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New Observational Design and Construction Method in Tunnels and Its Application to Very Large Cross Section Tunnel

터널의 신 정보화 설계시공법과 극대단면 터널에의 적용

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요 지

최근 터널의 정보화 설계시공이 중요시 되어지고 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. 본 논문에서는 터널의 신 정보화 설계시공법을 제안하고, 현장에서 관찰한 불연속면 정보를 근거로 하여 극대단면 터널에 적용했다. 터널의 신 정보화 설계시공법을 위한 수치해석 프로그램은 범용성, 정밀성, 신속성, 편리한 사용성을 검토하여 새롭게 개발되었다. 극대단면 터널에서는 표준지보에 의해 지지할 수 없는 불안정 키블럭이 7개 존재하는 것이 판명되었다. 7개의 키블럭에 대해서는 굴착전에 추가 지보를 실시했다. 극대단면 터널에 있어서, 터널의 신 정보화 설계시공법을 위해서 새롭게 개발한 수치해석 프로그램을 사용하여 정확한 키블럭 추출이 가능한 것을 검증하였다. 사용하기 쉬운 사용자 인터페이스를 가지고 있는 본 컴퓨터 시뮬레이션 기법은 키블럭의 안정성 계산뿐만 아니라 추가 보강대책공의 설계도 가능하다.

Abstract

The observational design and construction method in tunnels is becoming important recently. In many tunnels, enormous cost and time are consumed to cope with the falling or sliding of rock blocks, which could not be predicted because of the complexity of rock discontinuities. It is difficult to estimate the properties of rock masses before the construction. In this paper, a new observational design and construction method in tunnels are proposed, and then applied to the example of the very large cross section tunnel based on actual discontinuity information observed in situ. 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. At the very large cross section tunnel, 7 key blocks were judged to be unstable because they could not be supported by standard supports. Supplementary supports were installed to these 7 key blocks before the excavation. 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 in the very large cross section tunnel. This computer simulation method with user-friendly interfaces can calculate not only the stability of key blocks but also the design of supplementary supports.

Keywords : Computer simulation method, Discontinuity information, Key block, Observational design and construction method, Supplementary support, Very large cross section tunnel

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1. Introduction

In the design and construction of tunnels, the observational method has been becoming increasingly important (Hwang, 2003a; Hwang et al, 2004). The properties of rock masses are important factors relevant to the design and construction of tunnels (Ohnishi, 1999; Hwang et al, 2002). In discontinuous rock masses, rock blocks which have a variety of shaped and sizes are formed geometrically along discontinuities (Ohnishi, 2002; Hwang et al., 2003c). 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 (1985). 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 (Ohnishi et al, 1985). The key block analysis is extremely helpful in studying the design of excavation and support requirements.

This paper describes the development of a computer simulation method with user friendly interfaces to apply the key block analysis on site 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 using key block analysis is suggested, then applied to the example of the very large cross section tunnel based on actual discontinuity information observed in situ.

2. Introduction of Observational Design and Construction Method in Tunnels

An observational design and construction method actively utilizes various kinds of information, such as measurements, geological conditions, and construction procedures. It also helps engineers to make decisions concerning measurements, analyses and designing, construction, and optimization of designing and construction. The development of hardware, such as monitoring instruments, and technological revolution in the field of computer software have enabled such systems to be very effective. Normally, this gives more balanced and less costly solutions. The observational design and construction method is eminently well suited for tunneling. Tunnels are line structures, allowing for modifications in design and construction during their excavation.

The procedure of this observational design and construction method in tunnels is shown in Fig. 1. First, the TBM pilot tunnel is excavated. During the excavation of the TBM pilot tunnel, an investigation was performed, and discontinuity information was acquired. Before the excavation of the main tunnel, support pattern for the large section is designed based on the actual TBM excavation results. At the same time, discontinuity information from TBM tunnel wall was collected and unstable blocks of the main tunnel were detected by the key block analysis. When unstable blocks of the main tunnel were detected, additional reinforcement was applied before main tunnel excavation. The reinforcement from TBM

