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ORIGINAL PAPER

GEOMECHANICAL ASPECTS OF REOPENING OF ABANDONED SHALLOW AND FLOODED SLATE MINES: A CASE STUDY FROM THE ČERMNÁ A MINE (NÍZKÝ JESENÍK Mts., CZECHIA)

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ABSTRACT

The transformation of abandoned mines into tourist attractions presents unique opportunities and challenges. This study focuses on the geotechnical and numerical analysis conducted between 2016 and 2021 for the potential reopening of an abandoned, shallow, and flooded slate mine in Nízký Jeseník, Czechia. The mine, a relic of the region's rich mining history, has the potential to become the country's first accessible flooded mine. A comprehensive methodology was developed to ensure safety and stability, incorporating speleological mapping, laser scanning, and geotechnical surveys. These methods assess the mine's structural integrity, focusing on the rock mass properties and stability under various conditions. The study underscores the importance of a systematic approach to repurposing abandoned mines, contributing to sustainable tourism and the preservation of mining heritage.

INTRODUCTION

The Industrial Revolution profoundly transformed landscapes worldwide, with mining as a crucial driver of this change (Zalasiewicz et al., 2014). Mining has been essential for economic development, shaping entire regions. However, extensive mining activities often leave areas abandoned or degraded once resources are depleted (Owen et al., 2020). As we enter an era focused on sustainability and the preservation of mining heritage, it becomes imperative to rethink and repurpose post-mining landscapes. The future of closed, old, orphan and abandoned mines can take various forms. They are reused for education (Alrayyan et al., 2017), experimentation (Kaláb et al., 2012), waste storage (Athresh et al., 2017), and energy storage (Menéndez et al., 2019). The Czech Republic has been significantly affected by historical mining and quarrying. Klomínský et al. (2015) presented various examples of repurposing old mines in the Czech Republic, such as utilizing geothermal water from former coal mines for heating buildings, creating underground spaces for scientific experiments, developing medical facilities, and using abandoned mines as reservoirs for gas, water, or radioactive waste storage. Among the various uses belong mining tourism. Mining tourism proves valuable in this context and offers several benefits: expanding tourism into previously overlooked regions, stimulating local economies with new employment opportunities, and offering tourists unique experiences (Gregorová et al., 2020). Furthermore, mining tourism plays a crucial role in raising awareness about the historical significance of these sites, fostering a collective effort to protect and preserve our mining heritage (Edwards and Coit, 1996). Mining tourism represents a specialized form of tourism that involves exploring mining landscapes, interpreting mining technology, and providing educational and entertaining experiences for visitors interested in mining. This type of tourism is gaining widespread popularity globally, especially in developed nations (Różycki and Dryglas, 2017; Salmi and Sellers, 2022).

An interesting example of the rehabilitation of an abandoned mining landscape can be found in Nízký Jeseník, Czech Republic. After the Second World War, the landscape was abandoned, and the German-speaking population—many of whom were skilled mining experts—was deported. This loss of experienced workforce was one of the factors that hindered the full restoration of mining in the region. While mining was partially resumed in the 1990s at a few local sites, it never regained its former economic significance, leaving behind visible remnants of past activity. That led to increased unemployment and the gradual depopulation of the region. Nowadays is this trend different. Looking ahead, the transformation of abandoned slate mines in Nízký Jeseník holds

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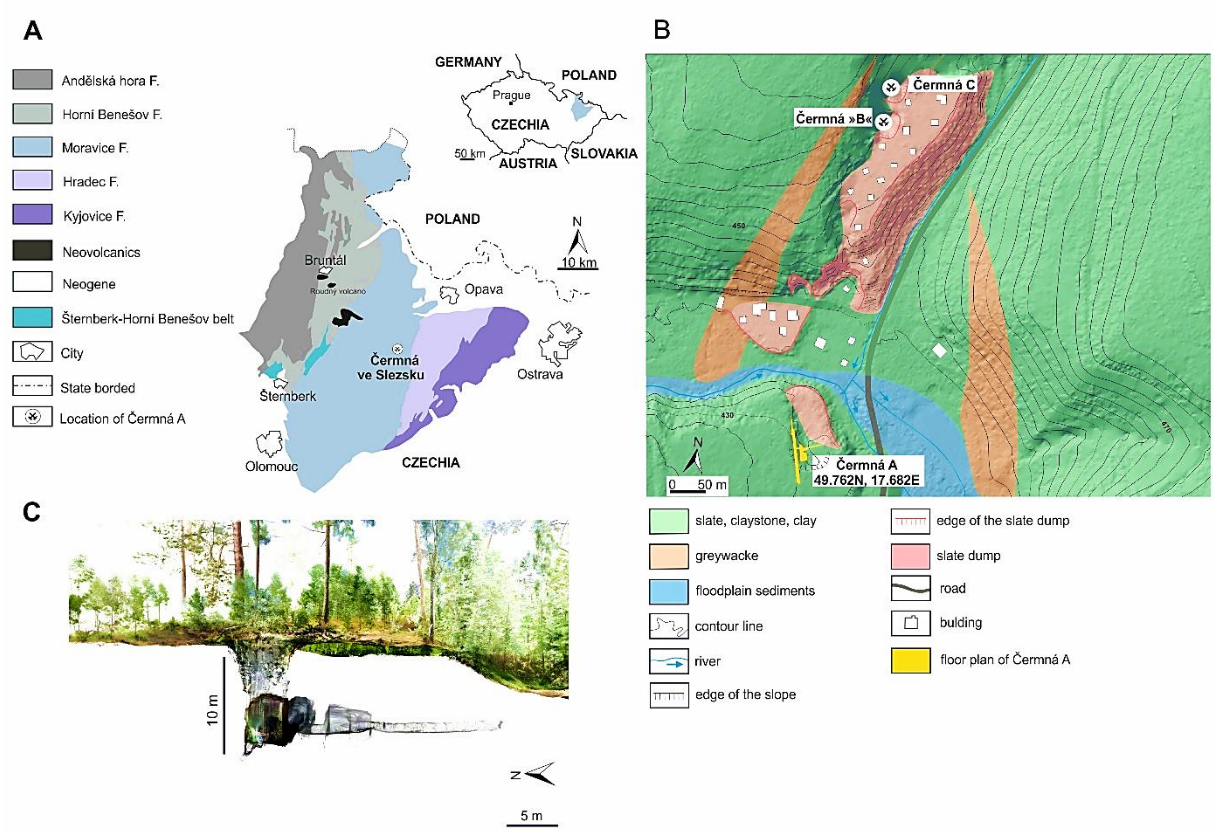

