RESPONSE TO REVIEWER's COMMENTS

The paper needs to be reviewed by a native English speaker.

Response: The paper has been reviewed by Prof. Marin Clark, native English speaker, among others.

Generally, DSM or DEM concepts are used as synonymous, but DEM is the model of the terrain
1) Line 24: "Digital surface model (DSM) of the terrain". This sentence is not correct.
Response: DSM was replace with DEM.

2) Keywords: DEM: DTM or DSM? "Restitution" what do you mean?
Response: Both DTM and DSM are used as keywords.
Restitution is the energy loss during impact of the falling rock.

3) Line 70: as line 24. No correct.
Response: DSM was replaced with DTM.

4) Figure 1 is still the previous one! The proposed new figure (with geological map) has not been replaced
Response: Figure 1 is not the previous one. We added a new Figure to localize the study area in Greece

5) Line 84: the correct definition is 800 m/s. sec doesn't exist!
Response: corrected

6) Figure 2 if the orthophoto of the site. It is quite difficult to see the "average slope" using this product. It is completely unhelpful. It is better to include the contour plots or making a 3D model.
Response: This Figure is presented in order to present the actual rockfall trajectory and indicate the source and end point of the rock. Subsequent figures are used to show slope.

7) Concerning the images or video. It is not declared the final GSD (ground sample distance). This parameter is fundamental working with digital images. Moreover, it is not declared the strategy adopted to collect the image or video. On photogrammetric point of view, which kind of flight plan have you adopted? It is necessary to include more detail about the data acquisition.
Response: Comments added at line 118-123

8) Figure 2 caption: study site is not correct: case study or test site.
Response: Corrected

9) In "introduction", 103-108, will be interesting to include an example of image. It is not clear if you have used the image or video. To be clarified
Response: **6 example images are shown in Fig. 5. As discussed in the text. Images were generated from the video**

10) Line 113: replace wase with was
Response: ok

11) Line 114: the sentence is wrong. Using SfM you have generated a DSM. After, with a data processing, you have generated a DTM.
Response: **Corrected**

12) Line 115: replace imagery with imaery
Response: ok

13) Lines 122-128: you have to specify the GCPs' distribution and why you have chosen this distribution, how the GCPs' have been detected (manually or automatically), It is not clear the quality of the GSP.
Response: Not within the scope of this manuscript. Methodology described by Manousakis et al. (2016).

14) Line 128: "DSM or DTM". This is a mistake!! They are not synonymous!!
Response: This is not a mistake. Both were generated. DSM first. DTM next. This is now clarified in the text in line 116-117.

15) Line 128: replace orthophotos.
Response: It is not entirely clear what it is asked in this comment. Orthophotos were generated.

16) It is important to define the setting configuration of PHOTOSCAN, for alignment, point extraction etc. a summary table needs.
Response: Not within the scope of this manuscript

17) Line 134: " two surfaces were found to be very similar". It is necessary to declare the entity of the differences, considering max, min and mean values.
Response: A reference is made subsequently in the text, where quantitative assessment of the DEM from the UAV and the DEM of the Greek Cadastre are compared. Refer to Manousakis et al. (2016) for more details.

18) Figure 4 is completely unhelpful. It is necessary to include a more clear figure about the flight plan, showing the final foot print of the images.
Response: We believe that this figure shows nicely the pictures overlapping using SfM method and we would like to retain it. Since the overlap of the imagery is listed, and an orthophoto is also shown we do no believe a specific flight plan is necessary.

19) Figure 4 caption: replace Shematic with Schematic. This picture has to be completely replaced. It is terrible!
Response: We do not think it is terrible since it demonstrates in a perspective view the way a real object detail is identified and projected on several overlapping images.

20) Line 135-136: image or video? No clear. It is necessary to define how the camera has been calibrated and to summarize the calibration parameter in a table. Have you tried to calibrate the images with other methods?
Response: Video captured clarified. Precalibrated camera parameters by the SfM software (Photoscan) were introduced.

21) In the proposed correction there is a new figure 3 (about SFm) but in the paper is not included.
Response: We are not sure we understand this comment. Apologies.

22) In Figure 5, it is important to include a bar scale
Response: A scale was provided in the images in Figure 5

23) Line 159: "Noise filtering and smoothing processing" which one? Could you describe them? It could be better to include a flowchart of your process, with purpose to better understand your activity
Response: We provided more clarifications about the process

24) Line 165:"a bare-Earth digital" is a terrible sentence!
Response: We use this term to describe an intermediate step where the vegetation has already been removed, but not the structures. Thus, this DEM cannot be called DTM nor DSM.

25) In the proposed revision, you include the link of GAT tool, but it is not included in the uploaded version. To be included
Response: Reference included (line 182)
Lindsay JB. 2016. Whitebox GAT: A case study in geomorphometric analysis. Computers & Geosciences, 95: 75-84. DOI: 10.1016/j.cageo.2016.07.003

26) Have you verified the performance of the GAT tool? Have you compared your DTM with a DTM generated by a laser scanner?
Response: No, we have not. This was not a focus of our study.

27) Using this algorithm (OTO), is there the risk to remove also some rocks? Could you describe the parameter adopted in the filtering?
Response: There could be a risk involved there, since there is no straightforward process to only remove vegetation from an SfM point cloud. No process is perfect, but we do not think any errors here had a significant impact on the results.

28) Line 224: replace m/sec with m/s
Response: **ok**

29) Line 275: it is not clear why you have selected 2 case and the main differences. Please, to be clarify
Response: The comment is not clear

30) Line 356: In 2D and 3D analyses, I suggest to include a table where the initial parameters are summarized. It is very difficult to understand.
Response: Table 4 refers to the parameters of the 3D analysis. The authors believe that a Table is not necessary.

31) 2D analyses: it is not clear how the filtering (DSM to DTM) give some influence to the final results and simulation. Is it possible that some trees or bushes have been removed? What is the power of the vegetation filtering (min object).
Response: Yes, the objective is for the trees and bushes to be removed in the DTM. As explained in the text, we used the filtering, in combination with the imagery to try to reasonably identify ground. As the reviewer probably knows, no process is perfect, but we do not think any errors here had a significant impact on the results.

32) Figure 14 needs to be more explained.
Response: A sentence was added in line 413-414.
Reach probability is the percentage of the falling rocks along a given trajectory that reach a specific point along the line of the trajectory.

33) You declare in the conclusion that "…was successfully used". How can you define the "successful" of the system and method? It is not clear and described in the paper. It is necessary to define the quality of final result.
Response: UAV-enabled reconnaissance assisted in 1) identifying the exact position of the detachment point, which was inaccessible, 2) identifying the rolling section and the discrete impact points along the bouncing section of the trajectory and 3) creating an accurate model for 3D rockfall analysis.

34) Line 477: you declare that the 3D analysis is more accurate than 2D. how you can define this level of accuracy? In the paper is not well described this aspect. You have to be more clear.

Response: The level of accuracy is qualitative and is based on comparing the actual trajectory with those produced by the 3D modeling. The 2D modeling trajectory could not match the characteristics (type of motion, impact points) of the actual trajectory. 3D modeling did much better.

35) Considering the results, it seems that it is not possible to define the correct position of the origin, even considering your expertize and your knowledge. It is not clear the real benefits of the model generated with UAV with respect the public model or a global DTM generated with RS.
Response: The position of the origin of the rock was clearly detected using the UAV, as it would be impossible to reach this point in the field due to the presence of dense vegetation and due to the inaccessible nature of the detachment location on the cliff. The impact points and rolling section of the path were also clearly visible.. We believe that the developed model is of very high resolution, of reasonably high accuracy and generated very effciently. We thus disagree with the reviewer's comment about the benefits of the model and find the reviewer's position biased.

36) References: check the references, because there are some incongruences (in some references pages are included in someone not, etc…)
Response: References were checked

UAV-based mapping, back analysis and trajectory modelling of a co-seismic rockfall in Lefkada Island, Greece

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Abstract

We present field evidence and a kinematic study of rock block motion mobilised in the Ponti area by a~~n~~ M_w 6.5 earthquake near the island of Lefkada on 17th November 2015. A detailed survey was conducted using an Unmanned Aerial Vehicle (UAV) with an ultra-high definition (UHD) camera, which produced a high-resolution orthophoto and a Digital ~~Elevation~~ Terrain Model (~~DEM~~DTM)~~ of the terrain~~. The sequence of impact marks from the rock trajectory on the ground surface was identified from the orthophoto and field verified. ~~Additionally, calculation of~~ E~~e~~arthquake characteristics ~~defined~~ were used to estimate the acceleration of the rock slope and the initial condition of the detached block. Using the impact points from the measured rockfall trajectory, an analytical reconstruction of the trajectory was ~~developed~~undertaken, which led to insights on the coefficients of restitution. The

measured trajectory was compared with modeled rockfall trajectories using recommended parameters. However, the actual trajectory could not be accurately predicted, revealing limitations of existing rockfall analysis software~~models~~ used in engineering practice.

Keywords

Rockfall, earthquake, ~~DSM~~DSM, DTM, modelling, restitution, UAV

1. Introduction

Active faulting, rock fracturing and high rates of seismicity contribute to ~~common~~ a high rockfall hazard~~s~~ in Greece. Rockfalls primarily damage roadways and houses (Saroglou, 2013) and are most often triggered by rainfall and, secondly, seismic loading. ~~Additionally~~ In~~in~~ recent years, some rockfalls have impacted archaeological sites (Marinos & Tsiambaos, 2002, Saroglou et al., 2012). The Ionian Islands, which include Lefkada Island, experience frequent M_w 5-6.5 earthquakes, as well as less frequent larger (up to 7.5) earthquakes. The historical seismological record for the island is particularly well constrained with reliable detailed information for at least 23 such earthquake events ~~since 1612~~ that induced ground failure since 1612~~s at the island of Lefkada~~. On average, Lefkada experiences a damaging earthquake every 18 years. In the recent past, a M_w 6.2 earthquake occurred on August 14 2003 offshore the NW coast of Lefkada, and caused landslides, rockslides and rockfalls along the western coast of the island (Karakostas et al. 2004, Papathanasiou et al., 2012). Significant damage was reported, particularly in the town of Lefkada, where a PGA of 0.42g was recorded.

On November 17th 2015, an M_w 6.5 earthquake ~~again~~ struck the island of Lefkada and triggered a number of landslides, rockfalls and some structural damage. The most affected area by large rockslides was the western coast of the island, especially along its central and south portion, which are popular summer tourist destinations

(Zekkos et al., 2017). The coseismic landslides completely covered the majority of the west coast beaches and damaged access roads.