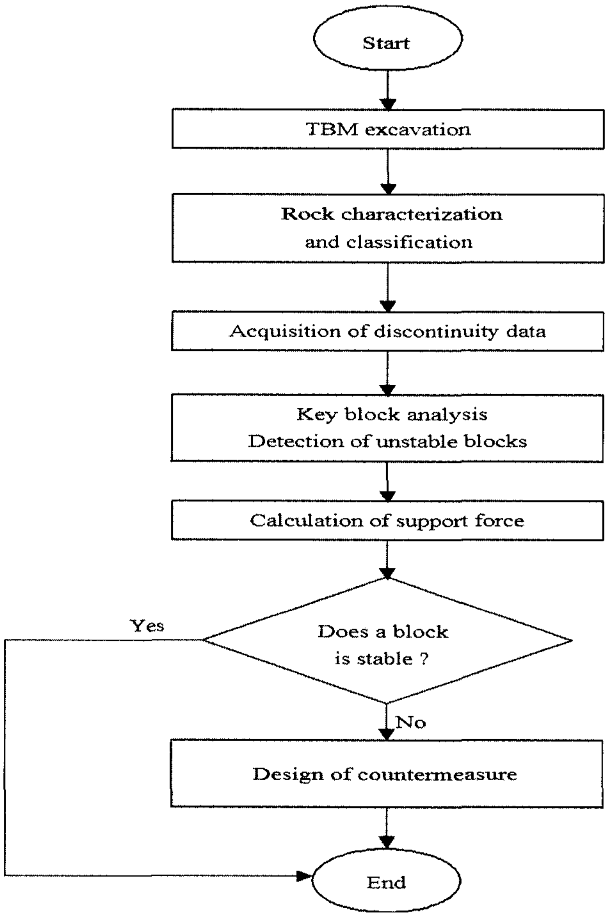


Fig. 1. Flow Chart of the Observational Design and Construction Method in Tunnels

tunnel made construction more safely and brought the saving of cost and construction lead time in terms of preventive action for unexpected collapse.

3. 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 produce techniques to specify the critical discontinuity 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. 2 shows key blocks around an underground space. Loss of the shaded blocks (1) would permit movement of blocks (2), then (3), and so on, destroying the chamber. 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 extremely helpful in studying the design of excavation and support requirements.

4. Development of Stability Analysis Program Using Key Block Theory

It is possible to detect key blocks all along the tunnel exactly by using the numerical analysis program developed in the very large cross section tunnel. This computer simulation method with user-friendly interfaces can calculate not only the stability of key blocks but also the design of supplementary supports if necessary. The items examined in developing a numerical analysis program for the new observational design and construction method are shown in the following.

(1) It can cope with an optional cross section and alignment of tunnel to make it have a generality.

(2) The shapes and locations of key blocks are detected precisely based on the geometrical information of discontinuities, which are absolute three dimensional coordinates, strike, dip, alignment for 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 discontinuities easily.

The program has been developed considering the above-mentioned items. The contents of the developed key block analytic procedure were described in the following.

4.1 Input Data of Tunnel Shape

The plan view of the tunnel and a cross section in the axial direction through the tunnel are inputted (Fig. 3 and Fig. 4). The cross sectional shape of the tunnel input.

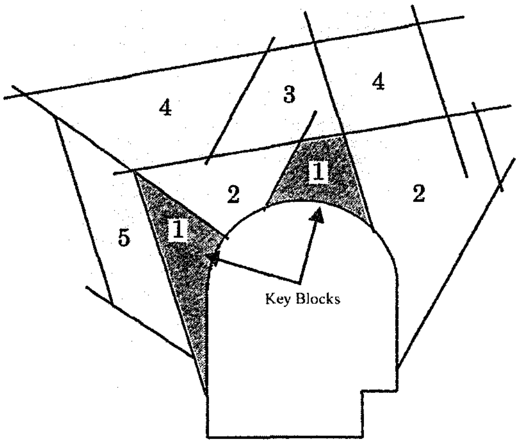


Fig. 2. Key Blocks in an underground space

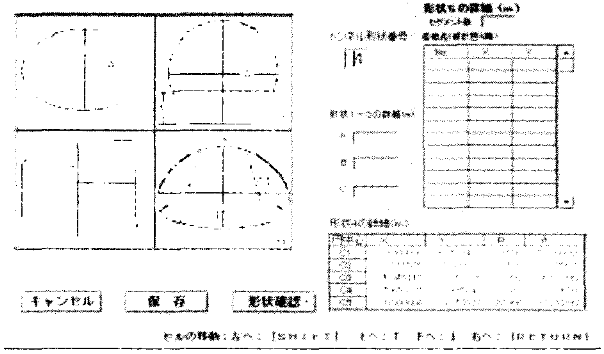
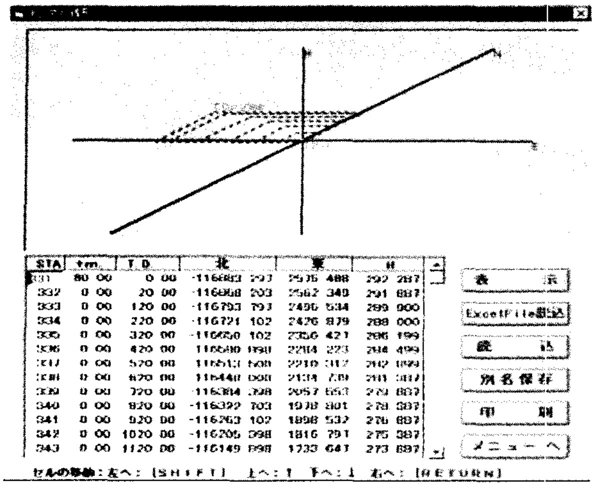


