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Contributed Paper

Comparison of Geological Mapping with Electrical Resistivity and Ground Penetration Radar Methods for Rock Fractured System Study

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ABSTRACT

Regional and local geological mapping play an important role in the understanding of fractured rock system. These techniques were applied in this study as well as in a comparison with active geophysical methods that respond to the physical properties of objects and materials below the earth surface, (i.e., electrical resistivity and ground penetrating radar; GPR, among others). The two geophysical methods were conducted within the tunnel outcrop. In addition, satellite imagery obtained from Google Earth was used to determine the main lineament pattern present in the area. The geological mapping that consists of the fracture system (i.e., discontinuity) mapping was used to compile the catalog of the fractured system. The electrical resistivity method that was applied alongside the tunnel was compared with the results from the ground penetrating radar method. This study, with the application of regional geological mapping using satellite imagery, was able to give a valuable comparison with in-situ geological mapping. The discontinuity data were plotted in the DIPS software to obtain the lineaments' orientations in rose diagrams. Low resistivity values were compared with ground penetration radar results and with the lineament pattern. The existence of water-bearing structures within the fractures system inside the rock mass affects the low resistivity values, at the same time as the directions of fractures furthermore match that of the ground penetration radar results. The high resistivity values, as interpreted from the electrical resistivity data, are an indication of a lesser amount of water-bearing structures and therefore a smaller amount of damaged units. The ground penetration radar method produces similar results with the lowest amplitude radar reflections from the water free region, and stronger reflections recorded in the area saturated with water. All the parameters used in this study contribute to a Tunnel Stability Rating System (TSRS) that is in development. The Tunnel Stability Rating System could be a useful method of determining the stability of tunnels, particularly tunnels without rock exposure (e.g. that is covered by shotcrete). The overall goal is to make the evaluation process of rock tunnels able to use an alternative assessment when electrical resistivity and ground penetration radar data are accessible.

Keywords: geological mapping, electrical resistivity, ground penetration radar and tunnel stability rating system

1. INTRODUCTION

Geological mapping for the prupose of tunnel stability is limited when the rock surface is covered by a shotcrete lining. Geologist face these problems in evaluating the stability of a tunnel when no previous record of geological mapping data is available. . Regional mapping will assist the lineament pattern and could be correlated with the fractured system in a rock mass. Geophysics can contribute a lot to the subsurface study of fractured bedrocks, by helping to identify the fractured and or weak zones in tunnels in which outcrops are unavailable. Electrical resistivity and ground penetration radar (GPR) are two methods used in this study to observe important signals related to the geological mapping of this area. Many works have been reported on faulting and fractured mechanisms in subsurface rocks, i.e., [2, 3]. In these previous studies, some include the application of the electrical resistivity to map the subsurface bedrock units. We have used some of this previous in this study [4-9]. The application is not limited to structural mapping only; previous researchers have identified the usefulness of these geophysical tools in environmental studies such as seepage mapping and groundwater delineation, [8, 10-14].

In this present study, we applied the electrical resistivity and ground penetration radar (GPR) to compare the results from these geophysical methods with geological mapping to examine the fractured rock system and to evaluate the tunnel systems within the Peninsula Malaysia. One goal from this work is to assess the Tunnel Stability Rating System as a useful method of determining the stability of tunnels, particularly tunnels without rock exposure..

2. METHODOLOGY

Regional geological mapping using Google Earth images contribute a better understanding about the in-situ geological parameters related to the rock fracture system. Two geophysical methods were used (electrical resistivity and GPR) to capture the subsurface information (Figure 1). This research also highlights the GPR method as a common non-destructive procedure useful in detection of geologic hazards including tunnel risks. Observation of support structures (rock bolts, dowels, anchors and shotcrete itself is gathered to establish tunnel stability rating system.

2.1 Satellite Imagery

A photo lineaments study was carried out to visualise the presence of the main lineaments in the bedrock of the surrounding areas by utilising the satellite image downloaded from Google Earth. The downloaded image was visualised by using an image processing software to enhance the visibility of the topographic features and hence the interpretation of lineaments.

Image enhancement has been undertaken using Adobe Photoshop software, and the lineaments were traced manually. DIPS software was employed to plot the lineaments' orientations into rose diagrams.

