Deformation Monitoring of Large Tunnel Wall under Construction by Digital Photogrammetry measurement at Ritto Tunnel

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ABSTRACT: The second Meishin (Tokyo-Kobe) highway that will be the most important to Japanese economy in the 21st century, is under construction. In this highway tunnels are the major structures which go through many mountainous areas. The standard cross-section of the tunnel in this highways is very large(250m^2)compared to ordinary tunnels and the tunnel width is very wide(18m). The tunnel is first bored by 5m diameter TBM and it is enlarged later. Photogrammetry measurement with a CCD camera is applied to deformation monitoring of large tunnel. Tunnels on construction sites like highways must be carefully and continuously observed for deformation during construction. Although geology is granite, it has many fractures under Tectonic process in Japan. In the tunnel, the fractured zone was detected widely by investigation by TBM pilot tunnel, we needed to check the stability of tunnel wall after enlarge section process. Conventionally proposed monitoring methods include total station. However, none of these are widely employed because of poor workability, insufficient precision and/or high running cost under tunnel work. For this reason, it decided to apply precision photogrammetry and the technique of investigating the tunnel deformation of the whole visually by three dimensions was developed. The reflective target of 121 or more sheets was stuck on tunnel wall, by taking a photograph, the 3-dimensional coordinates of a target were acquired and deformation of tunnel wall was visualized. In this paper, we show an example of the result.

1 INTRODUCTION

1.1 *Ritto Tunnel*

Ritto Tunnel construction site located in Kinki District include KIX (Kansai Airport) shown in Figure 1. A mountainous region around the tunnel is 300 to 600 meters above the sea level and a comparatively gentle slope is seen at the summit of the mountain. In addition, steep V shape valley develops along swamp and river around the tunnel. The geology of the tunnel mainly consists of biotite granite of the latter period of Cretaceous period called Tanakami granite, which is fresh and hard. Maximum unconfined compressive strength is 100 MPa and seismic velocity is more than 4.7 kilometers per second. However, a lot of small scale faults and fractures are distributed in this area. Longitudinal geological section is shown in Figure 2.

1.2 *Approach using Photgrammetry*

Photgrammetry with a CCD camera is applied to deformation monitoring of tunnels. Tunnels on construction sites like highways must be carefully and continuously observed for deformation at least during construction and, depending on the circumstances, for several months after completion. Conventionally proposed monitoring methods include total station, GPS and an optical fiver strain sensor. However, none of these are widely employed because of poor workability, insufficient precision and/or high running cost.

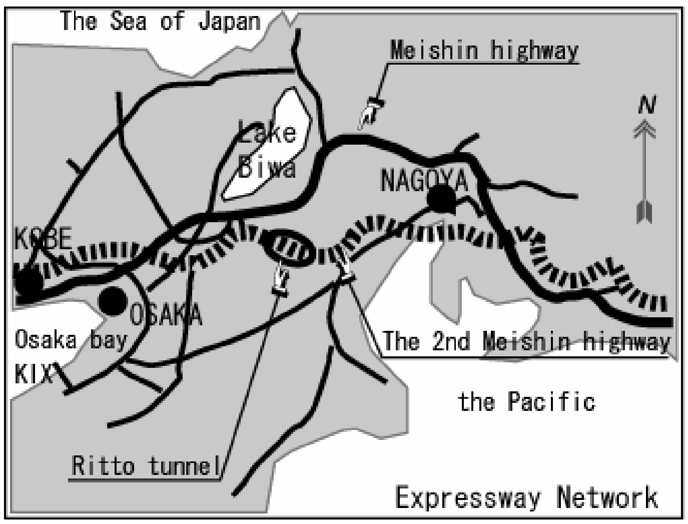

Figure 1. Location of Ritto Tunnel.

