Tunneling information - An oriented construction technique using geological information

KAZUHIRO ONUMA[1], HIROYOSHI KASA[2], HIROYUKI YAMAMOTO[3], SHINJI UTSUKI[4]

[1] *Hazama Corporation. (e-mail: onumakaz@hazama.co.jp)*
[2] *Hazama Corporation. (e-mail: casa@hazama.co.jp)*
[3] *Hazama Corporation. (e-mail: yamamotoh@hazama.co.jp)*
[4] *Hazama Corporation. (e-mail: utsuki@hazama.co.jp)*

Abstract: In the construction of a recent tunnel, we used the NATM (New Austrian Tunnelling Method) to carry out the design for the geological conditions. It is generally difficult to properly determine the geological conditions in a tunnel and as a consequence the design cannot always be the most appropriate It is therefore necessary to select the optimum research method for tunnel management, because of the increase in construction period and construction cost that may be generated. In this study, we propose a more advanced tunnelling information-oriented construction technique, which effectively utilizes all the geological and geotechnical information necessary for the construction.

Résumé: Dans la construction d'un tunnel récent, nous avions l'habitude le NATM pour effectuer la conception pour les conditions géologiques. Il est difficile de saisir correctement les conditions géologiques dans un tunnel et par conséquent ne peut pas toujours effectuer la conception la plus appropriée. Il est donc nécessaire de choisir la méthode optima de recherches pour la gestion de tunnel, en raison de l'augmentation de la période de construction et de la construction coûtées qui peuvent être produites. Dans cette étude, nous proposons un perçage d'un tunnel plus avançé information-orienté la technique de construction, qui utilise efficacement l'information géologique basée sur les résultats de l'information géologique utilisés spécifiquement pour le perçage d'un tunnel.

Keywords: Tunnels, Engineering geology, Geodata, Planning, Safety

INTRODUCTION

Various civil engineering structures are constructed every year around the world aiming to improve several aspects of our increasingly advanced lifestyles. Large-scale civil engineering structures such as dams and tunnels are often undertaken by the government, local councils, or large utility suppliers. For projects of that scale the quality and safety planning required are rated of high priority.

The foundation supporting a civil engineering structure is the most important element of the structure, and will have an affect on the quality, safety and construction costs of the project. Usually, the geotechnical properties of the foundations are determined through engineering geological surveys and ground investigations, prior to construction and will, in some cases, guide the planning and design.

However, it is difficult to determine the ground conditions at the required accuracy from primary geological surveys, especially when the project is a deep underground structure, which spans along an extensive area, and encounters complex geological structures. Carrying out the construction without sufficiently understanding the ground conditions may lead to small or large failures and fatal accidents. Therefore, it is considered important to carry out geological survey prior as well as during the construction in order to monitor the ground behaviour and obtain adequate information for the construction.

The raw geological and geotechnical information obtained from a ground investigation are not always directly useable from the engineer. It is therefore important for the engineering geologist to interpret the geotechnical information obtained and in a way translate it in the language of the engineer. It should be clear however from an early stage the purpose of the ground investigation in order for the appropriate methods to be used to obtain the ground properties in question.

Figure 1. A situation of drainage countermeasure in the tunnel

In the tunnel construction, a ground investigation such as surface geological survey, boring investigation, seismic prospecting refraction method, electrical exploration, etc. are carried out prior to construction, and the results are summarized in the geological profile. However, most of these investigations were conducted from surface, and several assumption were made in the interpretation of the ground profile. Therefore the accuracy of the geological information is questionable and sometimes insufficient for deep tunnelling in locations of complex geological structures. Thus, in the so-called Information-Oriented construction, the ground conditions of the tunnel face is observed and deformation is measured from inside of the tunnel during tunnelling, then compared with those assumed before the construction to confirm the design. If the estimation in the beginning is different from the observed geological conditions, changing or adjusting the design of tunnel support, etc. will be made to ensure the safety and quality of the tunnel construction.

However, from such investigation, it is very difficult to accurately locate all the geological discontinuities such as faults ahead of the tunnel face and other unexpected features, which may be often encountered as unpredicted geological structures. In a case study the condition of headrace channel tunnel with large water inflow occurred under tunnel excavation is shown in Figure 1 (Shiozaki *et al.*, 2000). In this case the water inflow arose near the fractured zone which was not observed during the ground investigation, causing the tunnel face to collapse putting the excavation on a halt, introducing financial implications. Furthermore, the amount of oxygen dissolved in the water inflow was rather small and the oxygen concentration in the tunnel was temporarily lowered to 16%, causing safety construction problems .

TUNNELLING GEOLOGICAL INFORMATION EVALUATION TECHNIQUE

It is important to predict the likely geological conditions ahead of the tunnel face. Various techniques are available to assist in these kinds of predictions. When the survey results are being utilized, the accuracy and reliability of the investigations must be evaluated sufficiently, because the characteristics of these investigations may vary by investigation principle or by characteristics of the research objects. Generally, the geological properties of a tunnel are complex even though the ground conditions of adjacent tunnels may be alike. Therefore, evaluation of the ground investigation results should be performed for every tunnel.

It is often possible that the obtained geotechnical classification based on the ground investigation results are often not as good as required for the construction. Considering that the most important thing is the usability of the obtained geological information for tunnel construction, the ground investigation purpose should be established beforehand, and evaluation classification of the survey results should be done accordingly. By accumulating the data on the characteristics of each geological survey method it is possible to use the geological information more rationally.

The ground investigation flowchart for geological evaluation under tunnelling is shown in Figure 2. According to that, based on the established investigation purpose, the survey is conducted using previous data, and the investigating method most suitable to the purpose would be selected. After evaluating the characteristics of the survey results, the obtained geological information would be utilized for the construction. In addition, the data related to the research survey method are renewed from the ground investigation results.

Although this geological evaluation flowchart is set for the ground investigation of tunnel under construction, it seems applicable for other civil engineering structure construction, and especially effective if the new research method is introduced.

