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Evaluating the Application of Close-Range Photogrammetry in Determining the Horizontal Displacement of High Structural Elements: A Case Study of the Thermal Station at Tishreen University

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Abstract
Large horizontal displacements and tilts in tall structural elements such as towers and factory chimneys resulting from soil movement or earthquakes may lead to their collapse. The traditional methods of tilt monitoring (GPS, total stations, digital levels) require direct contact with the monitored buildings. Although the measurement results of sensors are accurate, sensors are typically cumbersome to deploy and can only provide local and relative deformation information. In this study, close-range photogrammetry based on the principle of Structure from Motion technique (SfM Photogrammetry) was used to monitor high structural elements. This method is safe and economic as it doesn't require direct contact with the monitored building. In addition, it requires low effort, short practical time and low budget. The proposed methodology in this study was applied on the chimneys of the thermal station located at Tishreen University. Results were evaluated by comparing with the traditional survey methods based on the use of the total station measurements. The results show that the value of the maximum displacement at the highest level, determined by using an uncalibrated mobile phone built-in camera and SfM photogrammetry (0.081 m) is approximately equal to twice the displacement and inclination determined by traditional surveying (0.049 m); but through some precautions and conditions, the accuracy of this method can be increased.

1. Introduction

Large horizontal displacements and tilts in tall structural elements such as towers and factory chimneys resulting from soil movement or earthquakes may lead to their collapse. Therefore, such elements need to be monitored to ensure their safety. Great efforts have been exerted to monitor the displacements (or inclination) in the high structural elements using both traditional and modern methods. The traditional methods of monitoring inclination require direct contact between the monitoring device and the monitored object, and they mainly include the use of various transducers

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such as inclinometers, accelerometers, strain gauges, GPS, total stations, digital level, and seismographs. On the other hand, modern monitoring methods do not require direct contact with the studied element; some of these methods are TLSs (Terrestrial Laser Scanners), GBInSAR (Ground-based synthetic aperture radar interferometry), and Photogrammetry.

Traditional methods can be applied to monitor the displacement of old and new high buildings. For example, we find in many studies that a network of sensors equipped with an inclinometer, GPS, and a total station have been used as the main sensors to monitor the inclination and displacement of high structures such as Canton Tower and Shanghai Tower [2, 3]. In these studies, the sensors were mainly used to obtain information about monitoring points, including levelness, horizontal displacement, subsidence, stresses, and monitoring inclination. Although the measurement results of the sensors are accurate, these devices are usually cumbersome to deploy and can only provide information about local and relative distortions [4, 5].

Noncontact measurements are used to monitor deformations. Terrestrial Laser Scanners TLS have the advantages of high accuracy and high spatial resolution, which makes them widely used in this field. These scanners are used to obtain high-resolution geospatial data and to build 3D models of structures. Through the geometric measurement of the 3D model, deformation data such as displacement and inclination can be obtained. In addition, the 3D model provides a scientific reference for monitoring deformities in the future [6, 8]. However, this technology suffers from some drawbacks, including the long time required for processing point clouds and obstacles faced during scanning that block parts of the facilities. GBInSAR can also be used to monitor structure deformations. Although this technology has the advantage of accurate monitoring of the displacement of the structure surfaces, it is not suitable for monitoring structure inclination. Close-Range Photogrammetry had been used to determine the inclination of the structures by using the natural distinctive points available on the monitored structure itself, or by using artificial control points whose three-dimensional coordinates are calculated through photogrammetry, to analyze the displacement and inclination of the structure. Where in [10] an application of close-up photogrammetry to analyze the inclination of towers in Spain, in which a maximum absolute error of 10 mm was achieved. In this study, the accurate 3D coordinates of the monitoring points are obtained by processing with Analytical photogrammetry. On the other hand, Structure from Motion (SfM) photogrammetry can be considered as a form of 3D laser scanner simulator in terms of its ability to automatically generate a huge number of points from image orientation. As the density of these points may sometimes exceed the density of the points generated using the laser scanner. The privilege of these systems over the traditional Close-Range Photogrammetry systems is that they are fully automated and can handle all types of cameras and images [9]. These privileges entitle the SfM method to monitor structure deformations.