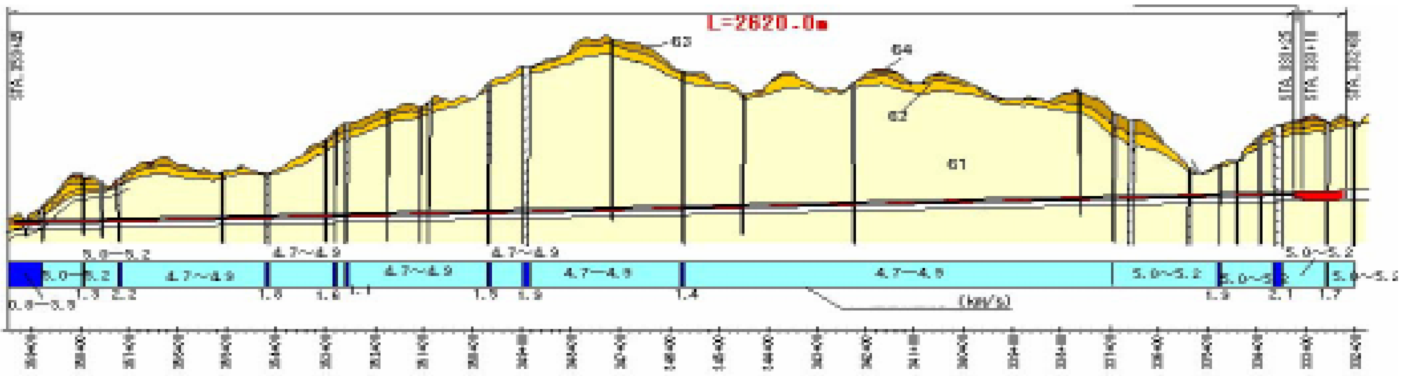

Figure.2 Geological Section. Geology is Granite. Solid lines are faults.

This paper discusses monitoring of tunnel deformations by photgrammetry with a CCD camera. Reflective targets are placed over a tunnel wall, and their object coordinates are measured by a photogrammetric technique. Their displacements are then statistically detected every two epochs of time. Since it is usually hard to deploy long scales at construction sites, an observation equation has been developed to detect target displacements without the need for scales. At every time epoch, object coordinates of targets are independently adjusted by a free-network. Parameters for detecting displacements are tested, in which the inconformities of coordinate systems are incorporated in test equations.
The strengths of the observation networks are compared by simulation and validated by experiments using a model space on a reduced scale of 1/20. In a typical case, 3mm target displacement over a 20m x 30m tunnel wall are proved to be detectable.

2 MEASUREMENT BY PHTOGRAMMETRY

The procedure for digital photogrammetry is generally illustrated in Figure 3.

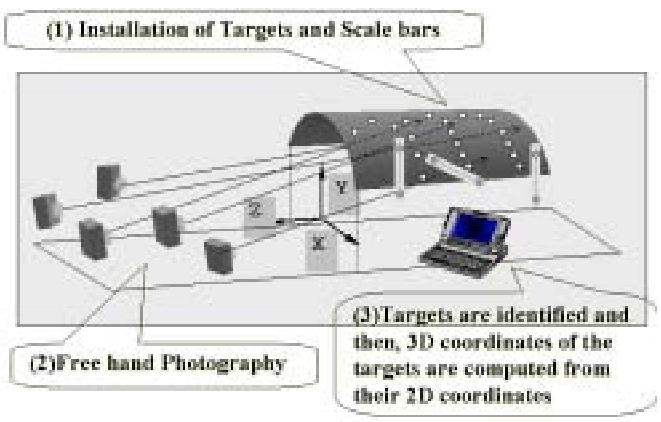

Figure 3. Procedure of measurement

In order to measure the displacements, we need to install the targets that can reflect the flashlight of camera as shown in Figure 4. The fundamental mathematical model of digital photogrammetry is an optical triangulation that describes the perspective transformation from two dimensional image coordinates into three dimensional object space coordinates. The ultimate extension of the principles is to adjust many photogrammetric measurements to ground control values in a single solution known as a bundle adjustment. The analytical process is so named because of the many lights rays that pass through each lens position constituting a bundle of rays. Any object point can be determined as the intersection of the corresponding rays from each of many images.

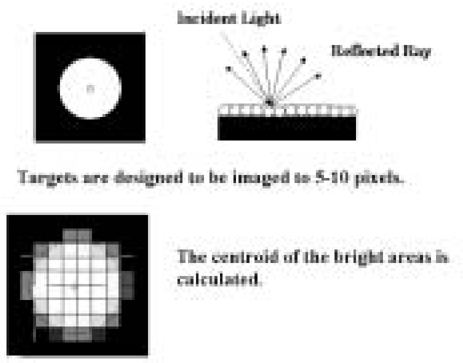

Figure 4. Target that we install on the object

All parameters describing the perspective transformation process can be also determined without prior knowledge of camera positions and calibration parameters.

