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Application of Precise Digital Photogrammetry to a Measurement System for Large Retaining Wall Monitoring

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ABSTRACT:
Excavated slopes often need retaining walls to ensure continued stability. Conditions in slopes can be deteriorated and deformable over long periods. Therefore, continual monitoring will be an important issue after construction. Deformations of a retaining wall on the slopes are especially significant indicators of the degree of slope stability. Recently, digital photogrammetry has been developed as one of effective measurement technique. The measurement method using photogrammetry has a great advantage over conventional ones because this method makes it possible to measure the three dimensional coordinates of measurement points with an easy measurement work at low cost. In this study, the authors simulate optimum photographing conditions such as camera locations, the number of images and the camera angles to obtain the measurement data with a high degree of precision and then measure the coordinates of targets installed on an object as measurement points. It is also shown that by using this digital photogrammetry the authors can observe deformation of a large retaining wall accurately. The results show that this measurement system using photogrammetry has high potential applicability in deformation monitoring for protection against disaster.

Keywords: photogrammetry, digital camera, retaining wall, monitoring, deformation

1. INTRODUCTION

In Japan, lots of natural disasters such as earthquakes, typhoons, and localized torrential downpours frequently cause slope hazards such as failures and landslides. In order to avoid or minimize slope hazards failures, it is essential to establish a measurement technique for slope behaviour monitoring.

This study aims to establish a measurement system for deformation monitoring on slopes by using a photogrammetric technique, which measures the photographic subject's deformation on digital camera images: photogrammetric technique, which applies the principle of stereoscopy in aerial photogrammetry, has been used not only for map production but also for quality control of industrial products because of its ability to reproduce the three dimensional shape of an object.

However, it has only been used for recognizing shapes and not for detecting deformation. The authors have developed the measurement system using digital cameras that can easily measure the distribution of displacements of a slope by using the shortest least squares solution. This paper presents the theoretical development of this photogrammetric system and experimental results to demonstrate that slope behaviour can be measured through simple measurements.

The technique to reconstruct the three dimensional shape of objects from the two dimensional photograph was established in the mid-nineteenth century. From the 1990s, since digital cameras and computers became sophisticated and inexpensive, a method of digital photogrammetry became popular as the way to measure the shape and dimensions of objects.

The way to use digital images taken from the ground is easy to use to measure, is used with inexpensive devices, and is being applied to civil engineering recently.

Although application to measure shape quantitatively has been reported so far, the technique to detect changes in the shape of objects by using digital photogrammetry taken at different moments has never been established. If this method is established, it is expected to become useful measurement system to monitor slopes and civil structures. Considering the background, the authors tried to make three dimensional measurements by digital photogrammetry more accurate to measure changes of deformation on a large retaining wall near a dam.

2. BASIC PRINCIPLES OF DIGITAL PHOTOGRAMMETRY METHOD

The principle of digital photogrammetry is to calculate three dimensional coordinates of measurement point solving the collinearity condition equations showing that the measurement point installed on an object, the measurement point's imagery appearing on the image taken and the center of the camera are in alignment. The collinearity condition equations are given by Eq. 1.

$$x + \Delta x = -c\frac{m_{11}(X - X_0) + m_{12}(Y - Y_0) + m_{13}(Z - Z_0)}{m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)}$$
$$y + \Delta y = -c\frac{m_{21}(X - X_0) + m_{22}(Y - Y_0) + m_{23}(Z - Z_0)}{m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)} \quad (1)$$

Here, focal length of lens is denoted by c. The unknowns in the equations are categorized into the following groups:

・Three dimensional coordinates of measurement points:(X,Y,Z)
・Coordinates of photographing positions: (X_0,Y_0,Z_0)
・Rotating matrix of object space coordinates of camera: m_{ij}(matrix made from the horizontal angle θ, vertical angle φ, and rotating angle κ around optic axis)
・Correction values concerning lens distortion: $(\Delta x,\Delta y)$

The coordinates of the measurement point's imagery on the left-hand side of Eq. 1 (two dimensional coordinates:(x,y)) are measured on the camera coordinates system with two dimensions which, and then the unknowns on the right-hand side of Eq. 1 including three dimensional coordinates of the measurement points in the ground coordinates system are calculated using the least square method.

