Geological risk reduction management ahead of tunnel face

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ABSTRACT**:** In construction of the mountain tunneling in Japan, the accident resulting from face collapse accounts for about 65% of the total. Therefore, in order to perform tunnel construction safely, it is important to grasp the situation of geology, bedrock and groundwater of an unexcavated part in detail before construction.

This paper reports the risk management example which reduced geological risks and performed suitable construction by various geological investigations during construction stage in deteriorated ground that was predicted to be in the mountain tunnel.

In these sections of ground, while geological survey had been inadequate in a prior stage, tunnel The recent trend of tunneling is toward larger and longer tunnels. From the viewpoint of safety and efficiency of operation, it is highly advantageous to grasp geological conditions before tunneling.

Geological evaluation ahead of tunnel face and face stability are especially an important issue to make effective use of the TBM was started, and face collapse accident was encountered.

Since this tunnel has long length and high overburden, suitable and more effective investigation technique which can be performed in a short time is needed during construction.

Test for physical properties and consistency of soil applied the concrete slump test was carried out in altered sandy Granite ground. Moreover, fractured and altered zone are distributed repeatedly in Rhyolitic welded tuff ground, it analyzed by the seismic imaging method using three-component geophone.

These investigation results were analyzed synthetically, drainage drift and advanced drainage boring were performed, the geological risk was reduced and tunnel construction was continued more safely and economically.

KEYWORDS : Mountain tunneling ,Geological risk reduction, Seismic imaging method

1. INTRODUCTION

The recent trend of tunneling is toward larger and longer tunnels. From the viewpoint of safety and efficiency of operation, it is highly advantageous to grasp geological conditions before tunneling.

Geological evaluation ahead of tunnel face and face stability are especially an important issue to make effective use of the TBM. In practical terms, prediction of deteriorated bedrock and weak zones such as faults are particularly important in managing the tunneling operation. For this purpose, various physical tests of ground sample and horizontal seismic profiling were tried in this study.

An important feature of the seismic imaging ahead of tunnel face must be rapid turn-around from data acquisition to analysis and precision of results.

Ideally, data acquisition should not interrupt tunneling operations, and data should be processed on-site to arrive at an interpretation of geological conditions ahead of tunnel face within 1 or 2 days.

In this paper, geo-engineering evaluation of face stability and geological condition of unexcavated ground are reported using two above-mentioned techniques.

Furthermore, prevention of the geological risk and the management reflected in tunnel construction are also described.

Face stability of altered sandy soil was grasped by the slump corn test that was able to be analyzed with low-cost and a short time.

On the other hand, it is shown that geological conditions ahead of tunnel face can be imaged with high resolution.

A three-dimensional seismic image is created using equi-travel time plane algorithm developed for analyzing the image of reflecting surfaces. In additon, required precision is improved by using seismic signals from three-component geophones in tunnel.

Based on these investigation results, the geological risk management in the viewpoint of risk efficiency is also described about two case examples.

2. MANAGEMENT EXAMPLES OF THE GEOLOGICAL RISK PREVENTION

2.1 Case Example 1

2.1.1 Background of investigation

Although Granite is distributed over periphery of west portal side in this tunnel, a part of these rock masses receive hydrothermal alteration and becomes fine-grained soil, is distributed complicatedly(refer to Figure 2.1).

