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Coefficient of Restitution for Gypsum Rockfall Modelling: Insights from Field Tests and Numerical Simulations

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Abstract

Appropriate determination of the coefficient of restitution is crucial for accurate rockfall numerical modelling. Although it is commonly used as a fundamental parameter in numerical models for calculating rockfall trajectories, its influence on rockfall kinematics, particularly in combination with horizontal acceleration, has not been sufficiently investigated for gypsum rock masses. This study presents an analysis based on a real test-field case in Macedonia, for which video documentation of simulated rockfalls on a gypsum slope is available, allowing a direct comparison between the real scenario and the results obtained from numerical simulations. Furthermore, the coefficient of restitution and horizontal acceleration are varied to examine their mutual interaction and their influence on the final simulation results. The RocFall software was used to simulate rock motion, analyzing trajectories, velocities, and bounce modelling along the slope, with special emphasis on calibration of the coefficient of restitution. As a final outcome, the study proposes a representative coefficient of restitution for the analysed gypsum rock slope. The proposed coefficient of restitution should be further verified using additional case histories from gypsum slopes worldwide. The obtained results are considered to contribute to improved rockfall modelling and more objective risk assessment for gypsum slopes.

Keywords

Rockfall modelling, Gypsum, Coefficient of restitution, Proposal.

1 Introduction

Rockfall processes represent a significant hazard for transportation, large civil structures and urban infrastructure in steep terrains, particularly in areas composed of weak and highly fractured rock masses. This is especially evident in gypsum formations, which are characterized by relatively low strength, high deformability, and strong sensitivity to water-related processes. Despite their interesting nature, relatively small number of recent studies on gypsum instabilities can be found in literature, such as in Tomás et al., 2018,Peruzzetto et al., 2026, Gutiérrez et al., 2023.

Other aspects of gypsum modelling and properties have been widely investigated. These include dissolution and saturation effects that can considerably reduce mechanical properties over time and contribute to the development of unstable slope conditions. Interesting findings from wetting and drying cycle effects on gypsum are presented in Xu et al. 2022. Structural properties have been investigated by Darıcı and Özel, 2018. Yilmaz, 2021 presents an overview of main problems associated with gypsum/anhydrite throughout the world. Mineralogical transformation due to exposure to various environments and conditions of the gypsum rocks has been investigated more thoroughly, but this overcomes the goals of the paper.

In this context, occurrences related to weakening and structural problems of gypsum rock masses arealso observedin several case studies from the Macedonian road network. In these complex environments, numerous problems with subsidence, rock caverns and rockfalls on the road infrastructure are noted. The study presented in this paper focuses on the aspects of numerical modelling of the rockfall trajectories, more specifically related to the defining of coefficient of restitution (COR) for the respective gypsum rock mass. The COR parameters have been assessed by many, while Shadabfar and Mahsuli, 2022 and the Rocscience Rocfall Material library, 2026, contain collection of confirmed values for COR of specific rock masses and surfaces.

To achieve this goal, the well known Rocscience RocFall2 software is used, which enables analysis of rockfall kinematics, including trajectories, velocities, and bounce characteristics. The reliability of these analyses strongly depends on the selection of input parameters, particularly the coefficient of restitution, which is often difficult to define for specific rock types such as gypsum. Furthermore, the influence of horizontal acceleration, as a representation of dynamic effects, adds additional uncertainty to the modelling process. Therefore, this study focuses on the calibration of COR as key parameter, through comparison between numerical simulations and real observations (video recorded rockfalls during rehabilitation of slopes). The overall aim is to improve the reliability of rockfall modelling and contribute to more objective risk assessment for gypsum cut slopes.

