RESPONSE TO COMMENTS

Title: UAV-enabled reconnaissance and trajectory modeling of a co-seismic rockfall in Lefkada

Journal: NHESS

We note that the reviewers are positive about our manuscript. We appreciate the time taken by both reviewers to consider the manuscript and agree that their comments have given us constructive ideas on how to improve this contribution.

The manner in which the comments are addressed is given below:

REVIEWER 1:

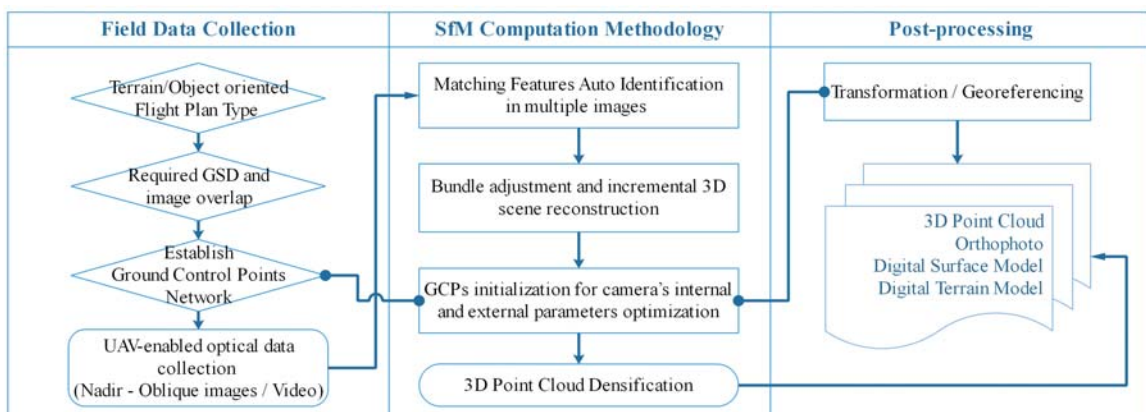
GENERAL COMMENTS

Comment 1: The title should probably be changed in something like "UAV-based back analysis and trajectory modelling of a co-seismic rockfall in Lefkada".

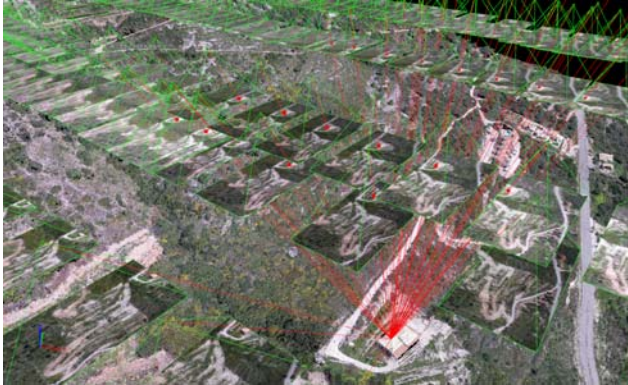
Response: We changed the title as follows:
UAV-based mapping, back analysis and trajectory modelling of a co-seismic rockfall in Lefkada Island, Greece".

Comment 2:

From the manuscript is not clear how the images or videos have been processed nor is the accuracy of the DSM discussed in detail.

Response: We follow the typical procedures for Structure-from-Motion as laid out in the following Figure, which will be added in the manuscript. These include the following steps:

In addition, the accuracy of the model has been examined by using portions of the ground control points and developing DEM of differencing between different models, an investigation that is described in our paper by Manousakis et al. (2016). Finally, we have also made a comparison, and we plan to add that in our paper, of the DEM

developed by the UAV against the satellite-based DEM that is part of the Greek cadastre. The two surfaces were found to be very similar.

The overlap between pictures was minimum frontal80%, side 65% and a total of 714 camera station (video frames extracted) were included (see the following Figure).

(Additional Figure)

Comment 3:

In the 3D simulations it looks like the authors used the DSM that still includes vegetation. This might create unrealistic obstacles.

Response: The vegetation was removed from the DSM.

