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VISUALIZATION KEY BLOCK ANALYSIS USING QUICK EVALUATION METHOD FOR DISCONTINUOUS BY VISION METROLOGY IN TUNNELS

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In this paper, a new visualization key block analysis method using quick evaluation method for discontinuities by vision metrology developed by the authors is proposed as a stability evaluation method in tunnels. To demonstrate the validity of this method, the model experiment of non-targeted measurement method by vision metrology is performed, and the vision metrology results are compared and investigated with results measured directly with a clinometer. In order to demonstrate the applicability of this proposed method, the visualization key block analysis method is applied to the tunnel based on non-targeted measurement by vision metrology, and the key blocks are predicted before the tunnel excavation.

Key Words : *visualization key block analysis, discontinuity, non-targeted measurement, vision metrology, tunnel*

1. INTRODUCTION

When the rock mass is excavated, the new shape of block appears on the excavated surface. The block theory was suggested by Goodman and Shi[1]). The thrust of the block theory is to produce techniques to specify the critical discontinuity blocks intersecting excavation. Excavations in discontinuous rock masses are frequently affected by key blocks[2]). The key block analysis is extremely helpful in studying the design of excavation and support requirements.

Rock masses in nature include various discontinuities such as joints, faults, bedding planes, fractures, cracks, fissures, schistosities and cleavages[3), 4)]. In general, discontinuities can vary from a few centimeters to many meters. The behavior of structures in hard rocks, therefore, is mainly controlled by numerous discontinuities[5)-8)].

For their design and construction to be efficient and safe, getting rock discontinuity data is a mandatory step in design and construction of rock structures. In spite of crucial needs, rock discontinuity investigation usually has not been done accurately and on a wide-range, because it requires experts and time to measure discontinuities.

In order to save the investigation time and to be able to be used easily by anyone without expertise, non-targeted measurement by vision metrology is suggested in this paper. It is expected to efficiently solve the problem of cost and time delays. In this study, a new visualization key block analysis method using quick evaluation method for discontinuities by vision metrology developed by the authors is proposed as a stability evaluation method for observational design and construction method in tunnels.

The process of the new visualization key block analysis method using quick evaluation method for discontinuities by vision metrology consists of five steps:

(1) Field work,
(2) Visual database,
(3) Analytics,
(4) Three-dimensional modeling,
(5) Key block analysis.

To demonstrate the validity of this method, the model experiment of non-targeted measurement method by vision metrology is performed. In order to demonstrate the applicability of this proposed method to the stability evaluation for observational design and construction method in tunnels, the visualization key block analysis method is applied to the tunnel based on non-targeted measurement by vision metrology.

2. FIELD WORK

The first step in any vision metrology project is to collect data in the field. This involves two main things: establishing a network of control points to establish a reference system between the images and the real world, and taking the actual images of the tunnel excavating face. It is not uncommon to acquire many images, using a single camera and laptop computer, and have these images uploaded and reviewed before leaving the field.

The photography step is very simple. Simply image the area or object of interest. As long as it can be seen, it can be measured. Digital cameras, film cameras, or video can be used. The most efficient procedure is using digital cameras.

In addition to images, some known scale information (distances, angles, etc.), or control (X, Y, Z) is required. We can use known distances (tape measure or scale rods), survey control points with total stations, or just approximate control based on known items in the images.

3. CREATE VISUAL DATABASE

The step required for image processing is dependant on the choice of cameras, and the accuracy required for the final measurements. Digital cameras streamline this process. They do not require scanning or reseau measurement. Additionally, digital images allow for image editing to correct for exposure problems, whereas film does not.

At the result of the vision metrological processing, all of the camera positions are known. Knowing this, and having the image, any object visible in the picture can be measured or modeled. In effect, the entire project area is available on the computer and can easily be measured by pointing at the picture. The visual database provides ease of measurement and reduced field time.

This visual database provides many benefits:

① Reduces the need to generate 3D models.
② All visible items can be measured, without being in the field, or requiring physical access.
③ The field locations, measurements, etc. can be gotten, when they are needed.

