REPLY TO COMMENTS OF REFEREE 1 FOR MANUSCRIPT esurf-2017-38

We would like to thank anonymous referee #1 for the constructive comments and suggestions, which will help us to improve the manuscript. Below, we respond to the suggestions of referee #1.

Comments to the Author

This manuscript reports on the performance of UAV derived topography processed using SfM photogrammetry for monitoring active slope processes in the foothills of the Swiss Central Alps. The manuscript is clearly written, well structured, and effectively documents the work undertaken by the authors. In this work, the authors apply COSI-Corr, M3C2 (Lague et al., 2013) and the GCD ArcGIS plugin (Wheaton et al., 2010) to report on the horizontal and 3D displacements, and sediment budget of the landslide complex. In my opinion, the combination of these three analyses provide a really robust characterisation of the short-term (inter-annual) dynamics of the earthflow investigated. Overall, I believe the manuscript could be suitable for publication, but the authors need to consider the main contribution of this work given: (1) the large body of UAV and SfM research already published in Physical Geography facing academic journals; and (2) the now frequent use of UAVs for hillslope monitoring by geotechnical consultants. Specifically I think the following questions need to be addressed before this work is formally accepted for publication: In what ways does the 'performance of UAV for monitoring ground surface displacements' need further investigation? How does this work build on from the work of Lucieer et al. (2014) [Progress in Physical Geography] who also used multi-temporal UAV imagery and SfM to report on surface change, and displacement (using COSI-Corr) associated with landsliding? Is the value of this work related to the fact that it is a SfM case study or should the scientific findings regarding hillslope failure be more prominent in the manuscript? In places, the work would benefit from citing a wider range of up-to-date UAV and SfM articles, especially those pertaining to the application of UAVs to hillslope failure. This year alone a large number of highly relevant manuscripts have been published and should be acknowledged and discussed in the manuscript. This will allow the contribution/novelty of this research, beyond representing another potential 'application of SfM' case study, to be better communicated to practitioners within this rapidly developing area of remote sensing.

Our main objective (page 3, line 30) is landslide monitoring. For this purpose, we first introduce the different methodologies to get topographic data and discuss quickly the trade-off between accuracy and spatial range. Then, we give an overview of the recent literature dealing with natural hazard monitoring, based on topographic reconstructions, and finally come to SfM.

We agree that we need to clarify the purpose of this paper, and will do so in the revised manuscript. The novelty of our research is the combination of horizontal, 3D displacements and sediment budgets derived from high-resolution 3D point clouds to get an in-depth understanding of landslide mechanisms. Indeed, this paper is not only about monitoring landslides using an UAV-SfM framework, as it analyses in depth the potential of using time series of very-high resolution topographic reconstructions. Consequently, we will reformulate the introduction to clarify this.

We agree that there is now a large amount of scientific papers about the use of UAV-SfM framework to reconstruct topography. But, as far as we know, this is still not the case for the monitoring of dynamic environments, and especially mass movements, and – to our knowledge - few published papers exist on dense time-series of UAV-Sfm reconstructions.

Some specific comments

- *P1. Lines 25-26: SfM for multitemporal analysis is not in its early stages. There is now a vast body of research that addresses this topic.*

"in its early stages" is indeed overstated. This will be rephrased. However, we do think that temporal analysis of earth surface topography using UAV-SfM derived topographic reconstructions is not yet mainstream. Although several papers have shown the potential of UAV-SfM for monitoring physical processes through time, e.g. riverbeds dynamic, glaciers, landslides, a profound assessment of the potential of dense time-series for 4D monitoring of geomorphic phenomena is – to our knowledge – an important contribution to the research field.

- *P7. Lines 3-5: I see you did not survey the entire earthflow in 2013 and 2015? Is this not problematic for your assessment of the hillslopes sediment budget?*

The areas are not the same every year, as explained on page 7, line 2. As a consequence, we divided the computation of statistics into two parts. First, on the intersection of the three datasets to allow comparison of absolute values over the entire period. And secondly on the intersection of each spatial interval, in order to get the most information of each pair of datasets. Therefore, it is not a problem, just a small limitation in the assessment of the hillslope dynamics.

- *P3. Lines 19-26: How did you classify the different morphogenetic units? Please provide more detail on the geomorphological mapping in this research with reference to the approach undertaken to classify this particular hillslope failure (e.g. with reference to key geomorphological mapping literature). This information should be provided in the methods section. You could also, for example, use digitised morphogenetic zones to produce a more detailed breakdown of geomorphological change using the 'budget segregation' feature in the ArcGIS GCD plugin provided by Wheaton et al. (2010).*

The geomorphological map has been produced in order to properly sketch the configuration of the study area before presenting the main results of the paper. The geomorphological setting of the area is difficult to perceive for the reader, only based on a simple shaded DEM or an orthophoto. The content of the digital geomorphological map is based on expert knowledge, and aims to visualize the main parts of the earthflow based on Varnes (1978).

We are aware of this budget segregation in the GCD plugin but in our opinion, the geomorphological map that results from the GCD plugin provide a lot of detailed information, and is not ideal to introduce the overall geomorphological setting of the study area.

- *P5. Lines 18-27: Did you use a multi-rotor or fixed wing aerial platform? What was the approximate distance between the camera and the surface of interest during image acquisition? Please add this detail and ensure all details pertaining to the camera settings are provided in the main body or appendix in line with the recommendations of O'Connor et al. (2017) [Progress in Physical Geography].*

We used a custom Y6 multirotor with embedded DJI controllers, and flew on average at an altitude of ca. 60 m above the ground. We will add the camera settings in the revised manuscript, as recommended in O'Connor et al. (2017).

