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First experiment of long-range panoramic images on a high-precision geodetic reference frame

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ABSTRACT

Geomonitoring of rockfalls and landslides is increasingly carried out by solutions that integrate different geomatics techniques to provide quickly 3D point clouds or models that are required to be rigorously in the same reference system. Methods based on remote sensing such as terrestrial laser scanning or photogrammetry need precise ground control, which is usually provided by means of geodetic surveys. However, when the study area is large with strong limitations due to particular orography, those geodetic techniques cannot always grant accurate target points optimally distributed within the monitored object, and only an external reference frame is available to provide absolute orientation to those 3D point clouds or models. In that case, terrestrial photogrammetry shows clear advantages compared to terrestrial laser scanning. Still, it may require a large number of high-quality images taken from well-distributed stations, thus hampering the desired fast data collection. A possible alternative to cope with this problem is the use of the panoramic photogrammetry method by using robotic devices like Gigapan along with a systematic collection procedure from stable stations of a reference frame whose coordinates are accurate and well-controlled. This contribution describes an experiment conducted in Cortes de Pallás (Spain), where an existing infrastructure consisting of 10 pillars and 15 check points is annually monitored at millimetric level, to investigate the potential of long-range panoramic photogrammetry as applied to deformation monitoring. The panoramic images were taken from 7 selected pillars using the Gigapan robotic device. The accuracy of oriented panoramic images, the performance of the method in long-ranges (500-1000 m), and the consistency with the geodetic techniques in the 15 check points were analyzed. Finally, some conclusions about the suitability of panoramic photogrammetry as applied to long-range deformation monitoring are drawn.

I. INTRODUCTION

Accuracy and consistency of the measured data are critical aspects for reliable rock slope modelling based on periodical point clouds or models obtained by integrating different remote sensing techniques such as terrestrial laser scanning (TLS), digital photogrammetry (DP), or mobile mapping systems (MMS). Since efficiency is also a general requirement for a quick deformation diagnosis, the collection of accurate and consistent data should be carried out by using optimal field processes that minimize the acquisition time and the need for external ground control as much as possible (Francioni *et al.*, 2018).

Nevertheless, external ground control cannot be eliminated completely because rigorous statistical assessment of possible displacements requires all point clouds or models to be strictly referred to a unique reference system. Furthermore, to prevent sub-optimal use of the remote sensing techniques, the reference system should have accuracy at least one order of magnitude better than the intrinsic precision provided by those techniques, which constitutes a real challenge. For instance, if the precision of a remote sensing technique in a broad area is expected to be around 1 cm to 3 cm, the reference system should be realized with an accuracy of 1 mm to 3 mm, which is beyond the capacity of standard surveying techniques based on GNSS or total stations. Therefore, irrespective of the technique used to collect the data, the proper integration into a consistent and reliable reference frame becomes critical and does not always receive all the attention it deserves. Cortes de Pallás (Spain), a complex area equipped with a ten-pillar network whose stability is periodically monitored at millimeter level by using high-precision geodetic techniques, is an ideal site for testing different remote sensing solutions as applied to deformation monitoring (García-Asenjo *et al.*, 2019; García-Asenjo *et al.*, 2022). Some of the techniques that were previously tested with dissimilar results are long-range TLS, terrestrial DP, or handheld MMS.

TLS is a recurrent and efficient solution for distances shorter than 200 m, but for distances longer than 800 m and complex orography, the technique becomes expensive and additional problems such as systematic instrumental errors, inaccurate registration or atmospheric refraction may arise (Fan *et al.*, 2015; Friedli *et al.*, 2019; Harmening and Neuner, 2019). In the case at hand, TLS provided unsatisfactory results because the point clouds were not detailed enough for the registration process, even though the CPs on the pillars were equipped with large white spheres (∅ 500 mm).

On the other hand, terrestrial DP proved to yield an accuracy of 1 – 3 cm as long as precise ground control is provided on-site. However, in broad and complex areas where a large number of long and close images from multiple stations are necessary, it is complicated to know the coordinates of each camera location with the required precision, and thus, the unique option for integrating the photogrammetric models into the reference system is the traditional approach, which relies on using CPs optimally distributed within the monitoring area. Nonetheless, this usual approach entails two disadvantages for rigorous deformation monitoring: first, it is paradoxical that points assumed not to be stable act as CPs for model orientation; second, the possible instability of CPs makes necessary the inclusion of a high-precision geodetic survey concurrent to each photogrammetric campaign, which is time-consuming and clearly diminish the efficiency of the method.