In this study, the SfM photogrammetry technique was used to determine the horizontal displacement and inclination for one of the chimneys of the thermal station located at Tishreen University., and then evaluated the results by comparing them with the traditional surveying based on the use of the Total Station. The novelty in this study is its attempt to take advantage of the capabilities of low-cost digital cameras and automated SFM software tools that are low-cost and easy to use in processing element images. It also takes advantage of the processing tools available in free academic point cloud processing software, which leads to reducing the cost of work. On the other hand, the study developed a practical methodology for performing this type of work that interested parties can benefit from.

2. The Importance and Objectives of the Study

The importance of this study lies in its attempt to present the SfM photogrammetry technique as an alternative to the traditional surveying methods in calculating the displacements and inclinations of high structural elements. In general, the objectives of the study can be summarized as follows:
1- To propose a practical mechanism for applying traditional surveying in determining the elements needed to calculate the displacements and inclinations of high elements.
2- To develop a flexible general methodology for calculating displacements in high elements based on dense point clouds resulting from processing the images of these elements using the SfM photogrammetry technique.

3. Methods and tools

3.1. The study element

The studied element is one of the chimneys of the thermal station located at Tishreen University, near the Engineering expansion Figure 1. The height of this chimney is 38.57 m, and its diameter is 2.75 m.

Fig. 1: The studied element

3.2. Photogrammetry data acquisition

The objective of the data acquisition phase is to obtain the inputs for the photogrammetry manually, including:
1- Securing the control inputs: control points on the various sections of the chimney and the adjacent elements. The completion of this stage requires carrying out traditional surveying work.
2-Taking photos with a digital camera: A group of control points was distributed in the area surrounding the chimney, and its coordinates were calculated locally, as these points were relied upon in calculating the coordinates of the occupied station using Resection. Some observing points have been identified on the chimney, in specific locations, so that they can be distinguished and accurately located when observed by the surveying device. The purpose of using these points is to calculate the geometry of the model and evaluate its geometric accuracy. The coordinates of seven points were

measured. Figure 2 shows the distribution of these points on the studied chimney and its neighboring elements.

Fig. 2: Distribution of control points on the studied chimney and neighboring elements.

Field measurements of the control points on the chimney and adjacent elements were made using South Total Station Figure 3, where its angle accuracy about ± 5″, and distances accuracy about ± 2 mm + 2 ppm.

Fig. 3: South total station

As for the images of the chimney, they were taken using the BLA-L29 camera integrated into the Huawei Mate 10 Pro mobile phone, with a resolution of 12 megapixels and a focal length of 3.95 mm.

3.3. Obtaining the Traditional Surveying Data for Determining the Tilt of Chimney

In this stage, several sections of the chimney circumference at different levels had been monitored. At each level, a group of points had been monitored to later determine the radius of the chimney and draw its parameter and determine the center of the circle representing this perimeter at each level. Surveying field measurements were carried out using South Total Station and all the monitored points on the chimney were observed based on the control points.

3.4. Processing software

3.4.1. Agisoft Metashape

This software was used for processing images and generating a dense point cloud. This software is a 3D modelling tool that represents the Image-based 3D modelling method of SfM, and it uses the latest 3D construction technology from multi-view images developed in the field of Computer-Assisted Vision [11]. Moreover, it enables the orientation (air triangulation) of the images taken from any location, considering that they fulfil the condition that any point of the element lies on at least two images.

3.4.2. CloudCompare

CloudCompare, the open-source software, was used to process the point cloud of the chimney and perform the necessary operations needed to get the necessary data to calculate the value of the horizontal transmission and the inclination of the chimney axis from the level. This software is widely used by researchers in the field of SfM and laser scanning as it has many tools for post-processing clouds, which range from editing and showing these clouds to many complex algorithms such as filters, generating surfaces, producing longitudinal and cross sections in clouds, recording models, calculation of distances and statistics, division and estimation of geometric features, etc. [12]. This program has a simple, conversational interface with a dynamic colour-rendering system, which facilitates the visualization of the 3D data. Many post-processing tools can also be automated using either the command line or using a programming language platform such as MATLAB.

