

Response to the reviews

In bolt: text added

Referee 1

Overall this is an interesting paper, but i think it requires some more scientific thought and the quality of the analysis and figures require improvement. As is the paper reads like a conference paper, not a journal paper. In general it is an interesting idea, but the tests are limited to three sites with dramatically different settings. This limits the authors ability to quantify the method, they should have focused on a slope type (close and rock, or far and soil) and tested three or four of that type. This would have led to a more robust analysis and conclusion. As it stands the authors state it works in some places better than others based on picture quality, lightening, etc. These are not geotechnical qualities, which should have been the focus. If the focus was on image quality, NHESS is the wrong journal for submission. I encourage the authors to dive deeper into their work and test many more sites and resubmit. Some specific comments: Stating LiDAR is expensive and demanding from a logistics point of view is irrelevant, especially when referencing a paper from 2014, that was likely written in 2012 or 2013. Modern applications of lidar are neither of those. Avoid general language with little meaning like “reasonably good” You state in Section 4 VisualSFM gave the ‘best results’ – this is arbitrary, you need numbers to back this up. What metric are you using to define ‘best’? Section 4.1: Standard deviation of the error below 20 cm – what error are you assessing? 3D vector, Z, or XY? Your volume estimates do not have ranges, yet your point cloud has alignment errors. You should report volumes with +/- amounts. Again, ‘reasonably good’ should not be used in a scientific paper. Same for ‘We hardly perceive’ ‘Same strong radial’ ? In your conclusions you state the method is useful to ‘quantify slope movements and displacements’ yet you did not show this anywhere in your paper. You showed the ability to measure failed volumes, not displacements. This is a misleading conclusion. On your change mapping images the colours below the limit of detectable change should be coloured grey. All figures need a scale bar. Figure caption 5 is too long. The min and max difference calculated in Table 1 adds no value, those points are likely outliers.

Comment: In general it is an interesting idea, but the tests are limited to three sites with dramatically different settings. This limits the authors ability to quantify the method, they should have focused on a slope type (close and rock, or far and soil) and tested three or four of that type.

Answer: *The idea behind the three different sites is to demonstrate the capacity of the method to work on different topographic areas with different slope types with different distances image point of view – site. The first site (Monaco) shows the modelling of an anthropic slope with a wall collapse. The danger of wall collapse on a transportation track can be found everywhere around the world. We find that this case study is pertinent because it is representative of a real danger for transportation networks. Site 2*

(Séchilienne) shows the capacity of the proposed method to model a large landslide away from the road. With 6 different time steps, results shows a slope evolution over the years which corresponds to the surface changes measured with LiDAR scans. The accuracy is obviously lower as the LiDAR accuracy, but it allows to observe the main surface change. The third site (Arly) focus on a steep slope threatening a road tunnel entry. A rockfall occurred already on this area and protective measures have been built. This site shows the limit of the method in the vertical axis because some images were taken close to the cliff which is much higher than the Monaco wall. We believe that the three sites on different slopes and different settings shows the capacity and limits of the method which can be deployed on several topographic situations.

Comment: As it stands the authors state it works in some places better than others based on picture quality, lightening, etc. These are not geotechnical qualities, which should have been the focus. If the focus was on image quality, NHESS is the wrong journal for submission. I encourage the authors to dive deeper into their work and test many more sites and resubmit.

Answer: *The manuscript presents a uncommon free method that obtain 3D point cloud of a slope without field visit. The focus is clearly not on image quality, but image quality must be mentioned as it is an important condition to obtain results. This is why those “no geotechnical qualities” are mentioned. With the manuscript improvement (see below), it focuses now more on the method (with an added flowchart) and its results.*

Comment: Some specific comments: Stating LiDAR is expensive and demanding from a logistics point of view is irrelevant, especially when referencing a paper from 2014, that was likely written in 2012 or 2013. Modern applications of lidar are neither of those

Answer: *Although LiDAR references are indeed not so actual, we still maintain that LiDAR, compared to the proposed method (free, any field work), is still more expensive and more demanding from a logistics point of view (except handle LiDAR like GeoSlam for the logistic point of view). Scanning cliffs of the case studies demand few hours of field work (as we made on site 2 and site 3).*

Comment: Avoid general language with little meaning like “reasonably good” You state in Section 4 VisualSFM gave the ‘best results’ – this is arbitrary, you need numbers to back this up. What metric are you using to define ‘best’?

Answer: *We totally agree with this remark. We try to define our magnitude order assessment with values or examples. We have for example now: “**This accuracy allows to detect object of tens cetimeters size**” still “reasonably good results”. “Best results” terms have been deleted.*

Comment: Section 4.1: **Standard deviation** of the error below 20 cm – what error are you assessing? 3D vector, Z, or XY? Your volume estimates do not have ranges, yet your point cloud has alignment errors.

Answer: “Error” is a wrong term. It is a distance between a mesh and a point cloud. The computed distance is a 3D vector from the mesh triangle to the cloud point. The sentence is now: “**The computed shortest distance, in signed values, between the mesh and the point cloud is a 3D vector from the mesh triangle to the 3D point.**” (Page 4, line 29)

<https://www.geometrictools.com/Documentation/DistancePoint3Triangle3.pdf>

https://tel.archives-ouvertes.fr/file/index/docid/500182/filename/manuscrit_19052006_electronic.pdf

(Page 36, Section 2.2.1, Figure 2.1 of the linked document)

Comment: In your conclusions you state the method is useful to ‘quantify slope movements and displacements’ yet you did not show this anywhere in your paper. You showed the ability to measure failed volumes, not displacements. This is a misleading conclusion.

Answer: Right, “displacement” is term a little bit too optimistic. It is possible to detect displacement in specific cases (displacement of few meters between the image sets, 3D point cloud with a accuracy of few decimetres, etc.) but we have replaced the term “displacement” with “surface changes”. Surface change on site 1 is the wall collapse, on site 2 it is the rockfall deposit and the rockfall scare, on site 3 there is no surface change because the landslide is located on a cliff part not visible with the GSV images.

Comment: On your change mapping images the colours below the limit of detectable change should be coloured grey. All figures need a scale bar. Figure caption 5 is too long.

Answer: All figures have a scale bar. Figure 5 is cut into 2 different figures with 2 captions.

Comment: The min and max difference calculated in Table 1 adds no value, those points are likely outliers.

Answer: Right, the min and max differences were deleted because their contribution was not very interesting for this manuscript. Point density of the 3D point cloud replaces those deleted values in the Table 1.

Referee 2

This is a very interesting paper with very useful and innovative ideas and I believe that research towards this direction is promising. However, reading the manuscript I missed a strong and solid part on technical specifications for the methodology that is used and for the quantitative analysis of the results, which is the core and the added value of this work. In that sense, I suggest to the authors, to enrich and support the description of the methodology, providing detailed information on the processes followed and to present a more thorough and detailed analysis of their results, in quantitative terms.

Answer: “Methodology” (#3) and “Results and discussion” (#4) sections have been significantly rewritten. Table 2 has been added, as Figures 3, 8 and 9.

Page 3: Lines 19-20

If these parameters are not known beforehand, three pictures is the minimum requirement (Westoby 2012), **and** about six pictures is preferred.

Answer: “And” added.

Page 4: Lines 16-17

We used two image sets from for the first study site, ~~height~~ **eight** images sets for the second study site and four image sets for the third study site, with dates ranging from May 2008 up to December 2016, as described in table 1.

Answer: “Height” replaced by “eight”.

Page 4: Lines 26-29

To perform temporal comparisons on each site, images were taken at the different dates proposed by GSV. We used the SfM-MVS programs VisualSFM (Wu 2011) and Agisoft PhotoScan (Agisoft 2015) for dense point cloud reconstruction and CloudCompare (Girardeau-Montaut 2011) for point cloud visualization and comparison. Comparison between two point clouds was made using point-to-mesh strategy.

Question: *It would be interesting to explain here, how the scaling and georeferencing was done, if you used control points and how many of them.*

Answer: *Sentence replaced by: “To perform temporal comparisons on each site, images were taken at the different dates proposed by GSV **with pre- and post-event images sets**. We used the SfM-MVS program VisualSFM (Wu 2011) **for dense point cloud reconstruction for the print screens images from Google Maps** and we used CloudCompare (Girardeau-Montaut 2011) software for point cloud visualization and comparison. Comparison between two point clouds was made using point-to-mesh strategy.”*

Further, sentence added: **“The rough scaling and georeferencing of the obtained 3D point clouds were been made without ground control points but only with coordinates of few points extracted from Google Maps or French geoportal (Géoportail, 2016).“**

Page 5: Line 1

from print screens

Question: *what is the resolution of the images print screen? could you please provide some more technical information on the process and the result of the print screen? Are there certain specifications in order to achieve the result that you mention here?*

Answer: *Sentence replaced by:* **“Beside the images taken from print screens as described above, we also obtained GSV images (4800 x 3500 pixels, 16.8 Mpx) from Google Earth Pro on sites 2 and 3 with the “save image” function.”** *for resolution information.*

Further, sentence modified: **“In addition, GoPro Hero4+ images from a moving vehicle on the road were taken by the authors on site 2, as well a series of images captured using a GoPro Hero5 Black camera standing on site 3 (image resolution of 4000 x 3000 pixels, 12 Mpx).”**

Following sentence modified and replaced by (about the process): **“This second way to get GSV allows to obtain images with a higher resolution as print screen images. Unfortunately, there is no timeline function in this program and it is only possible to save Google Earth Pro images from the last picture acquisition, i.e. generally post-event images. GSV images from Google Earth Pro were processed with the Agisoft PhotoScan (Agisoft 2015) software for dense point cloud reconstruction. The reason why we chose Visual SFM software to process GSV print screens images from Google Maps is because the processing of those print screens with Agisoft PhotoScan software is not possible while results of GSV images processing from Google Earth Pro is clearly better with Agisoft. The flowchart of SfM-MVS with GSV images combines also two image types from two different sources (print screens and saved images) processed into two softwares (Figure 3).”**

Figure 3 added (process flowchart): **“Flowchart of the SfM-MVS processing with GSV images on an area with the “back in time” function available. Pre-event images are print screens of GSV in Google Maps. Those GSV images are displayed using the “back in time” function in GSV and are processed in Visual SFM software. Post-event images arise either from print screens of GSV in Google Maps using or not the “back in time” function or from GSV images saved in Google Earth Pro. In this last case, the last available proposed GSV images have a greater resolution as the print screens and can be processed in the Agisoft PhotoScan software. (Figure 3 caption).**

Page 5: Line 12

This information was used for quality assessment purposes.

Question: It would be useful here, to get some information on the resolution of the images in each case.

Answer: Image resolution is now given (please see previous question).

Page 5: Lines 9-17

Different results are obtained as a function on the software used for SfM-MVS processing. VisualSFM gave the best results with print screens from GSV while Agisoft PhotoScan could not align any GSV images from Google Maps print screens despite adding a series of control points measured with Google Earth Pro. However, Agisoft Photoscan provided better results with images from Google Earth Pro than VisualSFM.

Question: Is it the same for all the case studies? Any possible interpretation?

Answer: Sentence modified: Different results are obtained as a function on the software used for SfM-MVS processing. **For all case studies**, VisualSFM gave the best results with print screens from GSV while Agisoft PhotoScan could not align any GSV images from Google Maps print screens despite adding a series of control points measured with Google Earth Pro. **Resolution of print screens images seem the be insufficient to be processed with Agisoft PhotoScan.** However, Agisoft Photoscan provided better results with images from Google Earth Pro than VisualSFM.

Page 5: Line 23

The alignment of both point clouds was done on a stable part of the cliff, with a standard deviation of the error below 20 cm (Figure 3C).

Question: What software has been used to htis end?

Answer: Paragraph modified: “It was possible on “Basse Corniche” site to estimate the fallen volume by scaling and comparing the 2008 (**Figure 4A**) and 2010 (**Figure 4B**) point clouds. **The 2008 3D point cloud is composed of 150’000 points with an average density of 290 points per square meter and the 2014 3D point cloud is composed of 182’000 points with an average density of 640 points per square meter (Table 1).** VisualSFM software could align the images and make 3D models before and after the wall collapse. It was possible to roughly scale **and georeference** the scene with the road width **and few point coordinates** measured on Google Earth Pro and on the French geoportal (Géoportail, 2016). After aligning the two 3D point clouds, meshes were built to compute the collapsed volume. The **point to mesh alignment in CloudCompare software** of both point clouds was done on a **small** stable part of the cliff with a standard deviation of the error below 10 cm (Figure 4C) **and on the entire cliff beside the vegetation with a standard deviation of about 25 cm (Figure 4E).**”

Page 6: Lines 7-9

The number of 3D points on the landslide area varies from 9'500 to 25'000 points for a processing with VisualSFM, while 236'000 3D points were generated when using Agisoft PhotoScan.

Question: What is the distance between points? Is the distance varying significantly as the distance from the camera increases?

Answer: in the Discussion (4.4), paragraph and figure (Figure 7) added: **“The point density was evaluated according to the distance between the image point of view and the subject and the image types and processing softwares. The obtained results and the derived trends indicate that the use of GSV images from Google Earth Pro with Visual SFM software increases of factor two the point density compared as the processing of GSV print screens with Visual SFM. The processing of GSV images from Google Earth Pro with Agisoft PhotoScan software increases of factor ten the point density compared as the processing of GSV print screens with Visual SFM (trend lines in Figure 7). Concerning the distance image point of view - area, the expected point density of the 3D point cloud from GSV print screens processed in Visual SFM software of a subject located few meters nears to the camera point of view (“Monaco” dots on Figure 7) is about 300 points/m², about 50 points/m² for an area located at about 100 m (“Arly” dots on Figure 7) and about 0.5 point/m² for an area located at about 700 m (“Séchilienne” dots on Figure 7).”**

Figure 7 caption: **“Correlation between distance camera - case studies and the expected density of points from the three case studies. The red colour dots are results of the three case studies point clouds obtained from Google Street View (GSV) print screens (PS) in Google Maps (GM) processed with Visual SFM software. The red colour dash line represents their trend line based on the three case studies. The orange colour dot is the result of the Séchilienne point cloud obtained from GSV images saved in Google Earth Pro (GEP) processed with Visual SFM software. The orange colour dash line is its estimated trend line only based on the Séchilienne point cloud (point density multiplied by three compared to the red colour trend line). The green colour dots are results of the Séchilienne and Arly point clouds obtained from GSV images saved in (GEP) processed with Agisoft PhotoScan software. The green colour dash line is their estimated trend line based only on the Arly and Séchilienne point clouds (point density multiplied by eleven compared to the red colour trend line). By way of comparison, the blue colour dots represent the result of the Séchilienne and Arly point clouds obtained with GoPro action camera images taken on the field and processed with Agisoft PhotoScan software.”**

Page 6: Line 12

(distance point to mesh in absolute values)

Question: the absolute value would be 2.1 and not -2.1.

Answer: Paragraph modified. Those values were deleted.

Page 6: Line 23

less accurate when using SfM-MVS processing

Question: Please explain

Answer: I think that it is now understandable with the different added text in the manuscript that low resolution print screens with Visual SFM software provide less accurate results as images saved from Google Earth Pro are processed in Agisoft PhotoScan software.

Sentence modified: “Results were less accurate when using SfM-MVS processing with VisualSFM and lower resolution print screen images from Google Maps **probably due to the too low image resolution of those print screens.**”

Page 7: Lines 16-17

the GNSS integrated in the camera;

Question: What about its scaling and orientation?

Answer: Sentence modified: “The 3D point cloud from the GoPro Hero5 Black images has been roughly georeferenced, **scaled and oriented** thanks to the GNSS **chip** integrated in the camera **and has been controlled and refined with point coordinate extracted from Google Maps and the French geoportal.**”

Page 7: Line 20

gives the least accurate results (Figure 5A).

Question: please provide some quantitative information on the accuracy (level of error, point cloud density). How are the errors distributed all the point cloud, with respect to the distance from the photo camera?

Answer: it converges to the question “Page 6: Lines 7-9”. In all paragraphs of section 4 “Results and discussion”, there is now more information about the clouds comparison.

Page 9: Line 12-13

According to the results, small-scale landslides and rockfalls (<1 m³) can be detected when the slope or the cliff is close to the road (0-10 m), as it was shown on site 1.

Question: Are there areas where this small changes correspond to errors although they have been detected, they are not realistic? Is their proportion important? Could you please comment on that?

Answer: Sentence further added: “**On such sites, small changes (<1 m³) can correspond to as well as realistic rockfalls as errors resulting of from processing like on the toe of the almost all Séchilienne landslide 3D point clouds (Figure 5 A2-H2).**”

Page 9: Lines 18-19

This is attributable to the occurrence of slope movements generating material increase or decrease and thereby, increasing standard deviations of the error.

Question: *In the case of low density of the point cloud (of some meters of example), the roughness of the terrain in case study 2, due to the different sized of the deposited blocks plays an important role when aligning the point clouds and calculating the errors. How has this been taken into consideration, where the point cloud density is low?*

Answer: *Sentences added: “It can also be due to a bad 3D point cloud alignment. Indeed, the cloud alignments is not always easy on some point clouds because of low point density, because of voids in the point clouds (like in the landslide toe in Figure 5 F2) and because of the roughness of the terrain due to the different sized of the deposited blocks. In such difficult alignment cases, it was tried to align the point clouds on parts where the point cloud quality was the best to make an alignment and where the parts were stables.”*

Page 17: Lines 1-5

Figure 4: Results at site 2 “Séchilienne”. Eight points clouds from different images sets taken at six different time with three different image sources and processed with two different programs. Figures A1-H1: Meshs resulting from the respective point clouds. Figures A2-H2: point clouds comparison with a 50 cm LiDAR DEM from 2010 (red colour points is material increase; blue colour points are material decrease from the 2010 LiDAR cloud). The information on the pictures source and date and on the program used is given in Table 1.

Question: *I think it would help to use the same colour scale for the easier comparison of the displacements at different point clouds.*

Answer: *All scales are now similar (-5 to +5 m).*

10 Using street view imagery for 3D survey of rock
11 slope failures
12

13 J., Voumard¹, A., Abellan^{1,2}, P., Nicolet^{1,3}, M.-A. Chanut⁴, M.-H., Derron¹, M., Jaboyedoff¹

14 ¹ Risk analysis group, Institute of Earth Sciences, FGSE, University of Lausanne, Switzerland

15 ² Scott Polar Research Institute, Department of Geography, University of Cambridge, United Kingdom

16 ³ Geohazard and Earth Observation team, Geological Survey of Norway (NGU), Norway

17 ⁴ Groupe Risque Rocheux et Mouvements de Sols (RRMS), Cerema Centre-Est, France
18

Format

Format

19 Abstract

20 We discuss here ~~the different~~ challenges and limitations on surveying rock slope failures using
21 3D reconstruction from ~~images~~image sets acquired from Street View Imagery (SVI) ~~and~~
22 ~~processed with modern photogrammetric workflows.~~ We show how ~~the “back in time”~~
23 ~~function~~rock slope surveying can be ~~used for a 3D reconstruction of~~performed using two or
24 more image sets using online imagery with photographs from the same site but acquired at
25 different instants ~~of time, allowing for rock slope surveying.~~ Three sites in the French alps
26 were selected: ~~(a as pilot study areas:~~ (1) a cliff beside a road where a protective wall
27 collapsed consisting ~~of~~ two images sets (60 and 50 images ~~in~~ each set) captured ~~in~~within
28 a six years ~~time-frame;~~ ~~(b~~time-frame; (2) a large-scale active landslide located on a slope at
29 250 m from the road, using seven images sets (50 to 80 images per set) from 5 different time
30 periods with three images sets for one period; ~~(c~~3) a cliff over a tunnel which has collapsed,
31 using two ~~images~~image sets ~~captured in~~ a four years time-frame. The analysis
32 ~~includes~~include the use of different ~~commercially available~~ Structure for Motion (SfM)
33 programs and ~~the~~ comparison between the so-extracted photogrammetric point clouds and a
34 LiDAR derived mesh that was used as a ground truth. ~~As a result,~~Results show that both
35 landslide deformation ~~together with~~and estimation of fallen volumes were clearly identified in
36 the different point clouds. Results are site and software-dependent, as a function of the image
37 set and number of images, with model accuracies ranging between 0.2 and 3.8 m in the best
38 and worst scenario, respectively. ~~Despite~~Although some ~~clear~~ limitations and
39 ~~challenges derived from the generation of 3D models from SVI were observed,~~ this ~~manuscript~~
40 ~~demonstrates that this original~~ approach ~~might~~ allow obtaining preliminary 3D models of an
41 area without on-field images. ~~Furthermore,~~ allowing extracting the pre-failure topography
42 ~~can be obtained for sites where it~~that would not be available otherwise.

43

44 Keywords

45 Street ~~view imagery,~~View Imagery (SVI), Structure from Motion, ~~(SfM)~~, photogrammetry,
46 3D point cloud, natural hazard, landslide, rockfall.

47 1 Introduction

48 3D remote sensing techniques are becoming widely used for geohazard investigations due to
49 their ability to represent the geometry of natural hazards (mass movements, lava flows, debris

50 flows, etc.) and its evolution over time by comparing 3D point clouds acquired at different
51 time steps. For example, 3D remote sensing techniques are helping to better quantify key
52 aspects of rock slope evolution, including the accurate quantification of rockfall rates and the
53 deformation of rock slopes before failure using both LiDAR (Rosser et al., 2005; Oppikofer et
54 al, 2009; Royan et al., 2013; Kromer et al., 2015; Fey and Wichmann., 2016) and
55 photogrammetrically derived point clouds (Walstra et al., 2007; Lucieer et al., 2013, Stumpf
56 et al., 2015; Fernandes et al., 2016; Guerin et al., ~~2016~~2017; Ruggles et al., 2016).

57 Airborne and terrestrial laser scanner (ALS and TLS, respectively) are commonly used
58 techniques to obtain 3D digital terrain models (Abellan et al., 2014). Despite their very high
59 accuracy and resolution, these technologies are ~~expensive~~costly and often demanding from a
60 logistic point of view ~~(Abellan et al., . Alternatively, 2014)~~. ~~Another way to obtain point~~
61 ~~clouds without these inconveniences is photogrammetry, in particular the~~ Structure from
62 Motion (SfM) photogrammetry combined with multiview-stereo (MVS) ~~that allow~~ generating
63 ~~reasonably good 3D point clouds using end-user digital cameras~~ to generate 3D point clouds
64 with a decimetre level accuracy in a cost-effective way in order (Westoby et al., 2012;
65 Carrivick et al., 2016).

66 Whereas most of the studies in SfM literature utilise pictures that were ~~directly~~ captured on-
67 ~~site, purpose~~ (Eltner et al., 2016), the potential of using internet-retrieved pictures ~~has for 3D~~
68 ~~reconstruction has not~~ been fully discussed before (e.g. Snavely et al., 2008; Guerin et al.,
69 2017). One of the large sources of pictures on-line is the Street View Imagery (SVI) services,
70 which offer 360 degrees panoramas from many roads, streets and other places around the
71 world (Anguelov et al, 2013). It allows to remotely observe areas ~~at a very reduced cost and~~
72 ~~without physically accessing them~~. ~~SVI is thus an interesting visual information source and so~~
73 in a cost-effective way, with applications in navigation, tourism, building texturing, image
74 localization, point clouds georegistration and motion-from-structure-from-motion (Zamir et
75 al. 2010; Anguelov et al, 2010; Klingner et al, 2013; Wang, 2013; Lichtenauer et al., 2015).

76 The aim of present work is to ascertain ~~whether~~ up to which extent 3D models ~~be~~ derived from
77 ~~SVI using photogrammetric workflows~~ can be used to detect geomorphic changes on rock
78 slopes.

79 1.1 Street View Imagery

80 The most common SVI service is the well-known Google Street View (GSV) (Google Street
81 View, 2017) that is available from Google Maps (Google Maps, 2017) or Google Earth Pro

82 (Google Earth Pro, 2013). We used both GSV as SVI service in this study. Alternatives
83 include ~~Streetside~~StreetSide by Microsoft (~~Streetside~~StreetSide, 2017) and other national
84 services like Tencent Maps in China (Tencent Maps, 2017). SVI was firstly deployed in urban
85 areas to offer a virtual navigation into the streets. More recently, non-urban zones can also be
86 accessed, and ~~will be~~used for the analysis of rock slope failures in this manuscript.

87 ~~Firstly~~GSV was firstly used in May 2007 for capturing pictures in streets of the main cities in
88 USA, ~~GSV and it~~ has been deployed worldwide over the forthcoming years, including also
89 rural areas. GSV images are collected with a panoramic camera system mounted on different
90 types of vehicles (e.g. a car, train, bike, snowmobile, etc.) or carried into a backpack
91 (Anguelov et al, 2010) ~~(Figure 1)~~.

92 The GSV first generation camera system was composed of eight wide-angle lenses and it is
93 currently composed of fifteen CMOS sensors 5Mpx each (Anguelov et al, 2010). The fifteen
94 raw images, which are not publicly available, are processed by Google to make a panorama
95 view containing an a priori unknown image deformation- ~~(Figure 1)~~. A GSV panorama is
96 normally taken at an interval of around ten meters along a linear infrastructure (road, train, ~~or~~
97 path).

98 GSV proposes a *back-in-time function* on a certain number of locations since April 2014.
99 ~~Historical~~In addition, other historical GSV images are available from 2007 for selected areas
100 only. The number of available image sets greatly varies ~~a lot because it depends on the~~
101 ~~number of acquisitions made by Google. While~~ at different locations: while some places have
102 several sets, many other locations have only one image set, ~~some places have several sets.~~
103 This. Back in time function is especially useful for natural hazards because it is possible to
104 compare pre- and post-events images.

