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ROCKFALL HAZARD IN GREECE

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Abstract

The geological structure of Greece (frequent occurrence of rock formations, existence of faults and fracturing of rocks), the steep topography and mountainous terrain as well as its high seismicity, creates a significant rockfall hazard. During the last decades, rockfalls in Greece are becoming a frequent phenomenon due to the increase of intense rainfall events but also due to the extension of human activities in mountainous areas.

The paper presents rockfall hazard in Greece trough an inventory of rockfalls and investigates the correlation of specific factors, namely: a) triggering mechanism (rainfall, seismicity), b) slope angle, c) lithology, d) fault presence, e) block size on the probability of occurrence of these, based on a statistical approach. The time and space frequency of the events is also investigated. Finally, the impact of the events on human and infrastructures (transportation infrastructure, inhabited areas, archaeological sites) is discussed.

Key words: *Earthquake, slope, rainfall, risk, impact.*

Περίληψη

Η γεωλογική δομή της Ελλάδας (συχνή εμφάνιση βραχωδών σχηματισμών, παρουσία ρηγμάτων και κερματισμός των πετρωμάτων) σε συνδυασμό με το απότομο και ορεινό ανάγλυφο καθώς και την υψηλή σεισμικότητα, συμβάλλουν στην υψηλή διακινδύνευση έναντι καταπτώσεων βράχων. Τις τελευταίες δεκαετίες, οι καταπτώσεις βράχων είναι συχνό φαινόμενο στον Ελλαδικό χώρο εξαιτίας της αύξησης των ακραίων βροχοπτώσεων καθώς και τις επέκτασης της ανθρώπινης δραστηριότητας.

Το άρθρο παρουσιάζει την διακινδύνευση έναντι καταπτώσεων στην Ελλάδα με τη χρήση μιας βάσης δεδομένων και προσδιορίζει τη σχέση συγκεκριμένων παραμέτρων, όπως: α) μηχανισμός γένεσης (βροχόπτωση, σεισμός), β) κλίση πλαγιάς, γ) λιθολογία, δ) παρουσία ρήγματος, ε) μέγεθος πίπτωντων τεμαχών με την πιθανότητα εκδήλωσης αυτών με χρήση στατιστικής προσέγγισης. Διερευνάται επίσης η χρονική και χωρική συχνότητα και τέλος η επίπτωση των καταπτώσεων στις ανθρώπινες δραστηριότητες (δρόμους, κατοικημένες περιοχές, αρχαιολογικοί χώροι).

Λέξεις κλειδιά: *Καταπτώσεις βράχων, σεισμικότητα, διακινδύνευση, βροχοπτώσεις.*

1. Introduction

Rockfalls occur when a mass of rock is detached from bedrock and moves downward. They pose significant hazard on human activities and infrastructure. The assessment of rockfall risks along roads and on other human activities is of great importance. Rockfall intensity increases during periods of low temperature and high rainfall. Geological assessment can lead to accurate prediction of the outbreak of such events, explain its mechanism of occurrence and assist in the effective design of protection measures. Koukis et. al. (1997) note that slope movements, which occur in the form of rockfalls have a relatively high frequency in Greece. The geological structure of Greece (frequent occurrence of rock formations, existence of faults and fracturing of rocks), the steep topography and mountainous terrain as well as its high seismicity, creates a significant rockfall hazard. The rockfall hazard poses a high to very high risk to transportation infrastructure (Highways and railways), domestic areas, archaeological and national heritage sites (ancient monuments, castles, etc.).

During the period 2000-2010, 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, are known along the transportation infrastructure of Greece, near inhabited areas and archaelogical sites. Rockfall protection measures have been applied in relatively few places along highways and other sites in Greece.

The major rockfall at Tempi valley in 2009, led to a loss of human life death and the closure of a section of the Athens-Thessaloniki national road for several months. Other rockfall events, which have also led to human life loss, are those in Kakia Scala (2010), Santorini (2011) and Kefalari, Argos (2012).

