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Digital terrestrial photogrammetry for a dense monitoring of the surficial displacements of a landslide

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Abstract. A new method for measuring spatially dense surface displacements of a landslide at daily intervals and over a long period of time is here presented. The method allows the evaluation of displacements based on a digital image correlation technique applied to a temporal sequence of photos, daily captured by one or more fixed cameras. In comparison to other topographical method this new procedure has a lower accuracy, but provides distributed daily measurements, spatially very dense over the entire landslide area. The multi-view configuration also allows the reconstruction and the update of the 3D surface of the landslide. This work presents some preliminary results obtained by applying this innovative technique to a complex landslide located in the municipality of Perarolo di Cadore (NE Italy), also known as Sant'Andrea landslide. The landslide is characterized by active slow movements involving detrital deposits, about 30 m thick, overlying gypsum-anhydrite rocks. Its activity is strongly correlated to both heavy and long-lasting rain events and to its particular geological conditions. Recently, the alternating phases characterized by slow movements and significant accelerations led to a progressive enlargement of the affected area. Three cameras installed on a stable slope facing the landslide allow to record the intermittent activity and the peculiar behaviour of different parts of the slope. The displacements thus obtained are also compared with those deriving from conventional techniques. Finally, the accuracy of this new method is discussed.

1 Introduction

The measurement of the deformation rates of a landslide through the monitoring activity allows to follow its evolution in real time as well as a deeper understanding of the mechanisms that lead to instability. This activity becomes even more important when the accelerations and decelerations of the sliding mass are related to the rainfall regimes and the infiltration rate. This is the case, for example, of landslides involving materials such as anhydrite-gypsum rocks, the hydration of which induces an important degradation of the material, a variation of their rheology and a possible sudden deterioration of stability which requires continuous monitoring. In recent years, there has been a rapid development of a new survey technique in the geotechnical field: drone-based photogrammetry. Together with terrestrial laser scanning, such a technique represents an increasingly valid alternative to the classic topographic survey, allowing a precise 3d reconstruction of the slope geometry and spatially dense identification of the surface displacements of a slope. However, it is known that both techniques are not particularly suitable for continuous monitoring both for costs and for their predisposition to a one-off use. At the same time,

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advances in digital image analysis and computer vision technologies have prompted the use of digital terrestrial photogrammetry as a promising low-cost option. This work presents some preliminary results obtained by applying this innovative technique to the Sant'Andrea landslide.

2 The Sant'Andrea landslide

The Sant'Andrea landslide is located in the municipality of Perarolo di Cadore, Belluno Province (Italy). It involves the downslope part of a larger old landslide that affected the southern slope of Mt. Zucco, the highest peak near the study area. In the actual configuration, a 30 m thick debris deposit sliding over an anhydrite-gypsum bedrock composes the geological model of the slope; in particular, the presence of a weak layer mainly composed of gypsum seems to strongly control the landslide triggering mechanism [1]. The slope is thus at high risk of sudden collapse of a significant volume of soil which could interest the downstream town and possibly obstruct the course of the Boite river. The interaction between gypsum and active water circulation is considered to be the main factor affecting the stability conditions on the slope. In fact, the presence of seepage causes both a process of deep hydration in the anhydrite rock mass and a dissolution in the layer of gypsum. For these reasons, the landslide dynamics is characterized by alternate phases of slow movements and sudden accelerations and a strong link between the landslide activity and rainfall has been observed, in response to both heavy and lasting rainfall events [2].