Because the positions and the angles of the camera are also taken as the unknowns, it is possible to take the images at the arbitrary camera positions. Moreover, correction values $(\Delta x,\Delta y)$ concerning the lens distortion are also taken as the unknowns, suggesting that this method has the advantage of using commercially available digital cameras without calibration of the lens distortion.

3. MEASUREMENT PROCEDURE

Because Eq. 1 is non-linear, the unknowns should be divided into the initial values and correction amounts for linearization, and then Eq. 2 is obtained using Tailor Expansion around the initial values. The correction amounts are then calculated by solving the resultant linear simultaneous equations. In addition, the solution is updated by using these corrected initial values, which is assumed to be the initial value of the following linearization. The unknowns are obtained by repeating this procedure until the solution is converged.

$$\mathbf{v} + A_1\mathbf{x}_1 + A_2\mathbf{x}_2 + A_3\mathbf{x}_3 = \mathbf{e} \quad (2)$$

Here, the subscript 1 shows the amount concerning the camera positions and the camera angles, subscript 2 shows the amount to correct the internal parameters of the camera, and subscript 3 shows the amount concerning the measurement point coordinates. Matrix Ai is the coefficient matrix, and e is the residual amount vector that consists of the difference between the measurement values and theoretical coordinates by collinear conditional equation. Because two equations are formed from one measurement point, the total number of equations becomes 2mn when the numbers of measurement points and images taken are n and m, respectively. .

On the other hand, the unknowns concerning the camera positions and the camera angles become 6m and the ones of three dimensional coordinates of the measurement points become 3n. The internal parameters of the camera are expressed by eight unknown numbers in this research, and when measurement points on the object are 100 and the image taken are 20, it means to solve a total of 428 unknowns by 4000 equations. Concretely, we calculate the unknowns that minimize the sum total of the square errors expressed by Eq. 3.

$$\Phi(\mathbf{x}) = \mathbf{v}^T\mathbf{v} = (\mathbf{e} - A\mathbf{x})^T(\mathbf{e} - A\mathbf{x}) \rightarrow \min \quad (3)$$

Equation (4) called the normal equation is obtained by partially differentiating with respect to x and taking zero to obtain the unknowns which satisfies Eq. 3.

$$(A^{\mathrm{T}}A)\boldsymbol{x} = A^{\boldsymbol{T}}\boldsymbol{e} \quad (4)$$

Three dimensional coordinates of the measurement points can be obtained with other unknowns by solving this equation.

4. EXPERIMENTAL RESULTS

Although the unknowns are obtained by using lots of images of an object (targets) taken at many camera positions, the accuracy and precision of the measurements, which are analytical results of coordinates of targets, depend on the camera positions and camera angles. In this study, the accuracy indicates the difference between the analytical value and the true value of displacement, and the precision shows the dispersion of the analytical results.

In general camera positions are not allowed to be selected arbitrary and too much images than necessary disturbs the efficiency of the analysis. Thereby, in this research the authors try to obtain the optimum photographing conditions by simulating the influence of the camera position/angle on the accuracy and precision of the measurements, or the analytical results. The arrangement of camera positions and the object (target) in the simulation is shown in Fig. 1.

