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Rockfall hazard and risk assessment: an example from a high promontory at the historical site of Monemvasia, Greece

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Abstract. The paper presents the kinematics of rock instability of a high limestone promontory, where the Monemvasia historical site is situated, in Peloponnese in Southern Greece. The instability phenomena poses a significant threat to the town located at the base of the slope. Rockfall episodes occurred in the past due to the relaxation of the high cliff, whereas significant undermining of the castle frontiers has been observed at the slope crest.

The predominant types of instability are of planar, wedge and toppling failure of medium to large blocks. In order to investigate the existing stability conditions and decide upon the protection measures, stability and rockfall analyses were carried out for numerous slope sections under different loading conditions and protection measures were suggested.

A rock-fall risk rating system is proposed, which is based on morphological and structural criteria of the rock mass and on vulnerability and consequences. The rating system is applied for individual sections along the slope and a risk map was produced, which depicted areas having different degree of risk against rockfall occurrences.

1 Introduction

The impact of rockfalls on archaeological sites and historical monuments in the Greek territory is significant, since most of the landscapes are mountainous and the sites are usually found near or on steep rock slopes. Geotechnical problems related to slope instability and the protection of historical sites in Greece have been addressed by several authors (Marinos and Koukis, 1988) and recently, among others, by Marinos et al. (2002) and Marinos and Rondoyanni (2005). The hazard of rockfalls is obviously higher in areas with intense seismic activity, where earthquakes are the principal triggering factor (Marinos and Tsiambaos, 2002).

The main scope of the paper is the presentation of a new rock-fall risk rating system, which is based on morphological and structural criteria of the rock mass and on vulnerability and consequences. This system is applied for the risk assessment of the rock slopes on the Monemvasia historical site. The archaeological site of Monemvasia in South Peloponnese, consists of a historic city situated at the foot of a 60 m limestone rock cliff and an ancient and a medieval city as well as the castle at the slope crest (Figs. 1 and 2). The site is a typical example with high impact of rockfalls. The city at the foot is inhabited and attracts many visitors under a high risk.

The structural conditions of the slope are mainly characterised by the relaxation of the face of the slope due to its high inclination, the spacing of discontinuities allowing the formation of large blocks prone to fall and the lack of persistency of the discontinuity planes, which results in instabilities only in specific parts of the slope. Fortunately there are a lack of weak zones, which could result in large shear failures.

The identification of similar comparable conditions resulted in the division of the slope in 5 areas, presented in Fig. 1. Additionally, cross-sections were drawn in specific locations in order to assist in the stability analysis (denoted as A to Z and shown in Fig. 11). A general assessment of the rockfall hazard was presented by Marinos et al. (2009).

Rockfalls existed long before the development of the city in the ancient time, as evidenced by the foundation of several ancient structures on large fallen blocks of rock as well as the abundance of rock fragments on the slope foot. In the recent years a number of severe rockfall events have occurred (Fig. 3a).

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Fig. 1. **(a)** Panoramic view of the rock promontory, **(b)** close view of Monemvasia historical site.

Fig. 2. Photo of a section of the high rock slope and the Monemvasia historical site (Section C in Fig. 11).

2 Engineering geological conditions

2.1 General

The geological formations encountered in the area consist of Jurassic bedded, dolomitic limestones and Cretaceous unstratified massive limestones. The rock slope overhanging the historical city consists of the Cretaceous limestone. Two major fault zones, with E-W and NE-SW strike, intersect the formation, respectively, forming the horst of the promontory.

2.2 Rockmass conditions

The limestone rock mass is moderately jointed, intersected by numerous major vertical fractures, which ultimately form the local face of the cliff. The limestone is karstified in places and solution voids of large dimensions are formed, undermining the rock slope.

The rock mass on the slope is intersected by three to five major discontinuity sets, as presented in the Schmidt stereographic projection in Fig. 4. These are steep in general (dip angle is greater than 60°) and two of them are parallel to the slope plane, thus, they form the rock slope face in some places. The distance of the discontinuity planes varies significantly depending on the degree of fracturing of the rock. The spacing of the discontinuities is relatively large (more than 1 m); hence the sizes of the rock blocks are large to very large. In places, mainly due to stress relief the size of the rock blocks is smaller, especially on the upper part and the crest of the slope, where the wall of the upper ancient city is founded. The distance of the discontinuity planes was measured along 10 vertical scanlines of the slope face and it was determined to range between 2.5 and 10 m, although locally the distance can be lower than 2.5 m. The discontinuity planes are rough (JRC ranges between 4 and 12 with a mean value of 6), while the joint wall compressive strength is high (JCS is equal to 70 MPa). The discontinuity planes have generally no infilling material. The basic angle of friction along the discontinuities was calculated equal to $\phi = 38°$ for a stress range up to 2 MPa.