2. Rockfall Inventory

2.1. Recorded Data

The case studies that were recorded are those, which have occurred as distinct rockfall episodes in natural slopes mainly and have impacted human activities, such as roads, inhabited areas and archaeological sites. Rockfalls, which occur from the road cut slopes along highways in the national road network, were not recorded in the present study. These are very often and especially encountered in Pindos mountain range but also in other mountainous areas. Some rockfalls on highways are

The following data were recorded for each rockfall episode: a) Location, b) Coordinates, Altitude, c) Type of site (roadway, inhabited area, archaeological site), d) Date (s) of rockfall events, d) Triggering mechanism (rainfall, earthquake, other), e) Fault scarp presence, f) Geological formation, g) Rock mass type, degree of fracturing, h) Slope height, i) Slope angle, j) Block size of fallen blocks, k) Impact type, l) Presence of vegetation (forest etc.), m) Energy level, n) Reference.

The recorded rockfalls are fifty-six events for the period between 1935 and 2013. The locations of these are presented in Figure 1. Additionally, the most important parameters of these events are given in Table 1.

It is evident that the frequency of rockfalls has increased significantly in the period between 2000 and 2010. This can be attributed to the increase of intense rainfall periods but also to the extension of human activities (infrastructure, increase of population etc.). In a number of sites, more than one event has occurred and thus it is possible to predict the return period of the phenomenon.

Koukis & Ziourkas (1991) and Koukis et. al. (2005) presented a landside frequency zone map for Greece. The relative frequency of rockfalls in these maps was 11 %. The maximum frequency of landslides in those maps, expressed in cases per surface area, is along the Pindos geotectonic zone,. Based on the present study, this maximum does not also depict the maximum frequency of rockfalls as it mainly reflects the large number of slope instabilities occurring in the flysch formation in the form of soil type or composite failures (rotational, translational etc.).

Rockfalls in Greece are more frequent in mountainous areas at slopes with angles greater than 50 degrees, as it can be seen by the concentration of events in Pindos Mt., Tempi valley and

Parnassos Mt., shown in Figure 1. Rockfalls also occur in low to medium altitude areas but with steep slope morphology, usually related to fault scarps, as it the case in Kakia Scala, Klokova, Monemvasia and elsewhere.

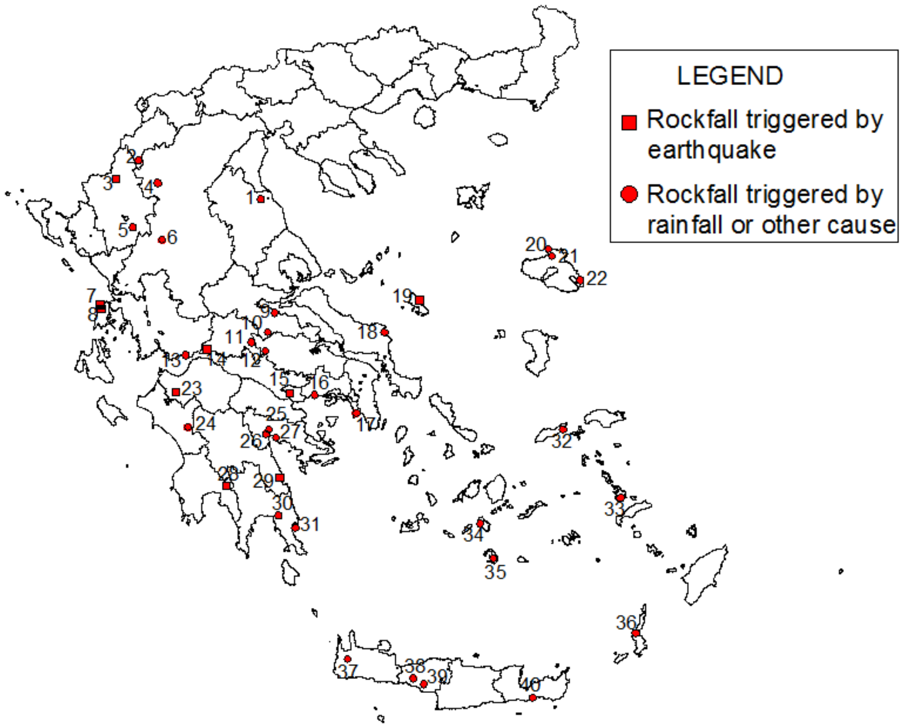

Figure 1 - Location of recorded rockfalls.

