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Original scientific paper

TECHNICAL ANALYSIS OF THE POSSIBILITY OF EXPANDING THE QUARRY WITH DEEP BENCHES AT THE TREBAČKO BRDO

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Abstract: This paper presents a comprehensive technical analysis of the potential expansion of the Trebačko Brdo quarry through the introduction of deep benches, with the aim of increasing extraction capacity while maintaining slope stability and ensuring compliance with environmental regulations. The geological, geomorphological, and engineering-geological characteristics of the site indicate favourable conditions for the continued exploitation of limestone. Laboratory testing confirms the high quality of the mineral resource, particularly in terms of its chemical composition (CaO > 50%) and physico-mechanical properties (compressive strength > 100 MPa).

The proposed expansion concept предусматри the successive development of benches down to an elevation of 470 m above sea level, increasing the total extraction height to 85 m. Slope stability has been verified through a calculated safety factor (F = 1.91), while the optimal working bench width (27.5 m) allows for the integration of spiral ramps, safety zones, and drainage systems. Special emphasis is placed on geotechnical challenges, including rock mass discontinuities, interaction with groundwater, and the need for adaptive planning.

The analysis also includes an assessment of environmental impacts, with particular focus on dust emissions, hydrogeological changes, and the necessity of technical reclamation. In conclusion, the proposed quarry expansion model demonstrates high technical feasibility, safety, and compliance with contemporary mining practices, thereby enabling the sustainable exploitation of technical stone at the Trebačko Brdo site.

Keywords: quary; deep benches; slope stability; limestone; geotechnical analysis

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1 INTRODUCTION

The exploitation of technical construction stone, particularly limestone, plays a significant role in the construction industry, road infrastructure development, and the production of lime and cement. The importance of technical stone extraction has been confirmed in numerous national and international studies, especially in the context of environmental impact and industrial development (Bektašević, Sjerotanović & Baraković, 2011a; Bektašević, Sjerotanović & Baraković, 2011b; Valjevac et al., 2024) . Global trends indicate that demand for this resource is increasing in parallel with urbanization and infrastructure expansion (Carrasqueira et al., 2024; Zhang et al., 2025; Firoozi et al., 2024).

Bosnia and Herzegovina possesses numerous limestone deposits, one of the more significant being located within the Municipality of Tešanj, at the Trebačko Brdo site. This area is characterized by favorable geological, geomorphological, and mining-engineering conditions for exploitation, but also by certain constraints related to environmental considerations and spatial planning. Similar challenges associated with environmental restrictions and land-use planning have been documented in other quarries in Bosnia and Herzegovina, highlighting the need to balance resource extraction with spatial and environmental protection (Bektašević et al., 2023; Bektašević et al., 2024).

The Trebačko Brdo deposit is characterized by a well-developed hilly–mountainous relief, with elevations ranging from approximately 600 to 680 m above sea level, which enables the application of surface mining methods. Figure 1 presents the morphological appearance of the broader Trebačko Brdo area, providing insight into the relief characteristics relevant to exploitation planning.