The computational model of the bundle adjustment is based on the well-known collinearity equations as shown in Figure 5.:

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

where x and y are the observed image coordinates; X_0,Y_0,Z_0 and X,Y,Z are the object space coordinates of the camera positions and object points, respectively; the a's are functions of three rotation angles of each image; $\Delta x, \Delta y$ and c are the interior orientation elements; Δx and Δy are perturbation parameters which describe departures from collinearity due to lens distortion and in-plane and out-of-plane image distortion, c being the focal length. This model including the interior orientation elements is known as a self-calibrating bundle adjustment. This method has the advantage of obtaining high photogrammetric accuracies with cameras having unknown calibration parameters.

The collinearity equations can be recast into the following observation equations by linearization:

$$v = A_1X_1 + A_2X_2 + \Delta \qquad (2)$$

where A_1,A_2 are the design matrices of the unknown exterior orientation elements, vector X_1, and object point coordinates, X_2; Δ is the discrepancy vector, v is the vector of image coordinate residuals. Solution for X_1 and X_2 is according to the method of least-squares.

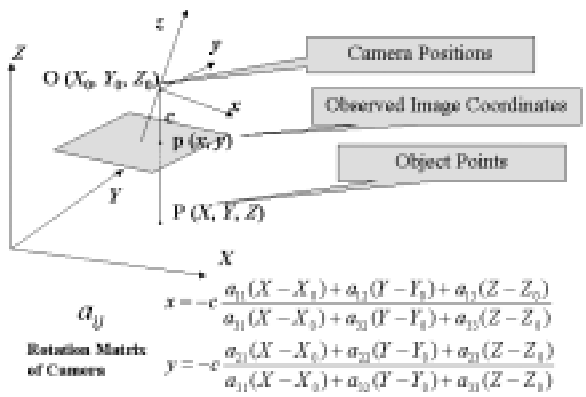

Figure 5. The concept of collinearity equations

3 TUNNEL EXCAVATION SYSTEM

The first excavation procedure at Ritto tunnel was bored by TBM shown in Figure 6. First, after TBM pilot tunnel was excavated, main tunnel is enlarged with NATM method. Before excavating a main tunnel, support pattern for the big section is designed based on the actual TBM excavation results. When we discover unstable blocks or zones of the main tunnel, additional reinforcement was applied. The procedure of this excavation system is shown in Figure 7.