Fig. 1 A) Location and geological map of Nízký Jeseník; B) Location of abandoned mine Čermná A from a geology and geomorphology point of view; C) Vertical cross section of Čermná A prepared by laser scanning.

promise. For the municipalities where such a mining site is located, and where it has previously been seen as a challenge, it can now become an economic benefit, as well as a positive factor for nature and the landscape. In 2021, preparations to reopen the abandoned underground slate mine Čermná A began. There was emphasis placed on geotechnical concerns to ensure a safe and enjoyable experience for visitors. Great emphasis was placed on the correct methodology during the work, as this is the first flooded mine made available for tourist purposes. The model methodology is outlined here, highlighting key aspects to consider and follow when evaluating geomechanical conditions in the rock massif during the reopening of an abandoned mine.

GEOLOGY AND GEOMORPHOLOGY OF NÍZKÝ JESENÍK

Nízký Jeseník is situated in the northeast part of the Czech Republic, in the Moravian-Silesian region and covers an area of almost 3000 km^2 (Fig. 1A) (Lenart, 2016; Czudek, 1988). This region is from geological point of view a distinct synorogenic formation known as the Culm within the European Hercynids (Dvořák et al., 1994). Culm sedimentation occurred from the Upper Devonian–Tournaisian interval to the Lower Namurian. It is characterized by a rhythmic alternation of greywackes, slates, and siltstones (Hartley and Otava, 2001; Fig. 1A). In the western part are older lithostratigraphic units, while the eastern part reveals younger lithostratigraphic units. Between the Carboniferous and Cretaceous periods was intense weathering. It results into isolated hummocks in the northern part of Nízký Jeseník (Lenart, 2016). The Pliocene witnessed a tectonic uplift in Nízký Jeseník, leading to the cutting of river courses into the homogenous upland. Deep, broad valleys formed, reaching depths of up to 200 m, particularly in the eastern and southern parts of the region (Czudek, 1971; Lenart, 2016). Several volcanic eruptions occurred during the Cenozoic. This geological activity created volcanic features, including the eruption of the Roudný Volcano during the Pleistocene (Slivka and Vavro, 1996; Miklín and Lenart, 2016). The Pleistocene climate, characterized by alternating glacial and interglacial periods, significantly influenced the relief formation and development of Nízký Jeseník. The direct reach of the continental glacier led to an intense alternation of frost weathering and slope processes, creating various rock formations in deeply incised valleys. These forms include rock cliffs, blockfields, rubble fields etc., (Janoška, 2001). The landscape of Nízký Jeseník results from weathering and erosion processes, shallow landslides, accumulation processes, the formation of alluvial fans, and, notably, human activity, which has also partially reshaped the terrain (Lenart, 2016).

HISTORY AND CHALLENGES OF ABANDONED SLATE MINES IN NÍZKÝ JESENÍK

The oldest written mention of slate mining comes from 1776 (Němec, 1949). Because slate has never been registered locally as a reserved mineral deposit under the mining law, anyone was allowed to excavate it. At the very beginning, the mines (described also as underground quarries from historical point of view, e.g. Lollino et al., 2013; Jirásek et al., 2019) were owned by local farmers and later became the property of german speaking population who were professionally engaged in slate mining (Jahn, 1917; Strohalm, 2003). The main excavating method was the room-pillar method with backfilling, known as the Rhenish mining method. During the 19th century, more than a hundred quarries and mines were in operation (Jahn, 1917). Hrušecký (1946) documented seventy-two small mines before the First World War. During the Industrial Revolution of 1860–1914, the slate mining in Nízký Jeseník was able to supply the whole Austro-Hungarian Empire. The post-war disintegration of the empire led to a mining decline (Strohalm, 2003). The renaissance of mining came during the 1930s, when the area was part of the Czechoslovak Republic. An almost final blow to the slate mining industry in the region came with the expulsion of Germans after the Second World War. The region lost generations of owners, mining experts, and qualified workers. Many skills, methods, and documents were lost along with them, and many mines remained abandoned since. Those in operation were confiscated during the process of nationalization that took place in the 1950s. Slate mining never regained its previous scale and significance, and after the democratic revolution in 1989, it finally ceased (Labus et al. 2020). Recently, the historical significance of slate mining in this region is overshadowed by the challenges posed by abandoned mines. These remnants of past mining activities pose various challenges, including environmental degradation and potential safety hazards (Georgieva et al., 2020). The problems associated with abandoned slate mines include the unknown actual number of mines, areas where their extent remains unmapped, their relatively shallow depth, and the presence of buildings constructed over them. As landscape development and infrastructure expansion continue, these mines are increasingly perceived as potential hazards due to ground instability, subsidence risks, and the unknown extent of underground voids. One of the major issues is the lack of information about slate production, ownership records, mine layouts, and, in some cases, even the exact location of the mines (Schuchová et al., 2023).

