Evolution of rock falls in the Northern part of the Peloponnese, Greece

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Abstract Rock falls are a common fast–moving type of slope failures. Earthquake triggered rock falls attracted widespread attention since they represent serious hazard during strong earthquakes, causing severe damages and even fatalities. Strong earthquakes and their associated rock falls give rise to a sudden change in landscape evolution in tectonically active areas. The associated risk can be high both to communities and to critical infrastructures even far away from the active source slopes. Distinguishing between climatic induced and tectonically induced rock falls triggered by past earthquakes is a challenging task based on the development and the fault related discontinuities of a rock slope. We chose two case studies located in the Northern part of the Peloponnese (in Iliia and Corinthia prefecture), the Skolis Mountain and the Acrocorinthos area, in order to establish the rock fall susceptibility for each case study through the implementation of shadow angle $\beta$. The proposed methodology is based on the integrated analysis of the recurrence of rock falls, their spatial distribution and their mapping through field survey and aerial photography. Our mapping is integrated through Geographic Information System taking into account also the catalogue of historical and recent recorded seismicity in an attempt to examine triggering mechanisms and causes including the effects of climatic conditions for each case study. After the analysis of the spatial relationships between rock falls and the distribution of seismic epicentres and active faults as seismogenic sources, we conclude that both studied areas have suffered extensive rock fall phenomena induced by shallow seismicity and that the relationship between geomorphologic parameters and rock fall occurrence is strong. The research steps are described, namely, the recognition, identification, mapping and evolution of rock fall phenomena through time. Our results propose a critical threshold value of 24$^\circ$ for shadow angle $\beta$ as the worst case scenario, suggesting that isolated boulders pose the greater risk on the associated communities.

1. Introduction
Rock fall is defined as individuals rocks are removed from a slope by sliding, toppling or falling and proceeding downslope [1]. The study of earthquake – induced rock fall distribution has a major importance for a better understanding of the relationship between rock fall density, type and size and the causal mechanisms. The increasing availability and precision of Digital Elevation Models improve the assessment of rock fall prone areas where only few data are available [2, 3, 4, 5, 6]. Two simple ways are usually applied to construct rockfall maps: the first is using the fahrböschung or reach angle [7, 8, 9] and the second one is using the shadow angle [8, 10, 11, 12]. The difference between them is the starting point of the travel distance estimation of a fallen block. The reach angle introduces the definition of the release point of a rock fall, whereas the shadow angle defines the talus apex as the...
starting point of the talus slope travel path (figure 1). Thus, determining the shadow angle $\beta$ is a common geometrical problem, calculating the arctangent $\beta$ as the result of the relationship $H_t/L_t$ where the $H_t$ and $L_t$ are defined by the intersection of the talus cone starting beneath a steep cliff with the maximum horizontal distance that a rock fall can travel to (see figure 1). In this way, the maximum travel distance of a block can be described by the shadow angle $\beta$ [12 and references therein]. According to Evans and Hungr [8] the shadow angle method is better suited for rock falls smaller than $10^5$ m$^3$ which is the scenario for both case studies here considered.

![Figure 1](image1.png)

**Figure 1 (a)** Sketch of a steep cliff susceptible to rock falls and the necessary parameters for the calculation of reach and shadow angle (modified by Copons et al. [12]). **(b)** Example of key elements needed for the shadow angle calculation in the Skolis area near Santameri.

This paper presents the preliminary results of a rock fall mapping survey carried out through a large set of optical high resolution photo archives and air photo archives for pre and post earthquake times. This approach is performed in 4 main steps which include: DEM creation, identification of geomorphologic features, mapping of lithology and preliminary rock fall assessment estimation of large unstable volumes. The current study aims to contribute to the understanding of the causal mechanisms of rock falls triggered by earthquakes by preparing detailed rock fall inventory maps and correlating them with seismic and morphological parameters. For this reason we concentrated and tried to analyze simultaneously, both geomorphological, lithological and climatic data. The employed rainfall data were acquired from meteorological stations at Portai and Velos villages in Ilia and Corinthia prefectures respectively (figure 2). These rainfall data show that the period from April to September is almost dry in both areas. The annual precipitation ranges between 800 and 1000 mm for the Ilia area and between 580 and 650 mm for the Corinthos area (figure 2). The study areas have little vegetation on the steep slopes, mainly bushes, but Skolis area displays few small tree clusters and Acrocorithos presents cultivated land. From the geomorphological point of view there are few surface streams draining both areas.