2.3 Size of unstable rock blocks

In order to assess the hazard against rockfalls, a detailed engineering geological mapping of the entire rock face was carried out. The scope of this mapping was to mark the main discontinuity planes on the slope and delineate the potentially unstable rock blocks, thus, allowing for a close approximation of their volume. An example of this procedure is shown in Fig. 5. The rock slope was divided in 5 distinct areas (as shown in Fig. 1) that possess (a) different slope geometry, (b) different impact type of rockfall on human activities, and (c) different engineering geological characteristics (e.g., size of potentially unstable blocks).

Based on this procedure, it was found that the most frequent rock volume of potentially unstable blocks lies between 0.5 and 1.0 m^3, but with a relative frequency of 22 % (out of a total number of delineated blocks equal to 343). The results of this statistical analysis are shown in the frequency chart in Fig. 6. Additionally, there is a large number of blocks with a volume ranging from 1.0 to 1.5 m^3 and 1.5–2.0 m^3 (14 % and 13 %, respectively). The rockfall barriers, further discussed, were designed to sustain blocks up to a volume of 2.0 m^3, which practically means 70 % of the potentially unstable blocks.

2.4 Rockfall history

A number of rockfall episodes have occurred in the past. The following evidence exists: (a) Numerous blocks (volume greater than 4 m^3) exist in the access road to the castle; (b) in section C, two recent rockfall episodes have occurred, in 2003 and in 2010 with a volume between 1 and 2 m^3, which ended on a house wall in the slope base. Individual fallen blocks exist elsewhere in the perimeter of the castle.

Fig. 3. (a) View of fallen rock blocks in area of section D **(b)** overhanging blocks in area of section Z. Range of volumes: 1.5 to 5 m^3.

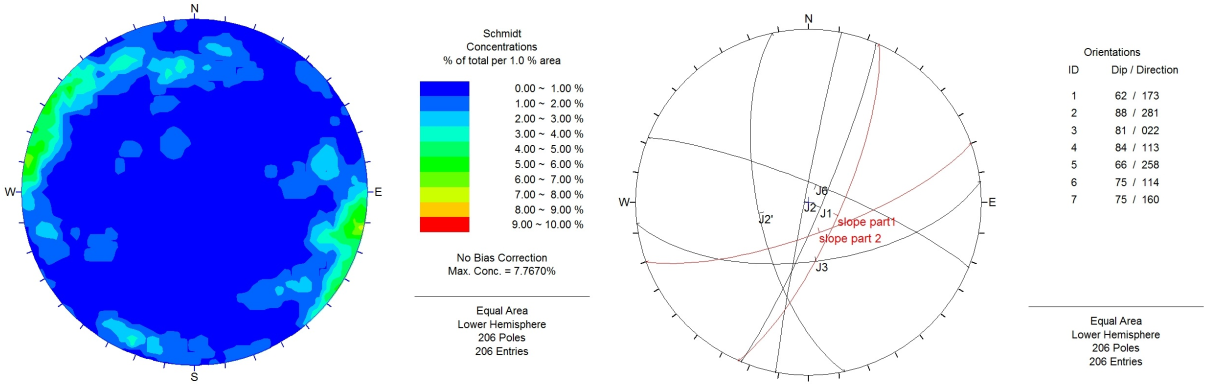

Fig. 4. Stereographic projection of main discontinuity sets and slope faces. Slope faces are denoted in red.

Fig. 5. Potentially unstable blocks in area 4 and 5 are shown in yellow.

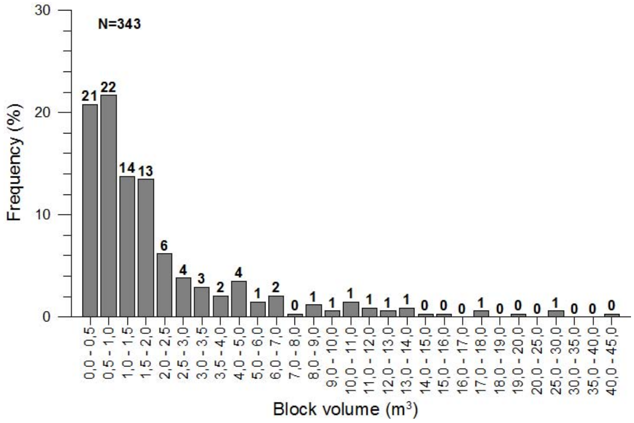

Fig. 6. Frequency chart of volume of potentially unstable rock blocks on the slope.

