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New Observational Design and Construction Method for Rock Block Evaluation of Tunnels in Discontinuous Rock Masses

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불연속성 암반에서의 터널의 암반블럭 평가를 위한 신 정보화설계시공법

황재윤

Abstract Rock masses in nature include various rock discontinuities such as faults, joints, bedding planes, fractures, cracks, schistosities, and cleavages. The behavior of rock structures, therefore, is mainly controlled by various rock discontinuities. In many tunnels, enormous cost and time are consumed to cope with the falling or sliding of rock blocks, which cannot be predicted because of the complexity of rock discontinuities. It is difficult to estimate the properties of rock masses before the rock excavation. The observational design and construction method of tunnels in rock masses is becoming important recently. In this paper, a new observational design and construction method for rock block evaluation of tunnels in discontinuous rock masses is proposed, and then applied to the tunnel based on actual rock discontinuity information observed in the field. It is possible to detect key blocks all along the tunnel exactly by using the numerical analysis program developed for the new observational design and construction method. This computer simulation method with user-friendly interfaces can calculate not only the stability of rock blocks but also the design of supplementary supports. The effectiveness of the proposed observational design and construction method has been verified by the confirmation of key block during the enlargement excavation.

KeyWords *Discontinuous rock mass, Observational design and construction method, Computer simulation, Key block, Tunnel*

초 록 실제 암반에는 단층, 절리, 층리, 균열, 단열, 편리, 벽개 등의 불연속면이 많이 포함되어 있다. 따라서, 불연속면이 암반구조물의 거동을 좌우하고 있다. 암반구조의 복잡성으로 인해 사전에 예측 할 수 없었던 암반의 붕락이 발생하여, 붕락대책에 막대한 비용과 시간을 낭비하는 사례가 많다. 암반 불연속면의 복잡성을 사전 조사 단계에서 충분히 파악하거나 대책을 수립하는 것은 어렵다. 최근 터널의 정보화 설계시공이 중요시되어지고 있다. 본 논문에서는 불연속성 암반에서의 터널의 신 정보화 설계시공법을 제안하고, 현지에서 관찰한 불연속면 정보를 근거로 하여 실제 터널현장에 적용했다. 실제 터널현장에 있어서, 터널의 신 정보화 설계시공법을 위해서 새롭게 개발한 수치해석 프로그램을 사용하여 정확한 키블럭 추출이 가능하였다. 사용하기 쉬운 사용자 인터페이스를 가지고 있는 본 컴퓨터 시뮬레이션 기법은 암반블럭의 안정성 계산뿐만 아니라 추가 보강대책공의 설계도 가능하다. 터널 굴착중에 키블럭을 확인하므로써, 제안한 신 정보화 설계시공법의 유효성에 대한 검증을 하였다.

핵심어 불연속성 암반, 정보화 설계시공법, 컴퓨터 시뮬레이션, 키블럭, 터널

1. INTRODUCTION

In discontinuous rock masses, rock blocks which have a variety of shapes and sizes are formed geometrically along rock discontinuities (Chikahisa et al., 1997; Ohnishi, 2000; Ohnishi, 2002; Hwang et al., 2003). Excavations in discontinuous rock masses are frequently affected by key blocks, which are critical blocks bounded by rock discontinuities and excavation surfaces (Ohnishi et al., 1985). Block theory (Goodman and Shi, 1985) is a geometry-based set of techniques that determines whether dangerous blocks can exist in a geological material intersected by variously oriented rock discontinuities in three

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dimensions. The key block analysis is very helpful in design of excavation and support requirements. The properties of rock masses are important factors relevant to the design and construction of tunnels (Hwang and Sato, 2004). In the design and construction of tunnels, the observational method has been becoming increasingly important (Hwang, 2003; Hwang et al., 2004).

This paper describes the development of a computer simulation method with user-friendly interfaces to apply the key block analysis on actual sites to investigate the stability of tunnels based on the behaviors of discontinuous rock masses and to design supplementary supports when detected blocks are unstable. A new observational design and construction method for rock block evaluation of tunnels in discontinuous rock masses is suggested, then applied to the example of the tunnel based on actual rock discontinuity information observed in the field.