![Figure 2](image2.png)

**Figure 2** Distribution of mean annual precipitation for the two study areas.
2. Geologic setting
According to Heim [7] one of the main factors necessary for rock fall initiation is the steepness of the slope. Gravity driven surface processes in mountainous regions are principally correlated to the steepness of the topography and the relief morphology which therefore reflect these instabilities [13, 14]. Apart from topography, Keefer [15, 16] suggested that moderate to strong earthquakes can also trigger landslides. Earthquake triggered landslides can be either located on active faults or in the affected epicentral area [15, 17]. The studied areas are extended in the Northern part of the Peloponnese. Both studied areas present rock fall distribution related to the main faults that are responsible for the mountainous relief and separate limestone bedrock from the Neogene deposits (figure 3).

Figure 3 (a, b) Geological maps of the studied areas. The red stars show the epicentres of the most recent strong earthquakes and the red lines the associated coseismic ruptures. (c, d) Cross sections of the studied areas.

2.1. The case of Skolis Mountain
The Skolis Mountain is a fault related open asymmetric anticline 9 km long and 1.5 km wide (figure 3a, c). The mountain consists of late Cretaceous – Eocene carbonates and late Eocene – Oligocene flysch. The concentration of rock falls, in Skolis Mountain, is related to the structurally damaged rockwalls [18]. On the 8th of June 2008, a strong earthquake of Mw=6.4 occurred in northwestern Peloponnese. North Peloponnese is located in the most tectonically and seismically active region of Greece [19, 20, 21, 22]. The 2008 event was the largest earthquake occurred in northwestern Peloponnese during the past 30 years [23]. The secondary effects following the Mw=6.4 earthquake, were landslides and liquefaction phenomena near the epicentral area [23, 24, 25, 26, 27, 28]. Santomerion village was greatly affected due to its proximity to the steep slopes of Skolis Mountain and its high elevation. As a result a large volume of rock falls and boulders, hit the village (figure 4a).

2.2. The case of the Acrocorinthos in the gulf of Corinth
The gulf of Corinth represents a sedimentary basin trending WNW-ESE across the Hellenic mountain range. Sediments of the basin are exposed at an elevation of almost 2 km approximately suggesting high post – orogenetic uplift rate. In combination with the fast uplift rate, current rates of extension in
N-S direction reach up to a rate of 15 mm/yr [30], while at the eastern end of the gulf this is reduced to 6 mm/yr [31]. The sedimentary processes are controlled by the tectonic activity creating high relief through seismic ruptures and suitable conditions for high sediment supply [22]. Historical and instrumental seismic catalogues in the eastern part of the gulf of Corinth include records of at least twelve rupture events from 426 BC [32, 33] up to the last destructive Alkyonides event in 1981 AD [34]. In many cases these events triggered significant rock falls and/or liquefactions in coastal areas as recorded in 1858 [35], in 1928 [19] and in 1981 event [11, 36] (figure 4b).

The Acrocorinthos represents a tectonic horst related to the activity of the north facing active normal fault called hereinafter Acrocorinthos fault. The Acrocorinthos fault juxtaposes fractured Mesozoic limestone from Neogene marls and conglomerate deposits (figures 3b, d). It has an almost E-W direction and its length is almost 5 km. The fault related damage zone has caused dense fracturing in the carbonate rocks which led to slope instability phenomena.

3. Methodology

Analog and digital air photos were used to analyze landslides evolution of the Skolis Mountain over the period from 1945 until 2008. Classical analog airphotos were available for the years of 1945 and 1996, digital air photos from the Greek Cadastral of 2008 and Quickbird satellite images (GoogleEarth) of 2007 and 2008. From the 1945 and 1996 orthorectified airphotos and from the 2007 GoogleEarth and 2008 cadastral digital mosaics the rock fall points and polygons were digitized. The onscreen digitations were performed at 1/1000 scale (figure 5). For the detailed description of the methodology see Koukouvelas et al. [18]. The same procedure was followed for the area of Acrocorinthos. Classical analog air photos were available for the years 1965 and 1987, while Quickbird satellite images (GoogleEarth) of 2006 to 2013 were also used. The interpretation of the rock falls was carried out using the air photo archives and the DEM derived for each study area. The DEM of the Skolis area and the Acrocorinthos area are generated using digitized contour lines from 1:5000 scale topographic maps with contour intervals 4m. An example of orthorectified air photos for both areas, is illustrated in figure 5 along with the rockfall dispersion in relation to different slopes.