STABILITY OF SHALLOW ABANDONED MINES

The instability of shallow mines results from a combination of factors, including the geological properties of the rock, the presence of water, overburden pressure, mine geometry, and both historical and ongoing human activities. Shallow mines are often located in soft rock formations, such as chalk or slate, which have lower strength and are more susceptible to collapse. Natural fractures and joint sets further weaken the rock structure, potentially leading to roof failures and surface subsidence (Smith and Rosenbaum, 1993).

Water plays a crucial role in mine destabilization. Groundwater inflows from rivers, infiltration from precipitation, or rising groundwater levels can significantly undermine rock stability. Increased pore pressure due to a rising water table is one of the primary factors contributing to the collapse of mine roofs (Helm et al., 2008). This issue has been exacerbated in recent decades by climate change. Summer droughts, followed by intense precipitation, can increase surface water infiltration into the subsurface, weakening load-bearing structures and heightening the risk of collapse (Didier et al., 2010; Lafrance, 2016).

Another factor influencing stability is mine geometry and overburden pressure. Due to their shallow depth, these mines lack sufficient natural support, making them more prone to subsidence. A combination of poorly designed pillars, water inflows, and naturally fractured rock often results in progressive failures that, in extreme cases, can lead to surface collapses (Smith and Rosenbaum, 1993).

Historical examples illustrate how severe the consequences of shallow mine collapses can be. In 1910, the collapse of underground workings in Château-Landon contributed to a catastrophic centennial flood of the Seine and Loing Rivers, as water flooded the mine rooms, further weakening their stability (Helm et al., 2008). A similar issue was identified in the partially flooded Maloghne phosphatic chalk mine, where multiple ground collapses occurred. This mine presents a significant hazard due to its shallow depth and proximity to critical infrastructure, including railways, highways, and built-up areas (Georgieva et al., 2020).

In Nízký Jeseník, slate mines are located at shallow depths, typically up to ~100 m below the surface (Grygárek, 2014). Many of them remain only as short exploratory adits or small mines, with individual mining rooms extending no more than a few dozen meters (Schuchová et al., 2023; Lenart, 2016). Medium and large mines tend to have more complex layouts, often featuring multiple entrances that combine adits and shafts at different elevations (Schuchová et al., 2023). These mines frequently branch into two interconnected levels, with overall lengths ranging from hundreds of meters to several kilometres and depths of a few dozen meters below the surface (Lenart, 2016). In rare multi-level mines, the lowest adits are often fully covered by backfill, forming load-bearing backfilled walls (Schuchová et al., 2023).

While most of these mines remain relatively stable, a few cases of surface collapse have been recorded. The greatest risk, however, lies underground, where collapsed sections have been

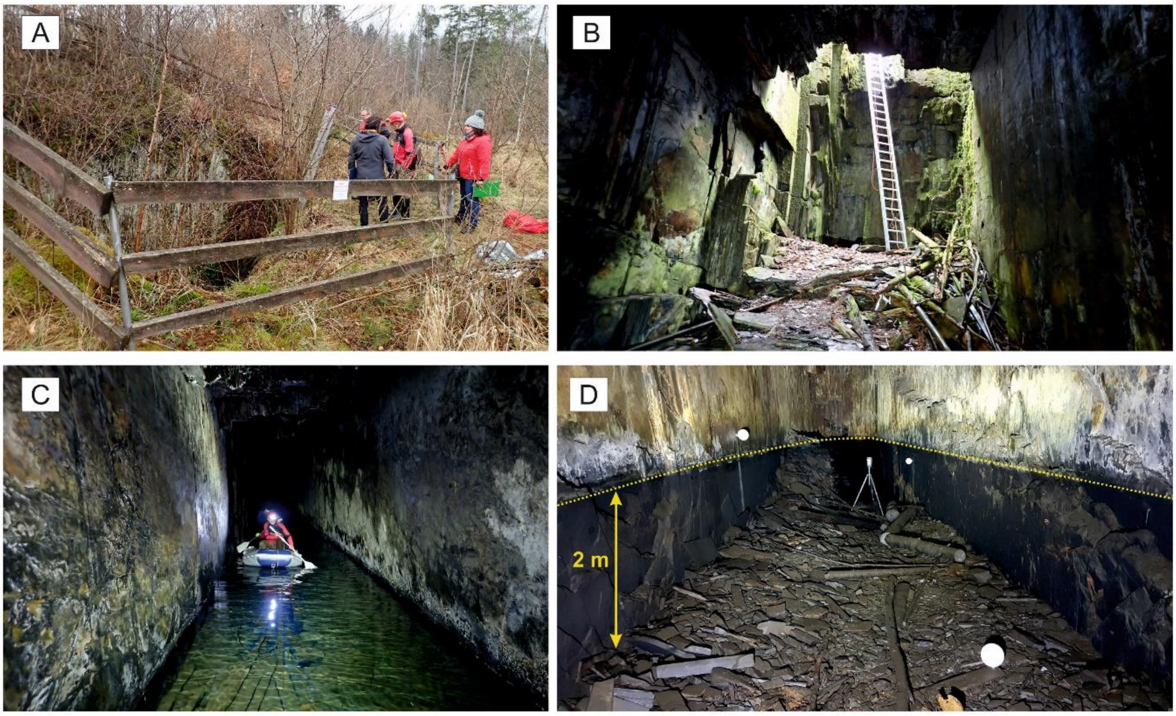

Fig. 2 A) entry to the Čermná A mine; B) entrance shaft to the mine from underground; C) flooded adit; D) illustration of the scanning methodology, where white targets are placed as reference points every 10 meters. The yellow line indicates the original water level height before drainage (photos from Radovan Kukutsch, 2021).

more frequently detected (Schuchová et al., 2023). The lack of precise information on the location, structure, and extent of these abandoned mines further complicates monitoring efforts and the implementation of safety measures (Georgieva et al., 2020).

