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3D Rockfall Analyses of Marl Slopes in Brovinje, Croatia

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Abstract

Rockfall is a geohazard involving the downslope movement of detached rock fragments by falling, rolling, or sliding. It is driven by factors such as weathering, dynamic triggers, hydrological changes, and anthropogenic drivers and is increasingly influenced by climate change, which accelerates erosion and weakens rock mass properties. The coastal site of Brovinje in the Istria Peninsula, Croatia, is particularly vulnerable due to its geological composition and exposure to marine processes. Although slope stability analyses indicate the absence of large-scale instability, the presence of detached rock blocks necessitates a detailed hazard assessment to evaluate rockfall risks. An integrated dataset including geotechnical laboratory testing, geophysical surveys, and high-resolution terrain models from UAV imagery and handheld LiDAR scanning was used. Slope stability was evaluated, confirming stability even under projected sea-level rise. Subsequently, 3D rockfall analyses were conducted using RocFall3 software. Two types of line seeders represented rock sources: limestone blocks from the slope crest and marl blocks from the eroded lower slope. Material properties and rigid body dynamics were applied to simulate trajectories and impacts. The simulations revealed highly energetic rockfall events, characterized by substantial velocities, elevated kinetic energy, and long runout distances. A significant proportion of simulated trajectories reached the beach area, indicating a direct hazard to people. Heatmap analysis identified zones with concentrated rockfall endpoints, which correspond well with field observations of fallen blocks on the beach and in the sea. The slope presents significant rockfall hazard which may be exacerbated by climate change. The study highlights the value of high-resolution data and 3D modelling for identifying hazard zones and supports the development of risk maps and mitigation measures.

Keywords

Rockfall, Marls, 3D rockfall analyses, UAV, Rockfall risk.

1 Introduction

Rockfall is defined as the downward movement of detached rock fragments by free falling, bouncing, rolling, and sliding (Hungr et al., 2014; Varnes, 1958). It is one of the most significant geohazards caused by weathering of natural slopes, mining activities, seismic events, intense rainfall, snowmelt, freeze-thaw cycles, root growth, and other factors. When rockfalls occur near human activities or infrastructure, they can result in severe economic losses and pose a significant threat to human life. The impacts of climate change further exacerbate rockfall hazards. Manifestations such as increased precipitation, prolonged droughts, higher frequency of extreme rainfall–drought cycles, intensified storm events, sea-level rise, and elevated wind speeds contribute to reduced soil and rock mass strength, accelerate weathering and erosion processes, increase surface runoff, amplify shrink–swell behavior in clay soils, intensify water and wind erosion, contribute to more frequent and severe storm surge–induced sea level rise, and impose greater loads from stronger winds and waves. Slope stability analyses and 2D and 3D rockfall analyses were performed at the Brovinje site on the south-eastern coast of Istria to create vulnerability and risk maps of the study area. The analyses were based on data from geotechnical laboratory testing, geophysical surveys, and high-resolution terrain models derived from Unmanned Aerial Vehicles (UAVs) and a handheld LiDAR scanner. Since the slope stability analyses determined that the slopes composed of marls with different properties are stable and there is no risk of sliding, even with a raised sea level, 3D rockfall numerical simulations were performed and will be presented in this paper. Rockfall hazard zones identified through rockfall numerical simulations, including elements of risk, will be used for the assessment of total rockfall risk in the study area. Rockfall hazard assessment remains challenging due to uncertainties in rockfall modelling and Crosta et al 2015 highlighted key difficulties related to rockfall path modelling, hazard and risk assessment. Accurate prediction of rockfall behaviour is therefore essential for the selection and design of effective protective measures and risk mitigation.

1.1 Location and geological context of the Brovinje site

According to the geological map of the Republic of Croatia (Croatian Geological Institute 2009), the study area of Brovinje in the Istra Peninsula consists of Liburnian deposits, foraminiferal limestones and transitional deposits, as well as flysch deposits. The red circle marks the position of Brovinje bay on the geological map (Figure 1).