Both study areas comprise a widespread rock fall terrain (figures 5, 6). The Skolis Mountain area shows 42 rock fall sites derived by the orthorectified air photos of 1945, 72 rock fall sites are noticed in 1996 orthorectified air photos, 75 are from the 2013 GoogleEarth images and 89 are recorded immediately after the earthquake. In correspondence 26 rock fall sites are present in the 1965 orthorectified air photos of the Acrocorinthos area, 38 are derived from the 1987 orthorectified air photos and 35 from the 2013 GoogleEarth Images.
4. Characteristics and distribution of rock fall sites

Having identified and mapped the hazardous areas we can produce a rockfall inventory map for each case study based on field observations, structural mapping and orthorectified air photo analysis. The Skolis Mountain was analyzed for sixty three years before the 2008 earthquake, while the north slope of Acrocorinthos was analyzed for half a century. Both areas have been affected by at least one earthquake during this time span. Thus, we can try to distinguish between climatologically and seismically induced rock falls by comparison.
4.1. The Skolis Mountain inventory map
The mapping of rock falls along the western slope of Skolis Mountain indicated that pre-existing instabilities have been increased in number immediately after the earthquake activity. Air photo mapping results suggest that the 2008 earthquake reactivated 72 taluses and triggered 17 new rock fall sites (figure 7). In addition a reactivation took place in almost all rock fall paths. To estimate the rock fall susceptibility, we identified the location of rock fall release points. These release points are recognized in a zone with elevation ranging from 450 m to 970 m. From these release points large boulders bounced or rolled on a slope surface ranging between 70-30° (figure 5), concentrated in talus cones with talus apex ranging between 650 m to 400 m elevation height. Typically the maximum spread of a block is described by the shadow angle β [8]. Pre earthquake mapping of rock falls show that boulders are dispersed at shadow angles between 30°-33°. On the contrary, post earthquake mapping of boulders reveals a change in this angle, calculated in 24° (figure 7).

Figure 7 Shaded relief map of rock fall susceptibility and their distribution across the Skolis Mountain before and after the earthquake of 8th June 2008.

4.2. The Acrocorinthos inventory map
In the Acrocorinthos horst the interpretation and evaluation of the air photo archive of the last 50 years show the susceptibility of the area to extensive rock falls (figure 5b). During field mapping and air photo mapping, two separate populations of boulders were recognized based on their lithology. The first one is composed of Mesozoic limestone and originates from the steep slope of the Acrocorinthos cliff, whereas the second one is composed of cemented conglomerate (figure 6). The second cluster
corresponds to the dismembered Neogene marine terraces (see figure 3d) and it is a common feature through the southern part of the gulf of Corinth. It originates from the toppling of marine caprock lying over marls. We do not take into consideration these boulders for the calculation of the shadow angle $\beta$ since our field observations show that these are not subject to large movements over time. Thus, we do not consider them as possible hazard even though they are in close proximity to the village of ancient Corinthos (figure 8 right photo).

**Figure 8** Typical boulders in Acrocorinthos area. Photo on the left shows the Mesozoic limestone boulders, while photo on the right, the Neogene conglomerate boulders.

**Figure 9** Shaded relief map of rock fall distribution across the north slope of Acrocorinthos. The 1965 mapping displays the distribution of rock fall susceptibility 37 years after the 1928 earthquake, the 1987 mapping shows the rock fall susceptibility 6 years after the 1981 earthquake and the 2013 mapping shows the rock fall susceptibility 32 years after the last earthquake.

The 1965 air photo mapping suggests a number of 26 rock fall sites. After the 1981 earthquake, the 1987 air photo mapping suggests that the identified rock falls are 38. Thus, they did not present a spectacular increase as in the case of Skolis Mountain. This increase is attributed to the 1981 earthquake swarm. However, the 26 km distance from the 1981 earthquake epicenter does not seem to have such a great impact on the Acrocorinthos area. Closest to the 1981 earthquake epicentres
extensive rock falls have been mapped at the Skinos – Alepochori area by Koukis and Rozos [36] and Marinos et al. [29]. In 2013 GoogleEarth images 35 rock fall sites can be identified. It seems that 30 years after the 1981 earthquake a talus cone can redistribute its fragments on much gentler slopes. If this is the case then the 1965 air photo archive mapping suggests a similar distribution after the 1928 earthquake that according to historical and recorded data had a great effect in the area. Field survey showed that boulders that bounced on the steep slopes and rolled over the Acrocorinthos northern slope rest at a distance of 300 m from the talus apex. The zone in which the apex of the talus can be identified is located at an elevation ranging from 250 to 350 m. Mapping of boulders shows that boulders are dispersed at shadow angle with threshold value of 24º after the 1981 earthquake, while the same angle is estimated at 27º from the 1965 and 2013 photo archives (figure 9).