3.4.3. AutoCAD Civil 3D

This software was used to determine the centers of circles that represent the chimney monitoring sections using traditional surveying techniques. The software has many capabilities to deal with 3D geometric shapes, as it enabled us to draw circles representing the monitoring section based on the measured points on their perimeter, and then determine the 3D coordinates of their centers, which are important inputs for calculating the horizontal transmission and the vertical deviation of the chimney axis.

4. Results and Discussion

4.1. Calculating the horizontal and vertical coordinates of the control points on the chimney

The coordinates of the occupation points were calculated within a local coordinates system using the resection method; then, the 3D coordinates of the control points on the chimney and its neighboring elements were observed as shown in Table 1.

Table 1: 3D coordinates of the control points

Point No.	X (m)	Y (m)	Z (m)
1	56.819	89.634	22.839
2	56.24	90.511	22.824
3	49.493	91.077	22.867
4	49.042	113.183	33.793
5	70.728	108.763	33.800
6	70.799	108.752	17.440
7	49.066	113.168	21.495

4.2. Taking photos of the chimney

Photos were taken from the ground and the buildings adjacent to the chimney so that the entire length of the chimney had been covered as best as possible, where about 181 images had been taken. Figure 4 shows a sample of the locations of these images.

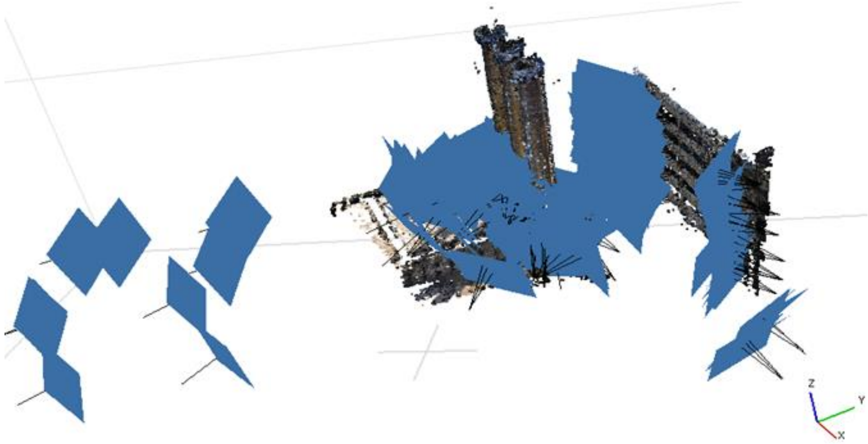

Fig. 4: Sample imaging sites.

This imaging process established through some precautions and conditions, as: every point of the chimney should have been shown in at least two images and all the imaging device stations had been separated; horizontally and vertically to maintain almost right angles between the images.

4.3. Chimney traditional surveying data

Five levels of the chimney perimeter had been monitored, starting with a level approximately equal to 13m and ending with a level close to 45m Figure 5. The level close to the base of the chimney wasn't observed due to the presence of dust, backfill, weeds and some trees that obscure this part and render the measurement process not possible. Table 2 shows the coordinates of the points representing the circumference of each studied level.

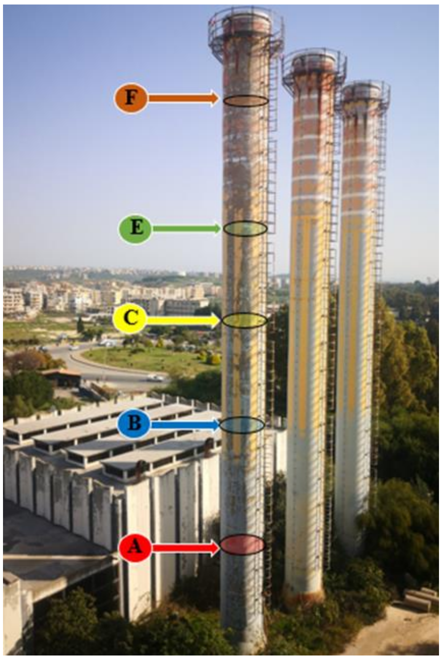

Fig. 5: Monitoring levels using traditional surveying of the chimney perimeter.

Table 2: 3D coordinates of the measurement level points.

