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DETERMINING ROCKFALL HAZARD AND RISK IN HISTORICAL SITES

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ABSTRACT

Cultural heritage and historical sites located near the foot of steep rocky walls, are affected by denudation leading to rockfalls of various types, magnitude and intensities. Given the multiple levels of importance of cultural heritage, the effects of rockfalls on historical sites extend from material to intangible, with social and economic consequences. The objective of this work is to present a methodology for assessing the rockfall propagation and the probability of reach of a rock block of given size at a location, which is a requirement for the rockfall risk assessment. The methodology is applied to the archaeological site of Delphi. For this purpose, the software Rockyfor3D is used. The required data are the Digital Elevation Model, the location of potential rockfall sources and the ground characteristics which affect the kinetic characteristics of the rock blocks during their propagation downhill. The analysis is applied for two block sizes: 0.008 m^3 and 5 m^3. Two analyses are performed. A first one, without considering protection measures, which serves as a basis for the design of protective steel fences. Then a second analysis is run considering the effect of steel fences on reducing the probability of reach of rock blocks. The results indicate that for rock blocks of the order of 0.008 m^3, there is a small probability of reach at the Stadium, with a respective reach energy of the order of 2.5 kJ. For the blocks of 5 m^3 and without considering protection measures, the reach probabilities at the archaeological site vary from 3% to 29.93% depending on the monument, with reach energies of few thousand of kJ. This implies the need for the installation of protection measures, such as steel fences, and further rockfall interception measures.

KEYWORDS: rockfalls, monuments, rockfall propagation, risk, landslides, historical structures

1. INTRODUCTION

Landslides are gravitational mass movements of rock, debris or earth leading to the denudation of the natural landscape. Landslides represent an important fraction of natural hazards affecting monuments worldwide (Pavlova et al., 2021), with an important impact on cultural heritage, visitors' safety, tourism and economy. It is difficult to evaluate the percentage of loss corresponding to landslides amongst other natural hazards like earthquakes and floods, as landslides act more locally, at the scale of the site (Canuti et al., 2009) and are often attributed to their triggers as for example seismic vibration or heavy rainfalls. Although the analysis of the earthquake threat for monuments has received a lot of attention (Hemeda, 2016; Amet et al., 2017; Salonikios and Morfidis (2018); Elyamani and Roca Fabregat, 2018; Elyamani et al., 2019), the landslide risk has been studied less.

When it comes to architectural monuments, historical structures and elements or structures of archaeological nature, landslide damage varies from non-structural to structural, the latter affecting partially or totally their stability. The expected damage typology varies according to the landslide type. Slow moving landslides result in differential settlements, distortion of the structure, foundation failure, with the demonstration of cracks and damage at the superstructure. Fast moving landslides as soil slides, rockfalls and debris flow cause damage of the structures situated at the toe of the slope due to mass impact on it and may lead to partial or total burial of the structure, due to accumulation of soil, rock and water as well as damage of their load bearing system. Examples of the UNESCO listed monuments endangered by rock slope instabilities include the archaeological site of Petra in Jordan affected by rocky slope failures (Delmonaco et al., 2013), Machu Picchu in Peru threatened by rock falls, debris flows, rock slides and debris slides (Margottini, and Spizzichino, 2014), and the tomb of Ramsis I at the Valley of the Kings, Egypt which is subject to falling blocks (El Shayeb and Verdel, 2005).

Historical structures are not the only elements of cultural heritage which are affected by landslides. Natural landscapes protected by UNESCO, including agricultural terraces, historical routes and trails providing access to cultural heritage sites are further elements to be considered when the direct impacts of landslides and the risk for visitors are studied. Besides direct physical damage, indirect damage includes tourism and economic loss that derives from the reduction of commercial activities and restauration services (Dhakal et al. 2020).