In process of data reduction, two-dimensional image coordinates of object points are transformed into three-dimensional spatial coordinates in object space for purpose of measurement. A reasonable method of data reduction must be chosen for this data transformation. Bundle adjustment method is the most versatile and accurate vision metrological positioning method adopted for data reduction. In this section, an available data reduction method named bundle adjustment method is summed up and evaluated. Bundle adjustment method is adopted for use of precise data reduction. The ground supporting the utilization of this method is analyzed.

DLT (Direct Linear Transformation) method was suggested by Abdel-Aziz and Karara[9]. Vision metrology is a process to obtain 3D coordinates of an object point (X, Y, Z) in an object coordinate system from its 2D coordinates of measured image point (x_c, y_c). For this purpose, the central work of Vision Metrology becomes to find the unique relationship between above 2 coordinate systems, that is, to determine the transformation coefficients $A_1 \sim A_{11}$. The process to obtain these coefficients is called orientation.

However, DLT method holds a number of disadvantages.

① Accuracy is lower; DLT is a linear treatment of what is essentially a non-linear problem so it gives approximate results. Only nine of eleven parameters are independent. The disadvantage of such redundant parameterization is that erroneous combination of these parameters can still make a good fit between experimental observations and model prediction in real situation when the observation is not perfect. This means the accuracy potential is limited in noisy situations. The other reason to cause the lower accuracy is that lens distortion cannot be considered. Many investigators have found that ignoring lens distortion is unacceptable when doing 3D measurement[10]. The extension of DLT does incorporate distortion parameters, the method has become nonlinear optimization instead of a closed-form solution.

② Analysis stability is bad; because only part of unknown parameters is independent, the precision of recovery of the parameters is typically considerably lessened.

③ Orientation parameters associated with interior geometry of camera (interior orientation parameter) can not be calibrated in off-line way.

④ Self-calibration can not be used. When the parameters of interior orientation and distortions are determined by utilizing the geometric strength of overlapping images without resort to any kind of additional object-space control, the solution is called self-calibration method. The closed-form solution of DLT needs object-space control.

The most versatile and accurate vision metrological positioning method is bundle adjustment. It was developed in the early 1950's[11]. The technique has been systematically refined up to a point where relative accuracies exceeding 1 part in 1,000,000 are achieved with film based cameras.

The same techniques have been applied to the calibration of CCD cameras and positioning since many years ago. The geometric quality of solid state imaging sensors could already be verified in some tests, where an accuracy of up to 1/50 of the pixel spacing was achieved with a 3D test field in 1987 [12]. The versatility of the methods was demonstrated among applications in high-speed robotics and under adverse industrial conditions.

In bundle adjustment method, all orientation parameters and space coordinates of points are determined simultaneously. The general collinearity equations are adopted directly as the determination equations. The adjustment procedure will be described in following sections.

To take metric camera as example, orientation parameters are $(\omega_1, \varphi_1, \kappa_1, X_{01}, Y_{01}, Z_{01})$ for left image and $(\omega_2, \varphi_2, \kappa_2, X_{02}, Y_{02}, Z_{02})$ for right one. The general collinearity equations are written down together for a stereo pair of pictures in the form:

$$x_i = -c_i \frac{a^i_{11}(X - X_{0i}) + a^i_{12}(Y - Y_{0i}) + a^i_{13}(Z - Z_{0i})}{a^i_{31}(X - X_{0i}) + a^i_{32}(Y - Y_{0i}) + a^i_{33}(Z - Z_{0i})}$$

$$y_i = -c_i \frac{a^i_{21}(X - X_{0i}) + a^i_{22}(Y - Y_{0i}) + a^i_{23}(Z - Z_{0i})}{a^i_{31}(X - X_{0i}) + a^i_{32}(Y - Y_{0i}) + a^i_{33}(Z - Z_{0i})} \qquad (1)$$

$$(i = 1,2)$$

where

Table 1 Equations and unknowns for vision metrology of a pair of images.