3 Rockfall analysis

3.1 General

The rock slope stability analyses were based on the prevailing mode of instability of each potential rock failure. The principal failure type is rockfall due to a sort of toppling, but some planar or wedge failures may also exist (Fig. 3b). The rock blocks were delineated by the engineering geological mapping and their geometry and mass was determined. Due to the inaccessible nature of the slope, the assessment of the above characteristics was based on the geodetic mapping of the rock cliff. These characteristics were grouped in five (5) areas and specific sections (A to H) were formed for separate analysis (Fig. 11).

The surveying and mapping of the high rock cliff was based on a new geodetic methodology (existing geodetic surveying method and its combination by the use of

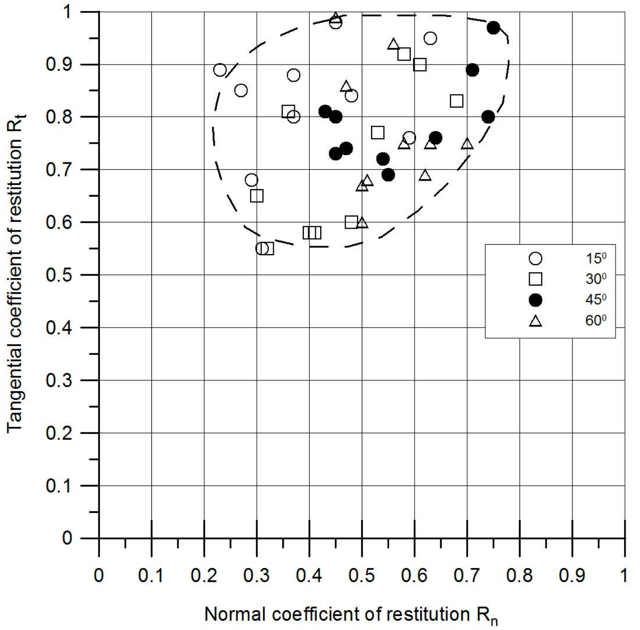

Fig. 7. Range of restitution coefficients, R_n and R_t for limestone based on laboratory tests (Saroglou et al., 2010).

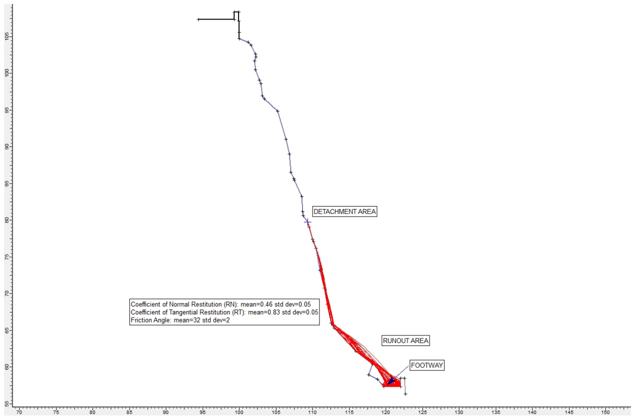

Fig. 8. Back analysis of known rockfall event, which occurred in section C in 2010.

modern reflector-less total stations), which resulted in a three-dimensional Digital Terrestrial Model (DTM) of the ground surface (Lambrou and Pantazis, 2006). The methodology is mainly based on the capability of the total station to automatically sweep the surface by means of the scanning mode, which takes automatic measurements at defined intervals predetermined by the user window. The advantage is that the coordinates x, y, z of an adequate number of points can be quickly determined. The result of the methodology is the creation of 3-D Digital Terrestrial Model (DTM) of the surface by an accuracy of about ±2 cm.

The height of the potential rockfall source is a minimum of 20 m above the base of the cliff, while in a few places

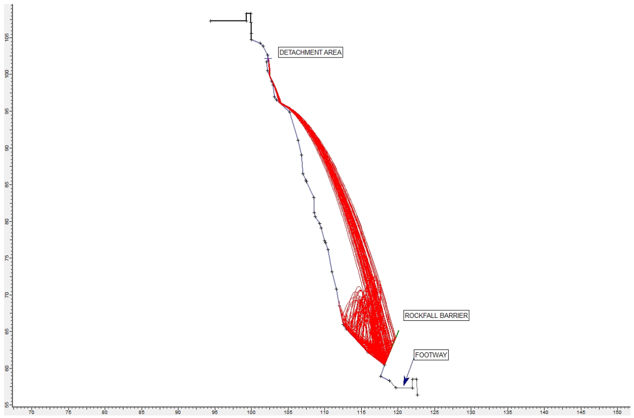

Fig. 9. Rockfall analysis at section C, in Fig. 11.

Table 1. Rockfall parameters of limestone slope face.