For vegetation removal, Point Cloud neighbourhood examination and DEM smoothing algorithms have been implemented. Firstly, a bare-Earth digital elevation model (DEM) from the input point cloud LAS file was interpolated, by specifying the grid resolution (2m) and the inter-point slope threshold. The algorithm distinguishes ground points from non-ground points based on the inter-point slope threshold. The interpolation area is divided into grid cells, corresponding to the cells of the output DEM. All of the point cloud points within the circle encompassing each grid cell is then examined as a neighbourhood. All points within a neighbourhood that have an inter-point slope with any other point and is also situated above the corresponding point, is considered to be a non-ground point. An appropriate value for the inter-point slope threshold parameter will depend on the steepness of the terrain, but generally values of 15-35 degrees produce satisfactory results. The elevation assigned to the grid cell is then the nearest ground point elevation (Whitebox GAT help topics).

Further processing of the interpolated bare-earth DEM was introduced 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 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, are identified and removed. Each of the edge cells of the peaks are then examined to see if they have a slope that is less than the user-specified Minimum OTO Edge Slope and a back-filling procedure is used. This ensures that OTOs are distinguished from natural topographic features such as hills (Whitebox GAT help topics).

Algorithms executed within Whitebox GAT Geospatial Analysis Tools platform (http://www.uoguelph.ca/~hydrogeo/Whitebox/index.html).

Comment 4: The influence of the slope roughness is not addressed in detail.

Response: In 2D modelling the slope roughness was not taken into account as the crossection is produced with great accuracy. This comment will be added in the manuscript.

Comment 5: The authors also use inconsistent and uncommon notation.
Response: notation has been corrected and is now consistent

SPECIFIC COMMENTS

Par. 3 (UAV)

1. UHD 4K is only relevant if you work with videos, for digital images the sensor size and the pixel resolution are most important.

   Response: The sensor is a 1/2.3" CMOS (6.47x3.41mm) and the effective pixel resolution is 12.4 MP (4096x2160 pixels). This information will be added in the manuscript.

2. In order to produce orthophoto and DSM you need to process the images, the UAV is a tool to capture the images.

   Response: Agreed. The process to do this has been described in the "General comment No. 2" and will be added in the paper.

3. see previous comments. Also, the Phantom 3 Pro has an integrated camera.

4. did you really process the video? or did you use full resolution still images? This is not clear, please provide more details. In addition, provide frame rate and/or number of images

Response: This information is now added in the paper as part of responding to "General comment No. 2"

5. again, the DSM results from the image processing. Also, specify the software you used
Response: The software used is Agisoft Photoscan. This will be added in the paper.

6. have you used the GCPs for georeferencing only or have you used them as well in the bundle adjustment?

Response: GCPs were used for both georeferencing and solving camera's internal and external parameters. Total RMS error for 6 GCPs is 0.07m while total RMS error for 4 Check Points is 0.20m.

7. How accurate is your DSM model? Provide some details.

Response: This is now discussed as part of the "General comment No. 2"
Total RMS error for 6 GCPs is 0.07m while total RMS error for 4 Check Points is 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.

8. Also, a DSM generally includes vegetation and does not represent the true ground surface, which is relevant for rockfall analysis. You should probably work with a DTM (digital terrain model) instead of a DSM. However, this is not straightforward with photogrammetry data. Please comment.

Response: A description on this is now added in comment "General Comment No. 3"

9. line 136 "Note that this resolution is still higher than the resolution of DSM that are used in rockfall analyses"

not completely true, depends on the scale

Response: We will add a comment that will indicate that this resolution is higher than commonly used for slopes of that size.

par. 5 (rockfall)

1. correct to COR_v

the normal (nCOR) and the tangential (tCOR)

Please use commonly used notation. Also what is with the rotational energy (see e.g. Volkwein et al. 2011, NHESS)

Response: The notation used is found in several relevant papers, therefore it is not uncommon. It is a fact though, that no agreement regarding notation is exist between researchers, as various notations exist for the COR (i.e. Rn, nCOR, Kn and others)

We have used a lumped-mass method in our analysis. "Lumped-mass methods consider the block to have either no mass or a mass concentrated into one point and do not take into account either the shape of the blocks or rotational movement" (Volkwein et al. 2011)

2. no impacts on trees were recorded, right?

Response: No impact on trees was recorded. This will be added in the manuscript.