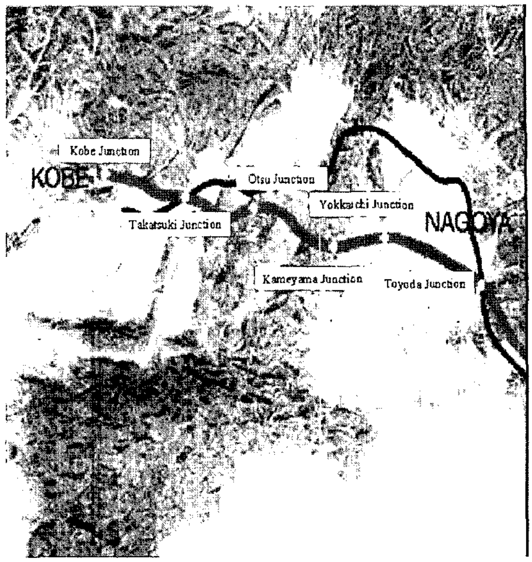


Fig. 1. Location of the study area

2. STUDY AREA AND TUNNELING METHOD

The actual example site selected in this paper is the tunnel in the New Second Meishin Expressway between Nagoya and Kobe. The new observational design and construction method for rock block evaluation of tunnels is applied to the tunnel with a large cross-section of about 200m^2. The large tunnel in the New Second Meishin Expressway is now under construction. This tunnel construction is the world's first large and long tunnel construction which is based on block theory.

The Second Meishin Expressway that will be important to the Japanese economy in the 21st century, is under construction and has been designed to enable cars to travel safely at speeds up to 140km/h, which will make it by far the fastest expressway in Japan. To accommodate for high speed driving, the curvature of the expressway becomes smaller and tunnel length becomes longer. The cross-section of the tunnel is big. The new road takes three lanes in each direction. Fig. 1 shows the location of the study area. The large tunnel in the New Second Meishin Expressway is about 4000m long and is located in Shiga Prefecture about 10km from the south end of Lake Biwa to the east-southeast. It passes through the mountain zone known as the Konan Alps.

Fig. 2 shows the standard cross-section of the tunnel. The standard cross-section of the tunnel is large (200m^2) and wide (18m) compared to ordinary tunnels. The final tunnel shape is a height to width ratio of 0.65. The 5m diameter TBM pilot tunnel is at the center in the proposed tunnel. After the TBM pilot tunnel is excavated, the main tunnel is enlarged by New Austrian Tunneling Method (NATM).

The TBM Pilot and Enlargement Excavation Method, in which a pilot heading is excavated efficiently

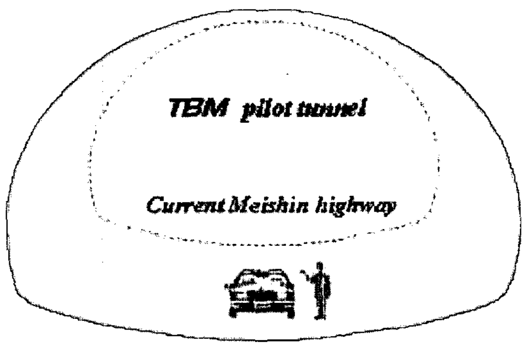


Fig. 2. Standard cross-section of the tunnel

in advance utilizing the TBM capability for .high speed excavation, is expected to provide various beneficial effects including drainage into the pilot and stability of the face (Hwang and Ohnishi, 2003). First, a working tunnel, which was 300m long, was excavated about 1km to the west from the east portal because of the topographical condition and the temporary storage yard of muck waste. Next, a pilot tunnel by TBM was excavated to the west. Finally, a pilot tunnel is now under enlargement by NATM.

The procedure of this excavation system is shown in Fig. 3. First, the Tunnel Boring Machine (TBM) pilot tunnel is excavated. During the excavation of the TBM pilot tunnel, an investigation was performed to get information about rock discontinuities. Before the excavation of the main tunnel, support pattern for the large section is designed based on the information acquired during the excavation of the pilot tunnel. As shown in Fig. 4, rock discontinuity information from TBM tunnel wall was collected and unstable blocks of the main tunnel were predicted by the key block analysis. Fig. 4(a) shows discontinuity map from TBM tunnel wall in the field. The strike of discontinuities is able to calculate from the angle between direction of TBM and discontinuities as shown in Fig. 4(b). When unstable blocks of the main tunnel were predicted, additional reinforcement was applied before main tunnel excavation. The reinforcement from TBM tunnel made construction more safely and saved the cost and construction lead time in terms of preventive action for unexpected collapse.