On the southeast side of Lefkada, near the Gulf of Vassiliki, a seismically-triggered rockfall in Ponti village was responsible for one of two deaths caused by the earthquake (Figure 1). Of particular interest, is the very long travel path of the rock block, which was about 800 m in plan view from the point of detachment to the end of its path. Near the end of the rock fall path, the block impacted a family residence, penetrated two brick walls and killed a person in the house. The block exited through the back of the house and came to rest in the property’s backyard.

The Ponti village rockfall site is a characteristic ~~of earthquake induced rockfall and an~~ example of how seismically-induced rockfalls impact~~s~~ human activities. It also provides an opportunity to evaluate 2D and 3D rockfall analysis to predict details of the rockfall trajectory, based on ~~measured by~~ field evidence. In order to create a highly accurate model of the rockfall propagation in 2D and 3D space, the rock path and the impact points on the slope were~~as~~ identified by a field survey. The study was performed using an Unmanned Aerial Vehicle (UAV) with an ultra-high definition (UHD) camera, which produced a high-resolution orthophoto and a Digital ~~Elevation~~ Terrain Model (~~DEM~~DTM) of the ~~terrain~~slope. The orthophoto was used to identify the rolling section and the ~~bouncing~~ impact points of the rock along its trajectory, which were verified by field observation. The high-resolution ~~DSM~~ DTM made it possible to conduct kinematic~~al~~ rebound analysis and a 3D rockfall analysis.

2. Ponti rockfall - site conditions

The locations of the epicenters of the 2003 and 2015 events, as well as the location of the rockfall case study~~ site~~ are shown in Figure 1. The southwest coast of Lefkada is part of the Triassic to Eocene age Paxos zone and consists of limestones and dolomites that are covered by Neogene clastic sedimentary rocks, mostly sandstones and marls. Figure 1 also shows faults and high rockfall hazard areas as identified by Rondoyanni et al. (2007). The rockfall at Ponti is not located in an identified high rockfall hazard area. Based on measurements conducted at one location along the rockfall path using the Multichannel Analysis of Surface Waves method, the in-situ shear wave velocity of the top layer was estimated to be around 800 m/s, which is a high velocity and is consistent with the limestone rock ~~rock conditions expected~~ at the site.

The slope overhanging Ponti village (shown in Fig. 2) ~~is made of limestone and~~ has a maximum height of 600 m and an average slope angle of 35^0 to 40^0 ~~(Figure 2)~~. The geological formations at the Ponti rockfall site are limestones covered by moderately cemented talus materials. The thickness of the talus materials, when present, ranges between 0.5 and 4.0 ~~to 5.0~~ m. ~~A few~~Several detached ~~fallen~~ limestone blocks were identified on the scree slope, with volumes between 0.5 and 2 m^3. Based on the size distribution of these rocks on the slope, the average expected block volume would be in the order of 1 to 2 m^3.

The rockfall release area was at an elevation of 500 m, while the impacted house (shown in Figure 3) at an elevation of 130 m ~~(Figure 3)~~. The volume of the detached limestone block was approximately 2 m^3 and its dimensions equal to 1.4 m x 1.4 m x 1 m. There was no previously reported rockfall incident ~~reported for the specific slope~~at Ponti that impacted the road or a house.

3. UAV mapping

3.1. Introduction

A quadrotor UAV (Phantom 3 professional) was deployed to reach the uphill terrrain that was practically inaccessible. The UAV was equiped with an Ultra-high definition (UHD) 12 MP camera and had the capacity to collect 4K video. The sensor was a 1/2.3” CMOS (6.47x3.41mm) and the effective pixel resolution was 12.4 MP

(4096x2160 pixels). An immediate UAV data acquisition expedition was conducted 2 days after the earthquake. A second more detailed mapping UAV expedition with the objective to create a ~~DEM~~ DTM was conducted 5 months after the rockfall event.

The first objective of the UAV deployment was to find the inititiation point of the rock and then identify the rockfall path (shown in Figure 2). A particular focus on that part of the task was the identification of rolling and bouncing sections of the rockfall path. In addition, ~~in order~~ to generate a high-resolution orthophoto of the rockfall trajectory, aerial video imagery was collected, and the resulting digital surface model (DSM) and digital terrain model (DTM) was used to perform rockfall analysis.

The aerial survey was conducted by capturing 4K video along a gridded pattern covering the area of interest, at a mean flight altitude of 115m above the terrain resulting image frames of a mean ground sampling distance (GSD) of 4.97cm/pix.The overlap between ~~pictures~~image frames was minimum frontal 80%, side 65% and a total of 714 camera stations (video frames extracted) were included as shown in Figure 4.

The Structure-from-Motion (SfM) methodology was implemented to create a 3D point cloud of the terrain and develop a 3D model. The methodology is based on identifying matching features in multiple images, and thus imagery overlap of at least 70% is required. Compared to classic photogrametry methodologies, where the location of the observing point is well established, SfM tracks specific discernible features in multiple images, and through non-linear least-squares minimisation (Westoby et al., 2012), iteratively estimates both camera positions, as well as object coordinates in an arbitrary 3D coordinate system. In this process, sparse bundle adjustment (Snavely et al., 2008) is implemented to transform measured image coordinates to three dimensional points of the area of interest. The outcome of this process is a sparse 3D point cloud in the same local 3D coordinate system (Micheletti et al., 2015). Subsequently, through an incremental 3D scene reconstruction, the 3D point cloud is densified. Paired with GPS measurements of a number of control points (for this site, 10 fast-static GPS points were collected) at the top, middle and bottom of the surveyed area, the 3D point cloud is georeferenced to a specific coordinate system and through post-processing a digital surface model (DSM), ~~or~~ a digital terrain model (DTM) and orthophotos are created. The SfM methodology was implemented in this study using the Agisoft Photoscan software. Precalibrated camera parameters by the SfM software (Photoscan) were introduced and then optimized during the matching process and the initialization of Ground Control Points.

In addition, the accuracy of the model has been examined by using portions of the ground control points and developing ~~DEM~~ DTM of differencing between different models, an investigation that is described ~~in our paper~~ by Manousakis et al. (2016). Finally, a comparison was made of the ~~DEM~~ DTM developed by the UAV against the satellite-based ~~DEM~~ DTM ~~that is part of the~~used for the Greek cadastre. The two surfaces were found to be very similar, as discussed subsequently.

~~The overlap between pictures was minimum frontal 80%, side 65% and a total of 714 camera station (video frames extracted) were included as shown in Figure 4.~~

3.2. High-resolution Orthophoto

A 5cm pixel size orthophoto was generated based on the methodology outlined earlier. As shown in Figure 5, the rolling section and the bouncing locations of the rock block throughout its course were identified. The rolling section was easily discerned as a continuous and largely linear mark left in the ~~densely~~ vegetated terrain~~ that was indicative of the damage caused~~. Impact points that are part of the bouncing section of the rock, were identified as circular to ellipsoidal bare earth craters with no disturbance in between. The last bouncing point before impacting the house is clearly identified on the paved road. The plan view ortho-imagery, along with the original footage of the video collected was crucial to the qualitative identification of these features. The alternative, i.e., land-based, conventional field reconnaissance was physically impossible to perform throughout the ~~in the densely~~ vegetated and steep terrain.

3.3. Digital Surface Model and Digital Terrain Model

A profile section and a 10 cm Digital Surface Model (DSM) ~~paired with the plan view orthophoto~~ were then~~first~~ developed (Manousakis et al., 2016) allowing the identification of ~~terrain~~ features such as structures, slope benches or high trees, which could affect the rock's path downhill. ~~However~~Subsequently, this resolution of the DSM proved to be not only unnecessarily high and thus difficult to manipulate in subsequent rockfall analyses, but also caused~~resulted in~~ numerical instabilities in ~~during~~ the rockfall analyses. Therefore, a downscaled 2 m DT~~S~~M was produced for the rockfall analysis as described next. First, ~~. This was implemented through~~ an aggregate generalization scheme where each output cell is assigned the minimum elevation of the input cells that are encompassed by that cell. In addition, noise filtering and smoothing processing were implemented to reduce the effect of ~~construction elements and~~ vegetation in the final rasterized model. Note that this resolution is still higher than the resolution of ~~DSM~~ DTM that are often used in rockfall analyses.

To create the DTM, a~~A~~lgorithms for vegetation removal were executed using~~within~~ Whitebox GAT Geospatial Analysis Tools platform (Lindsay, 2016) . ~~GCPs were used for both georeferencing and solving camera's internal and external parameters~~. The process involves Point Cloud neighborhood examination and DEM smoothing algorithms. Firstly, a bare-Earth digital elevation model (DEM) was interpolated from the input point cloud LAS file, by specifying the grid resolution (2m) and the inter-point slope threshold. The algorithm distinguished ground points from non-ground points based on the inter-point slope threshold. Thus, ~~T~~the interpolation area was divided into ~~grid~~ lattice cells, corresponding to the ~~cells~~ grid of the output DEM. All of the point cloud points within the circle ~~encompassing~~ containing each grid cell were then examined as a neighborhood. ~~All~~ Those points within a neighborhood that have an inter-point slope with any other point and are also situated above the corresponding point, are ~~considered to be a~~ attributed as non-ground points. An appropriate value for the inter-point slope threshold parameter depends on the steepness of the terrain, but generally values of 15-35 degrees produce~~D~~ satisfactory results. The elevation assigned to the grid cell was then the nearest ground point elevation (Lindsay, 2016.).

Further processing of the interpolated bare-earth DEM was ~~introduced~~ executed to improve vegetation and structures removal results by applying a second algorithm to point cloud DEMs, which frequently contain numerous off-terrain objects such as buildings, trees and other vegetation, cars, fences and other anthropogenic objects. The algorithm works by ~~finding~~ locating and removing steep-sided peaks within the DEM. All peaks within a sub-grid, with a dimension of the user-specified Maximum Off-Terrain Object (OTO) Size, in pixels, were identified and removed. Each of the edge cells of the peaks were then ~~examined~~ queried to ~~see~~ check if they had a slope that is less than the user-specified Minimum OTO Edge Slope and a back-filling procedure was used. This ensured that ~~OTOs are distinguished from~~ natural topographic features such as hills are not recognized and confused as Off-Terrain features (Whitebox GAT help topics).

The final DTM model had a t~~T~~otal RMS error after filtering for 6 GCPs was 0.07m, while total RMS error for 4 Check Points was 0.20m. When compared to a 5m DEM from Greek National Cadastre with a geometric accuracy of RMSEz ≤ 2,00m and absolute accuracy ≤ 3,92m for a confidence level of 95%, a mean difference of 0.77 m and a standard deviation of 1.25 m is observed, which is well into the range of uncertainty of the cadastre model itself.