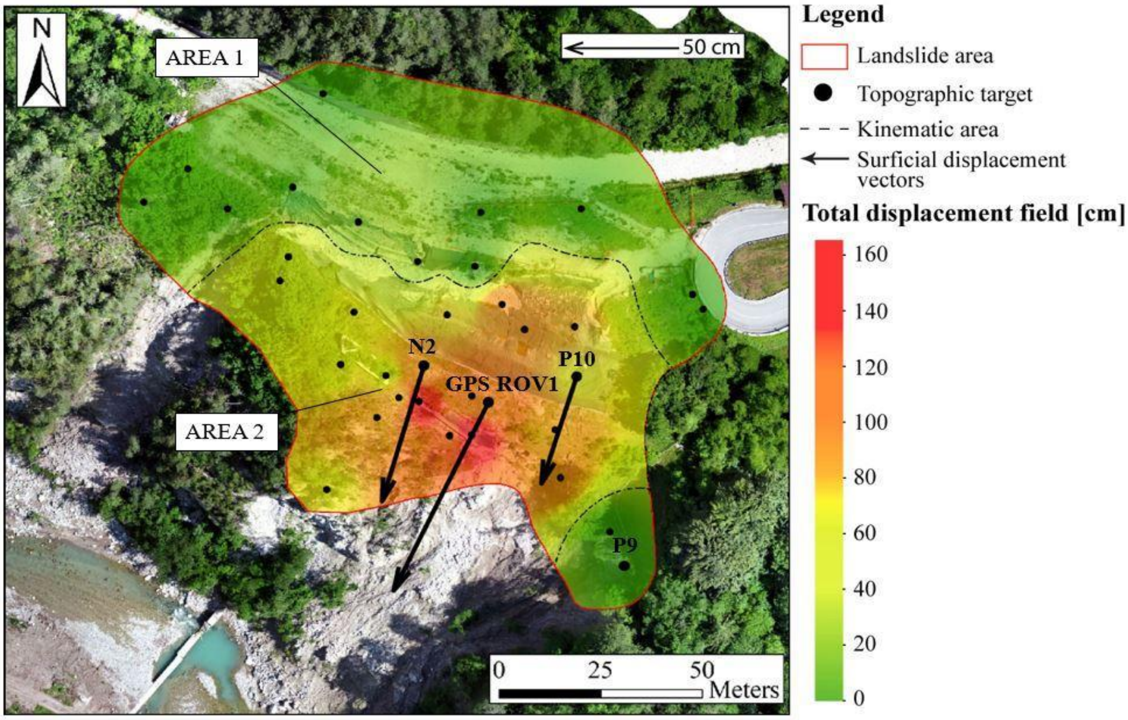

Figure 1. Distribution of surficial displacements of the Sant'Andrea landslide, obtained by RTS survey in the time span from July to December 2020. The vectors, here drawn only for 4 topographic targets chosen as references for the analysis, represent the horizontal displacements while the contour values refer to the total displacements.

The Sant'Andrea landslide is active since the end of the 20th century, but in recent years it has shown a progressive enlargement of the affected area and an irreversible worsening of its stability conditions. Over time, various types of instruments have been set up in the central part of the landslide, including inclinometers and short extensometers. In 2013, a geodetic monitoring system with a Robotic Total Station (RTS) was installed to record the kinematic evolution of the landslide. The RTS is a Leica TM30 station capable of continuously recording the positions of different reflective prism targets (currently

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36) installed in the unstable slope. The strengths of this kind of monitoring system are certainly the high precision and the high temporal resolution of the measurements. However, the points to be monitored must be chosen in advance. Moreover, if the targets move significantly, they can go out of the range of the total station (out of sight or excessive incidence angle), thus being no longer monitored until they are realigned. Finally, the displacement information is obtained for a finite set of points only, and therefore a simple data interpolation to have an overall view of the phenomenon could overestimate or underestimate the real movements in all the other areas. Figure 1 shows the spatial distribution of the total displacement, starting from the data measured in time span from 07.07.2020 to 01.12.2020. The displacement map is obtained by IDW (Inverse Distance Weighting) interpolation of the punctual displacement data acquired by the topographic system.

The contour map (figure 1) highlights two different areas. The uppermost part of the slope, called Area 1, is characterized by relative slow movements, lower than 20 cm in the time span monitored. The front of the slope, called Area 2, on the other hand, shows a much more precarious situation, with displacements over 40 cm in five months, moving quite homogeneously as a rigid block. Moreover, the central part of this area highlighted even larger displacements, exceeding 1.4 m of movements towards the valley. Evidence of collapses and surface erosion can be observed in the same figure. The black points drawn in the figure represent the positions of the topographic targets distributed on the slope and constantly monitored. In particular, the displacement vectors of 4 targets investigated in this work (N2, GPSROV1, P9 and P10) have been drawn, to emphasize the direction of slope deformation. Three of the four targets considered are located in Area 2 and consequently show significant displacements. On the other hand, the target P9, installed laterally with respect to the others, is located in Area 1, where the displacements measured are almost zero.