STUDY SITE

The Čermná A mine is located in the Čermenský Mlýn valley, approximately 3 km southwest of the municipality of Čermná ve Slezsku. It is situated 87 m above the Budišovka River, on the same geological strip as the Čermná B and Čermná C mines (Fig. 1). The continuous supply of water from the Budišovka River, which flows alongside the mine and is at the same elevation as the mine's rooms, is responsible for the flooding of the mine (Fig. 1). In connection with planned geotechnical measurement, water was pumped out of the mine. The level of water was lowered by approximately 1.2-2 meter. The entrance to the mine is through a vertical shaft with dimensions 4x3 m and a depth of 10 m (Fig. 1 and Fig. 2). The mine was originally accessed via horizontal adits that are currently impassable due to collapse and flooding (Fig. 1 and Fig. 2). The accessible layout comprises a 50 m long, partially flooded main room, with a secondary branch leading into a completely submerged room (Fig. 3). The history of mining within locality is short. The first landowner was Adam Kunz ~ 1850. He built underground slate mine (Čermná A and Čermná B). The slate mines were largest in the cadastre of the municipality of Čermná ve Slezsku. The Kunz family mined there until World War II (1939–1945). After the war, the mines were abandoned (Kupka and Pohunek, 2017). Čermná A mine was first investigated in 2018 (Schuchova et al., 2023). The geotechnical survey for reopening the Čermná mine (A) was conducted in 2021.

METHODS

In the initial phase of the investigation, it was important to collect historical materials and documentation about the Čermná A mine. Due to non-exist historical map, mapping was performed in 2018. The new map of Čermná A mine was created by the Leica Disto A3 range-finder. Background map was created in PocketTopo program and design after it in CorelDRAW X8 program (Schuchová et al., 2023). Following this, in 2021, 3D laser scanning was performed to obtain a high-precision spatial model of the underground spaces and the adjacent terrain (Fig. 3). The scanning was carried out using the FARO Focus S350 3D laser scanner in combination with the NEDO tripod. For a complete scan of the mine, water was drained from the mine using an electric pump. The laser scanner captured up to 1 million spatial points per second, enabling high-resolution capture of underground and surface areas. The scanning was performed in the full range of the used equipment, i.e., 360° in the horizontal and 300° in the vertical plane. Considering the scope of scanning works, the scanning detail size was set to 1/4 at double quality in

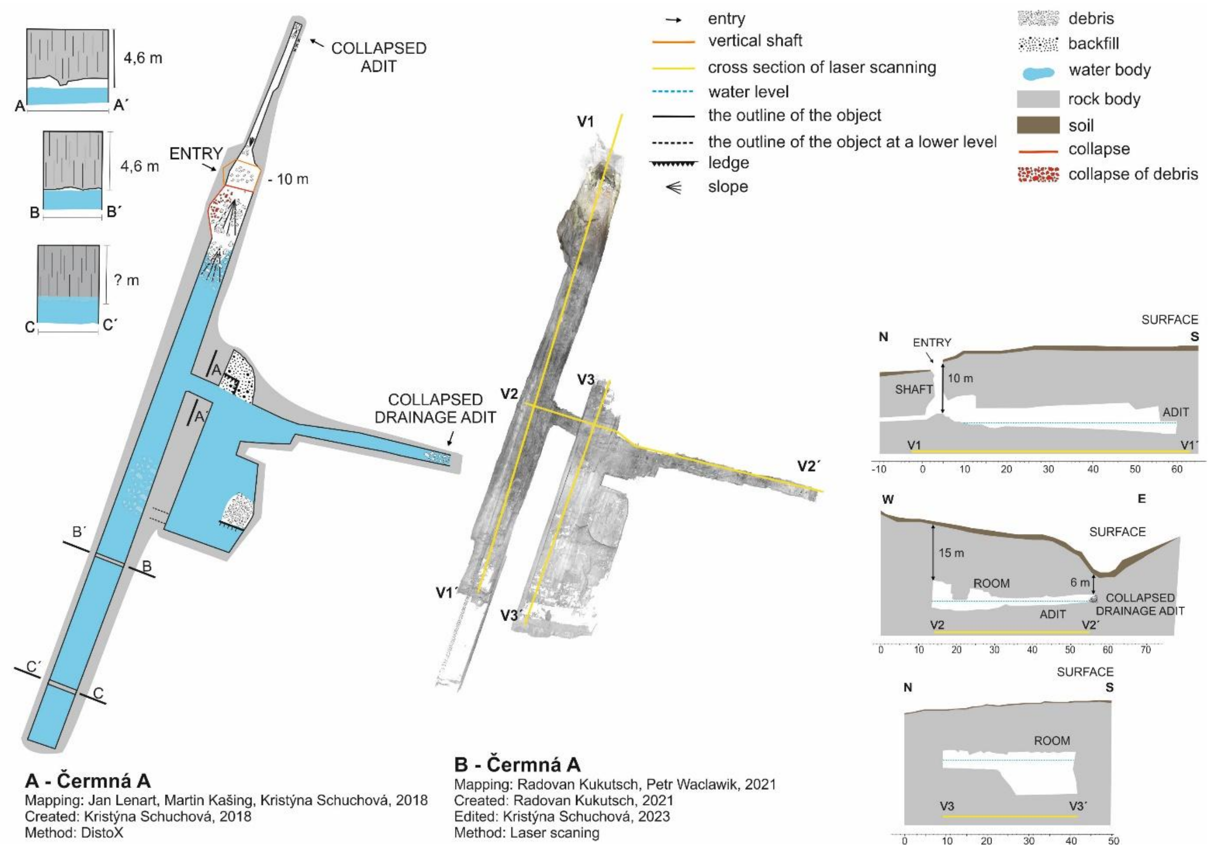

Fig. 3 Resulting maps of the underground slate mine with vertical cross-sections (A – map obtained using the Leica Disto A3 range finder; B – map generated by laser scanning).

underground spaces. This setting was suitable with a maximum distance of 10 m from the scanned object by white targets (Fig.2). For scanning the mine-surface transition, a higher resolution was selected to ensure an accurate connection between the pit and the surface, set to 1/2 at double quality. Surface scanning used a setting of 1/4 at the triple quality to capture the colour component for point cloud colouring. The actual scanning took place in 4 campaigns - underground, mine-surface transition, and two surface scanning campaigns (Fig. 3).