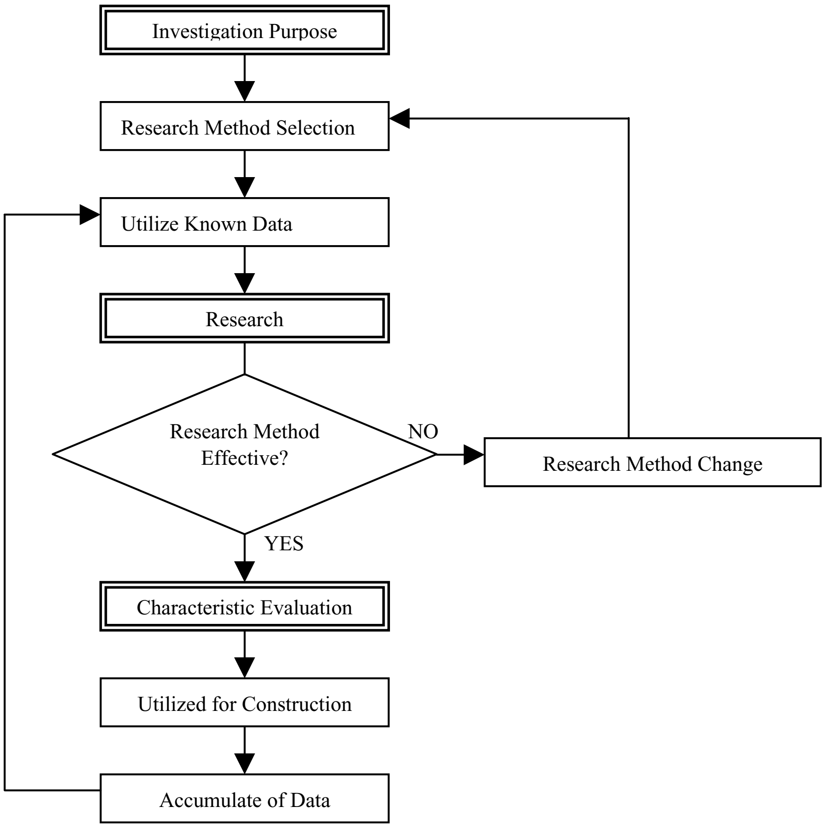

Figure 2. Flow chart for evaluation of the ground investigation results carried out under construction

CASE STUDY OF TUNNELING INFORMATION

The outline of the case study of tunnelling information

Case study on various ground investigation methods during tunnel construction was carried out in order to confirm the suitability of the evaluation flow. In this case, the established purpose of the ground investigation was to ensure the quality and safety under tunnel construction. Therefore, all geological structures supposed to be effective for quality and safety of the tunnel under construction, such as faults, fractured zones, water contained zones, large-scale cavities etc., became the researched survey object. And, the scale of fractured zone was supposed to be equivalent to the tunnel cross section as several metres width.

In this case study, the researched survey method includes a technique for estimating ground conditions near the tunnel face under construction by continuously collecting machine data of tunnel boring machines (TBM), as well as a technique for predicting geological conditions ahead of the tunnel face by TSP (Tunnel Seismic Prediction) method - a kind of seismic reflection method carried out in tunnel. Furthermore, based on obtained geological information from that survey, the tunnelling method is also examined.

Utilization of geological information based on TBM machine data

Outlines of utilization of geological information based on TBM machine data

The TBM (Tunnel Boring Machine) method is defined as machine controlled excavation of full cross section tunnelling method. Since the TBM method enables a tunnel progress of several decade meters, a rapid tunnelling construction is possible compared to conventional method. Typical features of the TBM method are as following:

Since excavation cross section of the tunnel is of a round shape, the stability of the tunnel wall is high due to the arch effect;

As the excavation energy is dispersed, there would be less damage to the tunnel wall.

Therefore, the TBM method is a rational tunnelling method because the tunnel support work is minimum.

However, the disadvantage of the TBM method is that it is unable of conducting geological observation of the tunnel face because the cutter head is fixed with a disk cutter, which is pressing against the tunnel face during the excavation. And keeping the excavation without understanding the change in the geology of the tunnel face may cause collapse of the tunnel face and the tunnel wall. On the other hand, auxiliary method for stabilizing the tunnel face, like the forepiling is difficult, while simple investigations such as drilling are also often constrained by construction space.

In excavation and construction of a tunnel using a TBM, the risk of accident is existed, though there is a merit for quality assurance, etc… Therefore, it is important to reduce the risk of the TBM method by clarifying the ground conditions around and ahead of the tunnel face, and incorporating this information in the construction management plan.

Considering that the excavation abilities of a TBM are related to the ground conditions of the tunnel, Fukui *et al.* (1997) had undertaken an advanced study to clarify tunnel geological conditions from TBM machine data. He resulted that the selection of the parameters used in the geological evaluation had not been found reasonable, and the usage to the construction has not yet been established.

In this paper, we evaluated the relationship between a TBM machine data and the ground conditions, and examined the tunnel construction techniques. Outlines of the tunnel and its geological characteristics are summarized in Table 1. The rock mass where the tunnel is located is a hard sedimentary rock of the Mesozoic age. For examination, geological observational survey of the tunnel wall after excavation was carried out, and geological evaluation characteristics of the TBM machine data collected during excavation are investigated. In addition, relationship between TBM machine data and tunnel stabilizing countermeasure, as well as the characteristics of the TBM machine data used for tunnel construction were also examined (Figure 3.).

Table 1. Outlines of the tunnel by examination

Tunnel outline			Geological outline		
Application	Extension (m)	Cross section (m^2)	Age	Rock type	Uniaxial compressive strength (MPa),
Headrace tunnel	3,035	5.3	Mesozoic era	Chart, Slate	101.0(mean value)

