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Practical experiences from application of remedial measures for slopes in gypsum rock masses

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Abstract

During the last decade, rockfalls occurring on steep slopes along the Macedonian road network have become a serious issue from safety, economic, and social perspectives. These events have caused delays in the transportation of goods, temporary traffic disruptions, and various social impacts, resulting in both direct and indirect costs for the affected areas.

This study presents a case of a very high slope formed in a jointed gypsum rock mass along the regional road from Mavrovo to Debar. Based on the identification of potentially unstable rock masses and the analyses presented in the design documentation, specific aspects related to the application of protection measures are discussed. During the execution of the works, the trajectories and bounce heights of rockfall blocks were observed for the defined slope geometry and block characteristics.

All data were collected during the application of special rockfall protection techniques on a slope exceeding 90 m in height. Several protection measures were implemented, including the prevention of rockfalls through the removal of potentially unstable rock masses by scaling using alpinist techniques, as well as the installation of rock bolts and rockfall protection barriers.

Direct observations of rockfall trajectories during the scaling phase were used to compare the values predicted in the design documentation with those observed in the field. The findings were used to draw conclusions regarding the importance of safety measures during this type of work and to highlight specific observations that may contribute to the design of protection measures in similar conditions.

Keywords

Rockfall, Rockfall hazard analyses, Protection measures, Special techniques, Protection barriers.

1 Introduction

During the last decade, rockfalls have increasingly affected steep slopes along the Macedonian road network, emerging as a serious challenge with safety, economic, and social implications.

A representative case is the very high slope formed in a jointed gypsum rock mass along the regional road between Mavrovo and Debar. In 2020, a major rockfall occurred at this location, depositing large blocks onto the roadway and directly endangering traffic. This event prompted the development of a stabilization and protection project prepared by the engineering company Geing, reviewed by the Faculty of Civil Engineering in Skopje, and supervised during implementation by the Public Enterprise for State Roads. The project included detailed geological investigations, evaluation of several design alternatives, and the selection of the most appropriate and economically viable solution (Strasevski, 2022).

Although numerous studies address rockfall modelling, analytical approaches, and trajectory simulations, practical documentation of stabilization projects remains limited. Classical references such as *Practical Rock Engineering* (Hoek, 2006) describe rockfalls as a probabilistic hazard, where trajectory modelling and protective structures are often more effective than conventional stability analyses. The focus is placed on risk reduction and containment rather than complete prevention. More recent contributions (e.g., Greer et al., 2025) highlight specialized rock-scaling projects using alpinist techniques; however, practical accounts of such interventions remain relatively scarce.

Given the significant uncertainty associated with selecting parameters for rockfall simulations, several authors have emphasized the importance of in-situ data and full-scale experiments, in which rock blocks are intentionally released from slopes of interest to calibrate and validate rockfall simulation models (Arnold et al., 2023).

By documenting this Macedonian case study, the paper emphasizes the integration of geological conditions, engineering design, and construction practices as essential components of sustainable and safe slope stabilization. Following this approach, the aim of the paper is to present practical experiences and challenges encountered during the execution of remedial measures rather than to focus solely on academic analyses. The execution of the works required careful planning of site access and stabilization procedures, with particular attention given to worker safety. Observations of rock mass behaviour during scaling and stabilization activities provided valuable insights into the practical challenges associated with implementing such measures in difficult field conditions.

2 Geological setting

The analysed site is located along the regional road R1201, on the Boškov Most–Melnički Most section near Kosovrasti. It comprises a slope situated directly above the roadway, extending approximately 150 m in length and representing an unstable zone with a high rockfall hazard.