	No. of Equations	No. of Unknowns	
	Equation (1) for 5 object points 20	$(\omega_1, \varphi_1, \kappa_1, X_{01}, Y_{01}, Z_{01})$ $(\omega_2, \varphi_2, \kappa_2, X_{02}, Y_{02}, Z_{02})$	12
		Coordinates of object points	8
Total	20	20	

$$\begin{bmatrix} a^i_{11} & a^i_{12} & a^i_{13} \\ a^i_{21} & a^i_{22} & a^i_{23} \\ a^i_{31} & a^i_{32} & a^i_{33} \end{bmatrix} = \begin{bmatrix} \cos\kappa_i & \sin\kappa_i & 0 \\ -\sin\kappa_i & \cos\kappa_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_i & \sin\omega_i \\ 0 & -\sin\omega_i & \cos\omega_i \end{bmatrix} \begin{bmatrix} \cos\varphi_i & 0 & -\sin\varphi_i \\ 0 & 1 & 0 \\ \sin\varphi_i & 0 & \cos\varphi_i \end{bmatrix}$$

$$(i = 1,2)$$

Equation (1) includes mathematically one equation equivalent to the coplanarity condition of corresponding rays. Thus, five coplanarity equations are obtained when Equation (1) is set up with five object points mathematically required in which only two points and one height are given as control points. Having five object points, total 20 equations are obtained (**Table 1**). In 5 object points, 8 unknowns of coordinates of object points exist. So, there are total 20 unknowns (12 coefficients of the general collinearity equations for the stereo pair and 8 unknown coordinates of object points). The necessary orientation parameters can be determined for the unique determination of all imaged object points. In fact, more than two points and one height are used as control points or more than 5 object points are treated by use of least squares method. That all orientation parameters and space coordinates of points are determined simultaneously makes the method to be a simpler and more attractive method.

When there are a lot of object points imaged and/or more than two points and one height used as control points, least squares method is used to determine simultaneously all orientation parameters and space coordinates of points.

Bundle adjustment method holds a number of advantages.

① Higher accuracy.

② Flexibility resulting from an ability to combine vision metrological and surveying observations simultaneously in the adjustment.

③ Lack of necessity to provide highly redundant object space control especially when free-net solution is incorporated.

④ Modeling of systematic errors such as lens and film distortion without recourse to making specific additional observations for this purpose; self-calibration can be incorporated to form self-calibration bundle solution.

⑤ Strong agreement between estimates of precision as given by statistical indicators such as root-mean-square (RMS) errors and accuracy determined with respect to check-point control.

4. ANALYTICS

This analytics step is step to calculate strike and dip from the points distributed in the tunnel excavating face. In this study, bundle adjustment solution is exploited. The general collinearity equations adopted are non-linear function of unknowns of orientation parameters and coordinates of object point. The process of data reduction of 3D coordinates of targets is a nonlinear optimization problem solved by Least Squares Method (LSM).

LSM is widely used in vision metrology where more measurements are available than the minimum necessary to evaluate the unknown elements. LSM provides a systematic method for computing unique values of coordinates and other elements in vision metrology based on a large number of redundant measurements of different kinds and weights. This allows for covariance matrices of estimates to be readily derived from the covariance matrix of the measurements. If a covariance matrix of the measurements is assumed, a priori analysis can be used to design a camera/object configuration and measurement scheme to meet criteria relating to precision, reliability and accuracy. This attribute of LSM is particularly useful in vision metrology where almost every measurement task has unique features. LSM is also flexible: it allows elements to be treated as unknowns, or as measurements, or as constants depending on circumstances; and algorithms within a LSM process can be devised so suit particular measurement tasks.

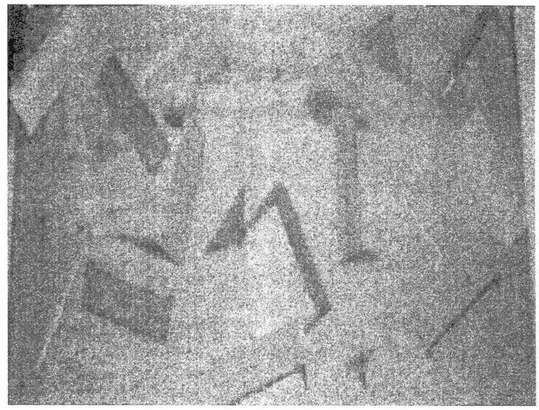

Photo 1 Experiment field measured by a clinometer.