P	X	Y	Z	Level	P	X	Y	Z	Level
1	56.851	89.33	13.827		**12**	54.176	89.863	30	
2	56.196	90.526	13.827		**13**	54.85	90.593	30	
3	55.103	90.701	13.827	**A**	**14**	55.217	90.796	30	**C**
4	54.38	90.253	13.827		**15**	56.234	90.525	30	
5	54.158	89.908	13.827		**16**	56.659	90.107	30	
6	56.866	89.366	23.678		**17**	56.883	89.454	30	
7	56.238	90.516	23.678		**18**	56.89	89.483	36.859	
8	55.077	90.696	23.678	**B**	**19**	56.357	90.452	36.859	**E**
9	54.459	90.329	23.678		**20**	55.16	90.706	36.859	
10	54.166	89.897	23.678		**21**	54.547	90.377	36.859	
11	54.166	89.896	23.678		**22**	54.207	89.918	36.859	
					23	54.203	89.899	44.643	
					24	56.579	90.231	44.643	**F**
					25	56.89	89.496	44.643	

4.4. Processing the traditional survey data and determining the transition values for the chimney axis

Processing data went through the following steps:

1- The monitored points on the perimeter of each level had been entered into the CIVIL 3D program, and the points were sorted into groups, each of which included the monitored points within the same level.

2- Considering that the cross-section of the chimney is a circle with a known radius, a fit for the best circle passing through the points of each level had been made by the capabilities available in the CIVIL 3D program Figure 6. Thus, the coordinates of the centers of the circles representing the five levels had been obtained.

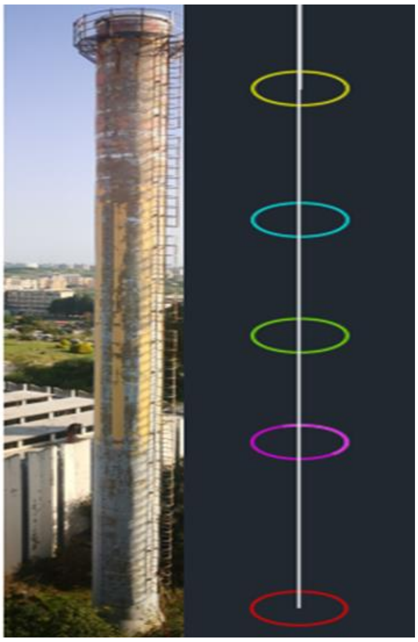

Fig. 6: Fitting monitoring levels with circles representing the chimney circumference.

3- Section A corresponding to the lowest surveying level was considered a reference level for calculating the horizontal shifts (in the XY level) of the center of each of the subsequent levels.

4- The horizontal shifts di were calculated according to the following relationship Equation (1):

$$d_i = \sqrt{\left(X_{ref} - X_i\right)^2 + \left(Y_{ref} - Y_i\right)^2} \quad (1)$$

Where: Xref and Yref are the horizontal coordinates of the center of the lower circle and Xi and Yi are the horizontal coordinates of the center of the circle i. Table 3 and Figure 7 show the results of the previous process.

Table 3: Chimney horizontal displacements at monitored levels.

Level	Height (m)	The coordinates of the center		Horizontal Displacement (m)
		X (m)	Y (m)	
A	13.83	55.444	89.335	0.00
B	23.68	55.459	89.342	0.017
C	30.00	55.481	89.336	0.037
E	36.86	55.490	89.337	0.046
F	44.64	55.493	89.338	0.049

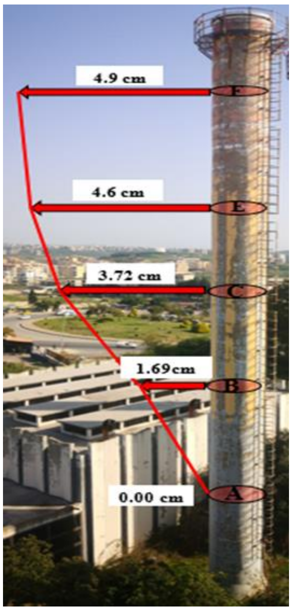

Fig. 7: Chimney horizontal displacements at monitored levels.

