# GEOLOGICAL EVALUATION AHEAD OF TUNNEL FACE USING TUNNEL SEISMIC PREDICTION METHOD AND JAPANESE HIGHWAY ROCK MASS CLASSIFICATION SYSTEM

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**by**

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## TABLE OF CONTENTS

**CHAPTER FOUR : RESULTS AND DISCUSSION**



**CHAPTER FIVE : CONCLUSION**



**APPENDICES**

## LIST OF TABLES

# LIST OF FIGURES

## LIST OF ABBREVIATION

| | |
|---|---|
| 3D | Three dimensional |
| AHP | Analytical hierarchy process |
| ANN | Artificial neural network |
| ATTTP | Alborz twin transit tunnels project |
| BH | Borehole |
| BP | Back-propagation |
| CRWST | Cheshmeh Roozieh water supply tunnel |
| ECM | Efficacy coefficient method |
| HBH | Horizontal borehole |
| JH | Japanese Highway |
| MP | Multilayer perceptron |
| NATM | New Austrian tunneling method |
| R1 | Receiver 1 |
| R2 | Receiver 2 |
| REF | Reference location |
| RGP | Rock grade point |
| RMR | Rock mass rating |
| RQD | Rock quality designation |
| RSF | Rock-bolt support factor |
| RSR | Rock structure rating |
| SMEC | SMEC International PTY LTD |

| | |
|---|---|
| SMHB | SMHB SDN BHD |
| SRF | Stress reduction factor |
| TBM | Tunnel boring machine |
| TDH | Tender drill hole |
| TEPSCO | Tokyo Electric Power Service CO., Ltd |
| TSP | Tunnel seismic prediction |
| UCS | Uniaxial compressive strength |
| VSP | Vertical seismic profiling |

# LIST OF SYMBOLS

| | |
|---|---|
| $\lambda_j$ | Standard coefficient in ECM |
| $\lambda_{max}$ | Largest or principal eigenvalue of the matrix |
| ABS | Absolute difference between the actual and predicted RGP |
| AR | Actual advance rate |
| Ar | Actual result |
| B | Tunnel width in feet in rock load classification |
| $b_j$ | Bias to aggregate signal |
| BP | BP neural network |
| CF | Competence factor |
| CI | Consistency index |
| CLI | Cutter life index in TBM advance rate |
| CR | Consistency ration |
| E’ | Squared error function |
| E | Young's modulus in competence factor |
| EC | Efficiency coefficient |
| ECE | Extension comprehensive evaluation |
| ED | Equivalent dimension |
| $E_{dyn}$ | Dynamic Young modulus |
| $E_m$ | In-situ static modulus of deformation |
| $E_{mass}$ | Deformation modulus in Q-system |
| ESR | Excavation support ratio |

| | |
|---|---|
| F | Average cutter load in TBM advance rate |
| $\gamma$ | Unit weight of rock mass in rock load classification |
| GW | Underground water |
| H | Overburden in competence factor |
| $H_p$ | Rock load factor in rock load classification |
| $H_t$ | Tunnel height in feet in rock load classification |
| $J_a$ | Joint alteration number in Q-system |
| $J_n$ | Joint set number in Q-system |
| $J_r$ | Joint rough number in Q-system |
| $J_v$ | Sum of the number of joints per unit length for all joint |
| $J_w$ | Joint water reduction number in Q-system |
| $k_j$ | Standard value in ECM |
| $K_v$ | Surrounding rock integrated coefficient |
| m | Negative gradient of deceleration |
| $\mu$ | Mean of absolute difference |
| n | The order of matrix |
| N | State of discontinuous structural planes |
| $net_{hj}$ | Each of the hidden neurons fed with total net input |
| $N_r$ | Number of random discontinuities |
| p | Number of training process in squared error function |
| PR | Penetration rate |
| $p_y$ | Support pressure in rock load classification |

| | |
|---|---|
| Q | Rock mass quality in Q-system |
| q | Quartz content in TBM advance rate |
| $\theta$ | Angle between tunnel axis and major structure plane |
| $Q_{tbm}$ | TBM advance rate |
| $Q_u$ | Unconfined compressive strength in competence factor |
| *r* | Ratings for UCS in conventional method |
| R | Ratings for UCS in proposed method |
| r | Density in competence factor |
| $R_c$ | Rock uniaxial compressive strength |
| $r_{co}$ | Ratings for joint condition in conventional method |
| $RE_{test}$ | Relative error obtained from testing the network |
| $RE_{train}$ | Relative error obtained from training the network |
| RI | Average of the resulting consistency index |
| RMR | Rock mass rating value |
| $RMR_c$ | Rock mass rating value from conventional method |
| $RMR_n$ | Rock mass rating value from proposed method |
| RSEC | Rough set efficacy coefficient method |
| S | Structural surface state |
| $\sigma_1$ | Major principal stress |
| $s_1$, $s_2$, $s_3$ | Joint set spacing |
| $\sigma_2$ | Minor principal stress |
| $\sigma_c$ | Unconfined compression strength |

| | |
|---|---|
| sc | Standard value |
| SD | Standard deviation of absolute difference |
| SIGMA | Rock mass strength in TBM advance rate |
| $\sigma_\theta$ | Induced biaxial stress on tunnel in TBM advance rate |
| $s_r$ | Random spacing of random joints |
| SRF | Stress reduction factor |
| $SSE_{test}$ | Sum of squares error of the testing network |
| $SSE_{train}$ | Sum of squares error of the training network |
| $\sigma_t$ | Tensile strength (point load) |
| T | Actual total time in hours |
| t | Target value in squared error function |
| U | Fraction of time utilized when boring |
| $V_p$ | P-wave velocity or compressional wave velocity |
| $V_p$ | Ultrasonic velocity in competence factor |
| $V_p/V_s$ | Ratio of P-wave velocity to S-wave velocity |
| $V_s$ | S-wave velocity or shear wave velocity |
| $w_{ij}$ | Associated adaptive weight coefficient |
| $x_i$ | Incoming signal |
| $x_{max}$ | Maximum index of the evaluation index in ECM |
| $x_{min}$ | Minimum index of the evaluation index in ECM |
| y | Produced actual value in squared error function |
| $y_j$ | Output neuron |

**PENILAIAN GEOLOGI DI HADAPAN MUKA TEROWONG DENGAN MENGGUNAKAN KAEDAH RAMALAN SEISMIK TEROWONG DAN SISTEM PENGELASAN BATUAN LEBUH RAYA JEPUN**