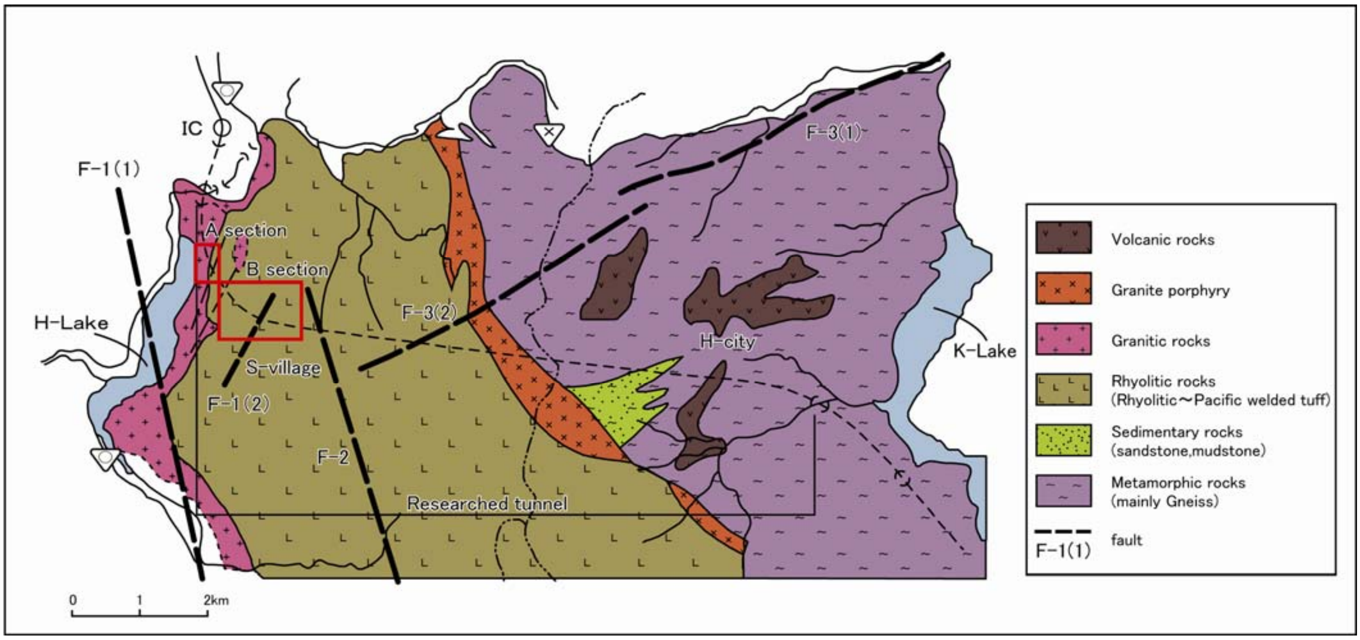

Figure 2.1 Locality and Geological map of researched tunnel.

In this section, although excavating of an advancing drift (pilot tunnel) was started using TBM, tunnel face collapsed in several places.

In order to continue excavation, it is required to study cause of face collapse and face stability in unexcavated part.

Then, physical test, consistency limit by a slump cone and X-ray diffraction analysis were carried out about the sandy soil sampled in tunnel.

2.1.2 Method for investigation and result

Investigation was conducted according to the flow chart shown in Figure 2.2.

Figure 2.3 shows collection position of ground sample and geological distribution in this tunnel. In addition, test result is shown in Table 2.1.

