Geological Prediction Ahead of Tunnel Face in the Limestone Formation Tunnel using Multi-Modal Geophysical Surveys

N F M Zaki¹ and M A M Ismail¹ Mohd Hazreek Zainal Abidin² and Aziman Madun²
¹School of Civil Engineering, University Science Malaysia, Engineering Campus, 14300 Nibong Tebal, Malaysia
²Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn, Malaysia, 86400, Batu Pahat, Johor, Malaysia

E-mail: ceashraf@usm.my

Abstract. Tunnel construction in typical karst topography face the risk which unknown geological condition such as abundant rainwater, ground water and cavities. Construction of tunnel in karst limestone frequently lead to potentially over-break of rock formation and cause failure to affected area. Physical character of limestone which consists large cavity prone to sudden failure and become worsen due to misinterpretation of rock quality by engineer and geologists during analysis stage and improper method adopted in construction stage. Consideration for execution of laboratory and field testing in rock limestone should be well planned and arranged in tunnel construction project. Several tests including Ground Penetration Radar (GPR) and geological face mapping were studied in this research to investigate the performances of limestone rock in tunnel construction, measured in term of rock mass quality that used for risk assessment. The objective of this study is to focus on the prediction of geological condition ahead of tunnel face using short range method (GPR) and verified by geological face mapping method to determine the consistency of actual geological condition on site. Q-Value as the main indicator for rock mass classification was obtained from geological face mapping method. The scope of this study is covering for tunnelling construction along 756 meters in karst limestone area which located at Timah Tasoh Tunnel, Bukit Tebing Tinggi, Perlis. For this case study, 15% of GPR results was identified as inaccurate for rock mass classification in which certain chainage along this tunnel with 34 out of 224 data from GPR was identified as incompatible with actual face mapping.

1. Introduction

Adverse geological problems which are frequently encountered in the tunnel construction of karst area is often caused by varying degrees of karst problems. Due to the complexity of geological conditions, it is difficult to accurately identify the nature of the adverse geological body, in the survey and design stage, especially in the case of deep buried tunnels [1]. Before commences any activity in tunnel construction especially in karst limestone area, it is important to adopt the risk assessment such as geological prediction ahead of tunnel face, identify the abnormal of geological reaction, karst cavities, crushed zone, groundwater pressure, fault fracture, and minimize the risk that potentially occurs during
the tunnel construction phase including structural collapse, underground water burst and other geological problems. In recent years, with the constant progress of science and technology, GPR technology has been widely applied to advanced geological prediction of tunnel [2]. GPR is a near-surface geophysical technique that can provide high resolution images of the dielectric properties about 20 meters of the earth. It is a very useful technique which employ the radio waves typically 16 to 2000 MHz frequency range, to study structure and features buried in the ground, groundwater, subsurface faulting, and underground cavities [3]. Ground penetrating radar produces a continuous cross-sectional profile or record of subsurface features, without drilling, probing, or digging [4]. The result of GPR prediction ahead of tunnel face (short range method) verified using geological face mapping method based on Q classification system which is able to identify the actual geological condition at site and classification of rock mass.

The numerical value of Q ranges from 0.001 (for exceptionally poor quality squeezing-ground) up to 1000 (for exceptionally good quality rock which is practically unjointed). The rock mass quality Q is a function of six parameters, each of which has a rating of importance, which can be estimated from surface mapping and can be updated during subsequent excavation [5].

2. Geological Background

Perlis is a small state in northern Malaysia, and it has both isolated tower karst hills as well as a long range of limestone hills. It has the southernmost limestone range on the mainland of Southeast Asia, the remainder of the limestone within Peninsular Malaysia occurs as isolated outcrops and towers. The Setul Boundary Range is riddled with caves, many of which have active streams that are rarely found elsewhere in the peninsula [6]. The Setul Formation is widely distributed in the North-western part of the Peninsular Malaysia and southern Thailand as show in Figure 1. The rock of the Setul Formation comprises crystalline, hard brittle, dark coloured, thick bedded, variably impure, crystalline limestone with subordinate detrital facies composed of quartzite, flagstone, carbonaceous shale, slate and black cherty mudstone [7]. In Perlis, the precipitous limestone cliffs rise abruptly above the surrounding plains and they form a relief up to several hundred metres. The limestone country are saturated with many sinkholes, dissolution cracks, and cavities, whereas hills are crisscrossed by deep cracks and sharp pinnacles.

Timah Tasoh tunnel is one of the flood bypass project starting from the Timah Tasoh Dam, passing through Bukit Tebing Tinggi and eventually drained into Straits of Malacca. This tunnel is 756 m long and a cross section of nearly 74 m² square constructed through the karst limestone hill area (featured by typical karst topography and formation which has abundant rainwater and groundwater and unknown geological condition of rock). The inlet and outlet chainage of this tunnel project starts from CH 3+590 (outlet) until CH 4+346 (inlet).