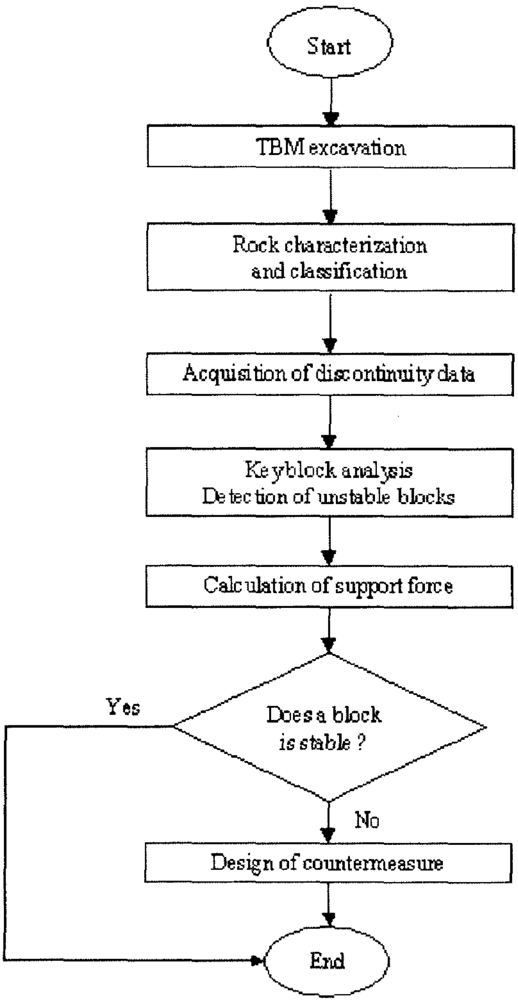
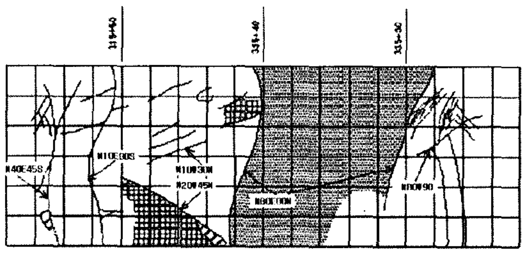


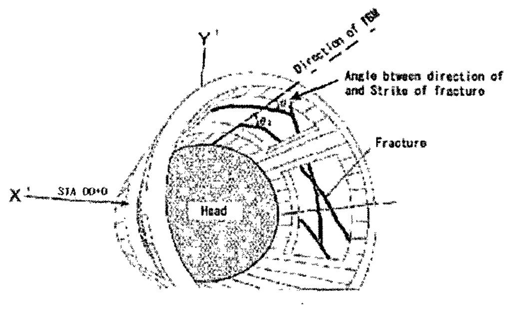
Fig. 3. Flow chart of the excavation system

3. GEOGRAPHY AND GEOLOGY

The district around the tunnel belongs to the Inner Side of Southwest Japan and consists, topographically, of the Mountains and the hilly lands



(a) Discontinuity map



(b) Acquisition in field

Fig. 4. Acquisition of rock discontinuity data

distributed on both sides of the mountains. The mountainous region around the tunnel is 300 to 600 meters above sea level and a comparatively gentle slope is seen at the summit of the mountains. In addition, steep V-shaped valleys developed along the swamp and river around the tunnel.

The Mountains are composed of the Paleozoic formations which are thought to be of Permian age, the granitic rocks which intruded into these formations during the Cretaceous, and a small amount of metamorphic rocks. In the hilly land, Miocene and Plio-Pleistocene strata and Quaternary terrace, fan and talus deposits are distributed. These members rest upon the pre-Neogene rocks unconformably or occur in fault contact with them. The geological map of the area is shown in Fig. 5. The geology of the tunnel mainly consists of Tanakami granite (Collaborative Research Group for the Granites around Lake Biwa, 1982; Kimura et al., 1998; Miyamura et al., 1981) from the Late Cretaceous. The Tanakami granite is a massive coarse-grained biotite granite with equigranular texture. The Tanakami granite is fresh and hard. The maximum unconfined compressive strength is 100 MPa and seismic velocity (P-wave) is more than 4.7 km/s. However, a lot of small-scale faults and fractures are distributed in this area. The longitudinal section is shown in Fig. 6.