2 Case study area properties

2.1 Location of the study area

The wider study area is situated in the western part of R.N Macedonia, within the mountainous terrain of the Radika River valley (fig.1). The regional road R1201 follows this valley and represents an important transportation route connecting several settlements in the region. The terrain is characterized by pronounced relief, with steep slopes and significant elevation differences between the valley floor and surrounding ridges. The analysed slope is part of a road cut, where excavation activities have exposed the rock mass and altered the natural equilibrium of the terrain. In addition to the natural terrain conditions, the area is influenced by the presence of the artificial reservoir “Spilje”, located at the immediate toe of the slope. Variations in the water level, together with general environmental conditions, affect the overall stability of the slope and contribute to the development of unfavourable conditions.

2.2 History of rockfalls

The specific analysed cut slope is located along the regional road R1201, on the section between Boskov Most and Melnicki Most, near the village of Kosovrasti. This section of the road is well known for frequent rockfall occurrences in gypsum rock masses, which have been recorded over a

longer period, and represent a serious hazard for traffic safety. According to field observations and available project documentation, the cut slope is characterized by the presence of numerous unstable rock blocks of different sizes. In many parts of the slope, the rock mass appears intensively fractured, with visible cracks, open joints, and locally overhanging elements. These conditions enable the formation of detached blocks that can be easily mobilized under the influence of external factors, leading to sudden and uncontrolled rockfall events.

The geometry of the slope further contributes to the instability. The height varies from approximately 30 m at the margins to more than 80 m in the central part, while the inclination is generally steep, reaching near-vertical conditions in certain sections. Such geometry allows detached blocks to gain significant velocity during movement, increasing both the travel distance and the impact energy.

Previous rockfall events have confirmed that falling blocks can reach the road level, directly endangering vehicles and road users. Due to the frequency of occurrences and the scale of potential consequences, the analysed cut slope is considered a critical location that requires detailed assessment and appropriate mitigation measures. At the investigated slope cut, there is a protection in the form of New Jersey barrier.

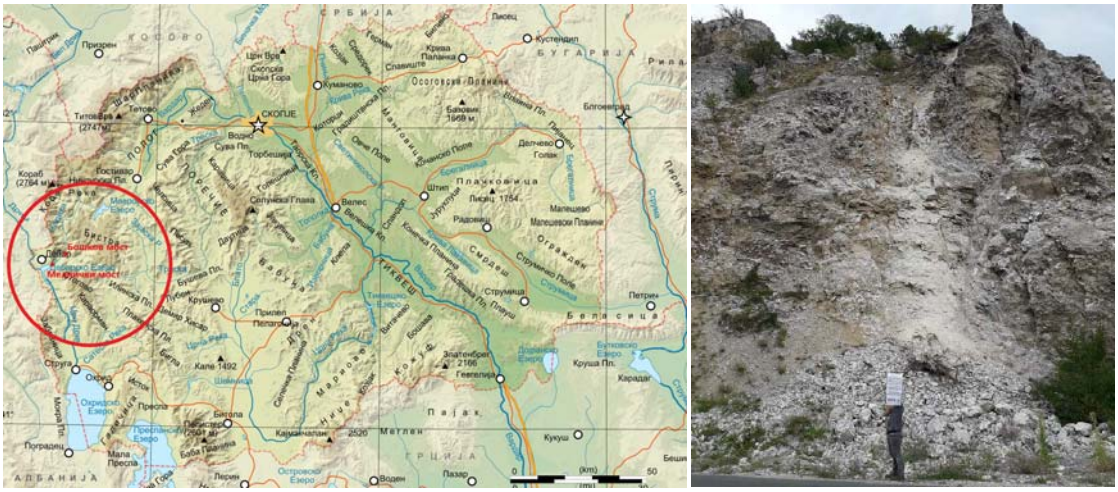


Fig.1 Left: Location of the study area in R.N. Macedonia; Right: Detailed view of the analysed slope along the road R1201.