Method	R_n mean value	R_t mean value
Back analysis	0.46	0.83
Laboratory test	0.48	0.77
Total mean value	0.47	0.80

it reaches 50 m. The size of the unstable blocks, which are more likely to fall, is between 1.5 m^3 and about 4 m^3, except the area between Sections A and B (Fig. 10) as well as section E where the size can be up to 30 m^3. In the area shown in Fig. 4, the potentially unstable blocks have very large dimensions.

3.2 Restitution coefficients of limestone

In order to model the trajectory of the falling rocks and design the rockfall barriers, it was necessary to calculate efficiently the normal and tangential coefficients of restitution (R_n and R_t, respectively) of the limestone. For this purpose, rebound tests of rock spheres on a limestone plate were performed in the laboratory for a range of slope inclination. Based on the test results, the range of the values of the coefficients of restitution were determined, as presented in Fig. 7. The normal coefficient of restitution, R_n, ranges between 0.3 and 0.7, while the tangential coefficient, R_t, between 0.60 and 0.95 (Saroglou et al., 2010).

The mean value of R_n for the whole range of slope inclinations is equal to 0.48, while for R_t equal to 0.77. This range agrees well with that proposed by Wu (1985) and Richards et al. (2001), who notes that the values of R_n are significantly lower than those proposed in literature or in rockfall analysis software.

Additionally, back analysis of a known rockfall event was performed in order to determine the coefficients of restitution and the friction angle of the limestone face. The back analysis was performed in section C, where a rock block with a

Fig. 10. Photo of a section of the slope having hanging blocks with very large dimensions.

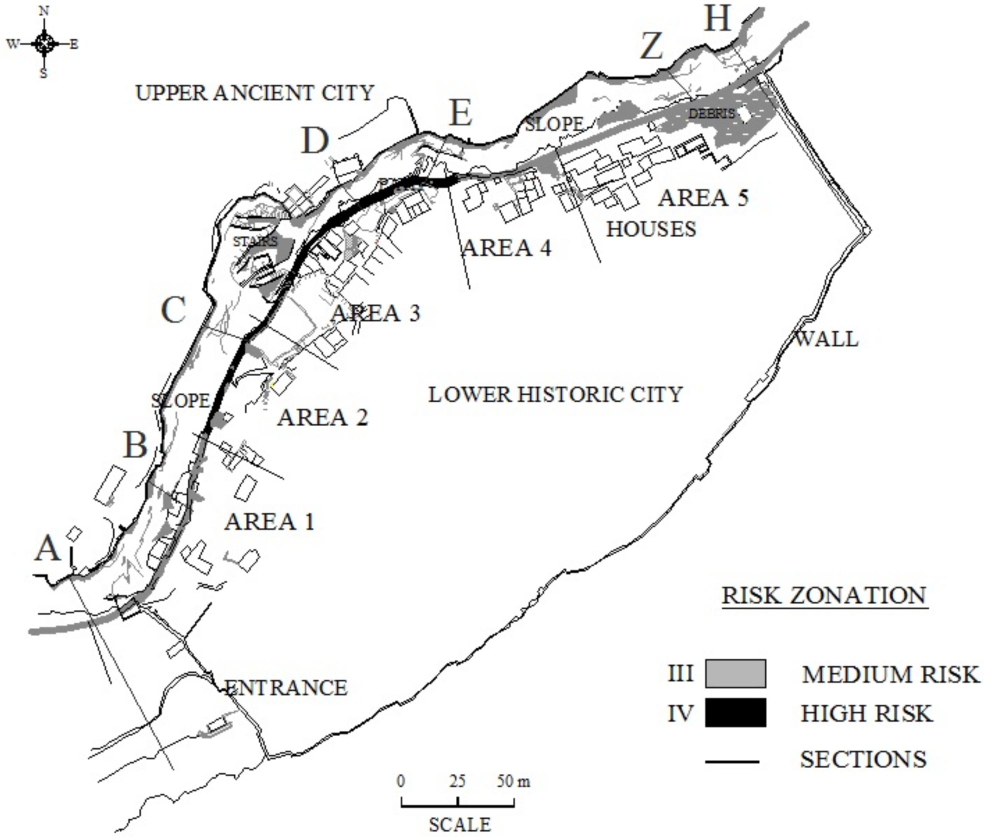

Fig. 11. Risk zonation of rock slope based on proposed rockfall risk rating system.

Table 2. Rockfall analysis results in different slope sections.