The second part of the study focused on geotechnical properties. These properties were assessed using the rock mass rating (RMR) method (Bieniawski, 1989). Six parameters were measured: (1) the uniaxial compressive strength (UCS) of the rock, (2) the rock-quality designation (RQD) value, (3) the frequency of fractures, (4) the characteristics of discontinuities, (5) the presence of groundwater, and (6) the orientation of discontinuities. Physical and mechanical parameters of the rock samples were analyzed in the specialized laboratories of the Institute of Geonics of the Czech Academy of Sciences in Ostrava. The third part of the study consisted of the model calculation of stress and strain state, performed in a 2D by the mathematical model of the commercial software Phase2 8.0 using finite element methods. The final part involved stability calculations, drawing on the approach described by Konietzky and Walter (2009), unpublished but mentioned by Wichert (2020) were used for the design of room-pillar mining in a slate mine, as well as similar calculations of the stability of rooms in an abandoned and flooded slate mine (Konietzky and Wichert, 2018 in Wichert, 2020). To account for the inherent anisotropy of slate, the "ubiquitous joints" model was used, which best describes the basic mechanical properties of slate. This consisted of a predisposed surface of discontinuity, which represents a cleavage plane, typical for slate. The deformation process is calculated in two separate phases. The rock mass has elastic-plastic behaviour according to the Mohr-Coulomb criterion, and cleavage is governed by the Coulomb elastic deformation criterion. To determine the deformation parameters for the rock mass, the RMR value was converted to the Geological Strength Index (GSI) based on the empirical relationship proposed by Marinos and Hoek (2000), as shown in Table 2.

$$GSI = RMR - 5 = 67 - 5 = 62$$

METHODOLOGY FOR STABILITY MODELING AND GEOMECHANICAL PROPERTIES

The determination of the RMR is outlined in Table 1, where the values and individual ratings are assessed. The parameters selected based on the in-situ

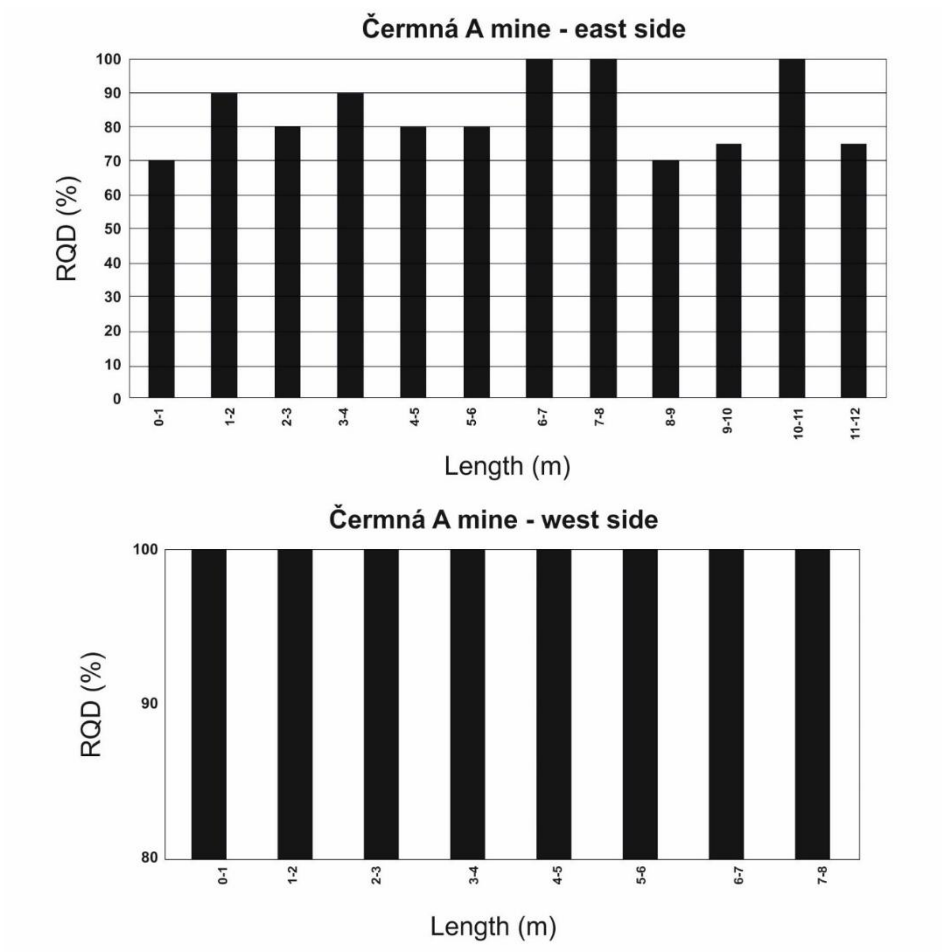

Fig. 4 Graphic display of results of RQD measuring from Čermná A mine.

assessment of the rock mass are highlighted in grey (Table 1). The calculated and determined mechanical and deformation properties used as input parameters in the numerical models are presented in Table 2.

