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Investigation of Two Co-Seismic Rockfalls During the 2015 Lefkada and 2014 Cephalonia Earthquakes in Greece

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ABSTRACT: The paper discusses two case studies related to earthquake-triggered rockfalls, one from Lefkada Island (Mw 6.5 earthquake, 2015) and one from Cephalonia Island (Mw 6.1 earthquake, 2014). The first one impacted a house in Ponti village resulting in one loss of human life while the second one occurred at the beach of Myrtos. Detailed characterization took place using an Unmanned Aerial Vehicle (UAV) and a high definition optical camera. Using the UAV-based imagery, three-dimensional models of the rockfall sites were created and were used as input for detailed rockfall analysis and to document the characteristics of the down-slope block movement. The rockfall impact points were identified by a field survey and UAV imagery. Based on the recorded earthquake ground motion characteristics, the initial velocity of the detached blocks was assessed and the rockfall trajectory was reconstructed in order to define the run-out distance for each case. It was found that the rockfall events were distinctively different in terms of kinematics, one having propagated by rolling of a very large rock boulder, while the other having a rolling and bouncing trajectory with "peculiar" characteristics.

INTRODUCTION

Earthquakes are known to cause rockfalls. The occurrence of rockfalls is highly dependent on the earthquake magnitude and distance from the causative fault. However, it is also dependent on the site conditions (both topographic and stratigraphy) that influence the peak ground velocity at the site as well as the pre-condition of the rock mass at the time of the earthquake and the potential for rock detachments. Hazard assessment methodologies against earthquake-triggered rockfalls have been applied by Gorum et. al (2011), Wasowski & Del Gaudio (2000), Rodriguez-Peces et al. (2011), Marzorati et al. (2002) and others. Harp & Jibson

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(2002) proposed that concentrated seismically triggered rockfalls might result from local amplification of seismic shaking.

Ambraseys & Jackson (1990), Pavlides & Caputo (2004) and Saroglou (2013) reported rockfalls triggered by historical and recent earthquakes in Greece. Based on the magnitude – source distance diagram developed by Keefer (1984) for landslides, which includes rockfalls, Saroglou (2016) studied the magnitude–distance relations for earthquake–induced rockfalls in Greece. According to this study, the magnitude of earthquakes that triggered rockfalls in Greece is at least M_w= 5.7, while the maximum distance from the epicenter to a reported rockfall was 37 km.

The present paper discusses in detail two recent co-seismic rockfalls in Greece that occured during the November 17th 2015 M_w 6.5 earthquake in Lefkada and the January 26th and February 3rd 2014 M_w 6.0 and 6.1 earthquake sequence in Cephalonia Island.

EARTHQUAKE CHARACTERISTICS

Cephalonia Island (M_w 6.1 earthquake, 2014)

On Jan. 26 and Feb 3, 2014 Cephalonia Island, Ionian Sea, Greece, was struck by two strong, shallow earthquakes (NOA local magnitudes ML5.8 and ML5.7, respectively). The earthquakes ruptured two sub-parallel, strike-slip faults, with right-lateral kinematics. During both earthquakes, ground-failure, such as liquefaction, road failures, rock falls, small/medium size landslides and stonewall failures were widespread all over the western part of the Island (Lekkas & Mavroulis, 2015).

Lefkada Mw 6.5 earthquake, 2015

Based on the focal mechanism study of the earthquake it was determined that it was related with a known active fault in Lefkada along the western coastline. This fault belongs to the north part of the zone of right slip faults with inverse component (Ganas et al., 2016, Papazachos & Papazachou 1997). The previous earthquake in this zone occurred in August 2003 with a magnitude of M6.2.

GEOLOGICAL CONDITIONS

Myrtos coastal area is located in the western part of Cephalonia Island in a transition zone, where Triassic–Middle Miocene limestones of Paxoi unit thrust with a reverse NW–SE striking fault (Agia Efthimia fault) over the Middle Miocene–Early Pliocene clay-clastic sequence of the same unit. This thrust fault, along with the presence of NE–SW and NW–SE striking active faults cut across Myrtos coastal area and form an unstable region. The slope is formed by white limestone, locally karstic. In places, the limestones are highly tectonised and form tectonic breccia due to the fault's presence and are overlain by slope scree formed by the weathering of the steep slopes, consisting of sands, gravels and irregular boulders (Figure 1).