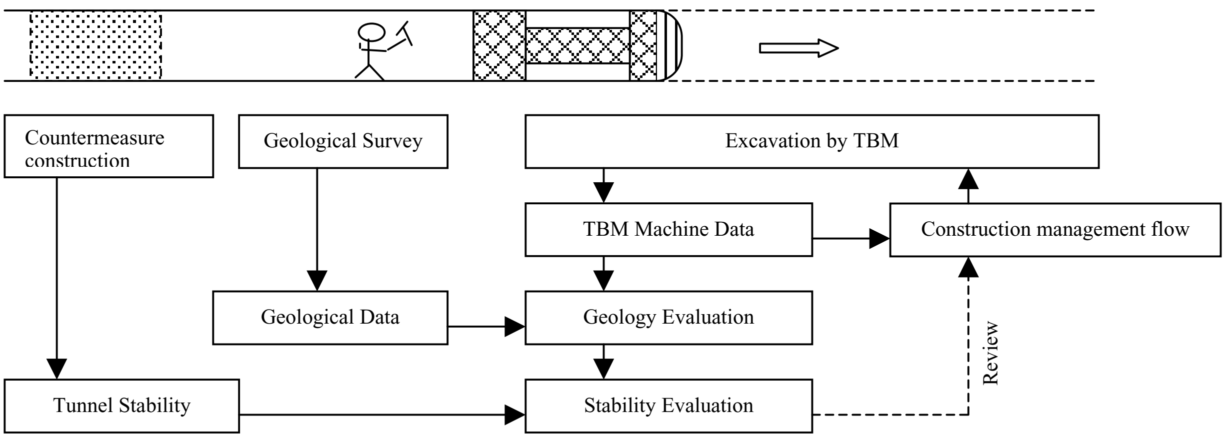

Figure 3. Evaluation flow of the TBM machine data

Geological characteristic evaluation according to TBM machine data

In evaluating the ground conditions according to the TBM machine data, each machine data item is subjected to examination. The excavation function of the TBM consists of drilling, by rotating of the cutter head, as well as a driving mechanism that promotes TBM machine ahead while promotion reaction force supports construction. During excavation, machine data are acquired. Within the acquired raw data, the following data were examined:

Cutter electric current: current of the cutter head rotating motor
Pure penetration rate: intrusion speed of the cutter head
Thrust: pressure of the promotion jack
Bearing capacity: oil pressure of gripper jack which ensures reaction force

Furthermore, examination was performed on following parameters, whose values were calculated from multiple raw data.

Rock mass strength
Excavation energy
Work volume
Rotational energy.

Still, it is necessary to remind that the TBM machine data are affected by the field conditions, including the interaction of excavation and rotation, the resistance by the TBM main body and the vehicles for power supply equipment, the artificial control by the operator, etc.

The geological data used for comparative examination was obtained from observation of the tunnel wall after the TBM excavation. Observation and/or measurement of rock types and the boundary, faults and joints, rock mass classification by CRIEPI (1992), point of water inflow and the inflow quantity were carried out, and the geological deployment map of the wall was made. Schmidt rock hammer tests were performed with equal spacing. Using these results, the correlation analysis between geological data and TBM machine data was done. In this case, because the index of rock mass classification is a qualitative value, so the middle value of initial shear strength for corresponding rock index suggested by Kikuchi *et al*. (1984) was used as the quantitative value as shown in Table 2. The TBM machine data was obtained from 2891 points. Result of the correlation analysis on 601 machine data points by all geological survey data is shown in Tables 3.

Table 2. Rock mass classification and correspondingly set shear strength

Rock mass classification	Shear strength set value (MN/m2)
B	5.1
C_H	3.4
C_M	1.8
C_L	0.5
D	0.15

Table 3. The correlation of TBM machine data and geological data

	RC	SR	T	BC	CC	PD	I	Rth	Rto	RE	W
Rock mass classification	1.00										
Schmidt rock hammer repulsion	0.62	1.00									
Thrust	0.71	0.59	1.00								
Bearing capacity	0.61	0.55	0.72	1.00							
Cutter electric current	0.70	0.58	0.81	0.63	1.00						
Pure drilling speed (intrusion)	0.08	-0.01	-0.07	0.07	0.21	1.00					
Intrusion ^1.5	0.06	-0.02	-0.09	0.05	0.20	1.00	1.00				
Rock mass strength (the thrust equivalent)	0.40	0.39	0.71	0.45	0.36	-0.66	-0.64	1.00			
Rock mass strength (the torque equivalent)	0.09	0.16	0.29	0.11	0.07	-0.84	-0.80	0.84	1.00		
Rotational energy	0.25	0.30	0.47	0.25	0.29	-0.80	-0.77	0.89	0.97	1.00	
Work	0.61	0.45	0.73	0.59	0.81	0.60	0.58	0.07	-0.34	-0.16	1.00

From the result, following matters were proven.

Correlation between Rock mass classification and Repulsion value by Schmit rock hammer was confirmed. And both of them can be used as appropriate variables for the rock mass strength.

About the rock mass classification and repulsion value by the Schmidt rock hammer, there are correlations with thrust, bearing capacity, cutter electric current. Among those parameters, thrust is of the highest correlation coefficient.

Correlation between the rock mass classification or repulsion value by the Schmidt rock hammer with the pure penetration rate could not be confirmed. The human error introduced by the operators was also considered in this case.

On the other hand, correlation with calculated value from multiple machine data tends to be lower than the raw data. This is believed to be the result of adding up the noise included in each data.

Therefore, the thrust seemed to be the most appropriate variable from TBM machine data for the geological evaluation.

Tunnel stability evaluation according to the TBM machine data

In the examined tunnel, the excavation is carried out by open type TBM, which requires 19 months for penetration. In this period, problems such as collapses, were encountered at 17 positions, for which stabilizing treatment had to be carried out. It was proven that the TBM thrust at the positions required stabilizing treatment (A ~ Q) was about 1.08 MN (110 tf) or less as shown in Figures 4. Therefore, a section with the thrust of 1.08MN or less was made to be the low thrust section, and the item affecting the stability of the section was examined. The initial excavation section was excluded from the examination since the TBM machine organization is different.

For the total of 39 low thrust sections (1.08MN or less), rock mass classification, number of the fractured zones, number of joints, and quantity of water inflow, as well as correlation analysis on countermeasure construction were done, and the factor specific was tried. Still, the quantitative evaluation for the countermeasure construction is difficult, moreover the quantitative measurement on the quantity of water inflow was not carried out this time, therefore, for these two parameters, numerical values of 0,1 and 2 were made for the accuracy. Therefore, this analysis only judges the correlation tendency, and the correlation coefficient is not a significant value.