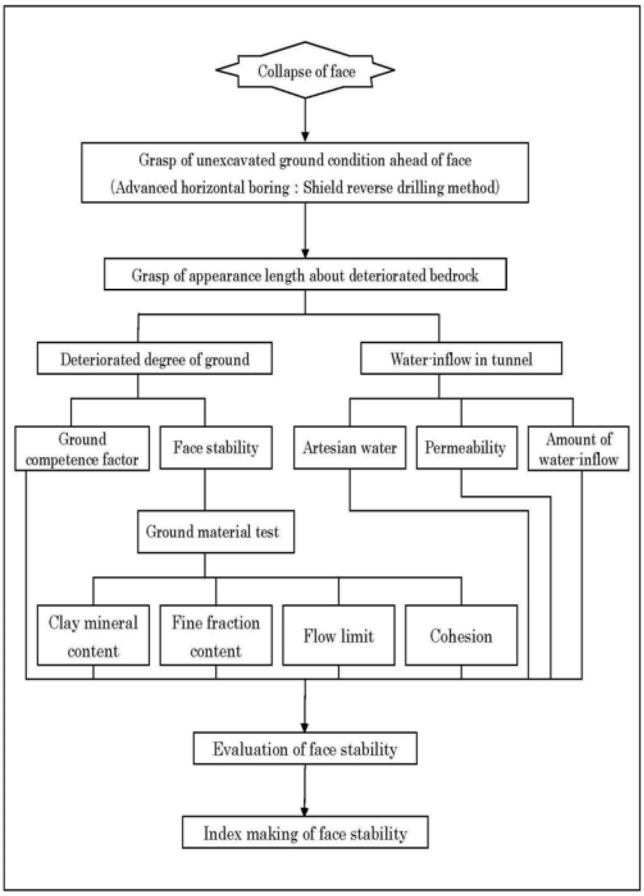

Figure 2.2 Flow chart of investigation

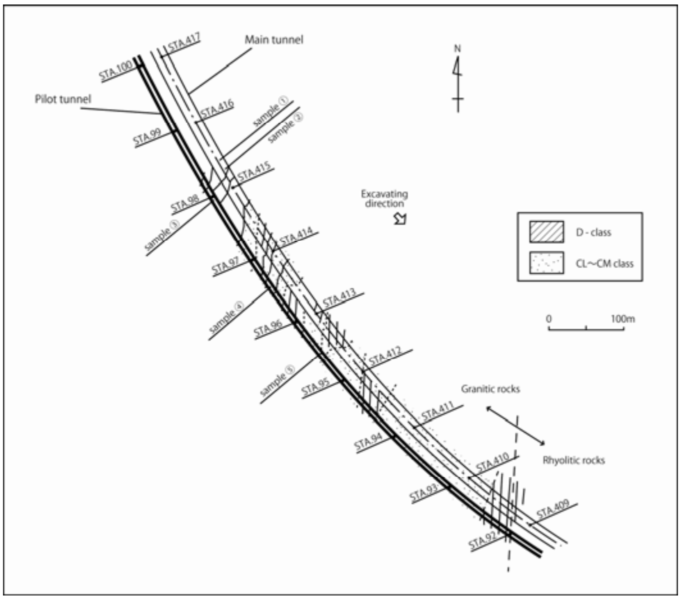

Figure 2.3 Collection position of ground sample and geological distribution in this tunnel.

Table 2.1 Results of the physical test about ground material sampled in tunnel.

Sample No.	Sampling Locality	Soil density ρs (g/cm^3)	water content Wn (%)	uniformity coefficient Uc	coefficient of curvature Uc'	fine fraction content (%)	flow limit (%)	face stability	
								collapse	non-collapse
①	main tunnel STA. 415+40	2.630	1.4	222.57	1.90	15.3	16.8		○
②	main tunnel STA. 415+26	2.632	1.7	87.54	1.19	10.0	9.0	○	
③	pilot tunnel STA. 97+90	2.643	8.7	90.58	1.87	16.1	8.8	vicinity of collapse point	
④	pilot tunnel STA. 96+53.8	2.639	3.6	313.74	2.94	14.8	-		○
⑤	pilot tunnel STA. 95+41.5	2.652	0.6	24.01	2.02	5.4	-	○	

2.1.3 Geo-engineering evaluation of the face stability

About the sample (sample numbers 2 and 5) collected in face collapsed part, the fine fraction content is 10% or less, and the uniformity coefficient is 90 or less.

Basic physical properties of the fine grained soil are thought to be ruled by degree of weathering, mineral composition of wall rock, fine fraction content and grain size distribution. Therefore, the consistency characteristics are effective as the index that evaluates qualitative change and gradation of physical properties synthetically.

The consistency characteristics were examined using flow limit (W*fl* : Nakayama et al., 1999) based on a slump-cone test. The water content for a slump of 30mm is defined to be the flow limit (Matsuo et al., 1970).

The flow limit value means deformation resistance by one's own weight of soil when the moisture ratio is changed. The value to which deformation resistance decreased suddenly was considered to be the moisture ratio that fluidizing starts.

W*fl* in a point where face collapses is approximately 9%. On the one hand, W*fl* in a point of self-standing face shows approximately 15%, and a clear difference is recognized in both (refer to Figure 2.4).