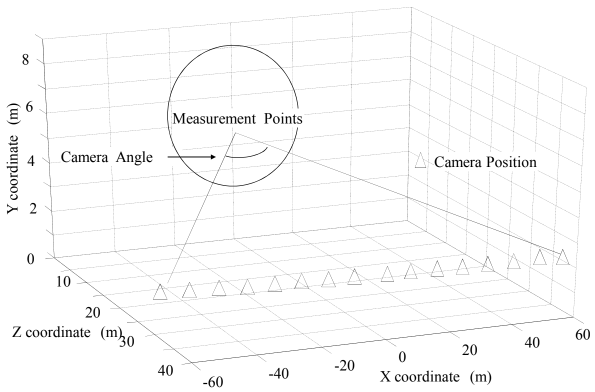

Figure 1. Photographing condition for simulation

It was assumed that a total of 40 targets were installed on the wall and a total of 32 images ware taken with the camera angle changing at each 16 location which was at the distance of about 40m from the center of the target group. Camera in the simulation had a resolution of 6,000,000 pixels, and the focal length of the lens was set to 35 mm. Firstly, the relation between the number of images taken and precision of the measurements is verified. The simulation results are shown in Fig. 2. In this figure, horizontal axis means the number of images used to calculate the three dimensional coordinates of the targets, and the vertical axis of Fig. 2 shows the precision.

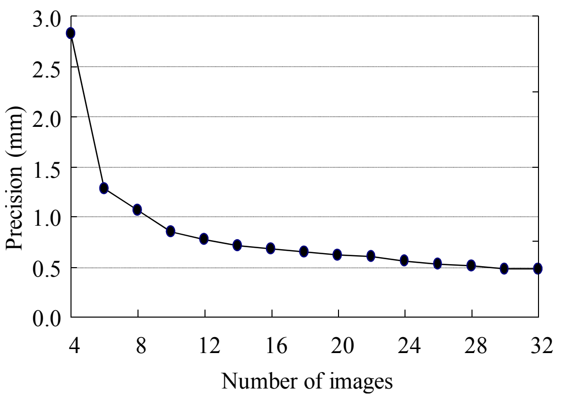

Figure 2. Relation between the number of images and the precision of the measurements

This figure shows that the precision can be improved with an increase of the number of images. Moreover, the precision σ_{xyz} varies with an increase of $1/\sqrt{}$ (number of images taken) , and although it is important to take a minimum necessary number of images in order to obtain higher precision, the precision does not improve when too much images are used. It is clear that considering the optimum number of images at the optimum photographing locations result in improvement of the efficiency of measurement work.

Next, the results of examining how the ratios of the object distance relative to the focal length of the lens have an influence on the precision are shown in Fig. 3. The ratios are defined as the scale ratios.

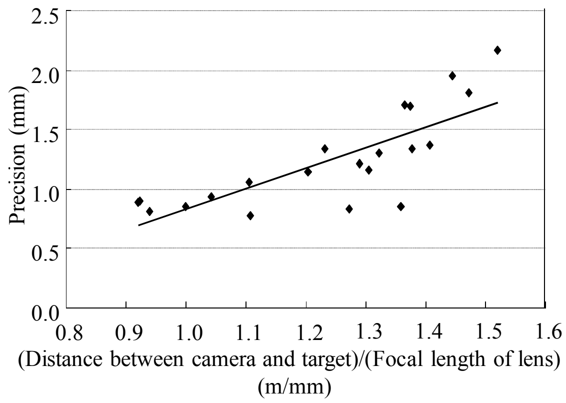

Figure 3. The relation between the scale ratios and the precision of the measurements

The precision of the measurements varies with an increase of the scale ratios in the case of a constant focal length of 35 mm as shown in Figure 3. It shows that the relation between the precision and the scale ratios are linear, and the longer the object distance becomes, the less the precision is. But, it also shows that the precision can be improved with an increase of the focal length of the lens. This suggests that when we take images from the long object distance, it is a better way to use the larger focal length of the lens. Next, the relation between the camera angles and the precision is shown in Fig. 4.