Fig. 3. Cross-Section Shape



STA	+m	T.D	北	東	H
331	80 00	0 00	-116883 293	2576 488	292 287
332	0 00	20 00	-116868 203	2562 340	291 887
333	0 00	120 00	-116793 793	2496 534	289 900
334	0 00	220 00	-116721 102	2426 879	288 000
335	0 00	320 00	-116650 102	2356 421	286 199
336	0 00	420 00	-116580 [illegible]	2284 223	284 499
337	0 00	520 00	[illegible]	2210 [illegible]	[illegible]
338	0 00	620 00	-116448 [illegible]	2134 [illegible]	[illegible]
339	0 00	720 00	-116384 [illegible]	2057 [illegible]	[illegible]
340	0 00	820 00	-116322 703	1978 801	278 387
341	0 00	920 00	-116263 102	1898 532	276 887
342	0 00	1020 00	-116205 598	1816 791	275 387
343	0 00	1120 00	-116149 898	1733 641	273 887

Fig. 4. 3D Coordinate of the Tunnel

4.2 Discontinuity Data Input

A position, strike, dip input (Fig. 5).

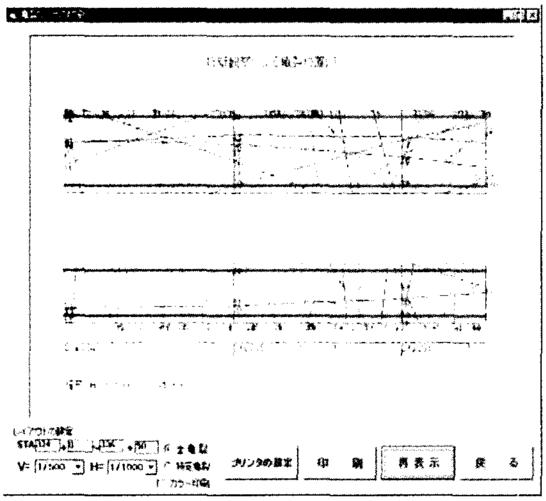


Fig. 5. Discontinuity Map at Tunnel Wall

4.3 The Detection of Unstable Blocks

Unstable blocks are detected using key block theory (Fig. 6).

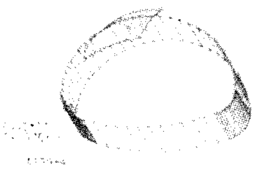


Fig. 6. The Detection of Unstable Blocks

4.4 Stability Analysis

A stable evaluation for reinforcement execution.

4.5 The Design of Additional Support

The most suitable position, number and length of rock bolts are calculated in order to anchor the rock mass outside the key blocks and to maintain the stability (Fig. 7).

5. Application to the Very Large Tunnel

5.1 Construction Outline and Tunneling Method

The actual example site selected in this paper is the

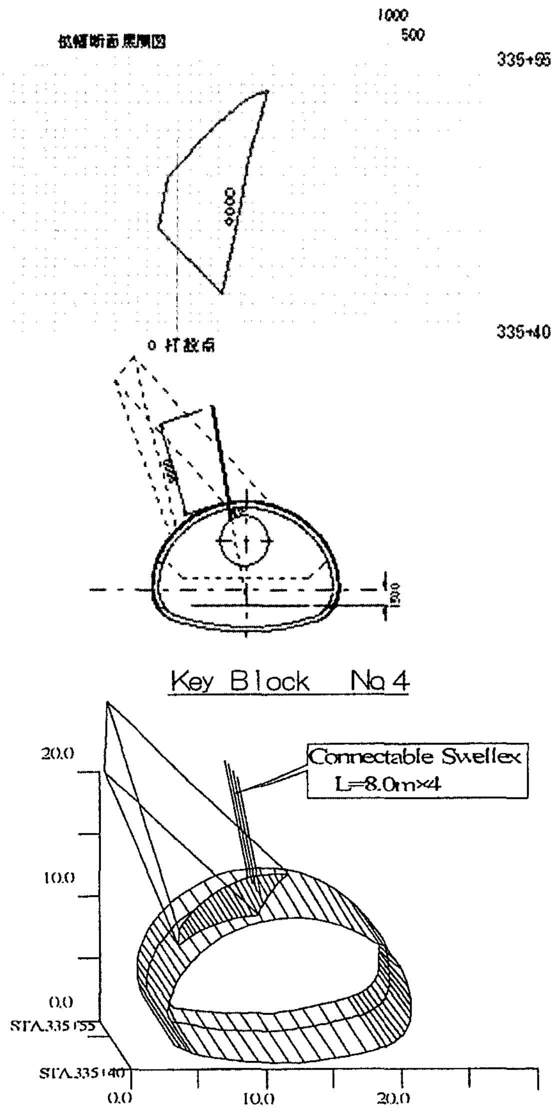


Fig. 7. The Calculation of Support Force

very large cross section tunnel in the New Second Tomei-Meishin Expressway between Tokyo and Kobe. The new observational design and construction method using key block analysis is applied to the large tunnel with a very large cross section of about 200 m^2. The very large cross section tunnel in the New Second Tomei-Meishin Expressway is now under construction examining standard support system for large rock tunnel in Japan. Moreover, the tunnel has a possibility for rock masses to fall of slide along discontinuities not only because the rock mass has a lot of discontinuities but also because the cross-section of the tunnel is very large and flat. Therefore, a key block analysis was introduced based on the behaviors of discontinuous rock mass during the construction of a tunnel as well as after opening it to the public. This tunnel construction is the world' s first large and long tunnel construction based on block theory.

