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ROCKFALL RISK ASSESSMENT USING 3D ANALYSES, A CASE STUDY FROM A CULTURAL HERITAGE SITE IN GREECE

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Abstract

Rockfalls pose a significant risk to human activities and infrastructure. The assessment of rockfall risk is critical in delineating zones of higher risk and mitigating the potential impact from such events in inhabited areas. This paper presents an example of how 3D rockfall modelling has been utilised to assess the risk from rockfalls at a cultural heritage site in Central Greece. The site is characterised by an Acropolis situated at the crest of a promontory, which is formed by steep limestone slopes. Following detailed UAV surveying, engineering geological mapping of rockfall prone areas, discontinuity mapping using different techniques and field measurements to identify the prevailing conditions on the slope, the analyses were performed using two dimensional and three-dimensional methods to calculate the rockfall trajectories under different scenarios. The 3D analyses results were compared to 2D rockfall analyses, to evaluate the accuracy of the two approaches. It was concluded that the 2D analysis predicted well the rockfall trajectories, in relation to the 3D analyses, but the zoning of high-risk zones was only possible when the 3D analyses where utilised. Different scenarios (i.e., earthquake, allocation of source areas) were assessed to determine the appropriate mitigation measures and zone areas where no further development should take place.

Key words

Risk, Rockfall, Rock, Slope, Cultural Heritage

1 Introduction

Rockfalls are types of ground failures that involve the detachment of rock blocks from rocky slopes followed by a rapid downhill movement. This movement is characterized as rolling, bouncing, sliding or free-falling (Varnes, 1978) and the trajectories of the rock blocks travel variable distances. Even through their economic impact is lower compared to large-scale landslides, rockfalls result in similar fatalities (same order of magnitude) as all other landslide types due to their sudden trigger mechanism coupled with the high velocities that the rock blocks travel (Hoek, 2000). During the last 2 decades, an increase in the number of rockfalls was noticed in Greece, due to intense rainfall events and earthquakes. A significant number of sites prone to rockfalls near inhabited areas and archaeological sites have been identified in Greece but rockfall protection measures have been applied in relatively few cases (Saroglou, 2013).

Risk assessment relies heavily on predicting accurately the trajectories of falling rocks, considering various factors such as the rock slope characteristics, the properties of the falling rocks, the triggering mechanism and others. Risk assessment is currently performed more frequently using three dimensional rockfall analysis allowing for a more robust assessment. The case study is located in Voiotia prefecture, central Greece and is characterised by an Acropolis (built around 4th century BC) situated at the crest of a limestone promontory. The Acropolis still preserves a 400-meter-long fortification that surrounds the north and east side of the promontory and persists into the sea. The slopes on which the Acropolis is founded are generally high and steep. The area is characterized as high risk regarding rockfall vulnerability due to the fragmentation of the limestone rock mass and the presence of overhanging rock blocks. In addition, a settlement is located around the perimeter of the hill at the base of the steep slopes, hence, the risk of rockfalls to human activity is very high.

In 2019, a rockfall event occurred after heavy rainfall and affected a house located at the base of the slope putting also into risk the integrity of the archaeological site. Site investigation proved that there have been more rockfall incidents formerly. Therefore, it is estimated that if stabilization measures are not applied, it is very likely that a potential rockfall may impact the area down slope, especially in the event of a heavy rainfall or an earthquake.

Figure 1. Left: An aerial photograph showing the location of the 2019 rockfall detachment (marked in red color) and the area of rock blocks deposition (marked in blue color); Right: A photograph of the rockfall event retrieved from the crest of the slope.

The paper assesses the risk from rockfalls by determining the trajectories and impact energy on the surrounding area of the promontory. Detailed UAV surveying of the study area, engineering geological mapping of rockfall prone areas, discontinuity mapping and field measurements have been undertaken as presented in Saroglou et al (2021).

2 Geology of the studied area

The area of interest comprises the following geological formations: The hill on which the Acropolis is located, consists of thick limestones and dolomites (T-Jik,d) which are underlain by a schist-chert formation (Jm-s.sh) at the base of the slope. This formation spreads to the north, northeast and the south (Figure 2). The western region in the area of interest consists of alluvial deposits.