(a)

(b)

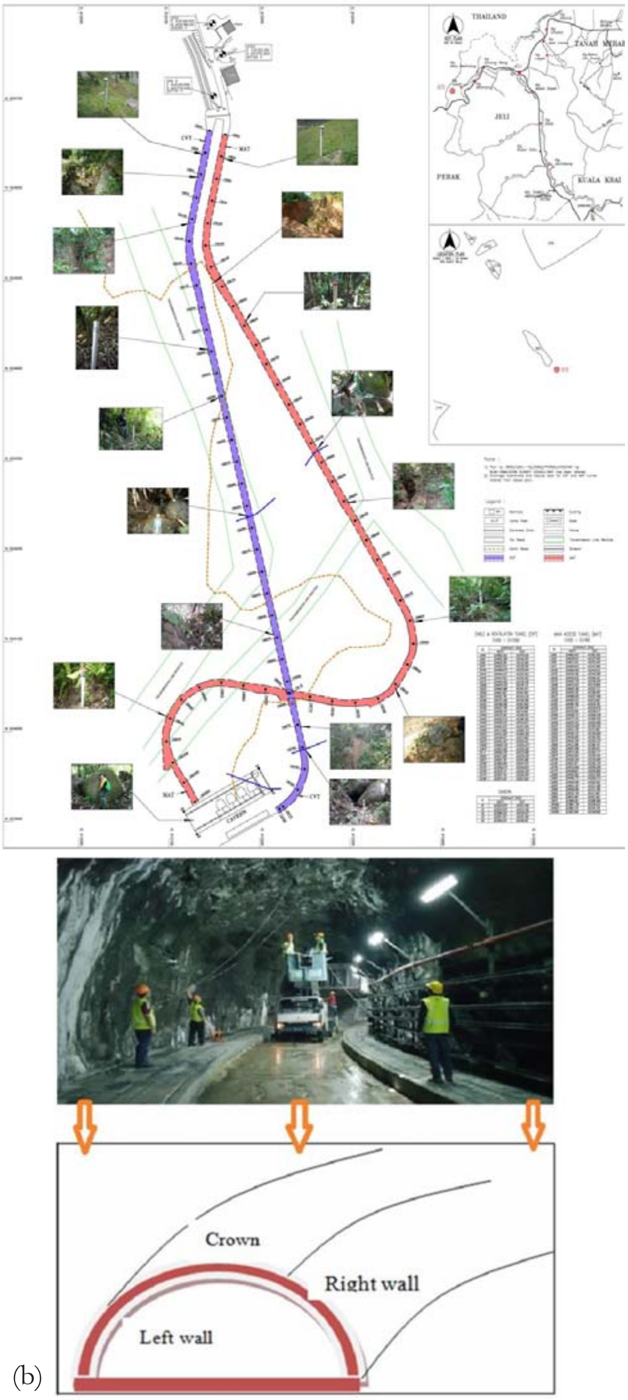


Figure 1. Map of the Tunnel showing: a) the geological and geophysical survey lines. b) the surface inside the tunnel and the sketch diagram of the tunnel used to conduct the geological and geophysical survey.

2.2 Local and Regional Geological Mapping

In this study, the degree of weathering for the rock masses is described using the classification scheme by IAEG (International Association For Engineering Geologists, in [15]. Some of the terminologies used to describe the discontinuity features and field estimation of the rock strength used the International Standard Rock Mechanics (ISRM) guideline. Other equipment used include Suunto or Silva Ranger geological compass and clinometers, digital camera and measurement tapes. The method that is used for geological and surface mapping is scanline method conducted at each 10 m interval along the entire length of the tunnels by walking along it. All notable geological features, (Figure 2), (rock types, weathering grade, fault, water or seepages, and discontinuities) and signs of tunnel instability, deterioration or degradation are recorded and noted at each 10 m along the tunnels. Beforehand, a photograph is captured along the tunnel with a 10 m interval to be inserted into the discontinuity survey form to make more precise and organised recorded geological features. Each geological feature is recorded and noted according to their symbols. Schmidt Hammer is also used at certain locations to test the shotcrete condition or outcrop and presence of stalactite and stalagmite that indicates there is a crack at the back of the tunnel walls. It is used to estimate and to test the strength and integrity of the shotcrete lining and exposed outcrop. A point load test is used to determine the rock strength and convert to the international standard classification of rock strength in MPa unit.