The Second Tomei-Meishin Expressway that will be of importance 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 140 km/h, which will make it by far the fastest expressway in Japan. In order 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 and flat because the new road takes three lanes in each direction. As shown in Fig. 8, the very large cross section tunnel in the New Second Tomei-Meishin Expressway is 3800 m long and is located in Shiga Prefecture of about 10 km from the end of the south of Lake Biwa to the east-southeast. It passes through the mountain zone called Konan Alps.

Fig. 9 shows the standard cross-section of the tunnel. The standard cross-section of the tunnel is very large (200 m^2) and wide (18 m) compared to ordinary tunnels. The final tunnel shape is flat with a height to width ratio of 0.65. The very large cross section tunnel is now under construction. The 5 m diameter Tunnel Boring Machine (TBM) pilot tunnel is at the center in the proposed tunnel. After the TBM pilot tunnel was excavated, the main tunnel is enlarged by New Austrian Tunneling Method (NATM).

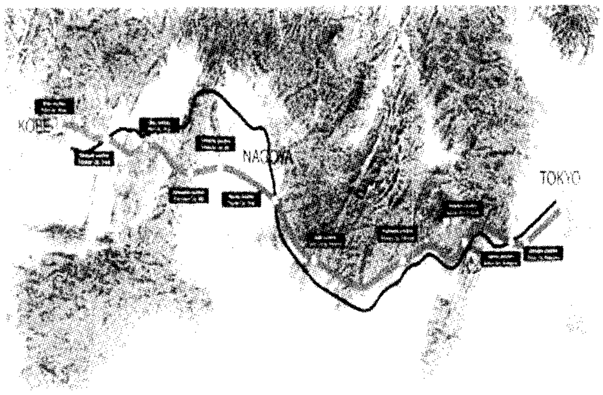


Fig. 8. Location of the Very Large Tunnel

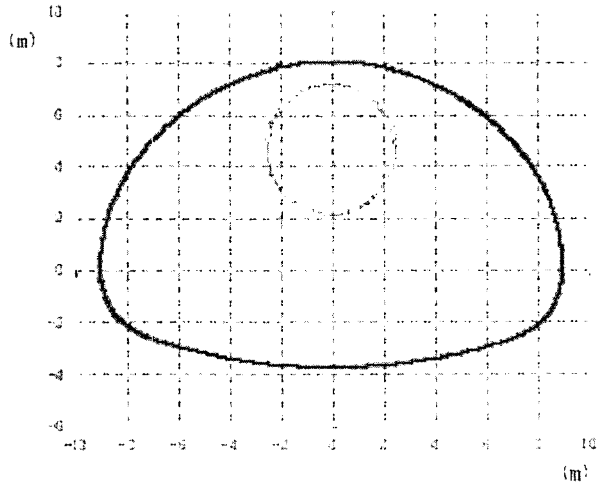


Fig. 9. Standard Cross-Section of the Very Large Tunnel

The TBM Pilot and Enlargement Excavation Method, in which a pilot heading is excavated efficiently 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 et al., 2003b). First, a working tunnel, which was 300 m long, was excavated about 1 km to the west from the east portal because of the topographical condition and the temporary storage yard of muck waste. Secondarily, a pilot tunnel by TBM was excavated to the west. Finally, a pilot tunnel is now under enlargement by NATM.

5.2 Geographical Features 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 distributed on both sides of the mountains. A 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 shape valleys developed along swamp and river around the tunnel.

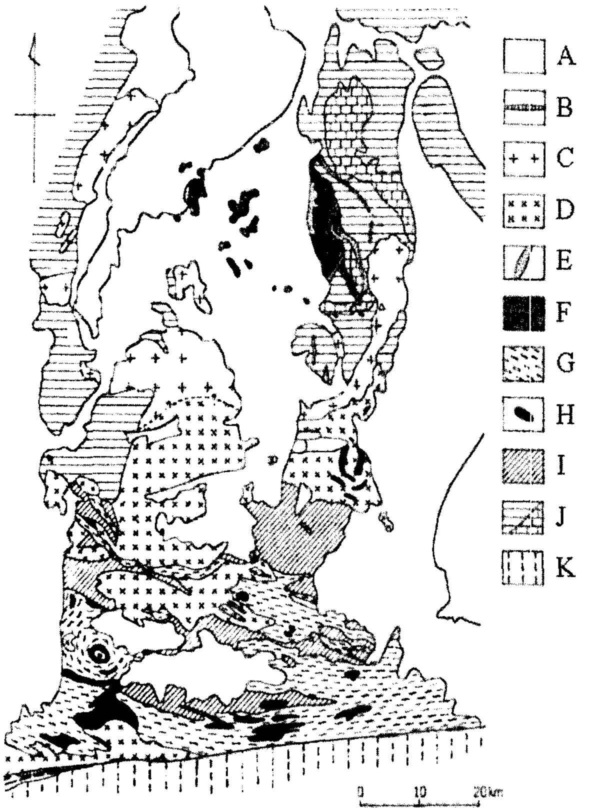


Fig. 10. Geological Map of the Study Area

(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.)

