope inclination	1V:1H ($\approx 45^\circ$)	Governs overall slope stability behaviour
Protection berm width	3 m	Provides crest protection and operational safety margin
Final reclamation type	Fish-farming lake	Defines the long-term post-mining land use

The proposed 45° slope inclination represents a relatively aggressive geometry for highly permeable alluvial materials subjected to long-term groundwater interaction. Consequently, this configuration was considered particularly important for the numerical assessment, as changes in pore-water pressure and seepage conditions may significantly influence long-term slope performance during both the operational and post-closure stages of the quarry lake development.

3.3 Numerical Modelling Approach

Slope stability is assessed using two complementary tools:

- SLIDE2 – 2D limit-equilibrium software, applied to evaluate factors of safety for potential slip surfaces using circular and non-circular search algorithms (Particle Swarm Search) and several equilibrium formulations (e.g., Bishop Simplified, Morgenstern–Price);
- RS2 – 2D finite-element software, used to simulate stress-strain behaviour and to compute stability via the shear strength reduction method.

The use of both approaches allows cross-checking of FoS values and better understanding of pore-pressure effects and failure mechanisms [5], [6].

Analysed Scenarios

Four hydrogeological scenarios are defined:

- Scenario S1 – Dry slope: no groundwater; the entire slope is assumed unsaturated; this scenario is mainly illustrative and serves as an upper bound of stability;
- Scenario S2 – Natural groundwater level: phreatic surface at 4.0 - 4.5 m depth, intersecting the slope; water level inside the excavation adjusted to match the external groundwater level.
- Scenario S3 and S4 – Partial filling at different levels: groundwater has risen in the pit due to initial lake formation; water level inside the lake is between the pit bottom and the natural phreatic level – drained analysis;
- Scenario S5 and S6 – Full Lake/ saturated slope: lake is fully developed with water level above the natural phreatic level – drained and seismic analysis;
- For each scenario, analyses are run using base-case parameters and, where relevant, pseudo-static seismic loading corresponding to $a_g = 0.10$ g from national seismic zoning.

In SLIDE2, representative cross-sections are constructed from project drawings and lithological logs, extending sufficiently beyond the lake to capture potential deep slip surfaces. Material zones corresponding to Units G and M are assigned with the parameters as above. For each scenario, the phreatic line and external water levels are defined in accordance with the conceptual hydrogeological model.

SLIDE2 Setup

4. Results

Under dry conditions, limit-equilibrium analyses indicate high stability of the 45° slopes in the dense gravel-sand unit. For the base-case parameters, the minimum FoS is typically in the range $\text{FoS} \approx 1.40 - 1.50$, depending on the method used – see Figure 2.

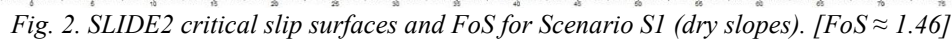


Fig. 3. RS2 plastic zones for Scenario S1 (dry slopes). [$FoS \approx 1.46$]

4.2 Natural Groundwater Level (Scenario S2)

When the natural phreatic level is introduced, the active part of the slope becomes partially saturated, and pore-water pressures reduce effective stresses in the lower half of the slope. For base-case parameters, SLIDE2 indicates minimum FoS in the range $FoS \approx 1.057 - 1.1$, see Figure 4.

RS2 analyses produce similar FoS values, with plastic zones extending deeper into the slope and closer to the gravel–clay interface.

Failure surfaces shift slightly upwards and become more circular, indicating a transition towards deeper rotational mechanisms influenced by the saturated zone – see Figure 5.