In the Ponti, Lefkada, rockfall site, the encountered geological formations are limestones covered by moderately cemented talus materials, which have a thickness of up to a few meters (Figure 2).

ROCKFALL CHARACTERISTICS

During the 2014 Cephalonia earthquakes, a limestone block with a volume of 180 m^3 (~ 7 x 5.5 x 5 m) was detached from the eastern steep slope of Myrtos, rolled downwards impacting the asphalt road in three points and stopped at the foot of the slope at a distance of 100 m from the shoreline at an elevation of approximately 10 m a.s.l. (Figure 1). The elevation of the detachment point was 280 m above sea level. Furthermore, a second smaller block detached from the same rock cliff at a similar elevation, rolled on the slope and stopped at a higher elevation (around 50 m a.s.l.).

During the 2015 Lefkada earthquake, a limestone block with a volume of 2 m^3 detached from a rock slope near Ponti village, impacted a residential house, penetrated two brick walls and caused the death of an elder woman. Of particular interest was the very long travel path of the rock block; about 800 m in plan view, from the point of detachment to the end of its path, as presented in Figure 3. The limestone slope has a height of 600 m and an angle of 35^0 to 40^0 (Figure 2).

Figure 1. View of rockfall site at Myrtos beach.

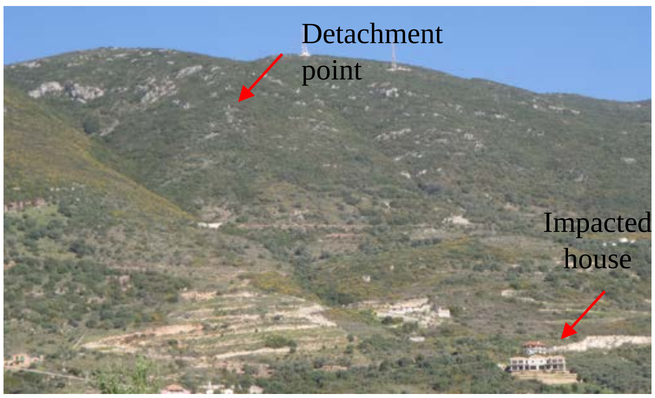

Figure 2. View of Ponti rockfall area in Lefkada.

UAV RECONNAISSANCE

The objective of the field reconnaissance was to identify the origin of dislocation of the rockfalls in the two study sites and trace their trajectories. A UAV (or drone with an ultra-high definition (UHD) camera was deployed to reach the inaccessible, steep and vegetated uphill terrain and through its virtual First Person View identify the origin of the rock blocks as well as their path. Aerial video imagery was also collected to produce a high-resolution orthophoto of the rockfall trajectories in the case study sites. The detailed UAV-enabled field survey produced a high-resolution orthophoto and a Digital Surface Model (DSM) of the terrain. The sequence of impact marks from the rock trajectory on the ground surface was identified using the orthophoto. Manousakis et al. (2016) to provide more information on the UAV reconnaissance survey for rockfall analysis.

<u>Myrtos, Cephalonia Island</u>
5cm pixel size orthophotos were produced by processing high-resolution image sequences through SfM photogrammetry software as shown in Fig. 3. The orthophotos were used to identify the rolling section of the rock throughout its entire course as shown in Fig. 4.

<u>Ponti, Lefkada Island</u>
5cm pixel size orthophotos were produced by processing high-resolution image sequences through SfM photogrammetry software and were used to identify the rolling section and the bouncing points of the rock block throughout its entire course (shown in Fig. 5). The rolling section of the rockfall path was distinguished by a destructive linear feature through the vegetated terrain, which alters its colouring with a bare earth tint. In contrast, bouncing impact points stand out as ellipsoidal bare earth craters with no linear traces connecting them.

The final bouncing point before impact on the house is clearly visible on the asphalt road. Top view ortho-imagery proved to be invaluable for these qualitative assessments.

