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Removability and Stability Analysis Method of Rock Blocks Considering Discontinuity Persistence in Tunnel Constructions

터널시공에서의 불연속면의 연속성을 고려한 암반블럭의 거동성 및 안정성 해석기법

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요 지

블럭이론에서는 불연속면의 유한한 연속성을 무시하여 불연속면이 암반내에서 무한이 연속되어진다고 가정하였다. 본 논문에서는 터널시공의 안정성 평가기법으로 불연속면의 유한한 연속성을 고려한 키블럭 해석기법을 제안하고, 실제의 현장에 적용했다. 불연속면 원반 모델을 이용하여 불연속면의 연속성을 고려한 3차원 암반블럭의 생성을 판정하였다. 이 판정기법은 블럭의 형상에 관계없이 모든 형상의 블럭이 인식가능하여 복잡한 굴착면의 문제에 적용가능하다. 판정된 암반블럭에 대해서 거동성 및 안정성을 해석하였다. 실제 건설중에 있는 대단면 터널현장에 적용하여 해석결과를 비교 검토하므로써, 본 논문에서 개발한 수치해석기법의 타당성과 적용성에 대한 검증을 하였다.

Abstract

Previous analytical models for key blocks have been based on the assumption of infinite persistent discontinuities. In this paper, a key block analysis method considering the finite persistence of discontinuities is proposed as a stability evaluation method in tunnel constructions, and then applied to an actual example site. Three-dimensional rock block identification with consideration of the persistence of discontinuities is performed by using discontinuity disk model. The removability and stability analyses of rock blocks formed by the identification method are performed. The identification method can handle convex and concave shape blocks. In order to demonstrate the applicability of this developed numerical method to the stability evaluation in tunnel constructions, the analytical results are examined and compared one another.

Keywords : Discontinuity disk model, Key block, Persistence, Removability and stability analysis method, Three-dimensional rock block identification, Tunnel construction

1. Introduction

Tunnels constructed underground must be mechanically stable. The mechanical properties of a rock mass are important factors relevant to the design and construction of the tunnel. Rock mass includes discontinuities such

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as joints, faults, bedding planes, cracks, schistosities, and cleavages. The behavior of civil engineering structures in hard rocks, therefore, is mainly controlled by various discontinuities (Cundall et al, 1977; Shi, 1989; Hwang et al, 2000; Hwang et al, 2002). The tunnel support design has been mostly empirical. The typical support design pattern is based on the rock/soil types, or based on the rock mass classification. However, both stress and rock structure induced failures should be considered in the design of rock support for tunnel design. As for the assessment of the rock structure induced failures, the so-called block theory was suggested by Goodman and Shi (1985). Block theory is concerned with the three-dimensional configuration of rock blocks as determined by the discontinuity geometry, and with how the removability and stability of these blocks are affected by excavation. The instability is a function of both the geometry and the mechanical properties. Block theory is a useful method to determine the removability and stability of rock blocks that were created by the intersection of discontinuities. In general, key block analysis in tunnels is classified into two parts, the kinematic analysis and the stability analysis.

However, in block theory, joint surfaces are assumed to extend entirely through the volume of interest; that is, no discontinuities will terminate within the region of a key block (Ohnishi et al, 1985). The block theory is based on the assumption of infinite persistent discontinuities, and does not consider the effects of finite discontinuity persistence, therefore cannot handle a complex concave shape block. In practice, it is necessary to consider the finite persistence of discontinuities in applying the block theory to successive large-scale excavations.

In this paper, a removability and stability analysis method considering finite discontinuity persistence is suggested for the tunnel design and the safe tunnel excavation. Then the method is applied to an actual example of a tunnel with a large cross-section of about 200m^2. The tunnel in the New Second Meishin Expressway between Nagoya and Kobe is now under construction. The tunnel is first bored by a 5m diameter Tunnel Boring Machine (TBM) and is enlarged later by New Austrian Tunneling Method (NATM). During the excavation of the TBM pilot tunnel, an investigation was performed, and discontinuity information was acquired. This paper presents a three-dimensional block identification method considering the finite persistence of discontinuities. The identification method can handle convex and concave shape blocks. The removability and stability analyses of rock blocks formed by the identification method using a volume element (voxel) propagation process are performed. The key block analysis method developed by the authors is applied to the large tunnel based on actual discontinuity information observed in situ. In order to illustrate the applicability of this proposed numerical method to the stability evaluation in tunnel constructions, the analytical results are examined and compared with those of the Japan Highway Public Corporation (JH).