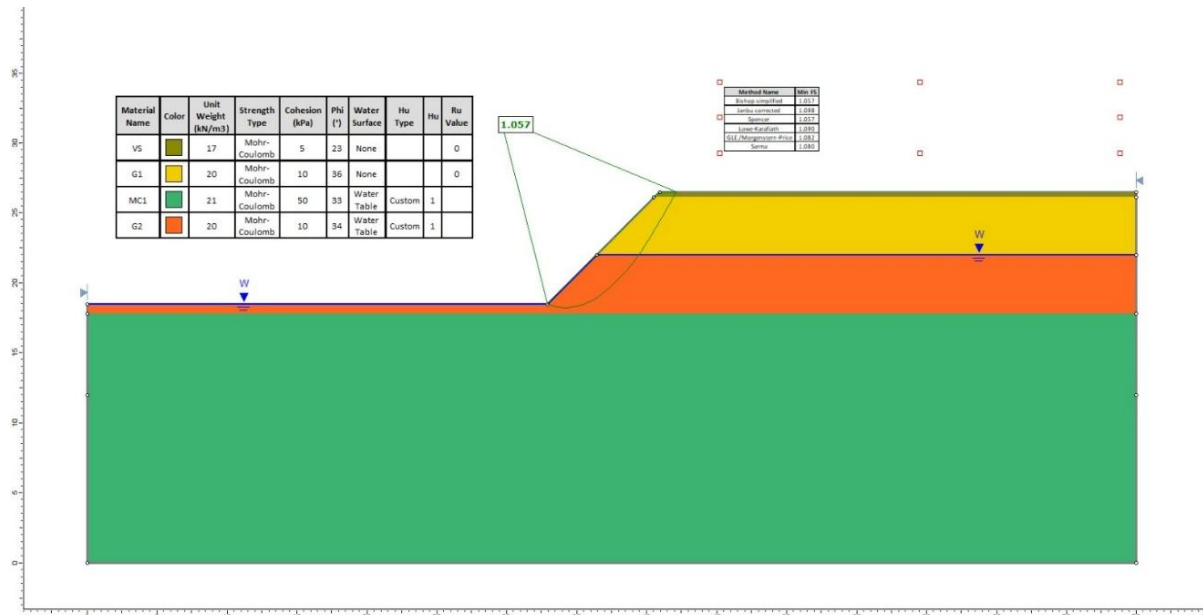


Fig. 4. SLIDE2 critical slip surfaces using Particle Swarm Search and FoS for Scenario S2 (natural groundwater). [FoS ≈ 1.057]

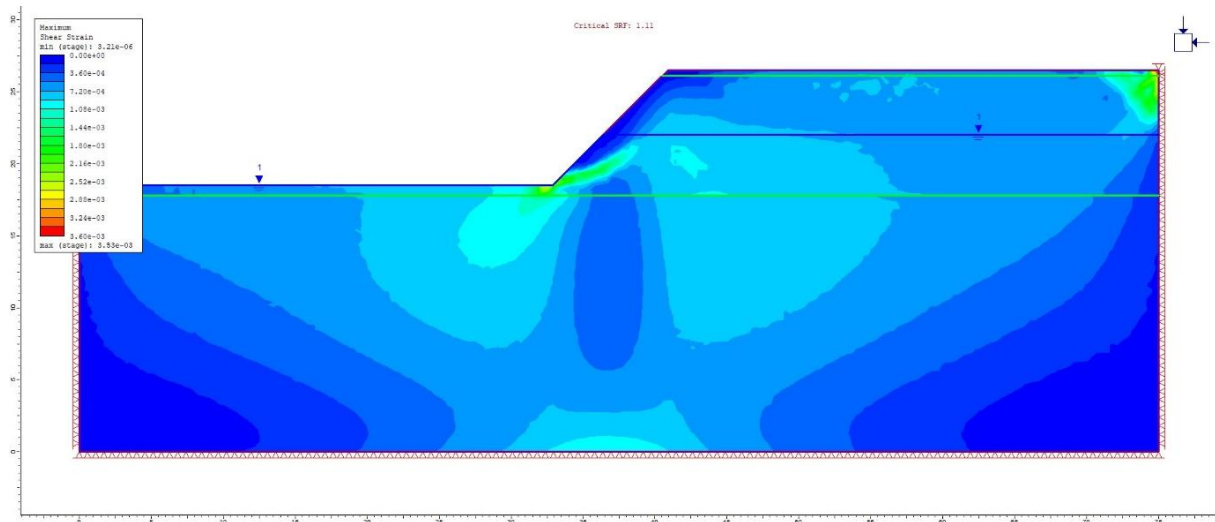


Fig. 5. RS2 shear strength reduction results for Scenario S2 (natural groundwater)

4.3 Partial Filling (Scenario S3 and S4)

During partial filling, water levels in the pit may lag or lead the external groundwater level, generating complex seepage patterns.

For base-case parameters, SLIDE2 estimates FoS values around $FoS \approx 1.3$ due to drained analysis, and water pressure counteracts towards the slope.

