Study on the Jointed Rock Mass for the Excavation of Hyper-Kamiokande Cavern at Kamioka Mine

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Abstract

Hyper Kamiokande (Hyper-K) which is a next generation megaton water Cherenkov detector has been planning at Kamioka mine. Feasibility studies for site selection and cavern stability are described in this paper. So at first, geological survey and basic elastic FEM analysis for the evaluation of cavern stability were performed. A proposed site for Hyper-K is in Tochibora mine which locates in south of Kamioka mine. The rock mass of this site is composed from hornblende biotite gneiss and migmatite. The condition of rock mass is very good for the excavation of huge caverns. As a result of basic stability analysis and comparison from various view points, the cavern type of two huge parallel tunnels is the most favorable for Hyper-K.

Next step, additional rock joint survey, laboratory test of rock joints and pull-out test for two types of cable bolts were performed. Joint orientation and mechanical properties of rock joints and cable bolt were obtained. Two types of analysis for jointed rock mass were performed to consider the effect of rock joints and support system. As a result, the shear strength of ST-cable bolt with dimples is 5 times higher than usual PC-cable bolt. This ST-cable bolt is a very effective support system. And joint orientation is very important factor to decide the cavern axis.

1. Introduction

Institute for Cosmic Ray Research University of Tokyo (I.C.R.R.) has a future plan of the Hyper Kamiokande (Hyper-K), which is a next generation megaton water Cherenkov detector. It is necessary for the construction to excavate huge cavern below 500m of overburden at Kamioka mine. Feasibility studies for site selection and cavern stability were performed. At first, geological survey based on the geological maps of Kamioka mine were performed to choose a favorable site for Hyper-K. And basic isotropic elastic FEM analysis was also performed to evaluate cavern stability and type.

However, this analysis is not able to consider the influence of rock joints in rock mass. So next step, two types of discontinuous analysis were applied to estimate the cavern deformation behavior and the effect of support system in jointed rock mass. These analyses need characteristics of joint orientation, mechanical properties of joints and support system. So investigation of joint orientation, obtaining joints samples and pull-out test of cable bolts were performed in the existing tunnel in the proposed site.

The items introduced in this paper are as follows.

- Geological survey
- Basic elastic analysis for cavern stability and type
- Investigation of joint orientation

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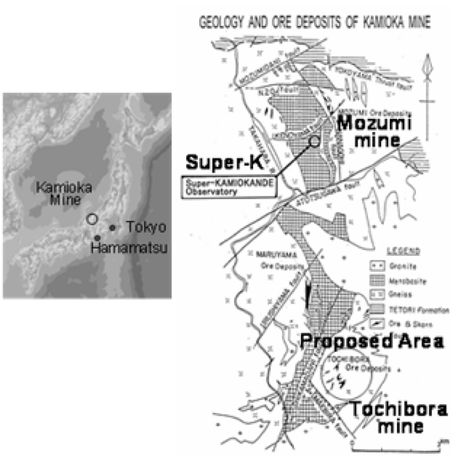

Fig. 1 Location of Kamioka mine and Tochibora mine.

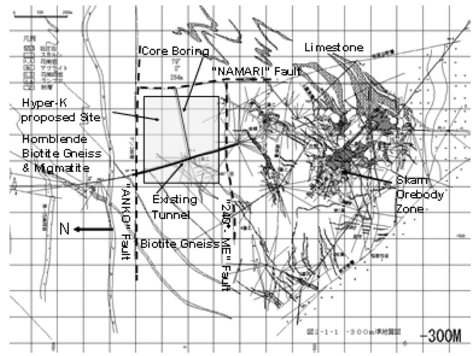

Fig. 2 Proposed site and geological map of +550mEL in Tochibora mine.

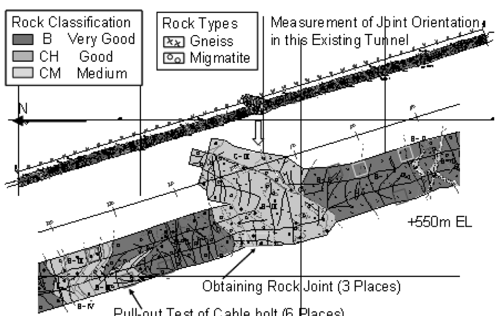

Fig. 3 Rock type and classification of the existing tunnel.