3 Photographic survey system

To overcome the limitations of traditional topographic monitoring and to integrate its information, a low-cost monitoring system based on the analysis of photographs was recently designed and installed. This new system allows to obtain an overall view of the site to survey, without the need for a priori choice of the specific areas to be monitored. Moreover, being based on the interpretation of images, the technique can be very cheap compared to other traditional solutions.

The monitoring system is designed as a time-lapse photo acquisition system. It can work autonomously for a long time and with the possibility of remote connection. The outputs are continuous sequences of images, taken at regular time intervals and automatically sent to a remote server through an FTP connection, in order to be immediately processed. All the operations are handled by a controller, to ensure the autonomous operation of the system, without the need of manual interventions.

In the case of the Sant'Andrea landslide, each monitoring system consists of a Canon EOS 1300D camera equipped with Canon EF-S 18-55mm lens, a controller for system management, a main router for internet connection, a power system with solar panel and battery to ensure operation independently from the electricity grid and a hard disk to save the photos locally (figure 2a). All the equipment is placed inside a special weatherproof fiberglass box. Finally, the box is secured and made stable by means of a special support frame, which supports the entire system and isolates it from vibrations, displacements or possible tampering (figure 2b). In this specific context, three image acquisition systems thus designed are installed to obtain three synchronized converging views of the landslide to monitor. These three cameras are set with a focal length of 24 mm and positioned on the opposite side of the landslide, at an average distance of 270 m from the area to be monitored. The furthest points of the slope reach distances up to 550 m.

Displacements of natural objects as well as any kind of textured surface on the slope are obtained on the image plane of each camera through a digital image correlation (DIC) technique. After that, this information is registered to the 3d surface of the landslide that is obtained from a stereo-photogrammetric reconstruction. The algorithm converts a coordinate in the image reference system (2d) to a coordinate in the global coordinate system (3d) through a depth map. The details of this algorithm are partially discussed [3, 4, 5] and will not be covered in this article.

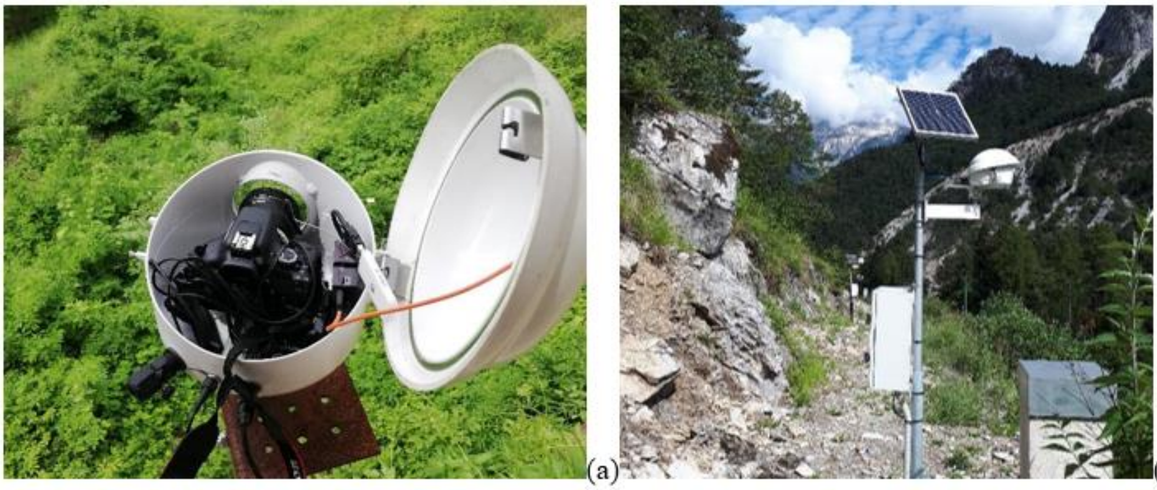


Figure 2. Photographic system survey. (a) Hardware system components; (b) Photographic system set up in Perarolo, on the opposite side of the landslide.