In Greece, home to world famous monuments and historical sites, rocky slope instabilities have been reported amongst others by (Christaras, 2003) to affect the Acropolis of Athens (Koukis, 1982; Andronopoulos and Koukis, 1988), the Delphi archaeological site (Marinos and Rondoyanni, 2005; Koroniotis et al., 1988; Constantinidis et al., 1988), Meteora and Mystras (Koukis, 1982). Further sites at risk are situated at Mount Athos, and Monemvasia. Slope instabilities threaten castles and urbanisms like the castles of Bochali in Zakyntos, and the ones of Koroni at Messinia, of Skopelos, and of Mythimna in Lesvos Island. The Arvanitia pathway, a natural sightseeing area in Naflio has also been facing rocky slope stability problems (Loupasakis et al., 2010).

To reduce the landslide risk for structures and people in cultural heritage areas, it is necessary to assess it using quantitative metrics, which provide an objective measurement of it and also of the effect of protection interventions. Additionally, the spatial variation of the risk within an area has to be assessed in order to optimise protection interventions. In this context, the goal of the present work was to assess the expected rockfall propagation for an event of unknown source around the entire historical site of Delphi for different block sizes, and in the presence or absence of protection measures. The objective was to calculate the kinetic energy and the probability of reach of a rock block of a given size at a given location within the archaeological site, which are both crucial components of the quantitative risk assessment.

2. APPROACHES FOR THE PROTECTION OF CULTURAL HERITAGE AGAINST ROCKY SLOPE INSTABILITIES

In many cases, the existence of rocky slope instabilities along the centuries in areas of cultural heritage interest is well known from historical archives. However, despite the undisputable value of historical structures, it is common that risk management policies are put into practice only after major events. Before, there is usually a low-risk perception related to the high return period of events, and the lack of vivid disastrous impacts.

In the last decades, the increase of tourism and visitors, on one side and the intensification of rainfall and temperature extremes that is associated with climate change on the other, are factors possibly contributing to the increase of the rockfall related risk at historical sites, that should be taken into consideration for the prioritization of their protection. Approaches to rockfall risk protection of cultural heritage, include the following steps 2.1 to 2.4.

2.1. *Susceptibility mapping*

Rockfall susceptibility mapping consists in the development of maps showing the subdivision of the terrain into zones that have a different likelihood of a rockfall occurring. It should indicate the zones where rockfalls may occur as well as the runout zones.

The potential for failure of a rock slope is controlled by the lithology, strength and geological structure of the rock mass. The discontinuities which are present in the rock mass, their slope, orientation, spacing, persistence and shear strength determine the failure mechanism (i.e. planar, wedge, toppling), and the stability of the rock mass, assessed through the calculation of the safety factor and the probability of failure. Triggering factors that initiate rockfalls can be intense rainfall leading to increase of water pressure in the discontinuities, seismic vibration, freeze-thaw action, thermal changes. To assess rock slope stability a variety of methods exist from empirical to conventional kinematic and limit equilibrium techniques, as well as few examples of numerical continuum–discontinuum codes.

Traditionally rockfall susceptibility mapping has been taking place through rock mass characterization and systematic sampling of rock discontinuities on the field. In the last decades the use of advances topographic equipment and techniques, likes Terrestrial Laser Scanners TLS and terrestrial-aerial (UAV) based photogrammetry have permitted the development of high-resolution 3D slope models that can be used for rockfall susceptibility assessment. Examples of the use of such techniques for monuments include the Valley of the Kings, Luxor, Egypt (Marija et al., 2022), the Vardzia cave monastery (Georgia) (Margottini et al., 2016), and the UAV-based rockfall susceptibility at Cultural Heritage Area of Kipinas Monastery, Greece (Konstantinidis et al., 2021).

2.2. *Rockfall monitoring and early warning systems*

Pre-failure deformations have been registered for some rocky slope failure, through monitoring using TLS and digital photogrammetry, through successive campaigns and change detection. However, it is also common that rock failures are brittle and that detachment occurs at low strain, as for the historical site of the Montserrat Monastery, in Spain (Janeras et al., 2017). In that case higher precision strain measurements are needed. Monitoring techniques available for rocky slopes vary in spatial resolution and temporal acquisition. The use of TLS and digital photogrammetry for displacement monitoring is discontinuous, in contrast with other techniques like the use Ground-based Synthetic Aperture Radar and the rock joint instrumentation which can be continuous.