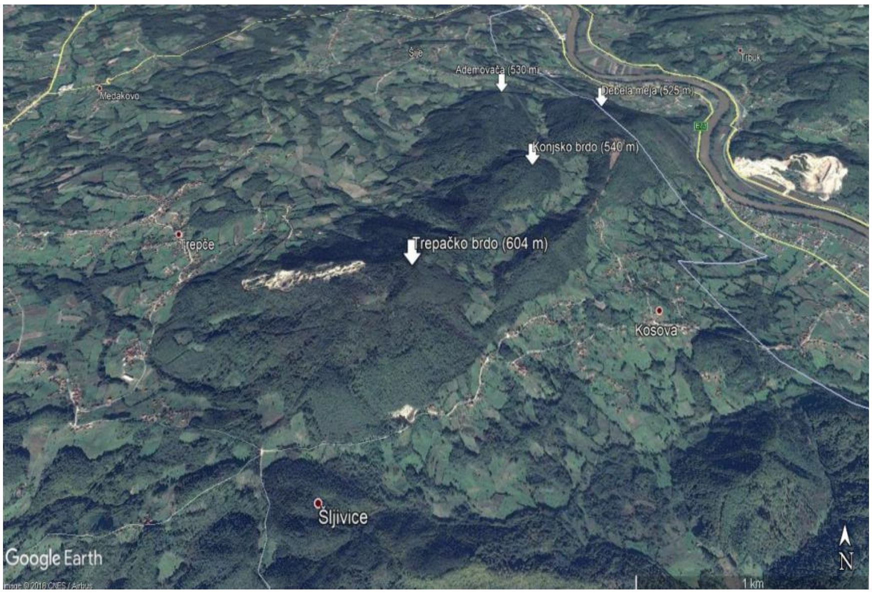

Figure 1 Morphological appearance of the wider Trebačko Brdo area [source: Google Earth]

Previous investigations included drilling operations, laboratory testing of the physico-mechanical properties of the rock mass, and reserve balance calculations. According to the available data, the deposit contains significant quantities of limestone suitable for various construction purposes. The chemical composition indicates a high $CaCO_3$ content, suggesting broad applicability in the construction materials industry (Kašić, Mihajlović & Đorđević, 2023).

In the context of technological development and the need to increase extraction capacity, the expansion of the quarry through the introduction of deep benches is being considered. This concept implies continuation of mining below the existing bench levels, while ensuring slope stability, adequate dewatering, and adaptation of the haulage system. The introduction of deep benches may substantially increase the volume of exploitable reserves; however, it also entails technical and safety challenges that require detailed analysis.

Slope stability represents one of the key factors in planning new bench development. The geomechanical characteristics of the rock mass—such as uniaxial compressive strength, modulus of elasticity, and resistance to water action—are crucial for determining optimal slope angles and bench heights (Hoek & Bray, 1981). Numerical methods, such as SWASE, have proven effective in calculating slope safety factors, particularly under complex geological conditions (Baraković, Bektašević & Sjerotanović, 2011).

Studies indicate that the mechanical properties of limestone change significantly with increasing confining pressure and under water-saturated conditions. Saturation may lead to strength reduction and increased deformability, which is particularly relevant when planning deep benches where interaction with groundwater is more likely (Šestak, 2006; Lama & Vutukuri, 1978).

In addition to geomechanical characteristics, the technological selection of excavation methods constitutes an important aspect. Quarries with deep benches require adequate planning of haul roads, drainage systems, and ventilation. Furthermore, the combined effects of surface and potential underground exploitation must be analyzed, as such systems may induce surface subsidence and alterations in the stress–strain state of the rock mass (Ma et al., 2023). Models developed in recent research enable the prediction of such displacements, thereby enhancing the safety and reliability of planned operations.

Alongside technical considerations, environmental issues are gaining increasing importance. Limestone extraction generates dust emissions, blasting-induced vibrations, landscape alteration, and potential disturbances to hydrogeological regimes. The impact of dust emissions on air quality has been extensively analyzed in several studies, which emphasize the need for the application of modern technologies and mitigation measures (Bektašević et al., 2012; Bektašević et al., 2015a; Bektašević et al., 2015b; Bektašević et al., 2018).

Contemporary approaches require the integration of environmental protection and sustainability measures into mining projects, including impact monitoring, controlled blasting techniques, and reclamation planning (Bell & Donnelly, 2006; Bektašević et al., 2013). Examples from other European quarries demonstrate that intensive exploitation can be successfully combined with high environmental protection standards through the use of modern technologies (Kaymierczak & Strazlkowski, 2019).