With a total RMR score of 67, the rock mass in the Čermná A mine is classified as Class II (Good Rock) according to the Bieniawski (1989) classification. The intact uniaxial compressive strength (UCS) of the rock was adopted from comprehensive database analyses conducted in connection with professional expertises at the nearby Svatoňovice and Modrá štola mines, which share identical lithofacies within the Moravice Formation. The measured values of UCS for these Culm slates range from 70 to 100 MPa (with peak local values reaching up to 140 MPa), which corresponds to 7 points in the RMR classification. The baseline RQD (rock-quality designation) was assessed from structural profiles within the mine. Because the geomechanical properties of rocks determined in laboratory conditions differ significantly from the large-scale behavior of the actual rock mass due to fractures, faults, cleavage, and bedding planes, the RQD rating adjusts the intact properties to better approximate the real rock mass state. The measured RQD profiles in the Čermná A mine indicate a high-quality rock mass structure, with local values reaching up to 98–100 % in the most competent zones (Fig. 4). To account for regional fracturing and to maintain a conservative engineering approach and after applying a 20 % reduction as a safety factor, a representative weighted RQD value was determined at 78 %, corresponding to a score of 13 points (Table 1). The spacing of discontinuities within the main adit of the Čermná A mine ranges predominantly from 0.6 to 2 meters, indicating a relatively low fracture frequency and contributing 15 points to the classification (Table 1). The condition of the discontinuity surfaces is characterized as rough to slightly rough with unweathered walls, evaluated at 25 points. The groundwater conditions, with an estimated total inflow of 25 to 30 l/min determined by technical monitoring during pumping, result in a damp-to-wet environment, adding 7 points (Table 1). The orientation of the principal joint sets and cleavage relative to the alignment of the mining excavation is favorable, receiving a rating adjustment of 0 points. Based on the final score of 67 points, the rock mass environment in the Čermná A mine can be classified as stable and favorable for engineering repurposing.

Table 1 Assesment of RMR (Bieniawski, 1989) in Čermná A mine.

	Parameter		Range				
1	Uniaxial compresive strenght [MPa]		>250	100-250	50-100	25-50	V.25
	points		15	12	**7**	4	2
2	RQD [%]		90-100	75-90	50-75	25-50	<25
	number of points		20	17	**13**	8	3
3	Frequency of discontinuity [m]		>2	0.6-2	0.2-0.6	0.2-0.06	<0.06
	number of points		20	**15**	10	8	5
4	Properties of discontinuitites		highly rough	softly rough little mouldered	softly rough strongly mouldered	slithery slippery	cleavage
	number of points		30	**25**	20	10	0
5	Presence of underground water	flow rate of 10m roadway [l/min]	<10	X.25	25-125	>125	
		coefficient of fracture water tension	0	0-0.1	0.1-0.2	0.2-0.5	>0.5
		general condition	dry	moist	wet	drop of water	running water
	number of points		15	10	**7**	4	0
6	Orientation of discontinuities		very favourable	favourable	middle	unfavourable	highly unfavourable
	number of points		**0**	-2	-5	-10	-12
	total number of points		100-81	80-61	60-41	40-21	20
	category		I	**II**	III	IV	V

Table 2 Mechanical, deformation, and strength properties used as input parameters in the 2D numerical stability modeling and stress-stráni calculations.

Rock mass	Density [kg/m³]	2 600
	Young's modulus [MPa]	20000
	Poisson's ratio	0.24
	Cohesion [MPa]	3.7
	Angle of internal friction [°]	45
	Tensile strength [MPa]	0.82
Cleavage	Angle of internal friction [°]	25
	Dip [°]	90
	Cohesion [MPa]	2.6

DISCUSSION

The selection of the vertical model sections V1, V2, and V3 (Fig. 3) was based on the results of the 3D laser scanning, which provided a comprehensive spatial representation of the mine layout. This high-resolution mapping allowed for the identification of critical areas where geotechnical conditions required detailed evaluation. Section V1 represents a north-south longitudinal section of the main adit; its southernmost part remains incomplete in the model due to completely flooded, inaccessible workings. Section V2 represents a west-east cross-section running through the connecting adit, the main room, and the collapsed drainage adit. Section V3 is a north-south cross-section localized directly within the largest mining room.

To evaluate the stress-strain state and assess underground stability, the distribution of values is represented by the maximum principal stress components (σ_1) and primarily by the Strength Factor (SF). The SF represents the ratio of the rock mass strength to the induced modeled load. Legally and physically, if the SF drops below 1.0, the modeled load exceeds the shear or tensile strength of the rock mass, indicating unstable conditions and a high probability of failure. Dynamic stresses caused by historical blasting or regional natural seismicity were not addressed in these static model calculations. Due to the