2. Discontinuous Rock Mass Modeling

2.1 Discontinuity Disk Model

To build a three-dimensional model considering the persistence of discontinuities, the problem concerning geometric shape and spatial extent of discontinuities must be addressed. Through the analysis of trace data and examination of discontinuity surfaces, several studies (Warburton, 1980; Long and Billaux, 1987; Pollard and Aydin, 1988; Priest, 1993; Ohnishi et al, 1994; Yu, 2000) have demonstrated that discontinuities are likely to be roughly elliptical or circular.

The fundamental feature of the discontinuity disk model is the assumption of circular discontinuity shapes (Mardia, 1972; Pahl, 1981; Dershowitz, 1984; Ohnishi et al, 1994; Zhang and Einstein, 2000) as shown in Fig. 1. The size of circular discontinuities is defined completely by a single parameter, the discontinuity radius. Discontinuity radius may be defined deterministically as a constant for all discontinuities, or stochastically by a distribution of radii. The best and most widely adopted sampling strategy for determining discontinuity size is based on the measurement of the lengths of the traces produced where the discontinuities intersect a planar face (Priest, 1993).

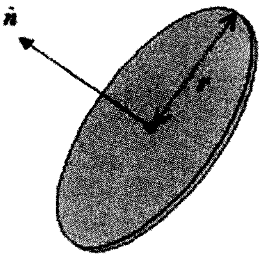
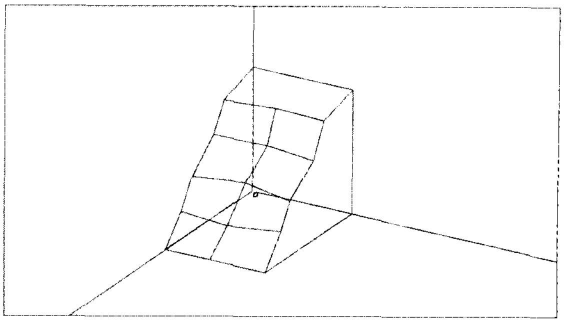


Fig. 1. Discontinuity disk model

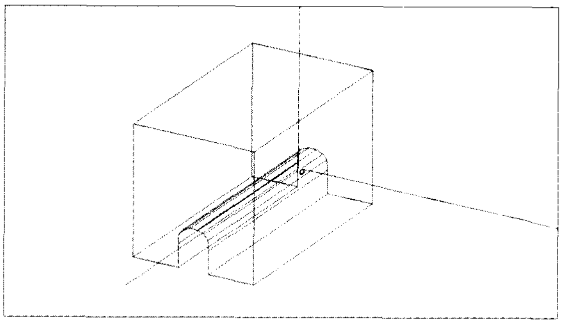
The probability distribution of discontinuity diameters may be inferred from the distribution of the trace length, which can be measured through excavation surfaces or natural outcrops. However, the direct estimation of trace lengths is often affected by varied biases, and the distribution inferred from trace length involves an integral that can only be evaluated numerically, and this also becomes a barrier when building a statistical model with Monte Carlo simulation. To overcome these problems, the stochastic discontinuity system modeling process of this program developed by authors first assumes that discontinuity diameter and trace length have the same distribution forms (e.g., lognormal or exponential distribution), then determines the mean and standard deviation of discontinuity diameters through model calibration. Discontinuity location may also be defined by a deterministic pattern or a stochastic process. The most frequently used model to define the spatial location of stochastic discontinuities is the Poisson model. In the discontinuity system modeling process of this developed program, the spatial location of stochastic discontinuities was assumed to follow the Poisson model. As a result of the joint location, shape and size process of the discontinuity disk model, discontinuities terminate in rock and intersect one another.

2.2 Analysis Region Modeling

The model region of 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 with or without interior holes. All excavation faces should form a closed domain of target rock mass for the analysis; if they do not form a closed domain, some fabricated faces, such as boundary faces, should be added. A curve face should be approximated by a number of polygonal faces. Fig. 2 shows examples of the analysis region modeling for an underground cavern and a slope.