Section Fig. 11	Elevation/height of block detachment (m)	Location of rockfall impact	Intensity of rockfall impact	Barrier energy required for block range 2–3 m^3 (kJ)
A	+98 (46)	Access road to castle	Low	1000–1150
B	+103 (40) +84 (21)	Castle wall	Medium	1250–1850
C	+102 (40)	Houses and pedestrian path	High	1950–3000
D	+93 (32)	Houses	High	410–600 (on slope)
E	+87 (29)	Houses	High	400–600 (on slope)
Z	+98 (48) +80 (30)	Houses	High	2250–3400 460–600 (on slope)
H	+95 (42)	Castle wall	Low-Medium	420–650

volume of 1 m^3 has fallen in 2010, whose trajectory (detachment location and run-out distance) was known (as shown in Fig. 8).

From the present analyses, it is evident that the values of coefficients of restitution are close to those proposed by Robotham et al. (1995) and Richards et al. (2001) for limestone rocks.

The values of the coefficients of restitution, as determined by the different methods, are presented in Table 1. From the back analysis it was found that the rolling friction angle is equal to 32°.

3.3 Results of analysis

The analysis was performed using the software RocFall of Rocscience Inc (1998). The coefficients of normal and tangential restitution for the limestone were determined as presented earlier. The initial velocity of the falls was taken equal to 0.48 $m\,s^{-1}$ due to seismic triggering (based on the acceleration coefficient of the area according to the Greek Earthquake Resistant Regulations, 2004). An example of the analysis in Section C is shown in Fig. 9. It is evident that the installation of a barrier in locations with an adequate catchment area can protect the structures and human activities at the foot slope.

It should be noted that the width of the zone, just behind the barrier, is very decisive for the impact energy since this portion of the slope provides considerable damping and, therefore, loss in energy. In some locations, such as in the area between sections D and E, there is no space behind the barrier resulting in enhanced impact energy. In such cases, the rockfall barriers in the analysis were installed on the slope face in order to arrest potential falling blocks before their trajectory impacts the houses at the slope foot.

Since the volume of the rocks varies, an analysis was carried out for a range of rock block volumes 2 m^3 and 3 m^3 and for a range of block detachment heights (between 20 and 50 m). The total kinetic energy, which is produced by the falling rock blocks, as calculated at the different sections of the slope, does not exceed 2500 kJ and only in some locations, as in sections C and Z, with blocks having a volume greater than 2 m^3 resulted in total kinetic energies greater than 2500 kJ. The results of the rockfall analysis for different sections of the slope are presented in Table 2, together with the maximum impact energy at the location of the barrier under consideration and the impact effect of rockfalls for each section.

4 Slope stabilization

The necessary support measures can be divided into two categories: (a) those which apply an external force on the rock face e.g., tensioned rock anchors and/or patterned rock bolts, and (b) those which offer protection once the rockfall occurs, mainly rockfall barriers. Other support measures, such as grouting of rock joints with associated drainage, construction of buttresses in overhanging areas and removal of unstable blocks are not always applicable or very difficult to construct on high rock cliffs.

The application of tensioned anchors or pattern bolting in the locations where large individual blocks exist (or spot bolting for smaller ones) at the slope crest is adequate. The application of sprayed concrete is not acceptable due to the archaeological restrictions of the area. The same is true for the installation of steel nets in a number of locations.

As mentioned earlier, the scale of some potential failures is such, that no stabilization measures can minimize or withdraw the risk of a potential rockfall after their application.

Table 3. Categories of parameters defining the risk and weight of each category.

Category of parameters	Description in the total risk score	Weight of category of category
A	Geometry of slope and release area position, slope roughness, presence of vegetation	25 %
B	Geology and rockmass conditions	25 %
C	Potential triggering factors (rainfall, seismicity), condition of drainage	10%
D	Consequences and associated factors, rockfall history	40 %

Even high-energy rockfall barriers would prove insufficient, as in the case of the rock block shown in Fig. 10 detached from the cliff. A possible support solution, in this case, would be to install tensioned wire-rope cables around the rock block to resist its movement.

5 Rockfall risk assessment

5.1 General

The assessment of rockfall risks along roads and on other human activities is of great importance (Budetta, 2004). In order to assess rockfall risk, a number of rating systems have been developed.

Just to mention, Pierson et al. (1990) have developed the Rockfall Hazard Rating System (RHRS), which is most widely accepted. A similar system is that proposed by Pritchard et al. (2005), who developed a rating methodology which is applied to predict rockfall risk along railways. McMillan and Matheson (1997) have developed the Rock Slope Hazard Index (RSHI) system for highway rock slope inspection in Scotland. Santi et al. (2009) have proposed a modification to the Colorado Rockfall Hazard Rating system, developed initially from Andrew (1994) for highway slopes in Colorado. Hungr and Evans (1999) have applied quantitative risk analysis for determination of total risk on highway and railways in British Columbia, which is based on data on the magnitude and frequency distribution of the rockfall hazards. Hungr et al. (2003) have proposed a new rockfall hazard rating system for use along a railway line, again with a Quantitative Risk Assessment (QRA) procedure.