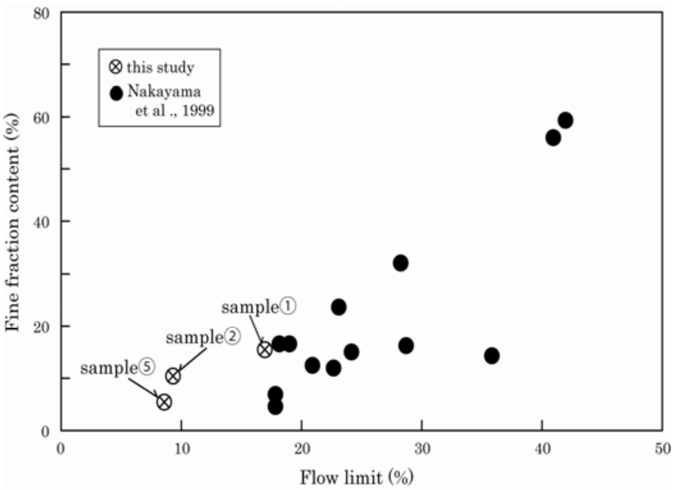

Figure 2.4 Relation between the fine fraction content and the flow limit

As shown in Figure 2.4, positive correlation is between the flow limit value and the fine fraction content.

In the sandy soil (altered decomposed granite soil), it is thought that it will become difficult to mobilize if fine fraction content increases. From analytical result of this case, the stability of face is increasing as fine fraction content increases.

Grain refining and clay alteration advance with alteration and weathering of the base rock.

As a result, when the amount of fine-grained fraction with high plasticity increases, flow limit also become large and the face is stabilized more.

The fine fraction content, uniformity coefficient and flow limit value can serve as an index to the stability of face. About the sample obtained by advanced drilling, the geological situation of unexcavated ground was considered using former two values requested comparatively handily in a short time.

2.1.4 Proposal of tunnel driving method for geological risk prevention

About unexcavated part, it was expected that sandy soil with high possibility of collapsing appeared, and restraint of TBM with face collapse and large volume of water-inflow was feared as well as already excavating part. In addition, complicated geological distribution and geological risk of relating to them were expected in the forward geological boundary from this point.

In order to prevent such geological risks and to construct safety and economical efficiency, construction by NATM instead of TBM was proposed in unexcavated part.

2.2 Case Example 2

2.2.1 Background of investigation

B section of figure 2.1 is located at geological boundary part with Granite and Nohi rhyolite. It was predicted that bed rock of ground in this section has deteriorated remarkably by alteration and the Quaternary fault movement.

About this section, it is necessary to grasp ground condition ahead of face by performing effective geological survey with short time in tunnel before excavation. Furthermore, it is important to make it feed back to construction promptly based on those analytical results.

It is reported on exploration result of above-mentioned bedrock deterioration section and comparison with actual excavation results. The outline of background about geological risk avoidance is also explained.

In addition, seismic imaging which was developed in our company recently, and advanced drilling was used for exploration.

2.2.2 Method for investigation and result

In the tunnel face seismic exploration, a seismic wave is generated by a source set in tunnel. Receivers also located in tunnel detect the signal reflected from a geological boundary ahead of face (Figure 2.4).

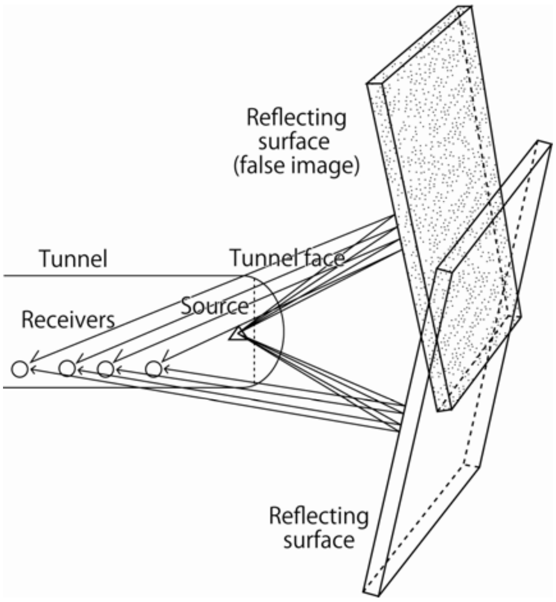

Figure 2.4 Conceptual diagram of seismic imaging ahead of tunnel face.

