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Application research on slope deformation monitoring and earthwork calculation of foundation pits based on UAV oblique photography

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Abstract. The stability of foundation pit slopes is a key concern during the construction of foundation pits. The deformation and instability of slopes will pose a major threat to the safety of foundation pits construction. Based on the foundation pit project of Shenzhen Dapeng People's Hospital, this study uses DJI phantom 4 RTK drone to collect oblique photography data of the foundation pit in different periods, reconstructs high-precision 3D virtual models through the Bentley ContextCapture software and generates the Digital Surface Model (DSM) data. The model quality report shows that the accuracy of the three-dimensional model is better than 5 cm, up to about 1 cm. Spatial analysis of DSM data in different periods using ArcGIS can obtain the deformation of the foundation pit slopes. This method can also be used for the calculation of earthwork excavation of the foundation pit, which can effectively reduce the field workload of traditional earthwork surveys.

1. Introduction

Deformation of the foundation pit slope is an important factor affecting the safety of foundation pit construction. As the foundation pit is excavated downward, the slope will deform and even become unstable. Therefore, slope support and deformation monitoring are very important. Through deformation monitoring, the deformation of the slope can be grasped and its safety can be analyzed. At present, the commonly used methods of foundation pit slope deformation monitoring are: inclinometer, robotic total stations, differential GPS (DGPS), etc. However, these methods are cost-consuming and have sparse spatial coverage, which result in the monitoring omission of key deformation part.

A new method for monitoring slope deformation of foundation pits is to utilize Unmanned Aerial Vehicle (UAV) to collect high resolution imagery. The use of UAV has become common in recent years due to technological developments such as miniature digital cameras, high precision GPS, excellent autonomous flight control systems, and lightweight carbon fiber airframes [1-10]. Some recent studies have revealed the ability of Structure from Motion (SfM) algorithms in slope deformation monitoring. SfM is an image processing technique based on the computer vision algorithm first developed in the 1990s. It allows the reconstruction of a 3D model without the need for ground control points (GCPs) or complex pre-calibration of the camera.

Rodriguez et al.[11] utilized the UAV photogrammetry to evaluate the instability areas, the severity of instability events, and the relationship between slope instabilities and the drainage network. And their research has achieved good results. Pirasteh et al.[12] studied the geometric deformation



measurements based on UAV, the high resolution Digital Elevation Model (DEM), Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) and associated with ground truth observations. Then they proposed a new algorithm, and refurbished generating landslide inventory dataset in a quicker time than existing and traditional methods. Rotnicka et al.[13] studied the DEM accuracy of the Beach-Foredune Topography by the use of UAV. The results showed that the marram grass can significantly affect the accuracy of the UAV-based model, and the uncertainty of the UAV-derived DEM increases together with increasing slope inclination and with increasing general slope curvature. Hamylton et al.[14] utilized images collected by UAV to monitor rehabilitation activities in order to evaluate three approaches to mapping vegetation. And the result showed that the accuracies were 82%, 85% and 91% respectively for three approaches, including: the pixel based image classification, the CNN machine learning and the visual interpretation / digitization algorithm. Lamsters et al.[15] presented the first high-resolution DSMs and orthomosaics of the largest Argentine Islands. The average resolution of DSMs and orthomosaics reached 3.4 and 6.8 cm/pixel, and the average RMS reprojection error is 0.22 m. This study showed that small and low cost UAV can be effectively used in polar conditions to obtain accurate DSMs and orthomosaics of the glaciated terrain. Anders et al.[16] studied the impact of flight strategy on the accuracy of UAV image data products, including the DSM and orthophoto. And the results showed that increasing cell size with increasing altitude, and differences between elevation values for different flight directions. Carrera-Hernández et al.[17] compared the UAV-SfM surveying method with the traditional surveying techniques, and the results showed that the UAV-SfM method obtains better results than the traditional method. Sanz-Ablanedo et al.[18] proposed an optimized flight design to improve the accuracy of UAV-SfM DEM. This study revealed that specific UAV flight designs can significantly reduce dome errors, especially those that have a higher number of tie points connecting distant images and hence contribute to a strengthened photogrammetric network. Hu et al.[19] investigated loess and landslides caves by the use of UAV and mapped by GIS. They successfully accomplished the interpretation of loess caves, landslides and bank erosion based on high-resolution UAV images and topographic data.

Although more research work has used UAV oblique photography technology, it has not yet been seen to apply this technology to foundation pit slope deformation monitoring research. Therefore, this study aims to study the application effect of UAV oblique photography in the deformation monitoring of foundation pit slope, and analyse the change of earthwork volume of the foundation pit.