5- The inclination of the chimney was calculated using the following relationship Equation (2):

$$\theta = \tan \frac{d}{\Delta Z} \quad (2)$$

Where d is the maximum horizontal displacement at the top of the chimney and ΔZ is the level difference between the reference level and the chimney top level. By applying Equation (2), it was found that:

$$\theta = \tan \frac{0.049}{44.64 - 13.83} = 0.091°$$

4.5. Processing photogrammetry data and determining the transition values for the chimney axis.

Processing photogrammetry data to get the values of the displacements went through the following stages:

1- Triangulation of images depending on the available control points.
2- Calculating the dense point cloud within the highest possible processing level available in the software.
3- Exporting the cloud to CloudCompare software and calculating the best cylinder by applying fitting to the dense cloud using the RANSAC algorithm.
4- Make sections in the best cylinder resulting from the previous step on the same levels used in the surveying process.
5- Fitting the best level for each section and deriving the coordinates of its center, which corresponds to the center of the circle at this level.
6- Calculating the displacements relative to the lower reference level by applying Equation (1).

Regarding the triangulation of the image block, all the control points had been used in the calculation process, where the scattered point cloud had been obtained of 127371 points, and the values of mean-square errors are shown in the following Table 4.

Table 4: Values of mean-square errors on the coordinates of the control points.

X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
1.62	1.56	1.20	2.25	2.55

The concept of pixel size in the pixel-object or the Ground Sampling Distance (GSD) had been used to evaluate the geometric accuracy of image triangulation, given that the median distance between the object (chimney) and the camera is about 20 m, where the specifications of the used camera are shown in Table 5.

Table 5: Specifications of the camera used for taking image blocks

BLA-L29	
Object to camera distance D (m)	20.00
Sensor width Sw (mm)	5.064
Focal length FR (mm)	3.950
Image width Imw (pixels)	3968
Pixel length in microns	1.2762

Ground Sampling Distance can be calculated by the following relation Equation (3):

$$\mathbf{GSD} = \frac{\mathbf{D \times S_W \times 100}}{\mathbf{Im_W \times F_R}} \tag{3}$$

By applying this relation, the GSD value is equal to 0.65 cm/pixel, where the allowable accuracy can be calculated by the following relation Equation (4) [13]:

$$\boldsymbol{\sigma_{xyz}} = (\mathbf{4} \rightarrow \mathbf{6}) * (\mathbf{0.3} * \boldsymbol{GSD} * \mathbf{2}) \tag{4}$$

By applying this relation, the allowable accuracy value is 3.25 cm. By comparing the result to Table (4), it was found that the calculated triangulation accuracy is acceptable.
Next, the dense point cloud was generated using the highest processing level available in the software used, where cloud of approximately 2,195,000 points were obtained Figure 8.

Fig. 8: Chimney dense point cloud.

After that, the dense point cloud was exported to CloudCompare software and the best cylinder was fitted using the RANSAC (Random Sample Consensus) algorithm, then the cross-sections were made in the generated cylinder at the same section heights applied in the previous traditional surveying Figure 9.

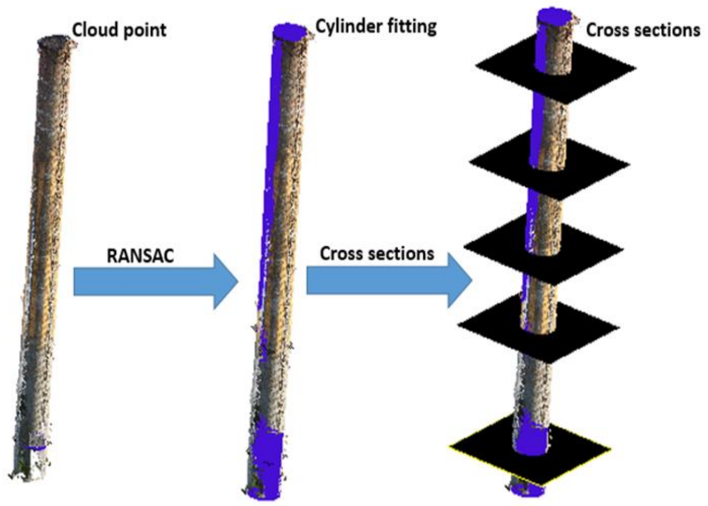

Fig. 9: Processing the dense point cloud of the chimney.