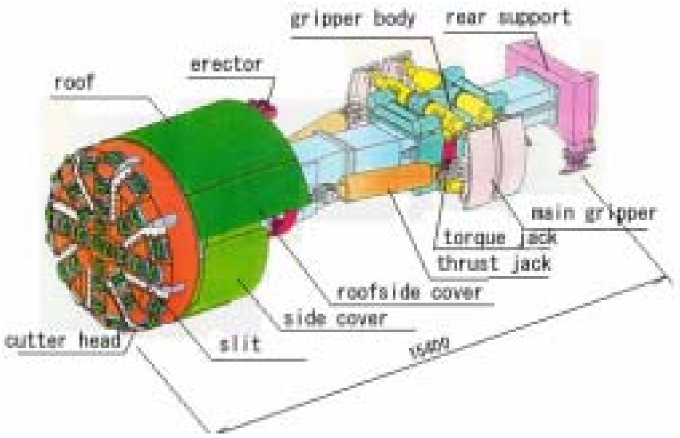

Figure 6. Tunnel Boring Machien

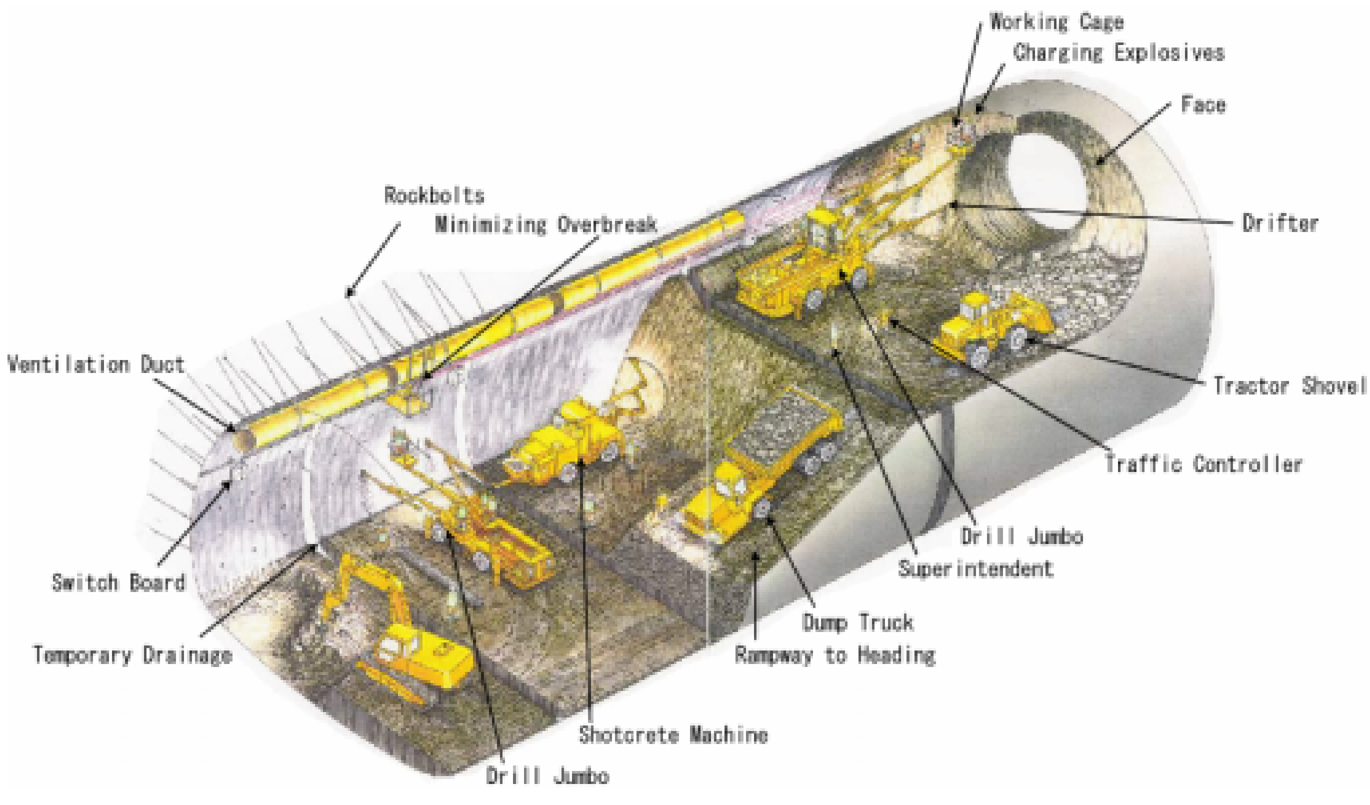

Figure 7. Procedure of TBM and enlargement system of large tunnel

4 FIELD EXPERIMENT AT RITTO TUNNEL

4.1 *The observational zone of the tunnel*

As shown in Figure 8, several discontinuous zone alternated with hard part of granite. Weak discontinuous zone classified D class shown as orange parts and especially claylike zone is colored by sky blue area located center part of tunnel along with the tunnel line. We observed these STA349+15～STA349+35(20m long).

The rock masses have bedding joint planes and also faults that are developed along with tunnel line. The geological property thus indicates that a sheared rock mass model should be applied for this site.

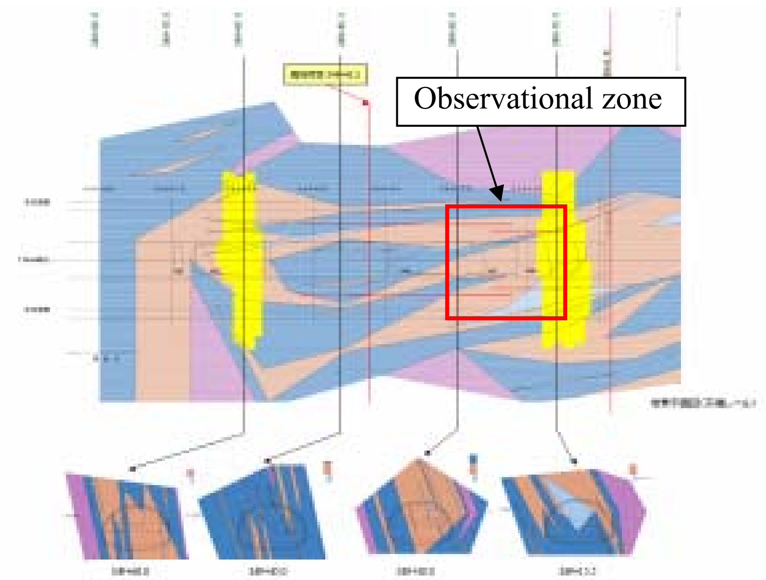

Figure 8. Geological Plan and Sections nearby Target zone. Purple: B class, Blue: C class, Orange: D class, Sky Blue: Weathered(Clay)