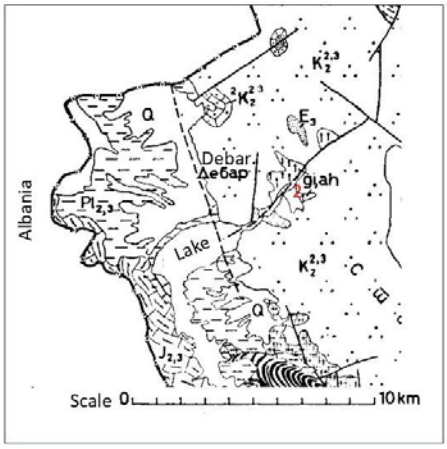


Figure 1. Geological map town Debar: gi, ah-gypsum and anhydrite rock mass complex; K2 2,3-Cretacoeus flysch complex; E3-Eocene flysch, Pl 2,3 - Pliocene Lake sediments; Q-sediments with quarterian geological age; 1-Location of analyzed slope in the article (Jovanovski and Peshevski, 2026).

As shown in Figure 1, the wider area is predominantly composed of Upper Cretaceous flysch sediments represented by sandstones, clay shales, siltstones, marls, marly limestones, and, less frequently, conglomerates and cherts. The gypsum–anhydrite deposits, which represent the most widespread sulfate rocks in the area, have an estimated thickness of approximately 500 m (Jovanovski and Peshevski, 2026).

The gypsum rock mass is characterized by pronounced fracturing and high sensitivity to water. The joint systems are unfavorably oriented toward the slope, forming wedge-shaped blocks and, in certain locations, creating conditions for block overturning. The rockfall hazard is primarily controlled by dominant discontinuities dipping toward the slope, enabling both planar and wedge failure mechanisms.

In addition, gypsum dissolution processes further weaken the rock mass, contributing to the formation of unstable blocks with overturning potential. The geological and structural setting of the slope significantly increases its susceptibility to the detachment and movement of rock blocks.

3 Protective measures and Project Approach

A distinctive feature of this site is that instability occurs along the entire slope length rather than being localized. This makes remediation more complex and necessitates the application of multiple protective measures.

Within the project solution, slope protection measures were designed with a limited scope, covering up to approximately 18.5 m above road level. This approach resulted from a combined technical–economic analysis, considering the considerable slope height and the complexity of the terrain.

The project incorporates a combination of interventions, including: scaling of the slope to remove unstable portions and establish a cleaner, more stable rock surface as a prerequisite for other protective systems; installation of protective nets to intercept smaller rockfalls; anchoring of the rock mass to improve stability and reduce block detachment; and installation of protective barriers at the slope toe to retain fallen material and prevent it from reaching the roadway.

Typical sections showing the designed mitigation measures and results of the rockfall analyses are presented in Figure 2 (Strasevski, 2022).

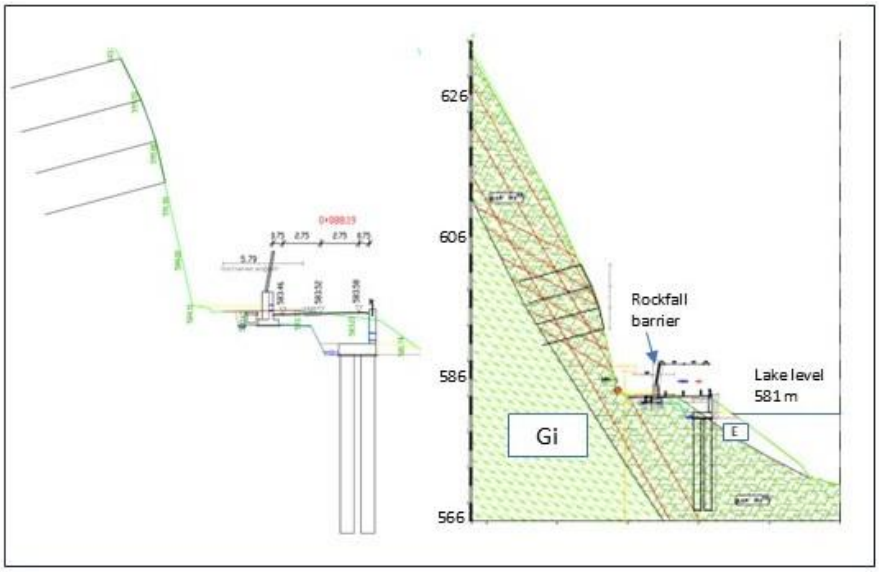


Figure 2. Left – Detail of technical solution; Right- Presentation of elements of technical solution with geology (Strasevski, 2022).