The best plan fitting to each cross-section resulting from the previous step Figure 10 had been applied to get the center of the sections.

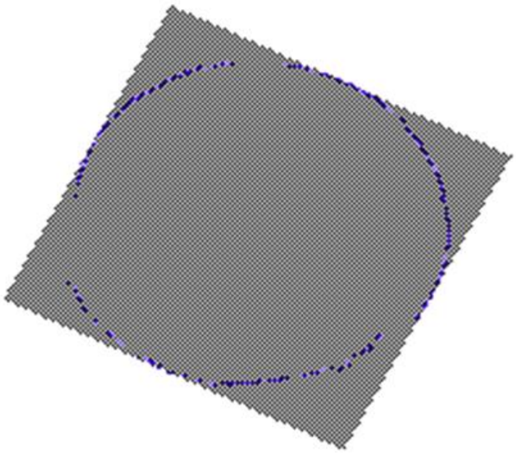

Fig. 10: Cross-section level fitting.

At the end of the previous stage, the coordinates of the centers of all the sections had been obtained, and the transitions by applying Equation (1) had been calculated. Results are shown in Table 6.

Table 5: Specifications of the camera used for taking image blocks

Level	Height (m)	The coordinates of the center		Horizontal Displacement (m)
		X (m)	Y (m)	
A	13.83	55.441	89.330	0.000
B	23.68	55.459	89.342	0.022
C	30.00	55.486	89.328	0.045
E	36.86	55.51	89.332	0.069
F	44.64	55.521	89.339	0.081

Next, the inclination of the chimney was calculated by applying Equation (2) as follow:

$$\boldsymbol{\theta = \tan \frac{0.081}{44.64 - 13.83} = 0.15°}$$

4.6. Results Comparison and Analysis

A comparison between the displacement values resulting from traditional surveying and photogrammetry shown in Figure 11, considering that traditional surveying is the most accurate reference method.

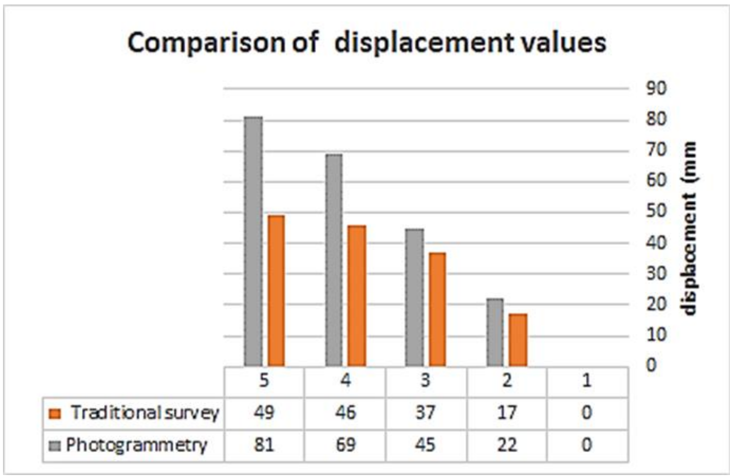

Fig. 11: A comparison of the displacement values resulting from traditional surveying and photogrammetry.

The main notes from this figure are:

1- Displacement values increase with the increase of height in both methods.
2- The values of displacements determined by photogrammetry are greater than those determined by traditional surveying at all levels.
3- The maximum displacement and inclination values at the top level determined by photogrammetry are approximately twice the displacement and inclination determined by traditional surveying.

These differences in displacement values can be explained as follows:

1- The camera used has a low recognition accuracy compared to those used in this type of work (industrial cameras), and it was not calibrated, so it is considered a source of errors that affect displacement values.
2- The small number of control points measured on the chimney used for image orientation, as well as the irregular distribution of these points on the element.
3- The difficulty of taking pictures of the chimney from the ground is due to the small distance between the camera and the chimney imposed by the site conditions.
4- The great height of the chimney led to take photo with a severe inclination that affects the geometric accuracy of image orientation and the displacement measurements taken from them.

Therefore, photogrammetry can be an alternative technique to traditional surveying for determining displacements if some items in this work were changed or modified as follow:

1- Calibrating the camera or using industrial cameras.
2- Using accurate and easy surveying devices to determine the control points better in terms of number and distribution.
3- Taking photos of the target with a crane or a drone will lead to getting more accurate results.