Figure 3. Orthophoto of Myrtos beach.

Figure 4. Rolling path of block in Myrtos.

Figure 5. Top view orthophoto – Rolling section and bouncing positions recognition for the Ponti (Lefkada) rockfall.

INITIAL VELOCITY

The peak ground acceleration at the rock slope represents the intensity of base shaking modified by site and topographic effects (Mavrouli et al., 2009). In the present case, local shaking intensity in terms of horizontal PGA was considered. The analysis results of the strong motion station recordings during the earthquakes are presented in Table 1.The normal to the slope ground motion, which happens to be the E-W component of acceleration was considered for the determination of the initial velocity for both sites.

Table 1. Accelerometer recordings of the earthquakes.

Comp.	Argostoli, Cephalonia		Vassiliki, Lefkada	
	Acceleration (cm/sec^2)	Velocity (cm/sec)	Accel. (cm/sec^2)	Velocity (cm/sec)
NS-comp	640	53	363	59.3
EW-comp	379	31	326	34.1
Z-comp	239	14	256	17.7

Myrtos, Cephalonia Island

An accelerometer recorded the earthquake in Argostoli, which is located at a distance of 16.4 km from the rockfall site. The horizontal component of the peak ground acceleration at the slope base (PGA_b) was considered equal to 0.379 g.

The acceleration at the detachment point, which coincides with the crest, is PGA_{cr}= 1.5*PGA_b and was calculated equal to 0.57 g.

Ponti, Lefkada Island

A strong motion station recorded the earthquake in the village of Vassiliki at a distance of 5 km from the site (Table 1).

The acceleration recording in Vassiliki is presented in Figure 6.

For the case of Ponti rockfall, the peak ground acceleration (PGA) on the slope face (PGA_{sf}) was obtained by linear interpolation between the acceleration at the base (PGA_b) and at the slope crest (PGA_{cr}). The acceleration at the crest is PGA_{cr}= 1.5 PGA_b and it is calculated equal to 0.48 g.

Therefore, the seismic acceleration on the slope at the detachment point was estimated to be equal to 0.45 g. The initial horizontal velocity was calculated equal to 0.67 m/sec, considering a displacement in the order of s = 0.05 m.

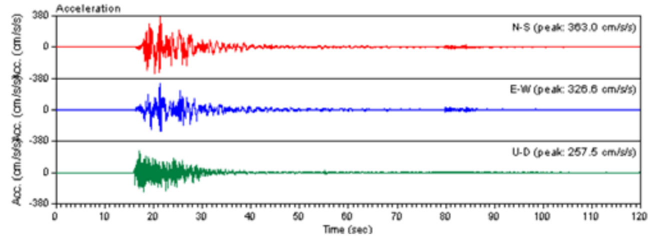

Figure 6. Acceleration recording in Vasiliki station during the 2015 Lefkada earthquake (ITSAK, 2016)

ROCKFALL ANALYSIS

Assumptions

2D rockfall analysis was performed in order to model the actual rockfall trajectories. The analysis was performed using the software RocFall of Rocscience Inc (1998).

The characteristics of the blocks, initial conditions and rockfall parameters used in the analysis are presented in Table 2. The coefficients of restitution are the most crucial input parameters in rockfall analysis. According to Asteriou et al. (2012), these coefficients are affected by several factors, such as impact angle of the block, hardness of the rock on the slope, velocity, among others.

Table 2. Initial conditions

	Myrtos initial model	Ponti initial model	Ponti back-analysis model
Block volume (m^3)	180	2	
Block weight (tn)	450	5	
Initial velocity (m/sec)	1.0	0.67	
R_n	0.35	0.35	0.60
R_t	0.85	0.85	0.85
Friction angle	0	0	

Analysis results

Ponti, Lefkada

Initially, a rockfall analysis was performed, considering an initial velocity of 0.67 m/sec and modeling rolling using friction angle of the slope material (limestone) equal to zero. As presented in Figure 7, the falling rock primarily rolled on the slope and stopped much earlier than its measured run-out distance, approximately 400 m downslope from its starting point. The restitution coefficients were considered as R_n=0.35, R_t=0.85, which represent properties suggested from the software for bedrock outcrops. The rockfall trajectory is presented in Figure 8.