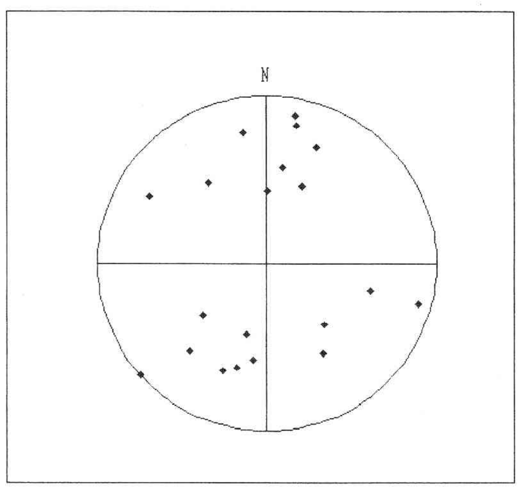

Fig.1 Schmidt net of discontinuities measured by a clinometer.

5. THREE-DIMENSIONAL MODELING

At this step, orientation, location, persistence, intensity, etc. of discontinuities in the tunnel excavating face can be measured, and geometries determined. The information can be used to create three-dimensional rock discontinuity model. The model region in this study is a closed domain with a certain number of faces. Model region may be of any shape closed by polygons. The excavation faces may be convex or concave polygonal faces.

6. MODEL EXPERIMENT OF NON-TARGETED MEASUREMENT BY VISION METROLOGY

The non-targeted measurement method by vision metrology is proposed and discussed. In this section, the model experiment results are presented. The vision metrology results are compared and examined with results measured directly with a clinometer. Each stage of the measurement system is examined through real survey task. The stages of non-targeted measurement method include field work, visual database and analytics.

A tunnel excavating face model with a size 1800 mm by 900 mm is taken as a measurement object (**Photo 1**). **Fig.1** shows the schmidt net of discontinuities measured by a clinometer. The non-targeted measurement of strike and dip by vision metrology are carried out on the experiment field. The measurement results by vision metrology are presented in this section.

The camera used in this work was a NikonD1 with color CCD sensor having 2000×1312 elements. **Fig.2** shows camera station geometry for this ex-situ experiment. The equations of planes by LSM are calculated.

To demonstrate the validity of the proposed non-targeted measurement method by vision metrology, strike and dip measurement by a clinometer is performed, and then the vision metrology results are compared and examined with results measured directly with a clinometer. **Fig.3** shows the schmidt net of discontinuities detected by quick evaluation method. The non-targeted measurement method by vision metrology shows a good match with results measured directly with a clinometer as shown in **Fig.1** and **Fig.3**.

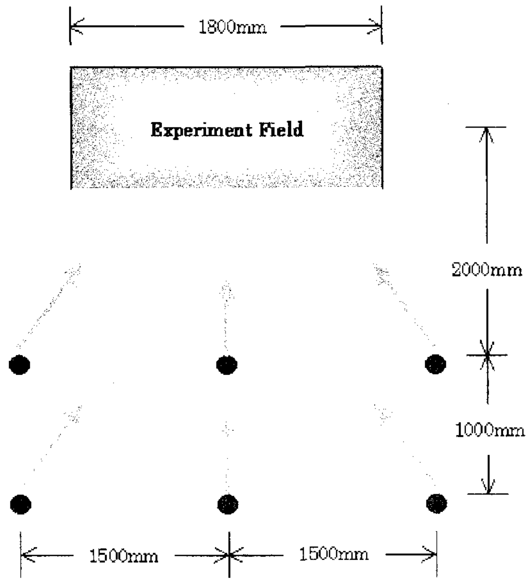

Fig.2 Camera station geometry.