- Laboratory test of rock joints
- Pull-out test of cable bolts
- Analyses for jointed rock mass

2. Geological Survey

Location of Kamioka mine is around the center of Japan as shown in Fig. 1. There are several mines for example Mozumi, Maruyama and Tochibora mine in Kamioka mine. Requirements for construction of Hyper-K are overburden of 500m at least and competent rock condition for huge cavern stabilizing for long term. Geological survey based on geological maps of Kamioka mine was performed. As the result, Tochibora mine around +550mEL is the most appropriate location with very competent rock condition. This proposed site is surrounding faults such as Anko, Namari and 240°-Me faults, and the extent is about 300m $\times$ 300m as shown in Fig. 2. Examining in-situ rock condition and geological sketching from rock engineering aspects were also performed along the existing tunnel in this site as shown in Fig. 3. The rock mass of proposed site is composed from hornblende

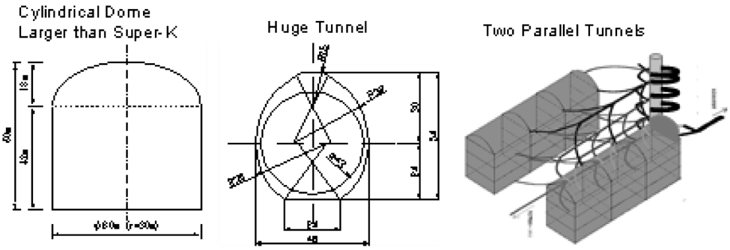

Fig. 4 Cavern type for Hyper Kamiokande.

Table 1 Comparison of cavren type.

Cavern Type		Multiple Domes	Single Tunnel	Two Parallel Tunnels
Construction Period & Cost		×	○	○
Early Observation Startup		△	△	○
Observation during Maintenance		○	×	○
Cost Performance of Detector Tank		×	○	△
Cavern Stability		◎	○	○
Total Evaluation		×	△	○
Size of one Cavern (m)	Height	60.0	54.0	54.0
	Width	Φ60	48.0	48.0
	Length	—	500	250
Vertical Cross Section Area (m^2)		3,368	2,076	2,076
Volume of one Cavern (m^3)		152,600	1,038,000	519,000
Required No. of Caverns		7	1	2
Total Volume of Caverns (m^3)		1,068,200	1,038,000	1,038,000

biotite gneiss and migmatite. And Japanese rock classification is B∼CH which represents very competent rock condition.

3. Basic Elastic Analysis

For Hyper-K cavern of megaton size, multiple domes, single tunnel and two parallel tunnels are considered as shown in Fig. 4. Basic isotropic elastic FEM analysis was performed to estimate the stability of these three type caverns. Young's modulus of rock mass is decreased empirically according to the rock classification. The dome cavern is the most stable, and also stabilities of single and two parallel tunnels are satisfied. The result of comparison of cavern type is shown in Table 1. Considering observation during maintenance and construction period & cost, type of two parallel tunnels is the most favorable.

In this basic elastic analysis, the influence of rock joint is indirectly considered to decrease Young's modulus. However anisotropic deformation behavior of jointed rock mass is not able to be considered. So after this section, additional investigation and laboratory & in-situ test are described to obtain the characteristics of joint orientation, mechanical properties of joint and support system for discontinuous analyses.

4. Investigation of Joint Orientation

Additional investigation of joint orientation was performed along the existing tunnel in the proposed site in Fig. 3. Joint orientation of strike and dip is represented as pole which is shown in stereographic projection. Fig. 5 shows the stereographic projections and pole density contours of gneiss and migmatite. The orientations of the first major joint set of gneiss and migmatite are strike of E-W and dip of ±70∼90°. The second major joint set of gneiss is strike of NE-WS and