4. Earthquake characteristics – Initial conditions

4.1. Seismic acceleration

The epicenter of the earthquake according to the National Observatory of Athens, Institute of Geodynamics (NOA) is located onshore near the west coast of Lefkada. The causative fault is estimated to be a near-vertical strike-slip fault with dextral sense of motion (Ganas et al., 2015, 2016). Based on the focal mechanism study of the earthquake, it was determined that the earthquake was related to the right lateral Kefalonia-Lefkada Transform Fault (KLTF), which runs nearly parallel to the west coasts of both Lefkada and Kefalonia island, in two segments (Papazachos et al. 1998, Rondoyanni et al. 2012).

A strong motion station recorded the ground motions in the village of Vasiliki located at a distance of 2.5 km from the Ponti rockfall site. The ground motion characteristics of the recording are summarized in Table 1 and are presented in Figure 6~~, according to an ITSAK preliminary report~~ (ITSAK, 2016).

4.2. Topography effect

Peak ground acceleration (PGA) along the rock slope is estimated from the PGA of the ~~the intensity of~~ base ~~shaking~~ (PGA_b) 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 E-W component of acceleration was considered for the determination of the initial velocity. The peak ground acceleration ~~(PGA)~~ on the slope face (PGA_{sf}) was considered equal to the acceleration at the slope crest (PGA_{cr}). The acceleration at the base was equal to 0.32g and thus at the crest PGA_{cr}= 1.5 PGA_b was equal to 0.48g.

4.3. Initial velocity of rock block

The initial horizontal velocity of the block, at the time of detachment, was calculated considering equilibrium of the produced work and the kinetic energy according to equation 1.

$$v_x = \sqrt{2 \times PGA_{sf} \times s} \quad (1),$$

where PGA_{sf} is the acceleration on the slope at the location of detachment and *s* the initial displacement of the block in order to initiate its downslope movement.

The initial horizontal velocity was calculated equal to 0.67 m/s, considering a displacement in the order of s = 0.05 m. The vertical component of the initial velocity is assumed to be zero.

5. Trajectory analysis

In order to estimate the possible rock paths and design remedial measures, simulation programs based on lumped-mass analysis models are commonly used in engineering ~~design~~ practice. The trajectory of a block is modelled as a combination of four motion types; free falling, bouncing, rolling and sliding (Descoeudres and Zimmermann, 1987). Usage of the lump-mass model has some key limitations; the block is described as rigid and dimensionless with an idealized shape (sphere); therefore the model neglects the block's actual shape and configuration at impact, even though ~~it is evident that they~~ both affect the resulting motion.

5.1. Modelling the response to an impact

The most critical input parameters are the coefficients of restitution (COR), which control the bouncing of the block. In general, the coefficient of restitution (COR) is defined as the decimal fractional value representing the ratio of velocities (or impulses or energies; depending on the definition used) before and after an impact of two colliding entities (or a body and a rigid surface). When in contact with the slope, the block's magnitude of velocity changes according to the COR value. Hence, COR is assumed to be an overall value that takes into account all the characteristics of the impact; including deformation, sliding upon contact point, transformation of rotational moments into translational and vice versa (Giani, 1992).

The most widely used definitions originate from the theory of inelastic collision as described by Newtonian mechanics. For an object impacting a rocky slope (Figure 7), which is considered as a steadfast object, the kinematic COR (v_{COR}) is defined according to Eq. 2.

$$v_{COR} = \frac{v_r}{v_i} \quad (2)$$

where v is the velocity magnitude and the subscripts i and r denote the trajectory stage; incident (before impact) and rebound (after impact) respectively.

Two different mechanisms participate in the energy dissipation process; energy loss normal to the slope is attributed to the deformation of the colliding entities, and in the tangential direction is due to friction between them. Therefore kinematic COR has been analyzed to the normal and tangential component with respect to the slope surface, defining the normal (n_{COR}) and the tangential (t_{COR}) coefficient of restitution (Eq. 3 and 4 respectively).

$$n_{COR} = \frac{v_{n,r}}{v_{n,i}} \quad (3)$$

and

$$t_{COR} = \frac{v_{t,r}}{v_{t,i}} \quad (4)$$

where the first subscript, n or t denotes the normal or the tangential components of the velocity respectively.

Normal and tangential COR have prevailed in natural hazard mitigation design via computer simulation due to their simplicity. Values for the coefficients of restitution are acquired from values recommended in the literature (e.g., Azzoni et al. 1995;

Heidenreich 2004; Richards et al. 2001, RocScience, 2004). Th~~e~~ese values are mainly related to the surface material type and originate from experience, experimental studies or back analysis of previous rockfall events. This erroneously implies that coefficients of restitution are material ~~constants~~properties. However, COR values depend on several parameters that cannot be easily assessed. Moreover, ~~the~~ values suggested in the literature~~by different authors~~ vary considerably and are sometimes contradictory.

5.2. Rockfall path characteristics

23 impact points were identified on the slope surface (Figure 8). Their coordinates are presented in Table 2, along block's path starting from the detachment point (where x=0). No trees were observed along the block's path.

The apparent dip of the slope at impact positions was measured from the DTM ~~topographic map~~; on each impact point a line was set with a length twice the block's mean dimension, oriented according to preceding trajectory direction. Moreover, the impact point was expanded on the ~~topographic map~~DTM to a rectangular plane with a side twice ~~as much~~ the mean dimension of the block (Figure 9). This plane was then oriented so that one side coincides with the strike direction and its~~'~~ vertical side towards~~ to~~ the dip direction. Thus, direction difference, $\Delta\varphi$, was measured by ~~the~~ strike direction and the preceding path and deviation, e, was measured as the angle between pre- and post- impact planes (Asteriou & Tsiambaos, 2016).

Having a detailed field survey of the trajectory path, a back analysis according to the fundamental kinematic principles was performed with the intent~~in order~~ to back-calculate the actual COR values.

5.3. Kinematic analysis and assumptions

The 23 impact points identified on the slope comprise a rockfall path of 22 parabolic segments. The vertical and horizontal length of each segment is acquired by subtracting consecutive points. Since no external forces act while the block is ~~in the~~ mid-air, each segment lays on a vertical plane and is described by the general equation of motion as:

$$y = x \tan \vartheta - \frac{gx^2}{2v_i^2 \cos^2 \vartheta} \qquad (5)$$

where: θ the launch angle from the horizon and v the launch (initial) velocity (Figure 10).

Since no evidence can be collected regarding launch angle and velocity, innumerable parabolas satisfy Eq. 5. However, θ is bound between –β and 90°, so in order to acquire realistic values for the initial velocity, its sensitivity for that given range was ~~addressed~~ investtigated~~(Figure 11)~~.

For the case presented in Fig. 11 (the first parabolic segment) it is shown~~een~~ that for the majority of the release angles, initial velocity variation is low and ranges between 7.2 and 12 ms^{-1}. Additionally, the relationship between release angle and initial velocity is expressed by a curvilinear function, with~~thus~~ a minimum initial velocity value along with ~~its~~an associated release angle (denoted hereafter as θ_{cr})~~ can be easily acquired~~.

Given the minimum initial velocity and the critical release angle for each parabolic segment, the impact velocity and impact angle can be calculated. Subsequently~~Afterwards,~~, normal and tangential velocity components according to the apparent dip of the impact area, are calculated in order to evaluate COR values. Results are summarized in Table 3.

5.4. Coefficients of restitution

It is observed that v_{cor} (Table 3) is ~~slightly~~ greater than one in 5 out of 22 impacts. According to Eq. 3, this can only be achieved when impact velocity is less than rebound velocity. However, this indicates that energy was added to the block~~-~~ upon impact~~during contact~~, which is not possible according to the law of conservation of energy. Thus, impact velocity should be greater, which is possible if the launch velocity of the previous impact was higher~~more~~ than the assumed minimum.

~~Omitting the impacts with~~For the cases where V_{cor}<~~>~~1, it is observed that kinematic COR ranges between 0.55 and 1.0 and presents smaller variation compared to normal or tangential coefficient of restitution, similar to what was previously reported in relevant literature (i.e. Asteriou et al, 2012; Asteriou & Tsiambaos, 2016).

The ~~considerably~~ wide scatter of normal COR implies that the restitution coefficient cannot be a material constant. Yet, in most relevant software, normal COR is defined solely by the slope material. Moreover, normal COR values higher than one were calculated in 11 out of the 15 remaining impacts. Normal COR higher than one have been observed in both experimental (e.g. Spadari et al., 2011; Buzzi et al., 2012; Asteriou et al., 2012) and back-analysis studies (e.g. Paronuzzi, 2009) and are related to irregular block shape and slope roughness, as well as to shallow impact angle and angular motion. A more detailed presentation of the reasons why normal COR exceeds unity can be found in Ferrari et al. (2013). However, in rockfall~~relevant~~ software used in engineering practice, normal COR values are bounded between 0 and 1.

~~Moreover, it is observed~~As shown in Figure 12~~ that~~, normal COR increases as the impact angle reduces, similarly to previous observations by Giacomini et al. (2012), Asteriou et al. (2012) and Wyllie (2014). The correlation proposed by Wyllie (2014) is also plotted in Figure 13 and seems to describe consistently, but on the unconservative side, the trend and the values acquired by the aforementioned analysis and assumptions.

6. Rockfall modelling

6.1. 2-D analyses

~~Initially, a~~A deterministic 2D rockfall analysis was first performed using Rocfall software (RocScience, 2004). According to Asteriou & Tsiambaos (2016) the most important influence is posed by the impact configuration, which is influenced by slope roughness and block shape. In this study, roughness has been fully taken into account (considering the block's dimension scale) by the high resolution of ~~accurate~~ the cross-section used in the analyses (more than 1500 x-y points were used – approximately 2 points per meter). Based on our experience, this resolution~~accuracy~~ is significantly higher compared to other rockfall studies~~similar research projects~~. Moreover~~, with the available data and the performed lump-mass model analysis, ~~, it was not possible to simulate block shape effect, nor the configuration of the block at impact, using lumped-mass model analysis.

Considering an initial velocity of 0.67 m/sec, according to the numerical analyses, the falling rock primarily rolls on the slope and stops much earlier than its actual (field-verified) run out distance, approximately 400 m downslope from its initiation~~starting~~ point (Fig. 8; case 1). The restitution coefficients were n_{COR}=0.35, t_{COR}=0.85, and were selected based on ~~which represent properties of bedrock outcrops according to~~ the suggested values for bedrock outrcrops provided in the software documentation ~~of the software~~.