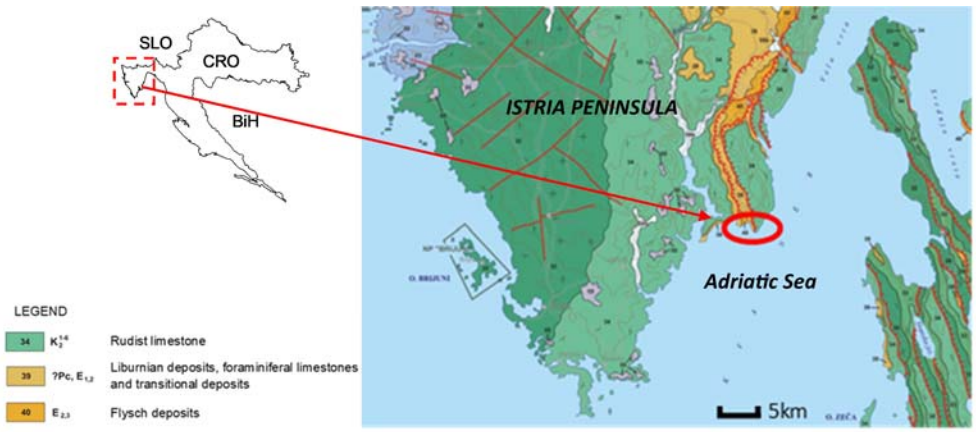


Fig. 1 Location and geological map of the Brovinje site (red oval) at the Geological map of the Republic of Croatia Scale 1:300.000 (Croatian Geological Institute, 2009).

Liburnian deposits, foraminiferal limestones and transitional deposits (Pc, $E_{1,2}$) occupy a significant part of the Croatian Dinarides, in a zone extending more or less continuously from Istria to Konavle. These deposits are transgressive onto older deposits, predominantly Upper Cretaceous limestones. Liburnian deposits formed only in the lower parts of the palaeorelief. They are characterised by an oscillating transgression over an exposed Cretaceous substrate, where bauxites and breccias typically occur at the lowest levels. Foraminiferal limestones were deposited either continuously over the Liburnian deposits or transgressively, most commonly over Upper Cretaceous limestones. Transitional deposits are composed of clayey limestones, calcitic marls and marls which, in addition to a fine-grained carbonate and siliciclastic matrix, contain individual bioclasts of benthic organisms and planktonic foraminifera. Eocene flysch deposits ($E_{2,3}$) were identified in central and northern Istria, the Croatian coastal area, the islands of Krk, Rab and Pag, and further south in some areas as far as Dubrovnik and Konavle. Repeated sequences formed alternating, most often thin, layers of sandstone and marl (Vlahović and Velić 2009).

The top of the slope is formed by a limestone plate, while the middle part consists of marl layers, covered by thin residual soil and colluvium, which are forested (Figure 2a). Homogeneous marls with variable weathering are present at the foot of the slope (Figure 2b) and on the sea bottom. These eroded marl layers are exposed to direct wave impact and marine erosion, and are affected by weathering of the surface layer, primarily seen in the change of the original grey to yellow colour.