Vandewater et al. (2005) have proposed a rockfall hazard system for highways giving emphasis on the contribution of geological factors.

Most of the existing systems use hazard and consequence categories. These systems give a reasonable assessment of the relative hazards due to rockfalls from cut slopes adjacent to highways and railways. Thus, they include also the conditions of the anthropgenic cuts and not just those of natural slopes.

Some authors have proposed systems that are applicable to natural slopes, but most are specific oriented. Bolin et al. (2009) have proposed a new assessment system for rockfall risk (ASRFR) in the Wu Gorge area in China, which considers seven factors for hazard and eight factors for consequence.

Another approach for the calculation of risk is presented by Corominas et al. (2005) while Guzzetti and Reichenbach (2004) have used a methodology based on rockfall hazard maps produced by three-dimensional rockfall trajectories to determine risk along a part of the transportation network of Central Italy.

The Austrian Service for Torrent and Avalanche Control (Tartarotti, 2011) proposed a simple risk classification system which relies on four parameters, namely: (a) the probability of presence of an event, (b) vulnerability of structures, (c) the probability of occurrence, and (d) the process and energy class of a rockfall.

5.2 Proposed rockfall risk rating system

The rockfall risk rating systems in literature are well documented, but are mostly devoted to reasonable assessment of the relative hazards due to rockfalls from cut slopes adjacent to highways and railways. In the present study, a rockfall risk rating system is proposed which is mostly applicable to the calculation of rockfall risk of natural and man-made slopes and encompasses all those parameters, which are considered important for this purpose. It defines twenty (20) rating parameters, grouped in four (4) major categories according to the hazard and consequences, with a different weight in the assessment of the total risk.

The weight for each category varies, depending on the importance of the parameters involved. More specifically, category A is given a weight of 25 % to the total risk score of a slope, while B 25 %, C 10 % and D is given 40 %.

The first category of hazard, category A, involves parameters, related to the geometry of the slope (angle, height, slope roughness and vegetation) and the height of the rockfall release areas. Category B parameters refer to the geological

Table 4. Parameters of all categories and rating of proposed rockfall rating system for natural rock slopes to define risk.

Parameter	Category/ parameter weight factor	Rating					Score (Multiply rating with weight factor of parameter)
1. Slope angle $(^0)$	A/7 %	25–40	Medium 40–50	High 50–60		Very high >60 Overhanging	
Rating		10	30	60		100	
2. Slope height (m)	A/4 %	<15	15–30	30–60		>60	
Rating		10	30	60		100	
3. Release area height (H is total height of slope)	A/7 %	Rockfalls from low slope areas (H/4)	Rockfalls from middle slope areas (H/2)	Rockfalls from middle to upper slope areas (3H/2)		Rockfalls from whole slope (H)	
Rating		10	30	60		100	
4. Slope roughness	A/3 %	Rough, planar, (friction reduces acceleration)	Planar smooth (helps acceleration)	Rough, presence of narrow benches, (helps bouncing)		Very rough, presence of narrow benches	
Rating		10	30	60		100	
5. Vegetation of slope	A/4 %	Dense vegetation, occurrence of high trees	Low raised vegetation, bushes	Sparse vegetation		No vegetation	
Rating		10	30	60		100	
int roughness / Filling material in joints/ Joint Opening	B/6 %	Rough, stepped	Smooth, stepped	Undulating or filling material with angular fragments independent of roughness or moderate opening of joints 2.5 to 10 mm	Slightly rough planar or filling with stiff clay >5 mm independent of roughness or very wide opening of joints 10–100 mm	Smooth planar or filling soft clay >5 mm independent of roughness or extremely wide opening > 100mm	
Rating		10	15	30	60	100	
7. Joint Orientation (or combination of joints)	B/5 %	Favorable for stability		Moderate	Adverse	Very adverse	
Rating		10		30	60	100	
8. Joint Persistence (m)	B/4 %	Very low <1m	Low 1–2 m	Moderate 2–5 m	High 5–10 m	Very high >10 m	
Rating		10	15	30	60	100	
9. Joint compressive strength (JCS, MPa, affects friction on joints)	B/1 %	>30	20–30	5–20		<5, weathered	
Rating		10	30	60		100	
10. Strength of intact rock (MPa, helps splitting of falling blocks if strength is low Facilitates bouncing if strength is high)	B/1 %	<10	10–30	30–60		>60 MPa	
Rating		10	30	60		100	
11. Rock mass blockiness / Block volume (m^3)	B/4 %	<1	1–2.5	2.5–4.0	4.0–8.0	>8.0	
Rating		10	15	30	60	100	
12. Estimated number of blocks (for the width of slope under assessment)	B/2 %	Null	1–5	5–10		>10	
Rating		10	30	60		100	
13. Karstic features	B/2 %	No karst	Sparse	Moderate undermined conditions		Frequent Undermined conditions	
Rating		10	30	60		100	
14. Rainfall conditions and intensity	C/3 %	Seldom	Sparsely	seasonal	often	Very often, during whole year	
Rating		10	15	30	60	100	
15. Permeability/ Condition of slope drainage	C/3 %	Very high	High	Moderate	Low	Very low	
Rating		10	15	30	60	100	