3. use 1/cos^2

Response: We agree. All equations have been written again

4. you should also look in Volkwein et al. (2011 NHESS) as they summarize characteristic jump heights. How do your jump heights compare to those mentioned in the reference?

Response: The f/s ratio of the jumps are relatively high, more than 1/6 which characterizes the high jump. The maximum f/s ratio is ~1/3. A comment has been added in the manuscript.

Text added: "Finally, the bounce height of some impacts seems unrealistically high. For example, the 2nd bounce 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 suggested by Volkwein et al. (2011)".

5. **Par. 5.4 coefficients of restitution**

I cannot fully agree to this. The block starts by rolling along the slope, it should hence have a considerable rotational velocity. Your calculations however neglect the rotational energy. There is room for improvement here.

Response: As previously mentioned, rotational energy was neglected because of the selection of the lump-mass model for the analysis.

Also, it is shown in the literature, that high values of restitution coefficients can be related to the influence of the rotational velocity, low impact angles, block shape etc. (see e.g. Buzzi et al. 2012). This should be discussed in more detail.

Response: A more detailed discussion was added in this section and was enriched with more references (Buzzi et al., 2012, Spadari et al. 2012, Ferrari et al. 2013).

Text added: "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., 2012; Buzzi et al., 2012; Asteriou et al., 2012) and back-analysis studies (e.g. Paronuzzi, 2009) and are connected 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)."

6. The values in the literature vary and calibration of these values with back analysis is generally suggested. Your back analysis suggests a value of n_COR close to 1.

Response: Indeed. This observation is perfectly in-line with those of Buzzi, Giacomini, Wyllie, Asteriou and others. Low impact angle, block's configuration at impact (slope roughness and block's shape) and, maybe, angular velocity lead to n_COR values close to one or even higher. Yet, in the lump-mass model approach, that is the most popular in current practice, those parameters are not taken into consideration.

Also, what about the slope roughness? It is well known that it has a major influence on the block trajectory.

Response: 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 (looking on the block's dimension scale) by the accurate cross-section used in the analyses (more than 1500 x-y points were used – apx 2 points per meter).

Based on our knowledge, this accuracy is significantly higher compared to other similar research projects.

Moreover, with the data on hand and the lump-mass model analysis we performed, we were not able to simulate block shape effect nor the configuration of the block at impact.

7. "friction angle was set to zero"

Doesn't this imply that the rock is sliding instead of rolling? How did you create your 2D slope profile? What about slope roughness?

Response: According to Rocfall software code (Rocscience Ltd) when friction angle is set to zero the motion of the falling block is rolling.

In the 2D analysis, the roughness of the slope was intentionally set to zero, as the analysis was deterministic. We didn't consider a standard deviation for the coefficients of restitution, the friction angle and roughness of the material on the slope.

8. Line 310 "Finally, the bounce height of some impacts seems unrealistically high" maybe you can also compare these to the once you back calculated

Response: See reply to earlier comment discussing jump heights. Text added in manuscript.

9. par. 3D rockfall analysis
You address slope roughness here but not in your 2D simulations.

Response: 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 of 70%, 20% and 10% (rg10, rg20, rg70) of the trajectories (according to the suggested procedure in Rockyfor3D).
As mentioned earlier, the slope roughness was not taken into account in the 2D analysis as the slope terrain was produced with much great accuracy.

10. Line 393 "estimation of the initial velocity of the blocks plays a significant role in the accurate re-production of the rockfall trajectory.

Did you do a sensitivity study on the initial velocity in order to conclude this?
Response: Yes, a sensitivity study was performed using a range of values for the initial velocity.

11. Table 3
use same notation as in the text
   Response: Corrected

12. **Figure 3**
number all impacts

Response:
All impacts are numbered in Figure 6, where it is important to compare the actual trajectory with the rockfall analysis. Figure 3 shows the actual trajectory and we believe it is not necessary to number all the impacts on this figure.

use consistent numbers, change the numbers according to the number of impact as also shown in Fig. 6
Response: See previous comment

is the block rolling from the detachment point until the first impact
Response: The block is rolling from the detachment point until the first impact, as clearly stated in par. 3.2.