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4 Main elements of application of measures using alpinist techniques

In this study, rockfall behaviour was evaluated through direct field observations during the scaling process, i.e., the manual removal of unstable blocks from the slope and monitoring of their trajectories. Unlike classical approaches based on computer simulations, emphasis is placed on real field conditions and the behaviour of rock blocks during detachment and fall.

4.1 Work Approach and Organization

Before commencing operations, workers inspect their equipment and secure alpinist ropes to at least two safety points. A stability and safety assessment of the terrain is performed. Access to the slope is difficult, requiring up to 40–50 minutes of walking to reach the working position. Upon arrival, suitable natural anchoring points (typically trees) are selected, supplemented by drilling and installation of anchors to secure the ropes. Ropes are tied using appropriate knots and tensioned, after which workers begin scaling from top to bottom. During descent, the ropes must not rub against or shift along the slope. Any minor disturbance in stability, uncertainty in movement, or lack of coordination within the team can lead to undesirable consequences.

Safety is paramount, and no activities are allowed beneath the working zone in order to prevent injuries caused by falling material.

4.2 Scaling Execution

Rock scaling is a critical safety operation. Practical experiences documented by transportation agencies and mining industry organizations indicate an increasing use of mechanized methods; however, manual “barring down” remains a technical necessity for final quality control. Current industry practice generally categorizes scaling into several primary approaches (Global Rock Works, 2026). In this case, manual scaling involved crews using long scaling bars to remove loose rock and debris. The work was performed using rope-access techniques (rappelling) on steep highway slopes. Although highly flexible, this method is labour-intensive and presents a higher risk to personnel due to their close proximity to unstable rock faces (Figure 3).

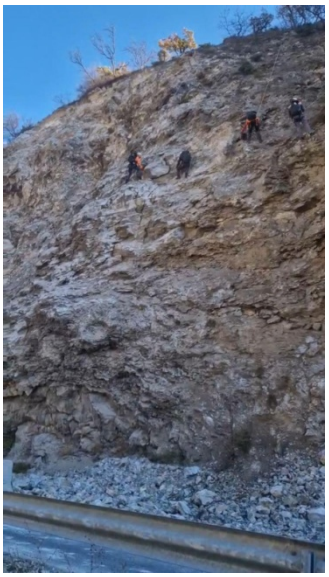


Figure 3. Photo from the scaling operations at the slope using top-down manual techniques (authors photo).

Other techniques, such as mechanical scaling, were not applied in this case.

Vegetation (trees and shrubs) is cleared using chainsaws, while unstable rock blocks are removed with hand tools (crowbars, rakes, and hoes). Scaling is performed gradually, with the team moving in parallel across the slope. Each potentially unstable section must be carefully inspected and treated in order to prevent hazards to both workers and traffic.

Larger blocks identified as unstable are occasionally removed using mechanized assistance, with cables used to secure and control their extraction.

A key aspect of the operation is that scaling must always be carried out from the top of the slope downward, preventing loosened material from falling onto workers positioned below.

4.3 Work Dynamics and Traffic Management

Operations are conducted under a special traffic regime. While the alpinists are positioning themselves on the slope, traffic is allowed to flow in one lane; during active scaling and rockfall movement, traffic is stopped in both lanes.

During periods when vehicles are allowed to pass, workers remain stationary in their positions. Before traffic is reopened, the roadway is cleared mechanically of larger rock fragments and manually of finer debris.