Ground-based Synthetic Aperture Radar (GBSAR) is founded on the use of Differential SAR interferometry, which detects deformation on the surface of an object measuring phase changes of the return signal. The radar is placed on a moving platform facing the rocky slope, at about 500 m distance and millimetric deformations can be registered (Margottini, and Spizzichino, 2014).

Rock joints can be monitored using sensors (extensometers) installed on discrete points of the rock mass surface across a joint of discrete blocks, in order to register potential pre-failure joint aperture changes. When combined with an automatic data acquisition system, monitoring can be real time and continuous, and can provide high precision data. Signal noise ought to thermal deformations should be taken into consideration for the interpretation of the results.

2.3. *Risk assessment and zoning*

Risk is a measure of the probability and severity of an adverse effect to health, property or the environment. Rockfall risk is defined as the sum of the probabilities of rockfall events of all potential magnitudes (size) and intensities (energy, velocity) multiplied by the consequences, considering all the exposed elements, for a given period of time.

Risk analysis involves the steps of scope definition, hazard identification, vulnerability evaluation and risk estimation and it can be qualitative or quantitative. For instance, the risk concerning the loss of cultural value related to historical structures would be rather expressed in qualitative terms, depending on the cultural importance of the monument. Instead, the number of visitors being threatened annually by rockfalls or the annual economic loss resulting from the closure of touristic monuments can be expressed in quantitative terms, using metrics like the number of injured/fatalities per year or financial loss in €/year.

Risk assessment concerns the process of making a recommendation on whether existing risks are acceptable or tolerable. Based on that, decisions can be taken for the design of structural and non-structural protection measures.

2.4. *Structural and non-structural protection measures*

The World Heritage Convention promotes sustainable development, and in particular environmental sustainability, by valuing and conserving places of outstanding natural heritage value, containing exceptional biodiversity, geodiversity or other exceptional natural features, which are essential for the human well-being. Environmental sustainability should be the basis for the design of the protection measures against natural hazards like rockfalls. Disaster risk management involves mitigation measures and adaptation strategies aimed at reducing the risks to movable and immovable heritage components.

Landslide protection measures aim at either hazard or vulnerability. Structural hazard reduction measures are used for the stabilization or the interception of rock blocks. Depending on the local conditions (slope height and morphology, accessibility, characteristics of unstable rock blocks), stabilization takes place by block removal of potential unstable rocks, or by reinforcement of the rock mass using rods, bolts, gunite/shotcrete, buttresses and support beams. These techniques are at certain point invasive and irreversible, although there are ways to smooth their visual impact (e.g. with appropriate shotcrete colors). Drainage or use of geotextiles, are an alternative.

On the other hand, interception and control methods aim at the reduction of the destructive potential of rock blocks, reducing their velocity and impeding their propagation. Structural measures include wire mesh and cable net systems as well as steel barriers and fences, like embankments and gabions to contain the run-out, and wooden, steel or concrete walls. In this case, for historical sites, structural interventions should be designed so as to reduce the visual impact using natural and green materials in harmony with the natural landscape and the historical sites.

Forest cover on rockfall corridors can also dissipate in a sustainable way part of the energy of rock blocks, through impact with stems and contact with ground vegetation increasing the surface roughness, with absolute respect to the natural landscape surrounding monuments and historical contexts. Ditches work as well as energy dissipators especially if filled with energy dissipative materials like sand.

Predesigned paths for the circulation of visitors based on risk assessment is a non-structural measure alternative to be considered, given the specific characteristics of the historical sites.

3. PRELIMINARY ROCKFALL RUN OUT ASSESSMENT AT DELPHI

3.1. The archaeological area of Delphi

The archaeological area of Delphi is situated at the foot of Mount Parnassos, in Fokida, Greece. There lies the Pan-Hellenic sanctuary of Delphi, which had the most famous oracle of ancient Greece, with Delphi, in the 6th century B.C., to be regarded as the cultural and religious centre of the world (Christaras and Vouvalidis, 2010).