4.2 *Photogrammetry-based Observed Tunneling*

We applied enough rockbolts to the weak zone which observed large deformation for the excavation of upper part of the tunnel. However, since cutting face is very large, observational method was indispensable. In case of space of discontinuity is narrower than observational points as shown in Figure.9 and 10, we could not recognize failure. For this reason, it decided to install many targets to observe deformation of the tunnel wall in the process of excavation of remaining bottom section. It determined to apply digital precision photogrammetry so that the monitor of the deformation of the whole surface of the tunnel wall can be carried out in detail. With regard to the unstable blocks identified in the block analysis and the block borders, i.e. faults, displacements of rock masses were monitored by photogrammetry right below the observational zone as shown in Figure.10.

During the observation procedure, 121 targets placed tunnel wall were photographed by the digital photogrammetry technology, each time when the cutting face progressed by excavation of bottom section.

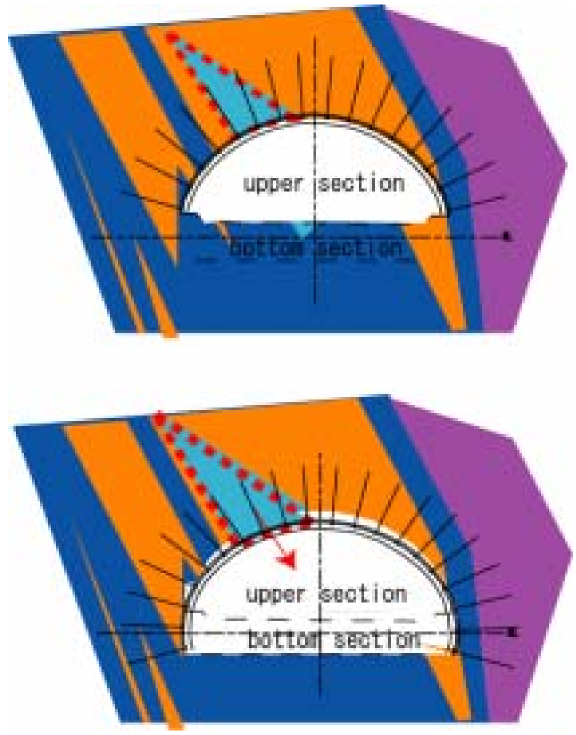

Figure.9 Excavation procedure and increasing risk for block failure

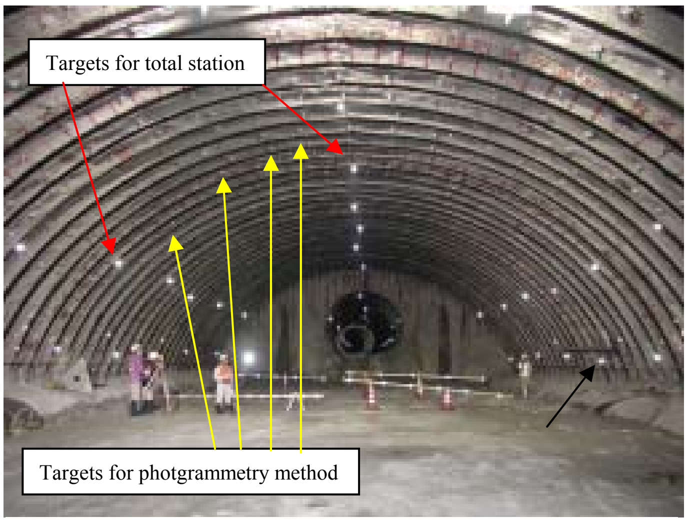

Figure 10. Setting of photogrammetry targets

(1) Photographing Equipment

Nikon D1 camera and a 18mm lens of the same manufacturer were selected. Nikon SB-28DX Speedlight Flash was used inside the TBM pilot tunnel.