In order to better simulate the actual trajectory, different combinations of geotechnical properties of the slope were considered (restitution coefficients, friction angle) and a deterministic back analysis of the trajectory was performed (with no standard deviation considered for the restitution coefficients).

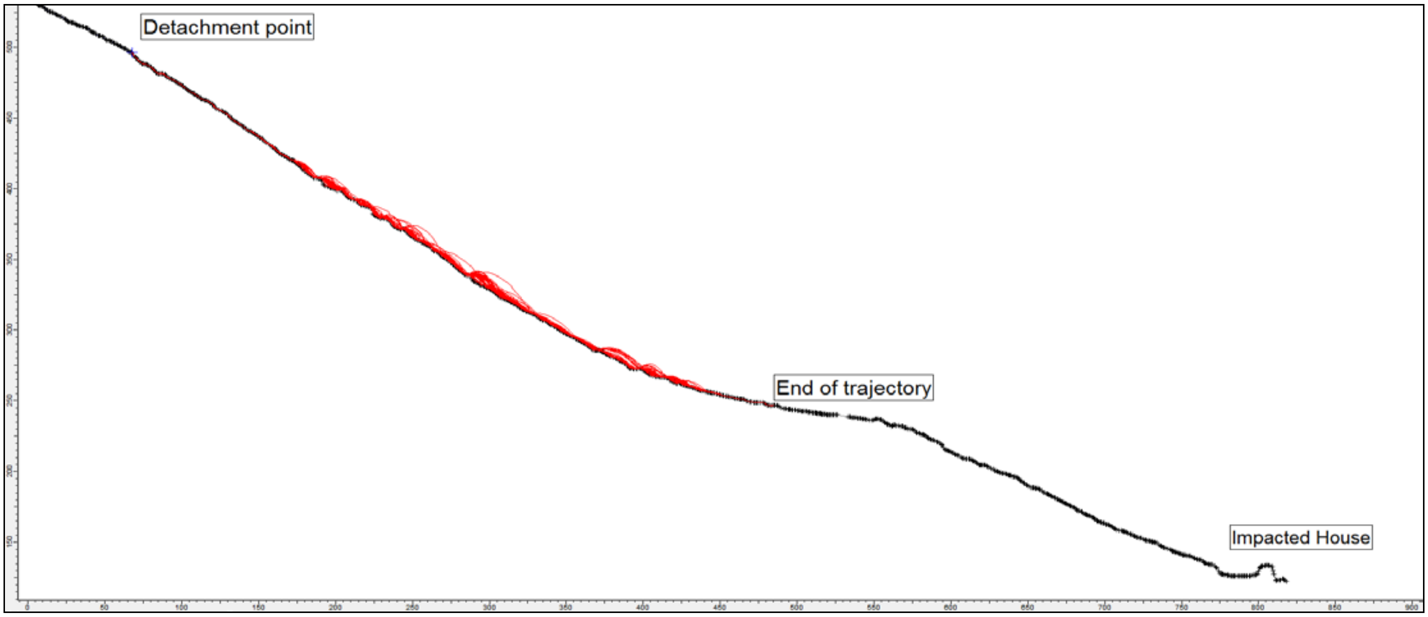

Figure 7. Rockfall analysis in Ponti site for initial best-estimate input parameters.