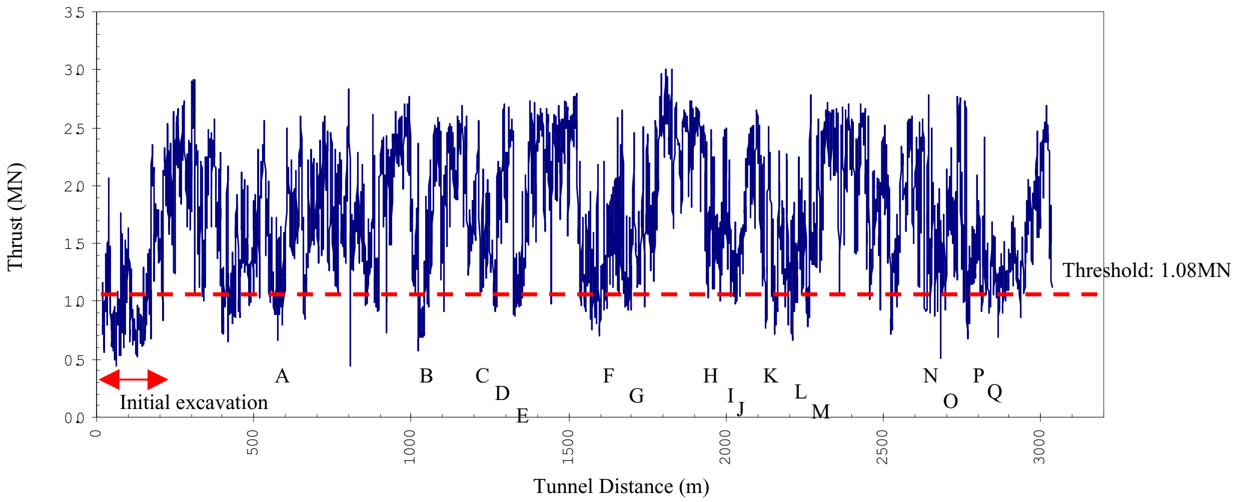

Figure 4. The change of the thrust in the TBM tunnel (A~Q: Countermeasure construction position).

Table 4. The correlation tendency between geological data

	Countermeasure	Rock mass classification	Fractured zone	Joint	Water inflow
Countermeasure construction	1.00				
Rock mass classification	0.61	1.00			
Fractured zone	0.37	0.30	1.00		
Joint	0.21	0.28	0.21	1.00	
Water inflow	0.71	0.33	0.39	0.07	1.00

The results of the correlation analysis are shown in Tables 4. Following tendencies in execution factor of the countermeasure construction are found:

There are correlation tendencies between the countermeasure construction and the rock mass classification or the quantity of water inflow.
Correlation tendencies with the fractured zone or joint are low.

Though the TBM machine data seemed to reflect the dynamic property of the tunnel geology, it was considered that the possibility of collapse of the tunnel wall is affected by the water inflow situation. Therefore, relating to the tunnel wall stability, it seems necessary to collect geological information such as quantity of water inflow besides the TBM machine data during excavation.

Tunnelling method utilizing TBM machine data

It seems that besides the TBM machine data of tunnels, the increase in measurement items such as the quantity of water inflow, which requires new measuring equipment, was connected with increase in construction cost and delay of the process. Therefore, in order to rationally utilize the geological information for the tunnel construction management, the tunnel geology should be evaluated with monitoring the transition of the TBM machine data as shown in Figures 5 (Onuma et al., 1992). As a result, it seems to be appropriate that additional investigation and tunnel stability evaluation should be carried out in locations where abnormal ground behaviour is noted. In this case, by carrying out characteristic evaluation for the raw data, the monitoring items are examined, and the evaluation items are selected and then the management value is defined. In addition, when abnormalities were detected by monitoring, the excavation should be interrupted for conducting observation and measurement of the tunnel face and wall. Anyways, carrying out stabilizing treatment whenever an unstable factor ahead of the tunnel face was confirmed by exploration drilling etc… is considered the most appropriate construction management technique.

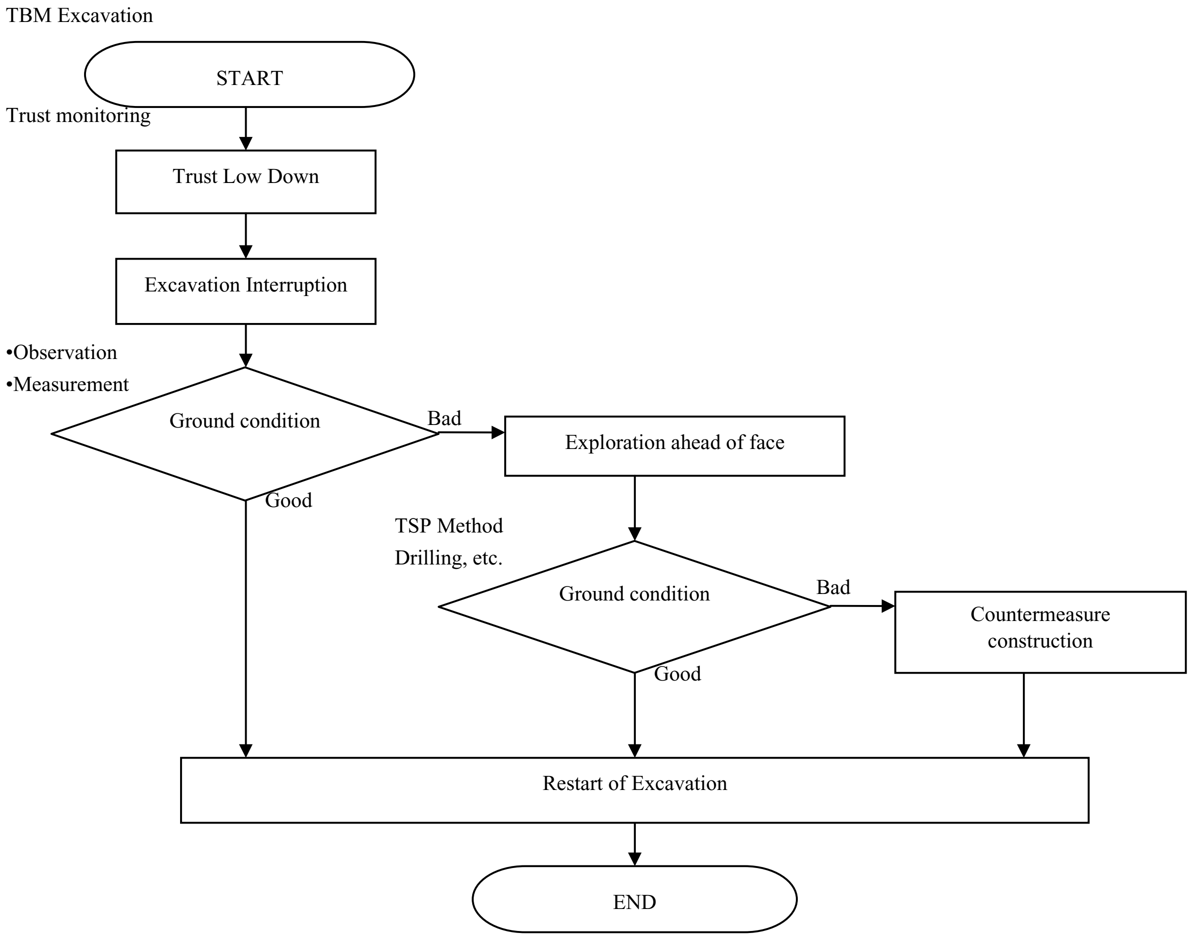

Figure 5. Construction management flow in the TBM excavation

Geological structure prediction by seismic reflection method (called TSP method)