As seen in Figure 2.5, for several source-receiver pairs, same number of corresponding ellipsoids can be drawn and their common tangent planes forms a plane of reflection.

Imaging by single-component records only provides amplitude component of propagating elastic wave in one direction. So, true propagation direction of waves cannot always be known. As such, direction of incident wave cannot be estimated, which may cause false image of reflecting surface. In addition, data may be contaminated by inclusion of reflection information from outside direction of tunnel axis. Three-com ponent recording is used to solve these problems.

By estimating direction of incidence from three-component records, it becomes possible to enhance arrivals from only around reflecting point on equi-travel time plane.

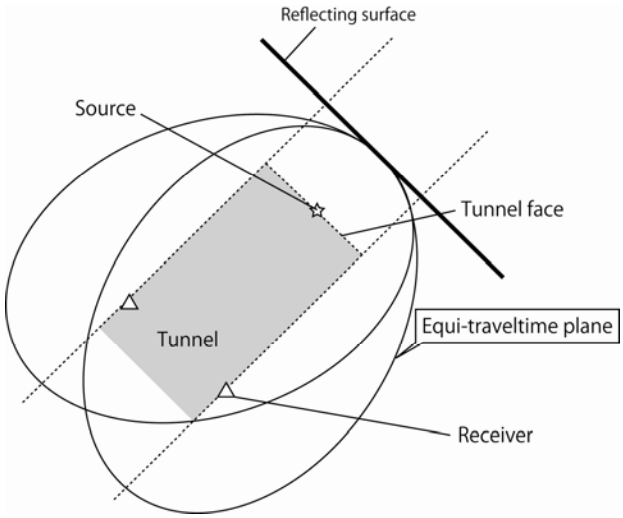

Figure 2.5 Imaging of a reflecting plane by tangential planes of two ellipsoids.

2.2.2 Geo-engineering evaluation of deteriorated ground section

Aspects of the section where the bedrock deterioration had been expected were geotechnologi cally evaluated by using various explorations ahead of face(refer to Figure 2.6 and 2.7). Exploration tools of every section and comparison between exploration result and actual excavation result are shown in Table 2.2.

It almost correspond to the position on reflecting surface detected using seismic imaging ahead of a tunnel face with three component geophones and distribution of deteriorated bedrock zone in actual excavation result.

Table 2.2 Comparison between exploration result and actual result

STA.No.	Probing ahead of face			Comparison between exploration result and actual excavation result.
	Advanced drilling	Drainage boring	Seismic imaging ahead of a tunnel face with three-component geophones	
STA.86+25 ～ STA.85+95	○ (Br.J)		○	It was judged that reflecting surfaces of No.1to 3 were corresponding to deteriorated bedrock that had been confirmed by advanced drilling. It almost agreed to these predicted deterioration part and excavation result.
STA.85+95 ～ STA.85+25	○ (Br.J)		○	According to actual excavation result, fractured brittle bed rock and crushed zone were distributed complexly in section of STA. 85+70 to STA.85+25. Reflecting surface 4 is correspond to appearance starting point of these deteriorated bed rocks .
STA.85+25 ～ STA.84+50	○ (Br.J and Br.K)		○	Altered bed rock and strongly fractured bed rock are distributed complexly in section of STA.85+15 to STA.84+60. Reflecting surface b and 5 are correspond to starting point and terminal point of these deteriorated bed rock zone respectively.
STA.84+50 ～ STA.83+92.4	○ (Br.K)			According to actual excavation, crushed zone appeared in the vicinity of STA.84+50, and a face was collapsed accompanied with water-inflow.
STA.83+92.4 STA.83+45	○ (Br.K)	○	○	The fracture zone of 1m in width corresponding to reflecting surface α. Moreover, reflecting surface β was corresponding to deterioration bedrock that had been confirmed by advanced drilling. However, the attenuation of elastic wave was more remarkable ahead of reflecting surface β, and exploration limit in this section was about 60m.
STA.83+45 STA.83+00	○ (Br.K)	○	○	

