QUICK EVALUATION METHOD FOR DISCONTINUITY PROPERTIES BY VISION METROLOGY FOR OBSERVATIONAL DESIGN AND CONSTRUCTION METHOD IN TUNNELS
トンネルの情報化設計施工のためのデジタル画像計測法を利用した不連続面特性の迅速評価手法

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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. The advantages of convenience, efficiency and high accuracy are stressed. In this study, a new quick evaluation method for discontinuity properties by vision metrology developed by the authors is proposed as a stability evaluation method for observational design and construction method in tunnels. The new evaluation method is particularly useful for stability evaluation in the often confined and uncomfortable tunnel environment. To demonstrate the validity and applicability of this method, the method is applied to the tunnel based on non-targeted measurement by vision metrology, and the vision metrology results are compared and investigated with results measured directly with a clinometer.

Key Words: Quick Evaluation Method, Discontinuity Properties, Non-Targeted Measurement, Vision Metrology, Observational Design and Construction Method, Tunnel

1. Introduction

Excavations in discontinuous rock masses are frequently affected by key blocks, which are critical blocks of rock bounded by discontinuities and excavation surfaces. Block theory (Goodman and Shi, 1985) is a geometrically based set of techniques that determine where dangerous blocks can exist in a geological material intersecting by variously oriented discontinuities in three dimensions.

For their design and construction to be efficient and safe, getting rock discontinuity orientation data is a mandatory step in both design and construction of tunnels, underground structures, rock slopes, etc. It is found to be particularly essential to continue the investigation of rock discontinuity during the entire stage of tunnel construction where rock characteristics can change dramatically in ways different from the preliminary inspection.

To know the properties of discontinuities is important because discontinuities are usually the spots where the breakdown of a rock structure has occurred. Orientation, spatial location, persistence and aperture are important properties of discontinuities to expect the breakdown and prevent it from failure in advance. Measurement is a key element for observation design and construction control system in tunnels. The comparison among the different methods used for rock measurement is summarized in Table 1. In spite of crucial needs, rock discontinuity investigation is usually not done accurately and on a wide-range, because it requires experts for mapping and time to measure dip and dip-direction for major discontinuities. In the case

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that additional investigation is needed in the construction stage, it causes a construction time delay. To save investigation time and 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 many cases.

Table 1 Comparison among the Methods Used for Rock Measurement

	Cost	Applicability	Convenience	Accuracy
Convergence measure	×	×	×	○
Electro-optical distance measuring instruments	×	○	×	×
GPS	×	×	○	○
Fiber optics technique	×	○	○	△
Digital theodolite	×	×	×	○
Vision metrology	○	○	○	○

In this study, a new quick evaluation method for discontinuity properties by vision metrology developed by the authors is proposed as a stability evaluation method for observational design and construction method in tunnels. The new method is particularly useful for stability evaluation in the often confined and uncomfortable underground environment. The advantages of convenience, efficiency and high accuracy of strike and dip measurements are stressed. In order to illustrate the validity of the method to stability evaluation in tunnel constructions, the model experiment of non-targeted measurement method by vision metrology is performed, and the vision metrology results are compared and examined with results measured directly with a clinometer.

The process of the new quick evaluation method for discontinuity properties by vision metrology consists of five steps:

(1) Field Work.

(2) Visual Database.

(3) Analytics.

(4) Three-Dimensional Modeling.

(5) Key Block Analysis.

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.

The most versatile and accurate vision metrological positioning method is bundle adjustment. It was developed in the early 1950's (Brown, 1958). 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 (Beyer). 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:

$$\begin{aligned} x_i &= -c_i \frac{a_{11}^i(X - X_{0i}) + a_{12}^i(Y - Y_{0i}) + a_{13}^i(Z - Z_{0i})}{a_{31}^i(X - X_{0i}) + a_{32}^i(Y - Y_{0i}) + a_{33}^i(Z - Z_{0i})} \\ y_i &= -c_i \frac{a_{21}^i(X - X_{0i}) + a_{22}^i(Y - Y_{0i}) + a_{23}^i(Z - Z_{0i})}{a_{31}^i(X - X_{0i}) + a_{32}^i(Y - Y_{0i}) + a_{33}^i(Z - Z_{0i})} \end{aligned} \qquad (i = 1,2) \qquad (1)$$

where, $$\begin{bmatrix} a_{11}^i & a_{12}^i & a_{13}^i \\ a_{21}^i & a_{22}^i & a_{23}^i \\ a_{31}^i & a_{32}^i & a_{33}^i \end{bmatrix} = \begin{bmatrix} \cos\kappa_i & \sin\kappa_i & 0 \\ -\sin\kappa_i & \cos\kappa_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_i & \sin\omega_i \\ 0 & -\sin\omega_i & \cos\omega_i \end{bmatrix} \begin{bmatrix} \cos\varphi_i & 0 & -\sin\varphi_i \\ 0 & 1 & 0 \\ \sin\varphi_i & 0 & \cos\varphi_i \end{bmatrix} \qquad (i = 1,2)$$