2. Methodology

2.1. Platform

Multi-rotor UAV are becoming popular and frequently used for commercial and recreational aerial photography. In this study, we used the DJI Phantom 4 RTK (Referred to as P4R) multi-rotor UAV. The P4R is a light and smart mapping and imaging UAV capable of highly accurate mapping functions. The drone has a built-in DJI On-board D-RTK, which can provide positioning data with centimeter-level accuracy. Raw satellite observations and exposure event records can be used for post-processed kinematic (PPK) differential corrections. The P4R has a 24 mm wide angle camera, high-precision and anti-shake gimbal, 1-inch CMOS sensor, and mechanical shutter. It can record videos at 4K and captures 20 megapixel photos.

2.2. Field Site

This study takes the foundation pit of Shenzhen Dapeng People's Hospital as the research object. The foundation pit is located in Kuiyong Street, Dapeng District, Shenzhen, and the excavation depth is 13.3 - 13.8 m. The planned basement has two floors, and the first floor and second floor do not overlap. The perimeter of the bottom edge of the first floor is about 1175 m, and the excavation area is 61,000 m². The perimeter of the bottom edge of the second floor is about 960 m, and the excavation area is 54,000 m².

2.3. Three-Dimensional Model Generation

We have completed two separate UAV surveys of the site, details of which are shown in Table 1. The flying height of the UAV is 70 m (relative to the take-off point), the ground sample distance (GSD) is 1.92 cm/pixel, the flight mode is five-direction flight, the forward overlap rate is 80%, the side overlap rate is 75% (see Figure 1), the oblique angle of the camera is 60°, and the image distortion correction is turned off. After the route planning is completed, the UAV will autonomously fly and collect photos without manual intervention. In order to obtain high-precision positioning data, the UAV is flying in RTK mode, and the differential mode is network RTK. The Qianxun RTK CORS system provides real-time differential positioning data, which can provide positioning data with 2-4 cm accuracy.

Table 1. Details of UAV surveys of Dapeng People's Hospital

Survey Name	Date	Interval (Days)	Weather Conditions
20191228	28 December 2019	-	Sunny, light winds
20200610	10 June 2020	165	Sunny, moderate winds

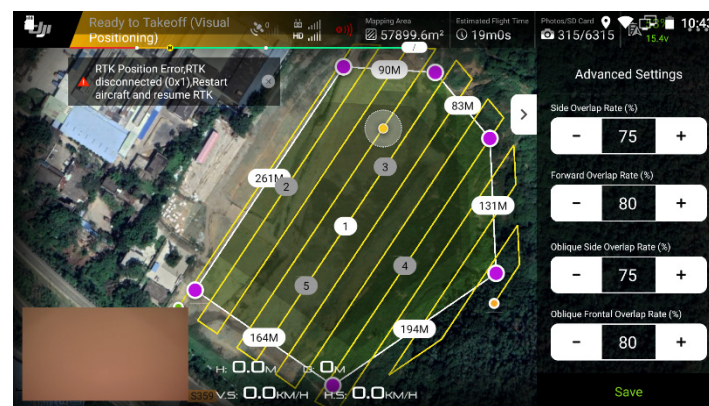


Figure 1. Overlap rate setting window of the P4R

Image collected during each aerial campaign were processed with the Bentley ContextCapture (Referred to as CC) software, which uses SfM techniques to reconstruct the scene based on a large number of overlapping photos. First, import the photos taken by the UAV into the CC software, then check the integrity of the photos, input the distortion correction parameters of the photos, and submit them to the aerial triangulation calculation. When the aerial triangulation calculation is successful (see Figure 2), the 3D model reconstruction is performed to generate a high-precision 3D real scene model (see Figure 3). The final step is to export a DSM (see Figure 4) and orthophoto based on the 3D model.