105 The GSV process can be explained in four steps (Anguelov et al, 2010; Google Street View,
106 2017): 1) Pictures acquisition in the field; 2) Image alignment: preliminary coordinates are
107 given for each picture, extracted from sensors on the Google car that measure GNSS
108 coordinates, speed and azimuth of the car, helping to precisely reconstruct the vehicle path.
109 Pictures can also be tilted and realigned as needed; 3) Creation of 360° panoramas by
110 stitching overlapping pictures. Google applies a series of processing algorithms to each
111 picture to attenuate delimitations between each picture and to obtain smooth pictures
112 transitions; 4) Panoramas draping on 3D models: the three LiDAR mounted on the Google car
113 help to build 3D models of the scenes. 360° panoramas are draped on those 3D models to give

114 a panorama view close to the reality. Each picture of the panorama has its own internal
115 deformation, and the application of the processing chain described above makes inconstant
116 deformation in the 360° panorama; in addition, the end-user does not have any information or
117 control on it.

118 1.2 SfM-MVS

119 Structure for Motion (SfM) with Multi-View Stereo (MVS) dense reconstruction is a ~~low-~~
120 ~~cost-effective~~ photogrammetric method to obtain a 3D point cloud of terrain using a series of
121 overlapping images (Luhmann et al., 2014). The prerequisites are that: (1) the studied object
122 is photographed from different points of view, and (2) each element of the object must be
123 captured from a minimum of two pictures assuming that the lens deformation parameters are
124 known in advance (Snavely 2008; Lucieer et al. 2013). If these parameters are not known
125 beforehand, three pictures is the minimum requirement (Westoby 2012), ~~and~~ about six
126 pictures is preferred. The particularity of SfM-MVS is that prior knowledge of both intrinsic
127 camera parameters (principal point, principal distance and lens distortion) and extrinsic
128 camera parameters (orientation and position of the camera centre (Luhmann et al., 2014)) is
129 not needed.

130 The workflow of SfM-MVS normally includes the following steps: 1) Feature detection and
131 matching (Lowe, 1999); 2) Bundle adjustment (Snavely et al., 2006; Favalli et al., 2011;
132 Turner et al., 2012; Lucieer et al., 2013); 3) Dense 3D point cloud generation (Furukawa et
133 al., 2010; Furukawa & Ponce, 2010; James & Robson, 2012); and 4) Surface reconstruction
134 and visualization (James & Robson, 2012).

135 2 Study areas and available data

136 We selected three study areas in France to generate point clouds from GSV images. This
137 country was chosen because GSV cover the majority of the roads and because the timeline
138 function works in most of the areas covered by GSV, meaning that several periods of
139 acquisition are available. Moreover, landslide events occur regularly on French alpine roads.
140 The aerial view of the three areas is shown in Figure 2A and examples of corresponding GSV
141 images in Figure- 2B and 2C.

142 The first case study (“Basse corniche” site) is a 20 m high cliff beside a main road in
143 Roquebrune – Cap Martin connecting the town of Menton to the Principality of Monaco, in
144 South-Eastern France. A wall built to consolidate the cliff collapsed after an extreme rainfall
145 event in January 2014, blocking the road (Nice-Matin, 2014). Two 3D models were built with

146 60 GSV images taken in 2008 before the wall collapse, and 50 GSV images taken in 2014
147 after the event.

148 The second case studies is Séchilienne landslide, located 15 km South East of Grenoble (Isère
149 department, France). The active area is threatening the departmental road RD 1091
150 connecting the towns of Grenoble and Briançon as well as a set of ski resorts such as L'Alpe
151 d'Huez and Les Deux Alpes to the plain. This landslide is about 800 m long by 500 m high
152 and it has been active during more than thirty years (Le Roux et al. 2009; Durville et al. 2011;
153 Dubois et al. 2014). The shortest distance between the landslide foot and the former road was
154 250 m- and the longest distance between the landslide head and the road is 1 km. A new road,
155 located higher in the opposite slope, has been opened since July 2016. Different SfM-MVS
156 processing were tested using from 50 up to 80 GSV images, at six different times from April
157 2010 to June 2015.

158 The third case study is located in “Arly gorges”, between Ugine and Megève on the path
159 Allevard – Chamonix-Mont-Blanc. A rockfall of about 8'000 m³ affected the road at the
160 entry of a tunnel on January 2014 (France 3, 2014). Different sets of images ranging from 60
161 to 110 GSV images were processed in order to obtain three 3D models of the road, the tunnel
162 entry and the cliff above the tunnel.

163 We used two image sets from for the first study site, ~~height images~~eight image sets for the
164 second study site and four image sets for the third study site, with dates ranging from May
165 2008 up to December 2016, as described in ~~table~~Table 1.

166 3 Methodology

167 First step to make SfM-MVS with SVI is to ~~get~~obtain images from a SVI service. GSV has
168 been used in this study (~~Figure~~Figure 1). Given that original images of the Google cameras
169 are not available, one of the only way~~two ways~~ to get images from GSV is to manually extract
170 them from the GSV panoramas. We took print screens (1920 x 1200 pixels, 2.3 Mpx) of GSV
171 panoramas of the studied areas at each acquisition step ~~(, separated by about ten meters).~~We
172 ~~took several, from Google Maps. Several~~ images were taken from the same point of view with
173 different pan and tilt angles (Figure 1C) when the studied object was too close to the road. In
174 such cases, it was impossible to have the entire area in one image because the image is not
175 wide enough to capture the entire studied area (for example a 10 m high cliff along road).
176 When the studied area was far away from the road, we took print screens of zoomed sections
177 of the panorama.

178 To perform temporal comparisons on each site, images were taken at the different dates
179 proposed by GSV, with pre- and post-event images sets. We used the SfM-MVS
180 programsprogram VisualSFM (Wu 2011) and Agisoft PhotoScan (Agisoft 2015) for dense
181 point cloud reconstruction for the print screens images from Google Maps and we used
182 CloudCompare (Girardeau-Montaut 2011) for point cloud visualization and comparison.
183 Comparison between two point clouds was made using point-to-mesh strategy. A To this end,
184 a mesh of onewas generated from the reference point cloud (~~whether~~ the point cloud with the
185 oldest images for ~~the~~ site 1 or the LiDAR scans for ~~the~~ sites 2 and 3) is compared withand
186 then the other point cloud was compared to obtain thethis reference mesh. The computed
187 shortest distance~~of each point of~~, a signed value, between the mesh and the point cloud is the
188 length of the 3D vector from the mesh triangle to the mesh3D point. Thus, average distances
189 and standard deviations for each comparison of point clouds have been computed. Point
190 density of point clouds was obtained using the “point density” function in ~~absolute~~
191 valuesCloudCompare with the “surface density” option.

192 Beside the images taken from print screens as described above, we also obtained GSV images
193 (4800 x 3500 pixels, 16.8 Mpx) from Google Earth Pro on sites 2 and 3 with the “save image”
194 function. This second way to get GSV allows to get images with a higher resolution than print
195 screen images. Unfortunately, there is no timeline (or “back in time”) function in ~~this program~~
196 ~~and Google Earth Pro~~; it is only possible to save ~~Google Earth Pro~~ images from the last
197 picture acquisition, i.e. generally post-event images. GSV images from Google Earth Pro
198 were processed with the Agisoft PhotoScan software (Agisoft 2015) for dense point cloud
199 reconstruction, which provides much better results than VisualSFM. GSV images from
200 Google Map were processed with VisualSFM because Agisoft was not able to process those
201 print screens. The flowchart of Figure 3 shows the processing applied to both types of images
202 (print screens and saved images).

203 A rough scaling and georeferencing of the 3D point clouds was made without ground control
204 points, only with coordinates of few points extracted from Google Maps or from the French
205 geoportal (Géoportail, 2016).

206 It is important to mention here that a series of issues are expected when attempting to use SVI
207 for 3D model reconstruction with SfM-MVS. Indeed, GSV images are constructed as 360°
208 panoramas from a series of pictures, so the internal deformation of the original image is not
209 fully retained on the panoramas. In other words, the deformation of a cropped section of the
210 panorama will be a main function not only of the internal deformation of the camera and lens

211 but to the panorama reconstruction process; ~~This~~this circumstance will significantly influence
212 the bundle adjustment process and so to the 3D reconstruction.

213 In addition, GoPro Hero4+ images from a moving vehicle on the road were taken by the
214 authors on site 2, as well a series of images captured using a GoPro Hero5 Black camera
215 standing on site 3- (image resolution of 4000 x 3000 pixels, 12 Mpx). Six LiDAR scans were
216 also taken on site 3. This information was used for quality assessment purposes.

217

218 4 Results and discussion

219 Different results are obtained ~~as a function~~depending on the software used for SfM-MVS
220 processing. For all case studies, VisualSfM gave ~~the best~~ results with print screens from GSV
221 in Google Maps while Agisoft PhotoScan could not align ~~any GSV images from Google~~
222 ~~Maps those~~ print screens despite adding a series of control points measured with Google Earth
223 Pro. ~~However~~Resolution of print screens images seem to be insufficient to be processed with
224 Agisoft PhotoScan. However, with higher point density and empty areas, Agisoft Photoscan
225 provided better results with images from Google Earth Pro than VisualSfM.

226 4.1 Site 1 – “Basse corniche” site

227 It was possible on “Basse Corniche” site to estimate the fallen volume by scaling and
228 comparing the 2008 ~~and 2010 point clouds~~. ~~VisualSfM software~~(Figure 4A) and 2010
229 (Figure 4B) point clouds. The 2008 point cloud is composed of 150'000 points with an
230 average density of 290 points per square meter and the 2014 point cloud is composed of
231 182'000 points with an average density of 640 points per square meter (Table 1). VisualSfM
232 could align the images and make 3D models before and after the wall collapse. It was possible
233 to roughly scale and georeference the scene with the road width and few point coordinates
234 measured on Google Earth Pro ~~and/or~~ on the French geoportal-~~(Géoportail, 2016)~~. After
235 aligning the two 3D point clouds, meshes were built to compute the collapsed volume. The
236 point-to-mesh alignment in CloudCompare of both point clouds was done on a small stable
237 part of the cliff, (Figure 4C) with a standard deviation of the ~~error below 20 cm~~ (Figure 3C).
238 ~~Not surprisingly, this one is less accurate than other studies using user end camera and~~
239 ~~equivalent sensor to object~~point-to-mesh distance ~~(Eltner et al., 2016)~~.of about 10 cm (Figure
240 9 and Table 2) and on the entire cliff beside the vegetation with a standard deviation of about
241 25 cm (Figure 4E). In the collapsed area, the maximal horizontal distance between the two
242 datasets is about 3.9 m- (red colour in Figure 4D). The collapsed volume (including a

243 ~~potentially hole~~possible empty space between the cliff and the wall before the event) was
244 estimated to be about 225 m³ using the point cloud comparison ~~method described above~~.
245 Based on Google Street images, we manually estimated the dimensions of this volume (15 m
246 long x 10 m high x 1.5 m deep), getting a similar value.

247 The ~~reasonably good results were~~obtained point clouds on site 1 allow to detect object of few
248 decimetres. This accuracy was adequate to estimate the collapsed volume with an accuracy
249 similar to the estimation made by hand based on the GSV photos and distances measured on
250 Google Earth Pro and the French geoportal. This relatively high accuracy is due to the
251 following factors: good image quality, reduced distance between the cliff ~~proximity to the~~ and
252 camera ~~location, the~~locations, good lighting, ~~the~~ conditions, absence of obstacles between the
253 camera location and the ~~wall~~area under investigation, no vegetation and ~~the~~ efficient
254 repartition of point of view around the cliff (Figure 2 A). ~~“Basse Corniche” results (Figure 5~~
255 ~~and Table 1) are the best results obtained among the three study areas.~~

256 4.2 Site 2 – ~~Sechillienne~~Séchillienne Landslide

257 Eight point clouds of which seven of SfM-MVS process with GSV images were generated for
258 Séchillienne landslide at six different time steps (from April 2010 to June 2015). Three
259 different image sources were used: GSV print screens from Google Maps, GSV images saved
260 from Google Earth Pro and images from a GoPro HERO4+ camera from a moving vehicle
261 (Figure 4~~5~~ and Table 1). Two different programs (VisualSFM and Agisoft PhotoScan) were
262 used for image treatment: in function of the image sources (Figure 3 and Table 1). The
263 number of 3D points on the landslide area varies from 9’500 to 22’500 points for a processing
264 with VisualSFM with an average density of 0.25 to 0.85 points per square meter, while
265 236’000 3D points were generated when using Agisoft PhotoScan: with an average density of
266 2 points per square meter (Table 1). In comparison, 1’500’000 points were obtained on the
267 same area using terrestrial photogrammetry with a 24 Mpx reflex camera. ~~Results were~~
268 ~~aligned on a 50 cm resolution LiDAR scan of the landslide acquired in 2010. Then, the street~~
269 ~~view SfM MVS point clouds were compared with a mesh from the LiDAR scan. The average~~
270 ~~distance of both point clouds are respectively 0.2 and 1.4 m (distance point to mesh in~~
271 ~~absolute values). The standard deviations are 1.6 m and 3.8 m (Figure 4 A-E). SfM-MVS~~
272 ~~point clouds from Google Earth Pro images processed with Agisoft PhotoScan provide the~~
273 ~~best results (Figure 4G). These images have a resolution about 7.3 times higher than the print~~
274 ~~screens from Google Maps (1920x1200 pixels for GSV print screens from Google Maps~~
275 ~~versus 4800x3500 pixels for GSV images exported from Google Earth Pro).~~

276 ~~Landslide changes between 2010 (Results were aligned on a 50 cm resolution airborne~~
277 ~~LiDAR DEM) and 2015 (SfM MVS) are observable with a material accumulation (red colour~~
278 ~~in Figure 4G) in the debris cone and some material losses in the upper partscan~~ of the
279 ~~landslide (blue colour in Figure 4G). Unfortunately, the back in time function does not exist in~~
280 ~~Google Earth Pro and it is thus not possible to save old GSV images acquired in 2010. Then,~~
281 ~~the street view SfM-MVS point clouds were aligned and compared with a mesh from Google~~
282 ~~Earth Pro. Finally, the comparison between the LiDAR mesh and the SfM MVS cloud~~
283 ~~derived from GoPro HERO4+ camera images (Figure 4H) gives similar results to those~~
284 ~~obtainedscan using the GSV images from Google Earth Pro (Figure 4G). Thus, the best~~
285 ~~results of the SVI derived models were obtained with Agisoft PhotoScan when using Google~~
286 ~~Earth Pro images. Results were less accurate when using SfM MVS processing with~~
287 ~~VisualSFM and lower resolution print screen images from Google Maps.~~

288 ~~This case study shows a good correlation between our ground truth (i.e. LiDAR point cloud)~~
289 ~~and some SfM MVS point clouds derived from SVI datasets.point-to-mesh strategy. The~~
290 ~~adjustmentalignment between the LiDAR point cloud and SfM-MVS point clouds derived~~
291 ~~from SVI is a key factor definingto define the quality of the clouds comparison. This manual~~
292 ~~adjustmentalignment on stable areas (manually selected) was not easy to perform because of~~
293 ~~the low density of points on the SfM-MVS clouds derived from SVI. We noted a huge~~
294 ~~difference onin the number of points between the different SfM-MVS clouds derived from~~
295 ~~SVI. This difference on the number of points shows the impacts of the image quality. Images~~
296 ~~with a good quality (resolution, exposition, sharpness) will give point clouds with a higher~~
297 ~~number of points as point clouds from low quality images.~~

298 ~~ImagesComparison results between SfM-MVS point clouds derived from SVI and airborne~~
299 ~~LiDAR scan highlight surface changes in the Séchilienne landslide over the years (Figure 8~~
300 ~~and Table 1). The 2010 point cloud (Figure 5 A2) compared with 2010 LiDAR scan does not~~
301 ~~show any significant changes. Orange and red colours small dots are spread out on the entire~~
302 ~~landslide surface suggesting artefacts and not a real slope change. The 2010-2011 point~~
303 ~~clouds comparison (Figure 5 B2) shows few little red colour pattern (materiel accumulation)~~
304 ~~in the deposition and in the failure areas. The 2016 point cloud (Figure 5 C2) highlights~~
305 ~~material deposition in red colour, in the left part. This is confirmed with comparison of a 2013~~
306 ~~terrestrial LiDAR. The blue colour pattern indicate a loss of material in the failure and the toe~~
307 ~~areas. The 2014 point cloud (Figure 5 D2) shows similar results than the 2013 point cloud~~
308 ~~with however a light increase of material in the deposition area and rock loss in the failure~~

309 area. The 2010 to 2014 point clouds (Figure 5 A-D) were process with VisualSFM with GSV
310 print screens in Google Maps (Table 1).

311 Three 2015 point clouds were processed: the first with VisualSFM and GSV print screens
312 (Figure 5E), the second with VisualSFM with GSV images from Google Earth Pro (Figure
313 5F) and the third with Agisoft PhotoScan with images form Google Earth Pro again (Figure
314 5G). The results should be the same for the three point clouds but we noticed significant
315 differences. The 2015 point cloud processed with VisualSFM and GSV images from Google
316 Earth Pro (4800 x 3500 pixels), has a higher point density than the 2015 point cloud processed
317 with GSV print screens (1920 x 1200 pixels). The 2015 point cloud with Agisoft PhotoScan
318 and images from Google Earth Pro has a point density significantly higher (Table 1). The
319 accumulation material (red colour in the left part) in the deposition area is clearly observable
320 on the three 2015 point clouds, as the rock displacement-toppling below the failure area (red
321 colour pattern in the failure area viewed as a material accumulation from the road). The loss
322 of material (blue colour) is also well observable in the failure area and, to a lesser extent, in
323 the right part of the deposition area. The last 2015 point cloud is very similar to the 2016
324 GoPro point cloud (Figure 5 H2) which confirms the results of SfM-MVS processing with
325 GSV images.

326 Results of site 2 show that images with low resolution and with low lighting generated a
327 lower number of points compared to the models generated with the last generation of GSV
328 cameras, having higher resolution ~~and~~, more advanced sensors and pictures taken with
329 favourable lighting conditions. The large distance between the road and the landslide
330 considerably limits the final accuracy due to low image resolution, as discussed in Eltner et
331 al., ~~2015~~2016; the closest distance between the road and the centre of the landslide is 500 m
332 and the largest distance between the upper part of the landslide and the point of view is about
333 1'400 m. Furthermore, the vegetation on the landslide foot and along the road as well as a
334 power line partially obstruct the visibility of the study area. In addition, clouds are present on
335 several images on the top of the scarp, degrading the upper part of the 3D point cloud. ~~Results~~
336 ~~show that it is not possible to bring out changes in the landslide over the years because of the~~
337 ~~insufficient accuracy of the SfM MVS point clouds with SVI, except for the 3D clouds~~
338 ~~resulting from the GSV images saved in Google Earth Pro and processed in Agisoft~~
339 ~~PhotoScan (Figure 4G). However, the main landslide structures such as little gullies observed~~
340 ~~in the failure zone and deposition area show an interesting approximation of the current~~
341 ~~landslide morphology as it was recorded with LiDAR.~~

342 4.3 Site 3 – Arly Gorges

343 Four point clouds of which three of SfM-MVS process derived from GSV images were
344 generated on the “Arly gorges” site, at four different times (from March 2010 to December
345 2016). Three different images sources (GSV print screens from Google Maps, GSV images
346 exported from Google Earth Pro and our own images acquired from a GoPro HERO5 Black)
347 were used (Figure 56 and Table 1). Two different programs (VisualSFM and Agisoft
348 PhotoScan) were tested. In addition, a LiDAR point cloud resulting from an assembly of six
349 Optech Iris scans has been used as ground truth- (Figure 6E). The number of points varies
350 from 35’000 points to 3.2 million points with an average density of 40 to 2’200 points per
351 square meter (Table 1).

352 The 3D point cloud from the “GoPro Hero5 Black” images has been roughly georeferenced,
353 scaled and oriented thanks to the GNSS chip integrated in the camera; and has been controlled
354 and refined with points coordinates extracted from Google Maps and the French geoportal.
355 The three point clouds processed from GSV images and the LiDAR scan have been roughly
356 aligned to this reference. Then the four SfM-MVS point clouds (three with GSV images and
357 one with GoPro images) were precisely aligned and scaled on the LiDAR point cloud, which
358 was considered as the reference cloud.

359 The analysis (Figure 9, Tables 1 and 2) shows that the 2010 model derived from GSV images
360 processed with VisualSFM gives the least accurate results (Figure 5A). WeFigures 6A and
361 7A): we hardly perceive on that figure the wall of the tunnel entry and the wide cliff
362 structures. The results of the 2014 point cloud from 2014-GSV images processed with the
363 same program are slightly better (Figure 5B)-6B and 7B): the right-hand tunnel entry is
364 modelled while it was not the case on the 2010 point cloud. The point cloud processed in
365 Agisoft PhotoScan derived from 2016 GSV images saved from Google Earth Pro displays
366 much better quality than the previous (Figure 5C)-We6C and 7C): we now see the protective
367 nets in the slope as well as the blue road sign announcing the tunnel. The vegetation is also
368 observable- and the tunnel entry is similarly modelled as the 2016 GoPro point cloud (Figure
369 6D).

370 The SfM-MVS point cloud derived from GoPro images gives a significantly better
371 representation of the scene (Figure 5D)-whole scene, especially on the top of the model. Slope
372 structures and protective nets are well modelled, but not the small vegetation. The comparison
373 between the 2016 LiDAR scan (Figure 5E6E) and the three SfM-MVS with GSV images

374 point clouds does not allow to identify terrain deformation on the cliff. Moreover, the source
375 area of the rockfall is not observable from the GSV images because it is located higher in the
376 slope, outside of the images.

377 A great majority of points consistently displayed distances between the LiDAR scan mesh and
378 the SfM-MVS point clouds ranging between +/- 2 m (Figure ~~5E-5G~~ 7 A-C). Protective nets
379 degrade the results because it generates badly modelled surfaces corresponding to the nets on
380 some cliff sections (such as the red-blue section on the top-right of the July 2014 cloud
381 (Figure ~~5F~~ 7A)). Considering the tunnel entry (Figure 7 D-F) the average distance point
382 clouds - LiDAR mesh varies from -3 to -6 cm (depends mainly on the alignments of the
383 clouds). Standard deviations vary from 22 cm for the 2010 point cloud to 11 cm for the 2016
384 point cloud. On a part of the wall above the tunnel (grey colour polygon on Figure 7 D-F), the
385 average distance point cloud - LiDAR mesh varies from -3 cm to -18 cm with standard
386 deviations of 3 cm for the 2010 point cloud, 4 cm for the 2014 point cloud et 6 cm for the
387 2016 point cloud (Figure 9 and Table 2). We observe again on this site that the improvement
388 of the GSV camera resolution and image quality improve the processing. The information on
389 the pictures source, date, point density and on the program used is given in Table 1.

390 A strong limiting factor on this site is the non-optimal camera locations. Indeed, the location
391 of the cliff above a tunnel portal does not allow for a lateral movement between the camera
392 positions with regard to the cliff. The maximal viewing angle (in blue colour on the Figure
393 2A) is about 35° compared to 170° for the site 1, and 115° for the site 2, that is 3 to 5 time
394 smaller than for the other studied sites.