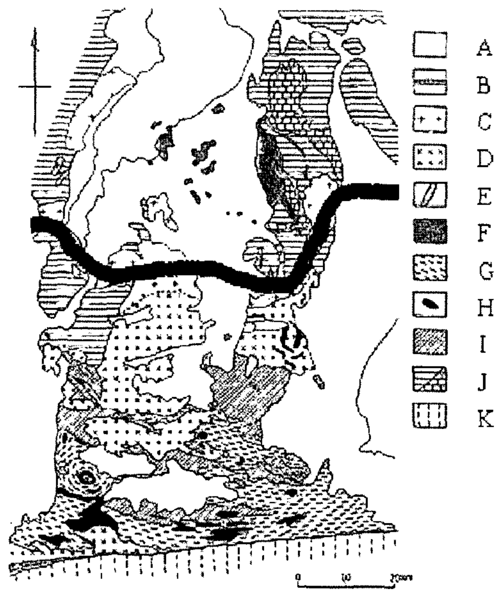


Fig. 5. Geological map of the study area. (A: Quaternary • Neogene. B: Izumi Group. C: Tanakami Granite, Suzuka Granite, etc. D: Young Ryoke Granitic Rocks. E: Granite porphyry, Quartz porphyry, Tonalite porphyry, etc. F: Koto Rhyolites. G: Old Ryoke Granitic Rocks. H: Gabbro, Diorite. I: Ryoke Metamorphic Rocks. J: Paleozoic and Mesozoic Terranes (Non-limestone/Limestone). K: Sanbagawa Metamorphic Rocks.)

4. KEY BLOCK ANALYSIS ON THE TUNNEL

4.1 Introduction of Key Block Theory

When the rock mass is excavated, the new shape of block appears on the excavated surface. As for the assessment of the rock structure induced failures, the so-called block theory was suggested by Goodman and Shi (1985). The thrust of the block theory is to provide a technique to specify the critical disco-

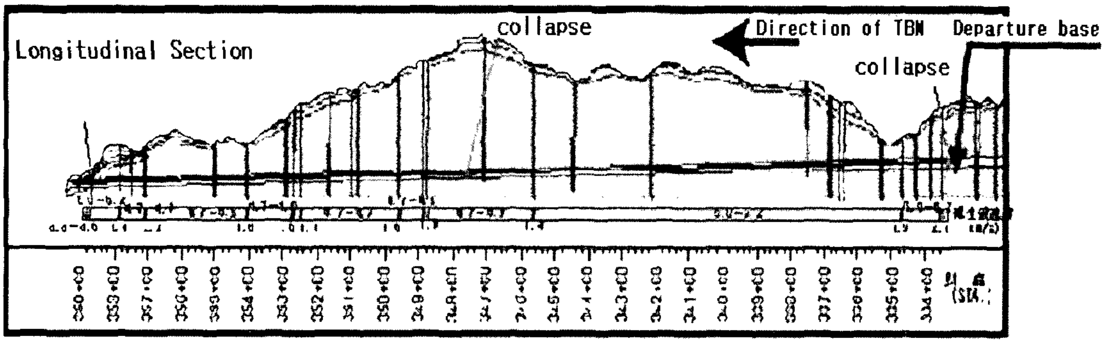


Fig. 6. Longitudinal section

ntinuity blocks intersecting an excavation. The block theory is concerned with the three-dimensional configuration of rock blocks as determined by the discontinuity geometry, and how the removability and stability of these blocks are affected by excavation. Fig. 7 shows key blocks around a tunnel. In general, the key block analysis in tunnels is classified into two parts, the kinematic analysis and the stability analysis. The key block analysis is very helpful in studying the design of excavation and support requirements.

The large tunnel is one of the tunnels of the New Second Meishin Expressway and is now under construction examining standard support system for large hard rock tunnel in Japan. Moreover, rock blocks around the tunnel have a possibility for rock masses to fall or slide along rock discontinuities not only because the rock mass has a lot of rock discontinuities, but also because the cross-section of the tunnel is large. Therefore, a key block analysis was introduced based on the behaviors of discontinuous rock mass during the construction of the tunnel as well as after opening it to the public.