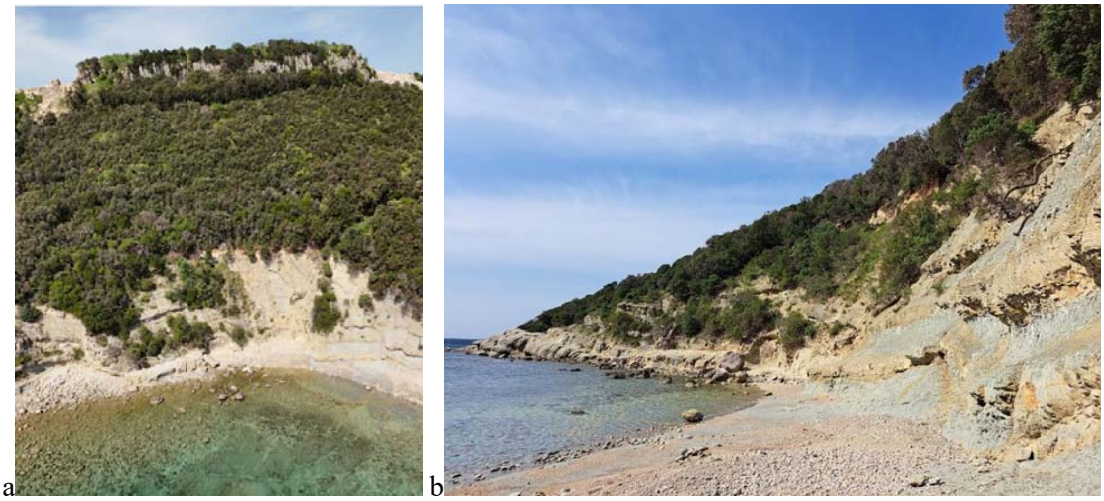


Fig. 2 a) View of the entire slope, b) alteration of differently discoloured layers of marls at the foot of the slope (photo M. Vivoda Prodan)at the Brovinje site.

Blocks of marl, breccia, and limestone are visible at the toe of the slope, on the beach gravel and inside the sea (Figure 3a), as well as in the gully along the slope (Figure 3b). Their presence poses a high risk of impact to people on the beach, indicating the need to conduct rockfall analyses.

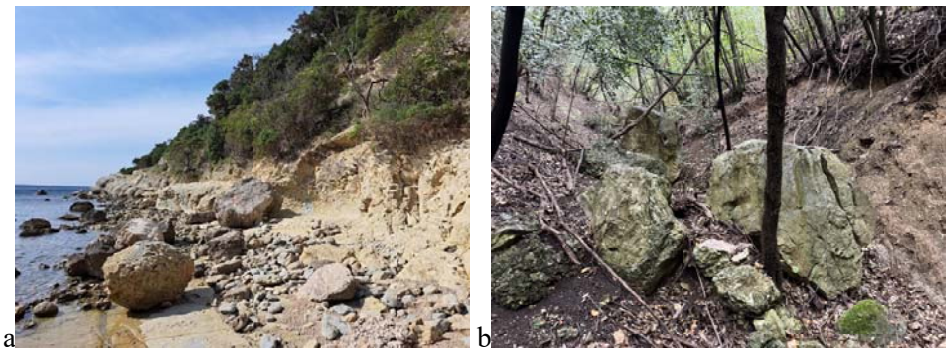


Fig. 3 Marl, breccia and limestone blocks a) at the toe of the slope (photo M. Vivoda Prodan), b) in the gully along the slope (photo: I. Ružić).

1.2 Dataset for slope stability analyses

Slope stability at the Brovinje site was evaluated using the Limit Equilibrium Method (LEM), as well as two-dimensional (2D) and three-dimensional (3D) rockfall analyses, incorporating results from high-resolution terrain models generated from UAV surveys and handheld LiDAR scanning, geophysical investigations and geotechnical laboratory tests at the Brovinje site.

The integration of UAVs and a handheld LiDAR scanner provided a robust and highly detailed dataset. These advanced tools enabled the generation of precise spatial data and surface models, which are critical for understanding and monitoring geomorphological changes over time. Using the DJI Mavic 3 Pro drone, high-resolution aerial imagery was captured, allowing for the creation of detailed orthophotos and digital terrain models (DTMs). In parallel, the LiGrip 01 Lite RTK scanner was used to acquire dense point clouds with high positional accuracy. The geophysical investigation enabled the characterisation, with metric resolution, of the surface portion of the subsoil in terms of thickness and resistivity, providing useful subsurface geological information. The geophysical investigation involved the acquisition of four geoelectrical profiles, using different interelectrode distances. Electrical resistivity tomography (ERT) profile revealed a heterogeneous subsoil with interruptions caused by fractures. The high-resistivity layer rests on a low-resistivity layer at 38 m depth could indicate the limit of a slip surface. Samples of homogeneous marls were tested in the Geotechnical Laboratory at the Faculty of Civil Engineering in Rijeka. Slight discolouration is visible on major discontinuity surfaces of marl samples, while some marl samples show superficial discolouration, indicating the