## ABSTRAK

Pengetahuan mengenai profil geologi di hadapan muka terowong adalah penting dalam langkah pencegahan untuk meminimumkan risiko dalam kerja penggalian terowong dan kawalan kos. Disebabkan kawasan pergunungan, siasatan tapak dengan pengalian secara tegak tidak disyorkan untuk mendapatkan profil geologi bagi projek Pemindahan Air Mentah Pahang-Selangor. Oleh itu, kaedah ramalan seismik terowong (TSP) digunakan untuk meramalkan profil geologi di hadapan muka terowong. Kajian awal hasil TSP menunjukkan bahawa kedua-dua halaju gelombang $V_p$ dan $V_s$ sejajar dengan penurunan kelas batuan. Untuk menilai hasil keputusan TSP, IBM SPSS Statistik 22 digunakan untuk menjalankan analisis rangkaian saraf tiruan (ANN). Salah satu kaedah di dalam ANN yang dinamakan sebagai perseptron berbilang lapisan (MP) telah digunakan untuk meramal mata gred batuan (RGP) daripada RGP yang sebenar dengan menggunakan input $V_p$, $V_s$ dan $V_p/V_s$ yang merupakan hasil daripada TSP. RGP yang sebenar diperolehi daripada sistem pengelasan batuan lebuh raya Jepun (JH). Keputusan yang diperolehi menunjukkan korelasi yang baik antara ramalan RGP dan RGP yang sebenar dengan korelasi sebanyak 0.851. Selain itu, $V_p$ adalah parameter yang paling penting dalam memberi gambaran awal keadaan geologi di hadapan muka terowong. Walau bagaimanapun, peranan $V_s$ dan $V_p/V_s$ tidak boleh dinafikan dalam sokongan bagi ramalan keadaan geologi. Pemetaan batuan menunjukkan kewujudan runtuhan dan lompang di kawasan yang diramalkan. Justeru, TSP boleh memberikan ramalan profil geologi di hadapan terowong dengan ketara dan mengekalkan pengunnaan TBM dalam kerja penggalian

terowong. Pengenalan zon kelompangan atau kecacatan batuan di terowong hadapan adalah penting bagi merancang langkah-langkah pencegahan terlebih dahulu untuk memastikan kerja penggalian terowong yang lebih selamat.

**GEOLOGICAL EVALUATION AHEAD OF TUNNEL FACE USING TUNNEL SEISMIC PREDICTION METHOD AND JAPANESE HIGHWAY ROCK MASS CLASSIFICATION SYSTEM**

## ABSTRACT

The knowing of geological profile in front of tunnel face is noteworthy to limit the hazard in tunnel excavation work and cost control in preventative measure. In order to acquire the geological profile for the Pahang-Selangor Raw Water Transfer project, site investigation with vertical boring is not suggested due to mountainous region. Tunnel seismic prediction (TSP) method is therefore implemented to predict the geological profile ahead of the tunnel face. Preliminary study of the TSP results showed that both wave velocities $V_p$ and $V_s$ are showing the downtrend with the lowering of the rock class. In order to evaluate the TSP results, IBM SPSS Statistic 22 is used to run artificial neural network (ANN) analysis. To assess the outcomes of the TSP, IBM SPSS Statistic 22 is used for the evaluation of artificial neural network (ANN). By using $V_p$, $V_s$ and $V_p/V_s$ from TSP results, a method in the program namely multilayer perceptron (MP) was used to compute the predicted rock grade points (RGP) from actual RGP. The actual RGP was obtained by Japanese Highway (JH) classification. The findings indicate a strong correlation between the anticipated RGP and the real RGP with the 0.851 correlation. Besides, $V_p$ is the most significant parameter in determination of geological condition ahead of tunnel. However, the role of $V_s$ and $V_p/V_s$ are undeniably significant as well in supporting the prediction. The predicted results were then compared to rock mass mapping. The rock mass mapping showed that there were collapse and void for the predicted area. As such, TSP can provide considerably ahead of tunnel face geological profile forecast while enabling for continuous excavation work for TBM. Identifying weak zones or faults in front of

the tunnel face is essential for preventive measures to be implemented in advance for a safer tunnelling work.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

A rapid construction development in Malaysia has made the tunnelling and underground work as an important alternative in present days. In the past, many tunnels have been constructed in Malaysia, and long tunnels particularly are one of the most significant issues in civil engineering field, because of their advantages in connecting two or more cities which geographically separated by the mountain, channelling excess river water into sea to keep the busiest city Kuala Lumpur flood-free and raw water transfer for treatment and distribution.

Generally, the safest tunnelling methods is tunnelling using tunnel boring machine (TBM). When conducting tunnelling works using TBM into unexpected geology, there are possibilities of water leakage, geological over-break, rock burst, squeezing or poor rock, collapse of the unstable tunnel face or blocking the cutting wheel. Eventually, these worst-case scenarios could delay the excavation progress schedule and subsequently increase the construction cost to get additional equipment which is unlikely necessary, such as digging tools and pumps to site. The tunnel to collapse completely is almost impossible since the whole tunnel diameter is filled with TBM and rarely endanger the workers' life. Unfortunately, the safety issues about TBM excavation are not only restricted to environment of tunnel but also solve the problem which are created to the surface above. The critical fault zones could be activated by drilling vibrations. Besides, the water ingress into tunnel could result in water table drawdown. Subsequently, settlement could occur and cause serious damage to nearby structures or utilities. As such, geological forecast in front of the tunnel face is indeed significant in tunnelling underground.

There are two ways to conduct geological forecast in front of the tunnel face which are destructive method, such as exploration hole or core boring, probe drilling, etc; and non-destructive method, such as geophysical approach and tunnel seismic prediction (TSP). Extrapolation results of the surface geological mapping is served as a reference for geological cross section of the tunnel trajectory. To reveal more details on the geological conditions below the surface, additional geophysical measurements are needed. However, extrapolating the geological information does not accurately provide the geological structure underground. The fault zone which is dipping apparently at the surface can be varied in depth. Besides, the changes in lithological might happen on the surface without noticeable indications. The implementation of the geophysical measurements in deep tunnelling project is extremely restricted. Moreover, the decrease of the information acquired vertically by depth will prevent a high-resolution characterization of the tunnel geology, particularly tunnelling in mountainous area. Hence, a non-correlative comprehensive cross section between the underground structure and the actual geology is encountered during tunnel construction. Apart from this, samplings derived from exploratory drillings could provide completely reliable sources of geological information. Majority of the Malaysia tunnelling projects were applying the conventional site investigation method to study the geological behaviour along the tunnel alignment. However, such exploratory method is time consuming and expensive. In addition, samples from this coring could reach in certain areas only and most of the time does not reach the intended depth of the tunnel alignment.