4 Results of the displacement analysis

In figure 3 the vertical displacement data (z-direction) of the four optical targets acquired by the RTS are compared with the corresponding average displacement data calculated by the photogrammetric algorithm in the same areas. The topographic monitoring system collects data on an hourly basis. The values obtained are then averaged in order to obtain daily measurements, which are represented in the graph through dotted lines. The absence of values in some periods for the photogrammetric method, instead, is due to the worsening of the resolution of the photos during days with poor visibility conditions for the presence of fog or heavy rain. In this case, the algorithm discards the photo to be examined and looks for the one that is temporally closest. The measurements obtained by the photogrammetric method are drawn as continuous lines, only in the time intervals in which values are available.

The trend of these movements over a period of almost five months shows a good agreement between the two survey methods, even if there are not negligible differences in the displacement values. It can be noted how this new technique is able to detect the variations of displacement rate following precipitation even if the trend sometimes deviates from the values measured by RTS. This can be attributed in part to the difficulty of pointing and tracking the movements of the small optical targets in the photos, where the surface in the background moves differently from the prism mounted on the pole in the foreground. Furthermore, the conversion of the 2d information evaluated on the image plane into 3d measurements in a world reference system is a source of inaccuracy. In fact, the quality of the depth map is of primary importance in the reliability of the projection. Moreover, since the slope shows significant deformations, the depth map must also be promptly updated, because the projection of current measurements on an outdated three-dimensional surface can reduce the quality of the measurements obtained.

Comparing the displacements trends with the accumulated rains (figure 3), the entire considered period can be divided into three main sub-periods, when, following an abundant cumulative rainfall, an acceleration in landslide displacement is observed. These acceleration phases occur about two days after the storm event both for the optical target and for this photogrammetric technique and the displacement rates (the slopes of these curves) are mostly the same for the two techniques.

The precision in detecting the relative displacement rates mainly depends on the goodness and reliability of the DIC analysis; particularly, if the photos taken at different times are still comparable over a large time interval and whether the DIC analysis is able to follow the changes. Instead, it is less dependent on the projection errors of the recorded measurements from a two-dimensional system related to photos to a global 3d system.

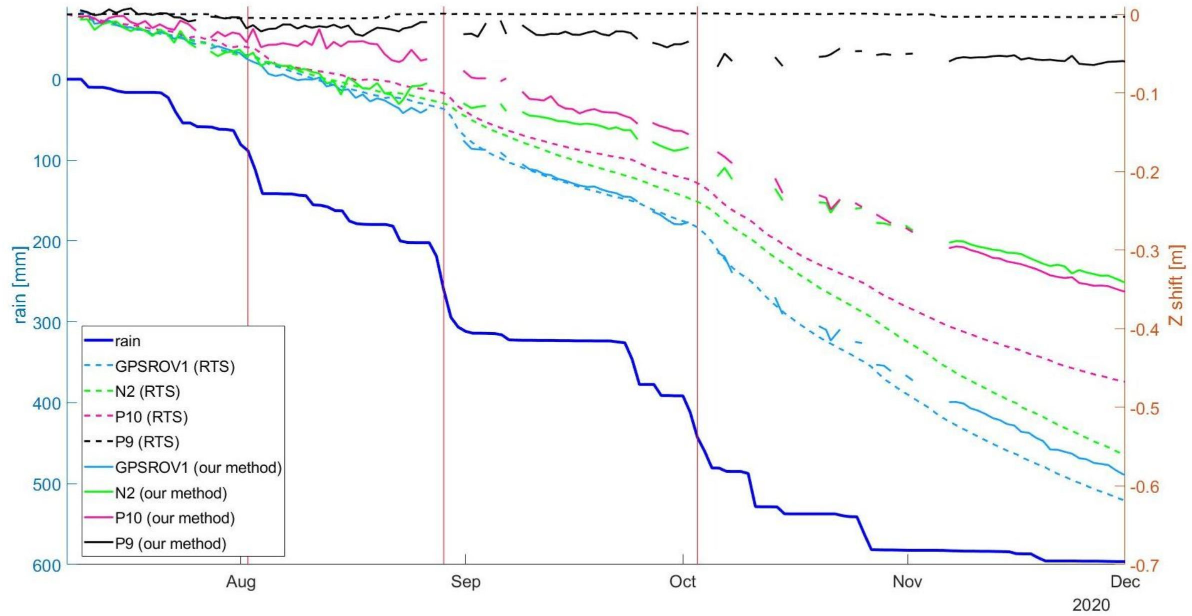


Figure 3. Comparison between the z-level of some points measured with RTS for the selected optical targets and estimated by the photogrammetric algorithm in the time span from July to December 2020.