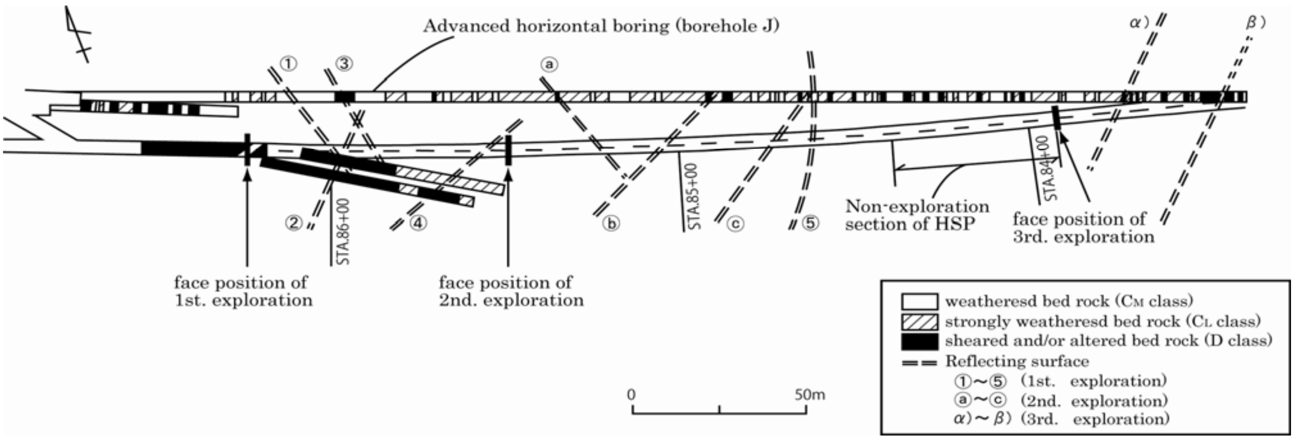

Figure 2.6 Position of the reflection surface based on HSP exploration

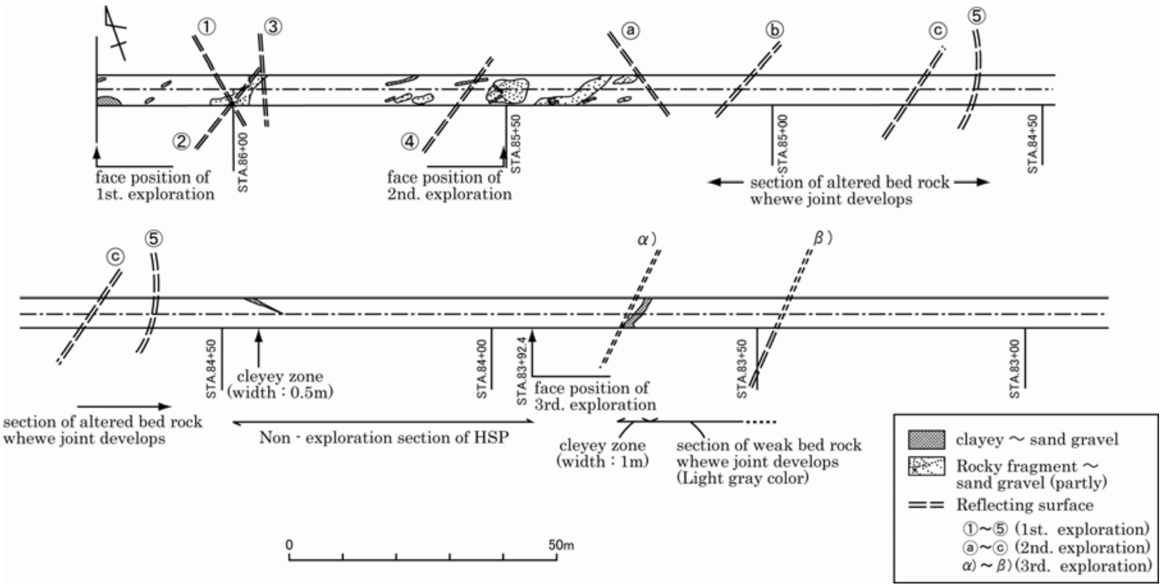

Figure 2.7 HSP exploration result and actual excavation result

Moreover, this method can be comparatively performed from exploration to analysis in a short time. On the other hand, a long horizontal boring investigation in tunnel becomes a long term of works and research cost also increases.