To forecast the geological condition in front of tunnel face, real time measurements could be used as a useful tool to correlate with the information which are obtained from exploratory drillings at the actual areas along the tunnel alignment. The objectives and needs of every prediction method ahead of tunnel face is to safely determine the fractures, faults, groundwater or lithology which are changing the rock properties and may cause disturbance to the TBM operation and the pre-determined tunnel lining. By studying the rate of TBM penetration, prediction of the geological prediction in front of the tunnel face could be enough to react accordingly within a minimum range of action distance.

Literally, the significant changes of seismic properties in TSP, such as wave velocities of both compressional wave ($V_p$) and shear wave ($V_s$) and bulk density are usually going along with the faults, fracture zones, lithology changes, existence of ground water and so on. The seismic methods could provide large range of penetration and flexible geometry of measurement. As such, the seismic methods are method of choice and widely accepted in exploration geophysics.

However, some of the methods are failed commercially because of the low penetration depth and constructional interference with the tunnelling work. Even though the exploratory drilling inside tunnel such as probe drilling could explore the geological ahead of tunnel face, but this practise needs free access through the cutting wheel into the tunnel face. Consequently, the tunnelling process must be paused for a period. As such, probe drilling is applicable only when there is suspicious geological ahead of tunnel face which need to be verified and required non-continuous information.

In this study, the geological prediction ahead of tunnel face therefore focuses only on the application of TSP method. This study was aimed to determine the TSP parameters that can be used to infer the geological condition prediction. The mentioned parameters are $V_p$, $V_s$ and $V_p/V_s$.

## 1.2 Problem Statement

Generally, tunnelling in mountainous area with deep overburden would be a very challenging work. The core boring from the ground surface is seem unsuitable for tunnelling project in this area. This is due to difficulty in mobilization of the drilling rigs and expected extremely long of coring length. Hence, there is quite limited soil investigation which can be carried out along the proposed tunnel alignment. As a result, there could be possibility of no warning in advance for the need to apply mitigation of measures when facing adverse geological features once the TBM is driving. For instance, the existence of ground water, discontinuity of rock and lineament. The existing of ground water in a great volume may flood the tunnel. Water table drawdown also will cause settlement to the nearby structure and utility. Whereas the discontinuity of rock and lineament will cause large breakout and collapse of tunnel.

The research area is in mountainous area which it consists mainly of granitic rock. As such, the study is focusing in geological conditions prediction such as rock fractures, discontinuity of rock and lineament. As the main research topics, the following research questions arise:

i. TSP method was firstly used in Malaysia tunneling project for medium to long range of geological prediction. Its performance and efficiency in geological condition prediction ahead of tunnel need to be further evaluated.

ii. There is no existing database to corelate the quality of granitic rock in Malaysia and TSP results, such as $V_p$, $V_s$ and $V_p/V_s$. RGP by JH method could be used as reference of granitic rock quality. Improper use of analytical method could lead to insignificant justification of the compatibility of TSP method and correlation in between RGP from JH method and TSP results.

iii. The geological conditions are anomaly which may cause the seismic to be overreacted. Then, the interpretation results may lead to insignificant justification. Hence, TSP results need to be studied and organized before analyses with RGP from JH method. The correlation between the actual RGP and the predicted RGP is expected insignificant if analyze all range of results using artificial neural network (ANN) method.

Parameters of TSP, such as $V_p$, $V_s$ and $V_p/V_s$ are adopted in the prediction of geological conditions such as rock fracture, discontinuity of rock and lineament. Among the TSP parameters, the most significant parameter to provide the most precise forecast of the geological condition in front of the tunnel to be studied.

### 1.3 Objectives

The objectives of this study are:

i. To forecast geological conditions in front of tunnel face by using TSP results, such as $V_p$, $V_s$ and $V_p/V_s$. The geological conditions are anomaly.

Theoretically, the sudden reduction in wave velocity will indicate the increase of fracture density or preferential flow path and vice versa.

ii. To determine the correlation between RGP from JH method and TSP results by using ANN method. In this study, ANN will be used to study the pattern of the output: actual RGP based on corresponding input: TSP results, such as $V_p$, $V_s$ and $V_p/V_s$ and compute the predicted RGP. The correlation between the RGP from JH method and TSP results can be known by comparing the actual RGP and the predicted RGP.

iii. To ascertain the parameters of TSP, such as $V_p$, $V_s$ and $V_p/V_s$ that influence the predicted geological condition results. In ANN analysis, the highest importance value will indicate the most significant TSP parameter in predicting the geological conditions.

## 1.4 Expected Outcomes

This study focuses on the forecast of geological condition in front of tunnel face by using TSP method. Shear wave could not propagate through liquids and would cause high reflectivity or amplitude of shear waves at those boundaries. The seismic wave propagates faster in high density rock. For instance, a sudden drop in wave velocity would indicate the increase of rock porosity or crack density. Hence, it is expected that the TSP can anticipate the risk ahead of tunnel face.

Basically, an observational method like rock mass classification method is applied when the prediction of geological behaviour is difficult, so that the design of tunnel support can be reviewed during construction. The essence of the observational method is to prepare a preliminary design based on the exploration at the time, then monitor and verify the structure is acceptable during construction. The contingency plan is needed to include into operation if the designed limits are overreached. In an otherwise unplanned "trial-and-error" operation, rock mass classification given the only systematic design assistance. The successful observational method could avoid the application of mitigation plans which are costly and time-delaying. In other word, if the TSP results is well correlated with the RGP from JH method which is one type of the rock mass classification, TSP could also serve the same purposes.

ANN can learn and study the patterns of input: RGP from JH method, and output: TSP results, such as $V_p$, $V_s$ and $V_p/V_s$ from the corresponding chainage to compute the predicted RGP. The correlation between the RGP from JH method and TSP results is then known by comparing the RGP from JH method and the predicted RGP. The main parameters from TSP which significantly affect the predicted RGP is $V_p$.

### 1.5 Content of the Study

In order to study and correlate the TSP results with actual geological condition, numerous literatures had been studied. The contents of the study, such as detail methodology, results, discussions and conclusions are then summarized as below.