Limestones and dolomites (T-Jik, d): The limestones and dolomites in the area are thick to massive with dip angle of bedding of 60^0 towards the northern slope of the promontory. The formation is intersected by three to four discontinuity sets resulting in a blocky-very blocky rockmass (GSI between 55 and 65). The discontinuities are moderately weathered, open to very open and partially filled with clay.

Schists and cherts (Jm-s.sh): This formation consists of shales alternating with radiolarites. They are interspersed with or impend (tectonically) ultramafic rocks, and they are locally strongly serpentinized. Inclusions of limestone blocks are often observed, and their thickness is between 50 and 80 m.
A geological map of the region is provided in Figure 2.

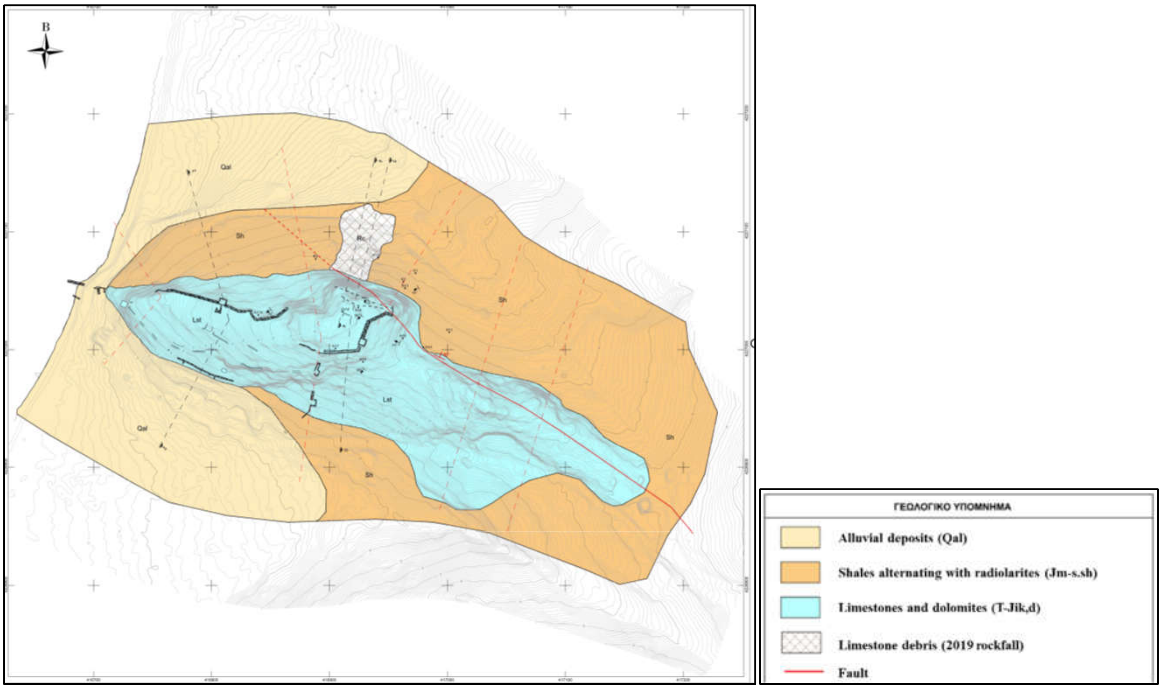

Figure 2 Geological map of the studied area (1:1000).

3 2D rockfall analyses

3.1 Methodology

The rockfall analyses (Rocfall2, Rocscience) determine the trajectory of the rock blocks, as well as the resulting total kinetic energy and the bouncing height. At a later stage of the analysis, the position of the rockfall barrier, which has a specific energy absorption capacity and a specific height, is selected.
After selecting the position and characteristics of the barrier, an additional analysis is carried out in which the effectiveness of the proposed barrier is confirmed. The analyses were performed in eight (8) characteristic cross-sections (Figure 3).
The following parameters are required to accurately calculate the trajectories of the falling rock blocks:
1. Starting position
2. Initial velocity (transport and angular)
3. Falling mass
4. Geotechnical parameters of geological materials along the slope.

The starting position of the rock blocks is generally considered by the highest point of the slope, close to its crest. In places where the relief of the slope has site specific characteristics (e.g. a terrace or a change in inclination) that may significantly affect the trajectory of the blocks, a second starting position at lower elevation of the slope was selected.