Outline of the geological structure prediction by TSP method

Sattel *et al.* (1992) proposed a technique, which carries out VSP exploration in the tunnel, and developed prospecting system called TSP202 including the data analysis software. This technique is called the TSP method, and it has been introduced in some construction companies in Japan. When TSP method is applied, the tunnel wall surface is equipped with exploration traverse line, which is parallel to the tunnel shaft. A receive point is set at 50m away from the tunnel face, and within this distance usually 24 shot points by explosion are set. Array measurement is carried out between the receiver and shot points. As an output in the TSP method may show the reflection event crossing position ahead of the tunnel face, the change of property of reflection plane can be judged from the change of the phase. The TSP method image is simple, but there is a little information on characteristic of geological structure such as the reflection event, so it becomes a difficult situation when the effect of the tunnel on quality and construction is being estimated. Experience of utilizing geophysical exploration in tunnel construction management is little, while the technique of utilizing exploration geological information ahead of tunnel face for construction management has not yet been established. In this paper, investigation characteristic of the TSP method was accumulated, and the utilization to the construction was tried. And a technique of utilizing geological information ahead of tunnel face for tunnel construction management was examined.

Geological structure evaluation by the TSP method

The fundamental principle of the TSP method requires propagation velocity of elastic wave (P wave) and the distance to reflection plane from the time-of-arrival, and the position of the reflection plane is established by an array measurement. The reflection of an elastic wave in the underground is generated on the boundary surface of the media with different acoustic impedance based on the Snell law (1). This time, it is possible to show the energy of reflected wave in the reflection coefficient (2).

$$z_i = \rho_i V_i \tag{1}$$

zi : Acoustic impedance

$$r_i = \frac{z_{i+1} - z_i}{z_{i+1} + z_i} \tag{2}$$

ri : The reflection coefficient

In case of *ri*<0, the reflected wave phase will reverse positive and negative, so the change of a medium acoustic impedance can be estimated from the phase change of reflected wave.

- In case of $z_{i+1}>z_i$, phase of the reflected wave is coordinate.
- In case of $z_{i+1}<z_i$, phase of the reflected wave is opposite.

In case of high acoustic impedance (zi), it is necessary that the velocity of elastic wave (Vi) or the density ρi (or both of them) should be high. Generally, when acoustic impedance increases, a change to the hard rock is assumed because both the density and the velocity of elastic wave in the hard rock are high. Therefore, it seems possible to estimate the change of the property in the reflection plane from the pattern of the phase change of reflected wave. Geological structure of 4 patterns, including fault, dyke and two kinds of rock type boundary are estimated from the reflection pattern as shown in Table 5.

Table 5. 1 Ground condition estimated by TSP (Kasa et al., 1996)

Reflection Type	Rock Strength Changes (Face Side)	Estimated Geological Structure
Fault	Decreasing / Increasing	Fault
Dyke	Increasing / Decreasing	Dyke
Boundary A	Decreasing	Hard Rock / Soft Rock
Boundary B	Increasing	Soft Rock / Hard Rock

It becomes a problem about the minimum width in the fault type or the dyke type. Though it seems difficult to uniformly decide the width, it is necessary that the width is decided based on geological information, the required conditions of exploration, the resolution of the reflected wave, etc… The resolution in seismic prospecting reflection method is called the limit by the elastic wave, which can separate as reflection plane of which two different physical properties of the underground are independent. Generally, the elastic wave has limited frequency band, and the limit of the resolution exists. Rayleigh showed the resolution, which could separate the wavelet of two homopolar-ness with the time *b*/2 from the central peak of the basic wavelet to adjoining trough. *b*/2 is correspondent here to 1/2 period (=1/(2•f_{pred})) of excellence frequency f_{pred}. And in the seismic prospecting reflection method, the resolution is expressed through the excellence wavelength λ_{pred}, as in equation (3) because it must be considered in both ways travel time, and this is called the 1/4 wavelength rule of Rayleigh. In eq.(3), V is average velocity of the elastic wave.

$$resolution = \frac{V \cdot \left(\frac{b}{2}\right)}{2} = \frac{V}{2} \cdot \frac{1}{\left(2 \cdot f_{pred}\right)} = \frac{\lambda_{pred}}{4} \tag{3}$$

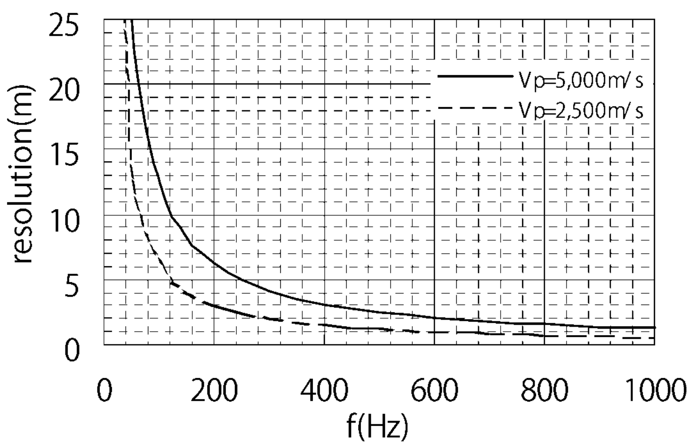

Figure 6. The relationship between resolution and frequency

In this way, the resolution of the reflected wave is decided by the wavelength, and the wavelength is decided by the frequency with velocity of elastic wave. In Figures 6, the relationship between frequency and resolution is shown for soft rock (Vp=2,500m/s) and hard rock (Vp=5,000m/s). In hard rock (Vp=5,000m/s), the resolution becomes 12.5m at the 100Hz frequency as seen in this figure. And, it is known for the elastic wave that the attenuation is big at high frequency. It is therefore considered that, low frequency component of the reflected wave would be dominant for the width of the geological structure. In the TSP method, the usage frequency band is set at 120Hz~2500Hz. In addition, for carrying out analysis, a low-pass filter or high-pass filter may be set at 100~150Hz or 2000~3000Hz, respectively, depending on the measurement situation. Therefore, the resolution proved to be about 10m when the TSP method was carried out in the hard rock.