#### 1.5.1 Chapter 2 – Literature Review

In this chapter, methods in pre-determine underground hazard were discussed. For instance, exploration hole like core boring, geophysical method, probe hole and TSP methods. Besides, rock mass classification system was further discussed too. There are few rating methods in rock mass classification system, such as rock quality designation (RQD), rock structure rating (RSR), rock mass rating (RMR), Q-system and Japanese Highway (JH) classification. Since there is possibility of error from TSP results, hence evaluation of the TSP performance is needed. Few analytical methods were referred and studied in this study. These analytical methods are ANN, analytical hierarchy process (AHP) and efficacy coefficient method (ECM). Advantages and limitations of these analytical methods were further discussed.

### 1.5.2 Chapter 3 – Methodology

In this chapter, the flow of analysis is discussed in detail for this study. Before the tunnel excavation, soil investigation along the proposed tunnel alignment was conducted to study the geological condition. Laboratory tests were carried out on the samplings of soil investigation, such as soil density, Young's modulus, ultrasonic velocity and unconfined compressive strength. Since due to the mountainous area, soil investigation was impossible to be carried out to detect the geological condition. As such, TSP was carried out to forecast the geological condition in front of tunnel face. The outcomes from TSP like $V_p$, $V_s$ and $V_p/V_s$ were analysed to forecast the risk in front of tunnel face. This predicted geological condition was then verified by the JH classification during tunnel excavation. JH classification could classify the tunnel face based on strength of intact rock, weathering or alteration, discontinuity spacing and discontinuity effect. These categories will have resulted in RGP which was then used to classify the tunnel face accordingly. This RGP will be analysed with TSP results in particular chainage by multilayer perceptron (MP) to produce a predictive model. This predictive model is the predicted RGP which will be compared with the actual RGP to determine its accuracy and compatibility. Rock mass mapping to be conducted for the exposed surface and the details were recorded.

### 1.5.3 Chapter 4 – Results and Discussions

In this chapter, soil investigation information and rock conditions were presented. The RGP at each chainage was plotted to determine the range of TSP results for evaluation. This is significant to reduce the error during ANN analysis. It is true that ANN can do massive data processing and learn the pattern of the dependent variables. However, if the dependent variables are varied and there is no specified pattern, the resulted predictive model will likely to be insignificant if compared to real case monitoring data. The TSP results, such as $V_p$ and $V_s$ were plotted to corresponding classed for easy understanding. The highest $V_p$ or $V_s$ is Rock Class A, while the lowest $V_p$ or $V_s$ is Rock Class E. When there is no fault in rock, the seismic could penetrate and return in high speed, otherwise vice versa. The correlation between the predicted RGP and the actual RGP is determined form the ANN. The most significant parameter in affecting the prediction results to be justified. Errors in analysis to be determined and discussion of the solution. The predicted RGP and the actual RGP were plotted for better comparison. Rock mass mapping to be referred to confirm and clarify the findings of the prediction results.

### 1.5.4 Chapter 5 – Conclusions

In this chapter, conclusion was done based on the outcomes gained from the assessment. Objectives of this study were justified from the results. Besides, the limitation during this study was listed out. Based on the limitations in analysis, several recommendations were listed.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Introduction

Underground tunnelling is indeed a risky construction work. In the past years, few underground tunnelling projects had encountered geological hazards. There were many disasters in tunneling projects, for example in China which caused by inrush water (Junwei et al., 2014). The inrush water and inrush mud had occurred in the construction of Lingnan Tunnel located in the railway of Hangguang and Liangshan Tunnel, which significantly delayed the project, increased project cost and caused destruction to the surrounding environment. Junwei et al (2014) then added on that the largest water burst of Maluqing tunnel of the Yiwan railway with about 180000 $m^2$ total water burst as shown in Figure 2.1.

Figure 2.1: Water burst in the Maluqing tunnel of Yichang-Wanzhou railway (Junwei et al., 2014).

On the other hand, there are many TBM tunnels underpass mountain examples, or in mountainous terrain, which due to inadequate pre-investigation have trouble with the abandonment (Barton, 2012b). Barton then explained the reason behind the TBM delay with the equations below:

$$AR = PR \times U$$
$$U = T^m$$
$$T = L / AR$$
$$\text{Hence,} \quad T = (L / PR)^{1/(1+m)} \qquad \text{(Equation 2.1)}$$

where AR is actual advance rate; PR is penetration rate; U is the fraction of time used when boring; T is the actual total hourly time; and m is the adverse gradient of deceleration.

Barton then clarified that Equation 2.1 is essential because the element "$^{1/(1+m)}$" is too big due to very adverse "m" values. When the fault zone is large where "L" is large and "PR" is small owing to gripper issues and collapses, then "L/PR" is too big to tolerate a large element "$^{1/(1+m)}$" in Equation 2.1. However, the basic significance of deceleration has not been recognized, at least in public. The author also listed the examples of fault ruined or permanently buried TBM in Dul Hasti, Pinglin and Pont Ventoux; and rock-burst impaired or ruined TBM in Olmos, Jinping II.

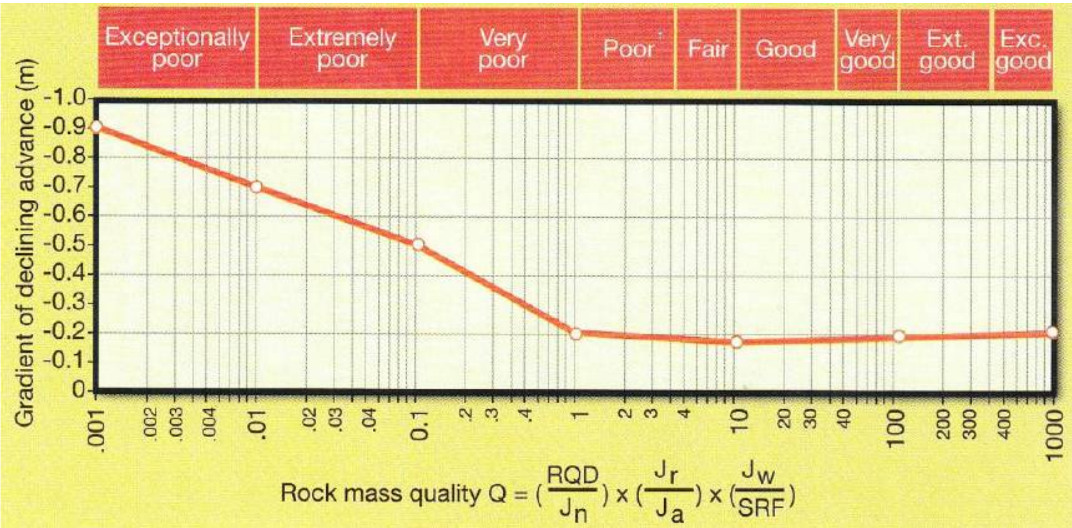


Figure 2.2: Empirical link between low Q-values and steep deceleration events (Barton, 2012).