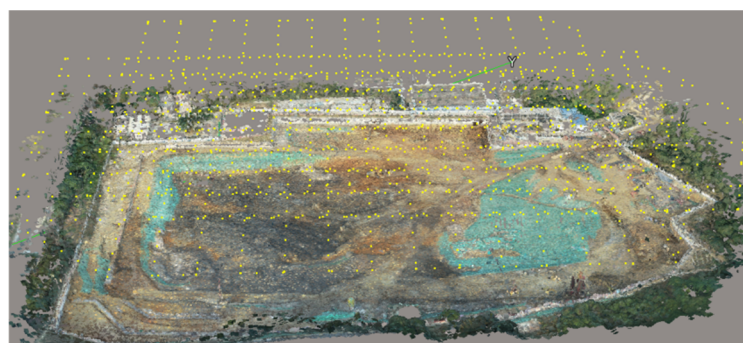


Figure 2. Aerial triangulation calculation results



Figure 3. 3D real scene model of the foundation pit of Dapeng People's Hospital; (a)20191228; (b)20200610

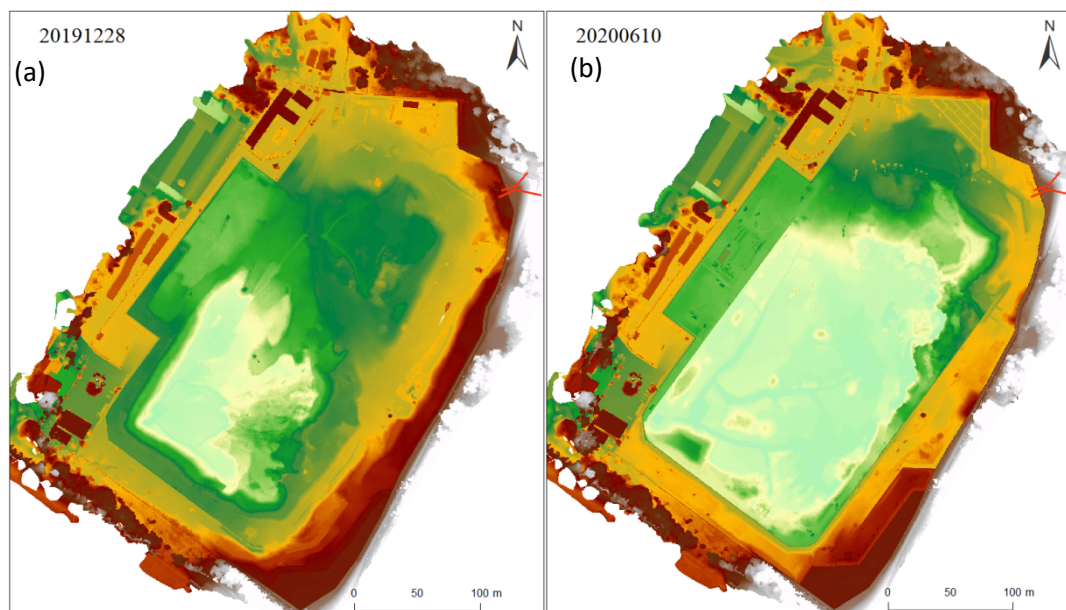


Figure 4. DSM data of the foundation pit of Dapeng People's Hospital; (a)20191228; (b)20200610

2.4. Slope Deformation Monitoring and Earthwork Calculation

The generated two-phase DSMs are used to calculate the deformation of the foundation pit slope and the amount of earthwork. For the analysis of foundation pit slope deformation, ArcGIS software is used to load the two-phase DSM data. The profiles AB and CD are drawn along the sliding direction of the slope (see Figure 5), penetrating the slope and the top of the crown beam. The elevation data of the two periods of DSMs are extracted through the profiles, and then the changes in the elevation data are compared to analyze the displacement of the slope along the sliding direction. For the calculation of the earthwork volume of the excavation of the foundation pit, the CUT-FILL function in ArcGIS spatial analysis is used to perform the analysis of the excavation and filling, and the elevation difference information of each pixel of the DSM is obtained, and the change of the earthwork volume can be visually viewed.