2.2. Time – space Frequency of Rockfalls

Based on the recorded data it was possible to define the frequency of rockfalls during the studied period. The frequency of rockfalls is shown in Figure 2.

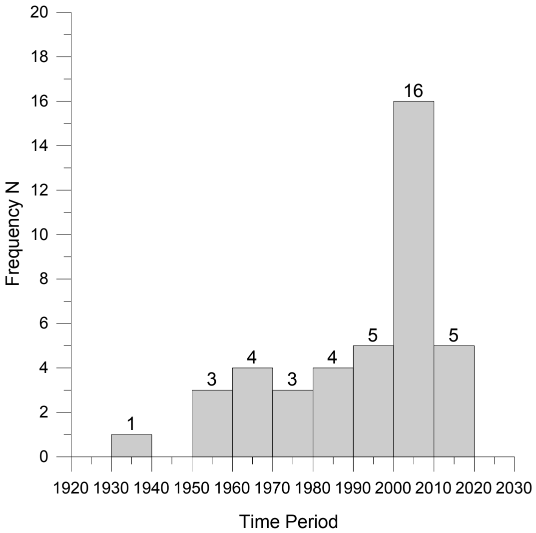

Figure 2 - Frequency of rockfalls in the period between 1930 – 2013.

Table 1 – Main data of recorded rockfalls in Greece.

Id	Location	Type	Date	Trigger	Rock type	Fault scarp	Block (m^3)	Imp-act	Ref.
1	Tembi Valley	R	17/12/2009 2004,1977[1]	ND	M		0.5 – 5, 50[2]	HLL, RC	R1, R2
2	Eptachori, Kastoria	D	1935, 51, 68, 70,87, 93, 94	R	M	Y	336[3]	DH	R3, R4
3	Konitsa,Ioaninna	D/A	8/1998	E	LA		2	DH	R5
4	Orliagas, Ziakas	D/R		ND	L	Y	1	ND	R6
5	Pramanta -Ioannina	R	9/3/2004	ND	L	Y	< 1	DR	
6	Nea Pefki, Trikala	R	20/10/2010	R	S		< 1	DR	
7	Drimonas,Lefkada	D/R	14/8/2003	E (6.4)	L	Y	< 1	DR	R7
8	Lefkada,Ag.Nikitas	D/R	14/8/2003	E (6.4)	L	Y	13.7	PDR	
9	Kamena Vourla	D	27/8/2012	ND	L		1	DH	
10	Tithorea, Parnassos	D	19/12/2010 1999, 1957	ND	L		10	DH	R8
11	Delfi ancient site	A	2003, 09[1]	R	L		8	V	R9, R10
12	Vageni Distomo	D/R		ND	C	Y	40	PDR	R11
13	Klokova Mt.	R	16/11/2012	ND	L		1-2	DR	
14	Itea, Monastiraki	R	18/1/2010	E (5.1)	L	Y	<1	DR	
15	Geraneia Mt.		24/2/1981	E (6.3)	L	Y			R12
16	Kakia Scala	R	20/11/2000	R	L	Y	0.5	HLL	
17	Vouliagmeni,Attica	D	1/1982	ND	L	Y	1-2		R13
18	Oksilithos, Paralia-Platana	R	13/8/2008	ND	MS		1.5	HI	R14
19	Skyros Island	A	26/7/2001	E (5.8)	L	Y	1-2	DC	R15
20	Mythimna, Lesvos	A	2001	R	A		0.3	ND	R16
21	Stypsi, Lesvos	D	1963, 1977	R	A		0.5-3.0	DH	R17,R18, R19
22	Taxiarches, Lesvos	D	1963, 3/11/09	ND	M	Y	1	DH	R20
23	Santomeri, Achaia	D	8/6/2008	E (6.5)	L	Y	4	DH	R21
24	Anc. Olympia	R	22/1/2013	R	L		0.5	DR	
25	Argos Castle	A	1987	ND	L			D	R22
26	Kefalari, Argos	D	20/4/2012	ND	L	Y	0.1	HLL	R23
27	Acronafplia	A	1/2010	ND	L		0.5	V	R24
28	Ladas, Eleochori, Poliani, Kalamata	D	13/9/1986	E (6.2)	L		<1	PDH	R25
29	Leonidio, Tiros	R	6/1/2008	E	L	Y	<1	RC	
30	Molaoi, Lakonia	D	2/2003	R	CA		1-2	PDH	R26
31	Monemvasia	A	2003, 2010[1]	R	L	Y	2	DH, V	R27