RS2 reproduces similar trends and highlights localised high strain gradients near the toe, where plasticity initiates, see Figures 6 and 7.

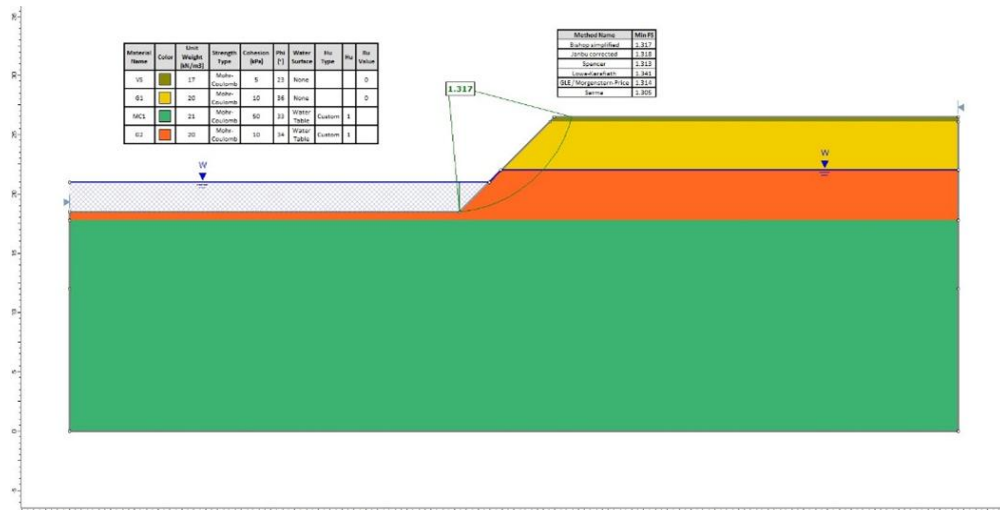


Fig. 6. SLIDE2 FoS for Scenario S3 (partial filling). [FoS $\approx$ 1.3]

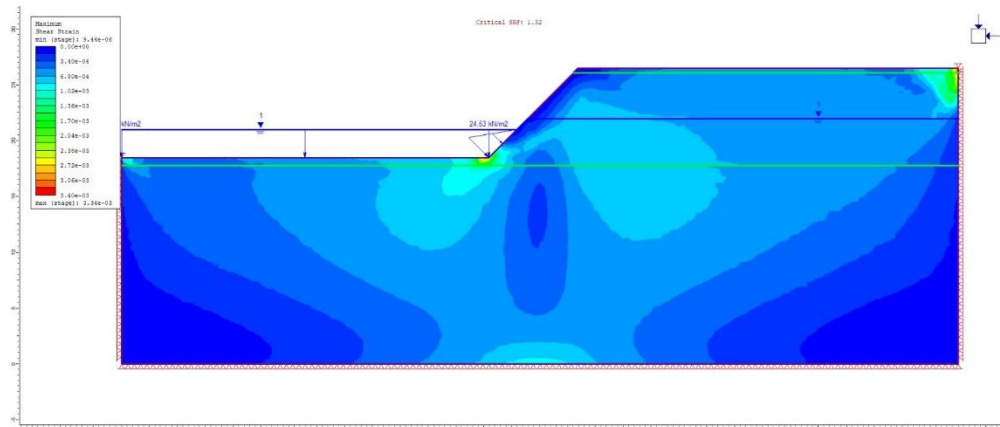


Fig. 7. RS2 shear strain field and plastic zones for Scenario S3

4.4 Full Lake / Saturated Slope (Scenario S5 and S6)

In the full-lake scenario, with the water level above the regional phreatic level, the slopes remain fully or largely saturated; however, this was not modelled, as we carried out a drained analysis. SLIDE2 results show that, for base-case parameters, the minimum FoS increases to $\text{FoS} \approx 1.9$, due to the water pressure exerted against the slope – see Figure 8.

RS2 shear strength reduction analyses confirm this behaviour, with extensive plastic zones within the gravel–sand unit and potential formation of a continuous failure surface connecting the slope crest to the toe. The presence of the stiff marly clay base prevents very deep failure, but it may induce localisation of shear at the gravel–clay interface, particularly where hydraulic gradients are large – see Figure 9.