4.2 Development of Numerical Analysis Program

The items examined in developing a program for the new observational design and construction method are the following ones: generality, precision, high speed, and friendly usability. It is possible to exactly detect all key blocks along the tunnel by using the numerical analysis program developed in the large tunnel. Fig. 8 is a flow chart that shows an algorithm

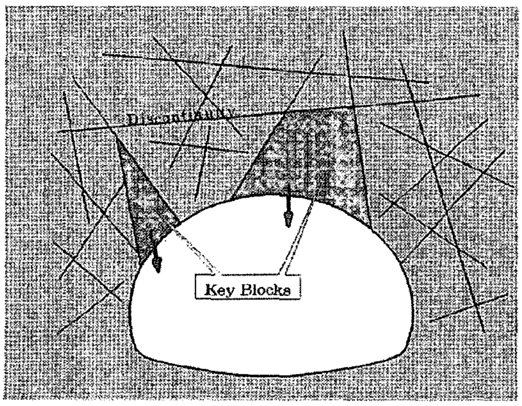
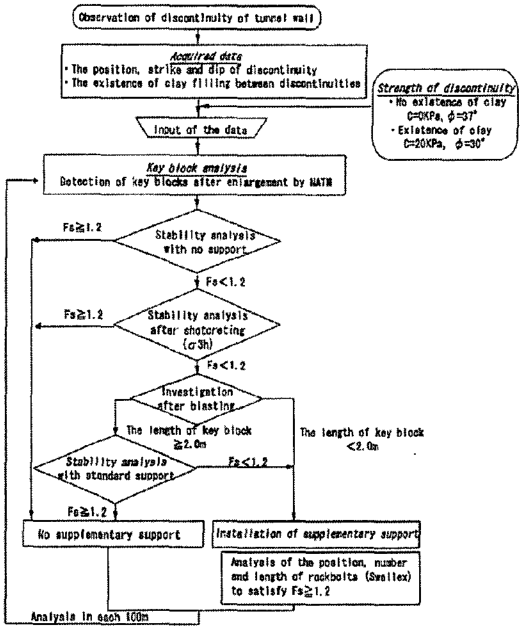
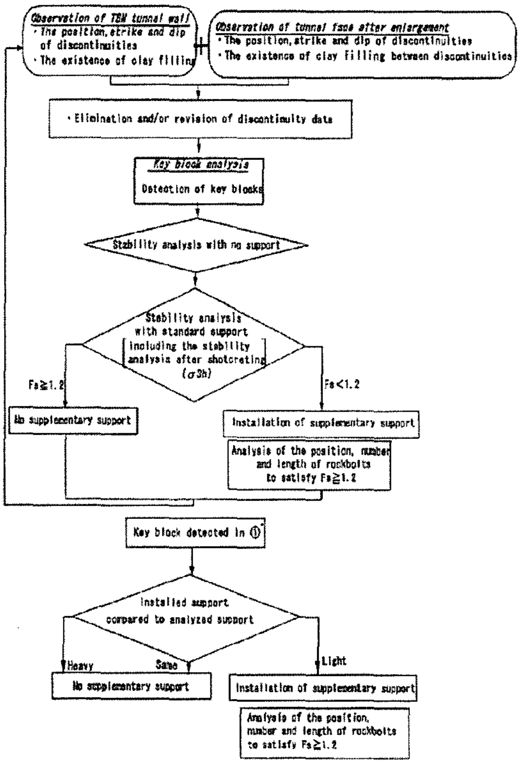


Fig. 7. Key blocks around a tunnel



(1) After completion of pilot tunnel by TBM



(2) Under enlargement by NATM

Fig. 8. Flow chart of key block analysis

of the key block analysis in this study. This computer simulation method with user-friendly interfaces not only can calculate the stability of key blocks, but also can provide a guideline of the design of supplementary supports if necessary. The items examined before developing a program are shown in the following.

1) It can cope with an optional cross-section and alignment of a tunnel to make it have a generality.
2) The shapes and locations of key blocks are detected precisely based on the geometrical information of rock discontinuities, which are absolute three dimensional coordinates, strike, dip, alignment of a tunnel and so on.
3) The result of key block analysis can be acquired in a short time for the daily management.
4) It is possible to eliminate and/or revise the data of rock discontinuities easily.