On the other hand, the strength points of photogrammetry are:

1- Photogrammetry provided a better visual expression of the geometry of the element in the form of a dense point cloud instead of simplified sections in the traditional surveying method.
2- The proposed processing methodology to deal with image orientation, generating point clouds, and deriving displacement and inclination values from them is a flexible and general methodology based on taking advantage of the capabilities of low-cost image processing software (such as Agisoft Metashape), free and reliable open-source software to deal with point clouds (such as CloudCompare).

5. Conclusions

Based on the previously presented theoretical and practical study, it was found that: following:

1- The value of the displacement calculated by photogrammetry in this study at the highest level of the studied element (81 mm) was almost double the value of the displacement determined by traditional surveying (49 mm), which is a significant difference. Without considering the effect of the quality of the camera, the number and distribution of control points, the site conditions and the method of getting photo

2- The photogrammetry technique allows getting all the necessary inputs to calculate the displacement values in the high elements, which are the images and the dense point cloud. The important point here is that the dense point cloud provides an accurate representation of the element as a whole, which is not provided by traditional techniques that are limited to measuring specific points on the element and measuring their displacements.

3- Photogrammetry provided a better visual expression of the geometry of the element in the form of a dense point cloud instead of simplified sections in the traditional surveying method.

4- The proposed methodology for calculating images and deriving displacement values from point clouds proposed in this study is a flexible methodology based on dealing with easy-to-use and reliable software. This methodology can be generalized for calculating displacements of high elements and monitoring the rock slopes in an open pit mine.

6. Recommendation

The practical work in this study could be modified while securing the requirements for getting higher accuracy, such as camera calibration, ensuring a sufficient number and uniform distribution of control points, with a mechanism to get better images, such as using a crane or a drone and applying the proposed processing methodology in the study.

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تقييم تطبيق المساحة التصويرية القريبة في تحديد الإزاحة الأفقية والميل في العناصر الإنشائية العالية- حالة دراسة المحطة الحرارية في جامعة تشرين

ملخّص

قد تؤدي الإزاحات الأفقية والميول الكبيرة في العناصر الإنشائية العالية مثل الأبراج ومداخن المصانع والناتجة عن حركة التربة أو الزلازل إلى انهيار هذه العناصر. تتطلب الطرق التقليدية لمراقبة الميل (GPS، المحطة الشاملة، التسوية الرقمية،..) وجود تماس مباشر بين جهاز الرصد والعنصر المرصود. نتائج هذه الطرق دقيقة، ولكن توزيع المستشعرات مرهق وهي توفر معلومات تخص التشوهات المحلية والنسبية فقط. من ناحية أخرى، لا تتطلب طرق المراقبة الحديثة وجود تماس مباشر مع العنصر المدروس، ومن هذه الطرق نذكر تلك التي تستخدم الماسحات الليزرية الأرضية ورادار الفتحة التركيبية الأرضي لقياس التداخل (GBInSAR)، والمساحة التصويرية. تُستخدم هذه الأخيرة للحصول على بيانات جغرافية مكانية عالية الدقة وبناء نماذج ثلاثية الأبعاد للمنشآت، ومن خلال القياس الهندسي للنموذج ثلاثي الأبعاد يمكن الحصول على بيانات التشوه مثل إزاحة وميل المنشأ.

تم في هذا البحث استخدام تقنية المساحة التصويرية القائمة على اقتطاع البنية من الحركة لتحديد الإزاحة الأفقية والميل لإحدى مداخن المحطة الحرارية الموجودة في جامعة تشرين. تم لاحقاً مقارنة النتائج مع نتائج الطريقة التقليدية القائمة على استخدام المحطة الشاملة في القياسات. بينت النتائج أن قيمة الإزاحة عند المستوي الأعلى للمدخنة المحددة باستخدام آلة تصوير غير معايرة مرفقة مع هاتف نقال وتقنية المسح التصويري القائم على اقتطاع البنية من الحركة (وقيمتها 0.081 m) تساوي تقريباً ضعف قيمة الإزاحة المحددة بطريقة المسح التقليدي (وقيمتها 0.049 m).