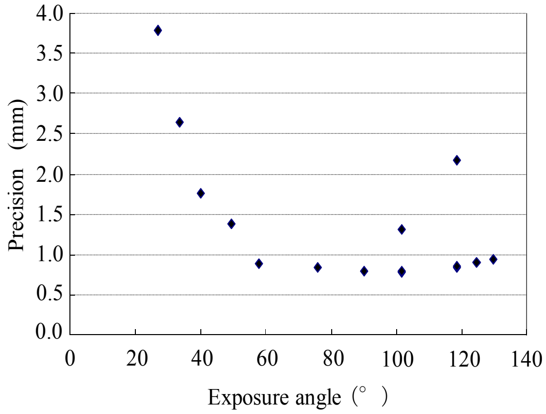

Figure 4. Relation between the camera angle and precision of the measurements

The camera angle means the range of camera locations, indicating the maximum angle formed from both ends of the camera locations. It can be said that the camera angle shows the geometrical relation formed by the object and the camera positions. In the case of 6 camera locations and 12 images taken, Fig. 4 shows the relation between

the camera angles and the precision of the measurements. In this figure, the precision becomes better with an increase of the camera angle and like the effect of the number of the images, the precision is not improved at too much camera angles. It is thought that the reason the precision decreased with an increase of the camera angle of more than 102° is that the images taken from the vicinity of the front were insufficient.
These results show that it is important to design the camera positions for obtaining good measurement results as well as the number of images and the scale ratios because the camera angles have a great impact on the precision.

From the experimental results described previously, the precision σ_{xyz} is defined as the following equation.

$$\sigma_{xyz} = \frac{q}{\sqrt{k}} \cdot \frac{d}{c} \cdot \hat{\sigma}_0 \qquad (5)$$

Here, each coefficient has the following meaning:

q: Coefficient decided by camera position
k: The number of images
d: Object distance from camera to the object
c: Focal length of lens
$\hat{\sigma}_0$: Standard errors of measurements of the image coordinates of measurement points' imagery

Here the image coordinates of measurement points' imagery mean two dimensional coordinates on the left-hand side of Eq. 1. In this method the principle of obtaining the three dimensional coordinates of measurement points from the two dimensional coordinates on the left-hand side of Eq. 1 are derived from the procedures based on the geometrical relation between the object, camera and images. This means that the errors of the measurements of the two dimensional coordinates of the measurement points' imagery are amplified by the values decided by the number of images and the camera angles, and then the precision of the estimated values of the unknowns is determined depending the errors. In order to measure the precise image coordinates of the measurement points' imagery, targets consisting of glass beads arranged in circles on the sheet are installed on the object. The targets are designed to induce strong diffuse reflection of incident flash light, and the image coordinates of the measurement point' imagery are obtained by calculating their centers of gravity of the imagery using an image processing. As a result, the image coordinates can be measured with an accuracy of 1/10 of one pixel.

In this study we design the arrangement of the targets and photographing conditions to satisfy the required precision at the actual measurement site by using Eq. 5. This procedure of design is programming and thereby we can make a plan of taking images easily.

5. OBSERVATION OF A RETAINING WALL USING DIGITAL PHOTOGRAMMETRY

The authors applied the digital photogrammetry to the observation of deformation in a retaining wall on a slope after simulating a plan of taking images.

Fig. 5 shows the procedure of the observation.