Therefore, at first, it is necessary to understand the ground condition in unexcavated section where problematic bedrock distribution is predicted using seismic imaging ahead of a tunnel face with three component geophones. Furthermore, it is more effective to confirm the section which poses a problem especially based on the result by advanced drilling.

2.2.4 Proposal of tunnel driving method for geological risk prevention

According to probing ahead of face in this section, it became clear that deteriorated part and hard-rock part of bedrock repeated complicatedly.

Moreover, the X-ray diffraction analysis about ground sample of faulted～altered zone showed swelling minerals were included. When deteriorated bedrock was encountered in already constructed section, TBM was restrained and considerable time and cost were required for restoration. Therefore, the ground which assumes such complicated aspect, it was necessary to correspond generated problem earlier and properly, and proposed to continue excavating by NATM.

3. GENERAL OVERVIEW OF THE GEOLOGICAL RISK MANAGEMENT BASED ON TWO CASE EXAMPLES

Management of risks have roots in geological features is predicting appearance of risk in advance, and preventing or avoiding beforehand. Especially, the uncertainty of geological risk in underground construction of our country is high with complexity of geological features, and it is not easy to straightforwardly classify geological risk management in several patterns.

However, geological risk working group of JGCA researched geological risk management pattern recently, and they divided into following three patterns.

Type A) A case of avoiding geological risk.

Type B) A case on which geological risk is actualized, and

Type C) A case of minimizing damage associated with geological risk which was actualized.

Above-mentioned case example 1 and 2 belong to Type A.

Case example 1: Geological properties of altered decomposed soil have not been grasped in prior stage, but face collapsed during construction. It learned to this phenomenon and suitable and efficient investigation about unexcavated part was promptly conducted in tunnel. This case example prevents face collapse based on those results of an investigation.

In this section, it proposed to change tunnel driving method from TBM into NATM through the viewpoint of ground characteristics, safety, constructibility and economical efficiency. And, geological risk management about observation of face, water-inflow and face design were performed in this section.

Case example 2 : About this section, bed rock deterioration of ground was expected to some extent from before construction. However, those scale and extension were uncertain. This case confirmed these situations by various explorations ahead of face and prevents face collapse of by geological risk beforehand. In this case, since bed rock deterioration which repeated itself complicatedly, we decided to continue NATM.

Furthermore, suitable correspondence of heaving and displacement of side wall were completed by geological risk managements such as convergence measurement, setup of control criteria value, and water-inflow management

Brief summary of the geological risk management is shown in Table 3.1.

Table 3.1 Brief summary of the geological risk management in this tunnel

Contents of geological risk management		Case example 1	Case example 2
Risk avoidance phenomenon	Appearance time of predicted risk	Construction stage	Construction stage
	Contents of predicted trouble	Collapse of face in altered and aquiferous ground	Face collapse and squeezing of side wall by continuous deteriorated bed rock
	Evaded phenomenon	・Collapse of face ・Restraint of TBM	・Collapse of face ・Generation of a large amount of water-inflow
Management of risk	Judged time	Construction stage	Construction stage
	Judged person	Geological consultant engineer	Geological consultant engineer
	Necessary information on judging	Ground condition and physical properties of altered and aquiferous ground	・Rock mass condition of altered and fractured ground ・Amount of water-inflow
Correspondence of risk	Some investigations in tunnel	・Physical test ・Consistency limit ・X-ray diffraction analysis	・Advanced core drilling ・Drainage boring ・Seismic imaging with three-component geophones
	Analysis of investigation result and consideration	Evaluation of face stability	・Location and properties of the bedrock deteriorated zone ahead of the face are grasped ・Volume estimation of water-inflow
	Countermeasure	Grouting type forepoling	Drainage Drift
Effect of risk management		Face stability and water-inflow control became an important problem on construction. It was necessary to do flexible correspondence to assumed various geological situations, and tunnel driving method was changed from TBM to NATM in consideration of constructi-bility and economical efficiency.	It was predicted that altered and faulted bed rock is distributed complicatedly in tunnel. Therefore, it decided to continue NATM in consider-ration of safety, constructibility and economical efficiency.