Some alternatives to optimize terrestrial DP are the use of Unmanned Aerial Vehicles (UAVs) or MMS, but these solutions are not always feasible in areas like Cortes de Pallás. In this case, the use of UAVs was disregarded because the complexity of the site, which includes a hydraulic power plant with many electricity power lines, car traffic, and tourism activities, does not favour the method. Concerning MMS, a test carried out in 2019 showed that the maximum attainable accuracy is in the range of 3 to 8 cm (Di Stefano *et al.*, 2020).

The panoramic images collected using a Gigapan robotic device may be a possible alternative to the aforementioned methods. Previous experiments conducted in smaller and well-controlled areas have demonstrated that both single-strip and spherical panoramas can be produced with an accuracy of several millimetres and centimetres, respectively. It proves to be accurate and efficient enough for deformation monitoring (Javadi *et al.*, 2021; Lee *et al.*, 2019).

One advantage of panoramic photogrammetry is that the number of images required can be largely reduced with respect to traditional terrestrial photogrammetry. Moreover, the entire area can be efficiently surveyed by systematically setting the Gigapan on well-distributed permanent pillars. In this way, if permanent and well-controlled reference frames can be optimally integrated into the resulting 3D models, there would be no need for additional ground control.

Additional advantages of using panoramic images are the possibility of 3D model reconstruction with photorealistic and high-resolution texture, and the use of dedicated algorithms for panorama orientation and restitution (D'Annibale *et al.*, 2013).

This paper describes a first experiment conducted in Cortes de Pallás (Spain) to evaluate the potentiality of the long-range panoramic photogrammetry method for deformation monitoring as an alternative to other remote sensing solutions which were previously tested under similar conditions. The following sections describe all the steps leading to the results obtained.

II. PANORAMIC PHOTOGRAMMETRY

A. *Panoramic images*

Panoramic photography, also known as wide format photography, is a special technique that stitches multiple images acquired from the same camera position together to form a single image with a field of view similar or greater than that of the human eye. Panoramic photography can be classified into three types: cylindrical, spherical, and planar. The cylindrical panorama includes inner-cylinder and outer-cylinder panoramas. The shooting technique of the cylindrical panoramic image involves three methods: horizontal, vertical, and oblique (Luhmann, 2004).

The aforementioned types of panoramic images can either be photographed in a single row (meaning one row of vertical or horizontal images) or multiple rows (higher focal length is often used to yield much higher resolutions. Multi-row panoramas often require special panoramic equipment). The mathematical model of panorama images is usually based on cylindrical coordinates. Since collinearity equations can be derived easily, all standard photogrammetric algorithms from space intersection to bundle adjustment can be applied (Luhmann, 2010).

B. *Image stitching*

The biggest challenge with panoramic photography is the proper stitching due to low quality of images, poor image correspondence, or possible parallax errors. Therefore, achieving a high-quality panoramic image requires adequate planning and selection of correct instruments and methods, such as stable mountings (tripods or pillars), automatic rotation devices, proper selection of image format, image overlapping, shooting mode, and white balance, among others. Moreover, determining the nodal point according to the lens used becomes crucial to eliminating the parallax error. Once the images have been taken, they have to be stitched automatically by using specialized software in order to produce panoramic images.

There is a variety of software for stitching images and creating panoramas. For this project, we opted for Microsoft Image Composite Editor. Among other advantages, this software has the ability to introduce the structure of the captured images, stitch images based on automatic matching, high speed processing, as well as good quality of the output panoramic images. Figure 1 shows an example of one of the panoramic images created for this project.

Figure 1. Panoramic image created from one reference station.

C. *Absolute orientation of panoramic images*

Panoramic images can be related to each other without the need for external information. However, the resulting 3D model has to be scaled and orientated to be consistent with the terrestrial coordinate system chosen as the reference system. The relationship between the model coordinates (x, y, z) and the terrestrial coordinates (X, Y, Z) are given by the well-known expression (Laganière and Kangni, 2010) (Eq. 1):

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \lambda R \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} + \begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} \tag{1}$$

where $(X_i \,.\, Y_i \,.\, Z_i)^T$ = terrestrial coordinates for point i
λ= scale factor
R = rotation matrix
$(B_X \,.\, B_Y \,.\, B_Z)^T$ = translation vector

The seven transformation parameters are obtained by using at least three no-aligned CPs whose terrestrial coordinates have to be known with better accuracy than the expected one provided by the photogrammetry method. This step of the process was carried out by using the Agisoft Metashape software.