(2) Targets

After selecting the camera and lens, the diameter of targets was determined according to the measured distance to ensure the images of the targets could come out in 5 pixel or larger in diameter. The diameter was set at 30mm here, and the targets were placed every 2m (11 targets in the transversal circumference direction) or 2m (11 targets in the longitudinal direction). As a result, 40 targets were photographed per image on average, which was sufficient for use in the analysis. An example of target layout is shown in Figure.11.

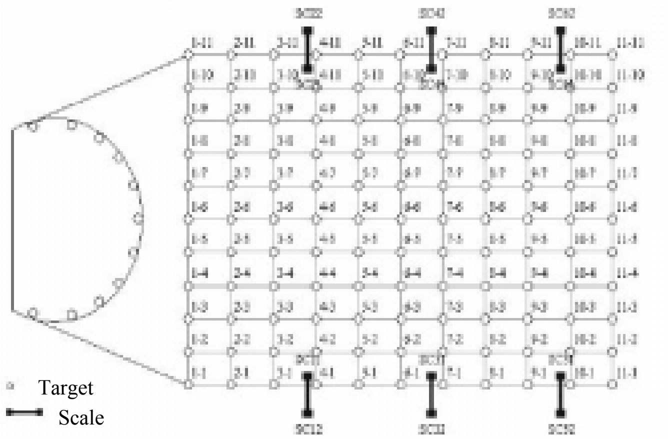

Figure.11 Target Layout

(3) Installation of Scales

At the Ritto Tunnel, it was difficult to install scales for external measurement due to such restrictions as the photographing cycle and the access from cutting face during the excavation work. It would be often the case in a tunneling work that there are no external fiducial points. Therefore, six to ten 1m-long fiducial scales were prepared and installed.

(4) Photographing Conditions

The lens stop was set at F22 at maximum. The infinite focus was selected. The shutter speed and ISO sensitivity were set at 1/250 and 200, respectively.

Photographs were taken for every 6m at 3 points each at both upper and lower locations for each transversal direction.

4.3 *Result of Observed Tunneling*

The estimated accuracy was about 0.5mm shown as Table.1, This must be considered of good quality, given the unfavorable condition of on-site photographing during the tunneling work.

Table.1 Precision of image coordinate measurements

date	Estimated accuracy (mm)					
	X	Y	Z	Max X	Max Y	Max Z
2002/01/06	0.307	0.185	0.362	0.881	0.422	1.514
2002/01/20	0.317	0.179	0.252	0.983	0.358	0.731
2002/02/17	0.516	0.314	0.470	1.568	0.685	1.884
2002/03/16	0.523	0.348	0.487	1.996	0.691	2.698

First, to make use of the 3-D coordinates consisting of 121 targets obtained by bundle adjustment, the displacement represented this way can compare the distance between corresponding to the convergence and roof settlement were defined, not only those on a same transversal section but also any given targets.

Once the 3-D coordinates have been obtained, various displacement diagrams can be shown by moving the view point three dimensionally on a computer screen.

As shown in Figure-12, bird views only are shown here due to space limitation. The dots in vertical and horizontal directions indicate the initial positions of photo targets. The lines extending from the initial positions represent displacement vectors. The displacements are multiplied for emphasizing purposes here. They remained within the threshold in practice, i.e. less than a few millimeters and 5mm in the horizontal and vertical directions, respectively.

The displacement, size and orientation of the rock masses were three dimensionally monitored with these diagrams. We can not detect an extraordinary rock behavior during excavation of bottom section carried out.

Figure.12 shows a region defined by as showed Figure.8, which is around the STA349+15 ～ STA349+35 section. Here, the rock mass is not showing a discontinuous behavior, with the vectors having continuous movements. There are some movements on the both-hand side of the borders due to enlargement toward bottom section, which are nonetheless considered as homogeneous movement of the rock mass as a whole.

5. CONCLUSIONS

A new control system for discontinuous rock masses has been proposed, which combines computer power and photogrammetry technologies. The effectiveness or stability of the countermeasure was proved through digital photogrammetry-based monitoring.

During enlargement sequence, many photo targets were placed in the pre-existing part of tunnel wall. The digital photogrammetry system to observe movement of pre-existing tunnel wall could tell us safety of enlargement excavation of bottom section and effectiveness of countermeasures for potential unstable rock blocks. Also this digital photogrammetry system could forecast the existence of weak zone and the information was utilized to take warning.