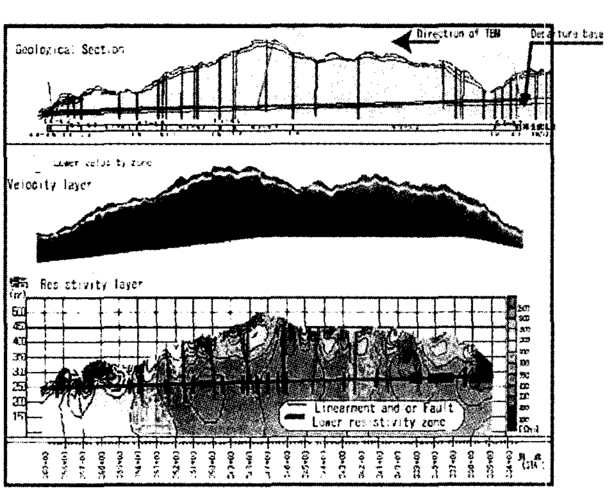
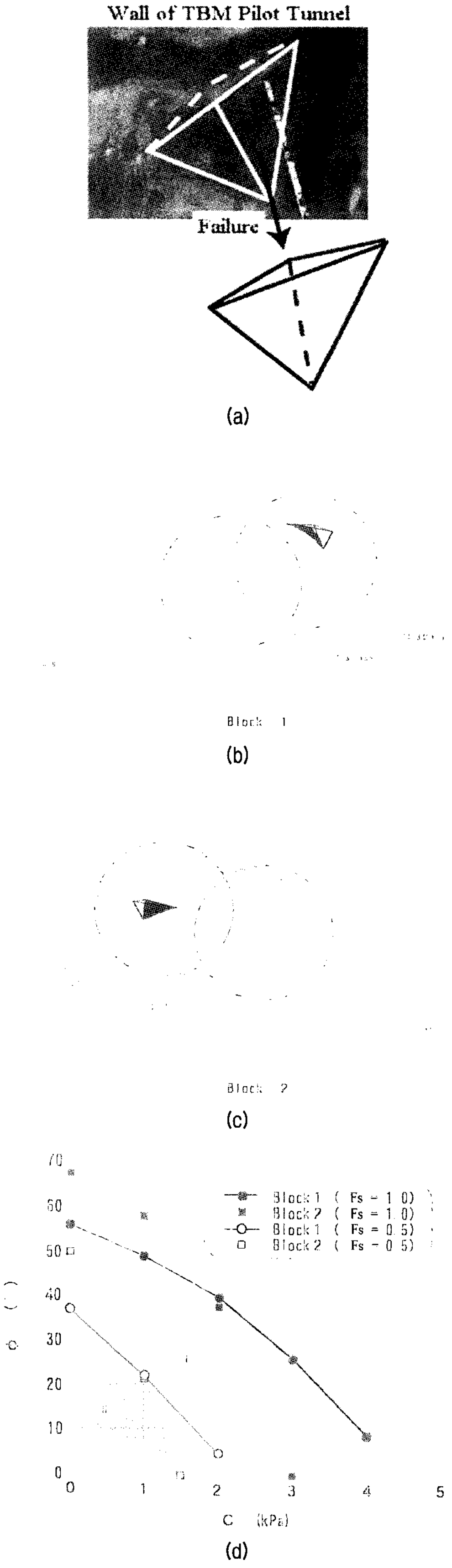


Fig. 11. Longitudinal Geological Section

The mountains are composed of the Paleozoic formations which are thought to be of Permian age, the granitic rocks 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. Fig. 10 shows the geological map of the area. 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. 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. Longitudinal geological section is shown in Fig. 11.

5.3 Investigation of Strength of Discontinuity

Before applying a key block analysis to the site, the input information to the program is absolute three dimensional coordinates, strike and dip of discontinuities, strength of discontinuities (cohesion C and angle of internal friction ϕ), unit volume weight, and so on. Among them, strength of discontinuities is one of the most important pieces of information which strongly affects the stability of the key block. In the example of key block analysis applied before, same values of strength of discontinuities were used regardless of conditions of discontinuities. However, the strength of discontinuities is different depending upon the existence of clay in the discontinuities. Therefore, two cases are examined. As a result of the examination shown in Fig. 13, cohesion C is 2.0 KPa and angle of internal friction ϕ is 30° in the case of existence of clay filling. On the other hand, cohesion C is 0 KPa and an angle of internal friction ϕ is 37° in the case of no existence of clay