At the local level, the Trebačko Brdo quarry has specific social and economic significance. Stone exploitation represents a potential driver for the development of the local construction industry and the creation of new employment opportunities, while simultaneously raising concerns among part of the public regarding spatial and environmental protection. Decisions concerning capacity expansion and the introduction of deep benches must therefore consider technical, economic, environmental, and social factors in an integrated manner.

The objective of this paper is to provide a detailed technical analysis of the possibility of expanding the quarry at Trebačko Brdo through the introduction of deep benches. The focus will be on the assessment of the geomechanical characteristics of the rock mass, technical and technological solutions for excavation and haulage, as well as the evaluation of environmental and community impacts. Particular emphasis will be placed on comparison with practical case studies and contemporary mining methods, with the aim of demonstrating the feasibility and sustainability of the proposed solutions.

2 GEOLOGICAL, GEOMORPHOLOGICAL, HYDROGEOLOGICAL AND ENGINEERING-GEOLOGICAL CHARACTERISTICS OF THE DEPOSIT AND LABORATORY TEST RESULTS

2.1 Geological and geomorphological characteristics

The Trebačko Brdo area belongs to the spatial unit known as the southern margin of the Pannonian Basin, characterized by complex geotectonic and geomorphological features. The relief consists of a series of hills aligned in the Dinaric strike direction (NW–SE), composed of magmatic–sedimentary rocks of Jurassic–Cretaceous and Neogene age. These geomorphological units are the result of the combined action of endogenous and exogenous processes, with fluvial–nival erosion playing a significant role (Rudarsko Projektovanje, 2023).

Within the broader area, three main morphological units can be distinguished: the lowland zone along river valleys (150–250 m a.s.l.), the hilly terrain (250–500 m a.s.l.), and the low-mountain zone (500–750 m a.s.l.). The maximum elevation of the investigated area reaches 604 m (Trebačko Brdo), while the terrain descends toward the Bosna River valley to elevations of 160–190 m a.s.l. Such hypsometric differences provide favorable conditions for surface mining, but simultaneously require careful slope design due to the pronounced relief dissection (Rudarsko Projektovanje, 2023).

Lithologically, the deposit belongs to the Upper Cretaceous (Turonian and Senonian), and is predominantly composed of limestones, calcarenites, and calcrudites. The limestones are gray to reddish in color, massive in texture, and crystalline in structure, exhibiting a vigorous reaction to diluted HCl acid (Geo IterMax, 2022). The stratigraphic position and lithological uniformity indicate significant potential for exploitation as technical construction stone, as confirmed by previous studies of similar deposits in Bosnia and Herzegovina (Ćosić, Kurtanović & Begović, 2007; Majstorović, Malbašić & Čelebić, 2015).

The bedding of the rock mass is characterized by variable thicknesses (5–25 cm), with a general strike direction of 310–330° and a dip angle of 25–32°. This layer orientation, together with the presence of joints and fractures, significantly influences the geomechanical behavior of the rock mass and slope stability, which is of particular importance when planning deep bench development (Hoek & Bray, 1981).

2.2 Hydrogeological and engineering-geological characteristics

The limestone massif of Trebačko Brdo is characterized by fracture–fissure and cavernous porosity, which conditions the formation of local aquifers with limited capacity. Recharge occurs predominantly through the infiltration of atmospheric (precipitation) waters, accompanied by significant fluctuations in dynamic reserves. The bedded and fractured limestones enable rapid percolation of precipitation into the deeper parts of the massif, while karstification processes further enlarge fractures and increase flow conduits (Milanović, 2004).

From an engineering-geological perspective, the fundamental parameters of the working environment are determined by lithofacies composition, tectonic framework, and the spatial orientation of discontinuities. Observations from accessible cuts and bench exposures indicate that the layers exhibit variable physico-mechanical properties: lighter-colored limestones demonstrate more favorable characteristics, whereas darker varieties show lower strength values. It has also been observed that the rock mass exhibits improved properties with increasing depth, consistent with general trends in carbonate rocks (Deere & Miller, 1966).