Table 4. Continued.

Parameter	Category/ parameter weight factor	Rating					Score (Multiply rating with weight factor of parameter)
16. Seismic hazard (acceleration coefficient α)	C/4 %	$\alpha < 0.16$	$0.16 < \alpha < 0.24$	$0.24 < \alpha < 0.36$	$\alpha > 0.36$		
Rating		10	30	60	100		
17. Width of catchment zone (m)	D/10 %	>20	10–20	5–10	2–5	No	
Rating		10	15	30	60	100	
18. Rockfall history	D/5 %	Null to few	Occasional	Numerous	Often	Continuous	
Rating		10	15	30	60	100	
19. Slope accessibility	D/5 %	All types of stabilization possible	Most types of stabilization possible	A number of types of stabilization possible	Few types of stabilization possible	Access very difficult	
Rating		10	15	30	60	100	
20. Potential result of impact and value of structures	D/20 %	Negligible; no human structures and permanent activities	Low; areas of little human activity	Moderate human presence; low frequency of houses	High; frequent human presence, numerous houses	Very high, constant human presence, densely inhabited areas	
Rating		10	15	30	60	100	
Total Score (Maximum 100)							

Table 5. Rockfall risk classes and indicative protection measures

Risk Class	Total weighted score 1–100	Risk	Indicative protection measures (the choice is site specific)
I	< 20	Very Low	Not necessary. May be sparse spot interventions.
II	21–40	Low	In limited extent
III	41–60	Medium	Light measures (such as bolts, nets, removal of unstable blocks, simple light fences)
IV	61–80	High	Combination of active (such as bolts, anchors) and passive (such as nets, wire rope cables, buttress walls, fences removal of unstable blocks) measures
V	81–100	Very High	Critical state of stability, combination of generalized or/and strong active and passive measures. Residual risk to be accepted.

and rock mass conditions of the slope. These parameters describe the condition of the rock discontinuities, the intact rock strength, presence of karst and the block volume and number of potential blocks. Category C parameters relate to the potential triggering factors (rainfall, seismicity of the area) and drainage conditions of groundwater on the rock stability. Category D parameters refer to the consequences – impact on structures and associated elements, as well as the accessibility of the slope. The categories and their weight in the total risk score are presented in Table 3.

The proposed risk rating system has been developed on an empirical basis, with the weight of categories and parameters and the parameter rating, based on reasonable geoengineering judgment and reasonable facts. The proposed risk system was designed with special emphasis on rating of natural rock slopes, which pose a rockfall hazard on human structures and activities, such as in the case of the historic city of Monemvasia.

Each parameter has an internal, exponential, increase of rating, between 10 and 100, as one moves from favourite to adverse conditions. The parameter is rated and then is

Table 6. Application of proposed risk rating system for the Monemvasia historic site high limestone cliff (The value in parenthesis is the unweighted rating for each parameter).