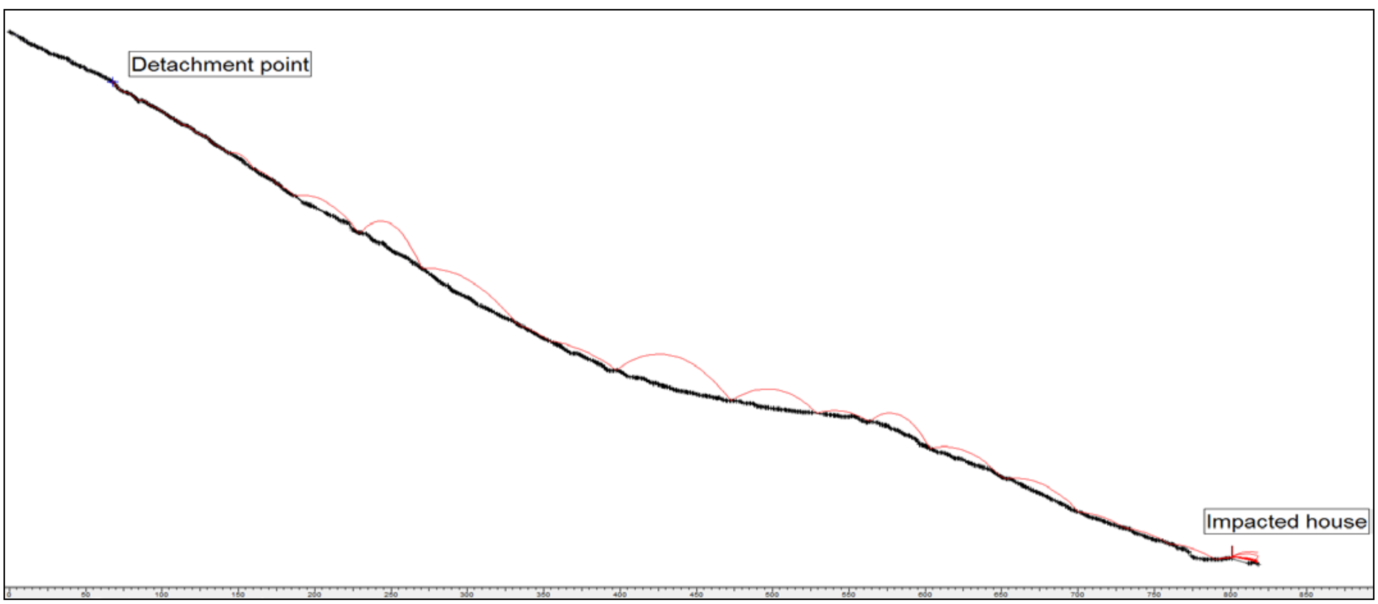

Figure 8. Back-analysis in Ponti site

These back calculated coefficients of restitution are equal to R_n=0.60 and R_t=0.85, while the friction angle was set equal to zero. Only in such an analysis, the rock block reaches the house; with a velocity approximately equal to v=18 m/s (Figure 8).

The coefficients correspond to bedrock material (limestone). It must also be highlighted that the friction angle of bedrock cannot be zero, as assumed pointing to limitations of the analysis.

Even with these coefficients, in the back-analysis, the modelled trajectory is not identical to the observed one. It was proven to be practically impossible to match the impact points identified in the field. One of the main differences is that the block is rolling downslope up to 200 m, while the actual rolling section is 400 m, as shown in Figure 5. Furthermore the impacts on the ground in the bouncing section of the trajectory are in different locations than the actual ones. Finally, the modeled bounce height of some impacts appears unrealistically high.

Myrtos, Cephalonia Island

The modeled rockfall trajectory analysis at the Myrtos site is presented in Figure 9. It can be observed that the detached rock rolls downslope and rests near the shoreline at an elevation of 10 m a.s.l. This run-out distance agrees well with the observed trajectory of the block. The mean total kinetic energy of the rock ten meters before it stopped is calculated equal to 12400 kJ. The abrupt stop of its course is due to the flat topography at the shoreline.

Impact energies

The calculated total kinetic energy (range and average values) and the velocity of the blocks at the location of impact are presented in Table 3.

Table 3. Impact characteristics of blocks (energy, velocity).

	Total kinetic energy - range (kJ)	Total kinetic energy – mean (kJ)	Velocity at final impact (m/sec)
Myrtos site	7870 – 17000	12400	-
Lefkada site	740 - 1340	1160	18

CONCLUSIONS

Based on the presented results, it becomes evident that certain limitations exist in modeling these two case studies, mostly related with the coefficients of restitution. In the case of Lefkada rockfall it was evident that the actual trajectory couldn't be accurately predicted using a standard 2-D analysis.

The rockfall trajectory in Lefkada site was rolling and bouncing while the trajectory in Myrtos was only rolling.