395 4.4 Discussion

396 ~~The main limitation found in this study is that SfM-MVS processing is designed to retrieve~~
397 ~~the internal orientation of standard cameras, whereas the images used in this research do not~~
398 ~~correspond to a standard camera due the construction of the panoramas. Indeed, the main~~
399 ~~problem comes from the different deformations on GSV print screens or images due to the~~
400 ~~panoramas construction. Same strong radial deformations on each images, like on fisheyes~~
401 ~~images from GoPro cameras, can be processed without limitation with SfM softwares like~~
402 ~~Agisoft PhotoScan. In addition, images from GSV are often over or underexposed (case~~
403 ~~study 3) and their resolution is low for distant subjects (cases study 2 and 3), making difficult~~
404 ~~to obtain good results with these constraints. Making zoomed print screens from GSV images~~
405 ~~do not allow increasing the SfM-MVS process results (case study 2) due to a low images~~

406 ~~resolution. Finally, the spatial repartition of SVI is often problematic because there are not~~
407 ~~enough images along the track path and because the road path does not often allow obtaining~~
408 ~~an efficient strategy concerning the camera positions around the studied area (case study 3).~~
409 ~~Accessing to RAW images together with valuable data of camera calibration would~~
410 ~~considerably help deriving 3D point clouds from GSV using modern photogrammetric~~
411 ~~workflows.~~

412 ~~Our study highlighted important differences on 3D model reconstruction using different~~
413 ~~software, consistently with previous works (Micheletti et al., 2015; Gomez-Gutierrez et al.,~~
414 ~~2015, Niederheiser et al., 2016).~~ ~~Agisoft Photoscan performed better than VisualSfM when~~
415 ~~using both GSV images from Google Earth Pro (Figure 4F-G) and pictures acquired from a~~
416 ~~GoPro Hero camera (Figure 4H). Nevertheless, VisualSfM performed better than Agisoft~~
417 ~~Photoscan on print screens captures from SVI. The only difference between these sources of~~
418 ~~information is the resolution: 2.3 Mpx for print screens from Google Maps, 16.8 Mpx for~~
419 ~~images saved from Google Earth Pro and 12Mpx for GoPro camera, stressing the importance~~
420 ~~of picture resolution on the quality of the 3D model.~~

421 With the experience acquired during the research, we can highlight the following
422 recommendations to improve results of SfM-MVS with SVI images. (A) Firstly, the distance
423 between the image point of view and the subject and the size of the subject are important
424 because it influences the pixel size on the subject. In ~~case study-case~~ 1, the location of the cliff
425 next to the road (< 1 m) allows to get images with a good resolution for the studied object. In
426 ~~case study-case~~ 2, the area under investigation is too far from the road (500 – 1'400 m) and
427 small structures cannot be seen in the landslide. (B) Secondly, the ability to look at the scene
428 from different angles (Figure 2A) is a determining factor to obtain good results. The greater is
429 this “view angle”, the better the results will be. Case study 1 with a view angle of almost 180°
430 is optimal because the object is observable from half a circle. View angle of case study 2
431 (115°) is enough to get many different views of the subject from different angles. The view
432 angle is too narrow to have enough different point of view of the cliff on case study 3 (35°).
433 (C) Thirdly, results are influenced by the image quality and especially by their exposition,
434 contrast and type of sensor, which has progressively been improved during the last years.
435 Image quality varies considerably on different images sets. Case study 1 is again the best
436 study case in term of image quality. Both image sets have optimal solar exposition and
437 shadows are not strong. Case study 2 has sets with very different images quality. Some sets
438 are well exposed, others not. Clouds are present on few image sets. For case study 3, we have

439 a lot of over- and underexposed images on behalf of the situation of the site (incised valley
440 with a southwest oriented slope with a lot of light or shadow). The problem of images quality
441 concerns Google too because it has removed from Google Maps very underexposed GSV
442 images taken in August 2014 on site 3 at the end of 2016. ~~With all these considerations and
443 not surprisingly, the best SfM-MVS results were obtained with the case study 1, whereas the
444 lower quality was obtained at study site 3.~~

445 According to ~~the results~~ our findings, small-scale landslides and rockfalls ($< 10.5 \text{ m}^3$) can be
446 detected when the slope or the cliff is close to the road (0-10 m), as it was shown on site 1.
447 Conversely, large slope movements and collapses ($> 1'000 \text{ m}^3$) can be detected when the
448 studied area is far away from the road (up to 0.5-1 km) like on site 2. On such sites, small
449 changes ($< 1 \text{ m}^3$) can correspond to either real rockfalls or errors resulting from processing
450 like on the toe of almost all point 3D clouds of Séchilienne landslide (Figure 5 A2-H2). The
451 measured differences between the point clouds on stable areas show ~~good~~ interesting results
452 once the point clouds alignment is well done. Thus, we observed standard deviations of afew
453 decimetre on stable areas on site 1 (Figure ~~3C~~ 3D), between 0.5 and 1.1 m on site 2 and
454 between ~~0.111~~ and ~~0.922~~ m on the tunnel entry on site 3. Standard deviations increase on site
455 ~~2 and 3~~ when point clouds are compared on their entire surface (Figure ~~4 A2 H2, Figure 5 E-
456 G and A2-H2~~, Table 1). This is attributable to the occurrence of slope movements generating
457 material increase or decrease and thereby, increasing standard deviations of the ~~error~~ distance
458 between the two compared point clouds. It can also be due to a bad 3D point cloud alignment.
459 Indeed, cloud alignment is not always easy on some point clouds because of low point
460 density, because of voids in the point clouds (like in the landslide toe in Figure 5 F2) and
461 because of the roughness of the terrain. In such difficult alignment cases, it was tried to align
462 the point clouds on stable parts where point density was high.

463 ~~4~~ Conclusion

464 ~~The proposed methodology provides interesting but challenging results due to some
465 constraints linked to the SVI. The inconsistent image deformations and the impossibility of
466 extracting the original images from a street view provider are the biggest limitations for 3D
467 model reconstruction derived from SVI. The constraints (distance and obstacles between the
468 studied area and the road, image quality, meteorological conditions, images repartition,
469 number of images, shadows/highlighted areas) strongly limit the proposed approach.~~

470 ~~However, SfM MVS with SVI can be a useful tool in geosciences to detect and quantify slope~~
471 ~~movements and displacements at an early stage of the research by comparing datasets taken at~~
472 ~~different time series. This information is of great interest when no other data of the studied~~
473 ~~area has been obtained.~~

474 Our study highlighted important differences on 3D model reconstruction using different
475 software, consistently with previous works (Micheletti et al., 2015; Gomez-Gutierrez et al.,
476 2015, Niederheiser et al., 2016). Agisoft PhotoScan performed better than VisualSfM when
477 using both GSV images from Google Earth Pro (Figure 5F-G) and pictures acquired from a
478 GoPro Hero camera (Figure 5H). Nevertheless, VisualSfM performed better than Agisoft
479 PhotoScan on print screens captures from SVI. The only difference between these sources of
480 information is the resolution: 2.3 Mpx for print screens from Google Maps, 16.8 Mpx for
481 images saved from Google Earth Pro (and 12 Mpx for GoPro camera), stressing the
482 importance of picture resolution on the quality of the 3D model.

483 The point density was evaluated according to the distance between the image point of view
484 and the subject and the image types and processing software. The obtained results and the
485 derived trends indicate that the use of GSV images from Google Earth Pro with VisualSfM
486 increases by a factor two the point density compared to the processing of GSV print screens
487 with VisualSfM. The processing of GSV images from Google Earth Pro with Agisoft
488 PhotoScan increases by a factor ten the point density compared to the processing of GSV print
489 screens with VisualSfM (trend strips in Figure 8). The expected point density of the 3D point
490 clouds from GSV print screens processed in VisualSfM of a subject located few meters from
491 the camera (“Basse-Corniche” dots on Figure 8) is about 300 points/m², about 50 points/m²
492 for an area located at about 100 m (“Arly” dots on Figure 8) and about 0.5 point/m² for an
493 area located at about 700 m (“Séchilienne” dots on Figure 8).

494
495 Despite the above mentioned prospects, some drawbacks were also observed. The main
496 limitation found in this study is that SfM-MVS processing is designed to retrieve the internal
497 orientation of standard cameras, whereas the images used in this research do not correspond to
498 a standard camera due the construction of the panoramas. Indeed, the main problem comes
499 from the different deformations on GSV print screens or images due to the panoramas
500 construction. Same radial deformations, that are stronger than common camera lens, on each
501 images, like on fisheyes images from GoPro cameras, can be processed without limitation

502 with SfM software like Agisoft PhotoScan. In addition, images from GSV are often over- or
503 underexposed (case study 3) and their resolution is low for distant subjects (cases study 2 and
504 3), making difficult to obtain results with few decimetric accuracy with these constraints.
505 Making zoomed print screens from GSV images do not allow increasing the SfM-MVS
506 process results (case study 2) due to a low images resolution. Finally, the spatial repartition of
507 SVI is often problematic because there are not enough images along the track path and
508 because the road path does not often allow obtaining an efficient strategy concerning the
509 camera positions around the studied area (case study 3). Accessing to original (RAW) images
510 together with valuable data of camera calibration would considerably help deriving 3D point
511 clouds from GSV using modern photogrammetric workflows.

512 ~~The quality of the final product was observed to be mainly dependent on the images quality~~
513 ~~and of the distance between the studied area and image perspectives. In this study it was~~
514 ~~possible to detect and characterize small scale landslides and rockfalls ($<1 \text{ m}^3$) for study areas~~
515 ~~relatively close to the road (from 0 to 10 m); complementarily, it was possible to detect large~~
516 ~~scale landslides or rock collapses ($>1'000 \text{ m}^3$) over areas located far away from the road~~
517 ~~(hundred meters or more). In other words, it will be difficult, if not impossible, to detect~~
518 ~~small scale slope movements of a cliff or a landslide far away from the road with proposed~~
519 ~~approach.~~

520 A simple development to improve our proposed approach would be that Google add the *back*
521 *in time function* into the Google Earth Pro ~~software~~. In this case, it would be possible to save
522 GSV images from any proposed time period and to process those images with Agisoft
523 PhotoScan (Figure 4G5G) and thus to obtain better results than when using VisualSFM
524 (Figure 4F5E). Knowing that Google services and functionalities of Google Maps and Google
525 Earth are evolving over time, it is possible that SfM-MVS with GSV images will be more
526 efficient and easier in a near future.

527

528 5 Conclusions

529 In this study it was possible to detect and characterize small landslides and rockfalls ($<0.5 \text{ m}^3$)
530 for study areas relatively close to the road (from 0 to 10 m); complementarily, it was possible
531 to detect large scale landslides or rock collapses ($>1'000 \text{ m}^3$) over areas located far away from
532 the road (hundred meters or more). This information is of great interest when no other data of
533 the studied area has been obtained.~~Despite of the observed limitations, the~~

534 The proposed methodology provides interesting but challenging results due to some
535 constraints linked to the quality of the input imagery. The inconsistent image deformations
536 and the impossibility of extracting the original images from a street view provider are the
537 most important limitations for 3D model reconstruction derived from SVI. Following
538 constraints strongly limit the proposed approach: large distances between the camera position
539 and the subject of investigation, presence of obstacles between the studied area and the road,
540 image quality, poor meteorological conditions, non-optimal images repartition, reduced
541 number of images, existence of shadows/highlighted areas. The quality of the final product
542 was observed to be mainly dependent on the images quality and of the distance between the
543 studied area and image perspectives.

544 Although of the above mentioned limitations, SfM-MVS with SVI can be a useful tool in
545 geosciences to detect and quantify slope movements and displacements at an early stage of
546 the research by comparing datasets taken at different time series. The main interest of the
547 proposed approach is the possibility to use archival imagery and deriving 3D point clouds of
548 an area that has not been captured before the occurrence of a given event. This will allow
549 increasing database on rock slope failures, especially for slope changes along roads which
550 conditions are favourable for the proposed approach.

551 56 References

- 552 Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N.J., Lim, M. and Lato, M.J., 2014,
553 Terrestrial laser scanning of rock slope instabilities. *Earth Surface Processes and*
554 *Landforms*, v. 39, p.80-97.
- 555 Agisoft, L. L. C., 2015, Agisoft PhotoScan user manual, Professional edition, version 1.2.6.
- 556 Anguelov, D., Dulong, C., Filip, D., Frueh, Ch., Lafon, S., Lyon, R., Ogale, A., Vincent, L.,
557 Weaver, J., 2010, Google Street View: Capturing the world at street level. *Computer*,
558 Vol. 43, IEEE, 32-38.
- 559 Carrivick, J. L., Smith, M. W., Quincey, D. J., 2016, *Structure from Motion in the*
560 *Geosciences*. John Wiley & Sons.
- 561 Dubois, L., Chanut, M.-A., Duranthon, J.-P., 2014, Amélioration continue des dispositifs
562 d'auscultation et de surveillance intégrés dans le suivi du versant instable des Ruines de
563 Séchilienne. *Géologues* n°182, p50-55.

- 564 Durville, J.-L., Bonnard, C., Potherat, P., 2011, The Séchilienne (France) landslide: a non-
565 typical progressive failure implying major risks, *Journal of Mountain Science*, Vol. 8,
566 Issue 2, 117-123.
- 567 Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F. and Abellán, A., 2016, Image-based
568 surface reconstruction in geomorphometry—merits, limits and developments. *Earth
569 Surface Dynamics*, 4(2), pp.359-389.
- 570 Favalli, M., Fornaciai, A., Isola, I., Tarquini, S., Nannipieri, L., 2011, Multiview 3D
571 reconstruction in geosciences, *Computers & Sciences* 44, 168-176.
- 572 Fey, C., Wichmann, V., 2016, Long-range terrestrial laser scanning for geomorphological
573 change detection in alpine terrain – handling uncertainties. *Earth Surf. Process.
574 Landforms*.
- 575 Fernández, T., Pérez, J. L., Cardenal, J., Gómez, J. M., Colomo, C., Delgado, J., 2016,
576 Analysis of Landslide Evolution Affecting Olive Groves Using UAV and
577 Photogrammetric Techniques. *Remote Sensing*, 8(10), 837.
- 578 Furukawa, Y., Ponce, J., 2010, Accurate, dense, and robust multiview stereopsis. *Pattern
579 Analysis and Machine Intelligence, IEEE Transactions on*, 32(8), 1362-1376.
- 580 Furukawa, Y., Curless, B., Seitz, S. M., Szeliski, R., 2010, Towards internet-scale multi-view
581 stereo. In *Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference
582 on* (pp. 1434-1441). IEEE.
- 583 France 3 : Important éboulement dans les gorges de l'Arly en Savoie, 2014, available at :
584 [http://france3-regions.francetvinfo.fr/alpes/savoie/important-eboulement-dans-les-](http://france3-regions.francetvinfo.fr/alpes/savoie/important-eboulement-dans-les-gorges-de-l-arly-en-savoie-400849.html)
585 [gorges-de-l-arly-en-savoie-400849.html](http://france3-regions.francetvinfo.fr/alpes/savoie/important-eboulement-dans-les-gorges-de-l-arly-en-savoie-400849.html) (last access 25 January 2017).
- 586 Géoportail, IGN (2016), 2016, available at <http://www.geoportail.gouv.fr> (last access 25
587 January 2017).
- 588 Girardeau-Montaut, D., 2011, CloudCompare-Open Source project. OpenSource Project.
- 589 Gómez-Gutiérrez, Á., de Sanjosé-Blasco, J.J., Lozano-Parra, J., Berenguer-Sempere, F. and
590 de Matías-Bejarano, J., 2015, Does HDR pre-processing improve the accuracy of 3D
591 models obtained by means of two conventional SfM-MVS software packages? The case
592 of the Corral del Veleta Rock Glacier. *Remote Sensing*, 7(8), pp.10269-10294.

593 Google Street View, Understand Street View, 2017, available at
594 <https://www.google.com/maps/streetview/understand> (last access 25 January 2017).

595 Google Maps, Google Inc. (2017), 2017, available at <https://maps.google.com> (last access 25
596 January 2017).

597 Google Earth Pro, version 7.1.2.241, Google Inc. (2013), 2013, available at
598 <https://www.earth.google.com/earth> (last access 25 January 2017).

599 Guerin, A., Abellán, A., Matasci, B., Jaboyedoff, M., Derron, M.-H., and Ravanel, L.: Brief
600 communication: ~~3D~~3-D reconstruction of a collapsed rock pillar from ~~web~~Web-
601 retrieved images and terrestrial ~~LiDAR~~lidar data – ~~The~~the 2005 event of the ~~West~~west
602 face of the Drus (Mont-Blanc massif), Nat. Hazards Earth Syst. Sci. ~~Discuss.~~, , 17,
603 [1207-1220](https://doi.org/10.5194/nhess-2016-316), ~~<https://doi.org/10.5194/nhess-2016-316>~~, ~~in review~~, [201617-1207-2017,](https://doi.org/10.5194/nhess-2016-316)
604 [2017](https://doi.org/10.5194/nhess-2016-316).

605 James, M. R., Robson, S., 2012, Straightforward reconstruction of 3D surfaces and
606 topography with a camera, Accuracy and geosciences application, Journal of
607 Geophysical research, Vol. 117, F03017.

608 Klingner, B., Martin, D., Roseborough, J., 2013, Street View Motion-from-Structure-from-
609 Motion, Proceedings of the International Conference on Computer Vision, IEEE.

610 Kromer, R., Abellán, A., Hutchinson, J., Lato, M., Edwards, T., Jaboyedoff, M., 2015, A 4D
611 Filtering and Calibration Technique for Small-Scale Point Cloud Change Detection with
612 a Terrestrial Laser Scanner. Remote Sensing vol.7, pp.13029-13052; DOI:
613 10.3390/rs71013029.

614 Lichtenauer, J. F., Sirmacekb, B., 2015, A semi-automatic procedure for texturing of laser
615 scanning point with google streetview images, The International Archives of the
616 Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-3/W3,
617 109-114.

618 Le Roux, O., Schwartz, S., Gamond, J. F., Jongmans, D., Bourles, D., Braucher, R., Mahaney,
619 W., Carcaillet, J., Leanni, L., 2009, CRE dating on the head scarp of a major landslide
620 (Séchilienne, French Alps), age constraints on Holocene kinematics, Earth and
621 Planetary Science Letters, Vol. 280, 236-245.

- 622 Lucieer, A., de Jong, S., Turner, D., 2013, Mapping landslide displacements using Structure
623 from Motion (SfM) and image correlation of multi-temporal UAV photography,
624 Progress in Physical Geography, Vol. 38(1), 97-116.
- 625 Luhmann, T., Robson, S., Kyle, S., Boehm, J., 2014, Close-range photogrammetry and 3D
626 imaging. Walter de Gruyter.
- 627 Lowe, D., 1999, Object recognition from local scale-invariant features. International
628 Conference of Computer Vision, Corfu Greece, 1150-1157.
- 629 Luhmann, T., Robson, S., Kyle, S., Boehm, J., 2014, Close-range photogrammetry and 3D
630 imaging, Walter De Gruyter.
- 631 Micheletti, N., Chandler, J. H., Lane, S. N., 2015, Investigating the geomorphological
632 potential of freely available and accessible Structure-from-Motion photogrammetry
633 using a smartphone. Earth Surface Processes and Landforms, Vol 40(4), 473-486.
- 634 Nice-Matin : La basse corniche coupée en direction de Monaco après un éboulement, 2014,
635 available at : [http://www.nicematin.com/menton/la-basse-corniche-coupee-en-direction-](http://www.nicematin.com/menton/la-basse-corniche-coupee-en-direction-de-monaco-apres-un-eboulement.1587292.html)
636 [de-monaco-apres-un-eboulement.1587292.html](http://www.nicematin.com/menton/la-basse-corniche-coupee-en-direction-de-monaco-apres-un-eboulement.1587292.html) (last access 15 October 2015).
- 637 Niederheiser, R., Mokroš, M., Lange, J., Petschko, H., Prasicek, G., & Elberink, S. O., 2016,
638 Deriving 3d Point Clouds from Terrestrial Photographs-Comparison of Different
639 Sensors and Software. International Archives of the Photogrammetry, Remote Sensing
640 and Spatial Information Sciences-ISPRS Archives, 41, 685-692.
- 641 Oppikofer, T., Jaboyedoff, M., Blikra, L., Derron, M.-H., Metzger, R., 2009, Characterization
642 and monitoring of the Åknes rockslide using terrestrial laser scanning. Natural Hazards
643 and Earth System Science 9: 1003–1019.
- 644 Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A., Allison, R.J., 2005, Terrestrial laser
645 scanning for monitoring the process of hard rock coastal cliff erosion. Quarterly Journal
646 of Engineering Geology and Hydrogeology 38(4): 363–375.
- 647 Royán, M.J., Abellán, A., Jaboyedoff, M., Vilaplana, J. M., Calvet, J., 2014, Spatio-temporal
648 analysis of rockfall pre-failure deformation using Terrestrial LiDAR. Landslides, pp.1–
649 13.
- 650 Ruggles, S., Clark, J., Franke, K. W., Wolfe, D., Reimschiessel, B., Martin, R. A., ... &
651 Hedengren, J. D., 2016, Comparison of SfM computer vision point clouds of a landslide

652 derived from multiple small UAV platforms and sensors to a TLS-based model. Journal
653 of Unmanned Vehicle Systems, 4(4), 246-265.

654 Snavely, N., M. Seitz, S., Szeliski, R., 2006, Photo Tourism: Exploring Photo Collection in
655 3D. In SIGGRAPH 06, 835-846.

656 Snavely, N., 2008, Scene reconstruction and visualization from Internet photo collections,
657 unpublished PhD thesis, University of Washington, USA.

658 Snavely, N., Seitz, S., Szeliski, R., 2008, Modeling the World from Internet Photo Collections
659 Int J Comput Vision, Springer Netherlands, 80, 189-210

660 Streetside, Microsoft Inc. (2017), 2017, available at
661 <https://www.microsoft.com/maps/streetside.aspx> (last access 25 January 2017).

662 Stumpf, A., Malet, J. P., Allemand, P., Pierrot-Deseilligny, M., Skupinski, G., 2015, Ground-
663 based multi-view photogrammetry for the monitoring of landslide deformation and
664 erosion. *Geomorphology*, 231, 130-145.

665 Tencent Maps, Tencent Inc. (2017), 2017, available at <http://map.qq.com> (last access 25
666 January 2017).

667 Turner, D., Lucieer, A., Watson, C., 2012, An Automated Technique for Generating
668 Georectified Mosaics, from Ultra-High Resolution Unmanned Aerial Vehicle (UAV),
669 Conference on 3D Imaging, Modeling, Processing, Visualization & Transmission
670 Imagery, Based on Structure from Motion (SfM) Point Clouds, *Remote Sensing*, 4(5),
671 1392-1410 IEEE, 479-486.

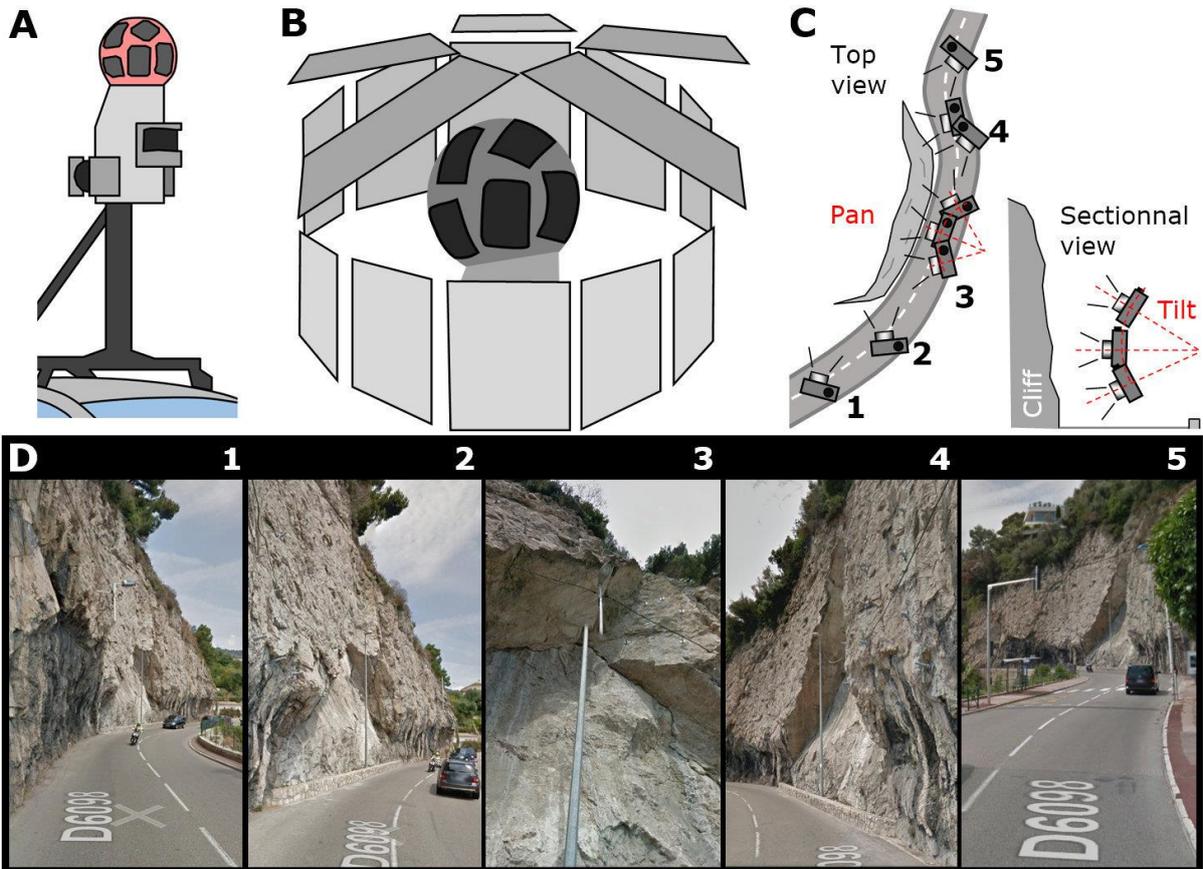
672 Walstra, J., Chandler, J. H., Dixon, N., Dijkstra, T. A., 2007, Aerial photography and digital
673 photogrammetry for landslide monitoring. Geological Society, London, Special
674 Publications, 283(1), 53-63.

675 Wang, C.-P., Wilson, K., Snavely, N., 2013, Accurate Georegistration of Point Clouds Using
676 Geographic Data, In *3D Vision – 3DV*, IEEE, 33-40.

677 Westoby, M.J., Brassington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012,
678 ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience
679 applications, *Geomorphology*, Vol. 179, 300-314.

