REPLY TO COMMENTS OF REFEREE 2 FOR MANUSCRIPT esurf-2017-38

We would like to thank anonymous referee #2 for the constructive comments and suggestions, which will guide for the revisions. Below, we respond to the suggestions of referee #2.

General comments/suggestions

In the manuscript, Clapuyt et al. present the results of UAV photogrammetric surveys carried out on an active landslide in Switzerland. Their results have been used to quantify the horizontal and the 3D ground surface displacements and the sediment budget of the landslide. The Authors focused the manuscript on the interpretation of the landslides dynamics based on the high resolution dataset provided by UAV photogrammetry and they used M3C2, COSI-Corr and GCD (ArcGis Plugin) to obtain a comprehensive analysis of the annual dynamic of the landslide.

The manuscript is well written and the work is very interesting and potentially useful for future developments of UAV photogrammetry for landslide monitoring. However, there are some points of the paper that require improvements. In my opinion, the manuscript require a minor revision before being considering for publication in ESurf. I include below some suggestions or comments that could be of interest for the authors to be incorporated in the final version of the manuscript.

1) Accuracy has been assessed comparing SfM photogrammetry with the ground control points used to georeferenced the dense point cloud. However, as visible in Figure 2, both surveys, 2013 and 2015, were able to cover some area outside the earthflow. In addition you used the digital elevation model (DEM) and the elevation difference on the common area to estimate the sediment budget. Why do not consider also the elevation difference between multi-temporal DEM on the stable areas outside the earthflow as additional analysis to evaluate the accuracy of the SfM reconstruction? This could be useful to evaluate the spatial distribution of elevation changes between the three survey campaigns.

This is a very good idea, and we will certainly take it along for future work in the area. Unfortunately, the 3D point clouds that we have do not allow us to use the “stable ridges” around the earth flow to monitor differences in surface displacements. In fact, the area that we have monitored is small and centred on the earthflow. (1) The ground control points were regularly scattered over the active area and its very-near surroundings. Even if a larger area has been captured, mainly due to oblique photos, there is a lack of ground control points outside the active area to have a proper 3D reconstruction, which is necessary for this kind of accuracy assessment. Also, (2) pastures directly surrounding the active part of the flow are also slightly moving downwards and can not be considered to be “truly stable”. (3) There are no distinctive features on our airphotos, e.g. massive boulders, roads, houses around the earthflow that can be considered as immobile over the period of interest.

2) In my opinion, the Authors not emphasize the advantages of very high resolution UAV data (both point cloud and DEM) for the landslide monitoring in comparison with the state of the art and previous investigations done by Schwab et al. (2007) and Savi et al. (2013) on the same study area. In addition, I suggest to better highlight how the results derived by the three different methodologies can be combined and which improvement their combination can provide on the interpretation of the landslide dynamic.

We agree with your comment. In the next version of the manuscript, we will discuss more extensively on the additional, but complimentary, value of very-high resolution 3D topographic data, with respect to previous research from Schwab et al. (2007) and Savi et al. (2013). In addition, as the referee #1 also suggested, we will develop the discussion more on the scientific findings regarding hillslope failure and highlight the new findings about landslide dynamic understanding based on the combination of techniques and results.

3) Concerning the structure of the paper I have some observations, starting from the introduction where, in my opinion, some information are missing and I found it a bit confused.

Introduction. The Authors report a general description of the high resolution techniques available for the reconstruction of earth's landform. Then, a sentence about the accuracy is provided, following by a more detailed description about spatial resolution and spatial extension for each sensor and platform. In the second paragraph, the concept of high resolution is repeat again regarding the landslides monitoring and surface displacements. In my opinion these two paragraphs, should be rewritten focusing on the target object, i.e. landslide monitoring, by giving a clear description of the advantages and disadvantages of different survey technologies currently used for landslides monitoring and surface displacements analysis. In the introduction, two times you wrote about the aspects that affect the choice of the technologies. In specific, at line 10 you mention that "the choice of the acquisition framework result from the trade-off between the spatial resolution needed and the extent of the study area", then at line 20 you mention that "return period for acquisition and the surveying cost remain important criteria for the selection of the data acquisition platforms". These two aspects (i.e. return period and cost)also affects the acquisition framework. I assume that the resolution and return period for acquisition necessary for landslide monitoring are strongly site-specific and depends by the magnitude and the assessment of associated hazard. However, I suggest to consider to write which are the main parameters (like resolution, data type, weather, accuracy, location accessibility, spatial and temporal resolution, coverage, cost) to consider when making a choice between different high resolution technologies, focusing on the landslide monitoring. Since you mentioned in the text different technologies, please consider that in the last decade both satellite (i.e. very high resolution satellite imaging) and aerial imaging system have benefited from great technology improvements reaching similar sub-meter resolution. Recently Stumpf et al. (2017) investigated the potential of Pléiades satellite images for landslide monitoring. I suggest to describe the real advantages of UAV data like the 3D point cloud, cm resolution, etc. Maybe, I suggest to refer here the comparison of your study with the previous investigations done by Schwab et al.(2007), and Savi et al.(2103).