Id	Location	Type	Date	Trigger	Rock type	Fault scarp	Block (m^3)	Imp-act	Ref.
32	Therma Ikaria	D	10/1978	ND	M	Y	1	PDH	R28
33	Kalymnos	D	12/2002	R	L		4	PDH	R29
34	Chora, Ios	D	-	ND	S		1	PDH	R30
35	Santorini	D	2011	R	P		0.5	HLL	
36	Carpathos,Akropoli	D	-	ND	L			-	R32
37	Topolia, Chania	R	23/2/2012	R	L	Y	0.5	FB	
38	Kourtaliotis gorge	R	4/3/2012	R	L	Y	1	DR	
39	Heraklion (Pitsid-ia,Akoumia)	D	14/5/1959	E (6.3)	L	Y	<1	DH	R12
40	Ag. Fotia, Crete	R	-	ND	S		<1	DR	

[1] More rockfall events exist, which are not presented here, [2] A record of fallen blocks is given in Gazetas et. al. (2010), [3]the largest rock block, 15 smaller rocks have fallen in this site, Type: R=Roadway, D=Domestic, A: Archeological, Trigger: R=rainfall, E=Earthquake, ND=Not defined, Rock type: L= limestone, M=marble, CA= Calcitic agglomerate, LA=Limestone agglomerate, C= conglomerates, S=sandstone, M=marls, MS= marls/ sandstones, SG=Schist/gneiss, A= Andesite, P= Pyroclastics, Fault Scarp: Y=yes, Impact: HLL= Human loss, HI=Human injury, V=Potential impact on visitors, damage to archaeological site, DH=Damage to houses, PDH=Potential house damage, RC=Roadway closure, DR=Damage on roadway, PDR=Potential roadway damage, FB=fall on moving bus, DC=Damage on cars, ND= No damage. R1=IGME (1979), R2 Gazetas et. al. (2010), R3=IGME (1989), R4= Emmanouloudis & Filippidis (2000), R5= IGME (1998), R6= Papathanassiou et. al. (2010), R7= Vogiatzis et. al. (2004), R8= Papathanasiou et al. (2011), R9=Christaras & Vouvalidis (2010), R10=Marinos & Rondoyianni (2005), R11=IGME (2003), R12= Papazachos &Papazachou 1997, R13=IGME (1982), R14=Velissariou (2008), R15=Marinos & Tsiambaos (2002), R16=Marinos et. al. (2001), R17=Pangaea (1995), R18=IGME (2002), R19=Saroglou (2012), R20=Tsiambaos (2010), R21=Lainas et.al. (2010), R22=Sofianos et. al. (1988), R23=Kampouroglou & Chatzitheodorou (2012), R24=Konstantopoulou et. al. (2011), R25=Mariolakos et. al., (1987), R26= IGME (2003), R27=Saroglou et. al. (2012), R28= IGME (1979), R29= IGME (2003), R30=IGME (2002), R31=Antoniou, Lekkas (2010), R32=IGME (2003).

2.3. Triggering Mechanisms

The main triggering mechanism of rockfalls in Greece is rainfall. 13 rockfall events where triggered by rainfalls (frequency equal to 33%) and 1 event by a snowfall. A rise in rockfalls has occurred during the last years (2010 - 2013) due to heavy rainfall in limited time period usually during winter. Eighty six (86) instability phenomena were reported in 2010, from which 5% were rockfalls (Nikolaou et. al., 2011). The triggering factor of 95 % of those was intense rainfalls during February and November-December period. Additionally, the most affected area was Epirus Prefecture. Krautblatter & Moser (2009) proposed a model coupling rockfall and rainfall intensity.