(a) An example of slope



(b) An example of underground cavern

Fig. 2. Examples of analysis region modeling

3. Three-dimensional Rock Block Identification Method

Block theory (Goodman and Shi, 1985) and wedge theory (Hoek et al, 1995) are well known methods used to describe the relationship of individual rock blocks and discontinuity systems. However, these methods are based on the assumption of infinite persistent discontinuities, and do not consider the effects of discontinuity persistence, therefore cannot handle a complex concave shape block (Fig. 3). The rock block should be divided into convex sub-blocks. Thus for most actual excavations, it is very difficult, if not impossible, to predict the number, dimensions, and locations of blocks three-dimensionally with these methods.

When only the size and shape of individual discontinuities are incorporated, it is impossible to construct a

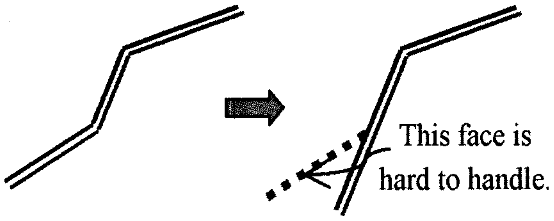


Fig. 3. An example of concave shape

general analytical method for block identification. In this paper, a three-dimensional block identification method, which takes into account the persistence of discontinuities, is briefly described below.

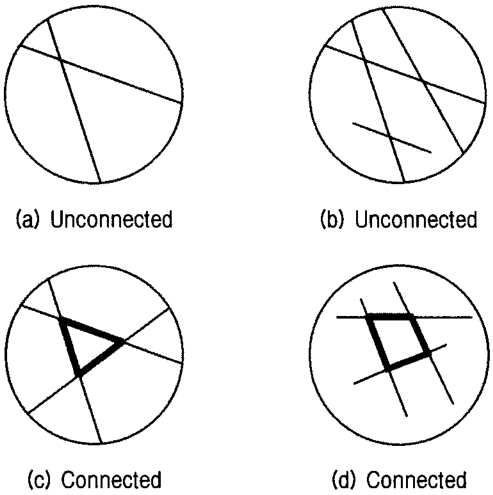
Unconnected discontinuities are eliminated from the discontinuity system, represented by the discontinuity disk model. The connectivity of discontinuities will be calculated. Then the discontinuities that form a block will be identified. An original voxel is positioned at a certain location, and then the voxel propagates. By counting the number of voxels, the volume of the block can be determined.

Using the above-mentioned process, the identification method can handle convex and concave shape blocks. The block identification method is presented in the following sections.

3.1 Identification of 2D Loop

In a discontinuity system, not all discontinuities (which may be deterministic or generated by stochastic simulation) are connected; some discontinuities do not intersect other discontinuities. Before the block identification stage, unconnected discontinuities should be identified and eliminated.

A discontinuity is referred to as connected only when it plays a part in block formation (i.e., it forms a surface of some block). A connected discontinuity must feature the 2 following characteristics: (1) it is connected to at least 3 discontinuities including excavation faces, (2) within the planar disk of the considered discontinuity, the intersections between the considered discontinuity and other connected discontinuities or excavation faces must form at least one connected loop. Fig. 4 shows some cases of connected discontinuities and unconnected discontinuities.


(a) Unconnected (b) Unconnected

(c) Connected (d) Connected

Fig. 4. Some cases of connected discontinuity and unconnected discontinuity

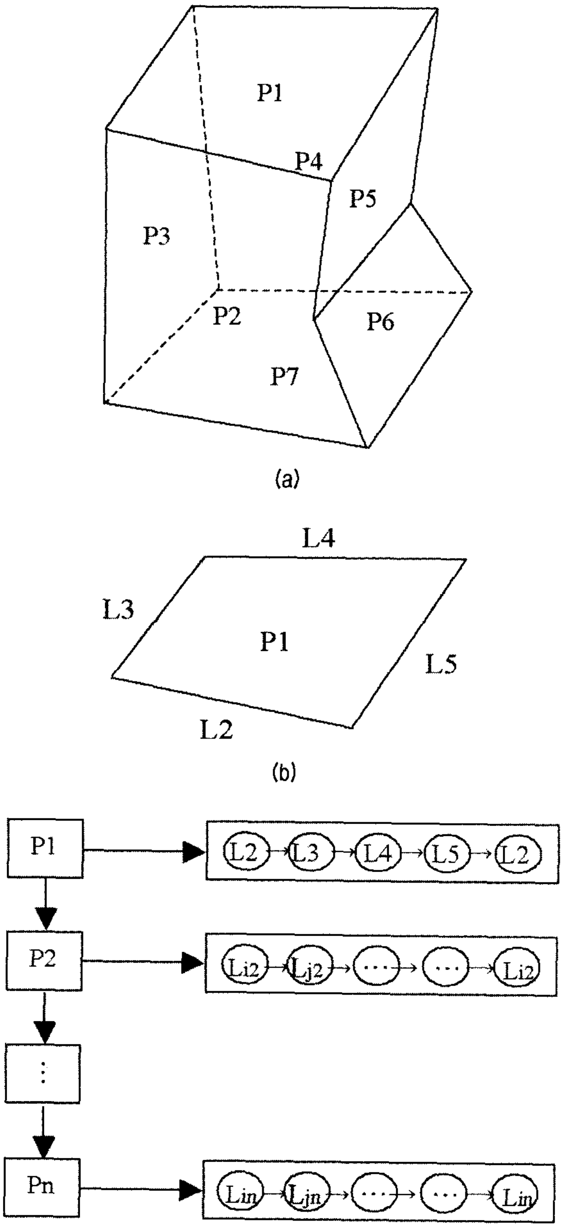
By checking every discontinuity against the two characteristics mentioned above, all unconnected discontinuities can be identified and eliminated. It should be noted that this is an iteration procedure. Some discontinuities, which look connected, may be identified to be unconnected after unconnected discontinuities are eliminated.