The time required for scaling and clearing a single section can extend to up to 5 hours without interruption, reflecting the complexity and intensity of the operation.

5 Field Reality versus Project Assumptions

Field observations revealed that some blocks disintegrate immediately upon detachment, indicating a highly degraded rock mass structure. From greater heights, blocks further fragment upon impact with the slope, producing smaller rock fragments.

Block sizes vary from small fragments to masses up to 1 m in dimension. Depending on the slope angle and height, rockfall movement ranges from direct sliding along the slope to significant bouncing. In certain cases, blocks were observed to rebound 12–15 m away from the slope.

A comparison between observations made during the execution phase and the results obtained during the design phase is presented in Figure 4.

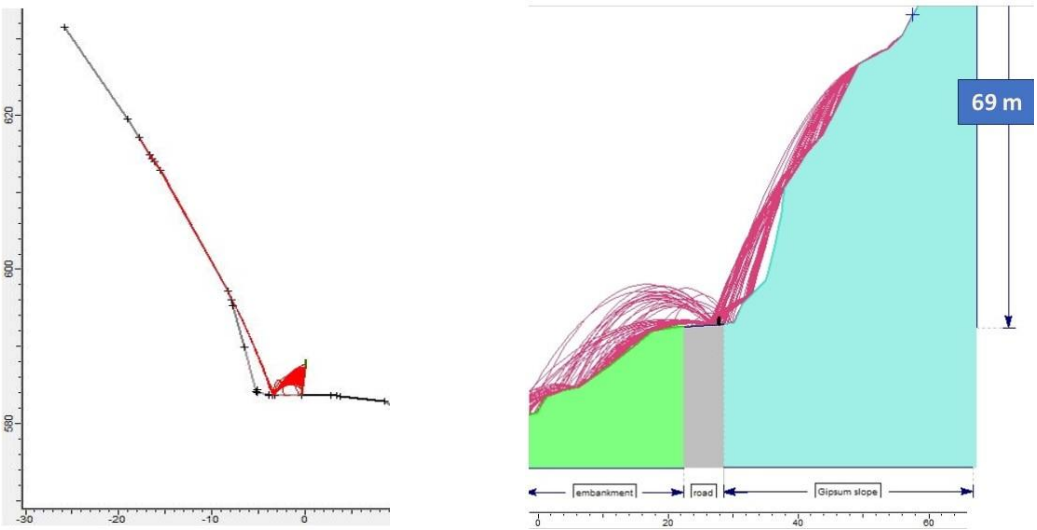


Figure 4. Left- Rockfall simulations from the design phases; Right-analyses during execution phase (Jovanovski and Peshevski, 2026).

In this case, ROCFALL2 software was used for rockfall risk analyses. The results confirm that the actual behaviour of the rock mass is consistent with the assumptions presented in the project documentation.

The combined approach of scaling and localized protective measures proved to be appropriate for this type of slope.

Field observations further highlight scaling not only as a preventive measure but also as a valuable tool for understanding rockfall behaviour and providing useful insights for future analyses and designs.

6 Conclusion

The Kosovrasti case illustrates the challenges associated with stabilizing gypsum slopes affected by jointing, faulting, and dissolution processes. The implemented project demonstrates the importance of integrating geological investigations, engineering design, and practical execution. The study provides insights into real field conditions, emphasizing the relationship between the proposed protection measures and the behaviour of the rock mass during remediation works.

The combination of scaling, anchoring, steel mesh, and protective barriers represents a practical and effective approach to reducing rockfall risk to an acceptable level.

Direct field observations during scaling provided valuable insights into block detachment, fall trajectories, fragmentation, and rebound. The findings confirm that the observed behaviour of the rock mass is consistent with the assumptions presented in the project documentation, validating the selected approach and the implemented protection measures.

Scaling is reaffirmed as a fundamental preventive measure—often underestimated—yet essential for the removal of unstable rock masses and for creating the conditions necessary for the effective application of other protection systems.

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