onset of weathering processes (Figure 2a). The Uniaxial Compressive Strength (UCS) testing was carried out on a PLT device, and the moisture content of the tested marl samples was determined. The similar UCS at natural humidity were obtained regardless of the slight superficial discolouration.

2 3D rockfall analyses

Since slope stability analyses showed that slopes composed of marls with varying properties are stable and not prone to sliding, even under conditions of increased sea level, further assessment focused on rockfall processes.

Three-dimensional (3D) rockfall analyses were conducted using the RocFall3 program, Rocscience Inc, Canada, version 1.017 (Rocscience Inc, 2025) to predict rockfall trajectories, enabling the identification of rockfall risk zones and the design of appropriate mitigation measures. Since rockfall dynamics depend on block geometry, slope topography, surficial geology, and vegetation, the reliability of the analyses and the effectiveness of mitigation measures are strongly influenced by the accuracy of input data and the proper consideration of all relevant methodological factors. The DTM obtained from UAV surveys and handheld LiDAR scanning (Figure 4) was used to perform3D rockfall simulations.

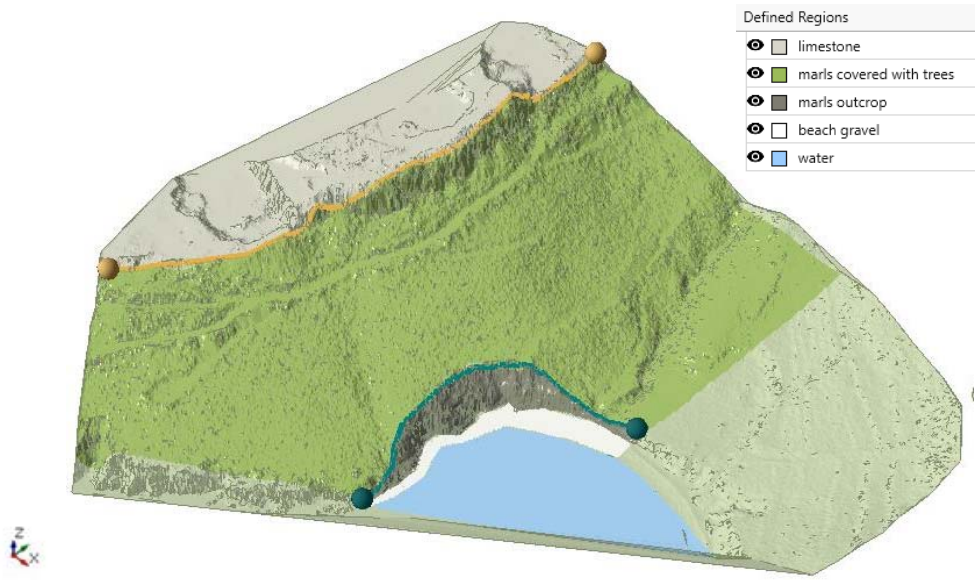


Fig. 4 3D view of the Brovinje site analysed in the RocFall3 program with two types of seeders and with different material regions.

2.1 Seeder properties

Through seeder definition, the rocks' origin locations and the rocks' initial conditions are specified i.e., velocity, mass, density, and shape. Line seeders were used to model rocks originating from a line or a polyline. The rock locations were generated with a uniform distribution along the length of the line seeder, i.e., a rock will start falling from any point along the length of the seeder with equal probability. Two types of line seeders were defined: Seeder1 grouped as limestone blocks falling from the top of the slope (yellow line on Figure 4) and Seeder 2 grouped as marl blocks falling from the eroded part at the foot of the slope (green line on Figure 4). One hundred rocks with icosphere shapes and zero initial velocity were specified identically for both rock groups. The following seeder properties: mass and density of the rock, were defined individually for each Seeder group (Table 1).