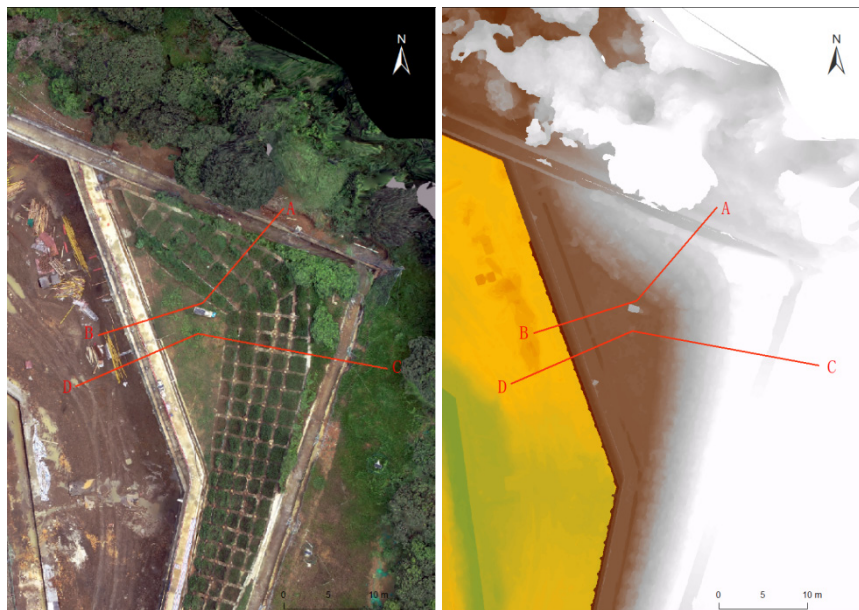


Figure 5. Distribution of the two profiles; (a) 20200610 orthophoto; (b) 20200610 DSM

3. Results

3.1. Accuracy of DSMs and Orthophotos

Results of the distance to input positions are showed in figure 6. For the 20191228 DSM, the minimum distance is 0.03 cm, the maximum is 1.83 cm, and the median position distance equals 0.51 cm. For the 20200610 DSM, the minimum distance is 0.02 cm, the maximum is 1.78 cm, and the median position distance equals 0.33 cm. Results of the photo position uncertainties are presented in table 2. The summary of reprojection errors for Dapeng People's Hospital DSMs and orthophotos is presented in table 3. It can be seen that typical root mean square (RMS) values of reprojection error of the two models is 0.45 and 0.53 pixels respectively.

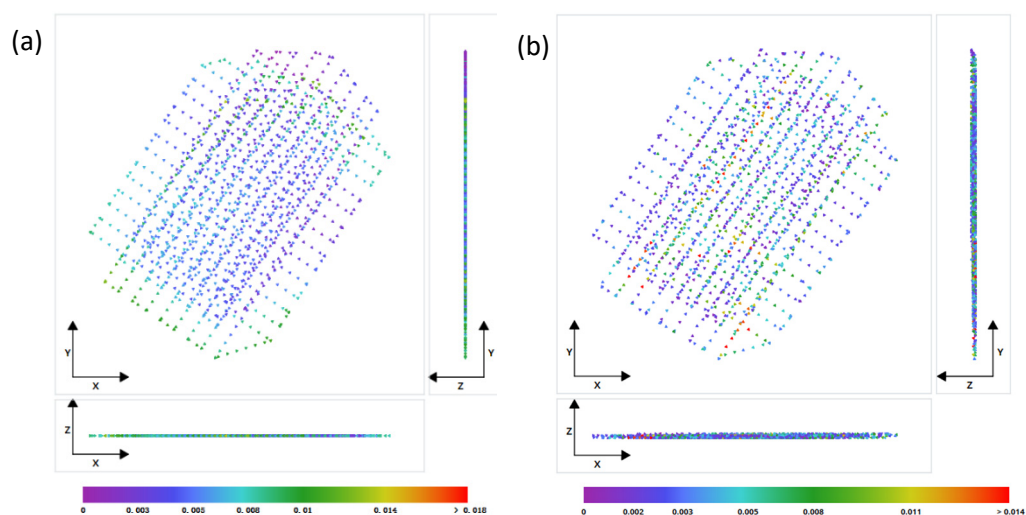


Figure 6. Results of the distance to input positions; (a) 20191228; (b) 20200610.

Top view (XY plane), side view (ZY plane) and front view (XZ plane), with arrows indicating the offset between the metadata positions and the computed photo positions; all arrows start from the metadata positions and point toward the computed positions. Gray points indicate uncalibrated photos that have metadata. Pink points indicate calibrated photos that have no metadata. The values are in meters.

Table 2. Results of the photo position uncertainties

Name	Date	Grade	X/cm	Y/cm	Z/cm
20191228	28 December 2019	Minimum	0.10	0.12	0.08
		Mean	0.24	0.24	0.17
		Maximum	0.67	0.52	0.30
20200610	10 June 2020	Minimum	0.11	0.13	0.08
		Mean	0.27	0.27	0.20
		Maximum	0.44	0.44	0.30