This area of study located at Bukit Tebing Tinggi, the limestone is represented by a grey to dark grey, finely crystalline variety with discontinuous laminae as show Figure 2. The karstic landforms observed around Tebing Tinggi included tower, pinnacles, sinkholes, cracks, caves and caverns during the preliminary stage. Construction through the karst limestone are becoming challenging and costly due to uncertainties. As the water tunnel will be built entirely below the ground level, a large amount of groundwater may be required to be drained to the ground surface, and this will be a difficult challenge for the construction activity to overcome. Thus, it is important to predict geological condition ahead of tunnel face using GPR and geological face mapping during the construction process.
Figure 1. Geological map of Perlis.

Figure 2. Location and Limestone of Timah Tasoh Tunnel in Bukit Tebing Tinggi, Perlis.
3. Methodology

At preliminary stage, all the primary data of geophysical and result testing was reviewed and studied including geological maps and existing geological literature concerning to the area of tunnel construction. Unpublished material such as design and construction report also important to be reviewed in order to improve the knowledge of rock condition at the site area.

3.1 Principles of Ground Penetration Radar

GPR was known as a method of geophysical survey that applied the propagation speed of electromagnetic wave and travel time of reflected impulse in front of the working face. The working principle of this method is transmitting antenna which will directionally transmits the high frequency short pulse electromagnetic waves. The electromagnetic waves will be reflected or refracted in a case, they encounter formation or unfavourable geology body with different electrical property as show in Figure 3.

![Figure 3. The principle of GPR.](image)

In term of geological risk assessment for Timah Tasoh Tunnel, Ground Penetration Radar (GPR) was conducted ahead of tunnel face using Model SIR-3000 with 100 Mhz antenna. The wave length using this prediction testing, reflected maximum of 30 meter depth for this karst limestone formation. Testing procedure of this method is to transmit 20-30 m range of wave length from the left side to the right side of tunnel face. Starting chainage by using this method is CH 3+590 to CH 3+610 as shows in Figure 4 and continuously performs until the end of tunnel at CH 4+346. Data collected will be analysed and processed by the analysis software package using Radan software matched with this geophysical survey instrument system. Analysis and interpretation will be carried out on the basis profiles during data processing. Then a comprehensive analysis will be carried out based on geological condition, properties and geometrical characteristics of prospected object. Forwarding and inverting models will be made if it is found necessary. This testing can predict fracture rock mass, able to detect fault zonation, karst caves and underground water through the anomalies of the reflected radar wave. Finally, the report of radar prospecting will be prepared. GPR output provides initial prediction of rock quality based on anomaly in rock condition such as fault fracture zone, cavities, weathered joint fissures that possibly effects the quality of rock. It classified into 4 major classes, A, B, C and D which represent as good, fair, poor and very poor condition. This classification was categorized based on the result from the wave frequencies, amplitude and travel time.
3.2 Geological Face Mapping

Report of GPR prediction then verified by geological face mapping that has been conducted at a site along the 756 meter of tunnel length to describe and classify the rock mass using Q value before selecting the tunnel support. Thus, geological mapping is the basis for the geological description. By using geological mapping, it can demonstrate the actual condition of the site due to Q value able to provide real description of the rock mass quality and its stability, in which high value of Q indicates for the high stability and good quality of rock. At this stage, the exposed rock and soil including the overburden also will be observed and recorded during the mapping process. The different rock types shown by different colour or symbols, major faults and fracture zone also will be recorded. Geological structures such as bedding, folds, foliation, history, faults and joints also will be described, while the orientation of these structures was measured as spike-dip or dip-dip direction.

The individual parameters are determined during geological mapping using tables that give numerical values to be assigned to a described situation. Paired, the six parameters express the three main factors which describe the stability in underground openings [8].

$$Q = \frac{RQD}{J_n} \times \frac{J_s}{J_n} \times \frac{J_w}{SRF}$$

(1)

Where,

$$\frac{RQD}{J_n} = \text{Degree of Jointing (or block size)}$$

$$\frac{J_s}{J_n} = \text{Joint friction (inter-block shear strength)}$$

$$\frac{J_w}{SRF} = \text{Active stress}$$
The amount of RQD was calculated from the number of joint per cubic meter with five stage starting from very poor to excellent condition with value comes from number of joint per cubic metre. $J_n$ represents number of joints set number occurring together, $J_r$ is a parameter of joint roughness, $J_a$ is a parameter describing the joint mineralization based on thickness of mineral filling. Then $J_w$ describes the joint water Reduction Factor which is dry or minor until high inflow of water. SRF (Stress reduction factor) describing the stress situation in tunnel. After collected all the parameter, the value is transformed to the equation to obtain $Q$-Value, thus suitable support will be estimated based on it.

4. Result and Discussion

Figure 5 shows a result obtained from Ground Penetration Radar (GPR) using Radan software in wiggle mode for CH3590 to CH3610 starting the tunnel face into 20 meter prediction and continuously until the end of tunnel. Based on the result of the reflected wave, starting from CH 3590 to CH 3595, (A and B in Figure 5) it shows an obvious signal reaction which was identified as slightly weathered with some little joint fissures. Geological anomalies show electromagnet wave encounters moisture content of different medium, diffraction and increase in amplitude. The amplitude increases when radar wave arrives at the interface between water and surrounding rock [9].