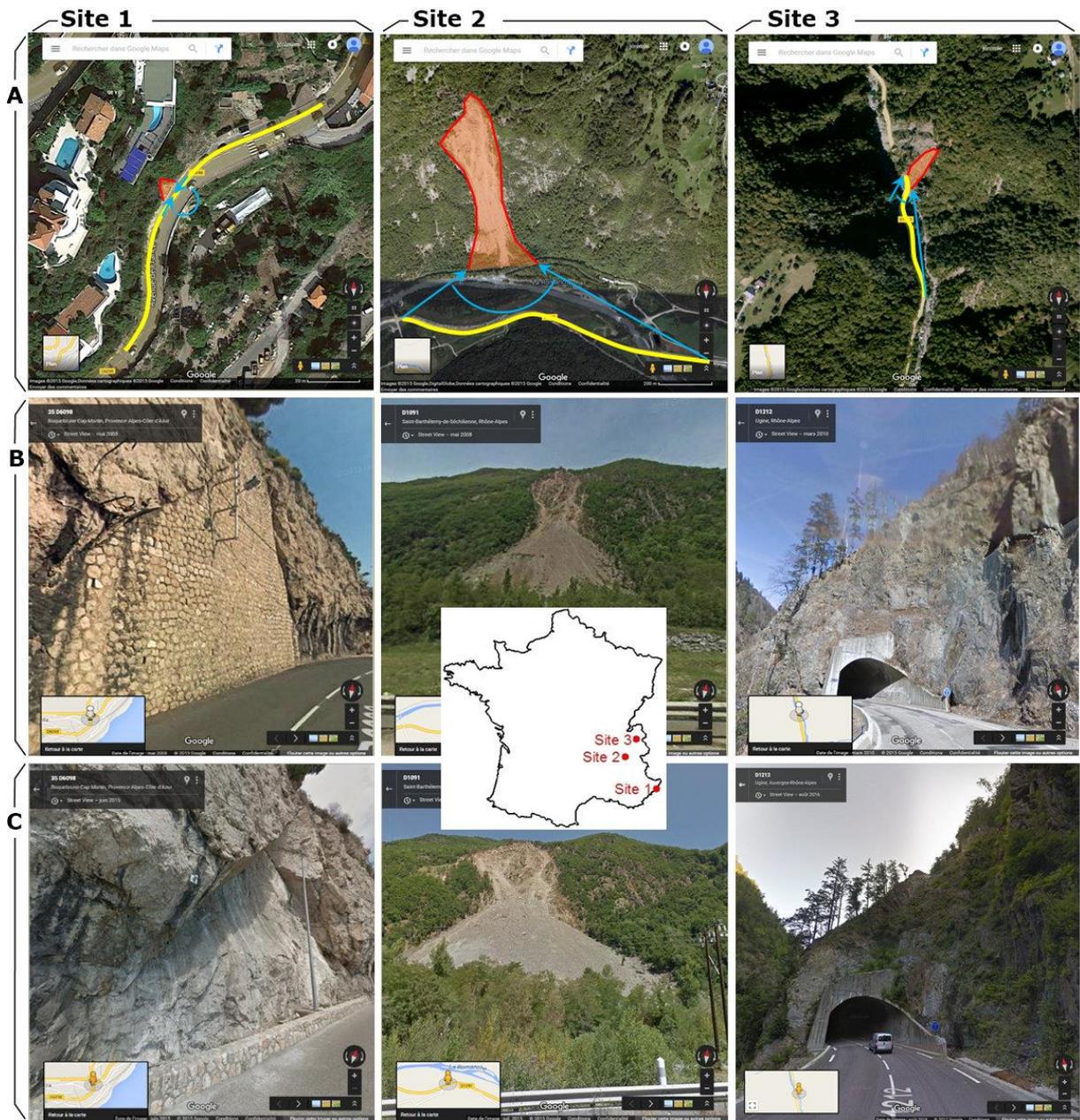
- 680 Wu, C., 2011, VisualSFM: A visual structure from motion system, available at
681 <http://ccwu.me/vsfm> (last access 25 January 2017).
- 682 Zamir, A. R., Shah, M., 2010, Accurate Image Localization Based on Google Maps Street
683 View, In Computer Vision – ECCV 2010, Springer, 255-268.

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687 *Figure 1: Google Street View (GSV) imagery functioning. A: Schema of the GSV spherical camera system mounted on a car*
 688 *roof. Sensors in black colour are LiDAR on which are draped the GSV images (based on Google Street View 2017). B:*
 689 *Functioning of the GSV spherical panorama built with fifteen images. C: Strategy of the GSV service for SfM-MVS*
 690 *photogrammetry. Numbers correspond schematically to the images in D. D: Screen captures of GSV photos from the study*
 691 *site 1. The image numbers correspond to those in C. Note the gap on the street-lamp in images 3 due to the panorama*
 692 *construction from the GSV pictures.*
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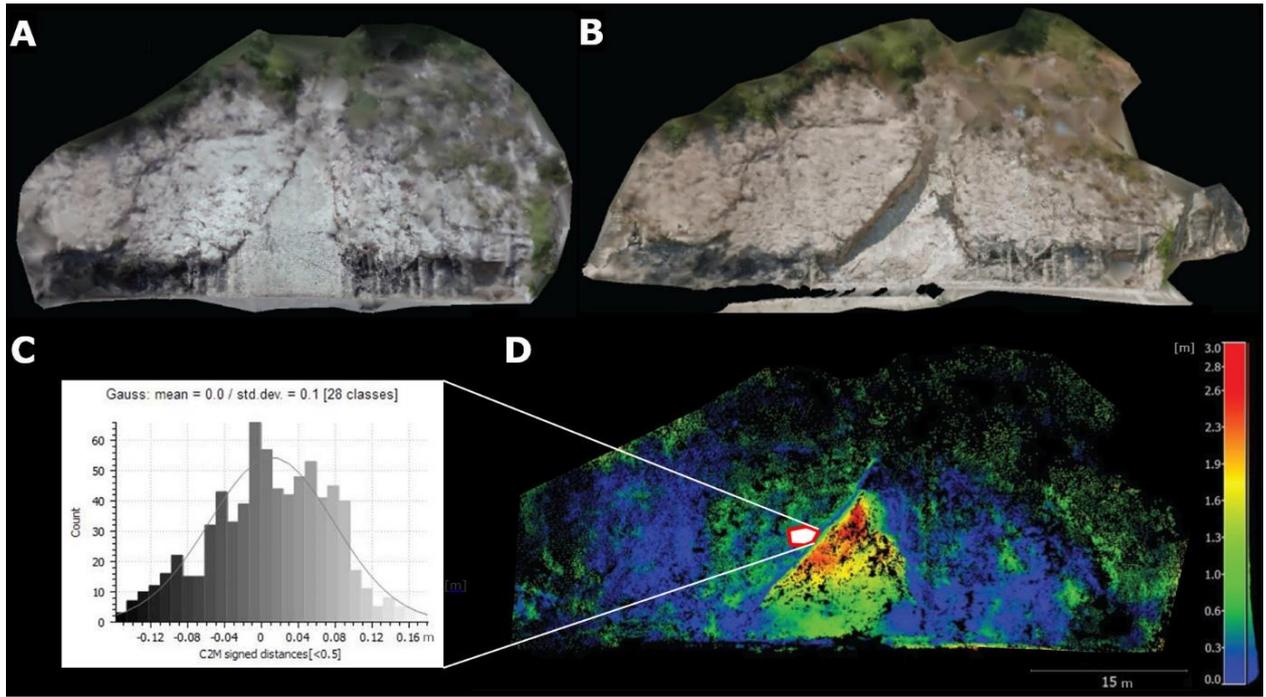
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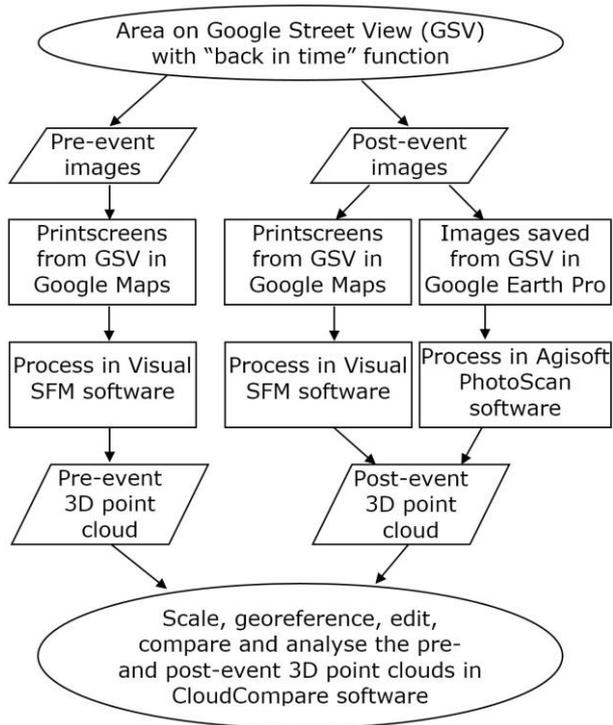
Figure 2 : The three French studied sites (1: Basse-Corniche, 2: Séchilienne and 3: Arly gorges). A: Google Maps aerial view of the sites (in red) with the road path (yellow) used to take the GSV images of the scenes and the view angle (blue) of the images point of view around the sites. B: First GSV of the sites. C: Last GSV of the sites.



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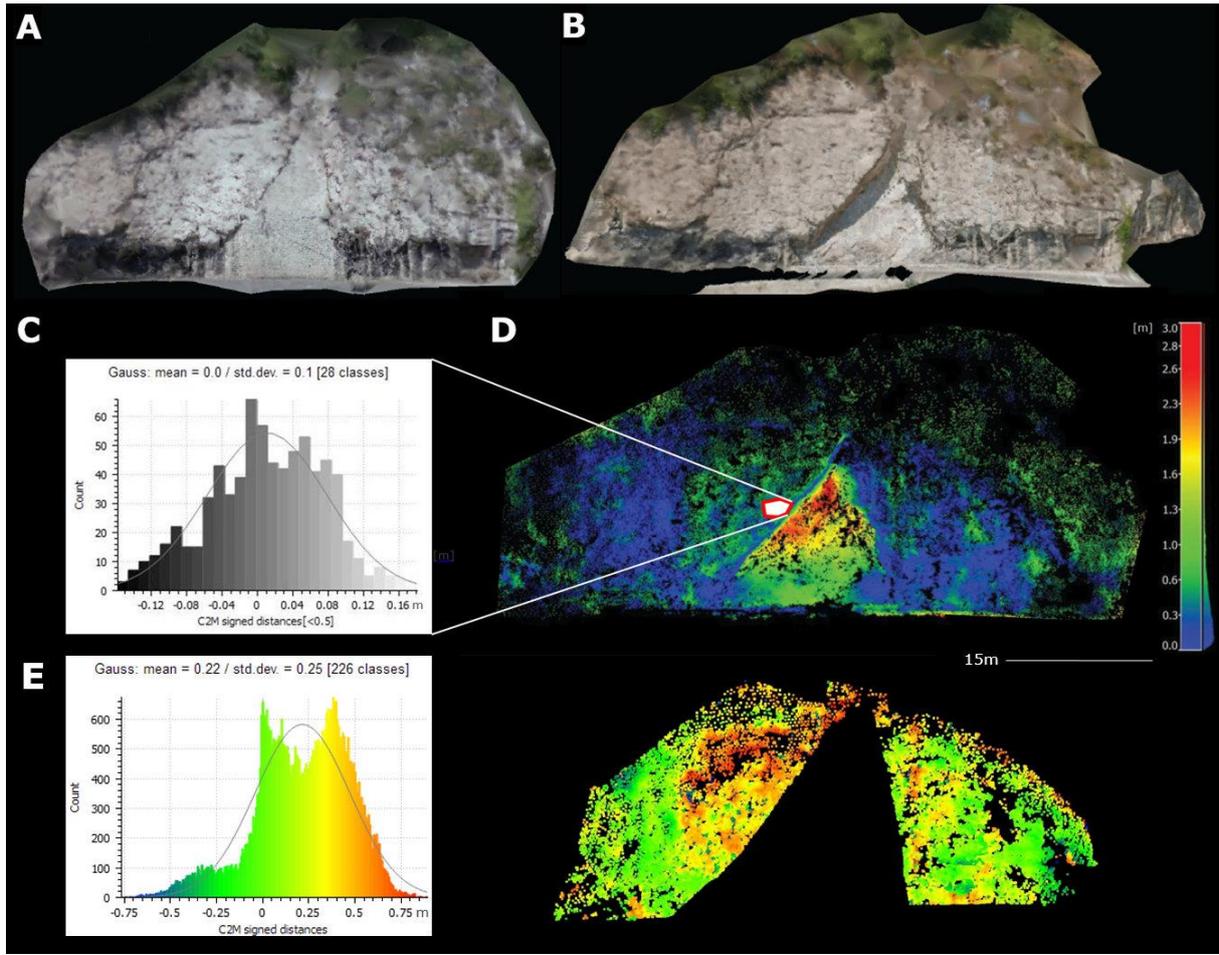
Figure 3 : Results at site 1 "BASSE CORNIEHE".



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701 *Figure 3: Flowchart of the SfM-MVS processing with GSV images on an area with the “back in time” function available.*
 702 *Pre-event images are displayed using the “back in time” function in GSV. Post-event images arise either from print screens*
 703 *of GSV in Google Maps using or not the “back in time” function or from GSV images saved in Google Earth Pro. In this last*
 704 *case, the last available proposed GSV images have a greater resolution as the print screens and can be processed in the*
 705 *Agisoft PhotoScan.*

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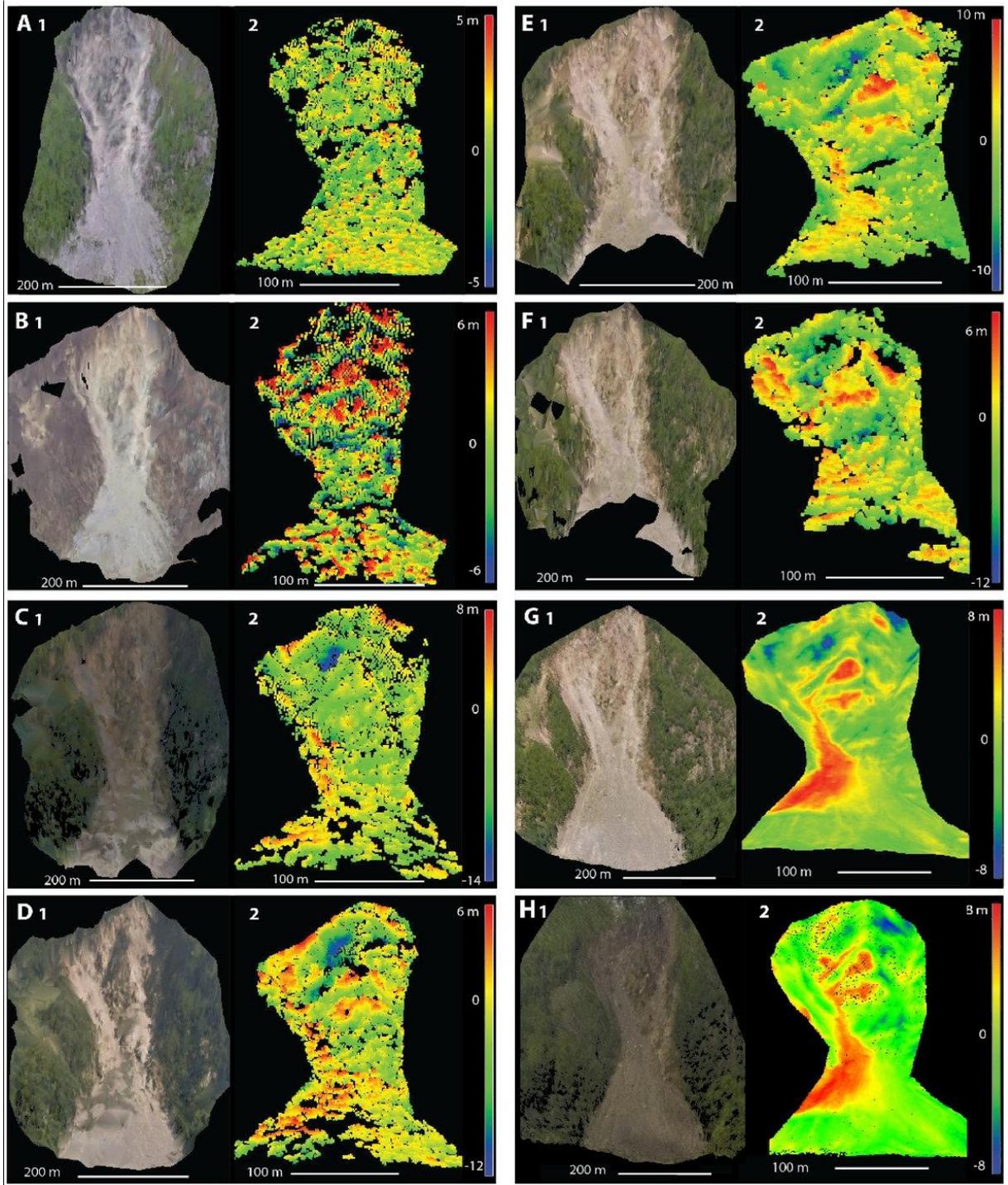
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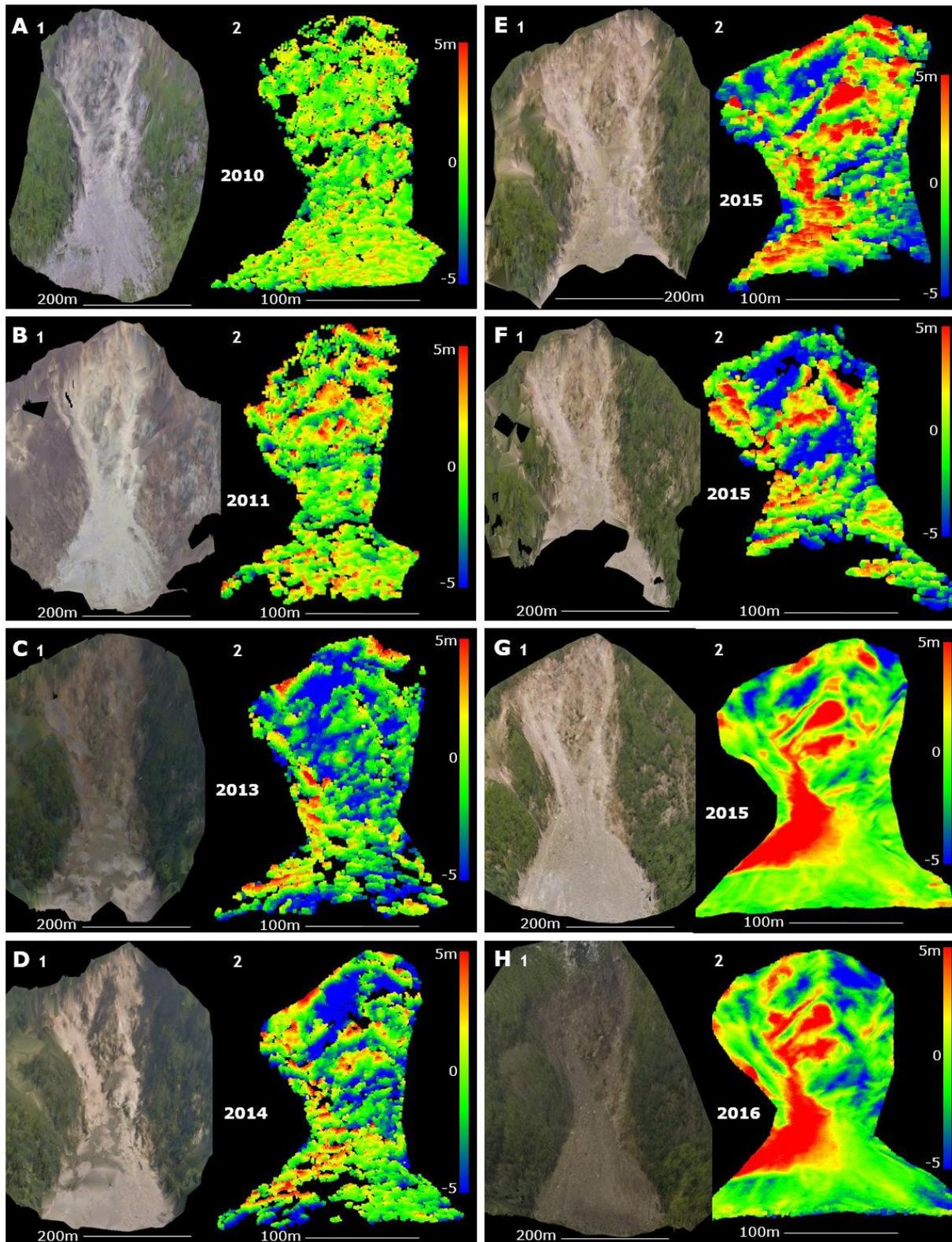
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Figure 4: Results at site 1 "Basse-Corniche". A: 3D model produced with GSV images taken before the event in 2008. B: 3D model produced with GSV images taken after the event in 2014. C: Statistics on a small part of the wall (red colour polygon on figure D) of 7'510 points between the two point clouds- with the point-to-mesh strategy in the CloudCompare. D: Comparison of the two point clouds of 2008 and 2014- on the entire surface of the 3D point clouds. The maximal horizontal depth of the cliff is about 3.9 m. E: Comparison of the two point clouds of 2008 and 2014 on the entire stable parts of the cliff (i.e. without vegetation) by not taking into account the collapsed wall (black triangle in the centre of the point clouds). The information on the pictures source and date, point density and on the program used is given in TableTables 1 and 2.

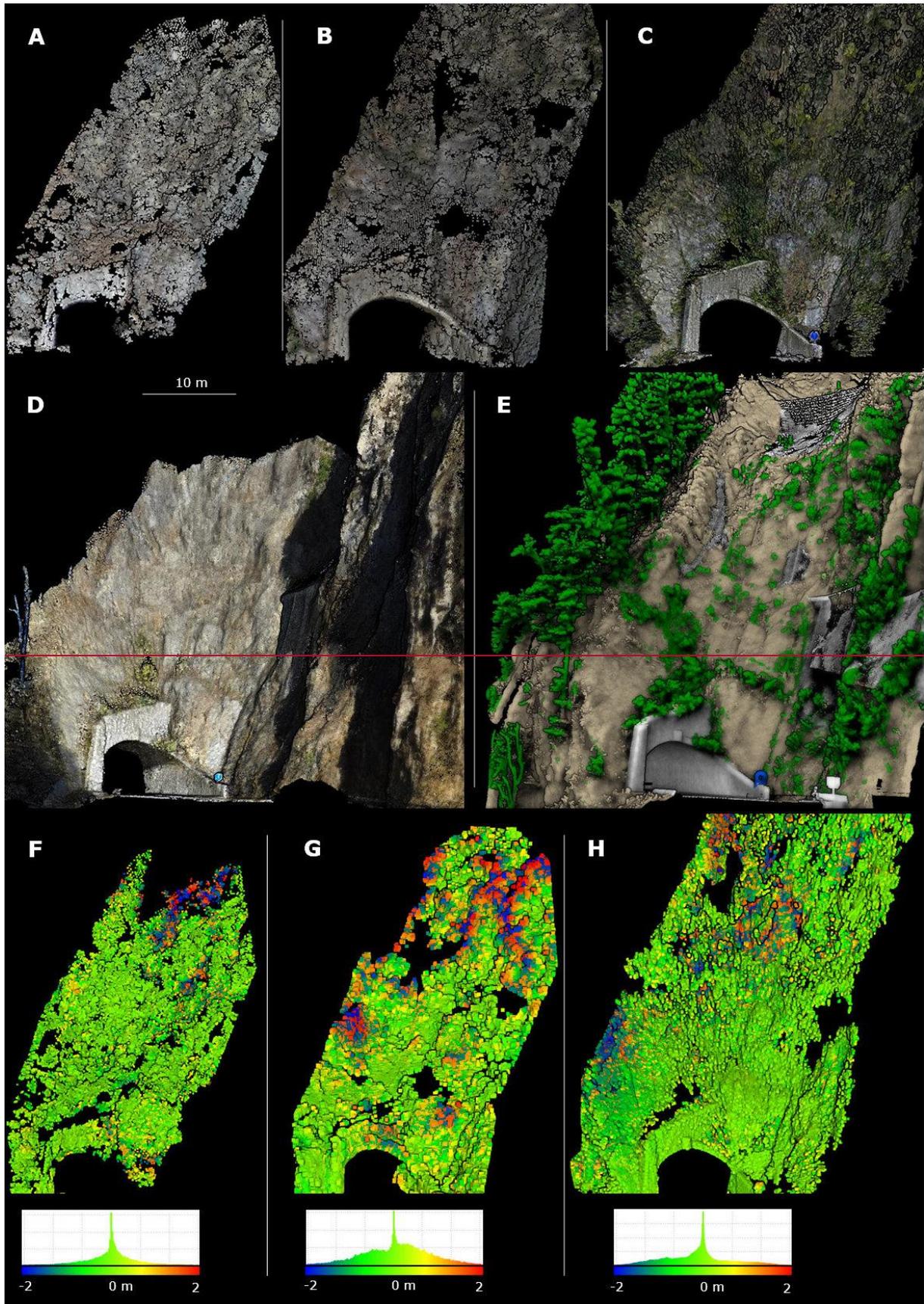


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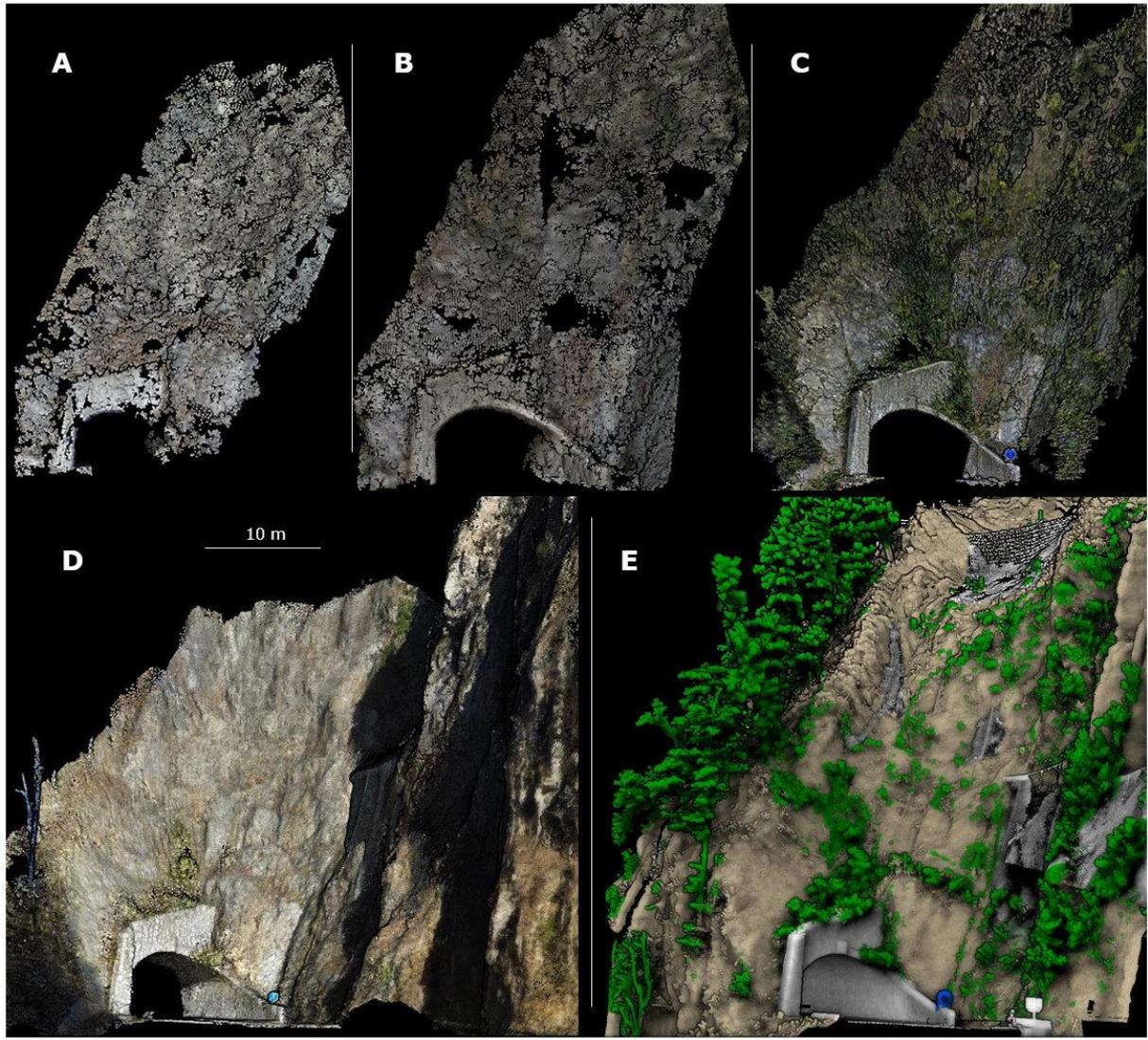
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Figure 45: Results at site 2 "Séchilienne". Eight points clouds from different images sets taken at six different time with three different image sources and processed with two different programs. Figures A1-H1: Meshes resulting from the respective point clouds. Figures A2-H2: point clouds comparison with a 50 cm LiDAR DEM from 2010 (red colour points is material increase; blue colour points are material decrease from the 2010 LiDAR cloud-) with the point-to-mesh strategy in CloudCompare. The information on the pictures source and date, point density and on the program used is given in Table 1.