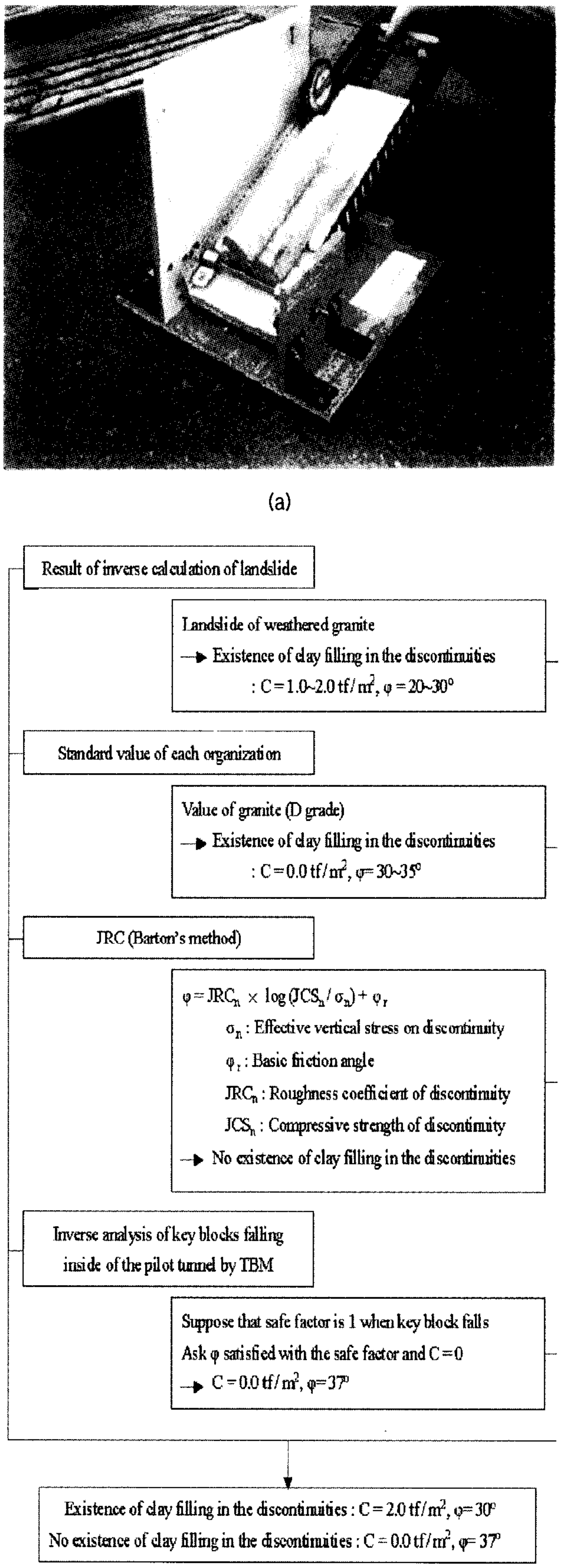
(a)

(b)

(c)

(d)

Fig. 12. Inverse Analysis of Key Blocks Falling Inside of the Pilot Tunnel by TBM


(a)

Result of inverse calculation of landslide

Landslide of weathered granite
→ Existence of clay filling in the discontinuities
: C = 1.0~2.0 tf/m², φ = 20~30°

Standard value of each organization

Value of granite (D grade)
→ Existence of clay filling in the discontinuities
: C = 0.0 tf/m², φ = 30~35°

JRC (Barton's method)

$\varphi = JRC_n \times \log(JCS_n / \sigma_n) + \varphi_r$

σ_n : Effective vertical stress on discontinuity

φ_r : Basic friction angle

JRC_n : Roughness coefficient of discontinuity

JCS_n : Compressive strength of discontinuity

→ No existence of clay filling in the discontinuities

Inverse analysis of key blocks falling inside of the pilot tunnel by TBM

Suppose that safe factor is 1 when key block falls
Ask φ satisfied with the safe factor and C = 0
→ C = 0.0 tf/m², φ = 37°

Existence of clay filling in the discontinuities : C = 2.0 tf/m², φ = 30°
No existence of clay filling in the discontinuities : C = 0.0 tf/m², φ = 37°

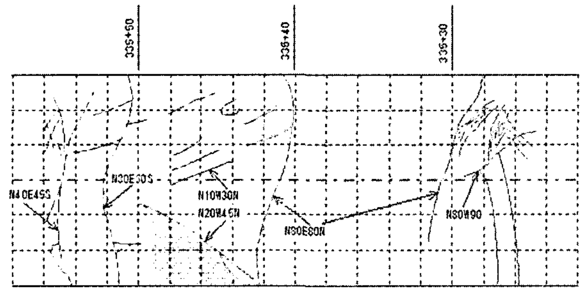
(b)

Fig. 13. Investigation of Strength of Discontinuity

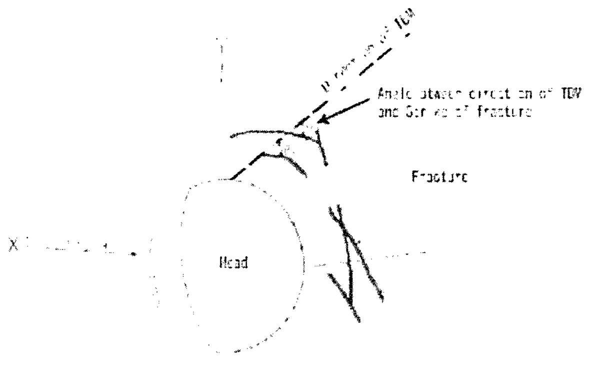
filling. Further, the strength of discontinuities to get more accurate C and ϕ by simple shear test was re-examined.