2.3 Tectonic setting

The area belongs to a tectonically active zone characterized by the presence of regional fault structures. The Radika River valley, where the study area is located, is associated with significant tectonic features that have influenced the formation and current condition of the rock mass.The presence of faults and associated discontinuities contributes to the fragmentation of the rock mass and the development of complex structural conditions. In addition, the region is affected by seismic activity, which represents an important factor influencing slope stability. Historical seismic events in the wider area indicate that dynamic loading may play a role in triggering or accelerating instability processes.These tectonic conditions, combined with the already fractured nature of the gypsum rock mass, create a highly sensitive environment where slope stability is strongly controlled by structural features.

2.4 Hydrological conditions

Hydrological influences represent one of the key factors affecting the modelling of gypsum rock masses. Due to their chemical composition, gypsum and anhydrite are highly susceptible to dissolution when exposed to water. This process leads to gradual weakening of the rock mass and reduction of mechanical properties over time. Field and laboratory observations indicate that water infiltration significantly affects the strength of the rock mass, particularly along discontinuities. The presence of water reduces cohesion and frictional resistance, facilitating block detachment and movement. In addition, long-term exposure to water may lead to changes in the internal structure of the material, further contributing to instability. These findings are presented in Jovanovski et al., 2026 and Jovanovski and Peshevski, 2026.

3 Methodology

3.1 Rockfall modelling using RocFall2

The assessment of rockfall hazard at the analysed cut slope was performed using numerical simulations in the Rocscience Rocfall2 software. The methodology is based on the integration of field observations, available project documentation, and rockfall modelling, with the aim of reproducing realistic rockfall modelling during fall. The geometry of the slope was defined using representative profiles of the analysed section, taking into account its height, inclination, and general morphological characteristics. Rock blocks were assumed to be released from the upper parts of the slope, where unstable conditions have been identified. The existing New Jersey protection wall was treated as a rockfall barrier with defined properties. Multiple trajectories were generated in order to capture the variability of possible rockfall paths, including bounce heights, velocities, and runout distances. Seeders in the simulation were defined on the basis of video recorded events taken during rehabilitation works (fig. 2). Rocfalls were modelled with the lump mass approach and seismicity of the area was taken into account. Major properties of the slope are presented in table 1.