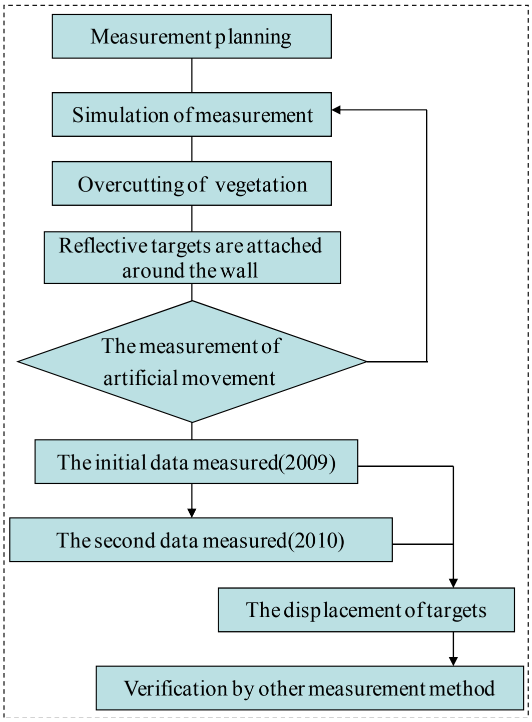

Figure 5. Procedure of the measurement

The retaining wall was constructed 55 years ago to prevent a landslide in a crystalline schist area of the slope. The retaining wall is a large concrete structure which is 120 m in width and 30 m in height. Lots of cracks in the wall which occurred due to the landslide were inspected during construction. After construction the displacements of the cracks have been measured by extensometers since 1979, and the measurements show that the maximum rate of displacement across a horizontal crack is 5 mm per year. Fig. 6 shows the measurement condition of the wall installed extensometers and targets.

This continuous deformation with cracks has not been measured over the whole area by extensometers. For this reason, precise digital photogrammetry was conducted. The authors installed a total of 128 targets on the wall and measured the displacements using a digital camera with 18 mm lens and 13.5 million pixels. The optimum locations of the targets and the optimum camera positions were simulated to obtain the precision less than 5 mm. The averaged object distance was about 30 m. The measurements were conducted two times in October 2009 and October 2010. The authors took a total of 147 images at a total of 51 locations. Several images were taken at each position rotating the camera to reduce the

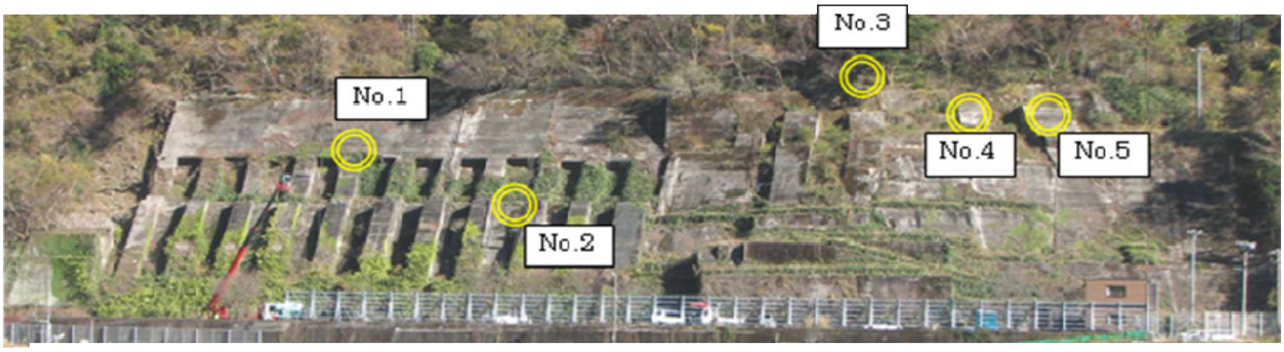

Figure 6. Retaining wall (double circle indicates locations of crack extensometers)

lens distortions and at 3 different locations in height using a mobile elevating work platform to improve the camera angles above discussed. Fig. 7 shows one of examples of installed targets.

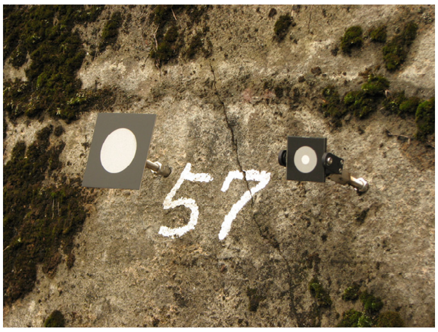

Figure 7. Targets on the wall across a crack

6. MEASUREMENT RESULTS

The authors tried to find three dimensional coordinates of targets installed on the retaining wall by using photogrammetry developed in this study. Fig. 8 shows the distribution of the precision of the measurements. The averaged values of the precision ± σ were 1.77 mm , which mean the standard deviation of the measurements. This result shows that we can obtain the desired precision in the measurements.