Note that for this analysis, t~~T~~he friction angle was set to zero. A standard deviation for the coefficients of restitution, the friction angle and roughness of the material on the slope was not used~~, as the~~ for this deterministic analysis~~ was deterministic~~. For~~If~~ ~~the~~ friction equal to~~angle is set to φ=~~ 32^0 (as suggested by the software documentation), the rock travels downslope only 50 m.

Additional~~ separate~~ analysis was also performed, with lower coefficients of restitution that are representative of ~~, resembling that of~~the talus material on the slope (n_{COR}=0.32, t_{COR}=0.82, φ=30^0) per ~~as proposed by the suggested values provided in~~ the software documentation~~ of the software~~. In this case, the rock block rolled only a few meters downslope. Therefore, it is evident that the actual rock trajectory cannot be simulated.

In order to more closely simulate the actual trajectory~~ as much as possible~~, various combinations of restitution coefficients and friction angle were considered. The closest match occurred for n_{COR}=0.60 and t_{COR}=0.85, while the friction angle was set to zero and no velocity scaling was applied. For these input parameters~~Only in such an analysis~~, the rock block reaches the house~~;~~ with a velocity of ~~equal to v=~~18 m/s approximately (Fig. 8; case 2). ~~According to the suggested values, t~~These values for the restitution coefficients correspond to a bedrock material (limestone).

In this case, the modelled trajectory is significantly different from the actual one. The main difference is that the block ~~is~~ rolls~~ing~~ up to 200 m downslope while the actual rolling section is 400 m (as shown in Figure 8). Furthermore the impacts on the ground in the bouncing section of the trajectory are considerably fewer~~different~~ in number (14 versus 23) and in different locations compared to~~ from~~ the actual ones. Finally, the bounce height of some impacts seems unrealistically high. For example, the 2nd bounce has~~presents~~ a jump height (f) of ~17.5m over a length (s) of ~50m, resulting to a f/s ratio of ~1/3, when the characteristic f/s ratios for high, normal and shallow jumps is 1/6, 1/8 and 1/12 respectively, as suugested by Volkwein et al. (2011).

6.2. 3-D rockfall analysis

The rockfall trajectory model Rockyfor3D (Dorren, 2012) has also been used in order to validate the encountered trajectory and assess~~determine~~ the ~~reach~~ probability that~~of~~ the falling rock (from the specific source area) ~~on~~ reaches the impacted house.

The 3D analysis was based on the down-scaled 2 m resolution Digital ~~Elevation~~ Terrain Model (~~DEM~~DTM) that was generated from the 10 cm DSM. ~~The terrain features such as low vegetation (e.g. bushes) and the trees were removed from the~~

~~DEM as they affected the rock's path downhill.~~ The following raster maps were developed for the 3D analysis: a) rock density of rockfall source, b) height, width, length and shape of block, c) slope surface roughness and d) soil type on the slope, which is directly linked with the normal coefficient of restitution, n_{COR}.

The slope roughness was modeled using the mean obstacle height (MOH), which is the typical height of an obstacle that the falling block encounters on the slope at a ~~possibility percentage~~probability of 70%, 20% and 10% of the trajectories (according to the suggested procedure in Rockyfor3D). No vegetation was considered in the analysis, which favours a longer trajectory. The parameters considered in the 3D analysis for the different formations are summarised in Table 4. The spatial occurrence of each soil type is shown in Figure 13 and the assigned values of n_{COR} are according to the Rockyfor3D manual. The values for soil type 4.1 in Figure 13 are slightly different from those of soil type 4 (proposed in the manual), denoting talus with a larger percentage of fallen boulders. The block dimensions were considered equal to 2 m^3 and the shape of the boulder was rectangle. In order to simulate the initial velocity of the falling rock due to the earthquake, an additional initial fall height is considered in the analysis, which for this case was set equal to 0.5 m.

The energy line angles were recalculated from the simulated trajectories and it was determined that the energy line angle with highest frequency (39%) was $30\text{-}31^0$. Based on the 3D analysis no rock blocks would impact the house, although the rock paths are closer to the actual trajectories compared to RocFall software. The reach probability of the falling rocks, initiating from the source point, is shown in Figure 14. Reach probability is the percentage of the falling rocks in relation to the total number of falling rocks that reach a specific point along the line of the trajectory.

6.3. Lateral dispersion & Deviation

Lateral dispersion is defined as the ratio between the distance separating the two extreme fall paths (as seen looking at the face of the slope) and the length of the slope (Azzoni and de Freitas 1995). According to Crosta and Agliardi (2004) the factors that control lateral dispersion are (a) ~~classified in three groups:~~ macro-topography factors, factors related to the overall slope geometry; (b) micro-topography factors controlled by the slope local roughness; and (c) dynamic factors, associated with the interaction between slope features and block dynamics during bouncing and rolling. Based on ~~Assessing the results of~~ an experimental investigation, Azzoni and de Freitas (1995) ~~commented~~noted that the dispersion is generally in the range of 10% to 20%, regardless of the length of the slope and that steeper slopes ~~present~~ exhibit smaller dispersion. Agliardi and Crosta (2003) calculated lateral dispersion to be up to 34%, using~~via~~ high-resolution numerical models on natural rough and geometrically complex slopes.

Lateral dispersion cannot be defined from the actual rockfall event in Ponti since only one path is available. Using the simulated trajectories from RockyFor3D, which are in the 3d space (Figure 15), a lateral dispersion of approximately 60% is shown in the middle of the distance between detachment point and the house. This is significantly higher dispersion than ~~compared to~~ the findings of Azzoni and de Freitas (1995) and Agliardi and Crosta (2003). ~~Moreover, based on the actual event and intuition, t~~The lateral dispersion computed by RockyFor3D is extremely pronounced and most likely due to the topography effect of the area of detachment. Specifically, the origin of the rock block is located practically on the ridgeline, facilitating the deviation of the rock fall trajectory from the slope line. ~~Examining Figure 15, it is notable that the rock paths are severely affected by topography. Therefore, assessing lateral dispersion seems to be a case specific task.~~

Asteriou & Tsiambaos (2016) defined deviation (e) as the dihedral angle between the pre- and post-impact planes that contain the trajectory. They found that deviation is controlled by the direction difference $\Delta\varphi$, the slope inclination and the shape of the block. For a parallel impact (i.e. $\Delta\varphi=0^0$) a spherical block presents significantly less deviation compared to a cubical. Additionally, deviation is equally distributed along the post-impact direction and reduces as the slope's inclination increases. On oblique impacts, the block's direction after impact changes towards the slope aspect~~ of slope~~ and as $\Delta\varphi$ increases, this trend becomes more pronounced.

Figure 16 illustrates~~pres~~ the relationship of ~~ents~~ deviation with~~as a function of~~ direction difference. It is noted that for parallel impacts ($\Delta\varphi=0^0$), deviation is uniformly ~~also equally~~ distributed along the post-impact direction. As direction difference increases, deviation becomes positive, which means that the change of direction is following the direction of slope's aspect. These findings are ~~in line~~consistent with trends described by Asteriou & Tsiambaos (2016), but the deviation of the actual trajectory is significantly lower. This can be attributed to the different conditions (i.e. block shape, slope material, slope roughness, incident velocity and angle, and scale) between the experimental program conducted by Asteriou & Tsiambaos (2016) and the Ponti rockfall event.

7. ~~Discussion - c~~Conclusions

UAV-enabled reconnaissance was successfully used for the identification of the origin of the detached rock, the rockfall trajectory and the impact points on the slope, and especially discerning the rolling and bouncing sections of ~~emphasizing on the motion types of~~ the trajectory~~ (rolling and bouncing sections)~~. A UAV with an ultra-high definition (UHD) camera was deployed to reach the inaccessible, steep and partly vegetated uphill terrain. A high-resolution orthophoto of the rockfall trajectory, a ~~and a~~ 10 cm DSM and a 2 m DTM were generated~~as prepared~~ and~~, which~~ formed the basis for an analytical 2D kinematic analysis and a comparison with the outcomes of 2D and 3D rockfall analysis software.

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

~~estimation of the~~ initial velocity of the blocks plays a significant role in the accurate re-production of the rockfall trajectory.

Based on the ~~analytical~~ computational analysis performed, it was found that the coefficients of restitution cannot be directly connected to the material type, nor can be considered material constants. The impact angle seems to influence the ~~pose a consistent effect on~~ normal COR, which has been also observed ~~also~~ in other recent ~~relevant~~ studies, but has not been incorporated yet on analysis models.

It was proven impossible to replicate the actual trajectory of the rock fall by performing a 2D rockfall analysis with the recommended set of parameters indicating ~~recommended by the developers revealing some~~ limitations in the present formulations. In an attempt to match the actual rock path to the analysis output, the friction angle of the limestone slope was considered equal to zero. However, the falling rock still rolled on the slope and stopped much earlier than its actual runout distance while the impacts on the ground in the bouncing section of the trajectory were considerably different in number and in location compared to the actual ones.

Using the 3D analysis software~~,~~ and recommended input parameters, ~~some~~ rock trajectories better approximated the actual trajectory ~~using the suggested values by the software developers,~~ indicating that the 3D analysis can be more accurate than the 2D analysis.

Based on the aforementioned analyses it becomes evident that engineering judgement and experience must accompany the usage of commercial rockfall software in order to acquire realistic paths. One should never blindly use the recommended~~suggested~~ set of parameters since field performance can differ significantly, as demonstrated by this case study.