Discontinuities, particularly sub-vertical fractures, represent a significant risk factor for slope stability. Their infill consists of secondary calcite and reddish-brown clay, which is easily washed out, leaving cavities of irregular dimensions. Such conditions require careful geotechnical analysis when designing new benches, with particular emphasis on close coordination between geologists and mining engineers in determining optimal slope angles (Song et al., 2025; Cui & Gratchev, 2024).

2.3 Laboratory test results

The results of chemical, mineralogical–petrographic, and physico-mechanical testing indicate that the limestones from the Trebačko Brdo site meet the requirements for use in the construction industry. Chemical analyses revealed a high CaO content (above 50%) and a loss on ignition of approximately 40–43%, which is typical of high-quality carbonate rocks (Rudex, 2023). The content of undesirable components, such as sulfates, sulfides, and chlorides, is very low (below 0.01%), further confirming the suitability of the material for application in concrete mixtures and asphalt (shown in Table 1).

Table 1 Results of chemical analysis

Parametar	TB-1 (4.2–4.8 m)	TB-1 (11.8–12.5 m)	TB-2 (6.2–7.0 m)	TB-2 (17.0–17.6 m)	TB-3 (4.1–4.7 m)	TB-3 (11.0–12.6 m)
Loss on ignition (LOI)	40.79	41.67	41.12	41.00	41.24	40.27
SiO_2 + insoluble residue	7.20	3.43	4.8	5.15	5.25	6.85
Fe_2O_3	0.10	0.18	0.25	0.21	0.27	0.28
Al_2O_3	0.00	0.00	0.00	0.00	0.00	0.00
CaO	51.04	53.98	53.14	53.00	52.44	51.58
MgO	0.22	0.22	0.21	0.24	0.21	0.27
Na_2O	0.09	0.09	0.09	0.13	0.12	0.12

K_2O	0.01	0.01	0.02	0.02	0.02	0.03
MnO	0.02	0.02	0.023	0.025	0.035	0.033
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
SO^3	0.01	0.011	0.009	0.015	0.012	0.014
Chlorides (Cl^-)	0.001	0.0011	0.01	0.0011	0.01	0.0011
Sulfides	0.005	0.006	0.004	0.008	0.007	0.009

Mineralogical–petrographic analysis confirmed that the rocks belong to carbonate sediments, specifically crystalline limestones, calcarenites, and calcrudites. The primary mineral constituent is calcite, while quartz and siliceous fragments occur in minor proportions. No components were identified that could cause concrete degradation or undesirable reactivity under adverse conditions.

Physico-mechanical testing showed that the limestones exhibit high uniaxial compressive strength (exceeding 100 MPa in dry conditions), whereas in saturated conditions the values are slightly lower but still remain above the minimum standard requirements (presented in Table 2).

Table 2 Results of physico-mechanical testing

Parameter	B–1 (32.0–33.0)	B–2 (32.0–32.4; 32.5–32.8)	Asphalt concrete (requirement)	Concrete (specification limit)
Compressive strength (MPa) – dry condition	108.9	50.7	≥ 80.0	≥ 120.0
Compressive strength (MPa) – water-saturated condition	103.7	46.1	≥ 64.0	-
Compressive strength (MPa) – after 25 freeze–thaw cycles	97.3	38.5	-	≥ 96.0
Abrasion resistance by grinding (cm³/50 cm²)	20.2	36.1	≤35	
Abrasion resistance (Los Angeles coefficient)	21.8	35.5	≤35	
Water absorption (%)	0.68	1.52	≤0.75	
Mass loss in Na_2SO_4 (%) – freeze resistance (%)	3.06	5.61	≤5.0	
Porosity (%)	0.98	1.93	-	-
Bulk density (g/cm³)	2.643	2.492	2.0-3.0	
Specific gravity (g/cm³)	2.678	2.541	-	-

Freeze resistance and abrasion resistance indicate suitability for use in road construction, while water absorption is generally below 1%, confirming the good durability of the rock mass (Milišić, 2022).