Figure 1. (left) Orthophoto of the archaeological site of Delphi. In this study, the rockfall reach probability is calculated for the locations marked with A-G (A: Stadium, B: Theatre, C: Apollo Temple, D: Tholos of Athena Pronoia, E: Castalian Spring, F: Museum, and G: Gymnasium). The white lines indicate the location of areas of potential rock detachment from the cliff (rockfall sources); (right) View of Phaedriades rocks and the sanctuary.

Archaeological excavations of Delphi started in the 19th century. Vast quantities of soil and rock from numerous landslides had to be removed to reveal both the major buildings and structures of the sanctuary of Apollo and of the temple of Athena. Important monuments in the historical site also include the Theatre, the Treasuries, the Stoa of the Athenians, the Tholos, the Gymnasium, the Stadium, the Hippodrome, the Polygonal wall, and the Castalian Spring (Fig. 1). The Delphi Museum is home to the worldwide famous Charioteer of Delphi status. Delphi is situated at the foot of Phaedriades at the south of Mount Parnassos, a pair of cliffs about 700 m high, which consist of dark limestone formed in the Jurassic period. Herodotus mentioned that during the Persian invasion of Greece in 480 BC rock boulders crushed the Persians, leaving the monuments intact. Rockfalls (naturally of intentionally is not known) have also been said to protect the Sanctury against the Gallic armies in 279 BC. The imposing landscape of south Parnassos surrounds the historical site. In 2021, the archaeological area of Delphi and the Museum received 24825 and 9717 visitors, respectively.

Important geotechnical problems caused by rock falls and toppling slides present in the Delphi area have been reported amongst others by Marinos and Rondoyanni (2005), who described in detail the geological setting in the area consisting in: - intensely fractured steep limestone slopes - weak flysch formations - at least three different generations of scree - four sub parallel important normal faults. Detailed information about the faults can be found at Marinos and Rondoyanni (2005). Earthquake-induced rockfalls took place in 373 BC, causing extensive damage to the temple of Apollo. In the recent years heavy rainfalls damaged the temple of Athena in 1905, and the ruins of the Kerna spring in January 1980. In September 2009, a rock was detached from the Phaedriades slope and after fragmenting in 2 blocks of the size of a human head, it landed without causing any damage.

Rockfall occurrence in the area is triggered by earthquakes, intense rainfall, weathering and temperature changes. Although there is not an inventory of events, rockfalls are frequent, thus parts of the historical complex, at times, remain closed to the public due to the rockfall risk. Currently a steel fence has been constructed above the Stadium at about 18 m from the toe of the slope, at a length of 76 m.

Previous studies in the area have described the weathering process leading to rockfalls (Constantinidis et al., 1988), older stabilization works of the rock slopes at the region of Castalia (Koroniotis et al., 1988), and the extensive geological/geotechnical hazards in the historical site (Marinos and Rondoyanni, 2005). In Christaras and Vouvalidis (2010) the geological structure discontinuities that lead to potentially kinematic rockfall failures are described and the expected energy of blocks of 20 tn along three critical sections is calculated to conclude that the falling blocks could continue actively till the southern part of the archaeological site and to propose the installation of steel fences for the rockfall protection.

Following these works, the goal of the present work was to assess the expected rock block run-out for an event of unknown source around the entire historical site for different block sizes, and in the presence or absence of protection measures.

3.2. *Rockfall propagation analysis*

In the work which is presented here the rockfall run-out is calculated, taking into account uncertainties concerning the expected rock block volumes and the detachment zone.

For the run-out simulation, the software Rockyfor3D (Dorren and Berger, 2010) was used. The software requires as in input the digital elevation model DEM of the area, and the block size and density. It also takes into consideration the terrain roughness in order to calculate the kinematical properties along the trajectory of the rock blocks, impediments and loss of energy during their run-out, thus assessing their kinetical energy.

The analysis takes place at a Geographical Information System environment. The software QGIS was used for the preparation of the input data in raster format and the visualization of the results. Rockyfor 3D provides the option of a probabilistic analysis, considering uncertainties for the direction and size of the initial velocity of the detached rock blocks at the source and percent % variations of the rock block volume. In this way, the probability of reach of a block of a given volume at a given location, corresponding to a raster cell, can be calculated.