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TABLES

Table 1. Accelerometer recordings

Component	Acceleration (cm/sec^2)	Velocity (cm/sec)	Displacement (cm)
NS-comp	363	59.3	21.27
EW-comp	327	34.1	14.01
Z-comp	256	17.7	6.56

Table 2. Impact points characteristics

Impact point	X (m)	Y (m)	app_dip (^{0})	$\Delta\varphi$ (^{0})	e (^{0})
1	287.63	338	39.0	0	0
2	298.38	329.68	16.3	33	0
3	305.48	324.5	27.9	27	-1
4	321.54	314.83	41.0	11.6	0.5
5	365.34	287.6	30.4	11.9	0.3
6	373.32	284.85	39.7	10.6	1.8
7	425.1	261.64	14.7	6.6	-1.3
8	464.43	251.13	18.4	33.3	0.8
9	472.06	248.81	14.0	19.1	2.3
10	495.29	243.81	7.5	52.3	0.9
11	515.31	240.8	7.9	51	0.6
12	535.56	238.31	9.1	46.7	3
13	562.11	232.22	8.7	47.3	2.1
14	605.51	211.12	16.9	25.6	-1.7
15	619.1	204.48	27.1	4.6	-3
16	639.13	196.96	21.2	8	4.7
17	662.41	184	23.3	28.5	5.2
18	688.4	169.3	27.4	0.3	-2.5
19	712.23	157.67	25.4	0.5	0.1
20	745.28	143.16	21.9	0.5	-0.1
21	762.9	137.01	22.0	0.7	2
22	789.23	125.98	21.6	1.4	-0.8
23	801.53	132.75	8.4	0.2	0.1

Table 3. Parabolic paths characteristics for the minimum release velocity

Segment	Δx(m)	Δy (m)	θ_{cr} (^{0})	$v_{r,min}$	v_{impact}	a_i	v_{COR}	n_{COR}	t_{COR}
1-2	10.75	-8.33	26.8	7.19	13.19	44.5	0.55	0.71	0.31
2-3	7.1	-5.18	25.7	5.95	9.51	27.8	0.63	0.90	0.53
3-4	16.07	-9.66	31.5	9.45	12.68	9.6	0.75	3.86	0.38
4-5	43.79	-27.23	27.7	15.46	23.13	23.3	0.67	1.57	0.26
5-6	7.98	-2.75	35.7	7.47	10.49	14.9	0.71	2.52	0.30
6-7	51.78	-23.21	34.8	18.15	21.61	31.7	0.84	1.54	0.26
7-8	39.33	-10.5	35.9	17.23	24.01	36.1	0.72	0.94	0.56
8-9	7.63	-2.32	35.9	7.45	10.54	41.1	0.71	0.87	0.55
9-10	23.23	-5	40.5	13.58	13.12	30.7	1.03	1.65	0.70
10-11	20.02	-3.01	41.1	13.00	11.57	24.2	1.12	2.06	0.82
11-12	20.25	-2.49	40.9	13.26	11.22	17.6	1.18	2.94	0.82
12-13	26.55	-6.1	38.0	14.40	14.25	28.5	1.01	1.55	0.78
13-14	43.41	-21.1	32.9	16.33	25.70	40.9	0.64	0.64	0.63
14-15	13.59	-6.64	30.7	9.13	12.81	25.1	0.71	1.24	0.53
15-16	20.03	-7.52	33.8	11.67	15.42	29.8	0.76	1.33	0.42
16-17	23.27	-12.96	31.9	11.59	15.89	28.5	0.73	1.22	0.50
17-18	25.99	-14.7	29.9	12.20	20.11	30.9	0.61	0.95	0.42
18-19	23.83	-11.63	32.2	12.08	17.10	27.9	0.71	1.30	0.40
19-20	33.05	-14.51	33.6	14.55	20.62	32.1	0.71	1.14	0.43
20-21	17.62	-6.15	34.5	11.08	11.99	18.4	0.92	2.44	0.54
21-22	26.33	-11.03	35.1	13.11	16.33	27.3	0.80	1.47	0.49
22-23	12.3	6.77	58.1	14.30	13.97	48.9	1.02	1.34	0.28

Table 4. Restitution parameters for Rockyfor3D

Geological formation/ other	Mean n_{COR}	MOH			Soil type (Rockyfor3D)
		rg70	rg20	rg10	
Scree (Ø < ~10 cm), or medium compact soil with small rock fragments	0.33	0.03	0.05	0.05	3
Talus slope (Ø > ~10 cm), or compact soil with large rock fragments	0.38	0.05	0.1	0.2	4
Talus with fallen boulders	0.42	0.15	0.15	0.2	4.1
Bedrock with thin weathered material	0.43	0	0.05	0.1	5
Asphalt road	0.35	0	0	0	7

FIGURES

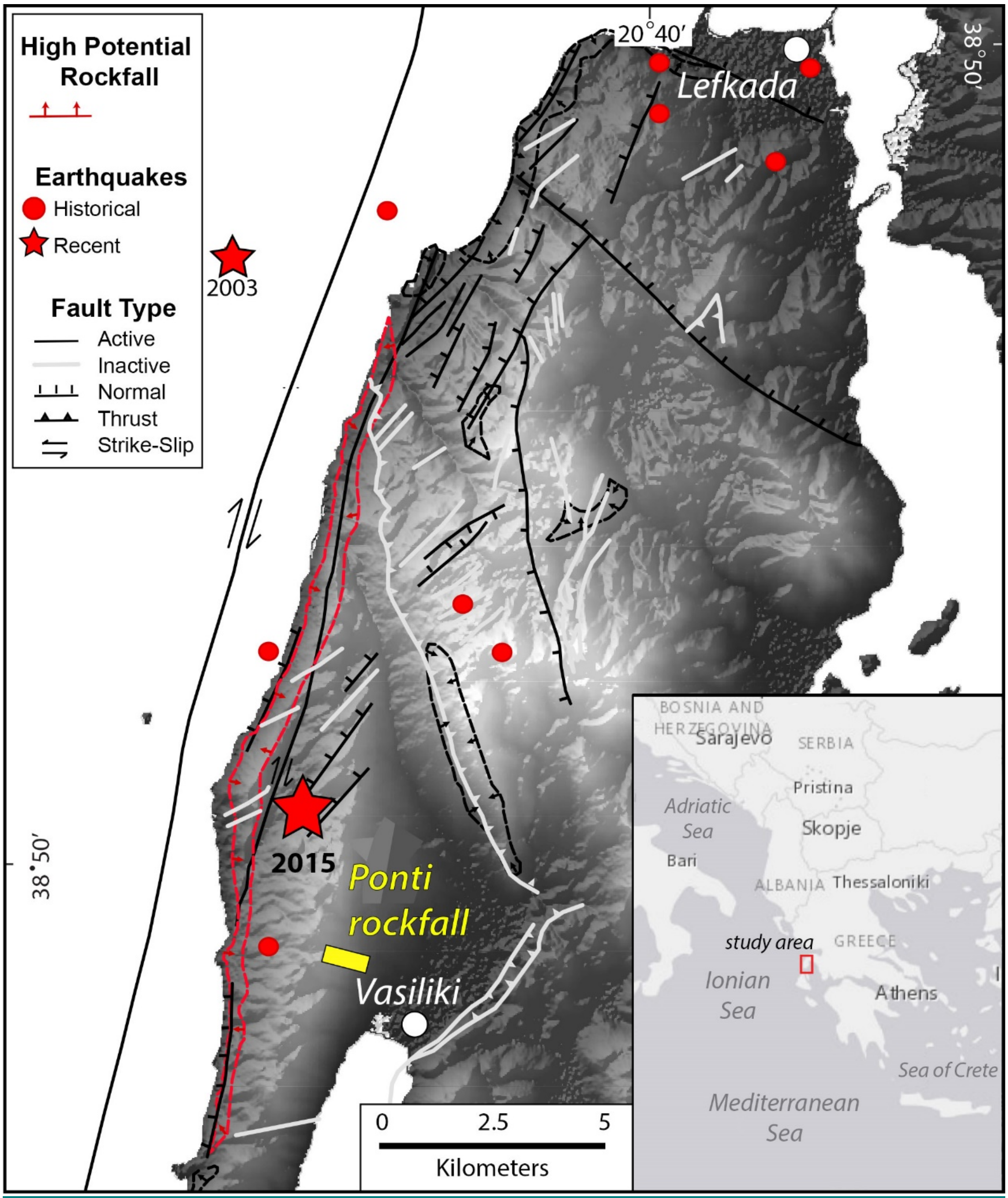


Figure 1. Map of Lefkada Island, Greece with location of study site (Ponti) and epicenters of recent earthquakes (stars) in 2003 (M_w6.2) and 2015 (M_w6.5), as well as historical ones (circles) Map also shows faults and high potential rockfall areas as identified by Rondoyanni et al. (2007).

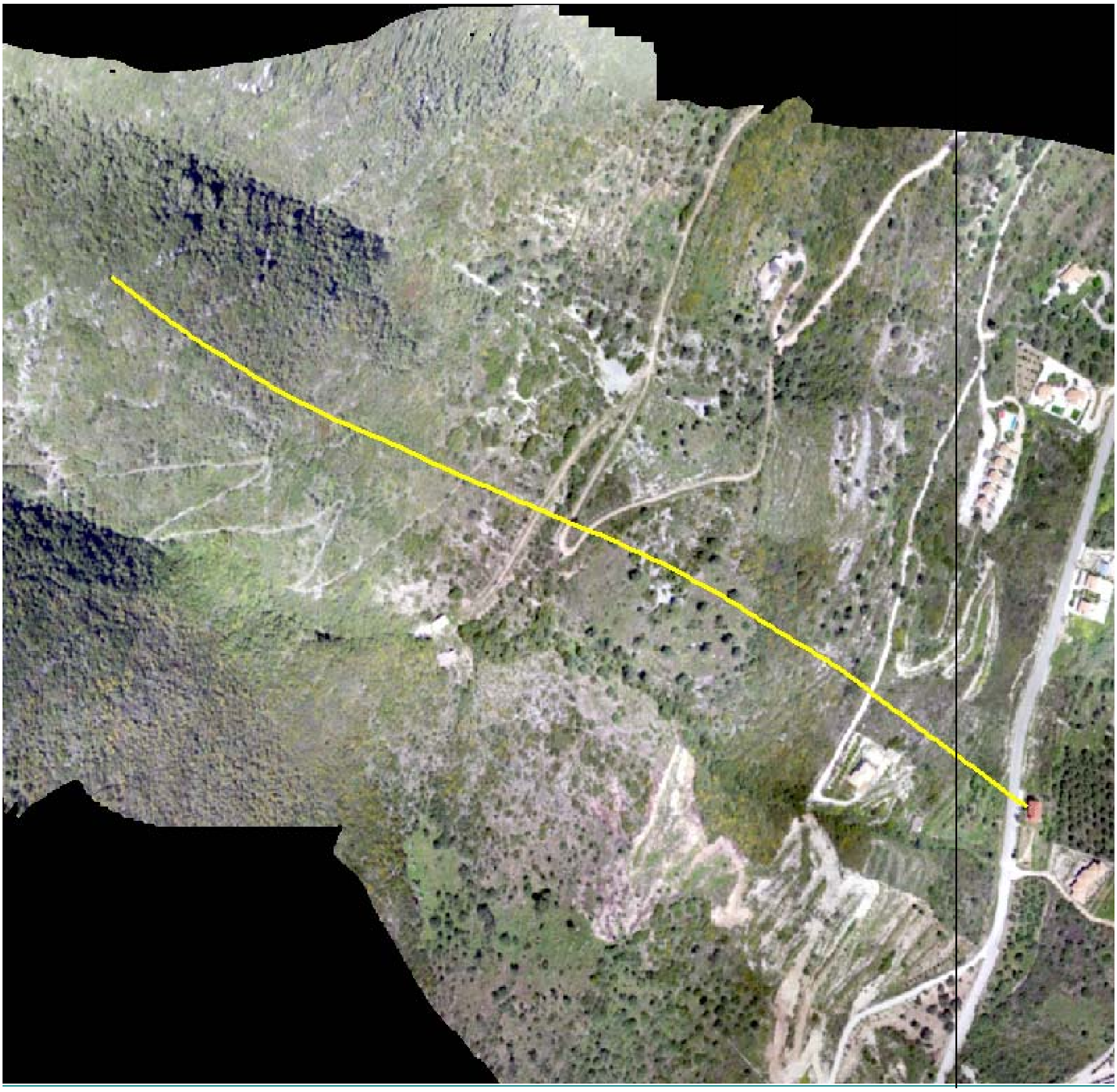


Figure 2. Orthophoto of case study. The total length of the trajectory shown with a yellow line, is 800 m.