To take into account the seismic shaking impact on the initial velocity of the rock blocks, an initial horizontal velocity is assumed:

$$m \times \gamma \times s = \frac{1}{2} m \times \upsilon^2 \Rightarrow \upsilon = \sqrt{2 \times \gamma \times s} \quad (1)$$

where m (kg) is the mass of the rock block, s (m) is the block's displacement to trigger the fall, u is the initial velocity (m/s) and γ is the pseudostatic acceleration acting on the block. According to the Seismic Hazard map of Greece (OASP, 2003) the research area belongs to seismic zone 2 (out of 3). The seismic acceleration factor for zone 2 is γ=0.24 g. However, due to the proximity of the area to active faults of the Corinthian Gulf a 50% increase is introduced and the design coefficient γ is 0.36g. Therefore, according to Eq. (1), an initial velocity of 0.2m/s is used for all the rockfall cases.

3.2 Geotechnical parameters for rockfall analysis

The friction angle and the normal and tangential restitution coefficients for the geomaterials along the slope are selected based on literature results on similar formations (Robotham et al., 1995 και Saroglou et al, 2012, Saroglou et al., 2018). These are summarised in Table 1.

Table 1. Geotechnical parameters for rockfall analysis.

Formation	Friction angle φ / standard deviation (^{0})	Normal restitution coefficient R_n / standard deviation	Tangential restitution coefficient R_t / standard deviation
Limestone	32/2	0.45/0.04	0.85/0.04
Schist	30/2	0.35/0.04	0.80/0.04
Limestone debris (2019 rockfall)	34/2	0.45/0.04	0.80/0.04
Talus with vegetation	30/2	0.32/0.04	0.80/0.04
Talus cover	30/2	0.32/0.04	0.82/0.04

In addition, based on the photogrammetric documentation of the slope as well as the recordings of fallen rock blocks in situ, the predominant volume of overhanging blocks was between 2 and 6 m^3. Based on this evidence the volume of a single block was assumed equal to 4 m^3 in the analyses.

3.3 Results

The results of the 2D rockfall analyses prove that the region in the vicinity of the promontory is characterized as high risk with regard to rockfall impact. In most cases, the rockfall trajectories reach the houses situated at the toe of the slope. In Figure 3, the orange circles mark the initial position of the rock blocks and the green ones their final position along each cross-section. The north-eastern part (cross-sections 7 and 8) is less affected since the width of the promontory is reduced and the length between the settlement and the promontory is high enough for the rock blocks to stop. Figure 4 illustrates two characteristic examples of rock fall trajectories along cross-sections 1-1 and 6-6.

Figure 4 Trajectories (initial and final positions) of the rock blocks simulated in the 2D analyses.