The program has been developed considering the above-mentioned items. The procedure of the key block analysis of the developed program are described in the following.

(1) Input Data of Tunnel Shape
The plan view and a cross-section view of a tunnel are inputted. An example of the cross-sectional view of the tunnel inputted the program is in Fig. 9.

(2) Rock Discontinuity Data Input
A position, strike, dip etc. are inputted (Fig. 10).

(3) Detection of Unstable Blocks
Unstable blocks are detected (Fig. 11).

(4) Stability Analysis
A stable evaluation for reinforcement execution of unstable blocks is performed.

(5) The Design of Additional Support (Fig. 12)

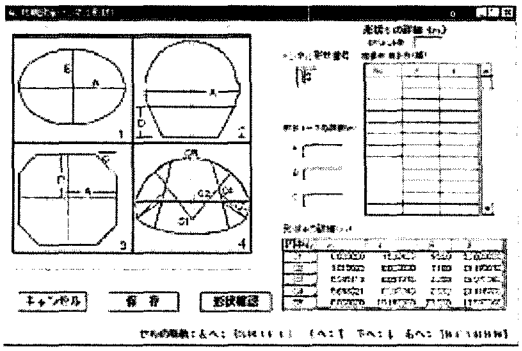


Fig. 9. Cross-section shape

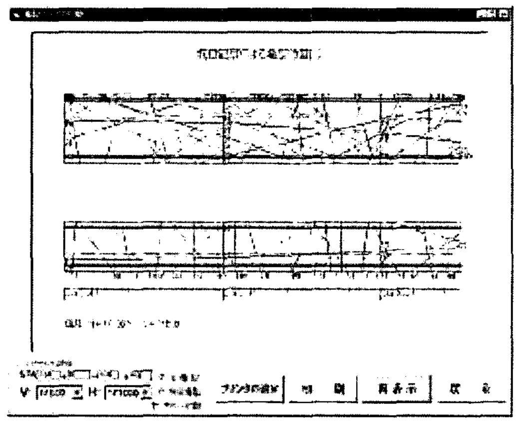


Fig. 10. Rock discontinuity map at tunnel wall

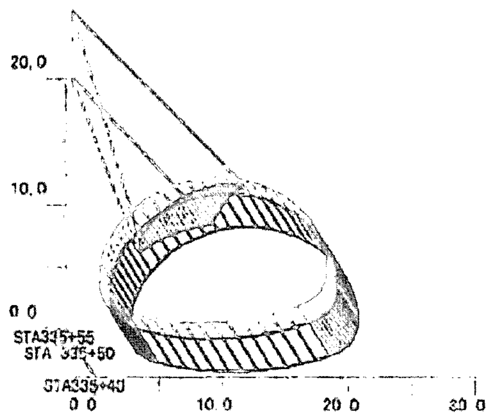


Fig. 11. Detection of unstable blocks

4.3 Investigation of Strength of Rock Discontinuity

Before applying a key block analysis to the site, the input information should be provided to the program such as absolute three dimensional coordinates, strike and dip of rock discontinuities, strength of rock discontinuities (cohesion C and friction angle ϕ), unit volume weight. Among them, strength of rock discontinuities is one of the most important information which strongly affects the stability of the key block. In the conventional application example of key