Considering all evaluated parameters, the material from the Trebačko Brdo deposit can be used in a wide range of construction applications:

- as an aggregate material in cement concrete mixtures,
- for the construction of upper load-bearing layers in pavement structures,
- for precast concrete elements, bank protection structures, lean concrete, and stone cladding.

3 MINING CONDITIONS AND POTENTIAL FOR QUARRY EXPANSION

3.1 Current operational status

The quarry at the Trebačko Brdo site is currently being developed within a limited area with clearly defined quarry boundaries. To date, mining has been conducted in accordance with conventional surface extraction methods, whereby the material is obtained through drilling, blasting, and subsequent loading into haulage equipment.

Figure 2 presents the boundaries of the existing quarry at the Trebačko Brdo site, together with the associated infrastructure elements and the topographic characteristics of the terrain.

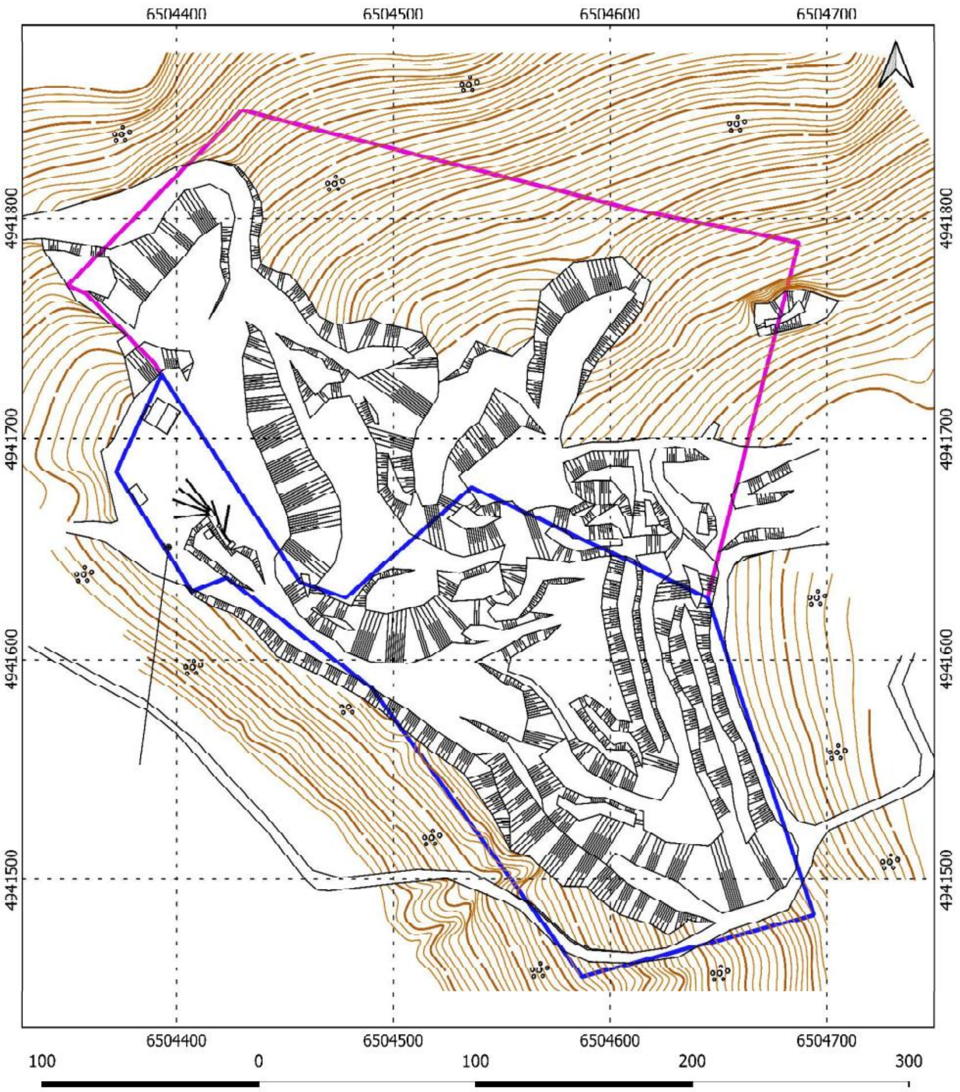

Figure 2 Topographic map of the Trebačko Brdo site with indicated quarry boundaries and infrastructure

The geometry of the benches is aligned with the natural stratification of the limestone rock mass, which has resulted in relatively good stability of the working slopes. However, the existing exploitable reserves in the upper parts of the massif are gradually being depleted, raising the issue of expanding the quarry to greater depths. Regional trends indicate that many quarries, upon transitioning to deeper benches, face increased technical and safety requirements (Sjoberg. 1996).

3.2 Concept of quarry expansion to deeper bench levels