5. Discussion
This study aimed to generate a comprehensive data base of rock falls triggered by moderate to strong earthquakes in two areas that are prone to slope instabilities. For this reason we used air photo archives and tried to correlate them with climatic and lithologic factors. In Skolis Mountain, the west dipping stratification in limestone and the joints affecting it seem to generate favourable conditions for producing rock fall hazard. The rainfall pattern seems to promote these instabilities in a rather slow way over long periods of time. On the contrary, the 2008 Movri Mountain earthquake accelerates and enhances this process, according to our observations derived from field survey and photo archive. Thus, seismicity events turn out to be more important than rainfall in the initiation of slope failures. Therefore, we consider seismicity as a substantial factor that influences the rock mass strength. Keeping in mind that the newly formed or reactivated rock falls of 2008 are the consequence of recent seismicity, distant boulders recognised in photos taken prior to 2007 can be attributed to past earthquakes.

Similarly, the Acrocorinthos area appears as triggering rock falls throughout time. The tectonic pattern and the fractured carbonate rocks create predisposing conditions in favor of slope instability, not only associated with strong earthquakes but also with heavy rainfalls that sometimes occur as flash floods (flash flood event of 1997, [37]). The maximum distance travelled by rock fall blocks from the talus apex reaches 300 m, while in Skolis Mountain reached 200 m beyond the active taluses (talus baseline). However, some scarce boulders rest at a distance of 600 m from the base of the steep slope. We suggest that this difference is associated to the slope gradient which is smoother and lower respectively in Acrocorinthos than in Skolis. The talus cones in the Acrocorinthos area accumulate on a slope ranging from 40º to 30º, whereas the slope angle in Skolis Mountain is between 45º to 30º (the Ht factor is higher in Skolis case). This variation reflects the difference in pre-earthquake shadow angle. Even though the kinetic energy of the fallen block is largely decreased after the first impacts on the talus surface, suggesting an unaffected shadow angle by the rock fall height (elevation height of the release zone which is substantial in the calculation of reach angle), a block is able to travel further away over a long inclined talus slope due to its friction coefficient. Thus, smaller shadow angles sometimes can be estimated in places where the talus and/or ground surface is relatively smooth and flatter, or large boulders roll over finer taluses [8 and references therein]. Fine grained taluses seem to accumulate in the Acrocorinthos area affecting the shadow angle envelope (figures 4, 10 left photo). Nevertheless, the post earthquake – induced rock fall distribution appears similar with the one described in Skolis Mountain. The worst case scenario of 24º minimum shadow angle is valid for both the Skolis Mountain and the Acrocorinthos area. Moreover, the difference on pre earthquake estimations of angle β between the two areas could also be influenced by the plant cover [38, 39, 40] of each area. In Acrocorinthos the plant cover is mostly rural with olive trees and vineyards just below the talus baseline (as defined in figure 1), while the Skolis Mountain slopes display tree clusters. These tree clusters offer some protection during heavy rainfalls that limit the travel distance of a fallen block (figure 10, right photo).
The 1987 mapping of Acrocorinthos shows that the taluses have grown bigger in size and number since 1965 mapping. Thus, after the earthquake pre existing rock fall sites reactivated along with the development of new rock fall sites and caused reduced shadow angle. However, the 2013 data analysis seems alike the 1965 one. Given that both maps describe the rock fall distribution 30 years after the occurrence of a strong earthquake it seems that boulders can be dispersed even further in a long period after the earthquake. As the boulders are released from the carbonate rockwalls they usually follow trajectory paths. These trajectories may be or not obvious but it seems that boulders are concentrated immediately after the earthquake. After a heavy rainfall or a flash flood some of these boulders especially the ones at the base of the talus cones of the Acrocorinthos area that lack protective forest plant cover may have been set in motion again to their final resting place \([41, 42]\) For this reason a protective metal - wired fence has been installed on the northern slope of the Acrocorinthos cliff.

6. Conclusions

In the current study we mapped and compared two areas hosting moderate earthquakes and prone to rock falls. Based on our results we summarize the following preliminary conclusions of the rock fall hazard in Skolis Mountain and Acrocorinthos area.

1) Both areas shows that the slope failures are related to fractured carbonate rocks and fault related structures.

2) Earthquake induced rock falls provoke the growth of pre existing rock fall sites or create new ones.

3) Isolated rock falls climatic or earthquake triggered, pose the greatest hazard for the residents of the area. However in both cases the road that crosses the rock fall terrain can act as a barrier for boulders travelling down slope.

4) The use of shadow angle $\beta$ shows that a 24° envelope captures the farthest travelled boulder and highlights the zone of potential rock fall hazard for both the Skolis Mountain and the Acrocorinthos area.

Acknowledgements

This work was supported by Grant E078 to V Zygouri and I Koukouvelas from the Research Committee of the University of Patras (Programme K. Karatheodori).

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