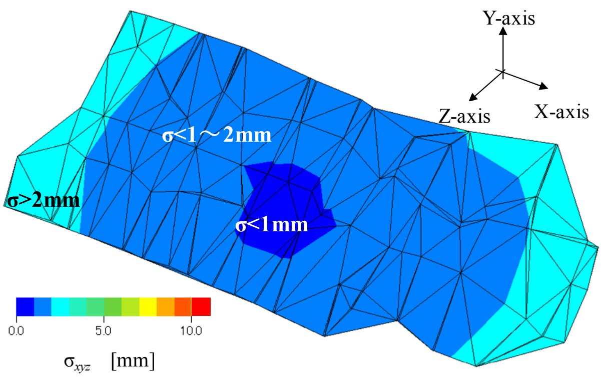

Figure 8. Distribution of the precision of the calculated coordinate values of the targets installed on the retaining wall

In order to evaluate the displacements which occurred in this retaining wall, we need to calculate the difference of the three dimensional coordinates measured at different periods. Because each three dimensional coordinate of the target analyzed by the method developed in this study is shown in the independent coordinate system for each analysis, we can calculate the differences of the distances between any two targets as the amounts of the displacements. It was revealed that all of the displacements calculated from the movements of any targets installed on the retaining wall were not more than 5 mm or more.

In this study, in order to examine the acquired amount of displacement, we compared it with the measurement results from extensometers during the same period. Fig. 9 shows accuracies which mean the amount of displacements by extensometers at 5 locations installed on the retaining wall (the location is indicated in Fig. 6) and the amount of displacements calculated for the distances between two measurement points by photogrammetry.

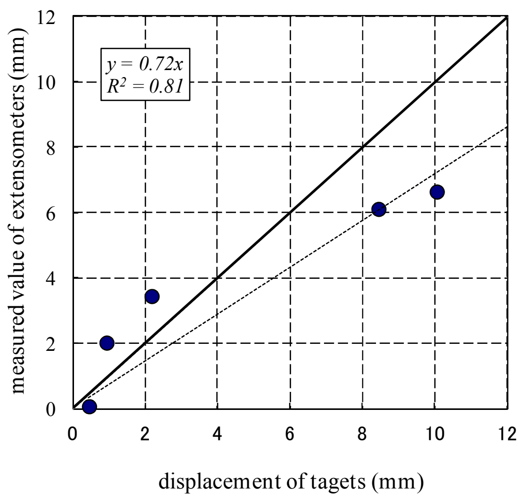

Figure 9. Relationship of displacement by digital photogrammetry and extensometers

In the Fig. 9, the solid and dotted lines show that the measurements by photogrammetry agree with the figures measured by extensometers. This figure indicates the displacements detected by photogrammetry were not 5 mm or more in the slope. Thus, it has been demonstrated that deformations calculated by the movements of every target installed on the slope can be simultaneously observed through a simple photographing procedure.

7. CONCLUSIONS

The authors developed a technique of the digital photogrammetry which detects deformation in the object with a precision of the order of a few millimetres through simple measurement work. By using a simulation method which can calculate the optimum camera locations and the optimum number of the images, it is also possible to make a plan of optimum photographing conditions which offer a high degree of precision. These developed methods make it possible to observe the displacements of a retaining wall on the slope through a simple photographing procedure with the same accuracy as the measurements by extensometers.

The authors plan to apply this measurement method using digital photogrammetry to observation of deformation of the retaining wall because the area-wide distributions of many measurement points can be obtained without any fiducial points. This method can be expected to be one of the disaster prevention management techniques on slopes.

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