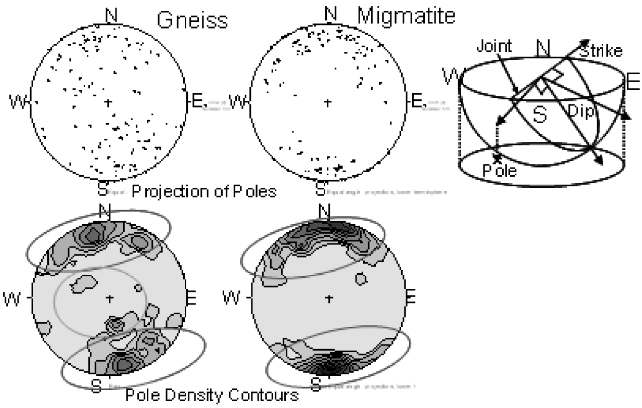

Fig. 5 Stereographic projections and pole density contours of joints.

dip of ±40∼50°. Because the direction of the existing tunnel is almost N-S, many joints of E-W direction are apt to appear along the existing tunnel. Conversely the joints of N-S direction are difficult to appear. It is desirable for correct evaluation of joint orientation to investigate additionally along the right-angled tunnel.

5. Laboratory Test of Rock Joints

In order to estimate the mechanical properties of rock joint, direct shear tests were performed. Specimens of gneiss rock joint (diameter=150mm, length=200mm) were obtained by core drilling at three places in the existing tunnel in Fig. 3. Migmatite rock joint was not able to be obtained because of inadequate rock condition. Regarding apparatus for direct shear test, its capacities of normal and shear load are 1MN respectively. Situation of core drilling and direct shear test are shown in Fig. 6.

The procedure of direct shear test is first applying established normal stress (2,5,10MPa), and secondly applying shear displacement. During the test, normal stress and displacement, shear stress and displacement are measured. Normal stiffness of joint is obtained as inclination between normal stress and normal displacement. Similarly shear stiffness is obtained as inclination between shear stress and shear displacement. Stiffness of joint is very important factor to represent the deformability of jointed rock mass. Cohesion and internal frictional angle are obtained from shear strength and normal stress. Dilatancy angle is obtained as inclination between normal displacement and shear displacement during shear. The results of these relationships are shown in Fig. 7. Obtained mechanical properties of joint are as follows.

- Normal stiffness = 67N/mm^2/mm, Shear stiffness = 60 N/mm^2/mm
- Cohesion = 0.57/mm^2/mm, Internal frictional angle = 33°
- Dilatancy angle = 2.4°

6. Pull-Out Test of Cable Bolts

For large cavern such as underground power house, usually PS (Pre-Stressed) anchor which applies compressive force to rock mass is adopted for support system. PS anchor is very effective but expensive. It is very important for Hyper-K to reduce construction cost. So, another economical and effective support system such as cable bolt should be applied.

Fig. 6 Situation of core drilling and direct shear test for joint.

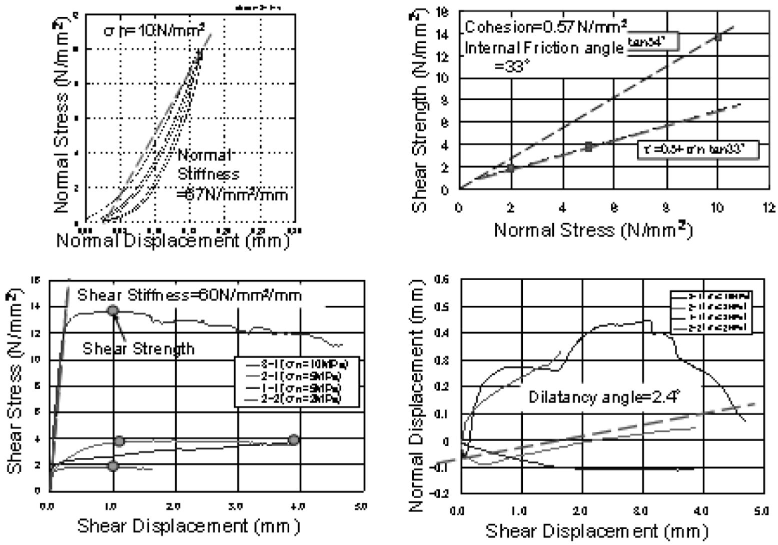

Fig. 7 Results of normal and shear test of joints

Usual PC-cable bolt without dimples and special ST-cable bolt with dimples were prepared. To estimate the mechanical properties of two type of cable bolt, pull-out tests were performed in the existing tunnel as shown in Fig. 3. PC and ST-cable bolts were inserted into the drilled holes of 70cm depth in gneiss and migmatite, and were grouted. After hardening, pull-out tests were performed by the equipment of jack, load cell and dial-gauge. Displacement and load were measured during the tests. The situation of pull-out test is shown in Fig. 8.