It was proved at this tunnel that the digital photogrammetry observation can verify the results. And according to this system a suitable construction and counter-measure method was properly decided.

This research proposes a new technology for controlling the complicated discontinuity-dependent rock mass behavior, which treats the behavior as 3-D data throughout the process from investigation to construction work using the digital photogrammetry and computer aided imaging technique. The authors believe that this research will greatly contribute to the further advancement of rock engineering.

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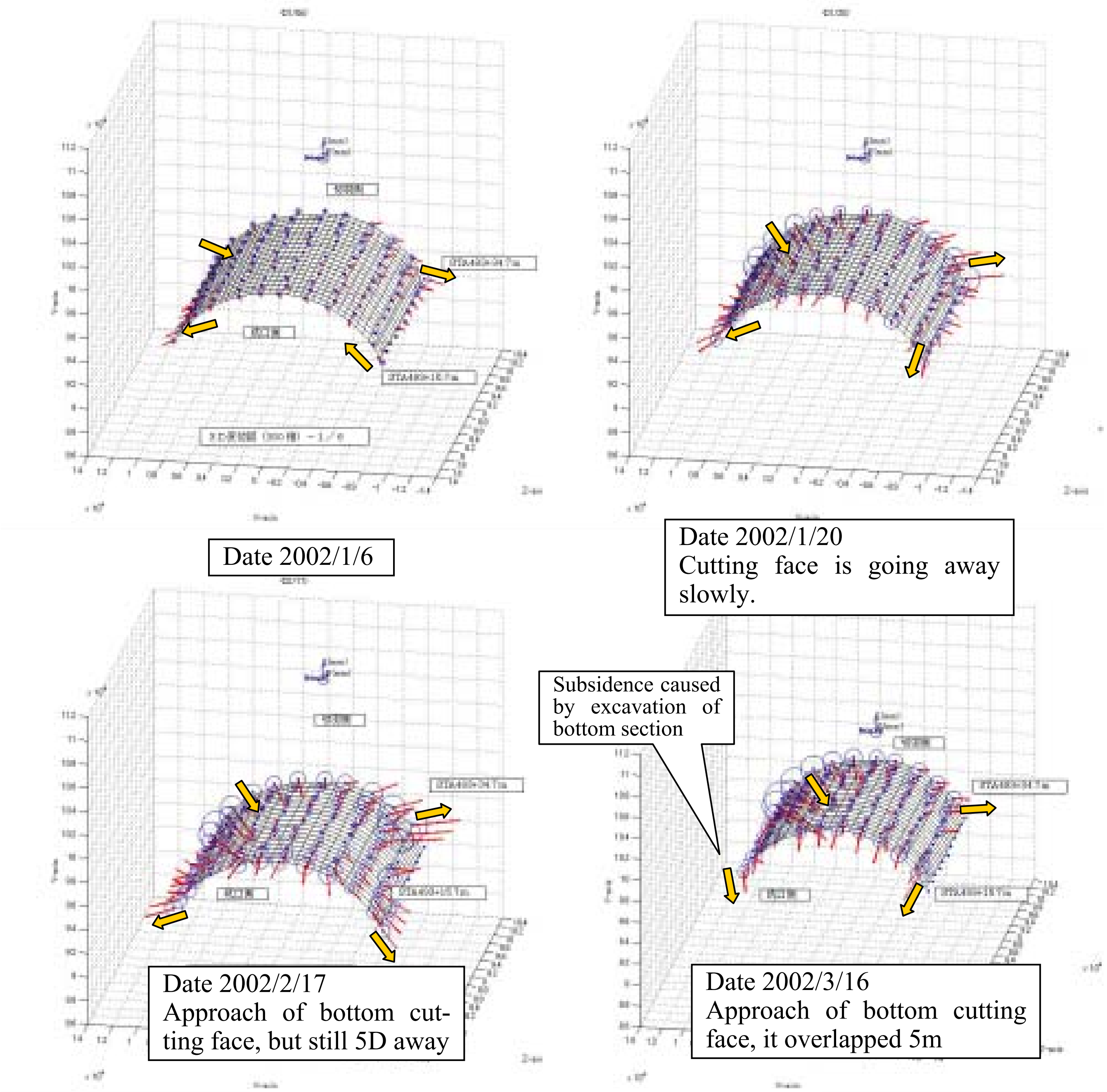

Figure.12 Results of observation at each excava-