Table 1. Seeder properties in RocFall3 analysis.

Seeder n^{o}	**Seeder type**	**Density (kg/m^{3})**	**Mass (kg)**	**Initial velocity (m/s)**	**Number of rocks**	**Shape**
Seeder 1	Limestone blocks	2500	2500	0	100	Icosphere
Seeder 2	Marl blocks	2463	1000			

2.2 Material properties

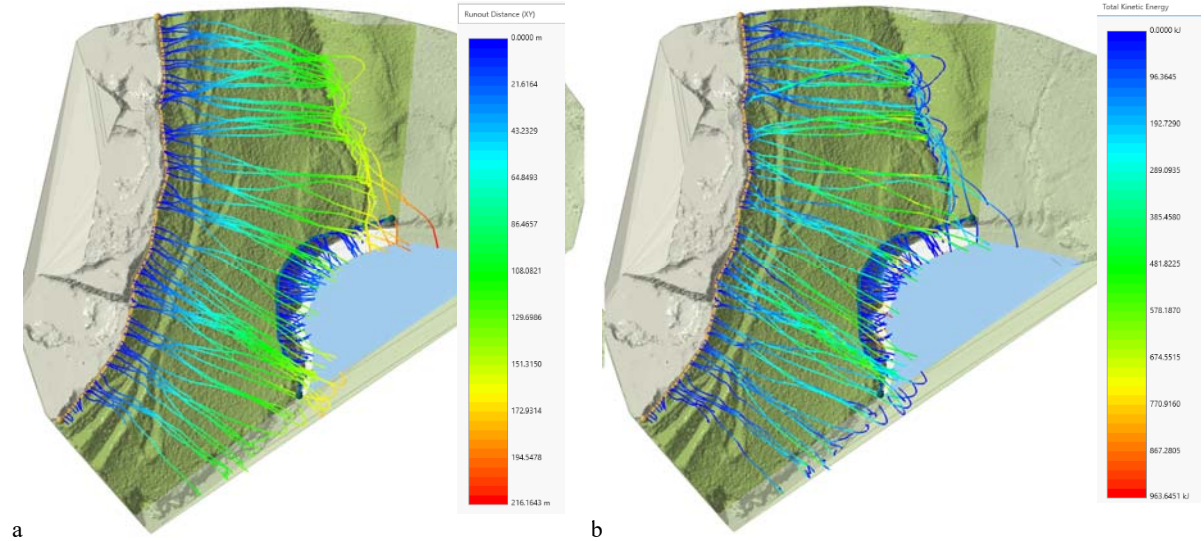
Different material properties can be applied in RocFall3 depending on whether lump mass or rigid body analysis is used. In this study, the rigid body approach was adopted to account the impulse reaction of the rock during the instantaneous contact period. The normal and tangential coefficients of restitution are used to calculate the outgoing velocities. From the change in velocity, the impulses at the contact point can be calculated and then the outgoing rotational velocities (Basson, 2012). The main contact parameters for rigid body analysis are the normal restitution coefficient and dynamic friction. Different material regions (Figure 5 and Table 2) were defined in the model: limestone at the top of the slope, marls covered with vegetation in the middle part of the slope and eroded marls and beach gravel at the foot of the slope and sea. The sea, region with water was modelled as fully damping, meaning any rock contact would immediately cancel the rock's kinetic energy and stop the rock.

Table 2. Material properties in RocFall3 analysis.