5 Considerations about the accuracy of the method

The proposed measuring method is based on digital image correlation analysis which was extensively used in satellite imagery as well as laboratory applications when the surface is almost flat and normally oriented with respect to the camera optical axis [6]. The accuracy estimated in these applications is fairly good and ranges from 1/10 to 1/100 px, where px indicates pixel, mainly depending on the type of monitored surface and the algorithm used [7].

In slope displacement monitoring these geometric conditions do not occur because the slope surface has an irregular orientation and the position of the camera is almost never orthogonal to it. For this reason, we can reasonably assume an accuracy of 1/10 px. Moreover, differently from laboratory conditions, the acquisition system can be subject to small translations and rotations that produce a systematic error in the detection of the displacements that must be corrected.

The cameras used in the case of Perarolo di Cadore landslide are positioned in a stable area, but their support, although rigid, is still subject to small vibrations, due in particular to the wind and the periodic passage of a nearby train. These movements have a strong impact on the results of the analysis due to the amplification induced by the large distance between the camera and the landslide. Figure 4 shows the effect of these micro movements on two months of analysis; the direction of the average displacements in the different areas of the landslide and their values are completely unreliable without a correction.

To correct this systematic error, a similarity transformation (roto-translation plus a scale factor) was applied to the input images in the pre-processing phase. The parameters for the image transformation are obtained through the continuous tracking of seven fixed targets positioned on easily recognizable structures (concrete wall, building, rocky outcrops) and not affected by the landslide movement. For example, without correction, in about 30 days the target positioned on the wall has a shift in the image plane of about 5 px, which corresponds to an error of about 25 cm in the real scale. With correction and compensation, the error is reduced to about 0.2 px which, at the distance of the target, correspond to 1 cm.