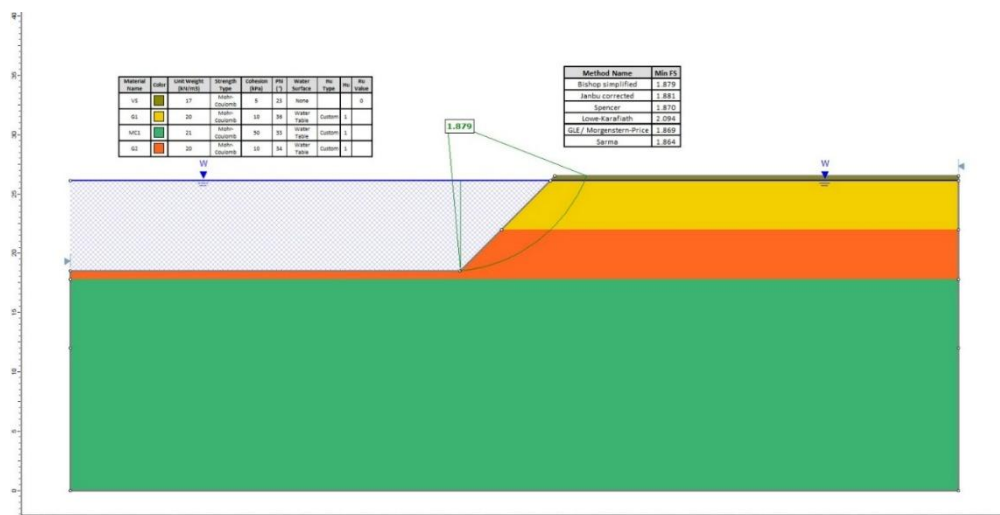


Fig. 8. SLIDE2 critical slip surfaces and FoS for Scenario S5 (full lake). [FoS $\approx$ 1.9]

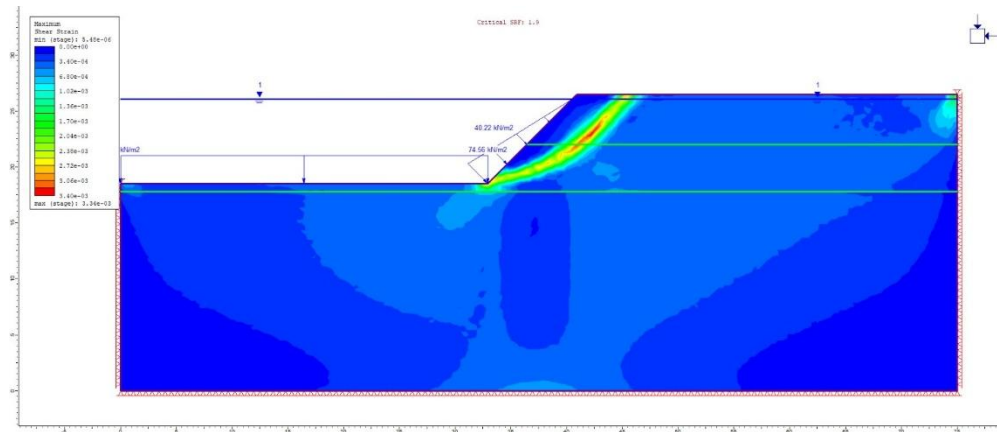


Fig. 9. RS2 plastic zones for Scenario S6 (full lake). [FoS $\approx$ 1.9]

5. Discussion

5.1 Influence of Groundwater on Stability

The numerical results clearly demonstrate that groundwater is the dominant factor controlling slope stability in the Simeria Veche-2 lake. The difference between dry and saturated cases is substantial, with FoS decreasing from approximately 1.4 - 1.5 to about 1.057 - 1.1 for the same slope geometry and soil parameters. This reduction is mainly due to elevated pore-water pressures and the associated decrease of effective stress in the lower part of the slope.

The high permeability of the gravel–sand unit implies that pore-pressure changes can propagate quickly, making the system sensitive to rapid changes in water level inside or outside the pit [7]. RS2 analyses show that under adverse gradients, stress gradients concentrate near the toe and at the contact with the marly clay, where plastic zones initiate.