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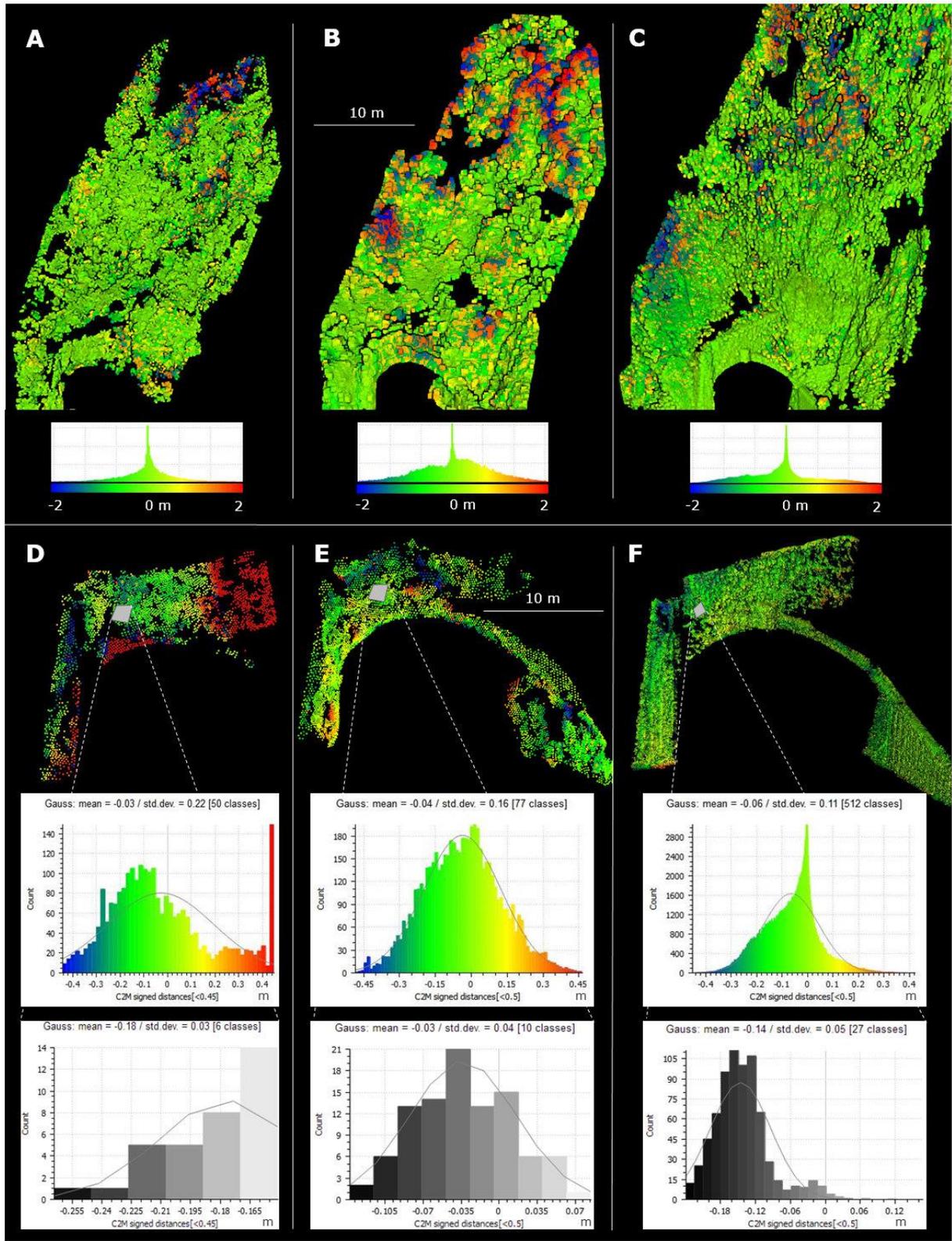
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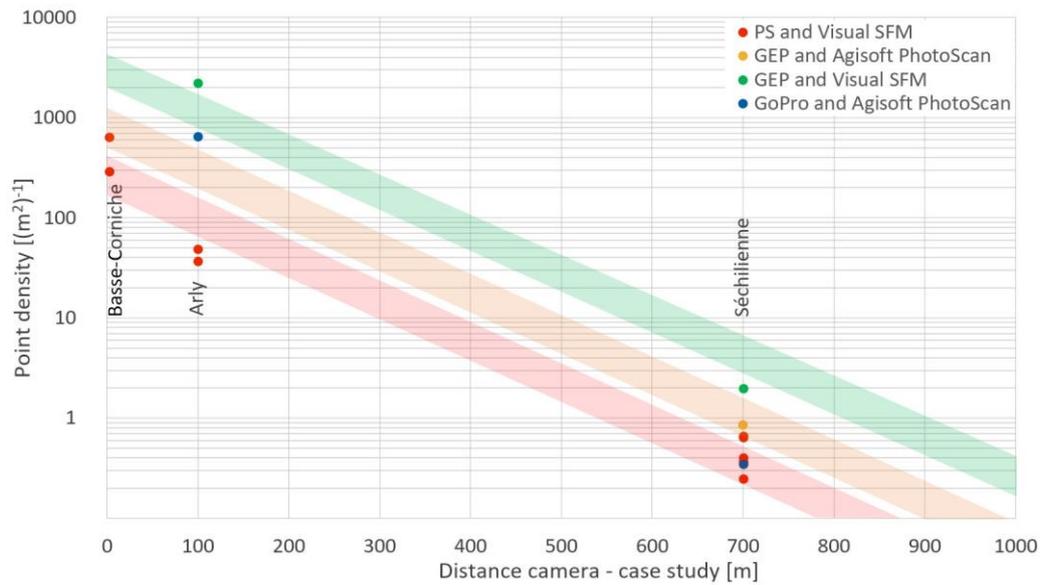
Figure 56: Results at site 3 "Arly gorges". Five points clouds from four different images sets sources and processed with two different softwares and one LiDAR scan. A: March 2010 point cloud. B: July 2014 point cloud. C: August 2016 point cloud. D: December 2016 point cloud taken on foot with a GoPro camera. E: December 2016 LiDAR cloud from an assembly of six Optech terrestrial LiDAR scans. The grey elements in the cliff are the protective nets. **F-G-H**



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730 *Figure 7: A-B-C: March 2010, July 2014 and August 2016 point clouds compared with December 2016 LiDAR DEM (red*
 731 *colour points is material increase; blue colour points are material decrease from the 2016 LiDAR cloud-) with the point-to-*
 732 *mesh strategy on the CloudCompare. D, E, F: tunnel entry and part of the wall overlooking the tunnel (grey colour polygon*
 733 *of the March 2010, July 2014 and August 2016 point clouds compared with December 2016 LiDAR DEM. The information*
 734 *on the pictures source and, date, point density and on the program used is given in TableTables 1 and 2.*

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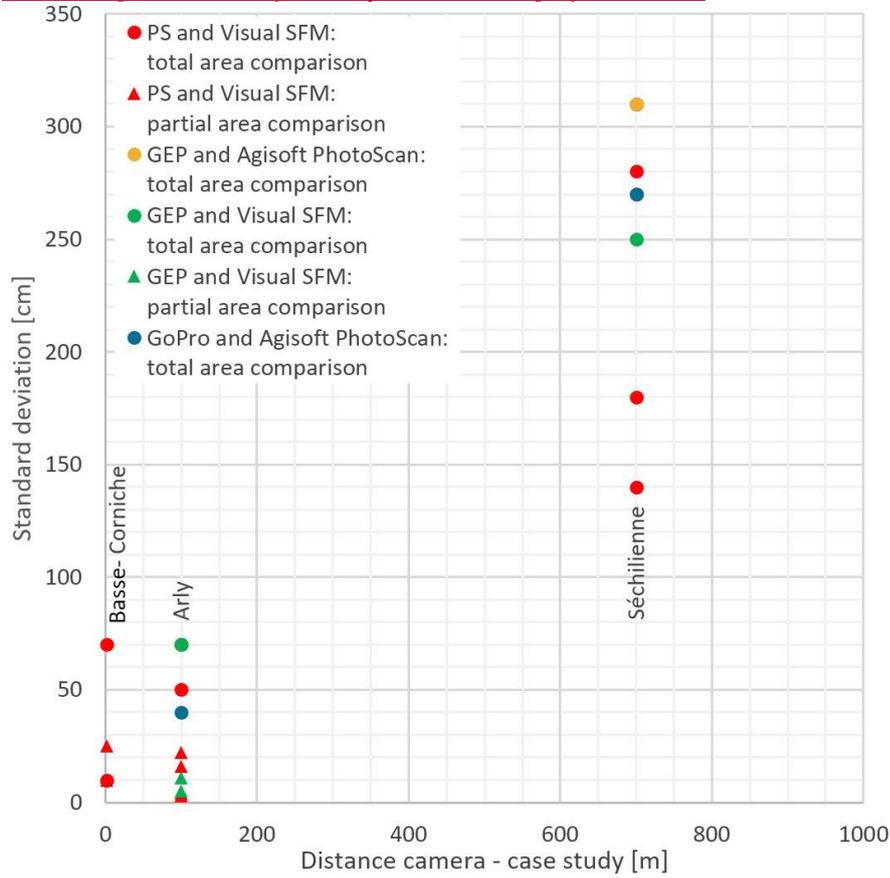
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Figure 8: Correlation between distance camera - case studies and the expected density of points from the three case studies. The red colour dots are results of the three case studies point clouds obtained from Google Street View (GSV) print screens (PS) in Google Maps (GM) processed with VisualSFM. The red strip represents the corresponding trend based on a negative exponential function. The orange colour dot is the result of the Séchilienne point cloud obtained from GSV images saved in Google Earth Pro (GEP) processed with VisualSFM. The orange strip represents the corresponding trend based on a negative exponential function. The green colour dots are results of the Séchilienne and Arly point clouds obtained from GSV images saved in (GEP) processed with Agisoft PhotoScan. The green strip represents the corresponding trend based on a negative exponential function. By way of comparison, the blue colour dots represent the result of the Séchilienne and Arly point clouds obtained with GoPro action camera images taken on the field and processed with Agisoft PhotoScan.

746 *Figure 9: Correlation between distance camera - case studies and the expected standard deviation from the three case*
 747 *studies. The dots are results of point clouds comparisons on the entire point cloud areas (Table 1). The triangle are results of*
 748 *point clouds comparisons on partial point cloud area (Table 2). The red colour dots and triangle are results of the three case*
 749 *studies point clouds obtained from Google Street View (GSV) print screens (PS) in Google Maps (GM) processed with*
 750 *VisualSFM compared on the entire area. The orange colour dot is the result of the Séchilienne point cloud obtained from*
 751 *GSV images saved in Google Earth Pro (GEP) processed with VisualSFM. The green colour dots and triangles are results of*
 752 *the Séchilienne and Arly point clouds obtained from GSV images saved in (GEP) processed with Agisoft PhotoScan. By way*
 753 *of comparison, the blue colour dots represent the result of the Séchilienne and Arly point clouds obtained with GoPro action*
 754 *camera images taken on the field and processed with Agisoft PhotoScan.*



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769 Table 1: List of the fourteen point clouds presented in this paper.
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Site	Figure	Date	Images source	Images size [pixel]	Image's number	Point density ¹ (pts/m ²)	Processing software	Number of points	Comparison				
									With	Min-Mean distance ² [m]	Max [m]	Average [m]	Std. dev. [m]
Site 1	Fig. 3A4A	2008.05	PS GSV _r -GM ³ from GM ³	1920 x 1200	60	290	VisualSF M	150'000	14.06 ⁵ 0	1.2	2.6	0.2	0.7
	Fig. 3B4B	2014.06	PS GSV _r -GM ³ from GM ³	1920 x 1200	50	640	VisualSF M	182'000	8.05 ⁶ 05 ⁸	-	-0.20	0.2	0.1
Site 2	Fig. 4A5A	2010.04	PS GSV _r -GM ³ from GM ³	1920 x 1200	54	0.40	VisualSF M	18'000	AR ⁸ Li R ⁹	5.5	4.9	-0.2	1.4
	Fig. 4B5B	2011.03	PS GSV _r -GM ³ from GM ³	1920 x 1200	52	0.25	VisualSF M	9'500	AR ⁸ Li R ⁹	6.6	6.8	-0.1	1.8
	Fig. 4C5C	2013.05	PS GSV _r -GM ³ from GM ³	1920 x 1200	45	0.37	VisualSF M	12'500	AR ⁸ Li R ⁹	13.9	7.9	-2.1	2.7
	Fig. 4D5D	2014.06	PS GSV _r -GM ³ from GM ³	1920 x 1200	52	0.66	VisualSF M	25'000	AR ⁸ Li R ⁹	12.8	6.3	-1.5	2.8
	Fig. 4E5E	2015.06	PS GSV _r -GM ³ from GM ³	1920 x 1200	62	0.64	VisualSF M	23'500	AR ⁸ Li R ⁹	11.4	9.7	-0.9	3.1
	Fig. 4F5F	2015.06	GSV _r -GEP ³ from GEP ³	4800 x 3500	80	0.86	VisualSF M	22'500	AR ⁸ Li R ⁹	11.9	7.4	-1.7	3.1
	Fig. 4G5G	2015.06	GSV _r -GEP ³ from GEP ³	4800 x 3500	80	1.99	Agisoft PhotoScan	236'000	AR ⁸ Li R ⁹	8.1	8.3	0.6	2.5
	Fig. 4H5H	2016.05	GoPro ³ GoPro ⁵	4000 x 3000	75	0.35	Agisoft PhotoScan	46'000	AR ⁸ Li R ⁹	8.9	8.1	-0.2	2.7
	Site 3	Fig. 5A, 5FFigs. 6A, 7A	2010.03	PS GSV _r -GM ³ from GM ³	1920 x 1200	66	40	VisualSF M	35'000	AR ⁸ Li R ¹⁰	2.2	2.1	0.0
Fig. 5B, 5GFigs. 6B, 7B		2014.07	PS GSV _r -GM ³ from GM ³	1920 x 1200	111	50	VisualSF M	53'000	AR ⁸ Li R ¹⁰	2.2	2.3	0.1	0.7
Fig. 5C, 5HFigs. 6C, 7C		2016.08	GSV _r from GEP ²	4800 x 3107	64	2200	Agisoft PhotoScan	3'1850'000	AR ⁸ Li R ¹⁰	2.3	2.5	-0.1	0.7
Fig. 5D6D		2016.12	GoPro ³ GoPro ⁶	4000 x 3000	50	650	Agisoft PhotoScan	2'217'000	AR ⁸ LiLiDAR ¹⁰	-	-4.20	3.4	0.4

771 ¹ Point density around a search radius of 2 m.
772 ² Average distance between the mesh of the reference point cloud and the compared point cloud using the point-to-mesh strategy.
773 ³ Print screens (PS) of Google Street View (GSV) from Google Maps (GM).
774 ^{3a} Google Street View (GSV) images saved in Google Earth Pro (GEP).
775 ^{3b} GoPro Hero4+.
776 ^{3c} GoPro Hero5 Black with GNSS chip integrated.
777 ⁵² Comparison between the entire point clouds of May 2008 and June 2014 (Figure 3D).
778 ⁶⁸ Comparison of a small cliff area of the May 2008 and June 2014 point clouds (Figure 3C).
779 ⁷⁹ Comparison with the 50 cm airborne LiDAR DEM from 2010.
780 ⁸¹⁰ Comparison with the December 2016 LiDAR DEM (6'930'000 points) without vegetation from an assembly of six Optech terrestrial LiDAR clouds.
781

782 *Table 2: List of the eight partial point cloud comparisons.*
 783

Site	Figure	Date	Images source	Images size [pixel]	Processing software	Comparative area	Comparison		
							With	Mean distance ¹ [cm]	Std. dev. [cm]
Site 1	Fig. 4C	2008.05	PS GSV from GM ²	1920 x 1200	VisualSFM	Small cliff part	4.06 ⁴	0	10
	Fig. 4E	2008.05	PS GSV from GM ²	1920 x 1200	VisualSFM	Entire cliff without wall and vegetation	4.06 ⁴	22	25
Site 3	Fig. 7D 1	2010.03	PS GSV from GM ²	1920 x 1200	VisualSFM	Tunnel entry	∅AR ⁵	-3	22
	Fig. 7D 2	2010.03	PS GSV from GM ²	1920 x 1200	VisualSFM	Small part of tunnel entry	∅AR ⁵	-18	3
	Fig. 7E 1	2014.07	PS GSV from GM ²	1920 x 1200	VisualSFM	Tunnel entry	∅AR ⁵	-4	16
	Fig. 7E 2	2014.07	PS GSV from GM ²	1920 x 1200	VisualSFM	Small part of tunnel entry	∅AR ⁵	-3	4
	Fig. 7F 1	2016.08	GSV from GEP ³	4800 x 3107	Agisoft PhotoScan	Tunnel entry	∅AR ⁵	-6	11
	Fig. 7F 2	2016.08	GSV from GEP ³	4800 x 3107	Agisoft PhotoScan	Small part of tunnel entry	∅AR ⁵	-14	5

784 ¹ Average distance between the mesh of the reference point cloud and the compared point cloud using the point-to-mesh strategy.

785 ² Print screens (PS) of Google Street View (GSV) from Google Maps (GM).

786 ³ Google Street View (GSV) images saved in Google Earth Pro (GEP).

787 ⁴ Comparison between the entire point clouds of May 2008 and June 2014 (Figure 3D).

788 ⁵ Comparison of a small cliff area of the May 2008 and June 2014 point clouds (Figure 3C).

789 ⁶ Comparison with the December 2016 LiDAR DEM (6'930'000 points) without vegetation from an assembly of six Optech terrestrial LiDAR clouds.

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1 Using street view imagery for 3D survey of rock 2 slope failures 3

4 J., Voumard¹, A., Abellan^{1,2}, P., Nicolet^{1,3}, M.-A. Chanut⁴, M.-H., Derron¹, M., Jaboyedoff¹

5 ¹ Risk analysis group, Institute of Earth Sciences, FGSE, University of Lausanne, Switzerland

6 ² Scott Polar Research Institute, Department of Geography, University of Cambridge, United Kingdom

7 ³ Geohazard and Earth Observation team, Geological Survey of Norway (NGU), Norway

8 ⁴ Groupe Risque Rocheux et Mouvements de Sols (RRMS), Cerema Centre-Est, France

9 Abstract

10 We discuss here different challenges and limitations on surveying rock slope failures using
11 3D reconstruction from image sets acquired from Street View Imagery (SVI). We show how
12 rock slope surveying can be performed using two or more image sets using online imagery
13 with photographs from the same site but acquired at different instants. Three sites in the
14 French alps were selected as pilot study areas: (1) a cliff beside a road where a protective wall
15 collapsed consisting of two images sets (60 and 50 images in each set) captured within a six
16 years time-frame; (2) a large-scale active landslide located on a slope at 250 m from the road,
17 using seven images sets (50 to 80 images per set) from 5 different time periods with three
18 images sets for one period; (3) a cliff over a tunnel which has collapsed, using two image sets
19 captured in a four years time-frame. The analysis include the use of different Structure for
20 Motion (SfM) programs and the comparison between the so-extracted photogrammetric point
21 clouds and a LiDAR derived mesh that was used as a ground truth. Results show that both
22 landslide deformation and estimation of fallen volumes were clearly identified in the different
23 point clouds. Results are site and software-dependent, as a function of the image set and
24 number of images, with model accuracies ranging between 0.2 and 3.8 m in the best and worst
25 scenario, respectively. Although some limitations derived from the generation of 3D models
26 from SVI were observed, this approach allow obtaining preliminary 3D models of an area
27 without on-field images, allowing extracting the pre-failure topography that would not be
28 available otherwise.

29

30 Keywords

31 Street View Imagery (SVI), Structure from Motion (SfM), photogrammetry, 3D point cloud,
32 natural hazard, landslide, rockfall.

33 1 Introduction

34 3D remote sensing techniques are becoming widely used for geohazard investigations due to
35 their ability to represent the geometry of natural hazards (mass movements, lava flows, debris
36 flows, etc.) and its evolution over time by comparing 3D point clouds acquired at different
37 time steps. For example, 3D remote sensing techniques are helping to better quantify key
38 aspects of rock slope evolution, including the accurate quantification of rockfall rates and the
39 deformation of rock slopes before failure using both LiDAR (Rosser et al., 2005; Oppikofer et
40 al, 2009; Royan et al., 2013; Kromer et al., 2015; Fey and Wichmann., 2016) and
41 photogrammetrically derived point clouds (Walstra et al., 2007; Lucieer et al., 2013, Stumpf
42 et al., 2015; Fernandes et al., 2016; Guerin et al., 2017; Ruggles et al., 2016).

43 Airborne and terrestrial laser scanner (ALS and TLS, respectively) are commonly used
44 techniques to obtain 3D digital terrain models (Abellan et al., 2014). Despite their very high
45 accuracy and resolution, these technologies are costly and often demanding from a logistic
46 point of view. Alternatively, Structure from Motion (SfM) photogrammetry combined with
47 multiview-stereo (MVS) allow using end-user digital cameras to generate 3D point clouds
48 with a decimetre level accuracy in a cost-effective way in order (Westoby et al., 2012;
49 Carrivick et al., 2016).

50 Whereas most of the studies in SfM literature utilise pictures that were captured on purpose
51 (Eltner et al., 2016), the potential of using internet-retrieved pictures for 3D reconstruction
52 has not been fully discussed before (e.g. Snavely et al., 2008; Guerin et al., 2017). One of the
53 large sources of pictures on-line is the Street View Imagery (SVI) services, which offer 360
54 degrees panoramas from many roads, streets and other places around the world (Anguelov et
55 al, 2013). It allows to remotely observe areas without physically accessing them and so in a
56 cost-effective way, with applications in navigation, tourism, building texturing, image
57 localization, point clouds georegistration and motion-from-structure-from-motion (Zamir et
58 al. 2010; Anguelov et al, 2010; Klingner et al, 2013; Wang, 2013; Lichtenauer et al., 2015).

59 The aim of present work is to ascertain up to which extent 3D models derived from SVI can
60 be used to detect geomorphic changes on rock slopes.

61 1.1 Street View Imagery

62 The most common SVI service is the well-known Google Street View (GSV) (Google Street
63 View, 2017) that is available from Google Maps (Google Maps, 2017) or Google Earth Pro
64 (Google Earth Pro, 2013). We used both GSV as SVI service in this study. Alternatives
65 include StreetSide by Microsoft (StreetSide, 2017) and other national services like Tencent
66 Maps in China (Tencent Maps, 2017). SVI was firstly deployed in urban areas to offer a
67 virtual navigation into the streets. More recently, non-urban zones can also be accessed, and
68 were used for the analysis of rock slope failures in this manuscript.

69 GSV was firstly used in May 2007 for capturing pictures in streets of the main cities in USA
70 and it has been deployed worldwide over the forthcoming years, including also rural areas.
71 GSV images are collected with a panoramic camera system mounted on different types of
72 vehicles (e.g. a car, train, bike, snowmobile, etc.) or carried into a backpack (Anguelov et al,
73 2010).

74 The GSV first generation camera system was composed of eight wide-angle lenses and it is
75 currently composed of fifteen CMOS sensors 5Mpx each (Anguelov et al, 2010). The fifteen
76 raw images, which are not publicly available, are processed by Google to make a panorama
77 view containing an a priori unknown image deformation (Figure 1). A GSV panorama is
78 normally taken at an interval of around ten meters along a linear infrastructure (road, train or
79 path).

80 GSV proposes a *back-in-time function* on a certain number of locations since April 2014. In
81 addition, other historical GSV images are available from 2007 for selected areas only. The
82 number of available image sets greatly varies at different locations: while some places have
83 several sets, many other locations have only one image set. Back in time function is especially
84 useful for natural hazards because it is possible to compare pre- and post-events images.