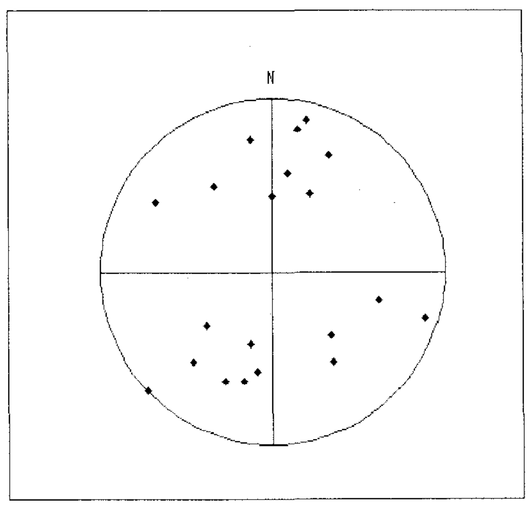

Fig.3 Schmidt net of discontinuities detected by quick evaluation method.

7. APPLICATION OF VISUALIZATION KEY BLOCK ANALYSIS TO TUNNEL

In order to illustrate the applicability of the suggested method for a stability evaluation in tunnel constructions, the removability and stability analyses of rock blocks detected by using non-targeted measurement by vision metrology are performed. The tunnel was modeled as shown in **Fig.4**.

Table 2 shows the number of formed blocks and key blocks predicted in this tunnel. 25 formed blocks were predicted in this tunnel. Nine key blocks were predicted in this tunnel. Key block No.1 predicted in this tunnel are shown in **Fig.5**.

8. CONCLUSIONS

In this paper, a new visualization key block analysis method using quick evaluation method for discontinuities by vision metrology has been proposed as a stability evaluation method for observational design and construction method in tunnels. The advantages of convenience, efficiency and high accuracy are stressed.

The process of the new visualization key block analysis method using quick evaluation method for discontinuities by vision metrology consists of five steps:

(1) Field work,
(2) Visual database,
(3) Analytics,
(4) Three-dimensional modeling,
(5) Key block analysis.

By using the above-mentioned process, the new visualization key block analysis method using non-targeted measurement by vision metrology in tunnels is suggested in this study.

To demonstrate the validity of this method, the model experiment of non-targeted measurement method by vision metrology is performed, and the vision metrology results are compared and investigated with results measured directly with a clinometer. To demonstrate the applicability of this proposed method to the stability evaluation for observational design and construction method in tunnels, the visualization key block analysis method is applied to the tunnel based on non-targeted measurement by vision metrology, and the key blocks are predicted before the tunnel excavation.

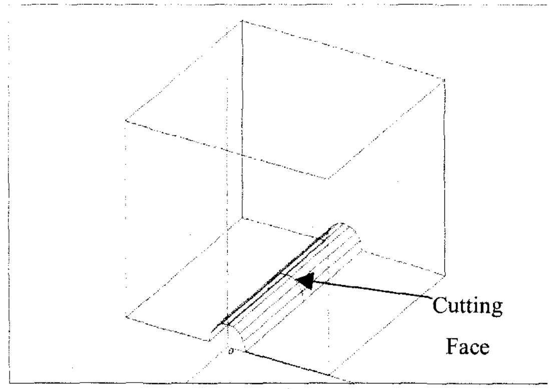

Fig.4 Modeling of tunnel.

Table 2 Number of formed blocks and key blocks.

Number of formed blocks	25
Number of key blocks	9

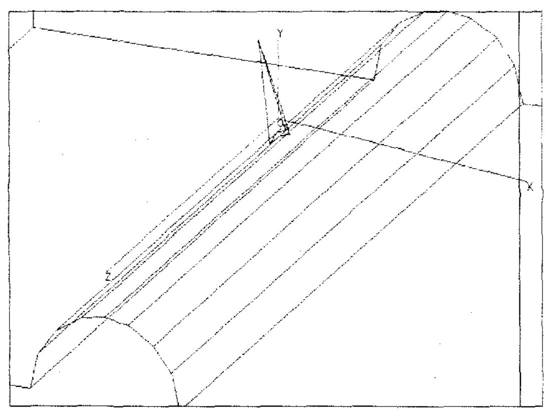

Fig.5 Place the caption below the drawing.

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