The introduction will be reshaped according to both referee comments, as they are similar at some point. We will focus more on the actual subject of our research, i.e. landslide monitoring and its associated scientific findings using UAV-SfM framework. We will emphasize the advantages and drawbacks of using specifically this methodology for landslide monitoring, along with the main parameters to take into account when choosing one particular methodology. We missed the recent paper of Stumpf et al (2017), but we will include it as it is very relevant in our review on landslide monitoring techniques.

Specific comments/suggestions

- *P4, line 8. I consider inappropriate to add a sentence about the effect of climate change on landslide hazard at the end of the introduction and after the description of your work. Maybe consider to start the introduction with this general topic that help to focus the object of the manuscript.*

We agree with this comment. In fact, this paragraph was at the beginning of the manuscript in a previous draft. As written earlier, we will re-structure the introduction of the manuscript.

- *P4, line 2. First you computed the 3-dimensional surface displacement, then the horizontal and the sediment budget. Please change the order. In addition I suggest to introduce the acronym 3D at the beginning (P3, line 14) and use it in the entire text. If you consider to extend the DoD on the stable area in order to analysis the accuracy of the photogrammetric DEM, I suggest to firstly describe the sediment budget based on the DoD, then the COSI- Corr analysis and at the end the M3C2. This also because for the COSI-Corr the hillshaded DEM is the data input (P6, line17). Moreover, the DoD provides information mainly about the* *vertical change, COSI-Corr the horizontal displacements and M3C2 is a full 3D analysis. I believe this sequence of the analyses more appropriate. If you change the order, then you should verify that you change it throughout the whole paper.*

We agree that this sequence is more logical and appropriate, i.e. from 1-D to 3-D. We will adapt the manuscript in that sense.

- *P5, line18. Please provide more information about the platform, data acquisition and processing like the type of the UAV platform, flight height and flight path, GSD for each epoch, number of oriented images and very important the locations of the GCPs on the survey area. If I understood well, the GCPs were used after the camera orientation to georeference the point cloud. Why you didn't consider to include some of these observations in the bundle block adjustment during the camera orientation and the remaining as check points? Perhaps worth a comment. Please consider to include in this section also the description of the DEM generation and the accuracy used for the different analysis. You explained that for the horizontal displacement a spatial resolution higher than 0.20 generated incoherent results. However, for the DoD you used 0.04 m cell size as the best possible spatial resolution. How did you estimated this, based on the GSD? Why not used the same cell size, considering that the mean annual horizontal displacement range between 5.7 m to a max. of 8.9 m? Usually photogrammetric point cloud is characterized by high noise. Did you remove the noise before to generate 4 cm resolution DEM.*

Some technical information are indeed missing because we did not want to overload the manuscript. However, as it is relevant, we will update Table 1 with the number of oriented images and ground sampling distance. We will add a figure depicting flight paths over the study area and location of ground control (or integrate it in Figure 2, if it can stay legible). In the methodology section, we will add details about the UAV platform, i.e. custom Y6 multirotor with embedded DJI controllers, and about the mean flight altitude, i.e. 60 m.

The choice of using all the GCPs for georeferencing was driven by the need to have the most accurate 3D reconstructions, as they are inputs for temporal analyses where errors propagates. As we already showed in a previous study (Clapuyt et al., 2016) that our methodology was accurate, we did not needed to perform a new analysis in that sense.