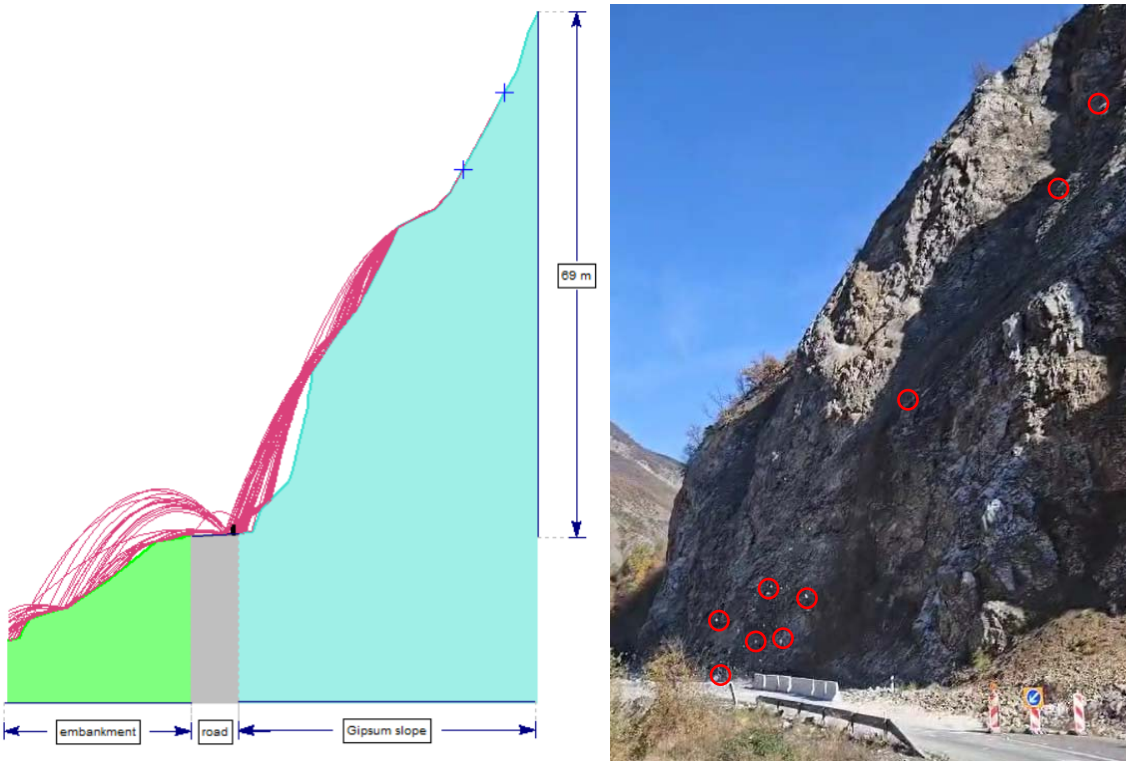


Fig. 2 Modelled cut slope along the regional road R1201 and screenshot of a videorecord with cicrled blocks.

The applied approach enables the comparable analysis of rockfall kinematics and interaction between falling blocks and the slope surface, which is essential for evaluating potential impact zones and hazard levels. Based on the simulation, the COR can be further analysed and discussed.

Table 1. Material and rockfall properties of modelled slope.

Material	Normal restitution (RN)	Tangential restitution (RT)	Friction angle (φ°)
Embankment	0.30 (std. dev.0.04)	0.80 (std. dev.0.04)	30 (std. dev. 2.0)
Asphalt	0.40 (std. dev.0.04)	0.90 (std. dev.0.03)	30
Gypsum	0.35-0.20 (std. dev.0.05)	0.78 (std. dev.0.05)	30

Seeder properties	Number of rocks	Horizontal velocity (m/s)	Vertical velocity (m/s)	Mass (kg)	Density (kg/m^3)
group 1	50	0.1-0.45	0.0	10	2700

Barrier properties	Type	Capacity (kJ)	Length/Height (m)
Embankment	New Jersey	80.00	1.0

3.2 Parameter variation and sensitivity analysis

A key aspect of the applied methodology is the analysis of the influence of selected input parameters on rockfall modelling, with particular focus on the coefficient of restitution (RN) and horizontal acceleration. These parameters were varied systematically in order to assess their effect on the kinematics of falling blocks and the associated hazard.

In the first set of simulations, horizontal acceleration was kept constant, while the coefficient of restitution was varied within a defined range. In the second set, the coefficient of restitution was fixed, and the horizontal acceleration was varied. This approach allows for the evaluation of both the individual and combined effects of these parameters on rockfall trajectories.

The influence of the coefficient of restitution was analysed through its impact on the mobility of rock blocks, including their travel distance, bounce modelling, and interaction with the slope surface. Variations in RN directly affect the energy dissipation during impacts, which in turn influences the ability of blocks to continue downslope and potentially reach the road level.

The applied sensitivity analysis provides a basis for further calibration of the numerical model through comparison with observed rockfall modelling. This approach enables the identification of representative parameter values that best describe the real conditions at the analysed site, but also suggest COR values for other cases of gypsum slopes.

4 Results

Figure 3 presents the results of the variation of coefficient of restitution in normal direction (RN) in relation to the percentage of retained rocks at the New Jersey barrier. Video records witness an 80% retention success, which is transmitted to the graph of figure 3. In order to account for the seismic risk of the area, for the value of RN of 0.26 the initial horizontal velocity was varied from 0.1 to 0.45m/s. Table 2 represents the obtained results for endpoints location differences in respect to horizontal seismic velocity.