Figure 2.2 shows an empirical relationship between low Q-values and steep deceleration occurrences as experienced when travelling through a significant faults or weakness zones. The author had suggested that pre-grouting is the best method to avert such interruptions and settlement due to groundwater drawdown. Performing probe drilling ahead of tunnel to anticipate beforehand once there is a steep deceleration gradient which presents the unfavourable geological conditions. A significantly increased Q-value would lead to reduction of “m” into even less negative values if extremely permeable unfavourable zones were drained and pre-injected.

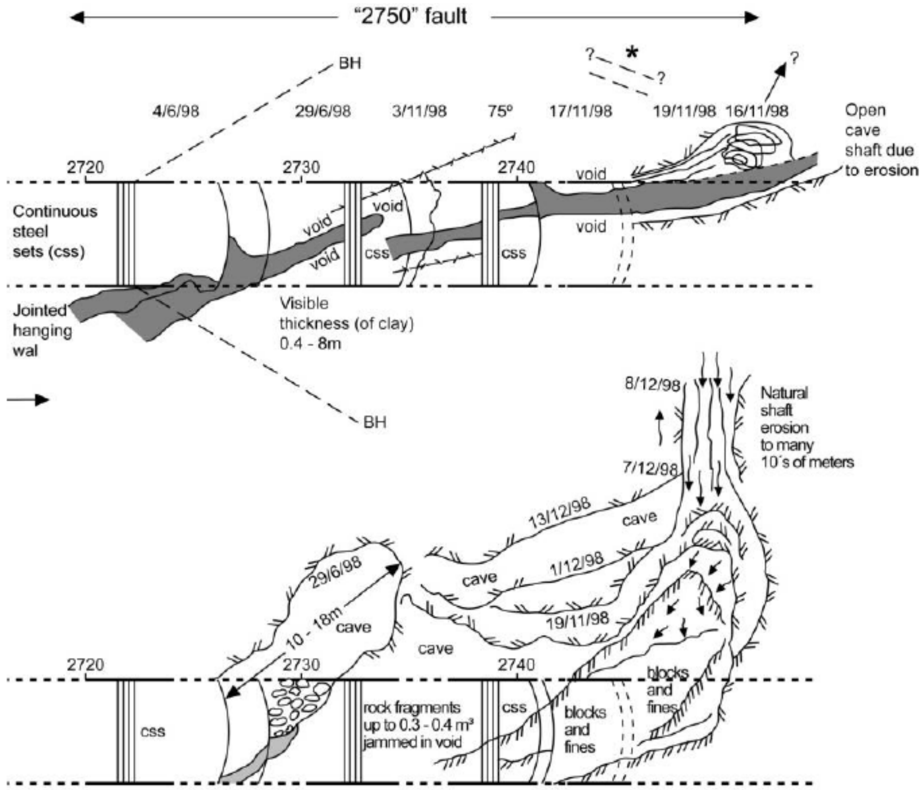


Figure 2.3: The Pont Ventoux headrace tunnel in northern Italy (Barton, 2015).

Figure 2.3 shows the Pont Ventoux headrace tunnel in northern Italy. In this tunneling project, an apparently minor unfavorable zone with a 1 m thickness of clay, combined with high water pressure on one side, had slow down the progress of TBM operation by 5 months in this 30m long section.

Figure 2.4: Water ingress in Pahang Selangor raw water transfer tunnel (Rahim et al., 2016).

Figure 2.4 presents the water ingress during the tunnelling work in Pahang Selangor Raw Water Transfer tunnel. The critical water leakage had caused the face collapse and the author believed that it was caused by fractured zone of Kongkoi fault and Lepoh fault. The collapse occurred just after the TBM passed the zone with the fall in of unstable rocks onto the TBM and created a 50m high and 5m wide hole with chimney shape above the TBM. Rahim et al. (2016) then concluded that the TBM performance, cost in time planning and project accomplishment time are significantly affected by geological conditions and discontinuity properties of rock mass. The unpredicted critical water leakage and imperfect rock mass conditions may significantly decelerate the tunneling progress rate.

As such, the geological prediction ahead of tunnel is indeed very significant. By knowing the geological profile ahead of tunnel, the risks can be mitigated to stabilize and strengthen the geological property in advance.

## 2.2 Geological Predictions Ahead of Tunnel Face

Geotechnical information is required at the very beginning on planning any tunnel project (Parker, 2004). The geological condition significantly influences almost each main decision that ought to be finalized in the planning, design, and construction of a tunnel because geological condition governs the cost, and even the performance of the completed structure. Crucial geotechnical explorations are required during the initial and final design interspersed with comparatively low levels of effort. When the contract documents are finalized in latter stages of final design, there is a crucial geotechnical support to assist the preparation of the Geotechnical Baseline Report (GBR) and the remaining of the contract documents.

Flow chart of site investigation (Gundewar, 2014) was summarized as below:

a) Phase 1: Preliminary exploration which include desk study of accessible maps, reports, literatures and others, such as satellite visual images, regional scale of aerial photographic analysis.

b) Phase 2: Site exploration which involve drilling and boring, trial pits excavation, penetration testing, coring sample collection, geophysical surveys and groundwater regime measurements.

c) Phase 3: Laboratory testing and determination of baseline geological information.

d) Phase 4: Field tests involving in situ tests on unfavourable mining areas before and during excavation and performance tests.

According to Bieniawski (1990), exploration of geological investigation consists of core borings, various tests like borehole visual images, pressure testing, piezometer set up, pump tests and observation wells within the boreholes and seismic survey. In his study, rock cores from 29 borings were adopted to identify geological condition of tunnel, whereas 10 boreholes were not reaching tunnel level. However, all core samples were immediately pictured on site once removed from the core barrel. Then, the core sample was registered, categorized and tested. Total of 15 boreholes photography were employed to ascertain the joint orientations and rock composition. In order to diagnose density, uniaxial compressive strength, triaxial strength, elasticity modulus, Poisson's ratio, water content, swelling and slaking, sonic velocity, and joint strength, the core specimens from 21 locations within the tunnel were selected. Measurements of in situ stress were carried out in vertical boreholes involving 15 experiments, sadly only 3 yielded the positive outcomes.