The results of pull-out test are shown in Fig. 9. The relationship between load and displacement of cable bolt is represented by bilinear model of strength and stiffness. The difference of strength and stiffness between rock types is small. And the difference of stiffness between cable bolt types is also small. However the strength of ST-cable bolt and PC-cable bolt are above 270kN/m and 53kN/m respectively. The strength of ST-cable bolt is 5 times larger than the strength of PC-cable bolt. This large strength is considered to be occurred by the dilatancy effect of dimples. So ST-cable bolt is considered to be a very effective and economical support system.

7. Analyses for Jointed Rock Mass

Two dimensional UDEC (Universal Distinct Element Code) and Crack Tensor method were applied for estimating the deformation behavior of jointed rock mass. Distinct element method has been proposed by Cundall et al [1], and UDEC is a

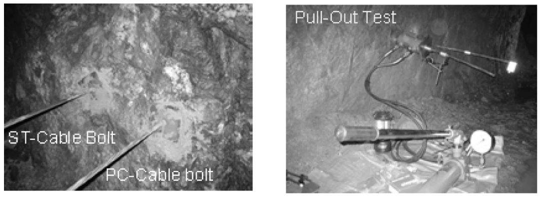

Fig. 8 Situation of pull-out test of cable bolt.

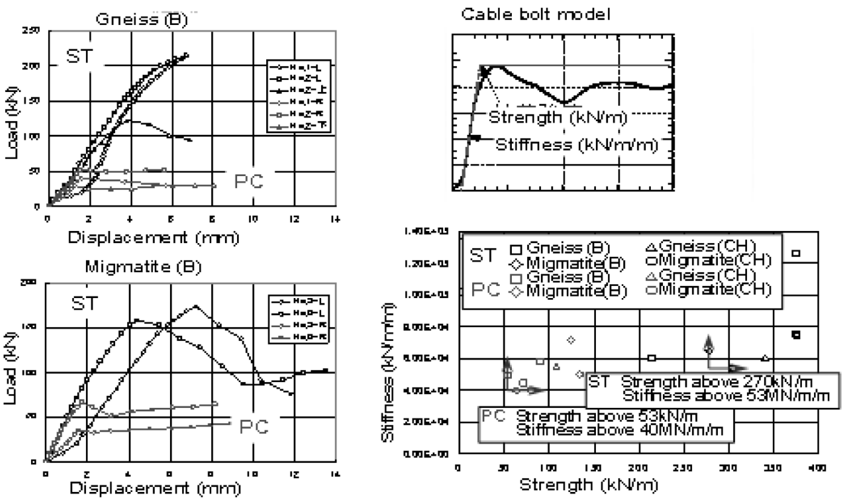

Fig. 9 Results of pull-out test

Table 2 Input parameters for UDEC anf Crack Tensor method.

	UDEC	Crack Tensor
Initial Stress	Isotropic Stress:σh = σv = 14.4 (N/mm²)	
Intact Rock	Young's Modulus=64.3 kN/mm² Poisson's Ratio=0.25	
Joint	Normal Stiffness=67N/mm²/mm Shear Stiffness=60N/mm²/mm	
	Cohesion=0.57N/mm² Frictional angle=33° Dairatancy Angle=2.4°	–
ST-cable bolt	Shear Strength=270kN/m Shear Stiffness=53MN/m/m	–
PC-cable bolt	Shear Strength=53kN/m Shear Stiffness=40MN/m/m	–

trade edition code. UDEC simulates the response of discontinuous media composed from intact blocks and discontinuities (such as jointed rock mass) with support system (such as cable bolt) [2]. Crack Tensor method has been proposed by Oda et al [3], which simulates the response of equivalent anisotropic continuum media considered the influence of joints. The input parameters of UDEC and Crack Tensor method are shown in Table 2. Estimation of support system by using UDEC and estimation of cavern direction by using Crack Tensor method

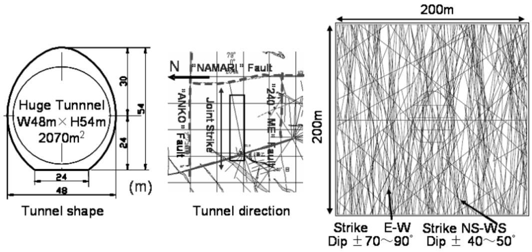

Fig. 10 Analysis model of UDEC.