Meanwhile, CH3600 to CH3605 (C in Figure 5) identifying a geological anomalies with a strong signal reaction represented as moderately weathered with joint fissures due to increases in electromagnetic wave amplitude throughout tunnel face area at CH3600 to CH3605, thus it was predicted as the structure layer was filled with little clay and water that potentially classified as a poor condition of rock. When the radar wave encounters the water, the conductivity of water increases, resulting in increases in attenuation coefficient and attenuation speed of the high-frequency wave. Therefore, the frequency of the radar wave decreases [9].

Figure 5. GPR reflected wave from CH 3590- CH 3610 in wiggle mode.

Figure 6 demonstrated the result of geological mapping at tunnel face for unfavourable geological condition such as encountering of cavity caves filled with clay and water, and some of drip water. Based on geological face mapping at this location, rock were classified as highly-moderately weathered and partial soil, weak to medium strong rock and highly weathered along the joints with locally cavity. The $Q$-value obtained from this mapping parameter was 1.98 and rock classified as poor quality of rock with
class C in range between $1 \leq Q < 4$. Figure 7 obtained from real observation at tunnel face with clearly shown the groundwater inflow mixed with soil from the cavity.

**Figure 6.** Geological mapping result at tunnel face.

**Figure 7.** Rock image obtained during mapping.
Figure 8. Profile of the Timah Tasoh Tunnel from CH 3550 to CH 4346.
From the Figure 8, results were presented in the form of GPR and Mapping simultaneously to show the differential of rock grade and classification methods for any chainage along tunnel profile in which the red colour represents a very poor quality of rock, while the orange colour represents a poor rock quality and the yellow colour represents a good quality of rock. Meanwhile, Figure 9 shows the rock mass class vs chainage using combination data of GPR and mapping along tunnel with 756 meter starting from CH 3550 to CH 4346. From both data observation and analysis, the results show that 34 out of 224 data from GPR identified as incompatible with geological face mapping. Thus, 15% of GPR is inaccurate to determine the rock mass classification in this case study by referring to geological face mapping.

![Rock Mass Class vs Chainage](image)

**Figure 9.** Rock mass vs chainage for GPR and Mapping along tunnel

### 5. Conclusion

Tunnel construction requires several considerations to minimize the risk of failure especially for karst limestone that may consist of cavities, sinkholes, pinnacles, dead-end valleys, cracks, caves, and caverns. Thus, risk assessment including prediction ahead of tunnel face is important to classify the risk of zonation during construction stage. For Timah Tasoh tunnel, Ground Penetration Radar testing conducted ahead of tunnel face for range 20 to 30 meter per reflection wave through the Bukit Tebing Tinggi in karst limestone formation. Then, geological face mapping also conducted at site in every 3 to 4 meters to determine the rock mass classification using Q-value system that shows the actual geological condition of karst surface. Summarization from both methods; prediction method (GPR) and actual method (geological face mapping) are not necessarily will produce the similar results to obtain the rock mass classification along of tunnel. The percentage of inaccuracy for both methods is 15%. From the analysis that had been conducted, the data shows that the tunnel face consists of water drip, under groundwater, filled with clay or soften soil, heavily joint and cavity which lead to inconsistent result between GPR and geological face mapping in determination of rock mass classification and quality.

### References

[1] Zhao N, Xia Y and Liu Y 2015 Analysis and Application of Ground Penetrating Radar Signal in Detecting Karst Fissure Water in Tunnel Construction, China, Volume 20, 1363-1375.
[2] Xu Z, Zhao C, Li S and Wu J 2015 Case Study of Ground Penetration Radar for Geological Prediction in Qiyueshan Tunnel, China, Atlantis Press, 100-103.

[3] Mazumder R K and Ansary M A 2011 Geophysical Investigation at Meghna Dhonagoda Irrigation Project (MDIP) Using Ground Penetrating Radar Method, Thailand.

[4] B. Venkateswarlu and Vinod C. Tewari 2014 Geotechnical Applications of Ground Penetrating Radar (GPR), Jour. Ind. Geol. Cong. Volume 6(1), 35-45.

[5] N. Barton, R. Lien and J. Lunde 1974 Engineering Classification of Rock Masses for the Design Tunnel Support, Volume 6, 189-236.

[6] L Price 2011 Tin Mining In The Limestone Caves Of Perlis Malaysia, Acta Carsologica Volume 40/3, 497–503.

[7] Ali C A and Mohamed K R 2013 Microfacies and Diagenesis in the Setul Limestone in Langkawi and Perlis, Bulletin of the Geological Society of Malaysia, Volume 59, 59 – 66.

[8] National Geotechnical Institute 2015 Rock Mass Classification and Support Design Handbook, Norway.

[9] Li S, Li S, Zhang Q et.al 2010 Predicting Geological Hazards During Tunnel Construction, China, Journal of Rock Mechanics and Geotechnical Engineering, Volume 2(3), 232-242.