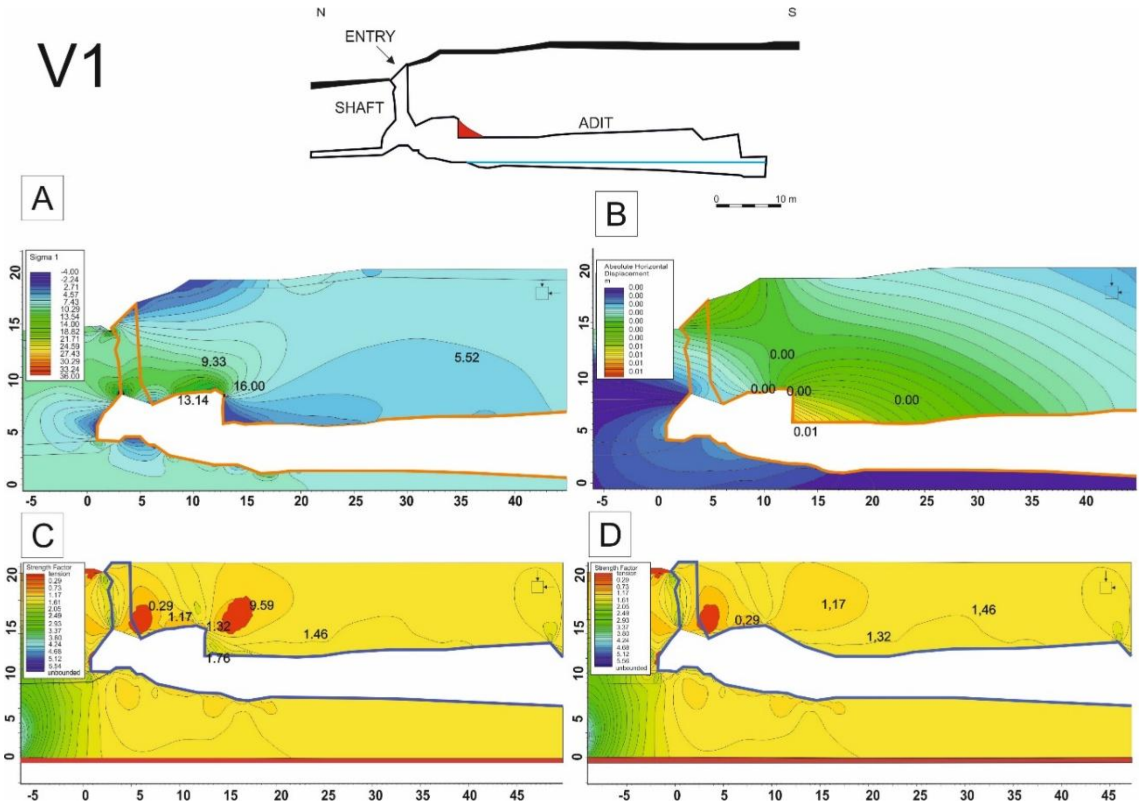

Fig. 5 Graphic display of V1 section showing: A – Sigma1 (maximum principal stress); B – absolute horizontal displacement (contours scaled to millimetre-range micro-deformations); C and D – Strength Factor (SF) distribution.

shallow depth of the workings below the topography, a constant gravity-induced stress field was considered.

The results of the calculations for section V1 are illustrated in Figure 5. Figure 5A represents the distribution of the maximum principal stress component (σ_1) around the adit. The highest stress concentrations are located in the initial part of the adit where the thickness of the overburden is smallest and the entry geometry induces stress concentration. The distribution of the absolute horizontal displacement corresponds to this stress pattern (Fig. 5B). The maximum horizontal displacement does not exceed 1 cm even in the most relaxed zones, which is a highly favorable factor for the overall stability of the adit.

Section V2 was simulated using separate modelling phases to evaluate: (1) the original state without intervention, (2) the current state of stresses and strains, and (3) the structural status after the implementation of the planned ceiling height increase (Fig. 6). The distribution of the maximum principal stress component (σ_1) before and after adding the ceiling excavation profile is shown in Figure 6A. An increase in induced tension is observed in the eastern part compared to the central and western areas of the mine workings. However, these stress values do not exceed the expected thresholds caused by the low overburden thickness and local surface morphology.

The absolute horizontal displacement fields for the V2 section are presented in Figures 6C and 6D. In both modeling phases, the displacements show only minimal, millimeter-scale changes that cannot compromise the operational stability of the mine openings. The distribution of the Strength Factor (SF), shown in Figure 6B, represents the most critical safety result. The lowest SF values are concentrated in the easternmost part of the adit, which is directly affected by its proximity to the ground surface. Additionally, local reductions in the SF can be seen along the transition pillars between the main room and the connecting adit.

Section V3, localized within the main room, is documented in Figure 7. The numerical simulation for this section yielded the most favorable stability results. This is primarily due to the larger thickness of the competent rock overburden and its relatively uniform surface topography. Minor stress anomalies are exclusively linked to the irregular, historic geometry of the room ceiling. The distribution of the maximum principal stress is shown in Figure 7A, while the absolute horizontal displacement is presented in Figure 7B, confirming negligible deformation. The SF values (Fig. 7C) are locally affected by the irregular overbreaks in the roof. Localized concentrations of lower SF values can be seen above the overhanging rock blocks. However, these stability issues can be effectively mitigated during the planned profiling and mechanical scaling of the room ceiling (Fig. 7C).