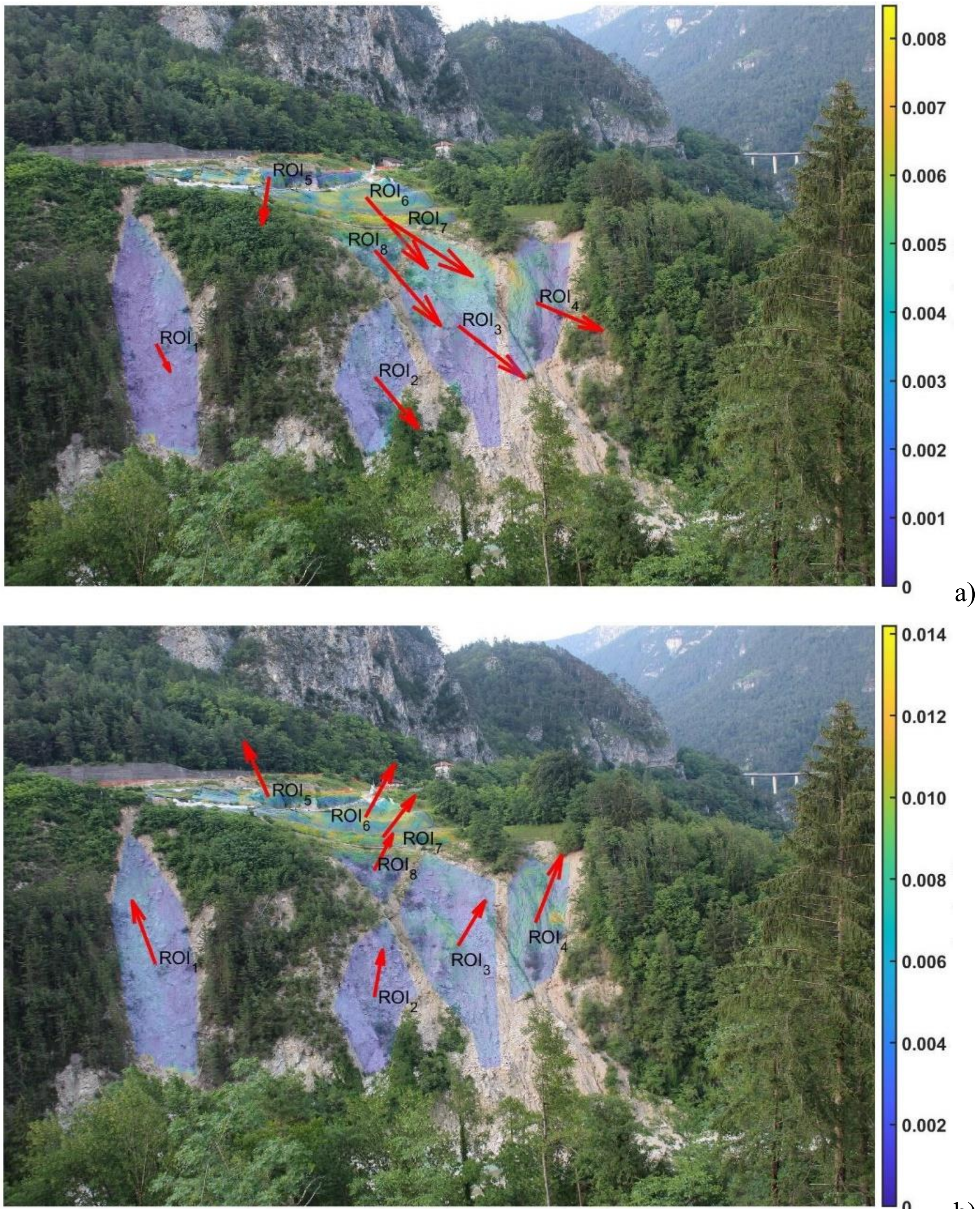
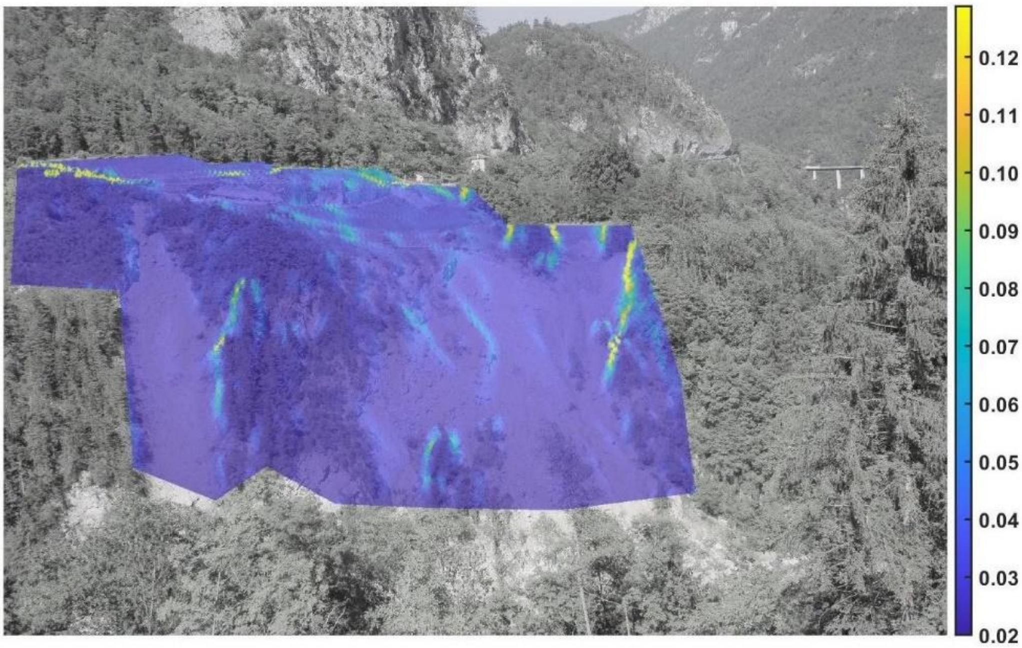