From such characteristics of the TSP method, detection by the reflected wave is summarized in Table 6 as a database for the geological structure evaluation. For example, by the TSP method, it is easy to detect the fault where the propagation medium shows high values on density and velocity of elastic wave, or to detect the dyke where the propagation medium shows low values on density and velocity of elastic wave. On a geological body, it seems easy to detect a large-scale feature from the resolution. When the propagation medium shows high values of density and velocity of elastic wave, the attenuation is small, so it is considered that the reflection pattern of the fault type is easy to detect.

Table 6. TSP reflection pattern and geology body of which the reflection is advantageous

TSP reflection pattern			geology body of which the reflection is advantageous			
Reflection Type	Density	Velocity of elastic wave	Density	Velocity of elastic wave	Scale	Remark
Fault	Low	Low	High	High	Large	Attenuation is small
Dyke	High	High	Low	Low	Large	Attenuation is big

Ability of TSP method in revealing geological structures

For utilizing geological information available from TSP method for tunnel construction, those characteristics were objectively examined, and the usage of the exploration results were examined. In the evaluation of the TSP method results, items such as the position in the reflection plane, variation of the hardness and inclination are considered essential due to a high degree of coincidence between the actual excavation results and prediction results. As the positional consistency with the excavation results is the most fundamental matter in the evaluation, thus the all-around validity of individual exploration execution results is supposed to be examined.

In this research, results from continuously using the TSP method in the tunnel of identical geotechnical condition and from geological survey of the tunnel wall conducted after excavating the entire exploration interval were subjected to comparison examination. The subject tunnel for examination was an expressway tunnel of 5.9 km long, located in Toyama Prefecture of Southern Japan. It was drilled by a ϕ4.5m TBM method. The geology at the site is composed mainly of rhyolitic tuff. The overburden at the TSP method execution interval has exceeded 150m and seemed to be able to disregard the effect of the surface reflection. Along the tunnel route, some faults and dykes have been anticipated by the preliminary survey, though the locations have not been shown exactly. Therefore, the TSP method was continuously carried out in total of 20 times in order to clarify the position of those faults and dykes beforehand.

As survey results of the TSP method, in order to decide the specific plane from a large number of planes, which satisfy the distance from the time-of-arrival of reflected wave to the concerned reflection plane, a strike angle is assumed so that based on it the inclination would be calculated.

That means, the strike (a connected direction in horizontal cross-section) of some exploration objects will be artificially decided as a constant value. For example, if the strike is set on 90°, all discontinuities of the exploration results are orthogonalized to the tunnel shaft. In this study, due to that fact, crossing points in the tunnel centre should be evaluated.

As geological data from observational investigation after excavation, a geological profile of the tunnel wall with extracted main geological structures were created for use as a part of the tunnelling quality control. The extracted items are geological boundaries, faults, joints, cracks and rock mass classification boundaries.

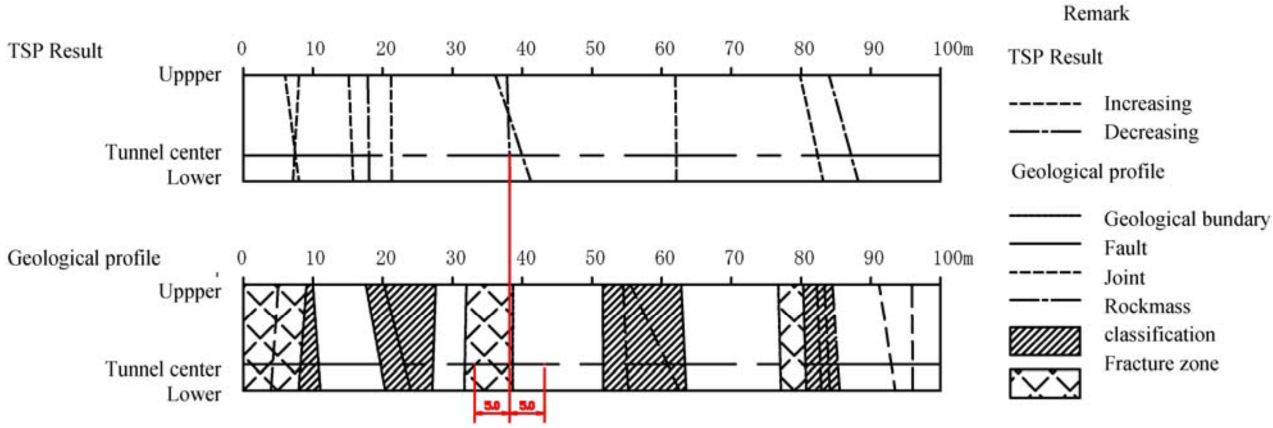

Figure 7. TSP exploration result and comparative excavation result

As already mentioned, in evaluation, the positional consistency was most emphasized at the contrast of both excavation results and exploration result, because TSP method is a technique for searching the crossing position in reflection plane and traverse line. Therefore, it is necessary to estimate the correspondence for each result. In this study, by making 10m-intervals (±5m before and behind the reflection plane) we have correspondence between each result. Actually, relying on our research experience so far, the use of 10m-interval was based on the general fault tolerance of the TSP method. Example of actual contrast data is shown in Figure 7.

Among the methods for examining the effective range of exploration, there is a method for estimating from attenuation condition of wave-form data, and another method for empirical estimation based on application experiences as mentioned in a research paper by Sattle et al. (1992). In the first method, estimation is based on the time by which the waveform is no longer read due to attenuation. In fact, the reading of accurate effective range from waveform data may become difficult due to the amplification effect to the noise by the filter. On the other hand, in the latter method, since one's empirical judgment is based on the exploration results, the effective range is said to be about 100m in usual cases according to research experience to date. However, under condition of small overburden, this value may become smaller. In this study, referring to recent case studies, a 100m distance from the working face (the same as the examination section) was accepted as the effective range of exploration since the effect of overburden thickness can be disregarded in this case.

In addition, objective evaluation of the validity of the TSP results is examined using some proposed index shown in Table 7 (Kasa *et al.*, 1996). The meaning of each index is as follows.

- The grasp rate:

It is the ratio of the number of discontinuities grasped in exploration over the number of the actual ones.

- The mistake rate:

It is the ratio of the number of discontinuities actually existing but missed by exploration to the total number of the actual ones. High mistake rate of exploration result indicate a big problem concerning safety assurance of the construction. The mistake rate is in mutually complemented relation with the grasp rate.