III. MEASUREMENT SETUP

A. *Description of the test field*

The test field used in this project is located in Cortes de Pallás (Spain). This site, which has recurrent geotechnical problems, was affected in April 2015 by a cliff collapse which seriously damaged some facilities of the near electricity power plant and the main access road to the village (Figure 2). In 2017, a geodetic network was commissioned by the *Diputació de València* as a primary component of a deformation monitoring plan to detect possible displacements of huge boulders and potential malfunctioning of the anchoring systems installed after the consolidation works. However, the detection of possible displacements of some centimetres with the required level of significance in a short period, *e.g.* two or three years, is a challenging task due to the peculiar topography of the site, which involves distances from 500 to 2000 m with height differences reaching 500 m. Furthermore, since the cliff of interest is facing a water reservoir, the measurements have to be undertaken from the opposite shoreline, which is about 600 m away. As a balanced solution, the *Diputació de València* eventually opted for both geodetic and image-based techniques (Di Stefano *et al.*, 2020).

Figure 2. Study site of Cortes de Pallás highlighted in red: top) oblique aerial view; bottom) front view.

B. *Permanent points*

The study area includes two types of points which are permanently installed on-site. The first type consists in a set of 10 pillars fixed on the ground (Figure 3a), which will be considered as reference CPs, while the second type consists of a set of 15 check points (ChPs) rigidly fixed to the object rock wall with small white spheres (∅ 145 mm) on top of 360-degree prisms (Figure 3b).

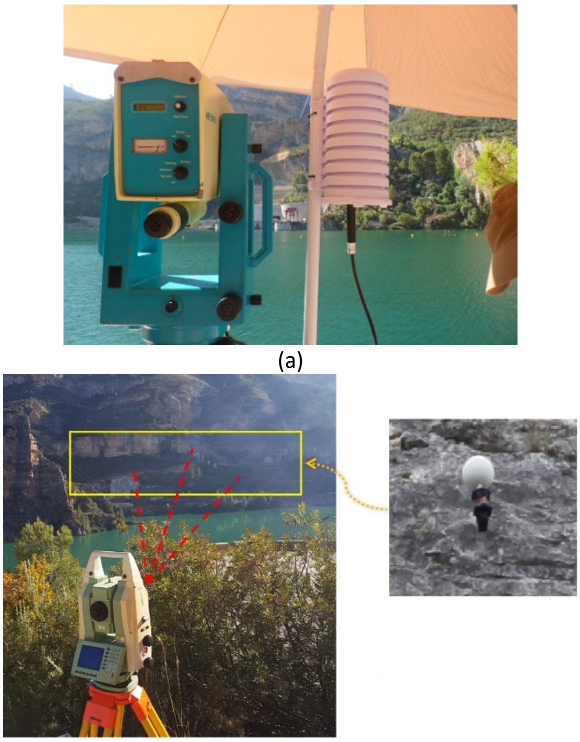
During the measurements, pillars were equipped with Testo 176P1 meteorological sensors (Figure 3a) for subsequent refraction correction of the EDM-based distances.

(a) (b)

Figure 3. (a) Check point; (b) Reference CP.

C. *Geodetic survey*

The geodetic instruments and their ancillary devices that were used for the geodetic observations: a sub-millimetric EDM Kern Mekometer ME5000 (Figure 4a) and a robotic total station Leica TM30 (Figure 4b). They were respectively used to detect the possible displacement of CPs on the pillars and ChPs from the years 2018 to 2020, and to monitor the CPs automatically and simultaneously with the Gigapan image acquisition.



(a)

(b)

Figure 4. (a) Sub-millimetric EDM Mekometer ME5000; (b) Robotic Total Station for automatic CPs observation.

The ten-pillar geodetic reference frame and the 15 ChPs fixed to the rock wall were annually measured from the years 2018 to 2020 by using sub-millimetric EDM techniques. For each annual campaign, coordinates for CPs and ChPs were obtained in a two-step process. In the first step, only distances between pillars were adjusted to provide a solution for the reference frame. In the second step, distances to CPs were included in order to obtain their 3D coordinates. The applied method provided coordinates with an overall accuracy of 0.5–1 mm for CPs and 1–3 mm for CPs, respectively (García-Asenjo *et al.*, 2019).