Figure 3. Impact of rock on house in Ponti, Lefkada, Greece.

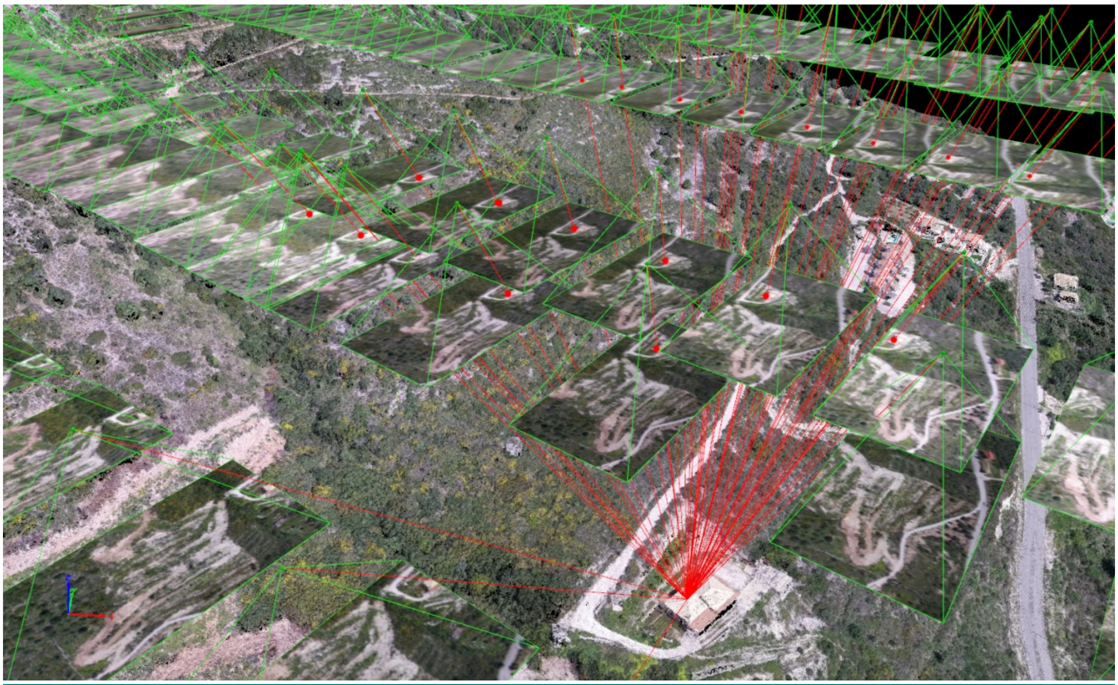
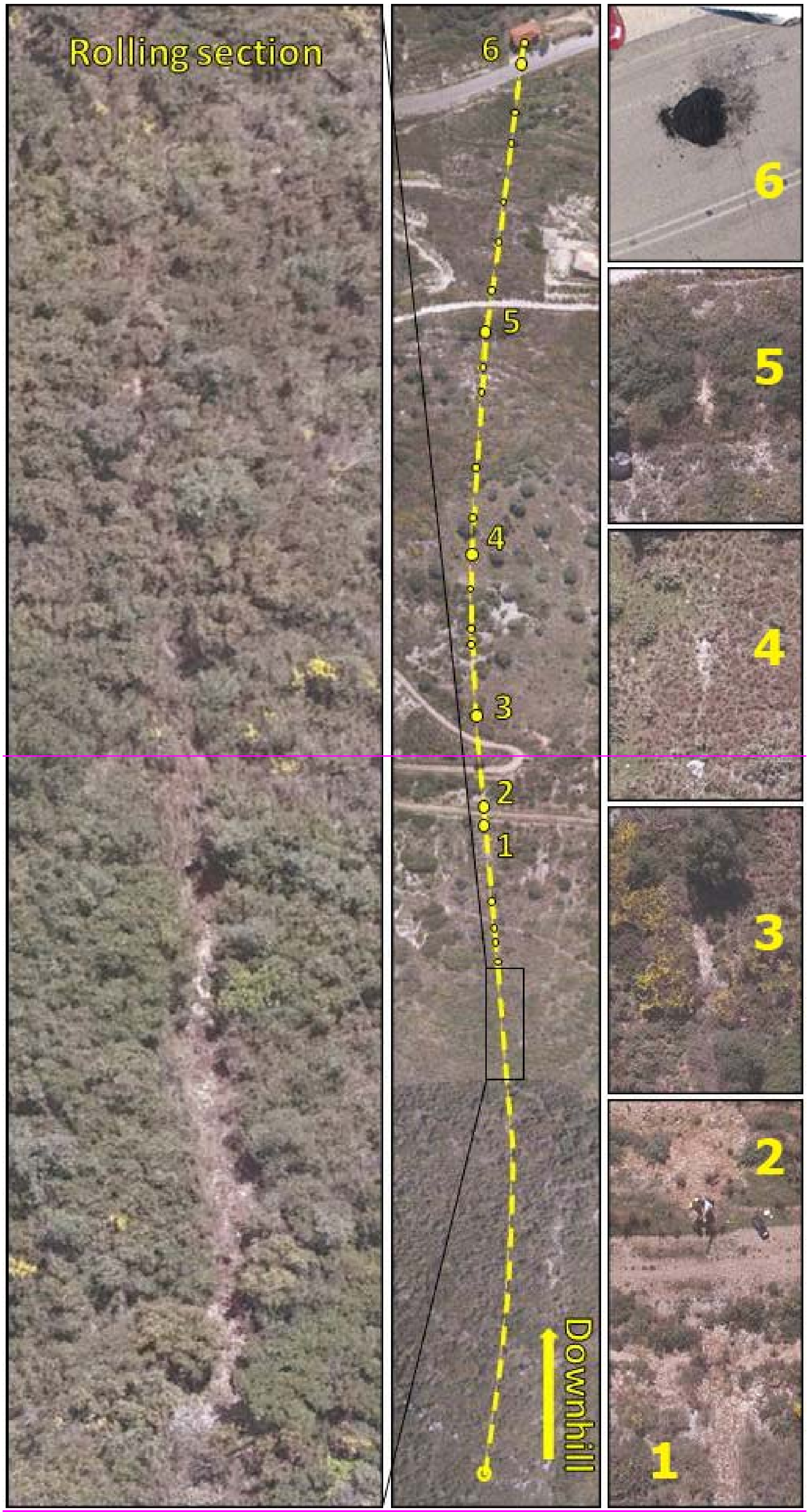


Figure 4. Schematic illustrating the overlap between pictures in the study site using SfM methodology.



Rolling section
6
5
4
3
2
1
Downhill

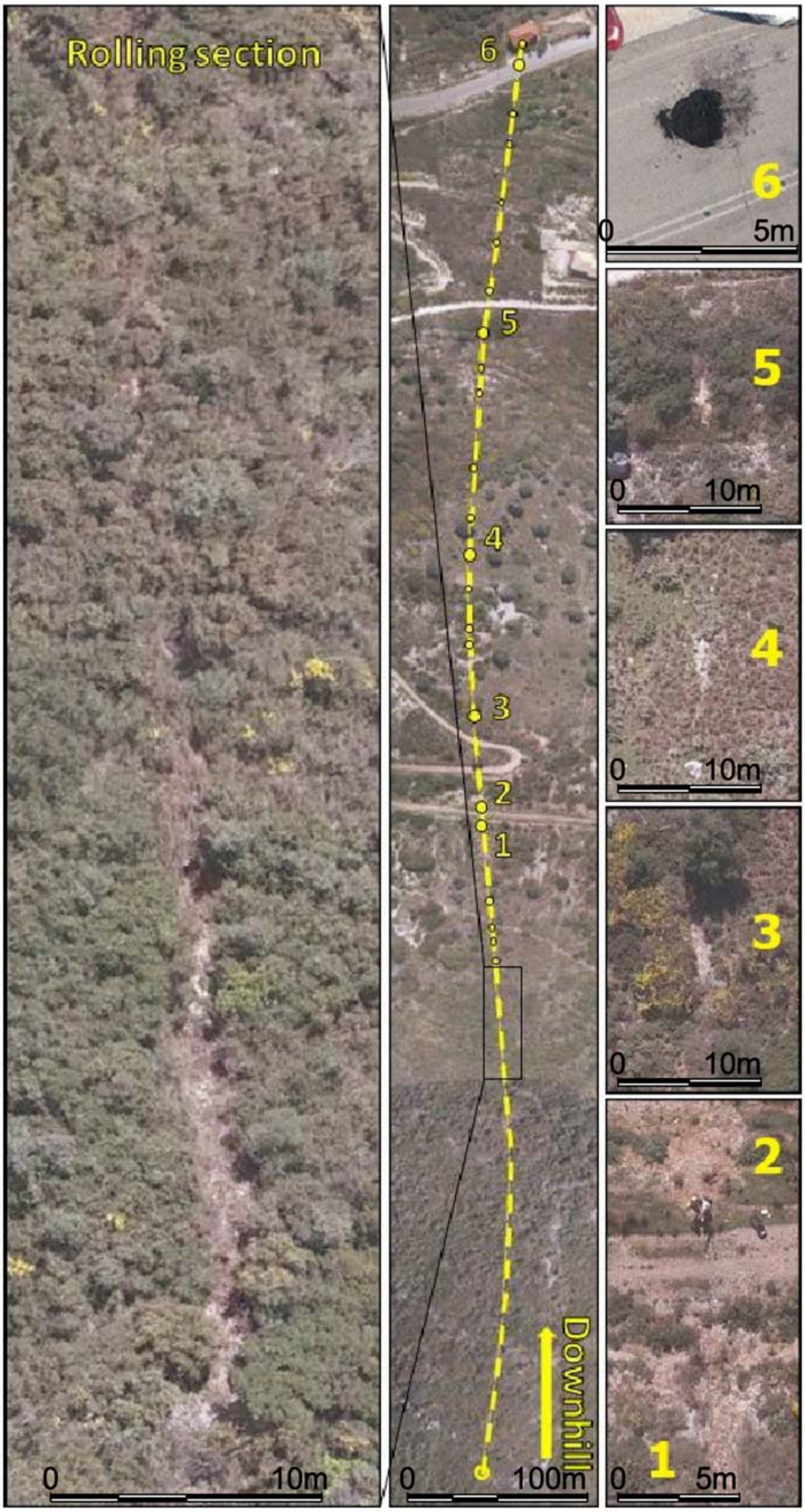


Figure 5. Top view orthophoto denoting rolling section, bouncing positions and indicative close-ups of impact points.