- The rate according to the misjudgement

It is the proportion of the number of the discontinuities that does not actually exist among all discontinuities estimated in the exploration. In fact, it reflects the reliability of the exploration result.

Table 7. Evaluation index

The grasp rate (%)	B/A*100
The mistake rate (%)	C/A*100
The rate according to the misjudgement (%)	D/(B+D)*100

A : Number of actual reflection plane.
B : Number of reflection plane grasped in the exploration.
C : Number of reflection plane missed in the exploration.
D : Number of reflection plane among those grasped by exploration but recognized as lacking actually.

Table 8. The summary of the evaluation index in the exploration of all 20 times (%)

No	Grasp	Misjudgement	Mistake
1	90	40	10
2	67	0	33
3	94	25	6
4	80	20	20
5	73	38	27
6	67	18	33
7	64	0	36
8	67	0	33
9	64	7	36
10	62	11	38
11	62	0	38
12	47	0	53
13	65	0	35
14	38	0	62
15	38	0	62
16	71	6	29
17	65	7	35
18	50	0	50
19	44	0	56
20	48	8	52

Summary of the results of 20 times examining exploration is shown in Table 8. As seen in this Table, the grasp rate varies within 38~90% with an average of 60%, the misjudgement rate varies at 0~40% with a low average of 9%, while the mistake rate was around 10~62% showing an average of 40%. These indicate that among total number of discontinuities extracted from exploration data of the TSP method results, only 60% corresponds to some actual discontinuities, while nearly 40% corresponds to no discontinuities.

As already explained, the TSP method can be used as a technique for grasping geological discontinuities such as joints and faults, Figure 9 presents the grasp rate for different geological properties from exploration results in this research. As shown in this figure, about the TSP method, over 70% of the actual faults can be grasped, but for dykes and geological boundaries the grasp rate was about 60%, while for joints and rock mass classification boundaries it was slightly lower at about 50%. That can be said that, the possibility of detecting by TSP method is higher when a geological discontinuity is relatively big such as faults, or when the mechanical contrast of the rock mass before and behind the discontinuity is clear.

For clarifying geological structures on the basis of TSP exploration results, it seems necessary to utilize such database for better understanding the characteristic of the TSP method.

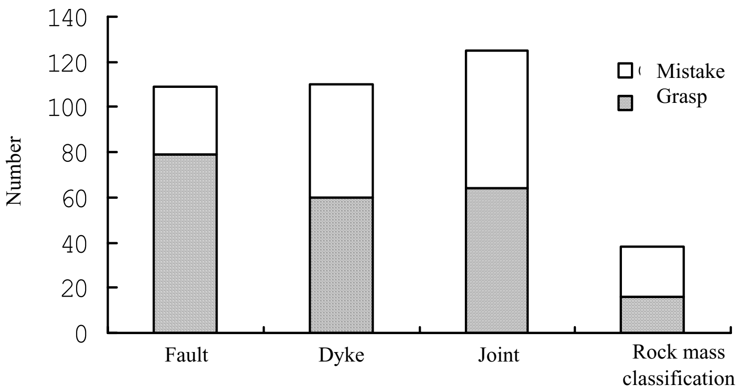

Figure 8. Geological structure grasped by TSP method

Evaluation database by the TSP method for support design

Geological information from TSP exploration utilized for design of support is examined. The tunnel on examination was constructed by NATM for an extension of 1177m long, located in Shimane Prefecture in the West of Japan. TSP exploration of 5 times in total was carried out for unfavourable rock divisions (fault, fractured zone and low velocity zone) was anticipated before the construction. The rational design of tunnel support based on the estimated location and width of the unfavourable ground was examined.

Table 9. The summary of the TSP method exploration result

Survey No. (*m)	Design	Excavation Result				TSP Survey		
	Support	Bad Ground condition	Width (m)	Remarks	Support	Reflector	Width (m)	Difference of Location(m)
1 (50)	CI	1-1	1	Joint	DI-i	×	–	–
		1-2	1	Joint		○	<5	-2.5
		1-3	2	Crack zone		○	<5	+9.0
		1-4	1	Joint		○	<5	-3.5
		1-5	1	Fault		○	<5	-4.0
2 (100)	B	2-1	1	Joint	CII	○	<5	+0.5
		2-2	1	Joint		○	<5	+0.5
	CII	2-3	2	Fault		○	<5	-4.5
		2-4	2	Crack zone		○	<5	-5.0
		2-5	2	Crack zone		×	–	–
		2-6	2	Crack zone		×	–	–
		2-7	2	Crack zone		×	–	–
		2-8	1	Joint		○	<5	-0.5
		2-9	**20<**	**Fault**		○	**10<**	**-5.0**
3 (100)	B	3-1	1	Fault	CII	○	<5	+2.0
	CI	3-2	2	Crack zone		○	5 10	+2.0
	DI-i	3-3	1	Fault		×	–	–
	CII	**3-4**	**20<**	**Fault**	**DI-i**	○	**20<**	**-3.5**
	B	3-5	4	Crack zone		○	<5	-2.5
4 (70)	B	4-1	1	Crack zone	CII	×	–	–
		4-2	1	Crack zone		×	–	–
		4-3	5	Crack zone		×	–	–
		4-4	**20**	**Fault**	DI-i	○	**20<**	**-6.0**
	CII	4-5	1	Fault		○	<5	-5.0
		4-6	6	Crack zone		○	10<	+2.5
5 (80)	CI	5-1	8	Crack zone	DI-i	○	<5	+3.5
		5-2	8	Crack zone		○	<5	+3.5
		5-3	13	Fault		×	–	–
		5-4	**30<**	**Fault**		○	**10<**	**0.0**
Total		29				20		

The geology of the tunnel is composed mainly of the rhyolite of Paleogene period. The rhyolitic features in this region demonstrate that, the fresh part is relatively homogeneous and massive rock mass, and a tendency of block collapses along the joint planes under the effect of weathering and alteration.

Initially, the rock inferior division, which could be a problem in the construction such as a fault, a fractured zone, a low velocity zone and a geology boundary, was assumed at 11 locations based on existing geological reports such as the geological profiles. The tunnel support patterns are divided into B, CI, CII, CIII, and D, in which B is slightly, and D is heavy. The tunnel support pattern designed for this tunnel it is mainly B and CI, and partly CIII ~ D for the intervals where problems were anticipated in the geology. For the assumed 11 rock inferior divisions, 5 times TSP were probed with the effective range of 50-100m considering the effect of the overburden etc. in order to clarify the position and width in the rock inferior division.