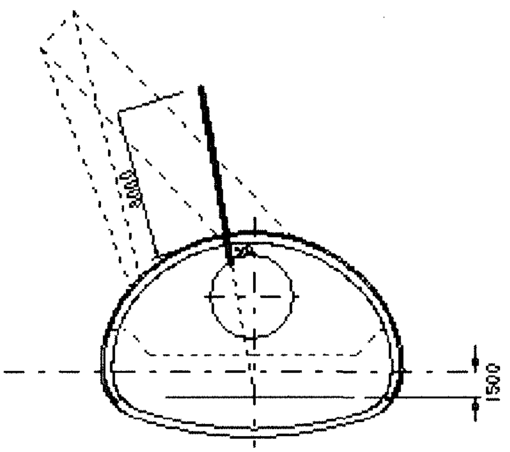


Fig. 12. Calculation of support force

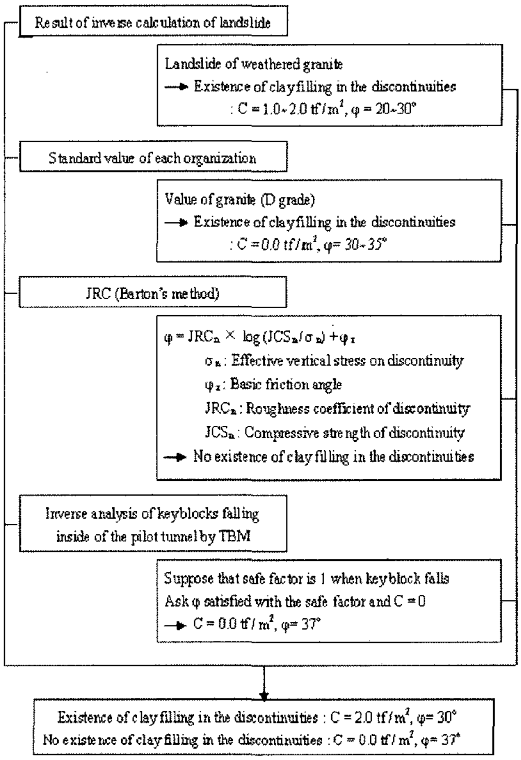


Fig. 13. Investigation of strength of rock discontinuity

block analysis, same values of strength of rock discontinuities were used regardless of conditions of rock discontinuities. However, the strength of rock discontinuities is depending upon the existence of clay in the rock discontinuities. Therefore, two cases for the existence of clay in the rock discontinuities were examined. Fig. 13 shows the Investigation of strength of rock discontinuity. As a result of the examination shown in Fig. 13, cohesion C is 2.0tf/m^2 and the friction angle ϕ is 30° in the case of existence of clay filling. On the other hand, cohesion C is 0.0tf/m^2 and an friction angle ϕ is 37° in the case of no existence of clay filling.

5. APPLICATION TO THE ACTUAL TUNNEL

5.1 Flow of the Application to the Tunnel

In the excavation of the large tunnel, a pilot tunnel by TBM is followed by enlargement by drill and blast in NATM. Key block analysis can be divided into two stages. The first stage is after completion of the pilot tunnel (D=5m) and the second stage is under construction by NATM. Fig. 8 shows the flowchart for the application of key block analysis in each stage. At the first stage, based on the information of rock discontinuities acquired during the excavation of the pilot tunnel, detected key blocks are supported before enlargement by NATM. At the second stage, based on the observation of the excavated surface after enlargement, in addition to the information of rock discontinuities which were not observed at the first stage, key block analysis is applied again. Furthermore, the stability of key blocks detected at the first stage is re-examined and supplementary supports are installed in case of unsafe ground condition.

5.2 Detection of Key Blocks

At the first stage, 38 key blocks were detected in total all along the tunnel. According to the analysis procedure shown in Fig. 8, seven key blocks were judged to be very unstable because they could not be supported by standard supports. Fig. 14 shows positions of these seven key blocks. Almost all of these seven key blocks have a slender wedge shape in the up-down direction because vertical rock discontinuities are dominant in the site.