The expansion of the quarry through the introduction of deeper benches represents a technically optimal solution for securing additional exploitable reserves, without the need for lateral expansion of the quarry. The concept is based on the formation of successive deeper benches below the final mining level, while maintaining geometric stability and operational functionality.

The current designed condition is shown in Figure 3, where the final quarry configuration is visible, with an elevation range from 520 to 570 m above sea level.

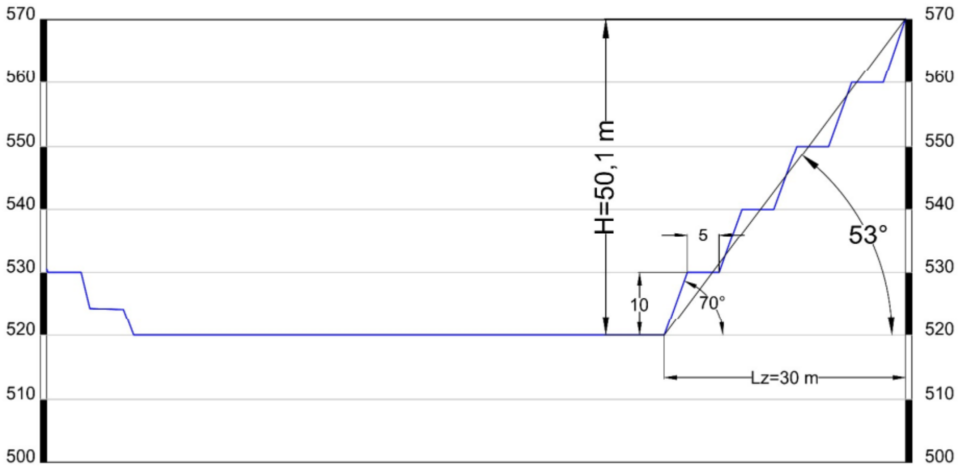

Figure 3 Existing designed cross-section of the Trebačko Brdo quarry

The planned expansion envisages the deepening of the quarry down to the elevation of 470 m above sea level, thereby increasing the total mining height from the current 50 m to 85 m. New benches will be formed successively below the existing mining level, with heights ranging from 10 to 15 meters, in accordance with the terrain geometry and the stability of the rock mass.

Access to the lower benches is provided by spiral ramps integrated into the existing quarry configuration, ensuring adequate working areas, safety zones, and haulage routes.

The working slopes in the expansion area are designed with an inclination of 70°, while the overall final quarry slope angle will be 56°, in accordance with stability requirements. The width of the final berm is 5 meters, providing additional safety during the final phase of exploitation.

The designed condition with the newly formed deeper benches is shown in Figure 4, illustrating the expanded quarry configuration with an increased elevation range from 470 m to 570 m above sea level.