A2 tunnel in Maastricht, Netherlands was proposed to be constructed using "cut and cover" method in the limestone. A thorough and varied site investigation was conducted to evaluate and localize geohazards and determine appropriate technique for following exploration phase (Ngan-Tillard et al., 2010). Along the tunnel route of 2.2km long, 17 boreholes were bored using different methods like sonic drilling, 55mm and 100mm diameter wire line rotary core drilling with double barrel with and, respectively, without inner plastic lining to perform in situ tests, recover "undisturbed" samples for laboratory testing and/or create lithostratigraphic profiles. Needle penetrometer test was carried out on cores at close spacing of 10 or 20 cm. Cone penetration tests and borehole geophysics were conducted in boring stage. Methods for borehole geophysics include borehole ground penetration radar, sonic log and gamma rays, cross-hole tomography, electric conductivity. However, borehole geophysics were not much success which suspected due to ground water to obstruct electro-magnetic wave penetration or formation damage caused by sonic drilling.

Next, surface geophysics, strength and deformability properties and permeability test were carried out to determine the faults.

Other than site investigation, we can also adopt other method to obtain the geotechnical information or to predict the geological profile for specific construction purposes. The methods to be applied in tunnel construction are probe drilling, tunnel seismic prediction and so on. Rock mass classification method is adopted to enhance the quality of site investigation by using the least available input data as classification parameters and deliver quantitative information for design and support system selection purposes. These geological prediction methods in tunnel construction will be further discussed below.

### 2.2.1 Probe Hole Drilling

Deep borings may not be able to detect the potential of fault or shear zone and high inflows that could exceed the handling of TBM capacity under normal operation, as such probe drilling ahead of tunnel is seem to be likely required to identify such zones before been encountered in the tunnel (Waggoner et al., 2010). However, probe drilling is costly delaying the TBM boring progress.

Probe drilling is a method to know geology ahead of tunnel in advance before conducting a full face drill and blast with the following qualities (Riaz, 2014):

- Low cost and easy,
- No additional mechanical nor technical resources are required, and
- Provide look ahead geological strata up to 30-60m but limit the maximum length of Jumbo capacity and deviation of rod inside rock.

Riaz (2014) had carried out the probe drilling method in Nahakkai Tunnel, Switzerland. The main observant parameter from probe drilling method would be velocity and it has a direct relationship with geology, whereas high velocity and low velocity of drilling speed will encounter soft rock and hard rock, respectively. Other interpretations and descriptions are as below:

- Rock type - clear difference in velocity would indicate the change of rock
- Water - water would come out from probe hole if encounters water
- Fault - fault can be predicted if high velocity is observed; a clear indication of negligible effect of drilling rod velocity if fault is more than 50cm.

In addition, the exploration drilling ahead of TBM is not simple to perform due to conditions.(Kogler & Krenn, 2014). The selection of equipment, the type of exploration, the location to position the drill behind the cutterhead and the aims of exploration are difficult decision to make. A quick method of probe drilling does indeed only briefly interrupt boring but producing results that are difficult to interpret and mostly inadequate. Rapid drilling methods would give hardly any chance to perform drill-hole investigations or tests. Apart from this, a higher quality drilling process such as core drilling would be time consuming but delivers considerably better results at the cost of the TBM advance rate. In an extreme case, an insufficient exploration drilling can lead to unexpected incidents such as collapses or water inflows and thus to the stopping of the TBM. The location and inclination of holes in the direction of the advance is indeed hardly to decide, because mostly TBM cutterheads are designed for the drilling ahead of the machine is not possible along the tunnel axis due to the lack of openings in the cutterhead. Hence, the drill-hole angle is generally made at 5 to 10 ° from the tunnel axis at the invert or crown of the tunnel cross-section. The selection of this drilling direction often determines the practical length of the holes since with these inclinations and, for example, a drilling depth of 100 m, drilling deviations of 10 to 20 m must be expected in some geologies. The drill rod is placed at 6 degrees away from the centerline of tunnel as shown in Figure 2.5. The available space determines the size of the drilling rig, size of the drilling equipment and the lengths of the rod and casings. The rod lengths would affect the duration of drilling. Depending on the type of machine, the size of the drilling equipment will significantly affect the drilling depth, which is different according to the drilling process, as well as on the drilling precision. Space is needed for any flushing pumps, air compressors, drilling equipment like rods, lifting devices for drill rods, mixers for flushing and mixers for grouting after the completion of the hole.

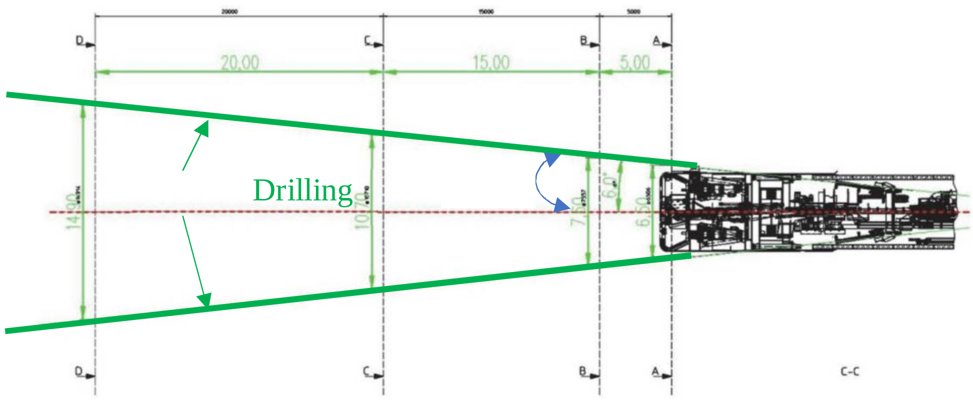


Figure 2.5: Diagram of possible drilling directions (Kogler & Krenn, 2014).