Therefore, the geodetic reference frame along with the 15 ChPs can be safely and reliably used to evaluate the accuracy and performance of panoramic photogrammetry over long distances.

D. *Photogrammetric survey*

A Gigapan robotic rotating device was equipped with a Canon 5DSR full-frame camera. The set was installed on seven selected pillars to acquire automatically 360° images of the area (Figure 5). Since the pictures were taken using a fixed 50 mm lens, each panorama included around 23 images.

Factors concerning the camera settings, the overlap and the software used for subsequent processing can strongly affect the overall quality of the produced panoramic images and, therefore, the geometric accuracy of the 3D models derived from them (Guerroui *et al.*, 2015; Javadi *et al.*, 2021). As mentioned earlier, Microsoft Image Composite Editor software was firstly used to create panoramic images. Afterwards, Agisoft Metashape software was used to orient the images in the geodetic reference frame.

Figure 5. Camera mounted on the Gigapan for acquiring the panoramic images.

We opted for a Canon 5DSR full-frame camera equipped with a fixed focal length of 50 mm to achieve a ground sampling distance (GSD) of 5 cm.

Concerning the geometry of the site, it was deemed optimal to form 360° panoramic images by taking only one horizontal strip with a 60% overlap (Figure 6), reaching 23 images per station and around 20 minutes, including the time required to set up the Gigapan device. In total, seven panoramas were collected from seven selected pillars of the reference frame.

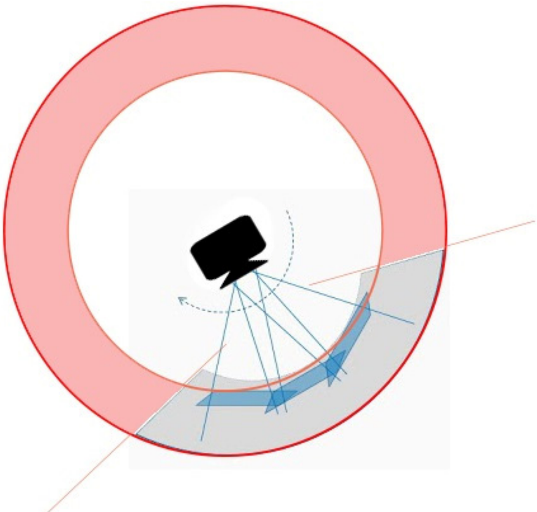


Figure 6. Overlapping frame pictures to build up eventually a panoramic image.

Please note that the difference in size between the spheres that are mounted temporarily on the pillars (Figure 3b), and the spheres mounted permanently on the wall (Figure 3a) is significant. Therefore, only panoramic images close to the targets will be considered as ChPs.

Agisoft Metashape software was used to process, align and orient the images, which were tested in two different types: (a) cylindrical panoramas (Figure 7); (b) partial frame panoramas (Figure 8).

Figure 7. The cylindrical (360°) panorama images from seven fixed stations.

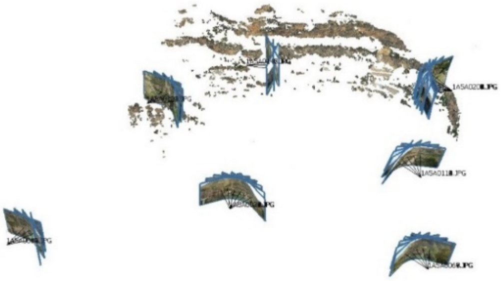


Figure 8. The partial frame panorama images from the seven fixed stations.

In (a), the entire captured area was involved in processing, also the average distance between the CPs was about 1000 m and the average distance of the stations to the ChPs was about 600 m (Figure 7).

On the contrary, for (b), a smaller target area was separated, processed and modelled (Figure 8). In this method, it was decided to remove areas with the bad and critical vision from the processing, which as a result made it possible to align the image, select manual markers and process at a higher speed.

The blue part in (Figure 6) is an example of the selected pictures in (b). This cut was made because, in some stations, the distance from the camera to the study area was about 600 m. In the opposite direction, the distance of features such as the road or the walls of the facility to the camera was about 50 m, and this caused aligning troubles.

IV. RESULTS

The results of the cylindrical panoramas (a) are summarized in Tables 1 and 2.