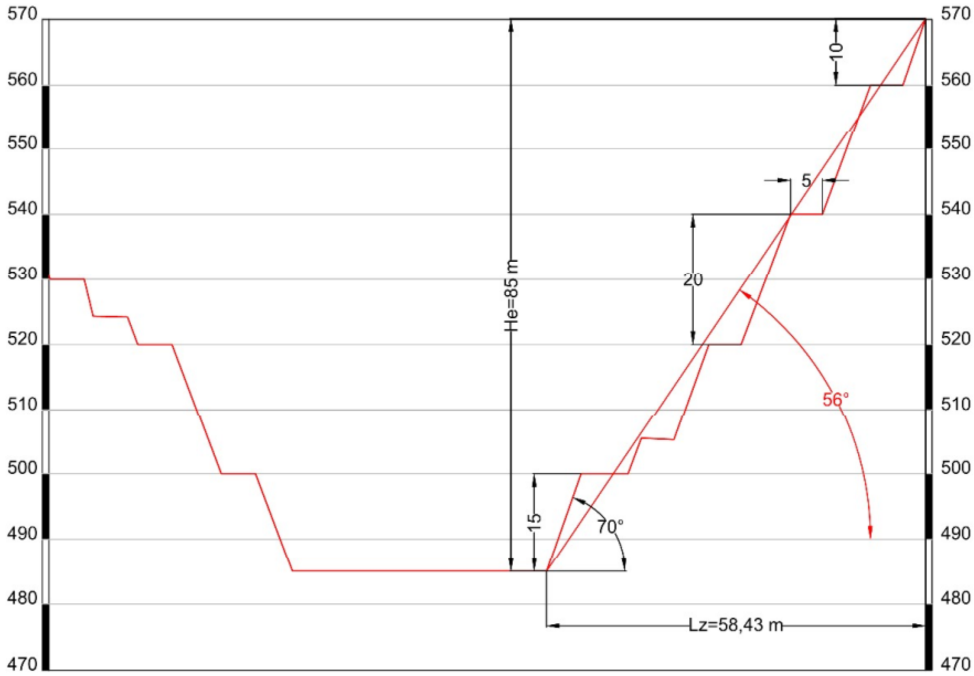

Figure 4 Presentation of the designed quarry profile with deeper benches at the Trebačko Brdo

The advantages of this approach include:

- increasing the volume of available reserves without the need to occupy additional land,
- maintaining continuity of mining operations,
- enabling more rational use of the existing infrastructure (roads, processing facilities, drainage systems).

The main challenges include the need to ensure the stability of deeper slopes, increased interaction with groundwater, and the adaptation of the haulage system to operating conditions at greater depths (Safari et al., 2025).

3.3 Slope Stability and Associated Geotechnical Challenges

Slope stability under conditions of deeper benches depends on the lithological and tectonic characteristics of the rock mass, the spatial orientation of bedding and discontinuities, as well as hydrogeological conditions. Numerical analyses (e.g., the finite element method and the limit equilibrium method) have proven particularly effective for calculating the factor of safety of slopes in complex carbonate massifs.

When planning new benches, it is necessary to:

- precisely define the slope angle and bench height,
- conduct geotechnical investigations for each bench,
- provide a drainage system to reduce pore water pressures,
- implement stabilization measures where necessary (anchors, mesh, retaining structures) in zones of weakened rock mass.

Previous experience from quarries in Croatia and Slovenia shows that the combination of geotechnical monitoring and adaptive bench planning significantly reduces the risk of landslides and rockfalls in deep mining operations (Markus, 2018; Lazar et al., 2020).

In order to confirm the technical feasibility of the expansion, two basic calculations were carried out: the slope stability factor and the optimal working bench width. These calculations contribute to a quantitative assessment of safety and the geometric functionality of the planned benches.