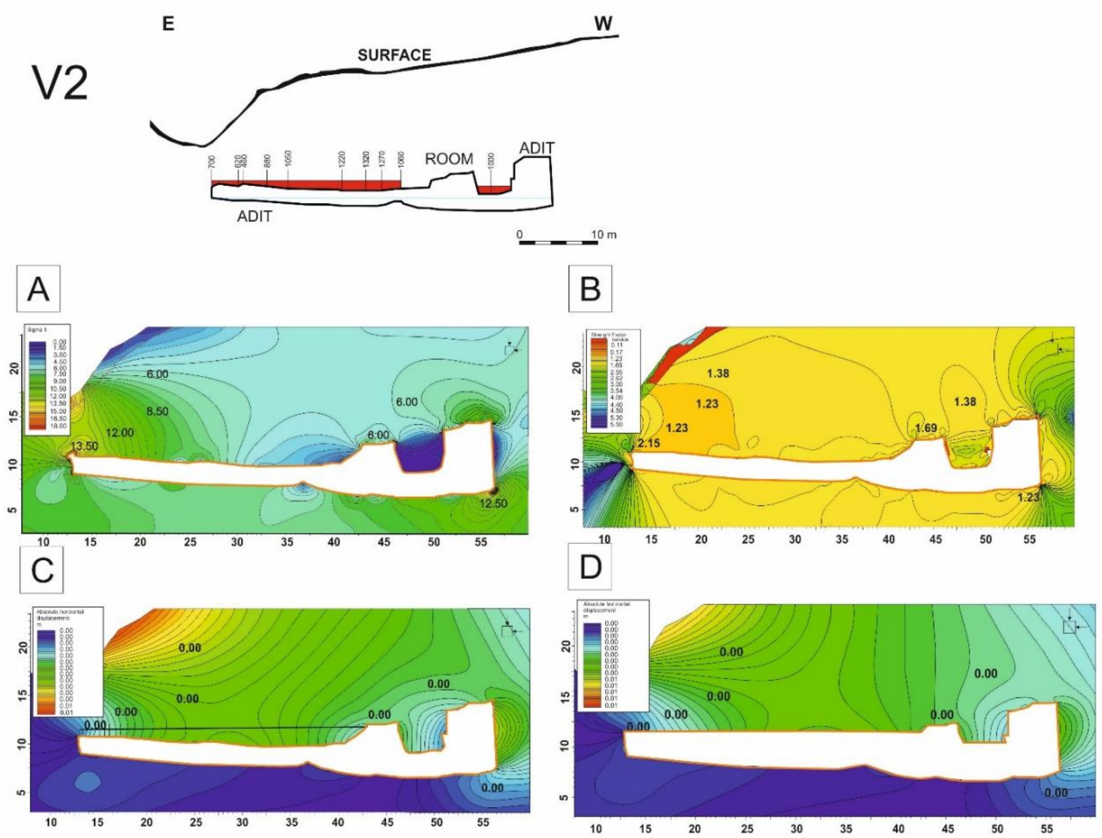

Fig. 6 Graphic display of the V2 section showing: A – Sigma1 (maximum principal stress); B – Strength Factor (SF); C – absolute horizontal displacement in the original state; D – absolute horizontal displacement after the planned ceiling excavation. Note: Contour colors in C and D illustrate the trend of minor micro-deformations within a millimeter-scale range.

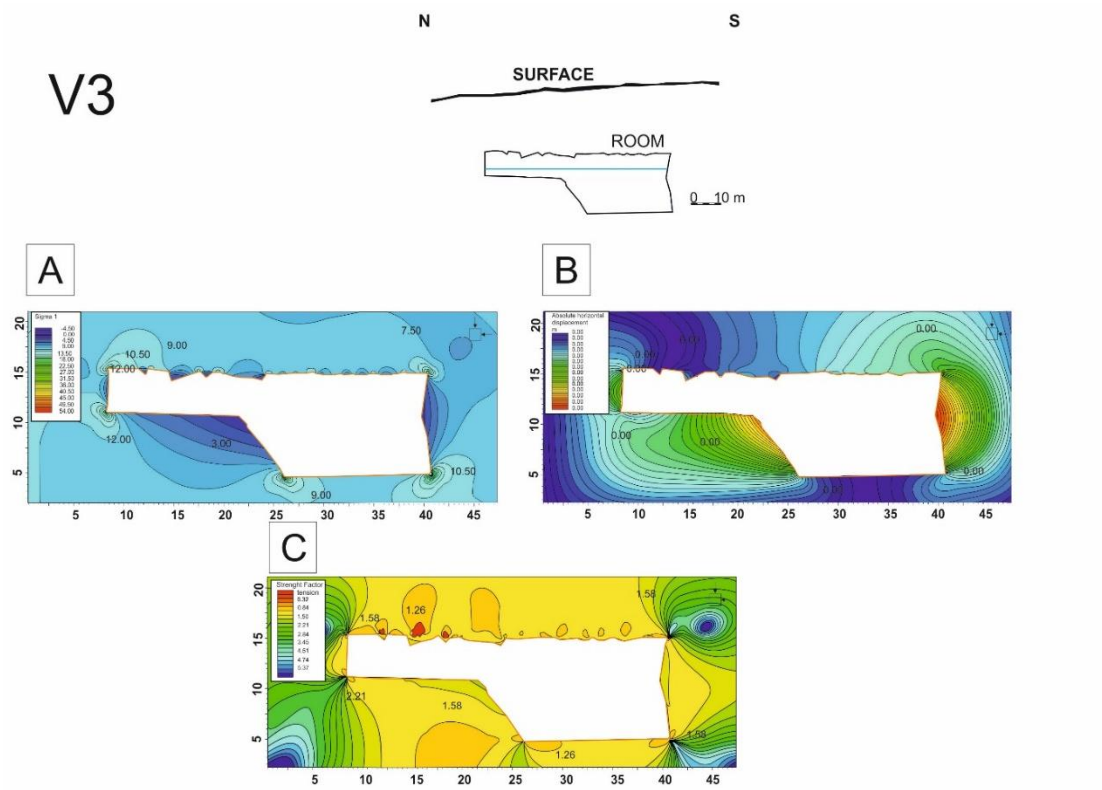

Fig. 7 Graphic display of V3 section showing: A – Sigma1 (maximum principal stress); B – absolute horizontal displacement (millimetre-scale trend); C – Strength Factor (SF).

CONCLUSION

In conclusion, the repurposing of the abandoned slate mines in Nízký Jeseník for mining tourism presents both significant engineering challenges and promising regional opportunities. The local geological conditions of the Culm slates have contributed to the long-term structural stability of the mine adits and rooms. The 2D numerical model calculations align with these empirical findings.

However, specific zones of local instability where the Strength Factor drops below 1.0 have been identified, particularly within sections V1 and V2. In section V1, the stability of the overlying rock layer decreases near the surface entrance, necessitating active support. Section V2, while generally stable, indicates a clear need for localized reinforcement in its easternmost adit segment due to the extremely shallow overburden. Developing mine tourism, particularly in a region with limited infrastructure, requires a strategic approach. Key steps include addressing legal and regulatory challenges, gaining a comprehensive understanding of the geological and geotechnical context, and implementing necessary risk mitigation measures.

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