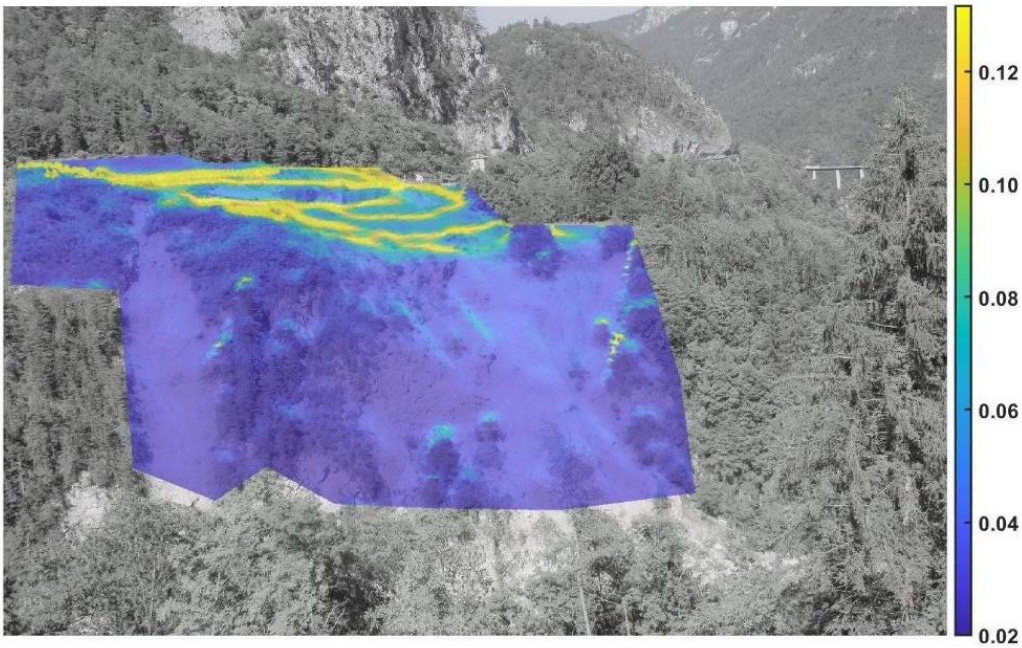
Figure 4. Mean displacement direction of 8 areas of the slope (a) with and (b) without correction in the time span from July to September 2020. Unit: meters per day.

The maximum error obtained after this transformation was quantified by repeating the DIC analysis on the re-projected points considered fixed: in the worst case the residual error results equal to 0.4 px.

Therefore, by considering the sum of the maximum estimated error of the DIC (0.1 px) and the maximum back-distortion error of the image and projecting it on the 3D surface of the slope, it is possible to obtain, point by point, a sort of accuracy map for the displacement detection. Considering the local orientation of the slope surface, the map shows an accuracy in the horizontal direction distinct from the vertical one. In general, it can be observed that even considering a homogeneous error on the image plane, this error becomes very different if the surface is irregular. This happens in particular where the angle between the normal to the plane and the line of sight reaches the highest values, i.e. in conditions of high incidence angle. In general, it can be observed that the accuracy is worse in the upper part of the slope and for vertical displacements and it is better for horizontal displacements, which are more parallel to the image plane.



a)



b)

Figure 5. Estimated accuracy map for movements along the (a) horizontal and (b) vertical components. Units in meters.

6 Conclusion

The paper presents the application of a monitoring technique based on digital terrestrial photogrammetry. The method allows to obtain the surficial displacements of a slow landslide from the acquisition and elaboration of several images, taken from some fixed cameras. The monitoring activity can be performed at low cost, obtaining dense information in time and space. It has to be underlined that this method does not aim to replace traditional techniques such as topographical monitoring, but rather to work side by side, filling in the gaps of such a monitoring. In fact, even if the photogrammetry and the image processing allow to obtain spatially and temporally dense results, it is also true that the precision of the measurement is not so high, compared to alternative techniques. The resolution and the accuracy of the method depends on several factors, such as the distance and the relative position between the monitored site and the camera, the technical characteristics of the cameras and their configuration. The directions of the slope displacements with respect to the image plane has in fact a strong influence on the quality of the final monitoring output.

Furthermore, image acquisition is strongly affected by environmental conditions: during night, during heavy rainfall or in the presence of snow or fog, the images are hardly usable. These critical issues currently pose important limits for monitoring by photogrammetry to be used as an early. In any case, the results obtained can be very important to study the dynamics of the movements, to identify accelerations and decelerations in the movements and to estimate the volumes involved in the landslide, in order to provide an overall view of the slope evolution.

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