5.2 Acceptability of the 45° Slope

Design guidelines and national standards typically require minimum FoS values of 1.3 - 1.5 for permanent slopes in static conditions and around 1.1 - 1.2 under pseudo-static seismic loading. Under dry or mildly saturated conditions (Scenarios S1 and S2), the 45° slope generally satisfies these criteria, especially for base-case parameters. However, under full-lake and adverse partial-filling conditions (Scenarios S3 – S6), FoS values should be evaluated using a fully coupled hydro-mechanical analysis to determine whether there is an unacceptable risk level for a permanent water body.

Consequently, maintaining a uniform 45° slope in the final lake configuration appears overly aggressive unless additional stabilising measures or strict operational controls are implemented. Flatter slopes or bermed configurations would provide greater safety margins, particularly considering parameter uncertainty and long-term geomorphological evolution.

5.3 Limitations and Uncertainties

The assessment relies on available geotechnical data, which, although extensive for a feasibility-level study, still involves uncertainties in parameters such as friction angles, cohesion and permeability. Long-term groundwater behaviour is not yet monitored and may differ from the assumed steady-state conditions, especially under climate variability and river-level changes.

Moreover, the analyses are two-dimensional and assume plane-strain conditions, which may not fully capture three-dimensional stabilising effects or local geometric irregularities. Nevertheless, the combination of SLIDE2 and RS2 provides a robust, conservative basis for design decisions at the current stage.

6. Conclusions and Recommendations

6.1 Main Conclusions

The numerical analyses and hydrogeological assessment carried out for the Simeria Veche-2 perimeter provide several important conclusions regarding the long-term stability behaviour of quarry slopes during the transition from active excavation to permanent lake conditions. The main findings of the study are summarised below.

- The Simeria Veche-2 site is characterised by a simple stratigraphy of dense gravel-sand alluvium over compact marly clay, with a shallow phreatic level at 4.0 - 4.5 m depth and planned excavation down to 8.0 m below ground surface;
- Numerical modelling with SLIDE2 and RS2 shows that 45° slopes in the gravel-sand unit are stable under dry conditions ($FoS \approx 1.4 - 1.5$) and moderately stable when only the natural groundwater level is considered ($FoS \approx 1.1 - 1.2$);
- Under partial filling and full-lake conditions, where slopes become largely saturated, and seepage gradients develop towards the lake, FoS values should be investigated using a coupled analysis, compared to the current drained analysis;
- The marly clay base acts as a stiff foundation that limits very deep failures, but it can also focus shear and hydraulic gradients at the gravel-clay interface, potentially contributing to localised failures;
- Groundwater dynamics, rather than soil strength alone, therefore, represent the controlling factor for long-term stability of the quarry-to-lake conversion at Simeria Veche-2.

6.2 Design and Management Recommendations

- Slope geometry optimisation:
 - Re-evaluate the final geometry with flatter slopes, for example 30 - 35° (1.5 - 1.7H:1V), using the same numerical framework, and adjust the design to obtain $FoS \geq 1.3$ under full-lake conditions for base-case parameters and $FoS \geq 1.2$ for unfavourable parameters;
 - Consider introducing berms at intermediate depths (e.g., every 3 - 4 m of vertical height) to interrupt potential slip surfaces and facilitate maintenance and access.
- Hydrogeological control:
 - Plan staged filling of the lake, avoiding rapid water-level changes that could produce adverse hydraulic gradients; use numerical scenarios to define acceptable filling rates;
 - Investigate the feasibility of toe drains or relief wells in areas where RS2 indicates high hydraulic gradients, to lower pore-water pressures and improve stability.
- Monitoring programme:
 - Install piezometers around the lake and within the slope to monitor groundwater levels and compare them with design assumptions; update numerical models as data become available;
 - Establish regular visual inspections of slopes, focusing on erosion, cracking, seepage emergence and any signs of movement, particularly after extreme precipitation or river floods.
- Further investigations and refinement
 - If subsequent analyses confirm marginal FoS for the current geometry, perform additional in situ and laboratory testing (e.g., triaxial tests, permeability tests) to refine parameter estimates;
 - Extend the modelling to three dimensions for representative sections if local geometrical effects (e.g., corners, buttresses) are expected to significantly influence stability.

The methodology and findings from Simeria Veche-2 illustrate the importance of integrating hydrogeological processes into geotechnical design for quarry-to-lake conversions in alluvial environments. Combining SLIDE2 and RS2 analyses, calibrated with site-specific data, provides a robust basis for risk-informed design and long-term management of post-mining lakes.

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