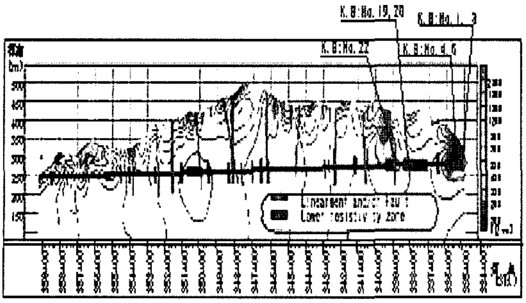


Fig. 14. Position of supplementary support

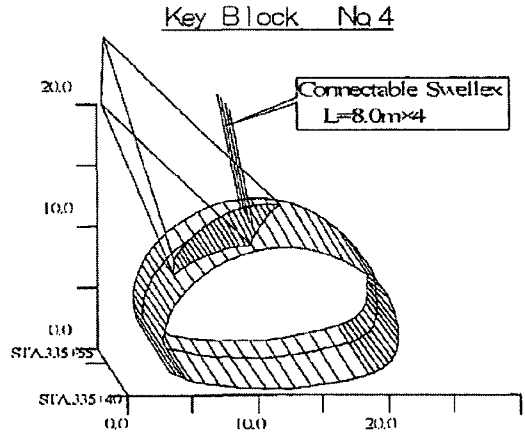


Fig. 15. Example of supplementary support

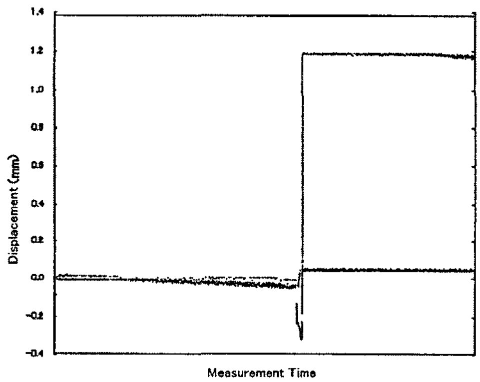


Fig. 16. Result of the Three-Dimensional Joint Displacement Measurement

5.3 Supplementary Support of Key Blocks

Supplementary supports were installed to these seven key blocks from inside of the pilot tunnel before enlargement by NATM. An example of supplementary supports of key block No.4 is shown in Fig. 15. As for the material of support, we used skin friction type of rock bolts, i.e. Connectable Swellex, because they had large resistance for shearing along rock discontinuities and adhesive strength to rock mass was strong in comparison with ordinary rock bolts. In addition, the most suitable position, number and length of rock bolts were calculated in this method to anchor the key blocks to the rock mass and to maintain the stability.

6. VERIFICATION OF THE EFFECTIVENESS OF SUPPLEMENTARY SUPPORT

6.1 Three-Dimensional Joint Displacement Measurement

One rock discontinuity of key block No.19, which was judged to be unstable, was measured. A three-dimensional joint displacement measuring instrument (measuring accuracy: 5/1000 mm) was installed crossing the detected rock discontinuity from inside of a pilot tunnel before enlargement by NATM directly below key block No.19. Behaviors of the rock discontinuity were measured and analyzed every thirty minutes automatically until the face passed through it. Fig. 16 shows the result of the three-dimensional joint displacement measurement. The result of the displacement measurement shows a good match with that of the analysis.

6.2 Example of Enlargement by NATM Below Key Block

The effectiveness of supplementary support to key block was verified by the falling of a rock block under enlargement below key block No.3. A rock block of 5m in height fell along a rock discontinuity of the key block. The rock block above the tunnel was supported and fixed by skin friction type of rock bolts. The outline of supplementary support is shown in Fig. 17.

7. CONCLUSIONS

This paper has proposed the new observational design and construction method for rock block evaluation of tunnels in discontinuous rock masses. Then the application of the new observational design

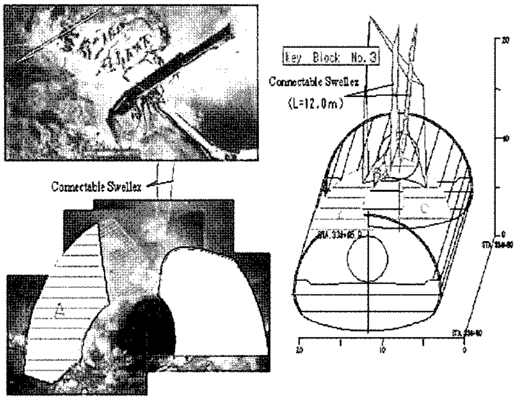


Fig. 17. Example of the Effectiveness of Supplementary Support

and construction method for rock block evaluation of tunnels to the large tunnel with a super-large cross-section is described. Block theory was suggested in 1985 by Goodman and Shi, but it was not put to a practical use until recently. In Japan, key block analysis was applied to the excavation of large scale underground rock cavern for the first time in 1996. However, this method has not been applied to a long road tunnel running through a mountain with complex geological condition. The large cross sectional tunnel is the first site that this method was applied based on actual rock discontinuity information observed in the field. The large tunnel is now under enlargement by NATM applying key block analysis. A user-friendly key block analysis software was developed and its application was introduced. It was possible to exactly detect key blocks on tunnel surface by using the numerical analysis program developed for the new observational design and construction method for rock block evaluation of tunnels in discontinuous rock masses. At the large tunnel, seven key blocks which could not supported by standard support were detected. Supplementary supports were installed to these seven key blocks from inside of the pilot tunnel before enlargement by NATM. The effectiveness of the proposed observational design and construction method has been verified by the confirmation of the predicted key block during the enlargement excavation.

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