- *P6. Lines 25-28: Please provide more information on the errors associated with each raster surface used for differencing (beyond what is presented in section 3.1). The propagated error values used to threshold the DoD need to be presented alongside your results and in Table 5. What is the uncertainty (in ±m3) associated with the estimates of erosion, deposition and the net volume of difference? How did you arrive at the minimum, best and maximum estimates – are they linked to your detection limits? Were these based on* *difference values used to threshold the DoDs? Did you use spot height checkpoints to derive propagated error values? You need to more clearly communicate these aspects in the manuscript.*

In Table 5, minimum and maximum estimates correspond to the estimate minus/plus the uncertainty, while the best estimate is the estimated value (see also Figure 6). All values are computed based on the thresholded DoDs, for which we first applied a uniform error surface on each DEM, i.e. the associated error to each topographic reconstruction presented in Table 1. We will explain this in more details in the revised version of the manuscript.

- *P9 Lines 25-26: You suggest that your study "confirms that the SfM algorithm in itself is robust and can be applied to convert raw image datasets into very-high resolution 3D point clouds." This is rather obvious and has been documented and addressed in great detail in a vast number of published manuscripts. I think you might need to reconsider what the main findings of your work actually are – perhaps the scientific findings are more interesting than the methodological ones?*

We agree with the point that SfM is now considered as robust for accurate 3D reconstruction of natural environments. As written earlier, we will refocus the discussion more on the scientific findings about hillslope failure mechanism and on the additional but complimentary value of very-high resolution 4D data for capturing landslide dynamics.

- *P9 Line 30-onwards: Is it worth commenting on the application of ground-control here and any influence control measurement may have had on the resulting pattern of morphological change? For example, did you have any issues placing GCPs on problematic terrain and did this impact your GCP spacing (suggested 25m spacing on P5. Line 25)? Does the GCP distribution weaken confidence in any of your findings? As I am certain you are aware, the application of GCPs is a time-intensive process that is important for reducing uncertainty in topography surveys. These themes (amongst other aspects of the SfM workflow) have recently been addressed by the work of James et al. (2017) via articles published in the journals ESPL and Geomorphology. On inaccessible and unstable terrain ground control cannot always be applied for practical/safety reasons (e.g. volcanic terrain). There has been some discussion about the potential for using direct georeferencing based UAV-SfM workflows in hazardous terrain (e.g. Carbonneau and Dietrich, 2017, ESPL). I think you would benefit from acknowledging these approaches/methodological papers when discussing the merits of the UAV-SfM approach for monitoring earthflows in this manuscript. In summary, the latest SfM findings need to be better integrated into this manuscript.*

The pattern of GCP is very regular, i.e. one GCP every ca. 25 m in each direction on the active area of the earthflow. A figure depicting the GCP pattern will be provided in the revised version of the manuscript. Even if the terrain was problematic/dangerous at some places, we managed to overcome this issue to put nearly all the GCP that we wanted, for the sake of accurate final 3D reconstructions. In fact, the parameter that mainly affects the accuracy is the error associated to the GPS measurements due to poor signal. This led us to remove some GCPs with high associated error, as errors propagate to the final global accuracy of the 3D reconstructions after point cloud georeferencing (Clapuyt et al., 2016). We will add an explanation about this in the revised version of the manuscript.

Direct georeferencing is of course a potential solution as long as you are able to embed an RTK GPS in the UAV platform to geotag each picture. Otherwise, in our opinion, it is still worth to take the time to measure GCPs manually, in order to have accurate outputs. At the time of the surveys, we had not yet integrated such a device in our UAV platform, especially because of the lack of suitable low-cost and lightweight RTK devices on the market at that time. But we will acknowledge recent papers about this issue in the introduction

- *P10 Lines 1-4: The regulatory framework for RPAS/UAV operation is rapidly evolving in many countries. Are you able to briefly highlight any specific considerations (with reference to support materials) pertinent to your work in Switzerland? I am sure this information will be beneficial to geoscientists/geomorphologists planning future work in Switzerland.*

As you mention, this type of legislation changes rapidly, so we prefer not include the specific rules for Switzerland as it is possible that they will change in the future. At the moment: under 30 kg, drones can be flown without a permit as long as the pilot maintains eye contact with the device.

Swiss aircraft regulation:

https://www.admin.ch/opc/en/classified-compilation/19940351/index.html.

Forbidden areas must be avoided:

(https://map.geo.admin.ch/?topic=aviation&bgLayer=ch.swisstopo.pixelkarte-grau&layers=ch.bafu.bundesinventare-vogelreservate,ch.bafu.bundesinventare-jagdbanngebiete,ch.bazl.einschraenkungen-drohnen&lang=en&layers_opacity=0.75,0.75,0.6&catalogNodes=1379)

- *Table 1: It would be great to see the GCPs plotted in a figure so the reader can assess GCP distribution and the impacts it may have had on the quality of the surface reconstruction for each survey.*

We will add a figure, which will contain the pattern of GCPs, along with the flight pattern (as requested by Referee #2).

Following technical corrections below will be changed in the text and do not need a specific answer at this moment of the review process.

Technical corrections

- *P2. Line 4: 'is' change to 'are'?*
- *P4. Line 12: "auttaumn" change to autumn?*
- *P5. Line 23: Change to "better capture complex 3D structures"?*
- *P10 Line 5: Title for the next section is duplicated in the main body of section 4.1.*

References

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.

Varnes, D. J.: Slope Movement Types and Processes, Transp. Res. Board Spec. Rep., (176), 11–33, doi:In Special report 176: Landslides: Analysis and Control, Transportation Research Board, Washington, D.C., 1978.