3.2 Identification of 3D Loop

A whole discontinuity does not form a surface of block. Therefore, after the elimination of unconnected discontinuities, intersections among discontinuities will be calculated, then the discontinuities which form a block will be identified.

A face in 3D closed region forms when other discontinuities cut the region. 2D line loop should be established at the surfaces of the 3D region. When this criterion is satisfied at all faces, one or more blocks are formed.

The algorithm of the 3D loop is demonstrated graphically by an example in Fig. 5. The 3D loop may be represented by its boundary 2D loops arranged in clockwise direction or counter-clockwise direction. For instance, a 3D loop 3DL1 on face P1 shown in Fig. 5(b) may be represented by a closed 2D loop series L2→L3→L4→L5→L2. Consequently, a 3D loop is represented by a number of 2D loops. Naturally, all the above identification processes will be performed automatically by computer.



(a)

(b)

(c)

Fig. 5. 3D loop

3.3 Finalization of Block Shape and Volume

The algorithm of block identification may be called voxel (volume element) propagation. It is similar to the method of spatial-occupancy enumeration which is often used when dealing with the problem of computer graphics, and in which a solid, composed of known faces, is decomposed into cells arranged in a fixed, regular grid (Foley et al., 1992).

The basic procedures of voxel propagation method are shown in Fig. 6. First, an original voxel is positioned at a certain location, and the voxel propagates. A cube-shaped voxel is assumed. In the propagation process, each voxel will continue to propagate until all the six sides of it are bounded with neighboring voxels or discontinuities. It are obvious that one propagation procedure can identify one block, and it is the location of the original voxel that determines which block will be found by a propagation procedure. By positioning a number of original voxels, all the blocks composing rock mass of the modeled region can be identified.

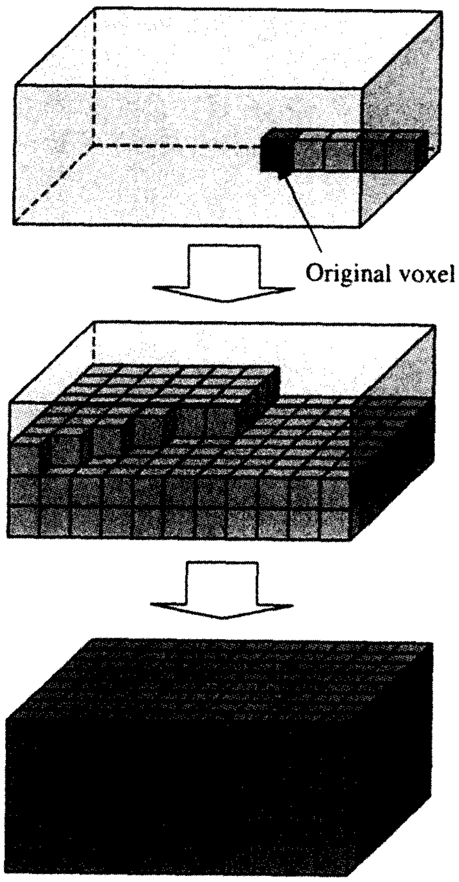


Fig. 6. Voxel propagation process

To make sure that the propagation process identifies a relevant block, the original voxel is positioned with the cursor of interactive graphics. The position of an original voxel is first determined in two-dimensional space by picking some point with the mouse on the two-dimensional graphic of a given excavation face. Then, the chosen point is transformed from two-dimensional space into three-dimensional space, and is slightly shifted along the direction perpendicular to the excavation face to make sure that the point is within studied rock mass. By counting the number of voxels, the volume of the block can be determined.