85 The GSV process can be explained in four steps (Anguelov et al, 2010; Google Street View,
86 2017): 1) Pictures acquisition in the field; 2) Image alignment: preliminary coordinates are
87 given for each picture, extracted from sensors on the Google car that measure GNSS
88 coordinates, speed and azimuth of the car, helping to precisely reconstruct the vehicle path.
89 Pictures can also be tilted and realigned as needed; 3) Creation of 360° panoramas by
90 stitching overlapping pictures. Google applies a series of processing algorithms to each
91 picture to attenuate delimitations between each picture and to obtain smooth pictures
92 transitions; 4) Panoramas draping on 3D models: the three LiDAR mounted on the Google car

93 help to build 3D models of the scenes. 360° panoramas are draped on those 3D models to give
94 a panorama view close to the reality. Each picture of the panorama has its own internal
95 deformation, and the application of the processing chain described above makes inconstant
96 deformation in the 360° panorama; in addition, the end-user does not have any information or
97 control on it.

98 1.2 SfM-MVS

99 Structure for Motion (SfM) with Multi-View Stereo (MVS) dense reconstruction is a cost-
100 effective photogrammetric method to obtain a 3D point cloud of terrain using a series of
101 overlapping images (Luhmann et al., 2014). The prerequisites are that: (1) the studied object
102 is photographed from different points of view, and (2) each element of the object must be
103 captured from a minimum of two pictures assuming that the lens deformation parameters are
104 known in advance (Snavely 2008; Lucieer et al. 2013). If these parameters are not known
105 beforehand, three pictures is the minimum requirement (Westoby 2012), and about six
106 pictures is preferred. The particularity of SfM-MVS is that prior knowledge of both intrinsic
107 camera parameters (principal point, principal distance and lens distortion) and extrinsic
108 camera parameters (orientation and position of the camera centre (Luhmann et al., 2014)) is
109 not needed.

110 The workflow of SfM-MVS normally includes the following steps: 1) Feature detection and
111 matching (Lowe, 1999); 2) Bundle adjustment (Snavely et al., 2006; Favalli et al., 2011;
112 Turner et al., 2012; Lucieer et al., 2013); 3) Dense 3D point cloud generation (Furukawa et
113 al., 2010; Furukawa & Ponce, 2010; James & Robson, 2012); and 4) Surface reconstruction
114 and visualization (James & Robson, 2012).

115 2 Study areas and available data

116 We selected three study areas in France to generate point clouds from GSV images. This
117 country was chosen because GSV cover the majority of the roads and because the timeline
118 function works in most of the areas covered by GSV, meaning that several periods of
119 acquisition are available. Moreover, landslide events occur regularly on French alpine roads.
120 The aerial view of the three areas is shown in Figure 2A and examples of corresponding GSV
121 images in Figure 2B and 2C.

122 The first case study (“Basse corniche” site) is a 20 m high cliff beside a main road in
123 Roquebrune – Cap Martin connecting the town of Menton to the Principality of Monaco, in
124 South-Eastern France. A wall built to consolidate the cliff collapsed after an extreme rainfall

125 event in January 2014, blocking the road (Nice-Matin, 2014). Two 3D models were built with
126 60 GSV images taken in 2008 before the wall collapse, and 50 GSV images taken in 2014
127 after the event.

128 The second case studies is Séchilienne landslide, located 15 km South East of Grenoble (Isère
129 department, France). The active area is threatening the departmental road RD 1091
130 connecting the towns of Grenoble and Briançon as well as a set of ski resorts such as L'Alpe
131 d'Huez and Les Deux Alpes to the plain. This landslide is about 800 m long by 500 m high
132 and it has been active during more than thirty years (Le Roux et al. 2009; Durville et al. 2011;
133 Dubois et al. 2014). The shortest distance between the landslide foot and the former road was
134 250 m and the longest distance between the landslide head and the road is 1 km. A new road,
135 located higher in the opposite slope, has been opened since July 2016. Different SfM-MVS
136 processing were tested using from 50 up to 80 GSV images, at six different times from April
137 2010 to June 2015.

138 The third case study is located in “Arly gorges”, between Ugine and Megève on the path
139 Allevard – Chamonix-Mont-Blanc. A rockfall of about 8'000 m³ affected the road at the
140 entry of a tunnel on January 2014 (France 3, 2014). Different sets of images ranging from 60
141 to 110 GSV images were processed in order to obtain three 3D models of the road, the tunnel
142 entry and the cliff above the tunnel.

143 We used two image sets from for the first study site, eight image sets for the second study site
144 and four image sets for the third study site, with dates ranging from May 2008 up to
145 December 2016, as described in Table 1.

146 3 Methodology

147 First step to make SfM-MVS with SVI is to obtain images from a SVI service. GSV has been
148 used in this study (Figure 1). Given that original images of the Google cameras are not
149 available, one of the two ways to get images from GSV is to manually extract them from the
150 GSV panoramas. We took print screens (1920 x 1200 pixels, 2.3 Mpx) of GSV panoramas of
151 the studied areas at each acquisition step, separated by about ten meters, from Google Maps.
152 Several images were taken from the same point of view with different pan and tilt angles
153 (Figure 1C) when the studied object was too close to the road. In such cases, it was impossible
154 to have the entire area in one image because the image is not wide enough to capture the
155 entire studied area (for example a 10 m high cliff along road). When the studied area was far
156 away from the road, we took print screens of zoomed sections of the panorama.

157 To perform temporal comparisons on each site, images were taken at the different dates
158 proposed by GSV with pre- and post-event images sets. We used the SfM-MVS program
159 VisualSFM (Wu 2011) for dense point cloud reconstruction for the print screens images from
160 Google Maps and we used CloudCompare (Girardeau-Montaut 2011) for point cloud
161 visualization and comparison. Comparison between two point clouds was made using point-
162 to-mesh strategy. To this end, a mesh was generated from the reference point cloud (the point
163 cloud with the oldest images for site 1 or the LiDAR scans for sites 2 and 3) and then the
164 other point cloud was compared to this reference mesh. The computed shortest distance, a
165 signed value, between the mesh and the point cloud is the length of the 3D vector from the
166 mesh triangle to the 3D point. Thus, average distances and standard deviations for each
167 comparison of point clouds have been computed. Point density of point clouds was obtained
168 using the “point density” function in CloudCompare with the “surface density” option.

169 Beside the images taken from print screens as described above, we also obtained GSV images
170 (4800 x 3500 pixels, 16.8 Mpx) from Google Earth Pro on sites 2 and 3 with the “save image”
171 function. This second way to get GSV allows to get images with a higher resolution than print
172 screen images. Unfortunately, there is no timeline (or “back in time”) function in Google
173 Earth Pro; it is only possible to save images from the last picture acquisition, i.e. generally
174 post-event images. GSV images from Google Earth Pro were processed with the Agisoft
175 PhotoScan software (Agisoft 2015) for dense point cloud reconstruction, which provides
176 much better results than VisualSFM. GSV images from Google Map were processed with
177 VisualSFM because Agisoft was not able to process those print screens. The flowchart of
178 Figure 3 shows the processing applied to both types of images (print screens and saved
179 images).

180 A rough scaling and georeferencing of the 3D point clouds was made without ground control
181 points, only with coordinates of few points extracted from Google Maps or from the French
182 geoportal (Géoportail, 2016).

183 It is important to mention here that a series of issues are expected when attempting to use SVI
184 for 3D model reconstruction with SfM-MVS. Indeed, GSV images are constructed as 360°
185 panoramas from a series of pictures, so the internal deformation of the original image is not
186 fully retained on the panoramas. In other words, the deformation of a cropped section of the
187 panorama will be a main function not only of the internal deformation of the camera and lens
188 but to the panorama reconstruction process; this circumstance will significantly influence the
189 bundle adjustment process and so to the 3D reconstruction.

190 In addition, GoPro Hero4+ images from a moving vehicle on the road were taken by the
191 authors on site 2, as well a series of images captured using a GoPro Hero5 Black camera
192 standing on site 3 (image resolution of 4000 x 3000 pixels, 12 Mpx). Six LiDAR scans were
193 also taken on site 3. This information was used for quality assessment purposes.

194

195 4 Results and discussion

196 Different results are obtained depending on the software used for SfM-MVS processing. For
197 all case studies, VisualSFM gave results with print screens from GSV in Google Maps while
198 Agisoft PhotoScan could not align those print screens despite adding a series of control points
199 measured with Google Earth Pro. Resolution of print screens images seem to be insufficient to
200 be processed with Agisoft PhotoScan. However, with higher point density and empty areas,
201 Agisoft Photoscan provided better results with images from Google Earth Pro than
202 VisualSFM.

203 4.1 Site 1 – “Basse corniche” site

204 It was possible on “Basse Corniche” site to estimate the fallen volume by scaling and
205 comparing the 2008 (Figure 4A) and 2010 (Figure 4B) point clouds. The 2008 point cloud is
206 composed of 150'000 points with an average density of 290 points per square meter and the
207 2014 point cloud is composed of 182'000 points with an average density of 640 points per
208 square meter (Table 1). VisualSFM could align the images and make 3D models before and
209 after the wall collapse. It was possible to roughly scale and georeference the scene with the
210 road width and few point coordinates measured on Google Earth Pro or on the French
211 geoportal. After aligning the two 3D point clouds, meshes were built to compute the collapsed
212 volume. The point-to-mesh alignment in CloudCompare of both point clouds was done on a
213 small stable part of the cliff (Figure 4C) with a standard deviation of the point-to-mesh
214 distance of about 10 cm (Figure 9 and Table 2) and on the entire cliff beside the vegetation
215 with a standard deviation of about 25 cm (Figure 4E). In the collapsed area, the maximal
216 horizontal distance between the two datasets is about 3.9 m (red colour in Figure 4D). The
217 collapsed volume (including a possible empty space between the cliff and the wall before the
218 event) was estimated to be about 225 m³ using the point cloud comparison. Based on Google
219 Street images, we manually estimated the dimensions of this volume (15 m long x 10 m high
220 x 1.5 m deep), getting a similar value.

221 The obtained point clouds on site 1 allow to detect object of few decimetres. This accuracy
222 was adequate to estimate the collapsed volume with an accuracy similar to the estimation
223 made by hand based on the GSV photos and distances measured on Google Earth Pro and the
224 French geoportal. This relatively high accuracy is due to the following factors: good image
225 quality, reduced distance between the cliff and camera locations, good lighting conditions,
226 absence of obstacles between the camera location and the area under investigation, no
227 vegetation and efficient repartition of point of view around the cliff (Figure 2 A).

228 4.2 Site 2 – Séchillienne Landslide

229 Eight point clouds of which seven of SfM-MVS process with GSV images were generated for
230 Séchillienne landslide at six different time steps (from April 2010 to June 2015). Three
231 different image sources were used: GSV print screens from Google Maps, GSV images saved
232 from Google Earth Pro and images from a GoPro HERO4+ camera from a moving vehicle
233 (Figure 5 and Table 1). Two different programs (VisualSFM and Agisoft PhotoScan) were
234 used for image treatment in function of the image sources (Figure 3 and Table 1). The number
235 of 3D points on the landslide area varies from 9'500 to 22'500 points for a processing with
236 VisualSFM with an average density of 0.25 to 0.85 points per square meter, while 236'000
237 3D points were generated when using Agisoft PhotoScan with an average density of 2 points
238 per square meter (Table 1). In comparison, 1'500'000 points were obtained on the same area
239 using terrestrial photogrammetry with a 24 Mpx reflex camera.

240 Results were aligned on a 50 cm resolution airborne LiDAR scan of the landslide acquired in
241 2010. Then, the street view SfM-MVS point clouds were aligned and compared with a mesh
242 from the LiDAR scan using the point-to-mesh strategy. The alignment between the LiDAR
243 point cloud and SfM-MVS point clouds derived from SVI is a key factor to define the quality
244 of the clouds comparison. This alignment on stable areas (manually selected) was not easy to
245 perform because of the low density of points on the SfM-MVS clouds derived from SVI. We
246 noted a huge difference in the number of points between the different SfM-MVS clouds
247 derived from SVI. This difference on the number of points shows the impacts of the image
248 quality. Images with a good quality (resolution, exposition, sharpness) will give point clouds
249 with a higher number of points as point clouds from low quality images.

250 Comparison results between SfM-MVS point clouds derived from SVI and airborne LiDAR
251 scan highlight surface changes in the Séchillienne landslide over the years (Figure 8 and Table
252 1). The 2010 point cloud (Figure 5 A2) compared with 2010 LiDAR scan does not show any

253 significant changes. Orange and red colours small dots are spread out on the entire landslide
254 surface suggesting artefacts and not a real slope change. The 2010-2011 point clouds
255 comparison (Figure 5 B2) shows few little red colour pattern (materiel accumulation) in the
256 deposition and in the failure areas. The 2016 point cloud (Figure 5 C2) highlights material
257 deposition in red colour, in the left part. This is confirmed with comparison of a 2013
258 terrestrial LiDAR. The blue colour pattern indicate a loss of material in the failure and the toe
259 areas. The 2014 point cloud (Figure 5 D2) shows similar results than the 2013 point cloud
260 with however a light increase of material in the deposition area and rock loss in the failure
261 area. The 2010 to 2014 point clouds (Figure 5 A-D) were process with VisualSFM with GSV
262 print screens in Google Maps (Table 1).

263 Three 2015 point clouds were processed: the first with VisualSFM and GSV print screens
264 (Figure 5E), the second with VisualSFM with GSV images from Google Earth Pro (Figure
265 5F) and the third with Agisoft PhotoScan with images form Google Earth Pro again (Figure
266 5G). The results should be the same for the three point clouds but we noticed significant
267 differences. The 2015 point cloud processed with VisualSFM and GSV images from Google
268 Earth Pro (4800 x 3500 pixels), has a higher point density than the 2015 point cloud processed
269 with GSV print screens (1920 x 1200 pixels). The 2015 point cloud with Agisoft PhotoScan
270 and images from Google Earth Pro has a point density significantly higher (Table 1). The
271 accumulation material (red colour in the left part) in the deposition area is clearly observable
272 on the three 2015 point clouds, as the rock displacement-toppling below the failure area (red
273 colour pattern in the failure area viewed as a material accumulation from the road). The loss
274 of material (blue colour) is also well observable in the failure area and, to a lesser extent, in
275 the right part of the deposition area. The last 2015 point cloud is very similar to the 2016
276 GoPro point cloud (Figure 5 H2) which confirms the results of SfM-MVS processing with
277 GSV images.

278 Results of site 2 show that images with low resolution and with low lighting generated a
279 lower number of points compared to the models generated with the last generation of GSV
280 cameras, having higher resolution, more advanced sensors and pictures taken with favourable
281 lighting conditions. The large distance between the road and the landslide considerably limits
282 the final accuracy due to low image resolution, as discussed in Eltner et al., 2016; the closest
283 distance between the road and the centre of the landslide is 500 m and the largest distance
284 between the upper part of the landslide and the point of view is about 1'400 m. Furthermore,
285 the vegetation on the landslide foot and along the road as well as a power line partially

286 obstruct the visibility of the study area. In addition, clouds are present on several images on
287 the top of the scarp, degrading the upper part of the 3D point cloud.

288 4.3 Site 3 – Arly Gorges

289 Four point clouds of which three of SfM-MVS process derived from GSV images were
290 generated on the “Arly gorges” site, at four different times (from March 2010 to December
291 2016). Three different images sources (GSV print screens from Google Maps, GSV images
292 exported from Google Earth Pro and our own images acquired from a GoPro HERO5 Black)
293 were used (Figure 6 and Table 1). Two different programs (VisualSFM and Agisoft
294 PhotoScan) were tested. In addition, a LiDAR point cloud resulting from an assembly of six
295 Optech Iris scans has been used as ground truth (Figure 6E). The number of points varies
296 from 35’000 points to 3.2 million points with an average density of 40 to 2’200 points per
297 square meter (Table 1).

298 The 3D point cloud from the “GoPro Hero5 Black” images has been roughly georeferenced,
299 scaled and oriented thanks to the GNSS chip integrated in the camera and has been controlled
300 and refined with points coordinates extracted from Google Maps and the French geoportal.
301 The three point clouds processed from GSV images and the LiDAR scan have been roughly
302 aligned to this reference. Then the four SfM-MVS point clouds (three with GSV images and
303 one with GoPro images) were precisely aligned and scaled on the LiDAR point cloud, which
304 was considered as the reference cloud.

305 The analysis (Figure 9, Tables 1 and 2) shows that the 2010 model derived from GSV images
306 processed with VisualSFM gives the least accurate results (Figures 6A and 7A): we hardly
307 perceive on that figure the wall of the tunnel entry and the wide cliff structures. The results of
308 the 2014 point cloud from GSV images processed with the same program are slightly better
309 (Figure 6B and 7B): the right-hand tunnel entry is modelled while it was not the case on the
310 2010 point cloud. The point cloud processed in Agisoft PhotoScan derived from 2016 GSV
311 images saved from Google Earth Pro displays much better quality than the previous (Figure
312 6C and 7C): we now see the protective nets in the slope as well as the blue road sign
313 announcing the tunnel. The vegetation is also observable and the tunnel entry is similarly
314 modelled as the 2016 GoPro point cloud (Figure 6D).

315 The SfM-MVS point cloud derived from GoPro images gives a significantly better
316 representation of the whole scene, especially on the top of the model. Slope structures and
317 protective nets are well modelled, but not the small vegetation. The comparison between the

318 2016 LiDAR scan (Figure 6E) and the three SfM-MVS with GSV images point clouds does
319 not allow to identify terrain deformation on the cliff. Moreover, the source area of the rockfall
320 is not observable from the GSV images because it is located higher in the slope, outside of the
321 images.

322 A great majority of points consistently displayed distances between the LiDAR scan mesh and
323 the SfM-MVS point clouds ranging between +/- 2 m (Figure 7 A-C). Protective nets degrade
324 the results because it generates badly modelled surfaces corresponding to the nets on some
325 cliff sections (such as the red-blue section on the top-right of the July 2014 cloud (Figure
326 7A)). Considering the tunnel entry (Figure 7 D-F) the average distance point clouds - LiDAR
327 mesh varies from -3 to -6 cm (depends mainly on the alignments of the clouds). Standard
328 deviations vary from 22 cm for the 2010 point cloud to 11 cm for the 2016 point cloud. On a
329 part of the wall above the tunnel (grey colour polygon on Figure 7 D-F), the average distance
330 point cloud - LiDAR mesh varies from -3 cm to -18 cm with standard deviations of 3 cm for
331 the 2010 point cloud, 4 cm for the 2014 point cloud et 6 cm for the 2016 point cloud (Figure 9
332 and Table 2). We observe again on this site that the improvement of the GSV camera
333 resolution and image quality improve the processing. The information on the pictures source,
334 date, point density and on the program used is given in Table 1.

335 A strong limiting factor on this site is the non-optimal camera locations. Indeed, the location
336 of the cliff above a tunnel portal does not allow for a lateral movement between the camera
337 positions with regard to the cliff. The maximal viewing angle (in blue colour on the Figure
338 2A) is about 35° compared to 170° for the site 1, and 115° for the site 2, that is 3 to 5 time
339 smaller than for the other studied sites.

340 4.4 Discussion

341 With the experience acquired during the research, we can highlight the following
342 recommendations to improve results of SfM-MVS with SVI images. (A) Firstly, the distance
343 between the image point of view and the subject and the size of the subject are important
344 because it influences the pixel size on the subject. In case study 1, the location of the cliff next
345 to the road (< 1 m) allows to get images with a good resolution for the studied object. In case
346 study 2, the area under investigation is too far from the road (500 – 1'400 m) and small
347 structures cannot be seen in the landslide. (B) Secondly, the ability to look at the scene from
348 different angles (Figure 2A) is a determining factor to obtain good results. The greater is this
349 “view angle”, the better the results will be. Case study 1 with a view angle of almost 180° is

350 optimal because the object is observable from half a circle. View angle of case study 2 (115°)
351 is enough to get many different views of the subject from different angles. The view angle is
352 too narrow to have enough different point of view of the cliff on case study 3 (35°). (C)
353 Thirdly, results are influenced by the image quality and especially by their exposition,
354 contrast and type of sensor, which has progressively been improved during the last years.
355 Image quality varies considerably on different images sets. Case study 1 is again the best
356 study case in term of image quality. Both image sets have optimal solar exposition and
357 shadows are not strong. Case study 2 has sets with very different images quality. Some sets
358 are well exposed, others not. Clouds are present on few image sets. For case study 3, we have
359 a lot of over- and underexposed images on behalf of the situation of the site (incised valley
360 with a southwest oriented slope with a lot of light or shadow). The problem of images quality
361 concerns Google too because it has removed from Google Maps very underexposed GSV
362 images taken in August 2014 on site 3 at the end of 2016.

363 According to our findings, small landslides and rockfalls ($<0.5 \text{ m}^3$) can be detected when the
364 slope or the cliff is close to the road (0-10 m), as it was shown on site 1. Conversely, large
365 slope movements and collapses ($>1'000 \text{ m}^3$) can be detected when the studied area is far away
366 from the road (up to 0.5-1 km) like on site 2. On such sites, small changes ($<1 \text{ m}^3$) can
367 correspond to either real rockfalls or errors resulting from processing like on the toe of almost
368 all point 3D clouds of Séchilienne landslide (Figure 5 A2-H2). The measured differences
369 between the point clouds on stable areas show interesting results once the point clouds
370 alignment is well done. Thus, we observed standard deviations of few decimetre on stable
371 areas on site 1 (Figure 3D), between 0.5 and 1.1 m on site 2 and between 11 and 22 m on the
372 tunnel entry on site 3. Standard deviations increase on site 2 when point clouds are compared
373 on their entire surface (Figure 5 A2-H2, Table 1). This is attributable to the occurrence of
374 slope movements generating material increase or decrease and thereby, increasing standard
375 deviations of the distance between the two compared point clouds. It can also be due to a bad
376 3D point cloud alignment. Indeed, cloud alignment is not always easy on some point clouds
377 because of low point density, because of voids in the point clouds (like in the landslide toe in
378 Figure 5 F2) and because of the roughness of the terrain. In such difficult alignment cases, it
379 was tried to align the point clouds on stable parts where point density was high.

380 Our study highlighted important differences on 3D model reconstruction using different
381 software, consistently with previous works (Micheletti et al., 2015; Gomez-Gutierrez et al.,
382 2015, Niederheiser et al., 2016). Agisoft PhotoScan performed better than VisualSFM when

383 using both GSV images from Google Earth Pro (Figure 5F-G) and pictures acquired from a
384 GoPro Hero camera (Figure 5H). Nevertheless, VisualSfM performed better than Agisoft
385 PhotoScan on print screens captures from SVI. The only difference between these sources of
386 information is the resolution: 2.3 Mpx for print screens from Google Maps, 16.8 Mpx for
387 images saved from Google Earth Pro (and 12 Mpx for GoPro camera), stressing the
388 importance of picture resolution on the quality of the 3D model.

389 The point density was evaluated according to the distance between the image point of view
390 and the subject and the image types and processing software. The obtained results and the
391 derived trends indicate that the use of GSV images from Google Earth Pro with VisualSfM
392 increases by a factor two the point density compared to the processing of GSV print screens
393 with VisualSfM. The processing of GSV images from Google Earth Pro with Agisoft
394 PhotoScan increases by a factor ten the point density compared to the processing of GSV print
395 screens with VisualSfM (trend strips in Figure 8). The expected point density of the 3D point
396 clouds from GSV print screens processed in VisualSfM of a subject located few meters from
397 the camera (“Basse-Corniche” dots on Figure 8) is about 300 points/m², about 50 points/m²
398 for an area located at about 100 m (“Arly” dots on Figure 8) and about 0.5 point/m² for an
399 area located at about 700 m (“Séchilienne” dots on Figure 8).

400

401 Despite the above mentioned prospects, some drawbacks were also observed. The main
402 limitation found in this study is that SfM-MVS processing is designed to retrieve the internal
403 orientation of standard cameras, whereas the images used in this research do not correspond to
404 a standard camera due the construction of the panoramas. Indeed, the main problem comes
405 from the different deformations on GSV print screens or images due to the panoramas
406 construction. Same radial deformations, that are stronger than common camera lens, on each
407 images, like on fisheyes images from GoPro cameras, can be processed without limitation
408 with SfM software like Agisoft PhotoScan. In addition, images from GSV are often over- or
409 underexposed (case study 3) and their resolution is low for distant subjects (cases study 2 and
410 3), making difficult to obtain results with few decimetric accuracy with these constraints.
411 Making zoomed print screens from GSV images do not allow increasing the SfM-MVS
412 process results (case study 2) due to a low images resolution. Finally, the spatial repartition of
413 SVI is often problematic because there are not enough images along the track path and
414 because the road path does not often allow obtaining an efficient strategy concerning the
415 camera positions around the studied area (case study 3). Accessing to original (RAW) images

416 together with valuable data of camera calibration would considerably help deriving 3D point
417 clouds from GSV using modern photogrammetric workflows.

418 A simple development to improve our proposed approach would be that Google add the *back*
419 *in time function* into the Google Earth Pro. In this case, it would be possible to save GSV
420 images from any proposed time period and to process those images with Agisoft PhotoScan
421 (Figure 5G) and thus to obtain better results than when using VisualSFM (Figure 5F).
422 Knowing that Google services and functionalities of Google Maps and Google Earth are
423 evolving over time, it is possible that SfM-MVS with GSV images will be more efficient and
424 easier in a near future.

425

426 5 Conclusions

427 In this study it was possible to detect and characterize small landslides and rockfalls ($<0.5 \text{ m}^3$)
428 for study areas relatively close to the road (from 0 to 10 m); complementarily, it was possible
429 to detect large scale landslides or rock collapses ($>1'000 \text{ m}^3$) over areas located far away from
430 the road (hundred meters or more). This information is of great interest when no other data of
431 the studied area has been obtained.