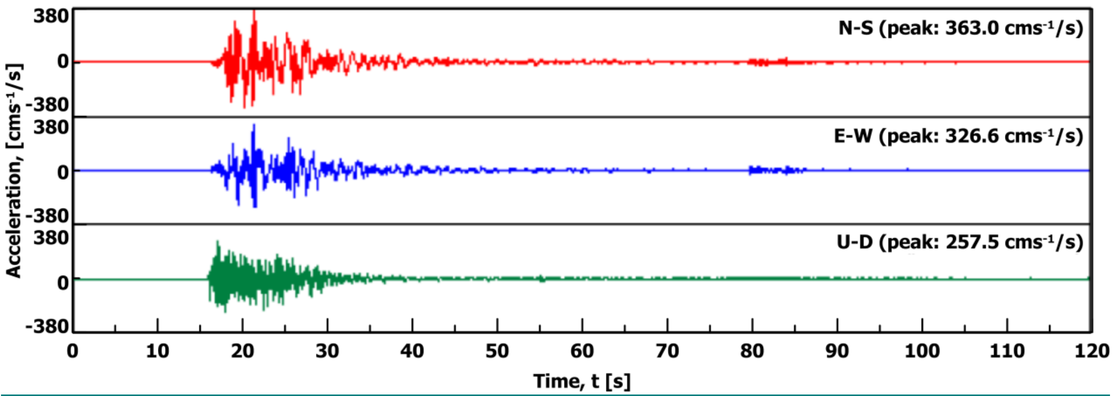


Figure 6. Acceleration time history recording at Vassiliki site (ITSAK, 2016)

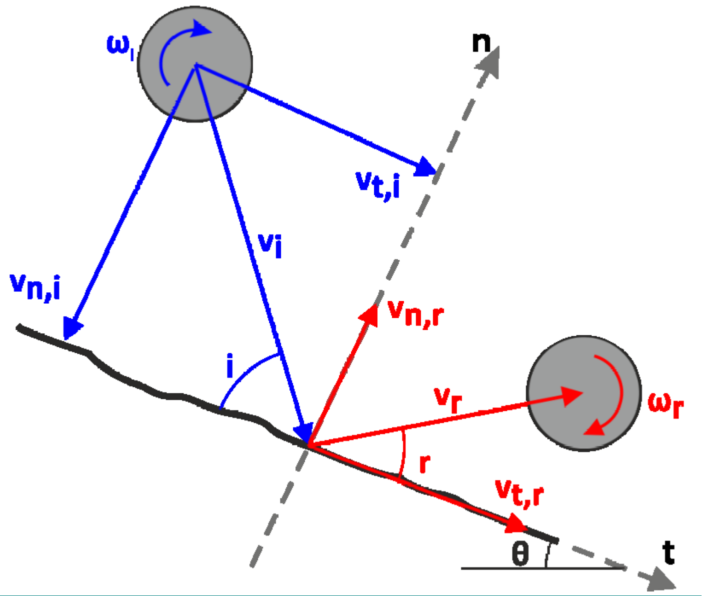


Figure 7. Coefficients of restitution

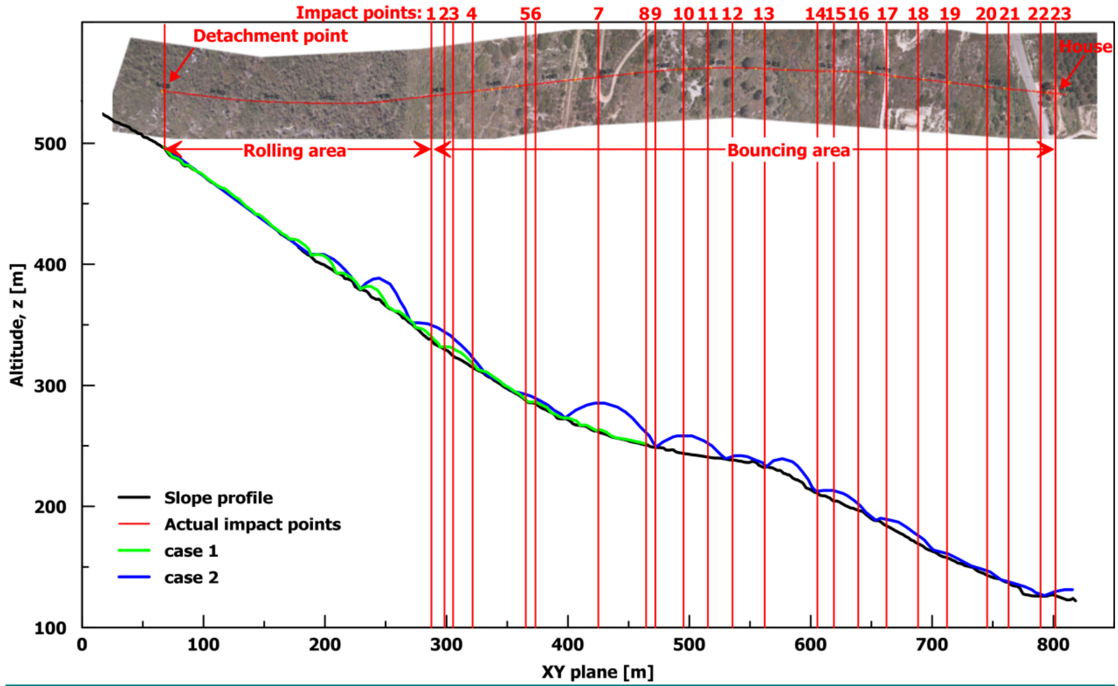


Figure 8. Plan view and cross section along block's path (units in m); 2D rockfall trajectory analysis results are plotted with green and blue line

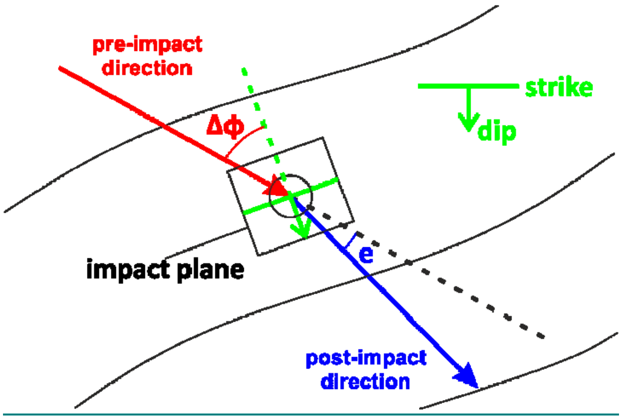


Figure 9 : Out of plane geometry

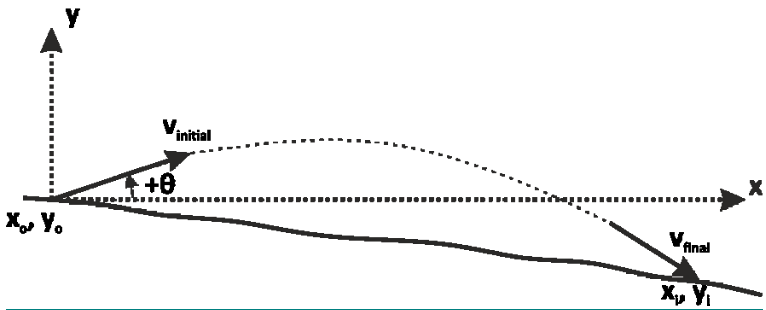


Figure 10. Parabolic segment

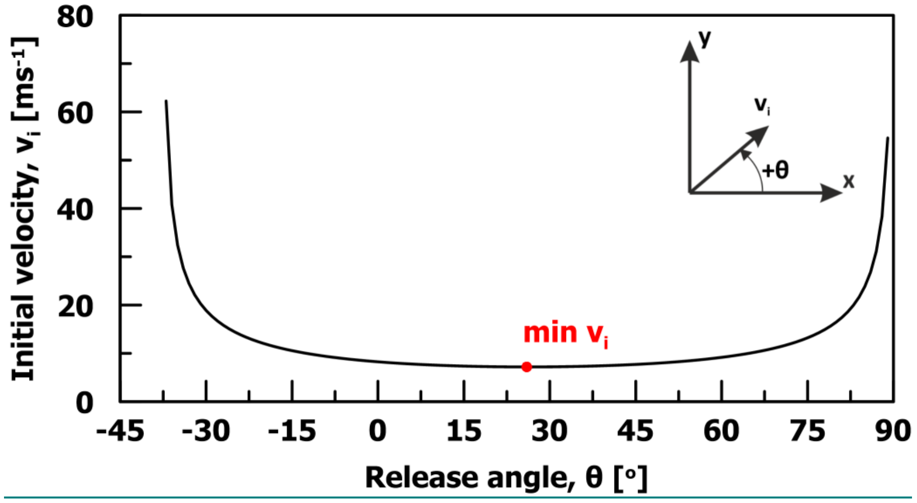


Figure 11. Release angle versus initial velocity for the first parabolic section (δx=10.75m, δy=8.33m)