Therefore, the theorem for the removability of a block formed by the identification method considering the finite persistence of discontinuities can be expressed as:

Hwang-Ohnishi theorem: If the common part of the half spaces, intersected by discontinuities and excavation planes on the stereographic projection, is the null event, then an actual finite block can be formed and its existence can be determined by the stereographic projection. If the stereographic projection zone of the half spaces is not the null event, then the actual block volume in three-dimensional space is infinite.

Based on the above theorem, the removability of rock blocks formed by the identification method considering the finite persistence of discontinuities can be detected.

4. Example of Application to Tunnel

The example site selected for this study is the large tunnel in the Second Meishin Expressway (Niida and Tanaka, 1999) between Nagoya and Kobe. This tunnel construction is the large and long tunnel construction based on block theory. The removability and stability analyses of rock blocks formed by the identification method using voxel propagation process are performed. To illustrate the applicability of the suggested method for a stability evaluation in large tunnel constructions, the analytical results are examined and compared with those of the Japan Highway Public Corporation (JH).

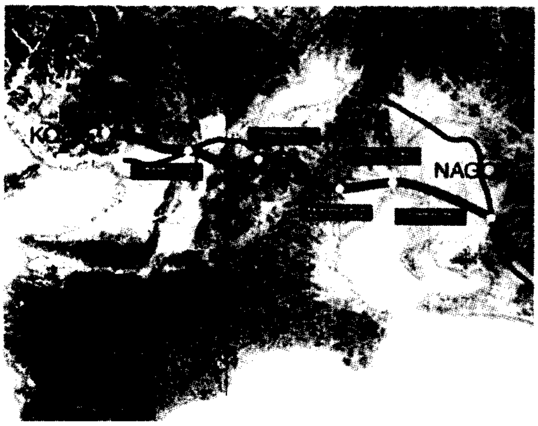


Fig. 7. Location of large tunnel

4.1 Large Tunnel Construction

The Second 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 the speed up to 140km/h, which will make it by far the fastest expressway in Japan. In order to accommodate 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. 7, the large tunnel in the Second Meishin Expressway is 3800m long and goes through the mountain district between Osaka and Nagoya.

Fig. 8 shows the standard cross-section of the large tunnel. The standard cross-section of the large tunnel in this expressway is very large (200m^2) and wide (18m) compared to ordinary tunnels. The ratio of width to height is 0.65. The 5m diameter 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). Before the excavation of the main tunnel, support pattern for the big section is designed based on the actual TBM excavation results.

4.2 Geographical Features and Geology

The district around the tunnel belongs to the inner side of Southwest Japan and consists, topographically, of the Suzuka Mountains and the hilly lands distributed on both

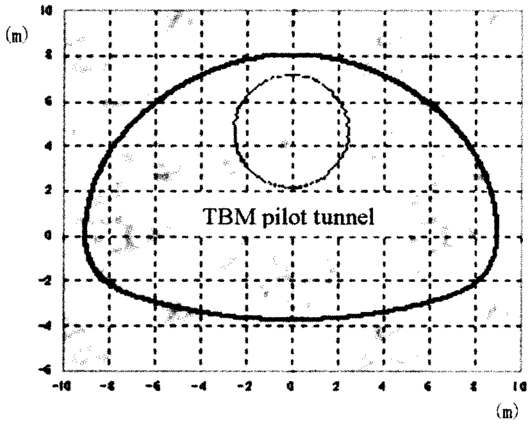
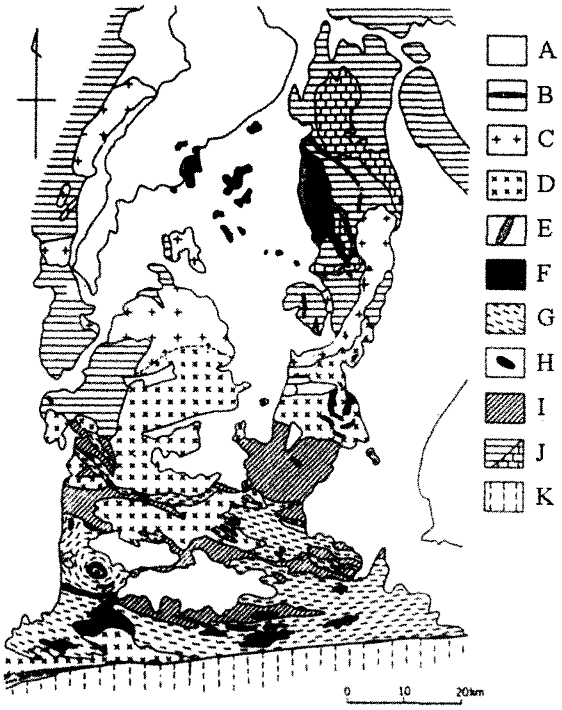