The excavation results and TSP exploration results are summarized in Table 9. Still, it is arranged in this table, as the excavation progresses from the top at the bottom in each time. As shown in this Table, the support pattern based on the excavation result has been changed with higher support rigidity compared with the original design. And the rock inferior division (No. 1-1 ~ 5-4) appeared to be 29 in total.

According to the construction results, in the intervals, which appeared in the rock inferior division as No. 2-9, 3-4, 4-4, 5-4 in Table 9 and may become problematic over the 10m wide in the construction, faults and large scale effect zones appeared. Especially, in No.3-4 and 4-4, a collapse of about 1 ~ 1.5m long was generated, and the tunnel support was changed to "more rigid" (pattern D). It was found that, estimation by TSP was almost accurately as evaluated, and that the result of the TSP method is effective as one of the judgment materials in examining the design of support.

With further accumulated exploration results, the construction management flow was revised from the viewpoint of the TSP method being a relative evaluation, in which the geological information obtained from the TSP results was utilized for construction management as shown in Figure 9.

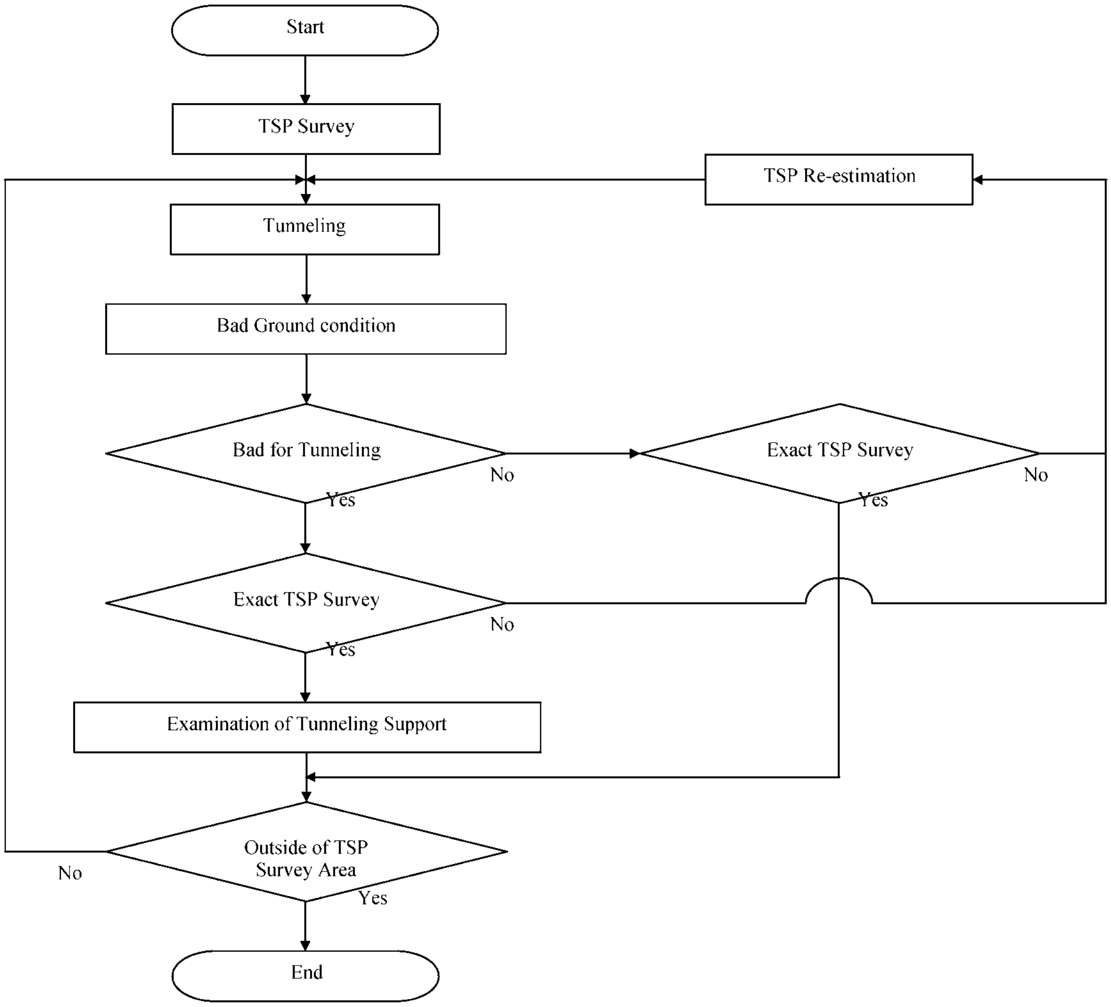

Figure 9. Design of support examination flow by the TSP method

According to the flowchart, if during excavation in the explored section a geologically unfavourable section appeared, re-evaluation including review of the TSP analysis results was carried out. As a result, the existence of predicted geologically unfavourable section that continued over 10m (which is emphasized as an interval with high possibility of the tunnel support pattern change) must be reflected in the design as well as in the construction. Consequently, if the unfavourable geological conditions are identified along with the prediction by the TSP method, the design changes as well as the tunnel support pattern changes must be examined. If some unfavourable geological conditions appears outside the predicted interval, the flow should be analysed again and the parameters setting corrected, etc.. For these reasons it seemed effective to utilize the geological information from the TSP exploration.

CONCLUSIONS

In this paper, different ground investigation techniques that utilized geological information during and after a tunnel construction were examined. A flowchart was established as a guide for the execution of the investigation. Based on this flowchart initially the purpose of the investigation is set, then the research method is selected and the characteristic evaluation for the investigation is carried out. A case study about acquiring geological information by utilizing the TBM machine data as well as by using the TSP method (a kind of elastic wave reflection method) was presented. It was found effective to utilize the information obtained by those methods in the construction of a tunnel.

As the data were accumulated for appropriate evaluation of the characteristic of the ground investigation, a database was developed. By improving this database, it is considered possible to quickly and accurately utilize the geological information attained from the ground investigation of a tunnel construction.

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Corresponding author: Dr Kazuhiro Onuma, Hazama Corporation, Toranomon 2-2-5, Minato-ku, Tokyo, 105-8479, Japan. Tel: +81 3 3588 5793. Email: onumakaz@hazama.co.jp.

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