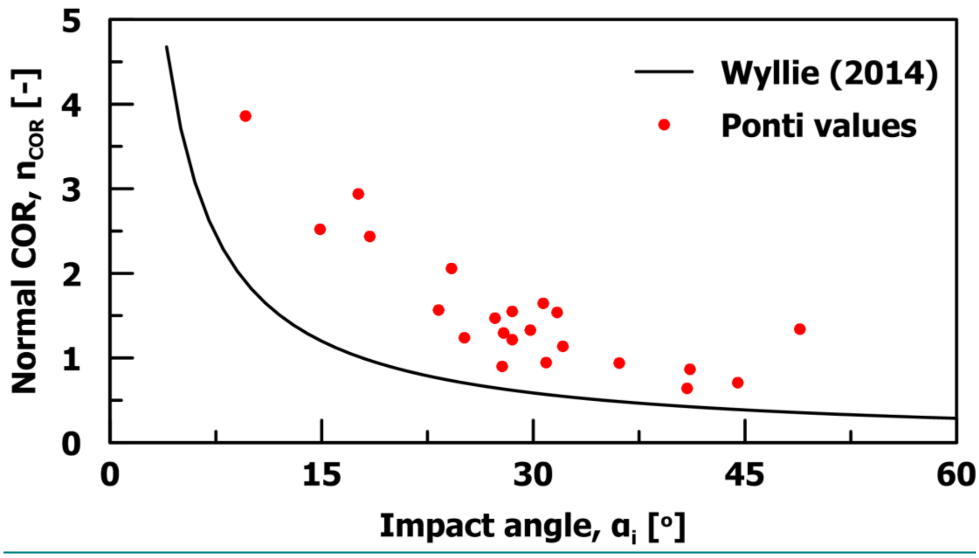


Figure 12. Normal COR versus impact angle

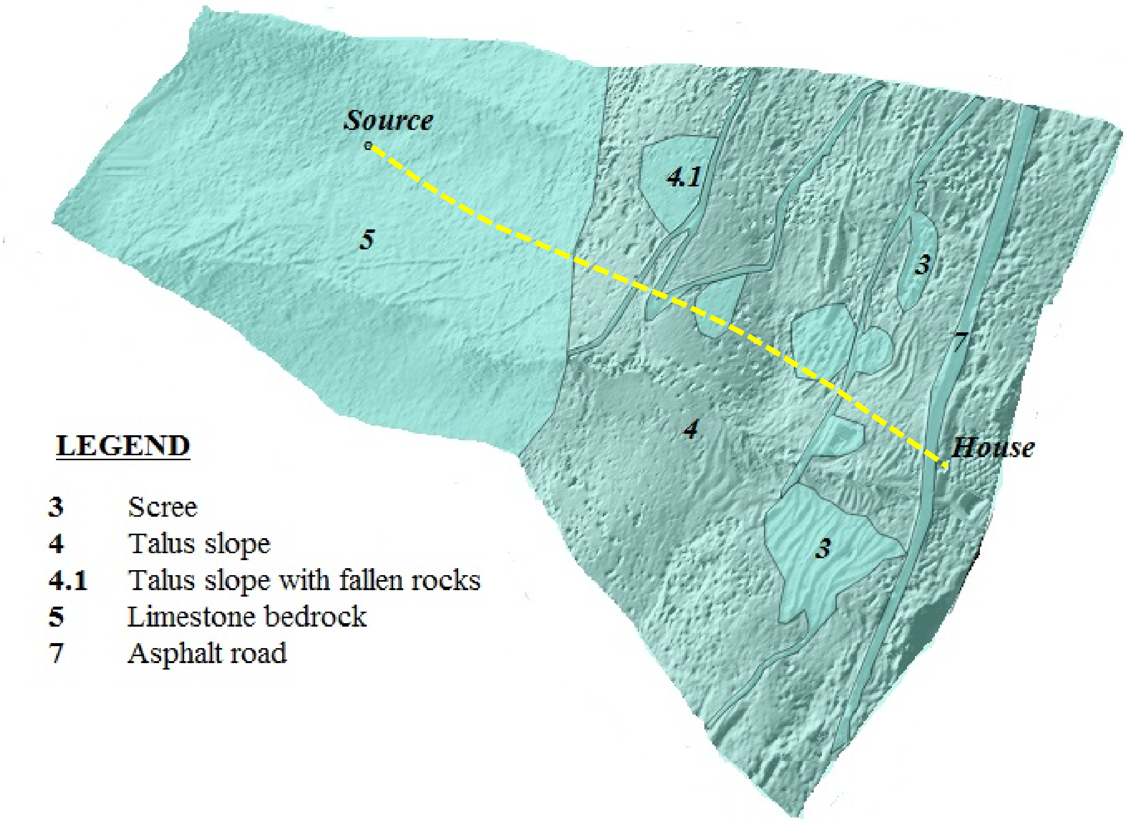


Figure 13. Soil types for 3D rockfall analysis (according to Rockyfor3D). Yellow path of trajectory is 800 m.

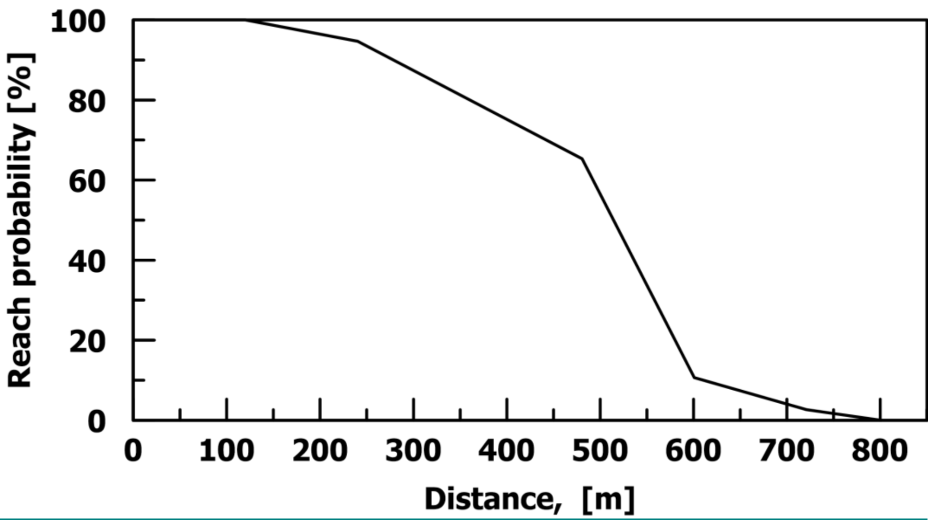


Figure 14. Reach probability graph calculated from 3D rockfall analysis

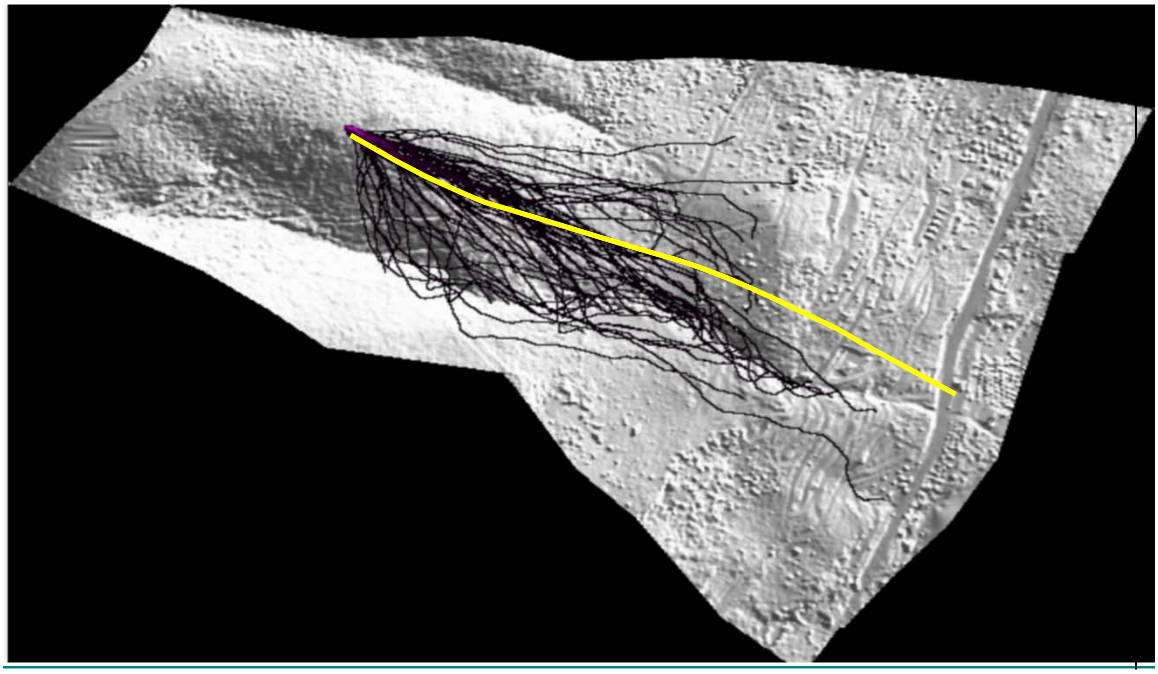


Figure 15. 3D trajectory analysis (from RockyFor3D analysis). Yellow line shows the actual trajectory. Black lines show the simulated trajectory.

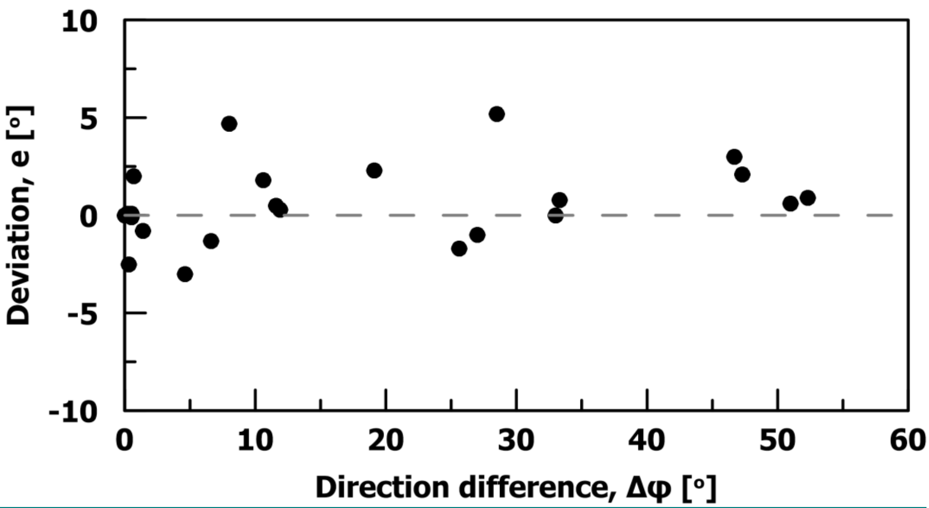


Figure 16. Deviation as a function of direction difference.