432 The proposed methodology provides interesting but challenging results due to some
433 constraints linked to the quality of the input imagery. The inconsistent image deformations
434 and the impossibility of extracting the original images from a street view provider are the
435 most important limitations for 3D model reconstruction derived from SVI. Following
436 constraints strongly limit the proposed approach: large distances between the camera position
437 and the subject of investigation, presence of obstacles between the studied area and the road,
438 image quality, poor meteorological conditions, non-optimal images repartition, reduced
439 number of images, existence of shadows/highlighted areas. The quality of the final product
440 was observed to be mainly dependent on the images quality and of the distance between the
441 studied area and image perspectives.

442 Although of the above mentioned limitations, SfM-MVS with SVI can be a useful tool in
443 geosciences to detect and quantify slope movements and displacements at an early stage of
444 the research by comparing datasets taken at different time series. The main interest of the
445 proposed approach is the possibility to use archival imagery and deriving 3D point clouds of
446 an area that has not been captured before the occurrence of a given event. This will allow

447 increasing database on rock slope failures, especially for slope changes along roads which
448 conditions are favourable for the proposed approach.

449 6 References

450 Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N.J., Lim, M. and Lato, M.J., 2014,
451 Terrestrial laser scanning of rock slope instabilities. *Earth Surface Processes and*
452 *Landforms*, v. 39, p.80-97.

453 Agisoft, L. L. C., 2015, Agisoft PhotoScan user manual, Professional edition, version 1.2.6.

454 Anguelov, D., Dulong, C., Filip, D., Frueh, Ch., Lafon, S., Lyon, R., Ogale, A., Vincent, L.,
455 Weaver, J., 2010, Google Street View: Capturing the world at street level. *Computer*,
456 Vol. 43, IEEE, 32-38.

457 Carrivick, J. L., Smith, M. W., Quincey, D. J., 2016, *Structure from Motion in the*
458 *Geosciences*. John Wiley & Sons.

459 Dubois, L., Chanut, M.-A., Duranthon, J.-P., 2014, Amélioration continue des dispositifs
460 d'auscultation et de surveillance intégrés dans le suivi du versant instable des Ruines de
461 Séchilienne. *Géologues* n°182, p50-55.

462 Durville, J.-L., Bonnard, C., Potherat, P., 2011, The Séchilienne (France) landslide: a non-
463 typical progressive failure implying major risks, *Journal of Mountain Science*, Vol. 8,
464 Issue 2, 117-123.

465 Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F. and Abellán, A., 2016, Image-based
466 surface reconstruction in geomorphometry—merits, limits and developments. *Earth*
467 *Surface Dynamics*, 4(2), pp.359-389.

468 Favalli, M., Fornaciai, A., Isola, I., Tarquini, S., Nannipieri, L., 2011, Multiview 3D
469 reconstruction in geosciences, *Computers & Sciences* 44, 168-176.

470 Fey, C., Wichmann, V., 2016, Long-range terrestrial laser scanning for geomorphological
471 change detection in alpine terrain – handling uncertainties. *Earth Surf. Process.*
472 *Landforms*.

473 Fernández, T., Pérez, J. L., Cardenal, J., Gómez, J. M., Colomo, C., Delgado, J., 2016,
474 Analysis of Landslide Evolution Affecting Olive Groves Using UAV and
475 Photogrammetric Techniques. *Remote Sensing*, 8(10), 837.

476 Furukawa, Y., Ponce, J., 2010, Accurate, dense, and robust multiview stereopsis. Pattern
477 Analysis and Machine Intelligence, IEEE Transactions on, 32(8), 1362-1376.

478 Furukawa, Y., Curless, B., Seitz, S. M., Szeliski, R., 2010, Towards internet-scale multi-view
479 stereo. In Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference
480 on (pp. 1434-1441). IEEE.

481 France 3 : Important éboulement dans les gorges de l'Arly en Savoie, 2014, available at :
482 [http://france3-regions.francetvinfo.fr/alpes/savoie/important-eboulement-dans-les-](http://france3-regions.francetvinfo.fr/alpes/savoie/important-eboulement-dans-les-gorges-de-l-arly-en-savoie-400849.html)
483 [gorges-de-l-arly-en-savoie-400849.html](http://france3-regions.francetvinfo.fr/alpes/savoie/important-eboulement-dans-les-gorges-de-l-arly-en-savoie-400849.html) (last access 25 January 2017).

484 Géoportail, IGN (2016), 2016, available at <http://www.geoportail.gouv.fr> (last access 25
485 January 2017).

486 Girardeau-Montaut, D., 2011, CloudCompare-Open Source project. OpenSource Project.

487 Gómez-Gutiérrez, Á., de Sanjosé-Blasco, J.J., Lozano-Parra, J., Berenguer-Sempere, F. and
488 de Matías-Bejarano, J., 2015, Does HDR pre-processing improve the accuracy of 3D
489 models obtained by means of two conventional SfM-MVS software packages? The case
490 of the Corral del Veleta Rock Glacier. Remote Sensing, 7(8), pp.10269-10294.

491 Google Street View, Understand Street View, 2017, available at
492 <https://www.google.com/maps/streetview/understand> (last access 25 January 2017).

493 Google Maps, Google Inc. (2017), 2017, available at <https://maps.google.com> (last access 25
494 January 2017).

495 Google Earth Pro, version 7.1.2.241, Google Inc. (2013), 2013, available at
496 <https://www.earth.google.com/earth> (last access 25 January 2017).

497 Guerin, A., Abellán, A., Matasci, B., Jaboyedoff, M., Derron, M.-H., and Ravanel, L.: Brief
498 communication: 3-D reconstruction of a collapsed rock pillar from Web-retrieved
499 images and terrestrial lidar data – the 2005 event of the west face of the Drus (Mont
500 Blanc massif), Nat. Hazards Earth Syst. Sci., 17, 1207-1220,
501 <https://doi.org/10.5194/nhess-17-1207-2017>, 2017.

502 James, M. R., Robson, S., 2012, Straightforward reconstruction of 3D surfaces and
503 topography with a camera, Accuracy and geosciences application, Journal of
504 Geophysical research, Vol. 117, F03017.

505 Klingner, B., Martin, D., Roseborough, J., 2013, Street View Motion-from-Structure-from-
506 Motion, Proceedings of the International Conference on Computer Vision, IEEE.

507 Kromer, R., Abellán, A., Hutchinson, J., Lato, M., Edwards, T., Jaboyedoff, M., 2015, A 4D
508 Filtering and Calibration Technique for Small-Scale Point Cloud Change Detection with
509 a Terrestrial Laser Scanner. Remote Sensing vol.7, pp.13029-13052; DOI:
510 10.3390/rs71013029.

511 Lichtenauer, J. F., Sirmacekb, B., 2015, A semi-automatic procedure for texturing of laser
512 scanning point with google streetview images, The International Archives of the
513 Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-3/W3,
514 109-114.

515 Le Roux, O., Schwartz, S., Gamond, J. F., Jongmans, D., Bourles, D., Braucher, R., Mahaney,
516 W., Carcaillet, J., Leanni, L., 2009, CRE dating on the head scarp of a major landslide
517 (Séchilienne, French Alps), age constraints on Holocene kinematics, Earth and
518 Planetary Science Letters, Vol. 280, 236-245.

519 Lucieer, A., de Jong, S., Turner, D., 2013, Mapping landslide displacements using Structure
520 from Motion (SfM) and image correlation of multi-temporal UAV photography,
521 Progress in Physical Geography, Vol. 38(1), 97-116.

522 Luhmann, T., Robson, S., Kyle, S., Boehm, J., 2014, Close-range photogrammetry and 3D
523 imaging. Walter de Gruyter.

524 Lowe, D., 1999, Object recognition from local scale-invariant features. International
525 Conference of Computer Vision, Corfu Greece, 1150-1157.

526 Luhmann, T., Robson, S., Kyle, S., Boehm, J., 2014, Close-range photogrammetry and 3D
527 imaging, Walter De Gruyter.

528 Micheletti, N., Chandler, J. H., Lane, S. N., 2015, Investigating the geomorphological
529 potential of freely available and accessible Structure-from-Motion photogrammetry
530 using a smartphone. Earth Surface Processes and Landforms, Vol 40(4), 473-486.

531 Nice-Matin : La basse corniche coupée en direction de Monaco après un éboulement, 2014,
532 available at : [http://www.nicematin.com/menton/la-basse-corniche-coupee-en-direction-](http://www.nicematin.com/menton/la-basse-corniche-coupee-en-direction-de-monaco-apres-un-eboulement.1587292.html)
533 [de-monaco-apres-un-eboulement.1587292.html](http://www.nicematin.com/menton/la-basse-corniche-coupee-en-direction-de-monaco-apres-un-eboulement.1587292.html) (last access 15 October 2015).

534 Niederheiser, R., Mokroš, M., Lange, J., Petschko, H., Prasicek, G., & Elberink, S. O., 2016,
535 Deriving 3d Point Clouds from Terrestrial Photographs-Comparison of Different
536 Sensors and Software. *International Archives of the Photogrammetry, Remote Sensing*
537 *and Spatial Information Sciences-ISPRS Archives*, 41, 685-692.

538 Oppikofer, T., Jaboyedoff, M., Blikra, L., Derron, M.-H., Metzger, R., 2009, Characterization
539 and monitoring of the Åknes rockslide using terrestrial laser scanning. *Natural Hazards*
540 *and Earth System Science* 9: 1003–1019.

541 Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A., Allison, R.J., 2005, Terrestrial laser
542 scanning for monitoring the process of hard rock coastal cliff erosion. *Quarterly Journal*
543 *of Engineering Geology and Hydrogeology* 38(4): 363–375.

544 Royán, M.J., Abellán, A., Jaboyedoff, M., Vilaplana, J. M., Calvet, J., 2014, Spatio-temporal
545 analysis of rockfall pre-failure deformation using Terrestrial LiDAR. *Landslides*, pp.1–
546 13.

547 Ruggles, S., Clark, J., Franke, K. W., Wolfe, D., Reimschiessel, B., Martin, R. A., ... &
548 Hedengren, J. D., 2016, Comparison of SfM computer vision point clouds of a landslide
549 derived from multiple small UAV platforms and sensors to a TLS-based model. *Journal*
550 *of Unmanned Vehicle Systems*, 4(4), 246-265.

551 Snavely, N., M. Seitz, S., Szeliski, R., 2006, Photo Tourism: Exploring Photo Collection in
552 3D. In *SIGGRAPH 06*, 835-846.

553 Snavely, N., 2008, Scene reconstruction and visualization from Internet photo collections,
554 unpublished PhD thesis, University of Washington, USA.

555 Snavely, N., Seitz, S., Szeliski, R., 2008, Modeling the World from Internet Photo Collections
556 *Int J Comput Vision*, Springer Netherlands, 80, 189-210

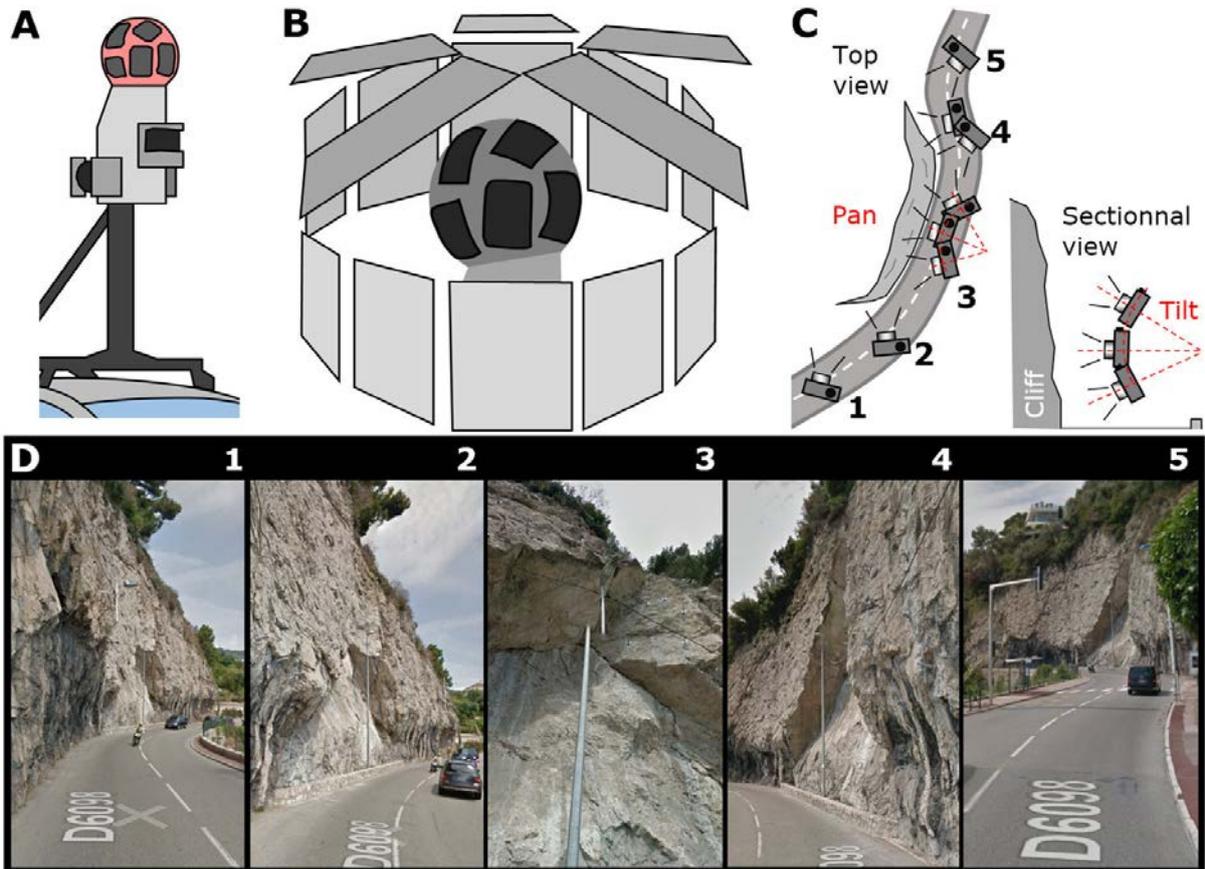
557 Streetside, Microsoft Inc. (2017), 2017, available at
558 <https://www.microsoft.com/maps/streetside.aspx> (last access 25 January 2017).

559 Stumpf, A., Malet, J. P., Allemand, P., Pierrot-Deseilligny, M., Skupinski, G., 2015, Ground-
560 based multi-view photogrammetry for the monitoring of landslide deformation and
561 erosion. *Geomorphology*, 231, 130-145.

562 Tencent Maps, Tencent Inc. (2017), 2017, available at <http://map.qq.com> (last access 25
563 January 2017).

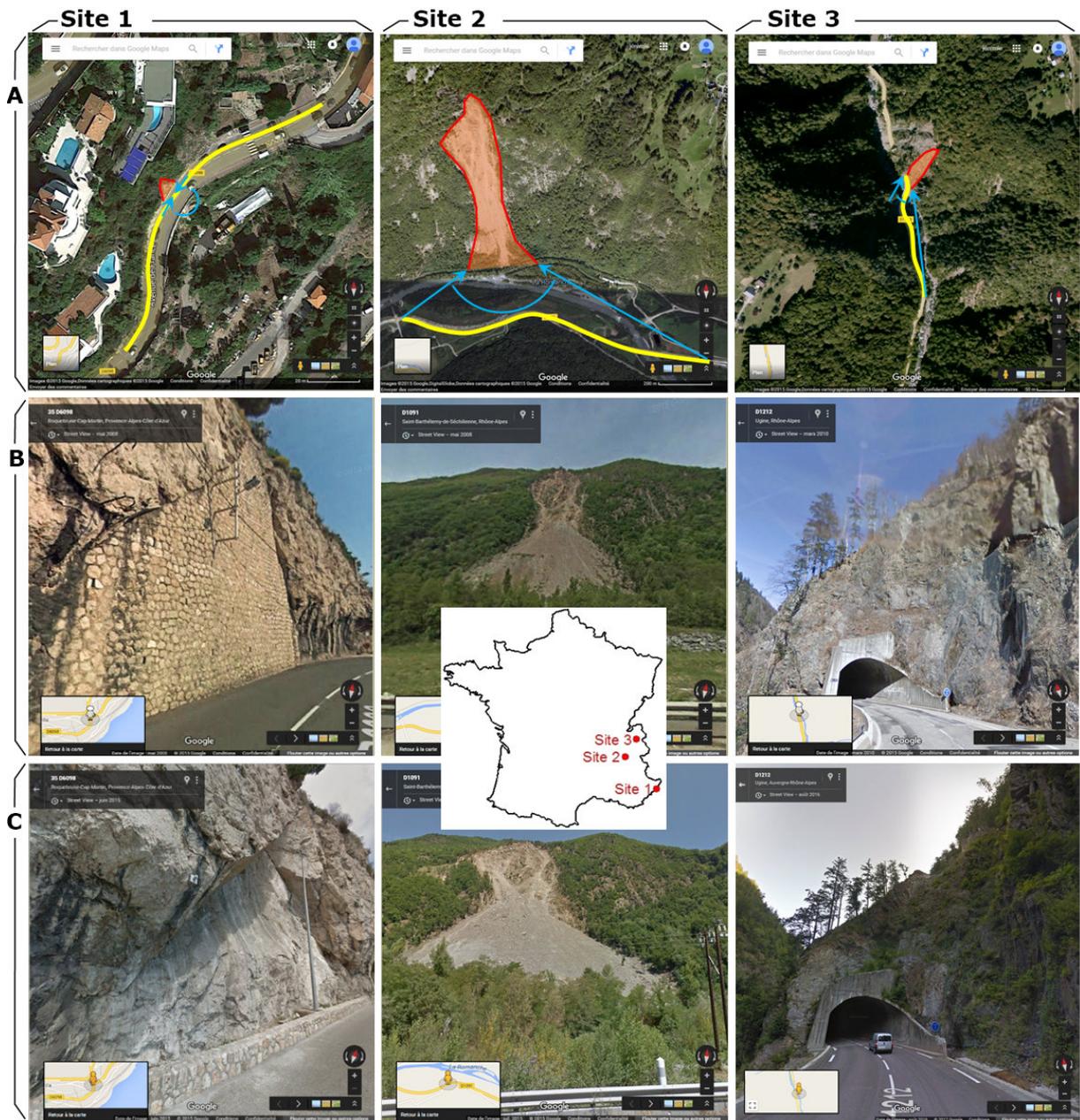
- 564 Turner, D., Lucieer, A., Watson, C., 2012, An Automated Technique for Generating
565 Georectified Mosaics, from Ultra-High Resolution Unmanned Aerial Vehicle (UAV),
566 Conference on 3D Imaging, Modeling, Processing, Visualization & Transmission
567 Imagery, Based on Structure from Motion (SfM) Point Clouds, Remote Sensing, 4(5),
568 1392-1410 IEEE,479-486.
- 569 Walstra, J., Chandler, J. H., Dixon, N., Dijkstra, T. A., 2007, Aerial photography and digital
570 photogrammetry for landslide monitoring. Geological Society, London, Special
571 Publications, 283(1), 53-63.
- 572 Wang, C.-P., Wilson, K., Snavely, N., 2013, Accurate Georegistration of Point Clouds Using
573 Geographic Data, In 3D Vision – 3DV, IEEE, 33-40.
- 574 Westoby, M.J., Brassington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012,
575 ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience
576 applications, Geomorphology, Vol. 179, 300-314.
- 577 Wu, C., 2011, VisualSfM: A visual structure from motion system, available at
578 <http://ccwu.me/vsfm> (last access 25 January 2017).
- 579 Zamir, A. R., Shah, M., 2010, Accurate Image Localization Based on Google Maps Street
580 View, In Computer Vision – ECCV 2010, Springer, 255-268.

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584 *Figure 1: Google Street View (GSV) imagery functioning. A: Schema of the GSV spherical camera system mounted on a car*
 585 *roof. Sensors in black colour are LiDAR on which are draped the GSV images (based on Google Street View 2017). B:*
 586 *Functioning of the GSV spherical panorama built with fifteen images. C: Strategy of the GSV service for SfM-MVS*
 587 *photogrammetry. Numbers correspond schematically to the images in D. D: Screen captures of GSV photos from the study*
 588 *site 1. The image numbers correspond to those in C. Note the gap on the street-lamp in images 3 due to the panorama*
 589 *construction from the GSV pictures.*
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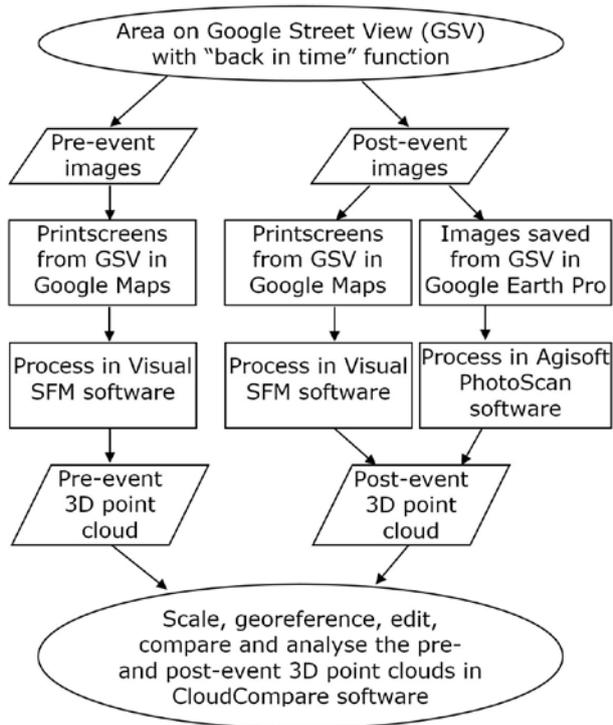
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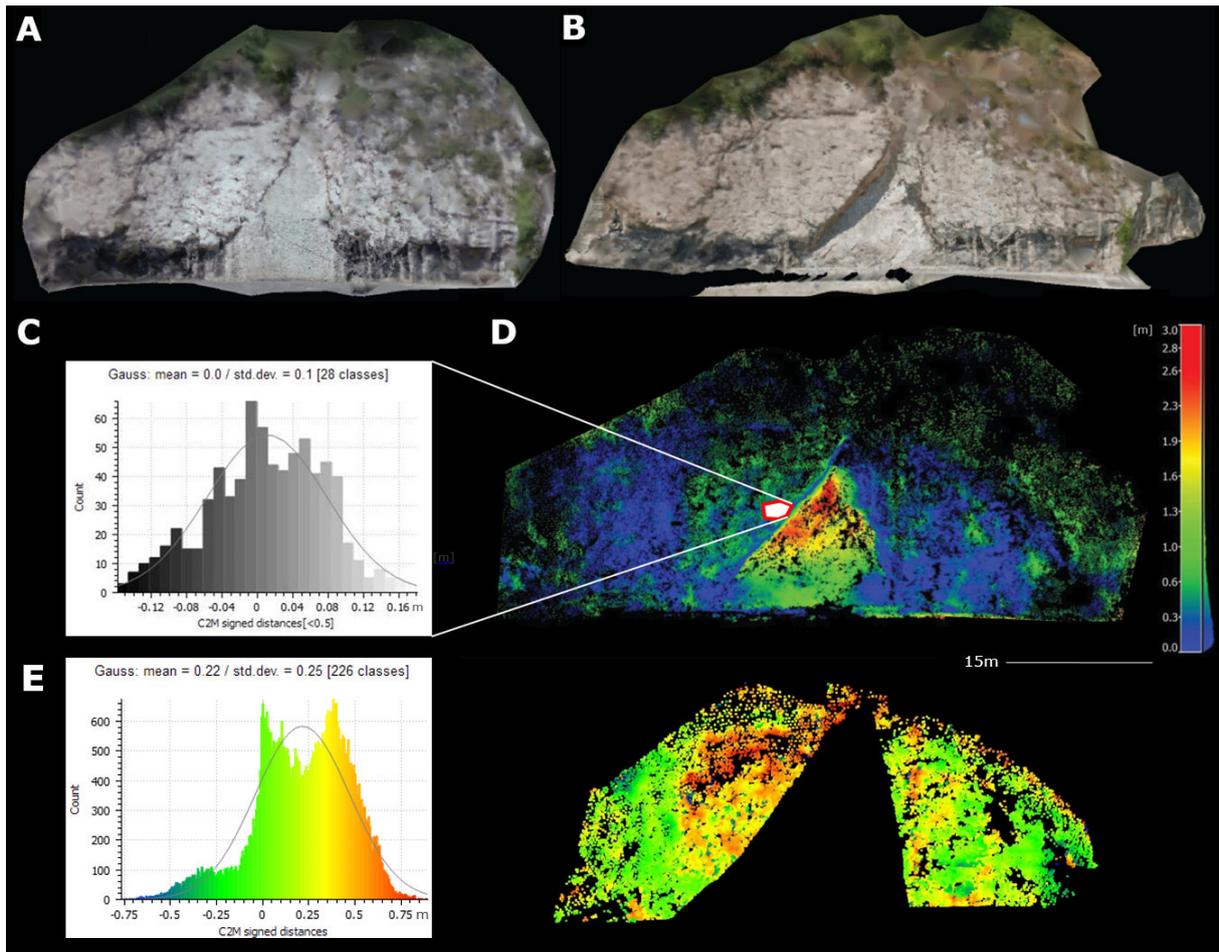
Figure 2 : The three French studied sites (1: Basse-Corniche, 2: Séchilienne and 3: Arly gorges). A: Google Maps aerial view of the sites (in red) with the road path (yellow) used to take the GSV images of the scenes and the view angle (blue) of the images point of view around the sites. B: First GSV of the sites. C: Last GSV of the sites.