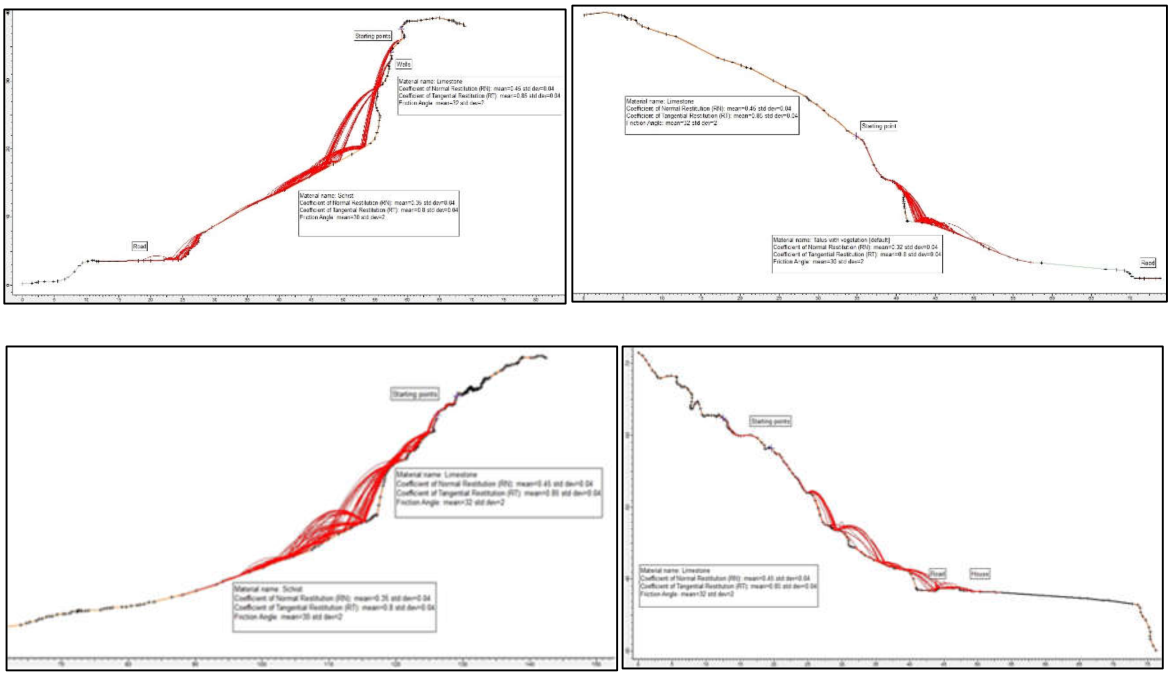

Figure 11 Typical trajectories of rock blocks along cross-section 1-1’ (top) and 7-7’ (bottom). Left: Northern slopes, Right: Southern slopes.

4 3D rockfall analyses

4.1 Methodology

To investigate thoroughly the risk of rockfall in the area, three-dimensional analyses were performed using Rockyfor3D (Dorren, 2016). Rockyfor3D simulates trajectories of individual rock blocks using deterministic models. The trajectories are simulated using vectors in three dimensions, and two equations of motion are applied, free fall and rolling. The input geotechnical parameters in Rockyfor3D include the geometry of the falling rocks blocks and the characteristics of the geological formations. Those are described below:

Soiltype: The soiltype is directly linked to the normal coefficient of restitution (R_n). Eight soiltypes are introduced: 1. Fine soil material >1.00m; 2. Fine soil material <1.00m; 3. Scree (Ø < ~10 cm), or medium compact soil with small rock fragments, or forest road; 4. Talus slope (Ø > ~10 cm), or compact soil with large rock fragments, 5. Bedrock with thin weathered material or soil cover; 6. Bedrock, 7. Asphalt road and 8. River, or swamp, or material in which a rock could penetrate completely.

Roughness (rg10,20,70): Each of these classes corresponds to the height of a representative obstacle that a falling block encounters 70%, 20%, and 10% of the cases during a rebound, respectively. The surface roughness is used to calculate the tangential coefficient of restitution (R_t). The roughness should be determined in the field by identifying homogenous zones in the study area or obtain data from similar formations.

Dimensions, shape and density of falling rock blocks: The height, width, length and shape are defined. As in the case of 2D analyses, the volume of a single block was assumed equal to 4 m^3. Based on the in-situ investigation, a rectangular shape (2m x 2 m x 1m) was selected. The density of the limestone rock blocks was estimated at 2500kg/m^3, meaning that the weight of a single block is 10 tons. The initial velocity of the rock blocks was set equal to 0.20m/s (as in the case of the 2D analyses).

4.2 Geotechnical parameters of the terrain

The geotechnical input parameters of the studied area are given in Table 2.

Table 2. Geotechnical input parameters for 3D rockfall analysis

Input parameters	Limestone	Schist	Alluvial deposits	Limestone debris (2019 rockfall)
Density (kg/m^3)	2500	-*	-	-
Shape of falling blocks	Rectangular	-	-	-
D_1 (m)	2	-	-	-
D_2 (m)	2	-	-	-
D_3 (m)	1	-	-	-
RG_{70} (m)	0	0.03	0	0.50
RG_{20} (m)	0.05	0.03	0	0.75
RG_{10} (m)	0.10	0.03	0.05	1.50
Soiltype (See Section 4.1)	6	3	2	6
*No source areas exist in these formations hence the corresponding input parameters do not need to be defined				

4.3 Results

The main parameters assessed to evaluate the 3D analyses results are:
-*The trajectories of the simulated rock blocks:* These determine whether the rock blocks reach or not a location in the area of interest.
-*The Reach Probability (RP):* The probability of a rock block to reach the location of interest.
-*The Kinetic Energy (E_{95CI}):* The mean kinetic energy (kJ) of the falling rock blocks in a specific location increased by 2 standard deviations (95% confidence interval assuming a normal distribution of energies).
-*The Passing height (Ph_{95CI})*: To mean height (m) of the falling rock blocks in a specific location increased by 2 standard deviations (95% confidence interval assuming a normal distribution of passing heights)
The results of these four (4) metrics are plotted on the map of the studied area as illustrated in Figure 5 and Figure 6. The probability of the rock blocks approaching a location close to the source areas is high and decreases downstream as the blocks are scattered or the trajectories stop. The kinetic energies of the rock blocks range between 200-1600 kJ in most parts of the map, but in some places (especially in the central, southern part) exceed 1600 kJ and in very few cases 3200 kJ. Finally, the passing heights Ph95CI rarely exceed 4 to 6 m.