Fig. 8. Cross-section of large tunnel

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 develop along the swamp and river around the tunnel.

The Suzuka 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. 9 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) 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.



(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. 9. Geological map of the study area

4.3 Key Block Analyses Using Discontinuity Information from TBM Pilot Tunnel

The removability and stability analyses in the large tunnel were performed. In this section, to demonstrate the validity and applicability of the proposed analysis method, the analytical results are examined and compared with those of the Japan Highway Public Corporation. The key block analysis of the Japan Highway Public Corporation (JH) was based on the assumption of infinite persistent discontinuities, and considering the effects of discontinuity persistence was not possible using it. However, the key block analysis of this study considered finite persistence of discontinuities.

The large tunnel was modeled as shown in Fig. 10, and discontinuities were generated within the modeled

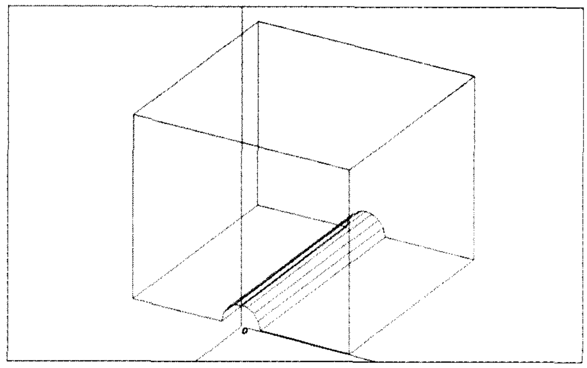


Fig. 10. Modeling of large tunnel

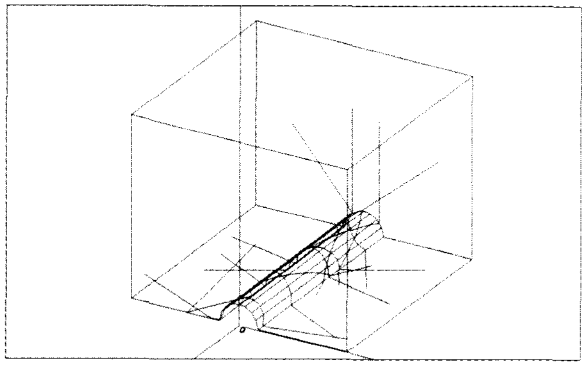


Fig. 11. Discontinuities generated by discontinuity disk model

region as shown in Fig. 11. In this study, the radii of discontinuity disks were determined to be 45m, which is 2.5 times the tunnel width (18m). The radii of discontinuity disks were determined by a trial and error method and the concept of representative elemental volume (REV). The effects of scale on rock properties, occurring because of rock heterogeneity and discontinuity, cause results on small-scale rock to be highly variable; this variability is increased by the presence of discontinuities. When the size is large enough that measured values are essentially consistent with repetition, the REV has been reached. This concept applies to all rock properties that are affected by the discontinuity structure.

Fig. 12 shows the polar points of the observed discontinuity orientations projected on the Schmidt (equal area) net. The polar points were plotted directly from discontinuity data acquired through the investigation of the TBM pilot tunnel in situ. Table 1 shows the number of key blocks in STA333 ~ 335. The distance between each STA is 100m. Three key blocks were detected in STA333 ~ 335. The number of key blocks in this study was exactly the same as that of the Japan Highway Public Corporation as shown in Table 1. The volume of key blocks in this study was almost the same as that of the Japan Highway Public Corporation. Table 2 shows the volume of Key block No.1.