For the assessment of slope stability in clayey–marly rock mass, a simplified version of Bishop's method is applied:

$$F = \frac{c' \cdot L + (W \cdot \cos\alpha - u \cdot L) \cdot \tan\emptyset'}{W \cdot \sin\alpha} \tag{1}$$

Where:

- Effective cohesion: c' = 28 kPa,
- Effective internal friction angle: φ' = 20°,
- Pore water pressure: u = 10 kPa,
- Weight of the sliding slice (segment): W = 200 kN,
- Length of the slip surface: L = 13.75 m,
- Slip (inclination) angle: α = 70°.

By substituting the given parameters $F = \frac{28 \cdot 13{,}75 + (200 \cdot \cos 70^0 - 10 \cdot 13{,}75) \cdot \tan 20^0}{200 \cdot \sin 70^0} = 1{,}91$

The slope stability analysis was carried out on clayey–marly rock mass to represent the most unfavorable scenario and to account for discontinuities filled with clay and marl. This approach ensures a conservative design, as the actual values for limestone indicate considerably higher slope stability.

For determining the minimum working platform width, the empirical formula proposed by Singh & Goel (2011) is used:

$$B = H \cdot \tan\theta \tag{2}$$

Where:

- B – working bench width,
- H = 10 m – bench height,
- θ = 70° – designed slope angle.

By substituting the given parameters $B = 10 \cdot \tan 70^0 = 27{,}5m.$

The obtained value represents the optimal working platform width, which includes space for the working area, safety berm, access ramp, and lateral stabilization zones. Considering that the technical documentation prescribes a minimum width of 8 meters, the designed value of 27.5 meters ensures additional safety and functionality during the deep mining phase.

The calculated factor of safety significantly exceeds the prescribed limit values (F = 1.05–1.10), thereby confirming the stability of the designed slopes under deep mining conditions.

3.4 Haulage System and Drainage

Mining operations at deeper bench levels require a reliable and functionally optimized haulage system. In practice, spiral truck ramps are most commonly used, enabling safe and continuous movement of equipment to the lower working benches. Alternatively, in some quarries, a combination of conveyor belts and truck haulage is applied, which is suitable for the continuous transport of larger quantities of fragmented material.

Drainage represents one of the key factors for the uninterrupted operation of the quarry, particularly under conditions of increased interaction with groundwater. The negative impacts of inadequate drainage include:

1. Reduced slope stability due to increased pore water pressure,
2. Difficult operation of machinery and equipment in saturated zones,
3. Accelerated damage and degradation of haulage infrastructure.

Due to these risks, it is necessary to design an integrated system of drainage channels, pumping stations, and settling ponds to control surface and groundwater, along with mandatory regular monitoring of groundwater levels. Such technical solutions have already been implemented in carbonate rock quarries across Central Europe, where deep bench mining is standard practice (Kamilov et al., 2024).

4 CONCLUSION

The technical analysis of the Trebačko Brdo quarry has shown that the site possesses valid geological, geometric, and infrastructural conditions for the continuation of mining at greater depths. Based on the available technical documentation, geological profile, and configuration of the existing benches, it has been determined that additional deeper benches can be formed while maintaining slope stability, transport efficiency, and compliance with both national and international standards.

The calculated slope stability factor, F = 1.91, significantly exceeds the prescribed limit values (1.05–1.10), confirming the high safety level of the designed slopes in the clayey–marly rock mass. At the same time, the designed working bench width of 27.5 meters considerably surpasses the minimum technical requirements, enabling the integration of a spiral ramp, safety berm, and drainage channels without compromising functionality.

Previous experience from quarries in Croatia and Slovenia confirms that the application of geotechnical monitoring combined with phased adjustment of quarry geometry represents an effective approach for controlling stability in complex geological conditions. Such an approach enables timely response to local changes in the rock mass, optimization of slope angles, and reduction of the risk of landslides and rockfalls. Comparable drainage methods, including drainage channels, pumping stations, and settling ponds, are already applied in deep carbonate rock mining operations in Central Europe, thereby confirming the technical justification of the proposed solutions.

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