Material name	Normal restitution	Dynamic friction
limestone	0.315	0.576
marls covered with trees	0.3	0.56
marls outcrop	0.315	0.576
beach	0.32	0.557
water	Lose all kinetic energy at contact	

3 Results of rockfall analyses

Results of the 3D rockfall analyses for each rock path in both seeders are presented below. Rock paths from different seeders are shown in Figures 5a and 5b and are categorised according to runout distance xy (m) and total kinetic energy (kJ). The maximum translational velocity was 27 m/s, kinetic energy exceeded 950 kJ, and runout distance was greater than 200 m, as obtained in the analyses.



a b

Fig. 5 Results of the 3D analyses of trajectories for each rock path in both seeders: a) runout distance xy (m), b) variation in total kinetic energy (kJ) along the slope.

The heatmap is shown in Figure 6 and is used to quickly identify patterns or trends in the dataset, which is especially useful when dealing with larger sets of rock paths. The colours of the surface heatmap represent the magnitude of scalar quantities of end points projected onto the slope surface. Each grid displays a colour representing the scalar magnitude of the variable of interest, in this case the end points (red indicates 28 end points and blue indicates none).

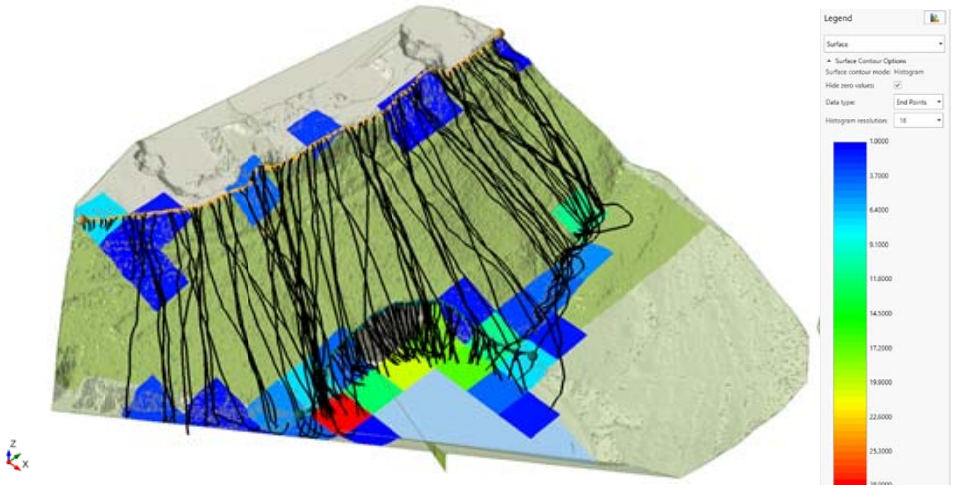


Fig. 6 Heatmap with magnitude of scalar quantities of end points projected on a slope surface.

4 Conclusions

Stability analyses at the Brovinje location, based on UAV measurements and geophysical and geotechnical laboratory investigations, presenting current data and considering rising sea level, has shown that there is no risk of global slope instability or instability at the foot of the slope. However, sea level rising would result in stronger and higher wave impacts, which would affect the appearance of the slope, increase material weathering, and could lead to localised instabilities, including sliding and rockfall processes. It is advisable to consider this influence in more detailed and sophisticated slope stability analyses in the future. Field observations show that rockfalls from both the eroded marl slope and the top of the slope endanger the beach area below the slope. 3D rockfall analyses using a point cloud model were conducted, identifying major rockfall trajectories and points at the slope toe most affected by rock impacts. The large number of blocks at the slope toe and in the gully along the slope was verified in the field and corresponds to the blocks observed on site. 3D rockfall analyses were superior to 2D analyses because they use high-resolution terrain data to account for topographic irregularities that influence rockfall paths and thus improve the design of protection structures. Rockfall hazard zones, corresponding to the accumulation areas of fallen rocks identified from the 3D simulations along the beach area below the slope, will be identified at the Brovinje site for the assessment of the total rockfall risk map. In the future, slope protection measures could be considered and analysed.

Acknowledgments

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