For the application to the study area, a Digital Elevation Model which was available online at the United States Geological Survey USGS website was used. The DEM has been created by the Shuttle Radar Topography Mission (SRTM), with 1 arc-second resolution.

Two different scenarios of block volumes were investigated: 0.008 m^3, 5.00 m^3, respectively with a volume variation up to 50%. The former volume corresponds to cubic blocks of 0.20 m edge and their volume varies from 0.004 m^3 to 0.012 m^3. The latter accordingly corresponds to cubic blocks of 1.7 m edge, that range from 2.5 m^3 to 7.5 m^3. The first scenario corresponds to the size of the two blocks that reached the archaeological site in 2009, mentioned to have the size of a human head. The two blocks were the result of the fragmentation of one bigger rockfall. The second one corresponds to the size of the rock blocks which are observed next to the road and inside the archaeological site, corresponding to historical events with a return period of hundred(s) of years. Parallelepiped shape was assumed. The detachment of larger rockfall volumes of hundreds of m^3 is kinematically possible in the area, however it is expected that after their occurrence and upon impact with the ground, they will disaggregate and fragment into smaller blocks. A more detailed analysis, which is out of the goal of the work presented here, would be required in order to determine the maximum credible rockfall volume to be detached from the slope face and its fragmentation depending on the local geological conditions (Mavrouli and Corominas, 2020).

The rock density was taken equal to 2500 Kg/m^3. As the exact location of rockfall sources is not known, potential rockfall sources were defined along the lines which are indicated in Fig. 3. The terrain was divided into 4 units corresponding to bedrock, soil terrain, built area and road, using terrain roughness and restitution coefficients as suggested at the Rockyfor3D manual. To assess the effect of intervention measures, the analysis was performed a) without any protection measures), and b) with steel fences.

3.3. Results and discussion

Two kinds of outputs were extracted from the analysis a) the probability of reach of a rock block at a given monument, taking into account the uncertainty of the rockfall source and 50% variation for the average rock block volume and b) the maximum kinetic energy of rock blocks, according to which the capacity of the protection measures can be chosen. In this case high dissipative steel fences of 5000 kJ capacity were chosen, with the location that is marked in Fig. 3. The calculated reach probability without and with protection measures is indicated in Table I.

To calculate the probability of a rock block of a given size reaching each monument, in case of a rockfall event, and considering the uncertainties regarding the rockfall source and the volume variation from the two selected average rock sizes (0.008 m3 and 5 m3), the propagation probabilities of the trajectories reaching the monuments are summed up.

Table I. Probability of reach (%) at each site

	Probability of reach (%)			
	0.008 m^3		5 m^3	
Site	w/o fence	with fence	w/o fence	with fence
A: Stadium	1.50	not reached	26.16	8.17
B: Theatre	not reached	not reached	14.19	8.22
C: Apollo Temple	not reached	not reached	3.00	0.75
D: Athena Pronoia Temple	not reached	not reached	4.48	2.25
G: Gymnasium	not reached	not reached	29.93	11.97