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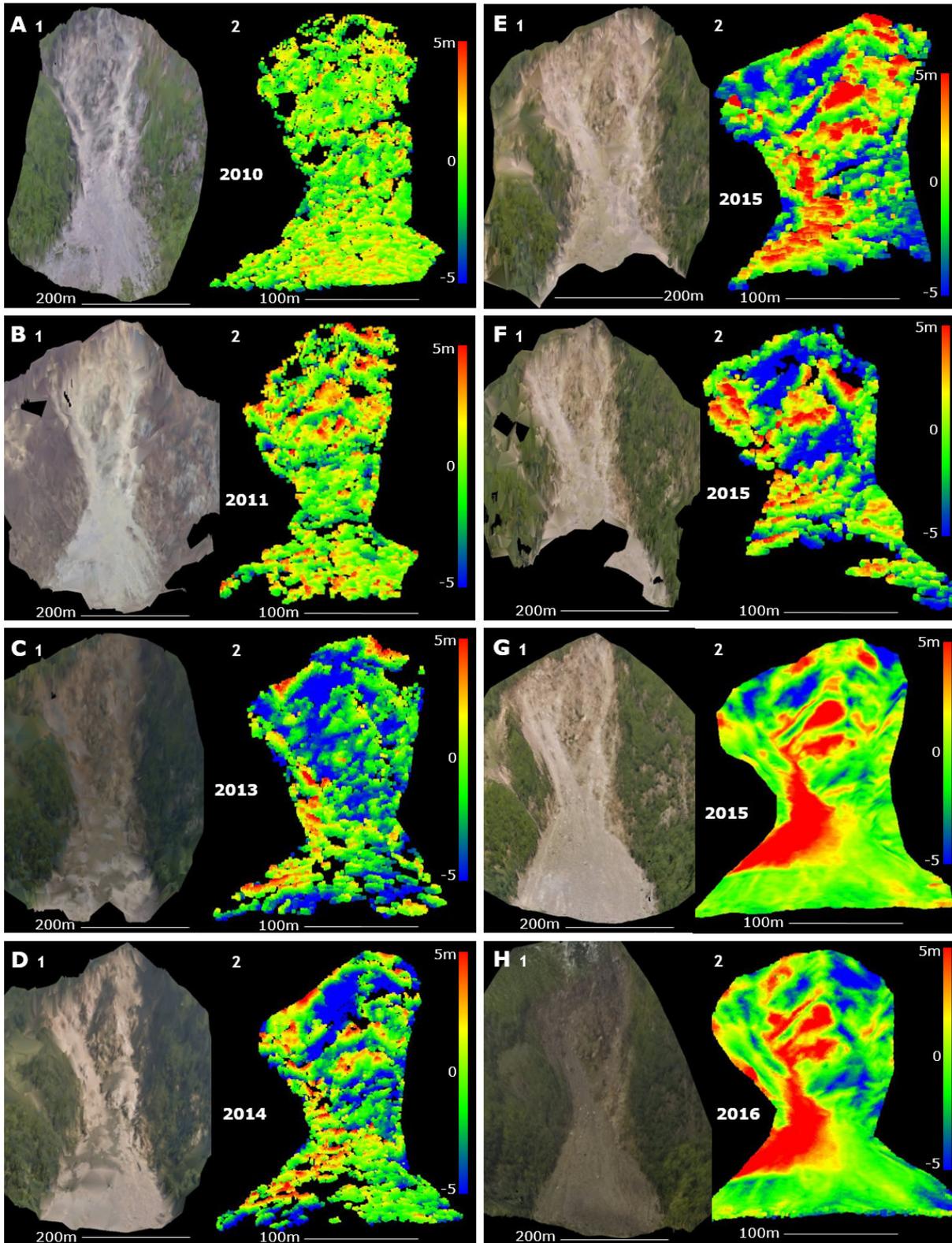
597 *Figure 3: Flowchart of the SfM-MVS processing with GSV images on an area with the “back in time” function available.*
 598 *Pre-event images are displayed using the “back in time” function in GSV. Post-event images arise either from print screens*
 599 *of GSV in Google Maps using or not the “back in time” function or from GSV images saved in Google Earth Pro. In this last*
 600 *case, the last available proposed GSV images have a greater resolution as the print screens and can be processed in the*
 601 *Agisoft PhotoScan.*

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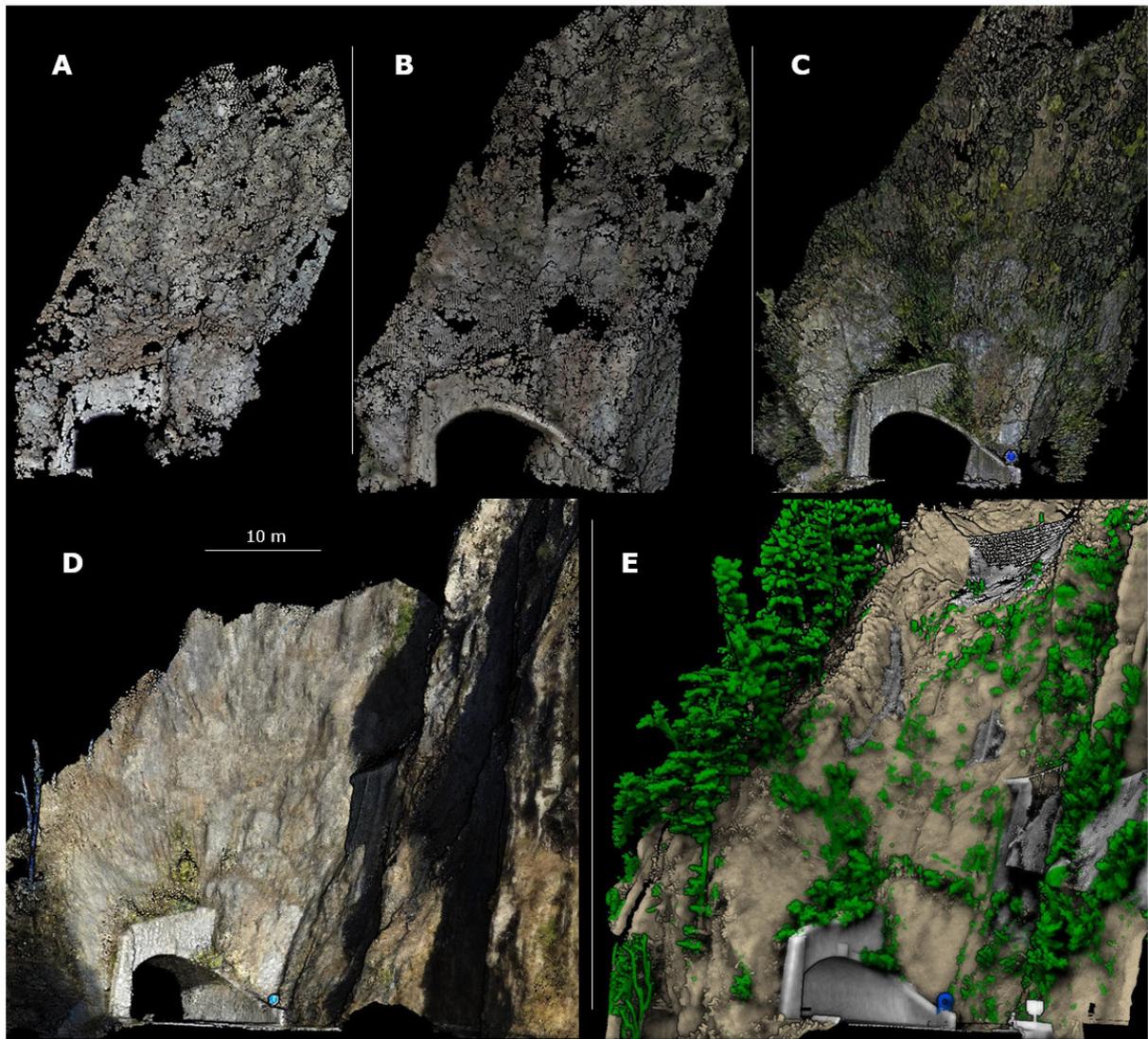
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604 *Figure 4: Results at site 1 "Basse-Corniche". A: 3D model produced with GSV images taken before the event in 2008. B: 3D*
 605 *model produced with GSV images taken after the event in 2014. C: Statistics on a small part of the wall (red colour polygon*
 606 *on figure D) of 7'510 points between the two point clouds with the point-to-mesh strategy in the CloudCompare. D:*
 607 *Comparison of the two point clouds of 2008 and 2014 on the entire surface of the 3D point clouds. The maximal horizontal*
 608 *depth of the cliff is about 3.9 m. E: Comparison of the two point clouds of 2008 and 2014 on the entire stable parts of the cliff*
 609 *(i.e. without vegetation) by not taking into account the collapsed wall (black triangle in the centre of the point clouds. The*
 610 *information on the pictures source, date, point density and on the program used is given in Tables 1 and 2.*



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Figure 5 : Results at site 2 "Séchilienne". Eight points clouds from different images sets taken at six different time with three different image sources and processed with two different programs. Figures A1-H1: Meshs resulting from the respective point clouds. Figures A2-H2: point clouds comparison with a 50 cm LiDAR DEM from 2010 (red colour points is material increase; blue colour points are material decrease from the 2010 LiDAR cloud) with the point-to-mesh strategy in CloudCompare. The information on the pictures source, date, point density and on the program used is given in Table 1.



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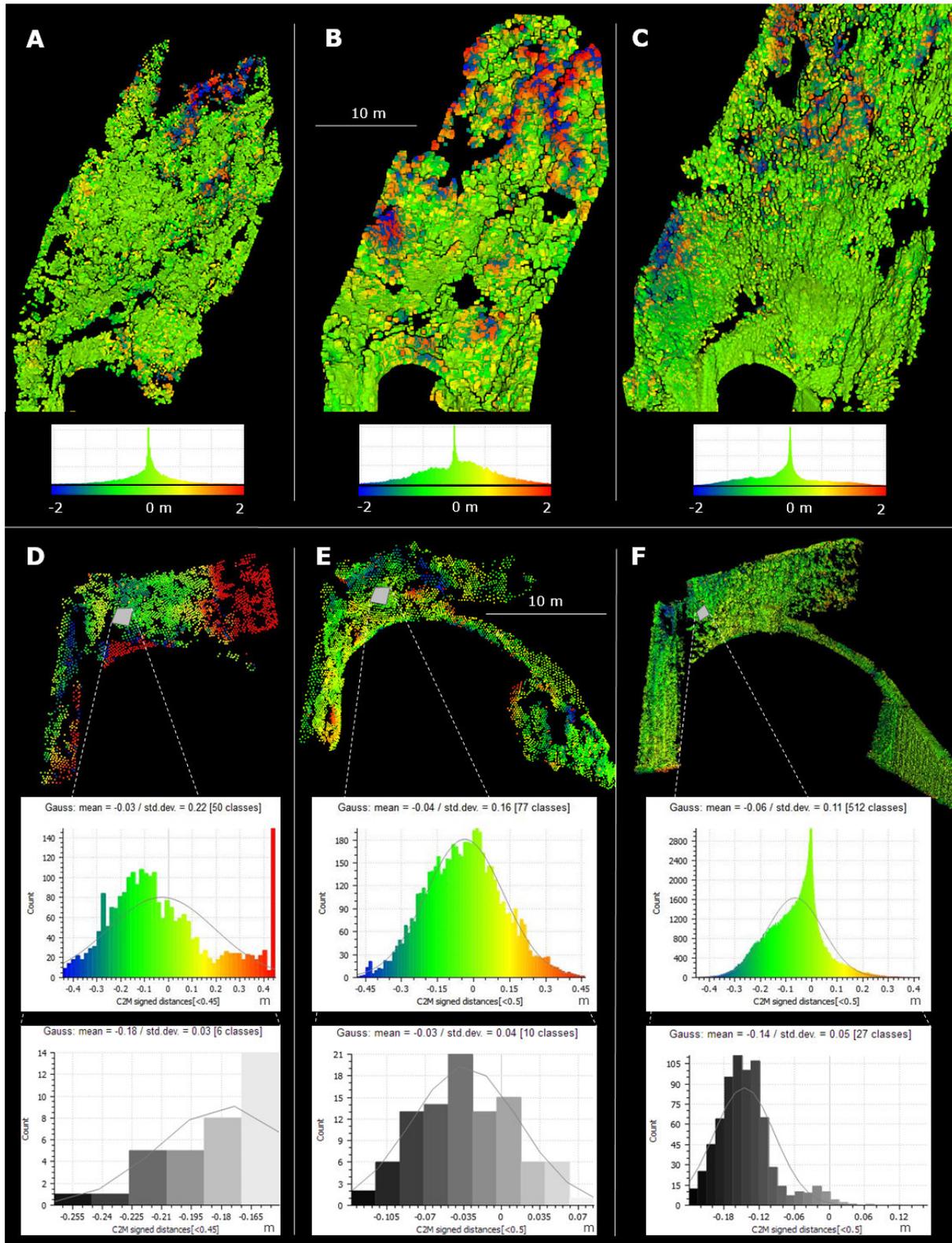
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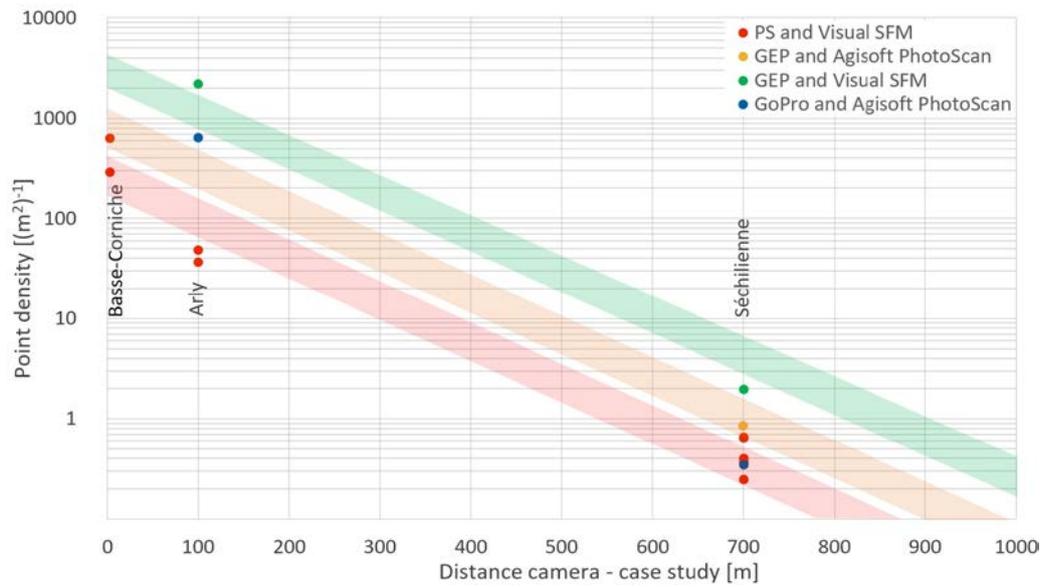
Figure 6 : Results at site 3 "Arly gorges". Five points clouds from four different images sets sources and processed with two different softwares and one LiDAR scan. A: March 2010 point cloud. B: July 2014 point cloud. C: August 2016 point cloud. D: December 2016 point cloud taken on foot with a GoPro camera. E: December 2016 LiDAR cloud from an assembly of six Optech terrestrial LiDAR scans. The grey elements in the cliff are the protective nets.



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624 Figure 7: A-B-C: March 2010, July 2014 and August 2016 point clouds compared with December 2016 LiDAR DEM (red
 625 colour points is material increase; blue colour points are material decrease from the 2016 LiDAR cloud) with the point-to-
 626 mesh strategy on the CloudCompare. D, E, F: tunnel entry and part of the wall overlooking the tunnel (grey colour polygon)
 627 of the March 2010, July 2014 and August 2016 point clouds compared with December 2016 LiDAR DEM. The information
 628 on the pictures source, date, point density and on the program used is given in Tables 1 and 2.

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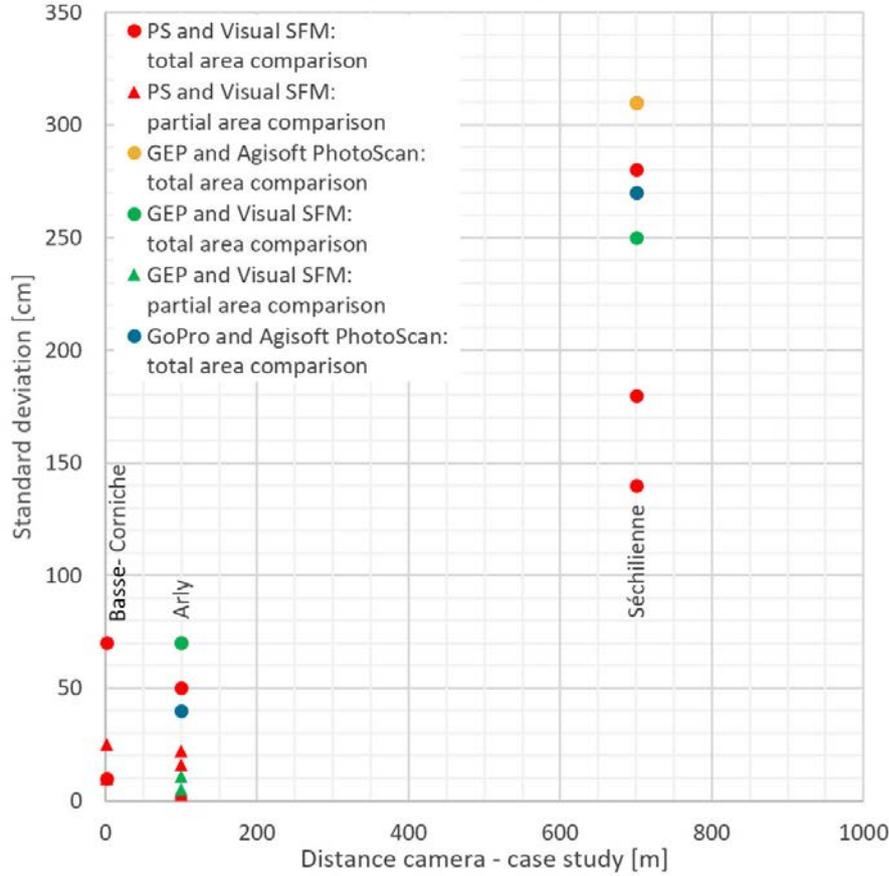


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Figure 8: Correlation between distance camera - case studies and the expected density of points from the three case studies. The red colour dots are results of the three case studies point clouds obtained from Google Street View (GSV) print screens (PS) in Google Maps (GM) processed with VisualSFM. The red strip represents the corresponding trend based on a negative exponential function. The orange colour dot is the result of the Séchilienne point cloud obtained from GSV images saved in Google Earth Pro (GEP) processed with VisualSFM. The orange strip represents the corresponding trend based on a negative exponential function. The green colour dots are results of the Séchilienne and Arly point clouds obtained from GSV images saved in (GEP) processed with Agisoft PhotoScan. The green strip represents the corresponding trend based on a negative exponential function. By way of comparison, the blue colour dots represent the result of the Séchilienne and Arly point clouds obtained with GoPro action camera images taken on the field and processed with Agisoft PhotoScan.

640 Figure 9: Correlation between distance camera - case studies and the expected standard deviation from the three case
 641 studies. The dots are results of point clouds comparisons on the entire point cloud areas (Table 1). The triangle are results of
 642 point clouds comparisons on partial point cloud area (Table 2). The red colour dots and triangle are results of the three case
 643 studies point clouds obtained from Google Street View (GSV) print screens (PS) in Google Maps (GM) processed with
 644 VisualSFM compared on the entire area. The orange colour dot is the result of the Séchilienne point cloud obtained from
 645 GSV images saved in Google Earth Pro (GEP) processed with VisualSFM. The green colour dots and triangles are results of
 646 the Séchilienne and Arly point clouds obtained from GSV images saved in (GEP) processed with Agisoft PhotoScan. By way
 647 of comparison, the blue colour dots represent the result of the Séchilienne and Arly point clouds obtained with GoPro action
 648 camera images taken on the field and processed with Agisoft PhotoScan.



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650 Table 1: List of the fourteen point clouds presented in this paper.
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Site	Figure	Date	Images source	Images size [pixel]	Images number	Point density ¹ (pts/m ²)	Processing software	Number of points	Comparison		
									With	Mean distance ² [m]	Std. dev. [m]
Site 1	Fig. 4A	2008.05	PS GSV from GM ³	1920 x 1200	60	290	VisualSFM	150'000	114.06 ⁷	0.2	0.7
	Fig. 4B	2014.06	PS GSV from GM ³	1920 x 1200	50	640	VisualSFM	182'000	18.05 ⁸	0.0	0.1
Site 2	Fig. 5A	2010.04	PS GSV from GM ³	1920 x 1200	54	0.40	VisualSFM	18'000	1AR ⁹	-0.2	1.4
	Fig. 5B	2011.03	PS GSV from GM ³	1920 x 1200	52	0.25	VisualSFM	9'500	1AR ⁹	-0.1	1.8
	Fig. 5C	2013.05	PS GSV from GM ³	1920 x 1200	45	0.37	VisualSFM	12'500	1AR ⁹	-2.1	2.7
	Fig. 5D	2014.06	PS GSV from GM ³	1920 x 1200	52	0.66	VisualSFM	25'000	1AR ⁹	-1.5	2.8
	Fig. 5E	2015.06	PS GSV from GM ³	1920 x 1200	62	0.64	VisualSFM	23'500	1AR ⁹	-0.9	3.1
	Fig. 5F	2015.06	GSV from GEP ⁴	4800 x 3500	80	0.86	VisualSFM	22'500	1AR ⁹	-1.7	3.1
	Fig. 5G	2015.06	GSV from GEP ³	4800 x 3500	80	1.99	Agisoft PhotoScan	236'000	1AR ⁹	0.6	2.5
	Fig. 5H	2016.05	GoPro ⁵	4000 x 3000	75	0.35	Agisoft PhotoScan	46'000	1AR ⁹	-0.2	2.7
Site 3	Figs. 6A, 7A	2010.03	PS GSV from GM ³	1920 x 1200	66	40	VisualSFM	35'000	1AR ¹⁰	0.0	0.5
	Figs. 6B, 7B	2014.07	PS GSV from GM ³	1920 x 1200	111	50	VisualSFM	53'000	1AR ¹⁰	0.1	0.7
	Figs. 6C, 7C	2016.08	GSV from GEP ²	4800 x 3107	64	2200	Agisoft PhotoScan	3'1850'000	1AR ¹⁰	-0.1	0.7
	Fig. 6D	2016.12	GoPro ⁶	4000 x 3000	50	650	Agisoft PhotoScan	2'217'000	1AR ¹⁰	0	0.4

652 ¹ Point density around a search radius of 2 m.
653 ² Average distance between the mesh of the reference point cloud and the compared point cloud using the point-to-mesh strategy.
654 ³ Print screens (PS) of Google Street View (GSV) from Google Maps (GM).
655 ⁴ Google Street View (GSV) images saved in Google Earth Pro (GEP).
656 ⁵ GoPro Hero4+.
657 ⁶ GoPro Hero5 Black with GNSS chip integrated.
658 ⁷ Comparison between the entire point clouds of May 2008 and June 2014 (Figure 3D).
659 ⁸ Comparison of a small cliff area of the May 2008 and June 2014 point clouds (Figure 3C).
660 ⁹ Comparison with the 50 cm airborne LiDAR DEM from 2010.
661 ¹⁰ Comparison with the December 2016 LiDAR DEM (6'930'000 points) without vegetation from an assembly of six Optech terrestrial LiDAR clouds.
662

663 Table 2: List of the eight partial point cloud comparisons.
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Site	Figure	Date	Images source	Images size [pixel]	Processing software	Comparative area	Comparison		
							With	Mean distance ¹ [cm]	Std. dev. [cm]
Site 1	Fig. 4C	2008.05	PS GSV from GM ²	1920 x 1200	VisualSFM	Small cliff part	4.06 ⁴	0	10
	Fig. 4E	2008.05	PS GSV from GM ²	1920 x 1200	VisualSFM	Entire cliff without wall and vegetation	4.06 ⁴	22	25
Site 3	Fig. 7D 1	2010.03	PS GSV from GM ²	1920 x 1200	VisualSFM	Tunnel entry	∪AR ⁵	-3	22
	Fig. 7D 2	2010.03	PS GSV from GM ²	1920 x 1200	VisualSFM	Small part of tunnel entry	∪AR ⁵	-18	3
	Fig. 7E 1	2014.07	PS GSV from GM ²	1920 x 1200	VisualSFM	Tunnel entry	∪AR ⁵	-4	16
	Fig. 7E 2	2014.07	PS GSV from GM ²	1920 x 1200	VisualSFM	Small part of tunnel entry	∪AR ⁵	-3	4
	Fig. 7F 1	2016.08	GSV from GEP ³	4800 x 3107	Agisoft PhotoScan	Tunnel entry	∪AR ⁵	-6	11
	Fig. 7F 2	2016.08	GSV from GEP ³	4800 x 3107	Agisoft PhotoScan	Small part of tunnel entry	∪AR ⁵	-14	5

665 ¹ Average distance between the mesh of the reference point cloud and the compared point cloud using the point-to-mesh strategy.
666 ² Print screens (PS) of Google Street View (GSV) from Google Maps (GM).
667 ³ Google Street View (GSV) images saved in Google Earth Pro (GEP).
668 ⁴ Comparison between the entire point clouds of May 2008 and June 2014 (Figure 3D).
669 ⁵ Comparison of a small cliff area of the May 2008 and June 2014 point clouds (Figure 3C).
670 ⁶ Comparison with the December 2016 LiDAR DEM (6'930'000 points) without vegetation from an assembly of six Optech terrestrial LiDAR clouds.
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