13. **Figure 13**
It is interesting to note that a very strong dispersion starts right at the source. Do you have a clear explanation for this? Also, the vegetation might play an important role during the rolling phase. Is the rolling phase more realistic in these simulations compared to the one of Rocfall? How many simulations did you perform? Could you

perform more simulations? Finally, it seems that the DSM includes a lot of vegetation but you also model roughness by MOH although you say no vegetation was considered in the analysis (line 323-327). This is kind of contradicting and needs to be clarified

Response:

It is true that there is a strong dispersion at the source. The reason for this dispersion is the topography effect of the area of detachment, as discussed in par. 6.3.
We performed a significant number of simulations (with a range of restitution parameters. The scope was to run the 3D analysis according to the restitution parameters and soil types suggested by Rockyfor3D and discuss the results. The total number of simulated falling rocks (total nr. of simulations) was 120 for each analysis.

As explain in the response of a previous comment, the vegetation was removed from the DSM. The roughness, which was considered in the 3D analysis, refers to the slope terrain (not the vegetation) and is modelled according to the suggested method of Rockyfor3D using coefficients rg10, rg20, rg70 (see previous comment).

REVIEWER 2:

Comment 1

How many days after earthquake was made the UAV acquisition

Response: There was an immediate UAV acquisition that was conducted 2 days after the earthquake. A second more detailed UAV acquisition with the objective to create a DEM was made 5 months after the rockfall event.

Comment 2

In the figure 1 may useful to have map that localize study area inside Greece, and also to add a scale bar to figure

Response: We added a map to localize the study area in Greece

ADD

Comment 3

In figure 3 is better to put the impact point photo in the same orientation of the track

Response: We rotated the figure (see below).

Comment 4

Figure 11 / Figure 13 it will be nice add the real path of rockfall for comparison with the results from simulations.
Response: We added the actual path on the Figures.