Table 2 Equations and Unknowns for vision metrology of a Pair of Images

	Number of equations	Number 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	

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 2). 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.

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.

Photo 1 Experiment Field

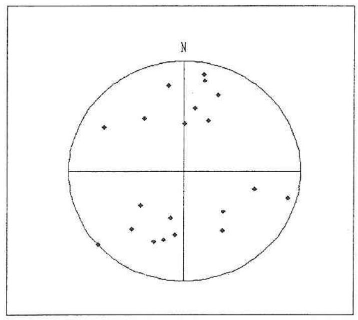

Fig.1 Schmidt Net of Discontinuities Measured by a Clinometer

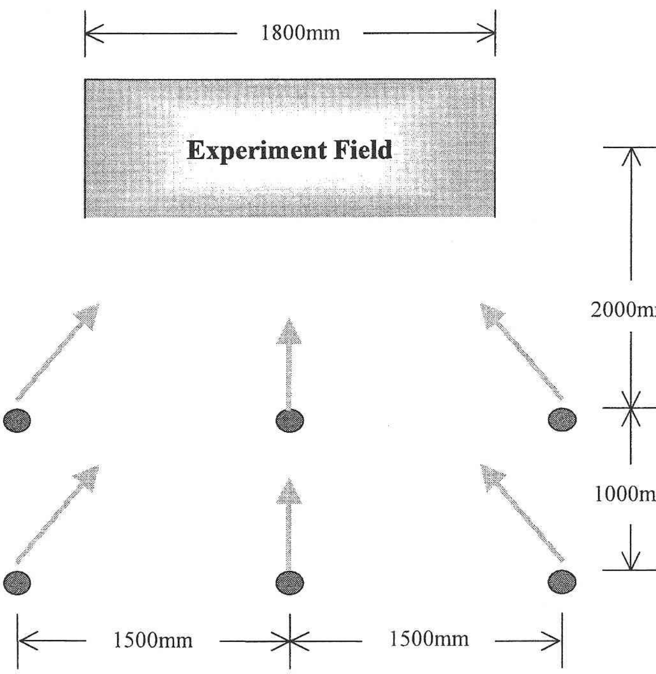

Fig.2 Camera Station Geometry

A tunnel excavating face model with a size 1800 mm by 900 mm is taken as a measurement object (Photo 1). 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.

In order to illustrate the validity and applicability 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 vision metrology. Fig.1 shows the schmidt net of discontinuities measured by a clinometer. 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.

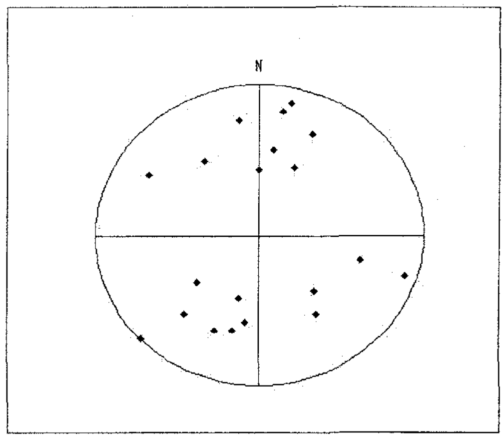

Fig.3 Schmidt Net of Discontinuities Detected by Vision Metrology

7. Conclusions

In this paper, a new quick evaluation method for discontinuity properties by vision metrology has been proposed as a stability evaluation method for observational design and construction method in tunneling.

The process of the new key block analysis method using non-targeted measurement 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 quick evaluation method for discontinuity properties by vision metrology is suggested in this study.

The method suggested in this paper is applied to the tunnel based on non-targeted measurement by vision metrology. The results have confirmed the applicability of the suggested method for observational design and construction method in tunnels.

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