Area (Fig. 1b)	1	2		3	4		5
Section on slopes (Fig. 11)	A	B	C	D	E	Z	H
Parameter							
1 Slope angle	4.2 (60)	7.0 (100)	7.0 (100)	7.0 (100)	7.0 (100)	4.2 (60)	4.2 (60)
2 Slope height	2.4 (60)	2.4 (60)	2.4 (60)	2.4 (60)	1.2 (60)	2.4 (60)	2.4 (60)
3 Release area height	7.0 (100)	7.0 (100)	7.0 (100)	4.2 (60)	7.0 (100)	2.1 (30)	7.0 (100)
4 Slope roughness	1.8 (60)	1.8 (60)	3.0 (100)	3.0 (100)	3.0 (100)	3.0 (100)	3.0 (100)
5 Vegetation of slope	4.0 (100)						
6 Roughness of joints/filling of joints/opening of joints	1.8 (30)						
7 Orientation of joints	1.5 (30)						
8 Persistence of joints	1.2 (30)						
9 Joint strength	1.0 (100)						
10 Strength of intact rock	1.0 (100)						
11 Block volume	4.0 (100)	4.0 (100)	4.0 (100)	4.0 (100)	2.4 (60)	4.0 (100)	1.2 (30)
12 Estimated number of blocks	0.6 (30)	1.2 (60)	0.6 (30)	0.6 (30)	0.6 (30)	1.2 (60)	0.6 (30)
13 Karstic features	0.6 (30)	0.6 (30)	0.6 (30)	2.0 (100)	1.2 (60)	2.0 (100)	1.2 (60)
14 Rainfall	0.9 (30)						
15 Permeability	0.45 (15)						
16 Seismicity	0.4 (100)						
17 Catchment zone width	1.0 (10)	10 (100)	10 (100)	10 (100)	1.5 (15)	3.0 (30)	10 (100)
18 Rockfall history	1.5 (30)						
19 Accessibility	3.0 (60)	5.0 (100)	5.0 (100)	5.0 (100)	3.0 (60)	3.0 (60)	1.5 (30)
20 Potential impact	3.0 (15)	20 (100)	20 (100)	20 (100)	12.0 (60)	12.0 (60)	3.0 (15)
Score on 10 to 100 scale	41.35	72.75	73.35	71.95	52.65	50.65	47.85
Risk	Medium	High	High	High	Medium	Medium	Medium

multiplied by a respective weight factor. Finally, the total risk score is calculated by summing the individual score of each parameter. The parameters of each category, the weight factor for each parameter and their rating are presented in Table 4.

Based on the rating method proposed, a slope with the highest risk will have a total weighted score of 100 in a 10 to 100 scale. In order to classify the risk against rockfalls and decide on protection measures, the proposed risk classification of rock slopes has five categories, very low to very high risk, as presented in Table 5.

6 Rockfall risk assessment for Monemvasia rock slope

The Rockfall Risk Rating system was applied at selected locations along the rock cliff of Monemvasia, since the parameter rating differs for each slope area. The locations coincide with the topographical sections (A to H, Fig. 11) as presented previously. The application of this risk rating is shown in Table 6.

The parameters that vary from one location to another are: (a) the volume and number of rock blocks, (b) the spacing and persistence of discontinuities, (c) the height of the release area, (d) the width of the available catchment zone, and (e) the existence of structures or human activity at the underlying area. The slope height and angle of Monemvasia slopes do not vary significantly. As it can be seen from the application of the risk system, 10 parameters out of 20 have the same rating for the Monemvasia slope.

The result of the application is a risk zonation of the cliff against rockfall occurrence, presented on the risk map shown in Fig. 11. The map depicts the areas having a medium and high risk due to either increased number of existing unstable blocks or restricted area for their catchment or combination of both.

The risk in section A and in the area between sections A and B (area 1) is medium. This area has very restricted catchment zone and the installation of barriers will be on the slope foot. However, the impact on the derelict structures in this area is relatively low, hence the risk is medium.

The slope foot area between sections B and E (area 2 and 3) presents high risk due to the numerous unstable blocks on the cliff and the proximity of structures as well as human activity (stairs to upper city). The area between sections E and H (area 4 and 5) has medium risk, due to the wide catchment zone at the base, which offers ideal conditions for installation of barriers.

The proposed system has to be further developed and ratified by back analysis for the optimum adjustment of the weight of the big variety of parameters involved. This could be the case of other rock slopes, where most of the parameters may have a significant range, in order to assess the sensitivity of each parameter in the determination of the total risk.

7 Conclusions

The rock slope stability of the high limestone cliff overhanging the historical site of Monemvasia promontory in Peloponnese in southern Greece was studied based mainly on kinematic analysis of the unstable blocks and calculation of their rockfall trajectories. In the case of blocks having weights higher than 10 tn, the installation of high capacity rockfall barriers cannot remove the hazard due to impact of falling rocks on structures, either because the impact energy is extremely high or the catchment zone is not sufficient for optimized protection. Therefore, the application of active support measures, such as bolts and wire rope nets will be necessary.

In order to calculate the potential risk of the rockfalls, a rating system for natural rock slopes was proposed and the locations with maximum risk are defined. This system involves 20 parameters, appropriately weighted, grouped in categories according to the geometry of the slope, the geological conditions, the potential triggering mechanisms of the rockfall and the consequences of the hazard. Support measures suggestions associated with the proposed risk rating assessment. An application of the proposed system is presented for the Monemvasia cliff. The proposed system has to be further developed and ratified by back analysis for the optimum adjustment of the weight of the big variety of parameters involved.

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