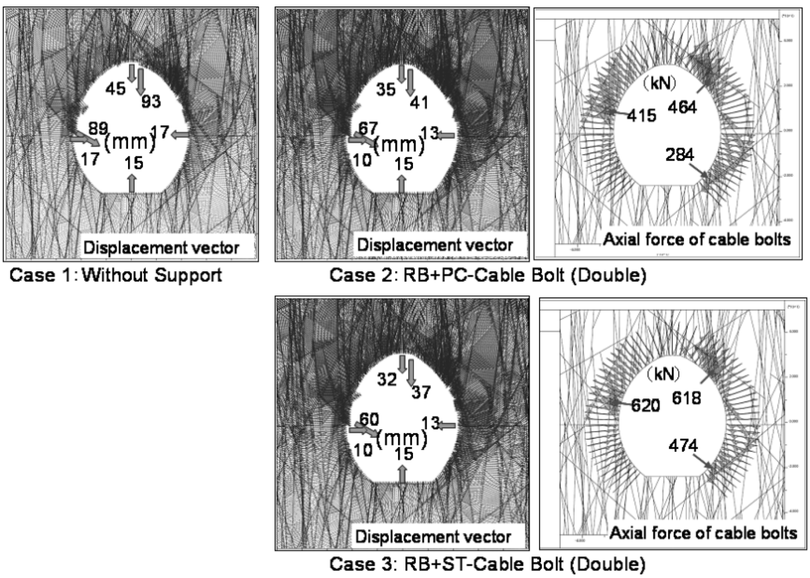

Fig. 11 Displacement and cable axial force of UDEC.

are described in this section. Analysis cases for UDEC and Crack Tensor method are as follows.

UDEC (Cavern direction is E-W)

- Case 1 : Without support
- Case 2 : Double PC-cable bolt(Length=15m,Space=2m) and rock bolt
- Case 3 : Double ST-cable bolt(Length=15m,Space=2m) and rock bolt

Crack Tensor method (Without support)

- Case 4 : Cavern direction is E-W
- Case 5 : Cavern direction is N-S

The model of UDEC is shown in Fig. 10. The cavern direction is E-W, and joints are generated statistically according the orientation of major joint sets. At first initial stress analysis is performed, secondly four excavation steps with support system are analyzed in order. The results are shown in Fig. 11. Unique deformation behavior of blocks appears around right roof and upper left side wall. The displacements of right roof and upper left side wall in Case 1, Case 2 and

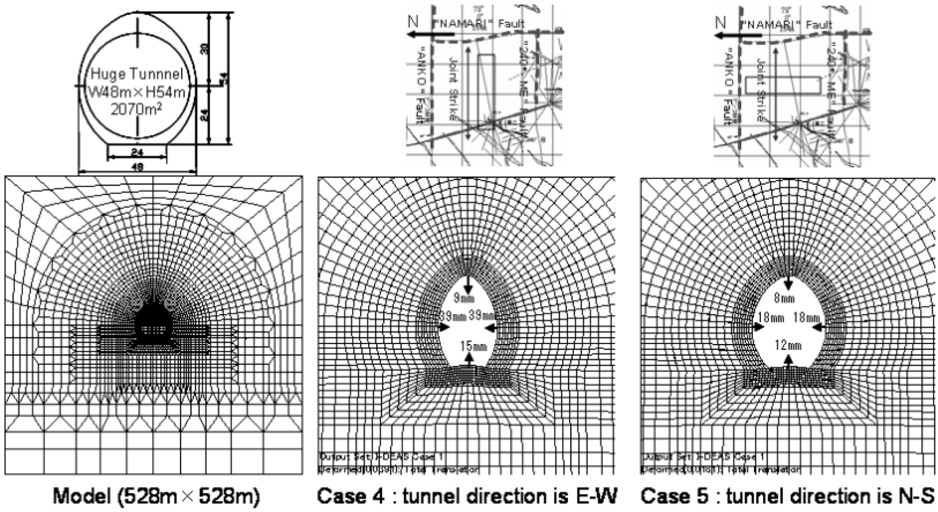

Fig. 12 Analysis model and displacement of Crack Tensor mathod.