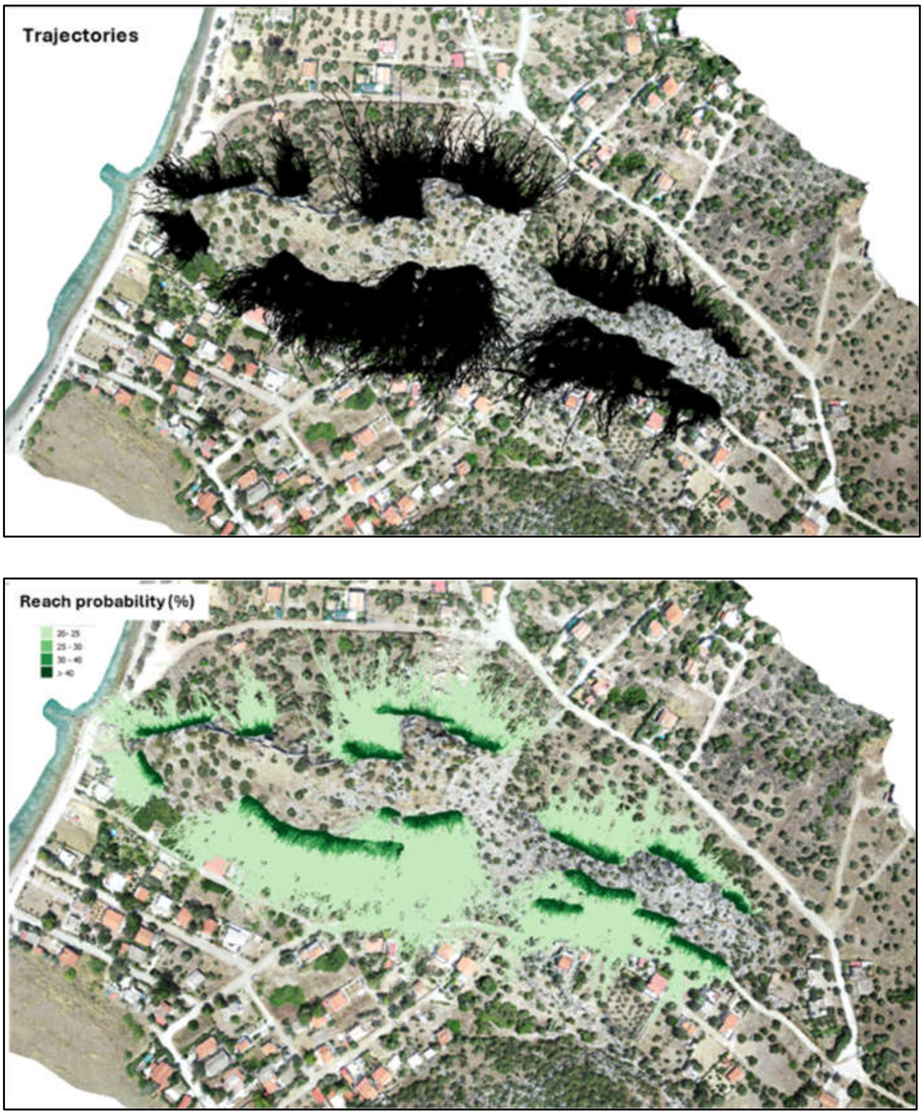

Figure 6 3D rockfall analyses results; Top:Trajectories of the simulated rock blocks, Bottom: Distribution of Reach probability (RP) of rock blocks/ on the area of interest.