Table 1. Orientation of the seven cylindrical panoramic images

	Number
Stations	7
Photos	7
Markers	21
Reference Points	21
Control Points	3
Check Points	18
Tie Points	6,767

Table 2. RMSE obtained in the orientation of the seven cylindrical panoramic images

	RMSE [m]	Error [pix]
Control Points	0.392	54.735
Check Points	4.907	39.448

The information resulting from the partial frame panoramas (b) is displayed in Table 3. According to Table 4, the orientation of the photographs is done with greater accuracy by calculating the CPs, ChPs, and tie points. In this processing type, was found to be 2 cm accurate at the points selected as the CP and 17 cm accurate at the ChPs.

Table 3. Orientation of the seven partial panoramic images

	Number
Stations	7
Photos	37
Markers	37
Reference Points	19
Control Points	3
Check Points	16
Tie Points	1,948,279

Table 4. RMSE obtained in the orientation of partial panoramic images

	RMSE [m]	Error [pix]
Control Points	0.028	1.170
Check Points	0.170	1.284

To improve the accuracy and quality of the output results, the final processing was continued by removing additional ranges as shown in (Figure 9).

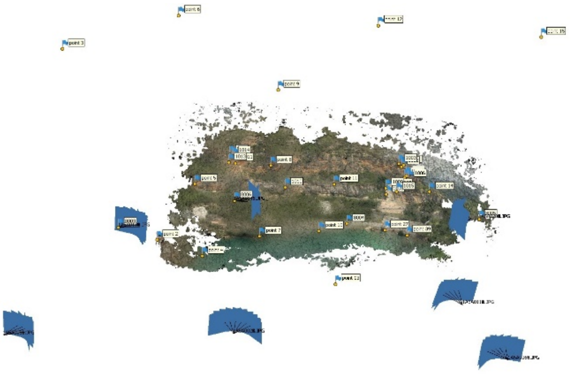


Figure 9. Position of markers and cameras in orientation.

Tables 5 and 6 show the root mean square error (RMSE) for each point.

Table 5. Control points RMSE

Label	X error [cm]	Y error [cm]	Z error [cm]	Total [cm]	Image [pix]
8003	1.87	0.11	-0.37	1.91	0.8 (7)
8004	1.74	-1.52	-0.39	2.34	0.8 (11)
8006	-3.61	1.41	0.76	3.95	1.4 (17)
Total	2.55	1.20	0.54	2.87	1.170

Table 6. Example Check points RMSE

Label	X error [cm]	Y error [cm]	Z error [cm]	Total [cm]	Image [pix]
8005	-34.09	-43.50	12.50	56.66	2.1 (10)
1001	-3.69	0.59	-0.89	3.85	0.6 (15)
1002	-3.24	0.24	-1.14	3.45	0.4 (13)
1003	-2.10	3.68	-1.21	4.41	0.7 (14)
1004	-1.85	-3.12	-2.23	4.26	0.3 (13)
1005	-1.71	-5.27	-2.29	6.00	0.4 (13)
1006	-0.33	-5.61	-2.55	6.17	0.3 (13)
1007	0.76	-6.80	-7.95	10.49	0.6 (14)
1008	3.58	-0.22	-3.04	4.71	1.7 (20)
1009	-0.23	2.07	-3.88	4.41	2.7 (19)
1010	-1.73	6.81	-8.24	10.84	0.3 (17)
1011	-11.81	10.53	-5.22	16.66	0.8 (14)
1012	-12.55	9.30	-1.49	15.69	1.2 (10)
1013	-5.14	8.60	-2.91	10.43	1.2 (10)
1014	-12.44	10.16	-2.97	16.34	1.6 (14)
1015	-1.20	-7.53	-7.40	10.63	0.7 (15)
Total	10.28	12.51	5.20	17.01	1.284

Given that there are 37 markers, 19 have coordinates, and 18 are just chosen on the images and manually to orient the images more accurately, so they are not shown in the table above.

These results are promising for such a large-scale project. Despite the small number of images, about 2 million points were obtained for surface determination, points cloud production and initial 3D modelling. Due to the good quality of the processed data, a dense cloud of points was built (Figure 10) in this small range, based on only 37 photos taken from different angles. However, by including the texture of the image, the 3D model of the area is produced to an acceptable level, which is shown in (Figure 11).

Figure 10. Dense point cloud of the main area.