Case 3 are 93,89mm, 41,67mm and 37,60mm respectively. The displacements of Case2 and Case 3 are less than the displacement of Case 1 because of the effect of support system. Case 3 shows support system of ST-cable bolt is more effective than PC-cable bolt due to the smallest displacement and bigger axial force of cable bolt. In each Case there is small difference of displacement between left and right side wall. The dip angle of major joint set is $\pm 70 \sim 90°$, therefore joints are distributed symmetrically in this cavern cross section model.

The model and results of Crack Tensor method are shown in Fig. 12. The displacements of left and right side wall in Case 4 are 39mm and 2 times bigger than the displacements of 18mm in Case 5. The joint strike direction of major joint set is pallalel to the cavern cross section model of Case 5, therefore it is considered that there are few joints in this cross section model and the displacement is small. Crack Tensor method is able to consider the influence between joint orientation and cavern direction. According to the results of this investigation of joint orientation, the cavern direction of E-W is more stabilized than N-S direction.

8. Discussion

Stability and deformability of huge cavern for Hyper-K by using basic isotropic elastic analysis, UDEC and Crack Tensor method were described. It is important for design of Hyper-K to combine several analysis methods. Basic isotropic elastic analysis is able to consider cavern layout, shape and size. Crack Tensor method should be used to estimate the anisotropic deformation behavior of jointed rock mass and cavern direction. And UDEC is useful to design and verify support system.

In these analyses, initial stress condition and Young's modulus of rock mass were assumed. Initial stress condition and Young's modulus of rock mass is one of the most important factors for the cavern anisotropic deformability and stability. In the future examination, measurements of initial stress and in-situ rock tests for estimation of Young's modulus of rock mass are indispensable. Investigation of joint orientation was performed along the one existing tunnel of N-S direction. Therefore joints of parallel to the tunnel direction are possible to be missed. Additional joint investigation should be performed along the different direction for example E-W and vertical direction.

9. Conclusions

In this paper feasibility studies for site selection and cavern stability were described. The following points are the most important aspects.

- Tochibora Mine around +550mEL is the most appropriate location with very competent rock condition for Hyper-K. The proposed site is surrounding faults such as Anko, Namari and 240°-Me faults, the extent is about 300m × 300m. Japanese rock classification is B∼CH and very good rock condition.
- For Hyper-K cavern of megaton size, multiple domes, single tunnel and two parallel tunnels are considered. Stability of three types of cavern is estimated by basic elastic FEM analysis. Type of two parallel tunnels is the most favorable, considering observation during maintenance and construction period & cost.
- Joint investigation, laboratory test of joints and pull-out test of cable bolts were performed to estimate joint orientation and mechanical properties of joint and cable bolt. The strength of ST-cable bolt with dimples is 5 times larger than usual PC-cable bolt. ST-cable bolt is economical and effective support system.
- UDEC and Crack Tensor method were used to simulate the deformation behavior of jointed rock mass. UDEC is useful to design and verify support system. Crack Tensor method is able to consider the influence between joint orientation and cavern direction. It is important for design of Hyper-K to combine several analysis methods.

References

[1] Cundall, P. A., *A Computer Model for simulating Progressive Large Scale Movements in Blocky Rock Systems* (1971) Proceedings of the Symposium of the International Society for Rock Mechanics(Nancy,France,1971), Vol.1, Paper No. 2–8.
[2] Itasca Consulting Group,Inc., *UDEC Universal Distinct Element Code User's Guide.* (2000).
[3] Oda, M., *Fabric tensor for discontinuos geological materials.* (1982) Soile & Foundations, Vol. 22, No. 4, pp. 541–556.