4. GEOLOGICAL RISK MANAGEMRENT BAESD ON RISK EFFICIENCY

In risk management, it is important to find a risk efficiency curve, and derive measure which creates the most desirable balance in it.

In this paragraph, a horizontal axis shows the expected value of excavation cost and a vertical axis is the standard deviation as an index of variation, and considers the risk efficiency about above-mentioned case example 1 and 2.

This conceptual diagram shows the relationship between variability of excavated cost and expected value in tunneling.

A_0 to A_3 expresses design stage, excavation stage and end of construction stage, respectively (refer to Figure 4.1).

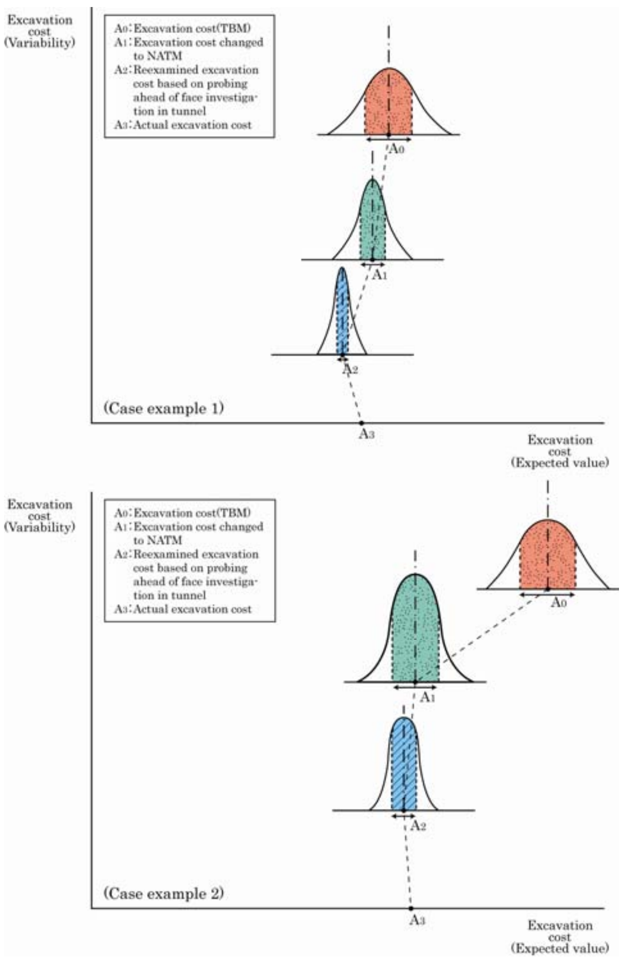

Figure 4.1 Pattern diagram showing the relationship between variation and expected value concerning excavation cost in pilot tunnel.

Because the variation of excavation cost became large, the alternative solution which decreases variation was proposed. Furthermore, in order to improve economical efficiency and the constructibility of alternatives, detailed investigation and analysis were done repeatedly, and the final draft was derived. A_3 is actual excavation cost. Case example 1 and 2 are examples where geological risk management was performed enough before excavation.

5. CONCLUSION

The geological risks predicted ahead of tunnel face on excavating have been grasped in advance by various investigations. Based on these results, it was able to manage about prevention of face collapse, review of tunnel driving method and generating of water-inflow, and the tunnel was able to be excavated economically and safely.

Furthermore, the geological risk management based on risk efficiency was also considered.

In addition, it becomes possible to predict with high accuracy about ground condition ahead of the tunnel face in advance by accumulating the following matters;

- Improvement of exploration technique of advanced horizontal boring.
- Comparison between exploration result ahead of tunnel face and actual excavation result, and consideration of difference between the two.
- Improvement of data acquisition technique about three-component geophones.

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