Next, the tile model is made with a resolution of 5 cm/pix, which ultimately achieves the initial DEM production of the area. The result of its production can be seen in (Figure 12), with a GSD of 10 cm.

Figure 11. 3D model of the main area.

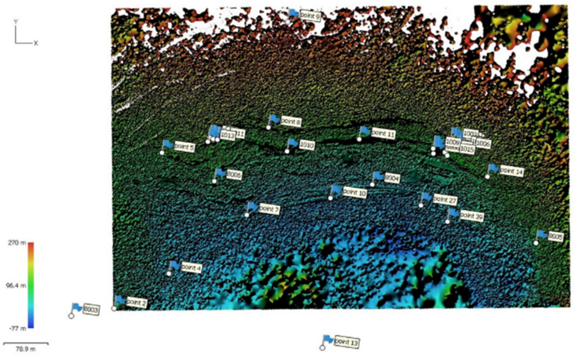


Figure 12. DEM of the main area.

V. DISCUSSION

In the light of the experiment conducted in Cortes de Pallás for testing the use of panoramic images as applied to long-range deformation monitoring, some critical aspects have been revealed.

First, the comparison of the proposed method with other remote sensing techniques, which has been only possible by the fact that there were both a well-controlled geodetic reference frame and ChPs available on the site, cannot be considered conclusive because the orientation of the 3D models obtained by other methods was done by using the traditional approach which is only based on ChPs on the wall and considered sub-optimal. Furthermore, the geometry of the seven pillars used as stations for collecting images was originally designed for geodetic surveying without considering their potential future usage as stations for collecting images.

Second, the right selection of camera, including sensor dimensions and lens used, is crucial when deformation monitoring is aimed. Those features strongly affect the quality of images, and thus the accuracy of the 3D models obtained. In the case at hand, the different size of the targeting spheres, ∅ 500 mm and ∅ 145 mm for CPs and ChPs respectively, did not help to make a balanced selection of the camera features.

Third, when it comes to efficiency, panoramic photogrammetry proved clearly superior to terrestrial photogrammetry. Concerning time for collecting the images, the proposed method took only 20 minutes for each station, while the terrestrial one required one complete day. The number of images taken is reduced and they can be easily processed. Alternatively, creating a 3D model is much faster. In addition, the angle of view of these panoramic images is not reduced because the whole area has been completely photographed (Fangi and Nardinocchi, 2013). Nevertheless, the current geometry of pillars, which was originally designed for geodetic purposes, does not prevent the photogrammetric survey from having hidden angles. For this reason, several stations have been included to cover the study area. Thus, the current network should be improved by including additional stations with precise coordinates in the same reference frame.

Fourth, as mentioned in the previous sections, the aim is to evaluate the performance of panoramic photogrammetry over long distances. However, the results showed that the accuracy obtained in the use of cylindrical panoramic images is not satisfactory, which can also be due to factors such as changing the dimensions of the final panoramic images after stitching, and different distances between some land features with the camera. However, the strategy of utilizing partial panoramic images, which concentrates primarily on the study region, has shown favourable and promising results. Therefore, it can be said that taking panoramic images, not in cylindrical (360°), but in the form of taking partial panoramic images only from the desired area can boost the rapidity of field operations, processing RMSE, and end result quality.

VI. CONCLUSION

Experience using panoramic images to monitor deformation can be an optimal solution for detecting instability over long distances. In this regard, orienting the overlap images taken from several different stations requires a network with the correct geometry. In addition, in close-range photogrammetry, it is important to select reference CPs to orient the images. But what sets this research apart is the use of panoramic images for possible adaptation to deformation monitoring from the reference CPs. In this research, instead of using traditional photogrammetry and taking several hundred photos to model an object (especially in open and natural environments), these images were used in two ways: cylindrical panorama (a), and partial frame panorama (b). However, taking panoramic images is much simpler and easier and reduces the time and cost of operations. Therefore, in the case of this project, where the reference stations are located at an average distance of about 1 km from each other, they should be oriented relative to each other in a cylindrical panorama (360°). But if we reduce this 360° panorama to just the part that is the main area and suspected of slipping, then there is no need to align and orient the extra areas. Also, the distance of the stations to the target area will be about 600 meters. As a result, the images will be oriented more accurately and the output will be improved. With this method an accuracy of 2 cm was obtained for CPs and about 17 cm for ChPs. This is a promising and acceptable result for image-based panoramic photogrammetry that opens the door to deformation monitoring at long distances.

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