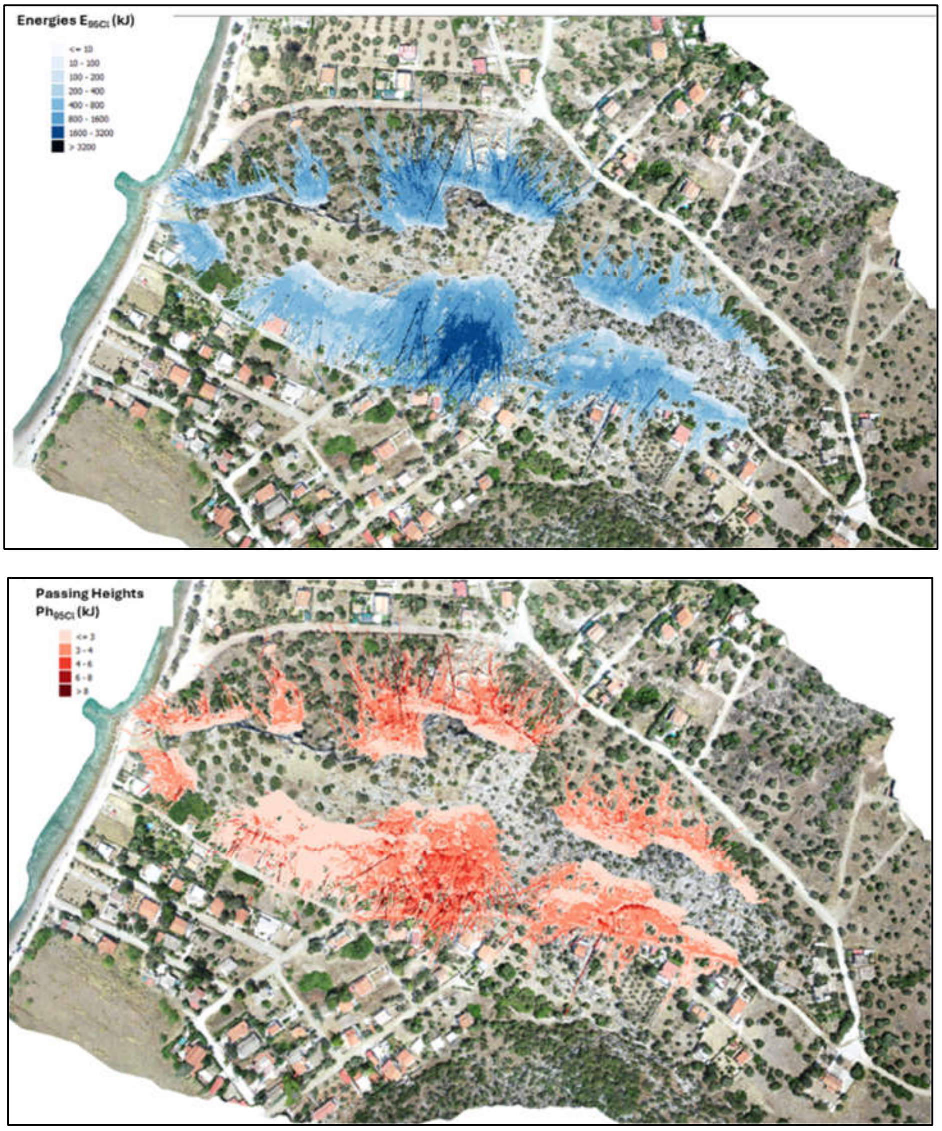

Figure 7 Top: Distribution of kinetic Energies E_{95CI} on the area of interest, Bottom: distribution of Passing heights Ph_{95CI} on the area of interest.

The data interpretation in the Figures above prove that rockfalls pose a significant risk to the houses as a significant number of rock blocks reach the residential area and thus, protection measures are necessary. The 3D and 2D analyses results match well and furthermore they allow the evaluation of the rock blocks' lateral deviation which facilitates the optimum dimensioning of protective barriers.

5 3D analyses with protective measures

To address the potential risk of rockfalls impacting the houses, it was proposed that rockfall barriers are installed at specific locations to stop the trajectories. The barrier design kinetic energy ranges between 500 kJ and 2000 kJ at maximum, dimensioned at the 95% percentile of kinetic energy distribution while their height is equal to 5 m. The optimum location and length are determined based on the 3D analyses as shown in Figure 8a. Figures 8b-d illustrate the distribution of the Reach Probabilities (RPs), kinetic Energies (E_{95CI}) and Passing Heights (Ph_{95CI}) for the analyses considering the mitigation with rockfall barriers.