Raw point clouds from SfM reconstruction were filtered out before performing any further analysis. The resolution of the subsequent DEMs, i.e. 0.04 m, is estimated based on the average point density of the point clouds, in order to exploit the high-resolution character of the data without altering it by using interpolation between points. Besides, in order to compute the horizontal displacement with the image correlation algorithm, the resolution of shaded relief surfaces has been chosen after performing a sensitivity analysis on the parameters of the algorithm, i.e. resolution of the input, the window size, the step between each sliding window and the search range. As the study area has a very complex topography, the sensitivity analysis showed that image correlation worked best with a lower resolution as false positive correlation between features was minimal at the 20 cm resolution.

- *P7, line 18. These results were not introduced in the methods. How did you generated this geomorphological maps? Please provide more details. In addition, since you mentioned the hillshaded DEM, I suggest again to revisit the manuscript and modifying the order of the analyses and corresponding results by describing firstly the DEM data.*

We will introduce the making of the geomorphological map in the methods. We prefer to keep the geomorphological map at the beginning of the results, as we think that it provides essential information on the geomorphological setting of the area that helps to get a clear picture of the study area and facilitate the interpretation of the results.

- *P8, line 26. "the absolute displacement of the frontal lobe of the earthflow is not properly captured, as the frontal lobe advanced by ca. 55 meters". Where can I see this observation? Is it possible to add a scale of the displacement vectors in the figures in order to have a clear view of the magnitude of the movement?*

We will add a figure showing the advance of the frontal lobe, based on the DEMs, from 2013 and 2014.

All other comments and suggestions below will be changed in the text and do not need a specific answer at this moment of the review process.

- *P5, line 11. Consider to change: Data acquisition and data processing.*
- *P5, lines 12-13. Is it really necessary "a 3D point cloud" or this is a sentence related to your study.*
- *P5, line 14. The acronym SfM is already introduced. In addition I cannot find the connection of this sentence where you introduce the SfM algorithms with the next one about the planning of the survey. Please clarify this sentence and consider to move it at line 28 when you introduce the SfM algorithms.*
- *P6, line 4. Consider to change the order of the analyses.*
- *P6, line 29. In order to avoid repetition, better to report the corresponding software in the specific paragraph. Please consider to specify exactly which are the main statistics that you considered for each analysis.*
- *P7, line 12. Please write here the acronym for the root mean square error.*
- *P7, line 19. Which field observations? Do you mean the targets measured during the flight? Please specify these observations in the method and for what analyses they were used. At page 8 and 9 you mention again the field measurements by comparing these observation with the results of horizontal displacement and sediment budget. This is not clear.*
- *P7, line 28. Please use the acronym M3C2.*
- *P8, line 13. The fluxes are well constrained by stable areas. Please, consider to better explain this statement.*
- *P8, line 21. Add over the same area of interest. Change meters with m.*
- *P8, line 31. Please clarify what do you mean with "the best estimate volume". I suggest to report also the information about the elevation changes in meters.*
- *P9, line 26. raw images. Do you mean raw uncompressed image format or simply the image dataset.*
- *P9, line 30. Actually one of the main drawback of the UAV photogrammetry is the need of GCPs to georeference the point cloud and often used to reduce possible systematic error that can occur especially in presence of flat terrain. Why do you compare here UAV-SfM with TLS but you not mention any comparison with terrestrial images or possible combination of ground-based acquisition with UAV in case of problems during the flight for example.*
- *Some acronyms are introduced in the text like SfM, M3C2, UAV, DoD, 3D. Please, use them in whole text.*
- *Figure 1. Please consider to add either a slope map or a DEM with contours of the study area.*
- *Figure 7. Please use the same number of significant decimal places in the legend. I suggest for Table 3 and Table 4 to use 2 significant decimal like in Table 2.*
- *Table 1. Some information are missing, like GSD and UAV details.*
- *Table 4. The caption of the figure. The COSI-Corr algorithm is applied on the hillshaded and not "from the 3D point clouds"*
- *Table 5. Please add information about the elevation change (e.g. mean and standard deviation).*

Reference:

Stumpf, A., Malet, J. P., Allemand, P., Ulrich, P. (2014). Surface reconstruction and landslide displacement measurements with Pléiades satellite images. ISPRS Journal of Photogrammetry and Remote Sensing, 95, 1-12.

Reference

Clapuyt, F., Vanacker, V. and Van Oost, K.: Reproducibility of UAV-based earth topography reconstructions based on Structure-from-Motion algorithms, Geomorphology, 260, 4–15, doi:10.1016/j.geomorph.2015.05.011, 2016.