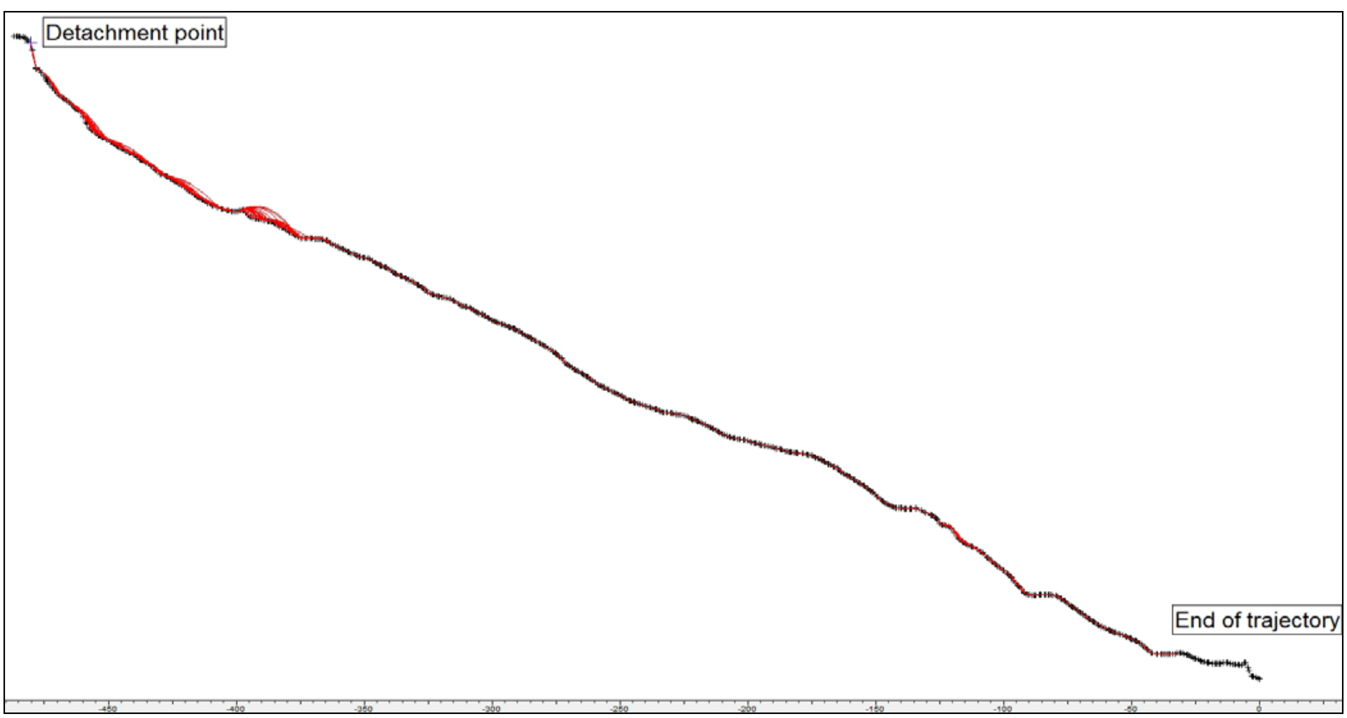

Figure 9. Rockfall analysis in Myrtos, Cephalonia site

In both sites, the initial velocity of the detached rock was estimated based on site conditions and amplification of the ground acceleration due to topography. It was found that the accurate determination of the initial velocity of the blocks plays a significant role in re-producing the rockfall trajectory.

The rockfall analysis of the two sites provided important insights on the limitations of modeling when using coefficients of restitution.

In Myrtos site, where the massive block rolled downhill, the trajectory was accurately modeled by using friction angle of the slope material (limestone) equal to zero. Furthermore, the runout distance of the block matched the field evidence.
On the contrary, when a similar assumption was made in the case of Ponti, the falling rock rolled on the slope and stopped much earlier than its runout distance, approximately 400 m downslope from its starting point, which essentially is less than half the observed runout length.

It should also be mentioned, that the energy level in Myrtos rockfall was calculated in the order of 10000 kJ, a magnitude that cannot be absorbed by standard rockfall protection structures.

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