The second most important triggering mechanism is seismic loading during earthquakes since 10 events by seismic loading (frequency equal to 25%). The rockfalls triggered by historical earthquakes in Greece, which are reported in literature (by Pavlides & Caputo, 2004, Ambraseys & Jackson, 1990), are summarized in Table 2. Recent earthquakes which have triggered large rockfall events are those in Skyros (2001), Lefkada (2003), Achaia (2008) and older events those during Alkyonides (1981) and Kalamata (1986) earthquakes. During Kalamata earthquake rockfalls occurred in the villages of Poliani, Eleochori and along the road linking Kalamata with Sparti (Papazachos & Papazachou, 1997). The rockfalls occurred along reactivated fault scarps (Mariolakos et. al., 1987). In some events the triggering mechanism was not defined.

Table 2 –Rockfalls during historical earthquakes.

Date	Location of Earthquake	Magnitude	Rockfall locations	Reference
550 BC	Sparta (Peloponnese)	Mi7.0	Rock falls from Taygetus Mt	Guidoboni 1989
469–464 BC	Sparta (Peloponnese)	M>7.0	fault traces (?), rock falls	Guidoboni 1989, Armijo et. al. 1991
1893 February 9	Samothrace	M= 6.5	Ground cracks and rock falls	Papazachos &Papazachou 1997
Earthquakes of 1870	(Arachova-Delphi)	Ms=5.3 - 6.7	Rock falls	‘’
1402	Achaia Diakofto	M=7	Rockfalls Xylokastro, Diakofto, Evrostini	‘’
1633	Zakynthos	M=6.9	Rockfalls	Barbiani 1864, Chiotis 1887
1636	Cephallonia	M=7.1	Livatho, Argostoli, Liksouri	Papazachos &Papazachou 1997
1694	Athens	M=6.4	Ag. Dionysios rockfall	
1928	Corinth	M=6.3	Geraneia Mt. rockfalls	
1959 May 14	Heraklion	M=6.3	Rockfalls Pitsidia, Akoumia, Kamilari	
1783, 1825, 1885, 1914, 1915, 1948	Lefkada	M=5.7 - 6.7	Rockfalls	Papathanasiou

2.4. Impact of Rockfalls

Based on the analysis of the data, the main impact of rockfalls is damage and temporary closure of roadways (frequency equal to 32%) and secondly damage to houses (frequency equal to 20%). The percentage of potential damage to roadways and houses is 5% and 13% respectively. Additionally, the percentage of loss of human life is 11%, which is considered exceptionally high. Furthermore, the frequency of potential impact on visitors and damage to archaeological sites is equal to 11%.

According to Nikolaou et. al. (2011), from the 86 instability phenomena (5% rockfalls), which were reported in 2010, 34% of the cases impacted the roadway network and 66% inhabited areas.

The most known and studied events, which have occurred along highways and other roads, are that of Tempi (shown in Figure 3a), Kakia Skala and Klokova area. Significant rockfall events impacting roads have taken place in Ag. Nikitas in Lefkada island (Figure 3b), in Oksilithos (Velissariou, 2008), along roads in Kourtaliotis gorge, in Topolia and Ag. Fotia in Crete island.

Recent events that affected inhabited areas are those in Eptachori in 1994, in Skyros in 2001 (Marinos & Tsiambaos), Santomeri in 2008 (Lainas et al., 2010) and Tithorea in 2010 (Papathanasiou et. al., 2011), which is presented in Figure 3c. Sites of high risk in inhabited areas need to be identified in order to minimize rockfall risk.

Additionally, there are a large number of rockfall incidents, which have occurred in archaeological and national heritage sites. These pose a significant danger to tourists and visitors as well as they affect the integrity of the monuments itself. Well known example is that of Delfi site (Marinos & Rondoyanni, 2005), where part of the archeological site was closed in 2009. Other studied sites are Mythimna castle (Marinos et. al., 2002), Monemvasia castle (Saroglou et. al., 2012), as presented in Figure 3d and others.

a b c d

Figure 3 - Impact of rockfall a) on highway in Tempi valley b) on roadway during Lefkada earthquake (photo from Geobrugg), c) Tithorea village, d) Monemvasia archaeological site.

3. DETERMINANT FACTORS

3.1. Slope Angle

Generally, Rockfalls occur at slopes with an inclination greater than 45 degrees. In the studied areas the slope angle ranged between 45 and 90 degrees with a mean value of 70 degrees.