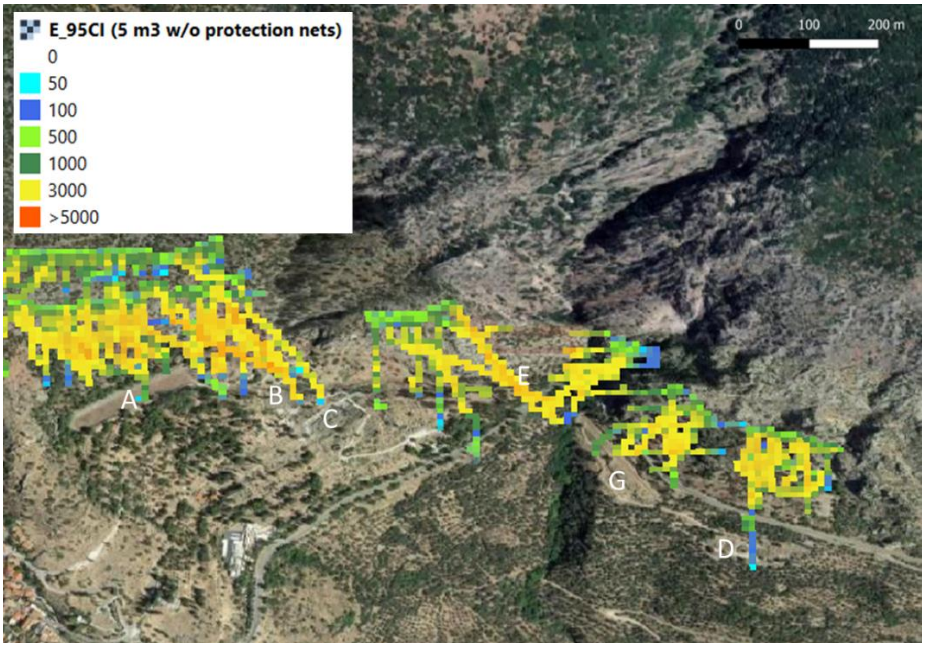

Figure 2. Kinetic energy (E_95Cl) for rock blocks of 5 m3 in kJ, without protection measures. The different colours indicate the expected levels of kinetic energy with which the specific location on the orthophoto is reached.