On the other hand, Dickmann (2012) had mentioned that investigative boring from the tunnel face generally is for the detection of lithologic heterogeneities ahead of the tunnel face but only yield the predictive range at most of about 50m. Besides, the probe drilling method only provide one-dimensional information and causes significant delays to excavation (Dickmann & Krueger, 2013). The same authors had suggested to apply the prediction methods which do not disrupt the tunnelling progress and yield the results quickly at moderate cost. A probe drilling to be carried out in safe range where the face is close to the predicted zone once the geological risk zone is identified.

### 2.2.2 Tunnel Seismic Prediction (TSP)

Dickmann and Sander (1996) had described the principle of TSP technique. The TSP system is a unique underground reflection seismic package of measurement instrumentation and interpretation software. TSP could predict the changes in geological properties ahead of and around spatially very restricted underground excavations by employing the principle of echo sounding as shown in Figure 2.6.

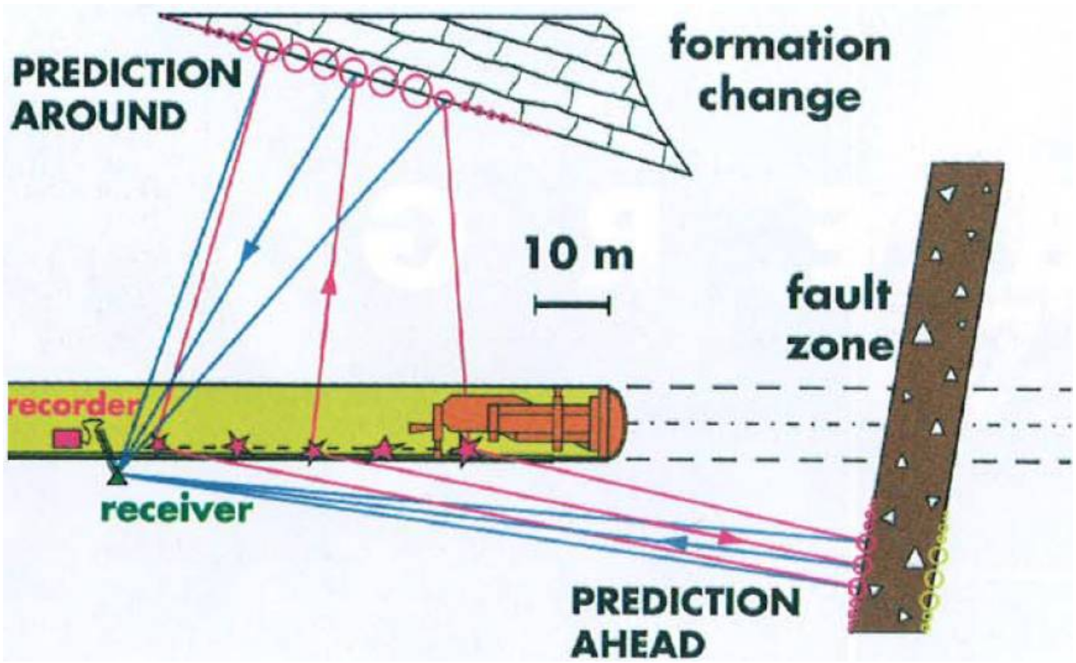


Figure 2.6: Principle of tunnel seismic prediction technique
(Dickman & Sander, 1996).

In a typical survey, explosive charges are detonated individually in approximately thirty numbers of 1.5m deep shot boreholes along the tunnel wall. Shot hole charges are connected via a trigger box to a blasting machine and recording unit. The recording unit is normally connected to two 2.5m long receiver rods, one in the left and the other in the right tunnel wall. The receiver rods fit tightly into steel casings cemented into the receiver boreholes at least 12 hours earlier to achieve optimum formation coupling. Receiver sensors are a series of high frequency accelerometers oriented in two directions parallel and perpendicular to tunnel axis. A fraction of the outgoing energy of each shot is reflected from the physical boundaries in formation ahead, such that it can be recorded by the survey array in the tunnel.

Apart from this, $V_p$ is chosen as the indicator of rock physical and mechanical parameter (Shi et al., 2014). Combined with the knowledge of past projects in TSP prediction, the grade division of discontinuous-structure surface was summarised in Table 2.1. For grade "Very strong" of the discontinuous-structure surface, the reflection of the P-wave is very powerful and the positive and negative reflection layers in reflection zone are plentiful and mussy. Besides, the $V_p$ and $V_s$ will vary regularly. However, the reflection of the P-wave is not obvious for grade "Very small" of discontinuous-structure surface.

Table 2.1: Grade division of discontinuous-structure surface (Shi et al., 2014).

| Grade | Detailed description |
|---|---|
| Very strong | The P-wave negative reflection is very strong, and the positive and negative reflection layers in reflection zone are abundant and mussy. The $V_p$ and $V_s$ decrease and change frequently. |
| Strong | The P-wave negative reflection is strong, and the single reflection has a wide bandwidth and a good extension. |
| Medium | The P-wave negative reflection is obvious. |
| Small | The P-wave negative reflection is weak. |
| Very small | The P-wave negative reflection is not obvious. |

The surrounding rock stability is affected significantly by the groundwater (Shi et al., 2014). The grade division of groundwater is summarised in Table 2.2. Basically, reflection energy of S-wave is significantly better than the P-wave in detecting groundwater, because S-wave has a good extension and a wide reflection bandwidth. Besides, $V_p/V_s$ or Poisson's ratio will increase significantly when encounter groundwater.

Table 2.2: Grade division of groundwater (Shi et al., 2014).

| Grade | Detailed description |
|---|---|
| Very strong | S-wave reflection energy is obviously stronger than that of P-wave. S-wave has a wide reflection bandwidth and a good extension. $V_p/V_s$ or Poisson's ratio increases greatly. |
| Strong | S-wave reflection energy is obviously stronger than that of P-wave. $V_p/V_s$ or Poisson's ratio increases. |
| Medium | S-wave reflection energy is obviously stronger than that of P-wave. |
| Small | S-wave reflection energy is stronger than that of P-wave. |
| Very small | The data does not show the aquifer characteristics. |

Dickmann and Sander (1996) then added on the investigation range for a standard TSP survey in most rock conditions is 150m to 200mm ahead of the tunnel face with a maximum boundary localization error of ±20m at the far range. When the length of the survey spread and shot charges are increased, investigation ranges of up to 1km can be achieved, but will result in greater error margin as presented in Table 2.3 below.