Key blocks in STA334 ~ 335 are shown in Fig. 13. Two key blocks were judged unstable because they could not be supported by standard supports. Both key blocks

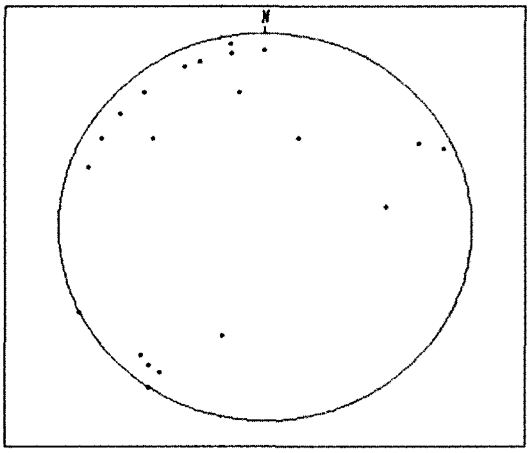


Fig. 12. Schmidt (equal area) net of observed discontinuities

Table 1. Key blocks in STA333 ~ 335

STA.	This study (R=45m)	Japan Highway Public Corporation (R=∞)
333 ~ 334	0	0
334 ~ 335	3	3

Table 2. Volume of key block No.1

No.	This study (R=45m)	Japan Highway Public Corporation (R=∞)
1	293.58	288.9

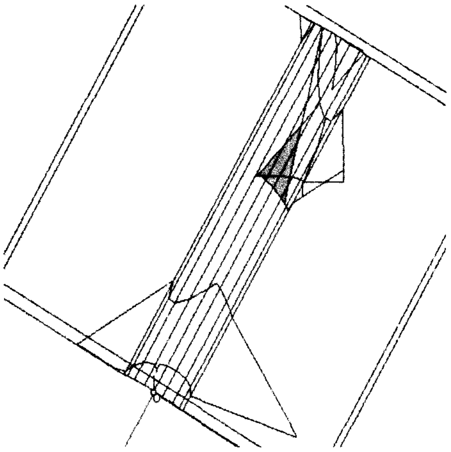
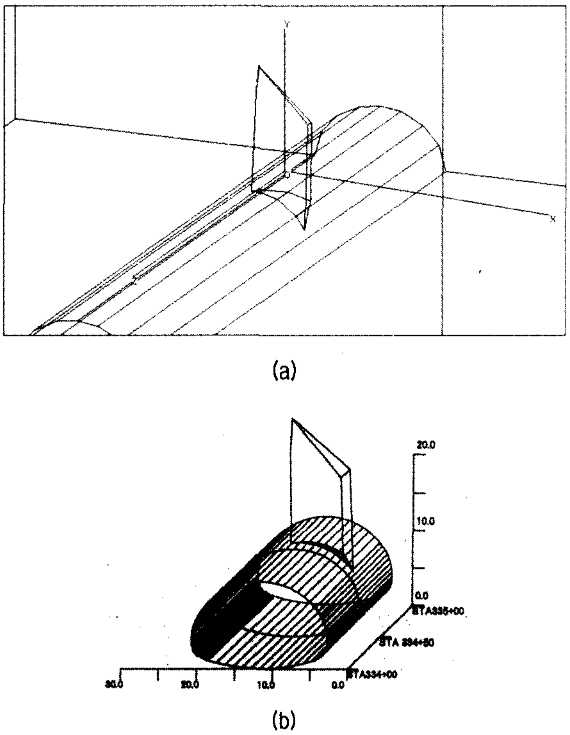


Fig. 13. Key blocks in STA334 ~ 335



(a)

(b)

Fig. 14. Key block No.1

have slender wedge shapes in the up-down direction because the discontinuities in the vertical direction are dominant in situ.

The upper case key block No.1 of this study is compared with that of the Japan Highway Public Corporation as shown in Fig. 14. Fig. 14(a) shows the upper case key block No.1 of this study. Fig. 14(b) shows the upper case key block No.1 of the Japan Highway Public Corporation. Viewpoints in each key block are slightly different. However, the upper case key block No.1 of this study shows a good match with that of the Japan Highway Public Corporation.

5. Conclusions

In this paper, a new key block analysis method considering the persistence of discontinuities has been proposed as a stability evaluation method in tunnel constructions. The key block analysis method considering discontinuity persistence is briefly described below.

(1) Discontinuities are represented by the discontinuity disk model.

(2) Unconnected discontinuities are eliminated from the discontinuity system, the connectivity of discontinuities will be calculated, and then the discontinuities that form a block will be identified. An original voxel is positioned at a certain location, and then the voxel propagates.