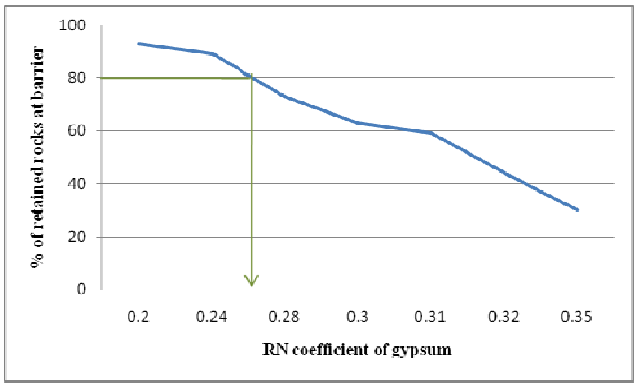


Fig. 3Correlation of RN coefficient of gypsum and number of retained blocks on the barrier.

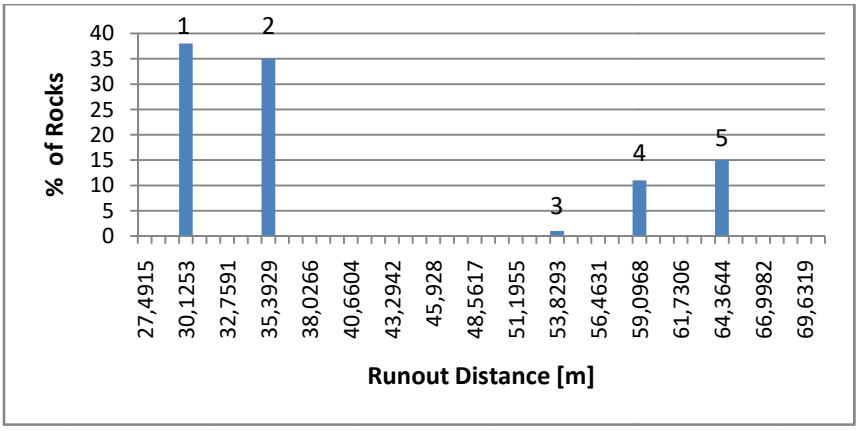


Fig. 4 Distribution of Rock Path End Locations with zones of hazard from 1 to 5.

Table 2. Sensitivity analysis of initial horizontal seismic velocity on rockfall runout distributions for the analysed slope.

Hazard Zone	Vel. 0,1 m/s	Vel. 0,3 m/s	Vel. 0,4 m/s	Vel. 0,45 m/s	Max Shift (cm)
Zone 1	8,2086	8,2127	8,2142	8,2149	0,63
Zone 2	9,4761	9,4801	9,4815	9,4822	0,61
Zone 3	29,7558	29,7585	29,7594	29,7599	0,41
Zone 4	34,8257	34,8281	34,8289	34,8293	0,36
Zone 5 (End Runout)	63,9777	63,9781	63,9783	63,9784	0,07

In similar manner as the initial horizontal seismic velocity was assessed, an effort was made to vary the value of the tangential coefficient of restitution RT. However, similar negligible differences were noted.

5 Conclusions

The main conclusion of the study is that normal coefficient of restitution for gypsum rock masses can be proposed with a value of 0.26. This conforms to previous studies on soft slopes surfaces and puts the gypsum RN value between the values reported for chalk and vegetated limestone scree surfaces. It is noted that mostly due to the steepness of the terrain, the taking into account of the seismic effect and assigning initial horizontal velocity of falling blocks did not influence the simulation results. Same conclusion is drawn for the change in tangential coefficient of restitution. In order to further investigate these aspects and obtain even more concise value of the RN parameter of gypsum surfaces it is envisaged to perform further simulations which will consist of comparison of several cut slopes with different inclination, variation of block sizes, rigid body simulations, variation of friction angle of the surface. It is considered that the proposed approach can be applied in practice for improved assessment of rockfall hazard and for supporting the design of appropriate protection measures. Considering that real field-scale rockfall tests are relatively rare, it is necessary to compare behaviour of gypsum rock masses in different physical-mechanical condition.

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