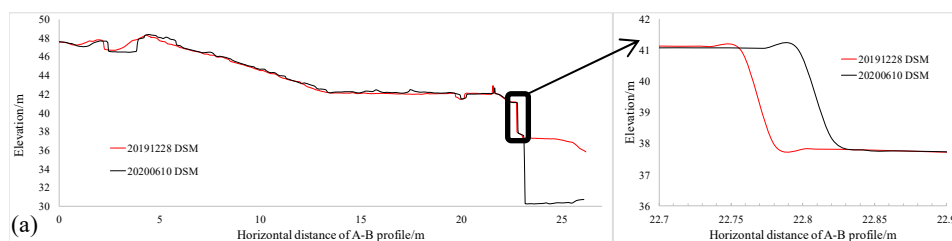
Table 3. Summary of reprojection errors for Dapeng People's Hospital DSMs and orthophotos

Name	Date	Number Photos Used in Model	Median Reprojection Error/pixels	RMS of Reprojection Error/pixels	RMS of Distances to Rays*/m
20191228	28 December 2019	1423	0.32	0.45	0.0465
20200610	10 June 2020	1423	0.4	0.53	0.0493

* A ray is the 3D line that starts from a photo position and passes through the tie-point position and passes through the tie-point observed in that photo. The orthogonal distance from the real tie-point 3D position to that ray is the distance to ray.

3.2. Results of the Slope Deformation and Earthwork Change

Deformation results of the foundation pit slope are shown in Figure 7. The AB profile shows that the slope of the foundation pit is mainly displaced in the horizontal direction towards the pit, with an average displacement of 5 cm. In addition, the end of the AB profile represents the excavation bottom of the foundation pit. Results of this study show that from December 28, 2019 to June 10, 2020, the bottom of the foundation pit descends about 7 m, which is consistent with the actual situation. The CD profile reveals a similar situation. The slope of the foundation pit has a horizontal displacement of about 6 cm towards the pit, and the bottom of the foundation pit descends about 6 m. Therefore, this study shows that UAV oblique photogrammetry can effectively reveal the settlement change of the excavation surface of the foundation pit.



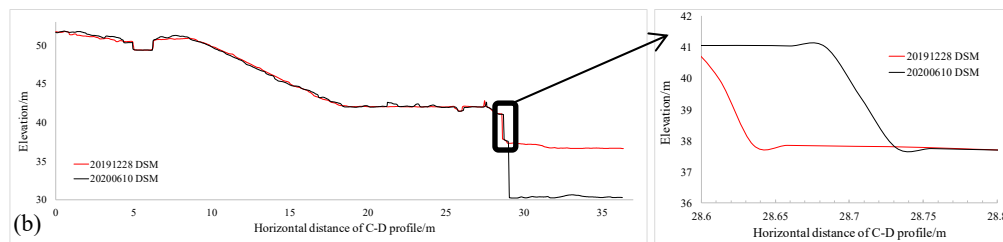


Figure 7. Deformation analysis results of the foundation pit slope; (a) A-B profile; (b) C-D profile

The result of earthwork volume change of the foundation pit is shown in Figure 8: red color represents fill, blue color represents excavation. The result indicates that large-scale excavation activities have taken place at the bottom of the foundation pit. The location of the supporting piles of the foundation pit has not changed, and the frame beams are basically unchanged. The slope surface is shown in red due to the growth of vegetation, indicating the increase in earthwork. Therefore, this study shows that UAV oblique photogrammetry can also effectively reveal the change of earthwork volume of the foundation pit.

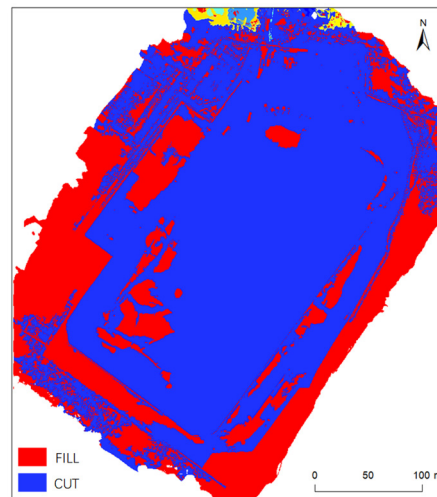


Figure 8. The results of earthwork volume change of the foundation pit

4. Conclusions

This study explored the use of UAV oblique photography for the deformation monitoring of the foundation pit slope and calculation of earthwork volume changes. And there are two conclusions were obtained:

(1) Using high-precision differential GPS positioning data and high-resolution cameras, UAV oblique photography can reconstruct a three-dimensional (3D) real scene model with centimetre-level accuracy. And the average RMS accuracy of DSM and orthophoto generated by the 3D model is 2-3 cm.

(2) Using GIS software to extract elevation data, the deformation of foundation pit slope can be effectively analysed. Using the CUT-FILL function, it is possible to calculate the changes of the earthwork volume of the foundation pit.

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