Table 2.3: Error margin vs TSP investigation range (Dickman & Sander, 1996).

| Investigation Range (m) | Error Margin in Predicting Distance Ahead Along Tunnel Access to Intercept of an Interpreted Boundary |
|---|---|
| 0-50 | ± 5% |
| 50-200 | ± 10% |
| 200-1000 | ± 20% |

By recording the full wave-field of reflected P-wave and S-wave signals, physical and mechanical parameters of the rock mass quality can be predicted up to 150 m ahead of the tunnel face (Dickmann & Hecht-méndez, 2017). TSP method had been applied in tunnel projects related to TBM throughout the world which involving various rock types and conditions, such as in the Himalayas, the Alps and the Andes. The authors had made a TSP case study with shield TBM in Uma Oya Multipurpose Development project, Sri Lanka. Figure 2.7 shows the rock property charts and reflectors' longitudinal view with colour shading in accordance to $V_p$ of Campaign #21.

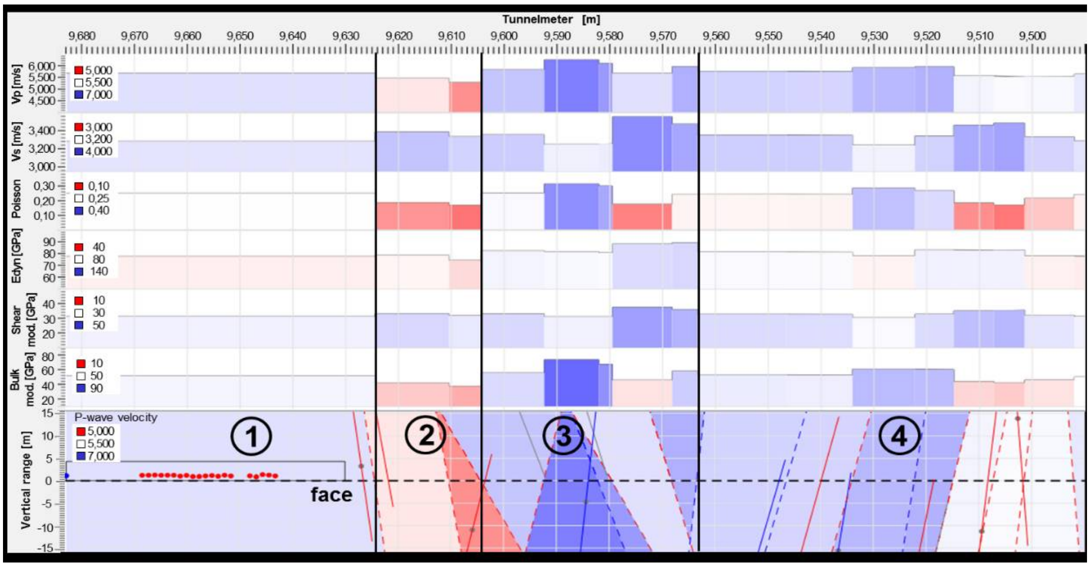


Figure 2.7: Rock property charts and reflectors' longitudinal view with colour shading according to $V_p$ of Campaign #21 (Dickmann & Hecht-méndez, 2017).

Results interpretation (Dickmann & Hecht-méndez, 2017) in Figure 2.7 are :

a) In Section 1, $E_{dyn}$ = 78 GPa and velocities of seismic waves are higher if compared to previous Campaign #20. These greater values show the fresh rock mass that is still joined in some fields along the layout. Weathered rock and moderately water-bearing rock also occur.

b) In Section 2, decrement of $V_p$ to 5.28 km/s to the end of the section lead to a slight decrement in $E_{dyn}$ = 74 GPa. The latter indicates a moderately reduction in rock stiffness mostly due to a greater joint density.

c) In Section 3, $V_p$ is increased to 6.25 km/s which also due to an increment of $E_{dyn}$ to 88 GPa. Since $E_{dyn}$ is greater than 80 GPa, it is concluded that this section contains mostly moderate to good rock mass. However, $V_s$ drops with a Poisson ratio greater than 0.32 indicate possible presence of water which mostly because of to the existence of single fractures.

d) In Section 4, $V_p$ = 5.755 km/s, $V_s$ = 3.35 km/s and $E_{dyn}$ = 81 GPa. The reduction in both waves' velocities and $E_{dyn}$ indicate the reduction of rock stiffness. The further decrement of $V_s$ and $E_{dyn}$ indicate a possible fracture zone. Possible of water presence can be expected at this zone since the Poisson ratio yields 0.29. A comparable decrease is noted towards the end in $V_s$ and $E_{dyn}$. Such changes in terms of rock conditions, however, are inappropriate owing to the loss of seismic resolution.

Based on the research, Dickmann & Hecht-méndez concluded that the findings of TSP provided prognosis that are in positively agreement with discovered geological conditions on the exposed tunnel face, without delay the tunnel operation and can be performed continuously even in shield's TBM. However, interpretation of TSP data become difficult when encountering low rock physical property contrasts, rock acoustic impedance as a result of rock density and seismic velocities, layering spatial disposition, and some parallel tunnel fractures.

TSP technique is a direct consequence of vertical seismic profiling (VSP) method (Baldi et al., 2006). VSP is an improvement of simple Check Slot Velocity survey which is down-hole or up-hole borehole velocity investigation. To conduct VSP, a geophone string is lowered into a cased well at known depth intervals to record the signals which is generated from the surface shot. The obtained seismic traces are used to construct a single seismic trace or a corridor seismic section, both to be compared with surface conventional seismic sections for calibration purposes or for prediction under the well bottom. TSP can set up the same thread in a tunnel, and hence could avoid the near surface noise and large depth of investigation, especially mountainous area. However, TSP could encounter the noise due to tunnel reinforcements and a low sensitivity regarding the 3D position of reflecting surfaces. It can be seen only like a cutting of tunnel route when a layer is sub-parallel to the tunnel.

## 2.3 Rock Mass Classification

Rock mass classification is a helpful empirical design method that corresponded the actual conditions found at the earlier site to predict the predicted scenario at the suggested site. It is commonly adopted in rock engineering to enhance the quality of site investigation by using the least available input data as classification parameters and deliver quantitative information for design and support system selection purposes. Rock mass classification could lead to a better engineering judgement and understanding to the site.

Terzaghi had introduced rock load classification as the earliest guideline to the application of rock mass classification for the design of tunnel support in 1946 (Bieniawski, 1990; Singh & Goel, 2011). The concept is to estimate the basics of a descriptive information to the rock loads that carried by steel sets. Terzaghi developed