5.4 Flow of the Application to the Tunnel

In the excavation of the very large cross section tunnel, a pilot tunnel by Tunnel Boring Machine (TBM) is followed by enlargement by drill and blast in New Austrian Tunneling Method (NATM). Key block analysis can be divided into two stages. The first stage is after completion of the pilot tunnel (D=5 m) and the second stage is under construction by NATM. At the first stage, based on the information of discontinuities acquired during the excavation of the pilot tunnel (as shown in Fig. 14), detected key blocks are supported before enlargement by NATM. At the second stage, based on the observation of the excavated surface after enlargement, key block analysis is applied again in addition to the information of discontinuities which were not observed at the first stage. 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.



(a) Discontinuity Map



(b) Acquisition in Field

Fig. 14. Acquisition of Discontinuity Data

5.5 Detection of Key Blocks

At the first stage, 38 key blocks were detected in total all along the tunnel. According to the above-mentioned method, 7 key blocks were judged to be unstable because they could not be supported by standard supports. Fig.

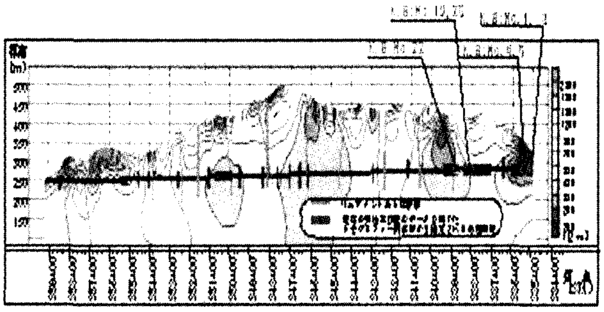
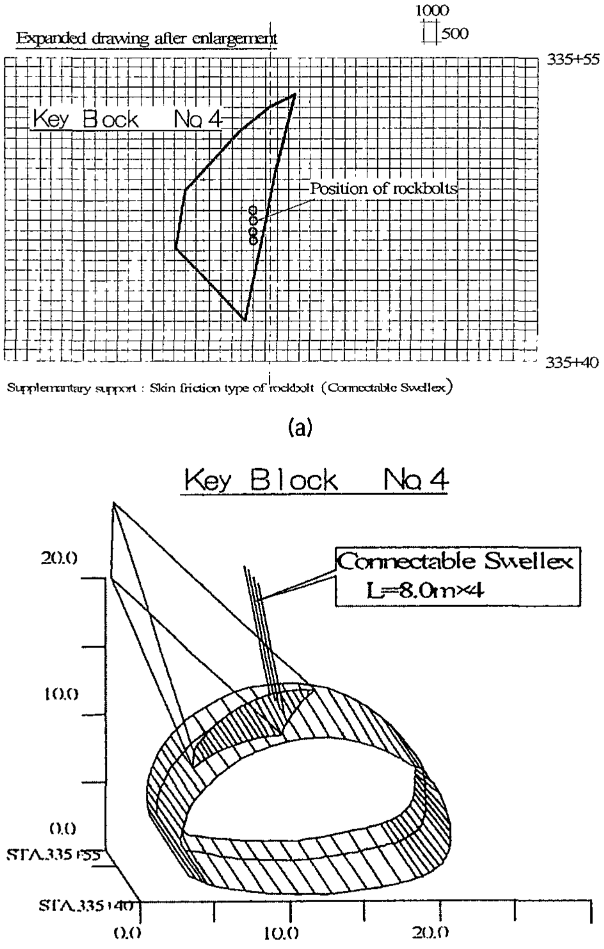


Fig. 15. Position of Supplementary Support



Supplementary support : Skin friction type of rockbolt (Connectable Swellex)

(b)

Fig. 16. An Example of Supplementary Support

15 shows positions of these 7 key blocks. Almost all of these 7 key blocks have slender wedge shape in the up-down direction because the discontinuities in the vertical direction are dominant in-situ.

5.6 Supplementary Support of Key Blocks

Supplementary supports were installed to these 7 key blocks from inside the pilot tunnel before enlargement by NATM. An example supplementary supports of key block No.4 is shown in Fig. 16. 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 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 in order to anchor the rock mass outside the key blocks and to maintain the stability.