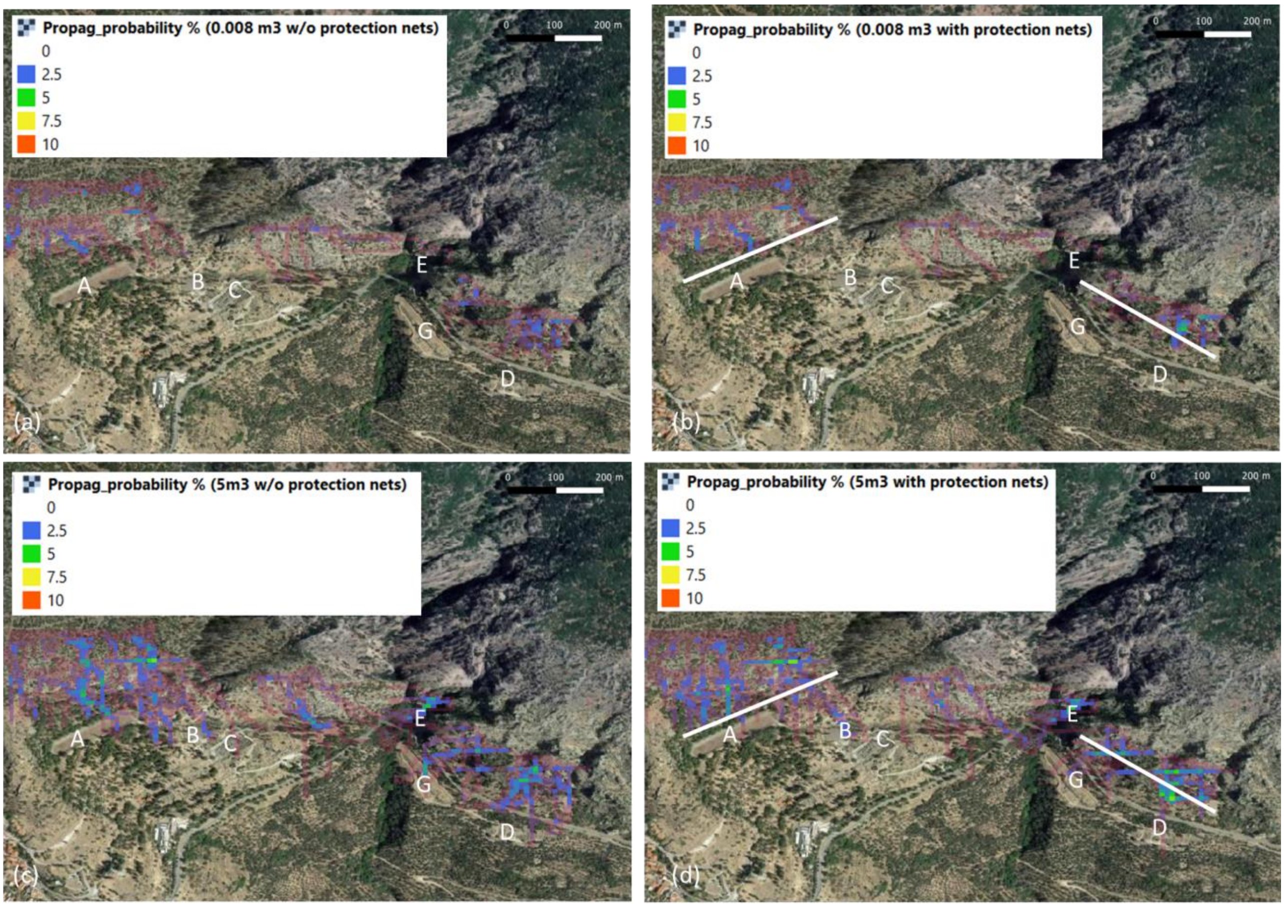

Figure 3. Probability of reach (Propag_probability) considering block volumes of 0.008 m3 (up) and 5 m3 (down), as well as the uncertainty of the rockfall source and 50% variation for the average rock block volume. On the left the results without considering protection measures are shown, while on the right, steel fences are taken into consideration and their proposed location is marked with a white continuous line

The performed analyses indicates that the Castalian spring is in all cases affected by rock blocks, and given the location of the area, a more detailed study is needed in order to design protection measures that include both stabilization and vertical interception techniques.

The results indicate that for rock blocks of the order of 0.008 m3, as the 2009 event, which occur every few years, the probability of reach at the analysed monuments is very small (Fig. 3). The reach energy at A is as low as 2.49 kJ. Nevertheless, given the risk for people circulating in the archaeological site, even for small blocks, prevention measures should be taken for their protection.

On the other hand, larger rock blocks of 5 m3, with a return period of hundreds of years are posing a significant threat according to the results. The calculated energies without considering protection measures reach up to few thousand of kJ (Fig. 2). Even for high dissipative steel fences of 5000 kJ, additional protection measures including stabilization or interception of rock blocks should be considered. Even after the installation of protection measures there exists a residual risk for the circulation of people in the site that should also be taken into account.

4. CONCLUSIONS

In Greece, the landslide and rockfall risk affects monuments and historical structures, historical paths, and surrounding landscapes. Seismicity and climate change, intensifying extreme weather phenomena, impose an increasing threat on cultural heritage sites.

Using the proposed methodology, it is possible to calculate the rockfall hazard in terms of probability of an event of a given magnitude, when the rockfall occurrence within a given period of time is known. To this purpose it is important to compile inventories of rockfall events, in order to use them as an input for the rockfall risk assessment.

Using the proposed method, it is also possible to calculate the rockfall propagation for different types of rockfall protection measures as embankments and ditches, that can be used as an alternative in order to minimize the visual impact which is especially important in the case of historical sites.

The preliminary rockfall propagation analysis at the Delphi archaeological site indicated that for the smaller blocks of 0.008 m^3, there is a low (1.5%) probability of reach of the blocks at the Stadium. The Theatre, the Apollo Temple, the Athena Pronoia Temple, the Gymnasium are not expected to be reached. The exception is the Castalian spring, which presents an exceptionally high rockfall hazard that requires further detailed study, which has not been included here. For rock blocks of the order of 5 m^3, all the studied monuments including the Stadium, the Theatre, the Apollo Temple, the Athena Pronoia Temple and the Gymnasium are expected to be reached with kinetic energy of a few thousand of kJ, with probabilities varying from 3% to 29.93%. When protective steel fences are considered, a residual probability of reach remains for these structures, which varies from 0.75% to 11.97%, with the Gymnasium being the most threatened. This residual probability of reach should also be taken into account for decisions concerning the circulation of people inside the archaeological site. The residual probability of reach can be further reduced with the application of interception or stabilization measures.

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