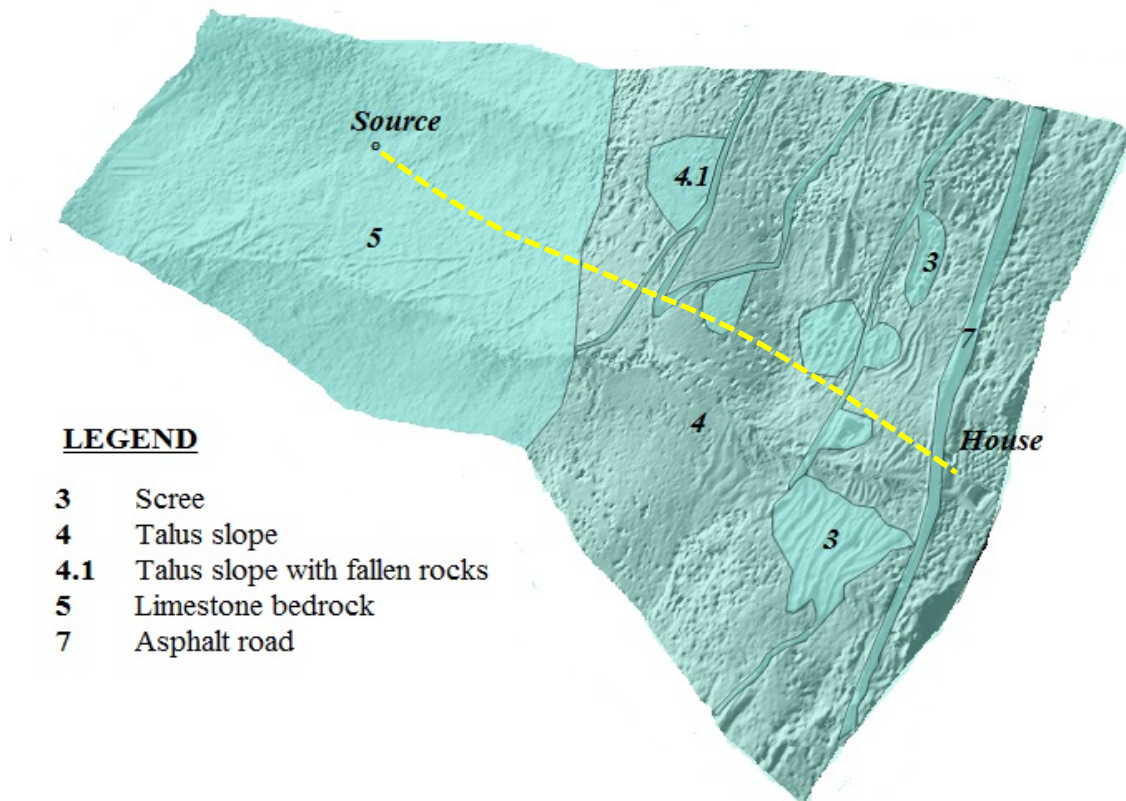



Figure 11

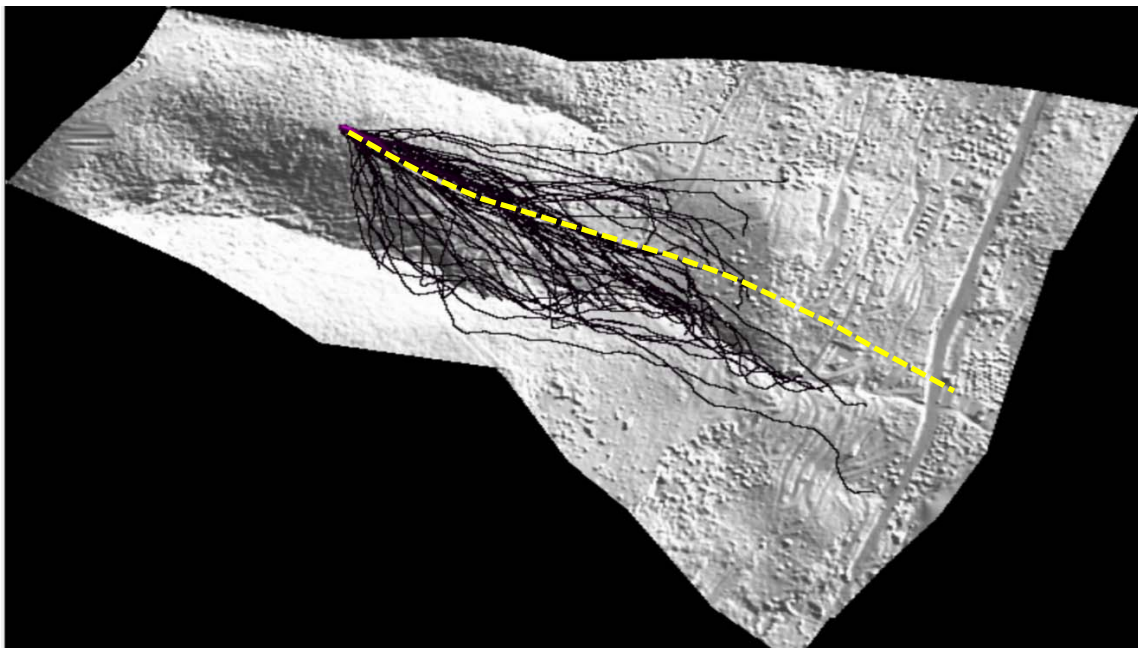



Figure 13

Comment 5
Revise to find and correct some typo errors like: > Line 113: the > the > Line 114 onhore > onshore ?
Response: Corrected

Comment 6

reference: check that all references are in the format required by NHESS Smith, P., Thomson, A., and Carter, T.:, 2006.

Response: Corrected

Additional references

Buzzi O, Giacomini A, Spadari M (2012) Laboratory investigation on high values of restitution coefficients Rock Mechanics and Rock Engineering 45:35-43

Ferrari F, Giani GP, Apuani T (2013) Why can rockfall normal restitution coefficient be higher than one? Rendiconti Online Societa Geologica Italiana 24.

Spadari, M, A Giacomini, O Buzzi, S Fityus, and GP Giani (2012). In situ rockfall testing in new South Wales, Australia. Int. Journal of Rock Mechanics and Mining Sciences 49, pp. 84–93.

Volkwein A., Schellenberg K. , Agliardi F. , Berger F. , Bourrier F. , Dorren L. K. A. , Gerber W. ,Jaboyedoff M. , Labiouse V. (2011). Rockfall characterisation and structural protection - a review. Nat. Hazards Earth Syst. Sci., 11, 2617-2651.