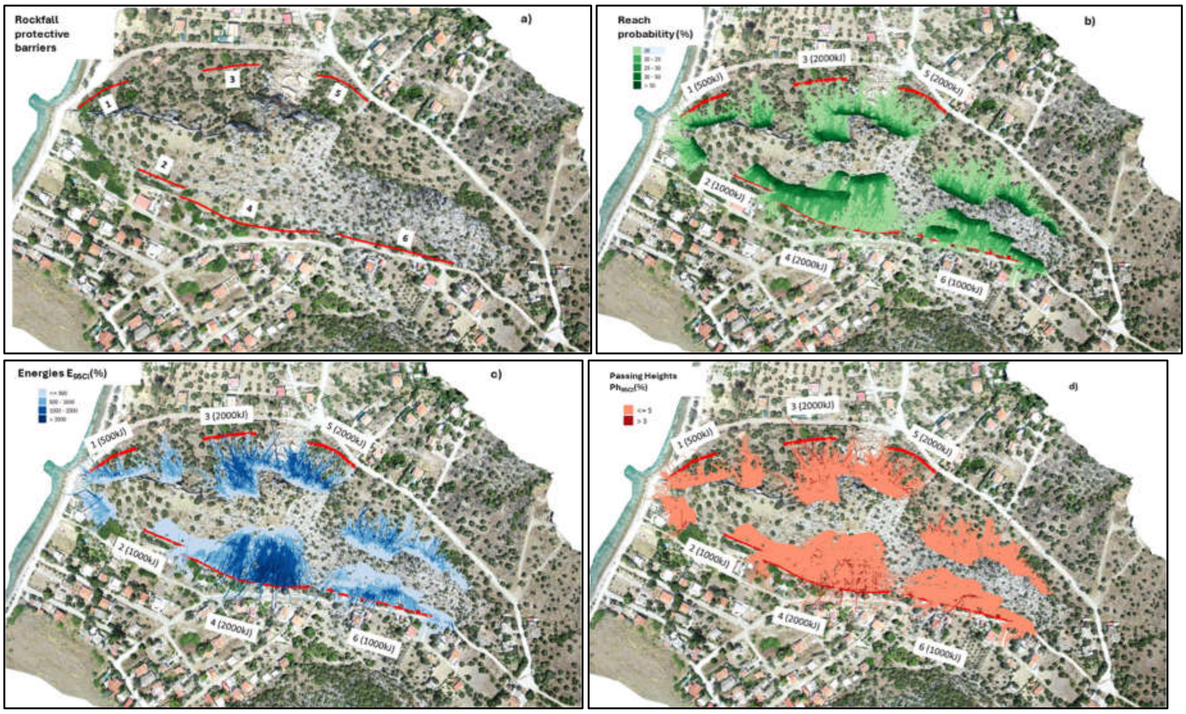

Figure 8 3D rockfall analyses results with protective barriers: a) Location of the rockfall protective barriers, b) Distribution of Reach probability (RP) of rock blocks, c) Distribution of kinetic Energies E_{95Cl}, d) Distribution of Passing heights Ph_{95Cl}.

The protective rockfall barriers stop the trajectories of the falling rock blocks and protect the residential area at the base of the limestone promontory. Some outliers exist (i.e., rock blocks that surpass the protective barriers), but their impact with the barriers decreases their kinetic energy hence their trajectories do not reach the houses.

6 Conclusions

The present study evaluates the rockfall risk of a cultural heritage site in Central Greece using both 2D and 3D rockfall analyses. It is concluded that the 2D analysis predicted well the rockfall trajectories, in relation to the 3D analyses, but the identification of high-risk zones was feasible only through more robust 3D analyses. 2D rockfall analyses neglects the effect of the topography whilst 3D analyses account for the lateral dispersion of rockfall trajectories (Crosta and Agliardi, 2004), i.e., the ratio of the lateral distance separating the trajectories to the slope length.

The studied area is vulnerable to rockfalls, a fact that was confirmed recently (2019) as a rockfall event impacted a house located at the base of the promontory. Based on the results from 3D rockfall modelling, protective measures consisting from rockfall barriers were proposed, and further analyses were carried out to assess their performance which was found to be sufficient to protect the residential area and the cultural heritage site.

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