3.2. Lithology – Degree of Fracturing

The most frequent geological formation encountered in the study areas, is limestone (with a frequency equal to 64%). The percentage of occurrence of the rocks forming the studied slopes is presented in Figure 4a. Generally, limestones are found broken to heavily broken, especially when in the vicinity of faults, resulting in blocky rock masses. Rockfalls are favoured in blocky or very blocky rock masses, since medium to large rock blocks are formed by intersecting discontinuities and can be relatively easily detached by the action of water or seismic loading.

In a large number of sites, scree is present at the foot of the slopes. The presence of a scree slope below the rock cliff suggests slope ravelling activity. According to Sartori et al. (2003), this activity can be linked to the progressive failure of the rock cliff, but can also be a precursory event of larger rockfalls. Dorren & Seijmonsbergen (2003) assigned rockfall susceptibility categories to geological formations according to their nature and ability to produce rocks blocks. They considered limestone to have high susceptibility, while schists, slates, marls and sandstones low to medium. The block size of the fallen blocks ranges between 0.5 m^3 and 50 m^3 with an exception of Eptachori rockslide. The blocks size is less than 1m^3 in 22 sites and between 1 and 5 m^3 in 8 sites, as presented in Figure 4b.

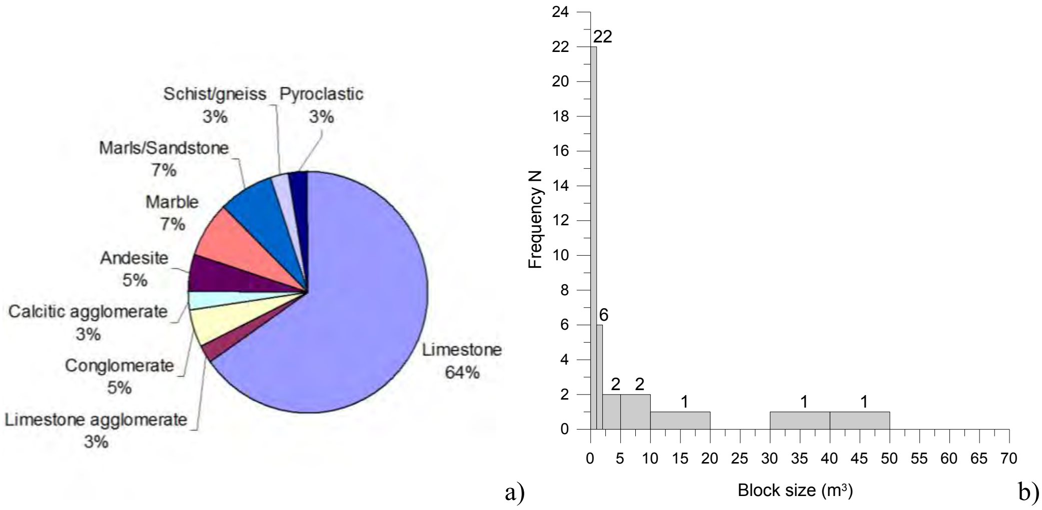

Figure 4 - a) Lithology in areas of rockfall events, b) Frequency of block size of fallen rocks.

3.3. Presence of Faults

Gallousi & Koukouvelas (2007) have correlated the triggering of the Marathias rockslide in Corinth Gulf with the seismicity of the area. The slide is formed along a fault scarp. In the study areas, twenty (20) slopes are related to the presence of faults and this contributes to the higher rockfall activity.

4. Conclusions

In the present paper a review of the rockfall activity in Greece was done for the period between 1930 until the present. A rockfall inventory was created, accounting for all the parameters determining the rockfall events. Based on the analysis of the data, it was shown that the number of rockfalls has increased substantially in the recent years. It is also concluded that the main triggering mechanism is rainfall, while a significant number of cases is related to earthquakes. Emphasis was given to the presence of faults and it was shown that almost half of the slopes were formed or relate to faults. In the study areas, limestone formations predominate, while the rock masses are blocky to very blocky resulting in block size range of the fallen block between 0.5 and 5 m^2 in the majority of the cases. Finally, the impact is severe in most cases having resulted in human life loss in four cases and usually in damages to roads and secondarily to houses, as well as potential risk to archaeological sites (visitors and structures).

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