6. Verification of the Effectiveness of Supplementary Support to Key Blocks

6.1 Three-Dimensional Joint Displacement Measurement

One discontinuity of key block No.19 (see Fig. 15), which was judged to be unstable and was supported supplementary, is now under measurement. Three-dimensional joint displacement measuring instrument (measuring accuracy: 5/1000 mm) was installed crossing the detected discontinuity from inside a pilot tunnel before enlargement by NATM directly below key block No.19. Behaviors of the discontinuity are measured and analyzed every thirty minutes automatically until the face passes through it.

6.2 Example of Enlargement by NATM Just Below Key Block

The effectiveness of supplementary support to key block was verified by the falling of rock mass under enlargement just below key block No.3. Rock mass of

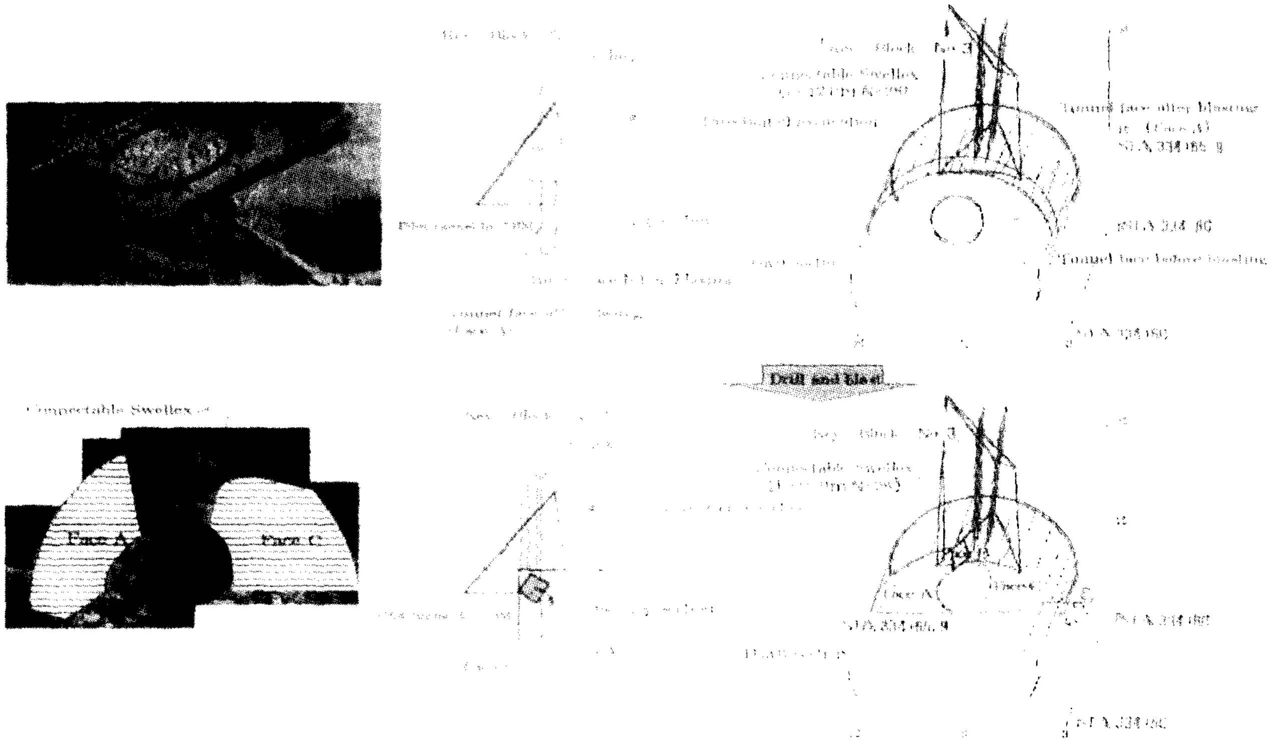


Fig. 17. An Example of the Effectiveness of Supplementary Support

5 m height fell along a discontinuity which is a composition of key block No.3. Rock mass above the tunnel section was supported and fixed by skin friction type of rock blots. The outline of supplementary support is shown in Fig. 17.

7. Conclusions

In this paper, the new observational design and construction method in tunnels have been proposed. And then application of the new observational design and construction method using key block analysis on the very large tunnel with a super-large cross-section is described. At the very large cross section tunnel, 7 key blocks were judged to be unstable because they could not be supported by standard supports. Supplementary supports were installed to these 7 key blocks from inside the pilot tunnel before enlargement by NATM. The effectiveness of supplementary support to key block was verified by the falling of rock mass under enlargement just below key block No.3. In the actual example, key block analysis in situ to investigate the stability of a tunnel based on the behaviors of discontinuous rock mass is applied to the new observational design and construction method in tunnels. Block theory was suggested in 1985 by Goodman and Shi, but it was not put to a practical use until recently. The very large cross section tunnel construction is the world's first large and long tunnel construction using the new observational design and construction method based on block theory. The very large cross section tunnel is now under enlargement by NATM applying key block analysis. The items examined in developing a numerical analysis program for the new observational design and construction method are the following ones: generality, precision, high speed, and friendly usability. The development of the key block analysis software which is user-friendly and how this software has been used have been explained.

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