(3) The removability and stability analyses of rock blocks formed by the block identification method are performed.

Using the above-mentioned method, a key block analysis method considering the persistence of discontinuities is developed in this paper.

The key block analysis method developed by authors is applied to the large tunnel based on actual discontinuity information observed in situ. The examination and comparison of the suggested with the analytical results have confirmed its applicability to stability evaluation in tunnel constructions.

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References

1. Collaborative Research Group for the Granites around Lake Biwa (1982), "Granitic masses around Lake Biwa, Southwest Japan - On the granites in the Koga area-", *J. of The Geol. Soc. of Japan*, Vol.88, No.4, pp.289-298.
2. Cundall, P. A., Voegele, M. and Fairhurst, C.(1977), "Computerized design of rock slopes using interactive graphics for the input and output of geometrical data", *16th U. S. Sym. Rock Mech.*, pp.5-14.
3. Dershowitz, W. S.(1984), *Rock Joint Systems*, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge.
4. Foley, J. D., Dam, A. V., Feiner, S. K. and Hughes, J. F.(1992), *Computer Graphics*, 2nd Ed., Addison-Wesley Publish Company, New York.
5. Goodman, R. E. and Shi, G. H.(1985), *Block Theory and Its Application to Rock Engrg.*, Prentice-Hall.
6. Hoek, E., Kaiser, P. K. and Bawden, W. F.(1995), *Support of Underground Excavations in Hard Rock*. A. A. Balkema Publishers.
7. Hwang, J.-Y., Park, S.-Z., Ohnishi, Y. and Ohtsu, H.(2000), "Application of Stability and Deformation Analysis for Discontinuous Rock Mass to Rock Slope", *Proc. 35th JSG Nat'l Sym.*, pp.1467-1468.
8. Hwang, J.-Y., Ohnishi, Y. and Nishiyama, S.(2002), "Key Block Analysis in Tunnel Construction for the Geological Disposal of High-Level Radioactive Waste", *Proc. 2nd Japan-Korea Joint Seminar on Geoenv. Engrg., Japan*, pp.91-98.
9. Kimura, K., Yoshioka, T., Imoto, N., Tanaka, S. Musashino, M. and Takahashi, Y.(1998), *Geology of the Kyoto-Tohokubu district. With Geological Sheet Map at 1:50,000*, Geol. Surv. Japan.
10. Long, J. C. S. and Billaux, D. M.(1987), "From field data to fracture network modeling; an example incorporating spatial structure", *Water Resources Research*, Vol.23, No.7, pp.1201-1216.
11. Mardia, K. V.(1972), *Statistics of Directional Data*, Academic Press Inc., London.
12. Niida, H. and Tanaka, Y.(1999), "Verification on Large-section Tunnel Support Structure in Fresh Granite Zone", *Tunnels and Underground*, Vol.30, No.1, pp.25-34.
13. Ohnishi, Y., Nagano, K. and Fujikawa, T.(1985), "Evaluation of Stability of Excavated Jointed Rock Mass by Block Theory", *J. Geotech. Engrg.*, JSCE, No.364 / III-4, pp.209-218.
14. Ohnishi, Y., Nakagawa, S. and Tanaka, M.(1994), "Methods of Estimation for Geometric Distributions of Rock Joints", *J. Geotech. Engrg.*, JSCE, No 499 / III-28, pp.59-68.
15. Pahl, P. J.(1981), "Estimating the mean length of discontinuity traces", *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, Vol.18, pp.221-228.

16. Pollard, D. and Aydin, A.(1988), "Progress in Understanding Jointing over the Past Century", *Geol. Soc. of America Bulletin*, Vol.100, pp.1181-1204.
17. Priest, S. D.(1993), *Discontinuity Analysis for Rock Engrg.*, Chapman & Hall.
18. Shi, G.-H.(1989), *Block System Modeling by Discontinuous Deformation Analysis*, Ph. D. Thesis, Univ. of California, Berkeley.
19. Warburton, P. M.(1980), "A sterological interpretation of joint trance data", *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, Vol.17, pp.181-190.
20. Yu, Q.(2000), *Analyses for Fluid Flow and Solute Transport in Discrete Fracture Network*, Ph. D. Thesis, Kyoto Univ., Kyoto.
21. Zhang, L. and Einstein, H. H.(2000), "Estimating the intensity of rock discontinuities", *Int. J. Rock Mech. Min. Sci.*, Vol.37, Issue 5, pp.819-837.

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