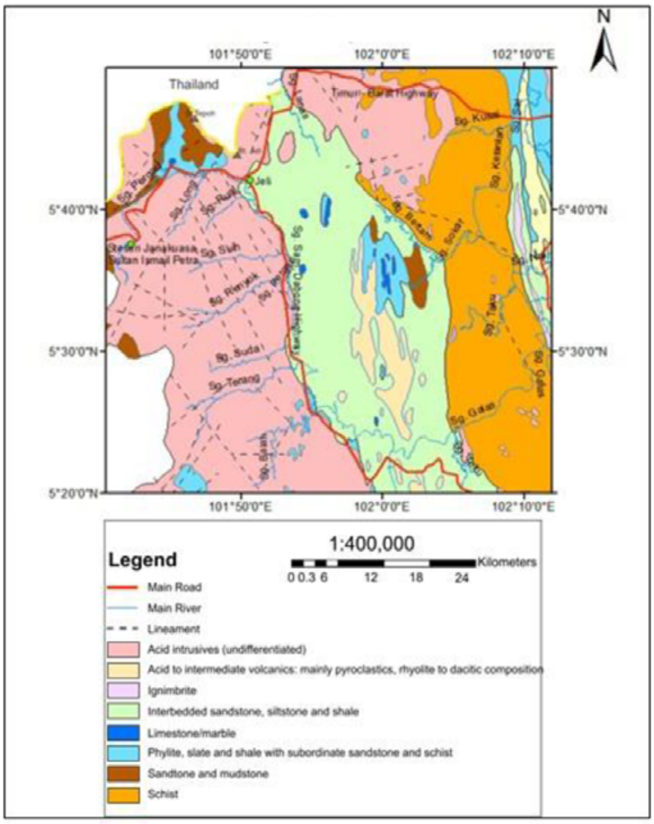


Figure 2. Simplified general Geological Map of the study area after, [19].

2.3 Electrical Resistivity Survey

Electrical resistivity used to determine the electrical properties of material inside the tunnels. The apparent resistivity is calculated using the basic formula $p_a=2\pi aR$. An ABEM Terrameter SAS4000 is used to derive the apparent resistivity. The resistivity measurement consists of a 41electrode system that is laid out along the survey line.. This method uses the international standard ASTM D6431-99 as a guide for conducting the survey. The data was processed using RES2DINV software [16, 17]. The length of survey lines was 200 m each with penetration depth target around 30m inside the both (left and right, wall and crown area).

2.4 Ground Penetrating Radar

Ground Penetrating Radar (GPR) uses an electromagnetic microwave that is similar to sound in ultrasonic pulse-echo methods. It is based on the propagation of electromagnetic energy through materials of different dielectric constants (analogous to acoustic impedance in sound). GPR operates by transmitting pulses of radio waves down into the ground through an antenna and measuring the reflected energy back to the receiving antenna. The greater the difference between dielectric constants at an interface between two materials, the greater the amount of electromagnetic energy reflected at the interface. RAMAC/GPR made by MALA GeoScience, Sweden with 250 MHz antenna is used for the survey. The estimated penetration depth is 9 metres. GPR method using [18].

3. Results

Compilation of results used to develop an understanding of tunnel stability, and the Shotcrete Lining covered of the tunnels; this assessment could provide very useful information.

3.1 Major Lineaments Pattern

The satellite image interpretation shows a well-developed lineament system in the region of the survey area. To objectively visualise the lineament pattern and distribution, the interpretation area was arbitrarily divided into 3 sections, namely: the Western/Northwestern, Central and the Eastern domains (Figure 3). The western and north-western domain is characterised by 3 sets of lineaments, in which the NW-SE set is most prominent, followed by the NE-SW and the N-S set. The same sets of lineaments were also identified in the Central domain; however some E-W lineaments were also encountered, making up a total of 4 sets of lineament in Central domain. The Eastern domain shares much in common with lineaments sets in those of the Central domain; i.e. 4 sets of lineament are present. However, the E-W oriented lineaments are more prominent in the Eastern domain compared to the Central domain. Figure 4 shows the major direction of lineament at the study area. The results of the Kinematics stability analysis is as shown in Figures. 5 (i to ii).

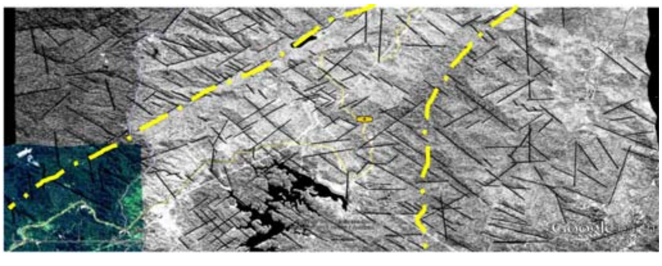


Figure 3. Lineament map from the interpretation of Google Earth's satellite image.

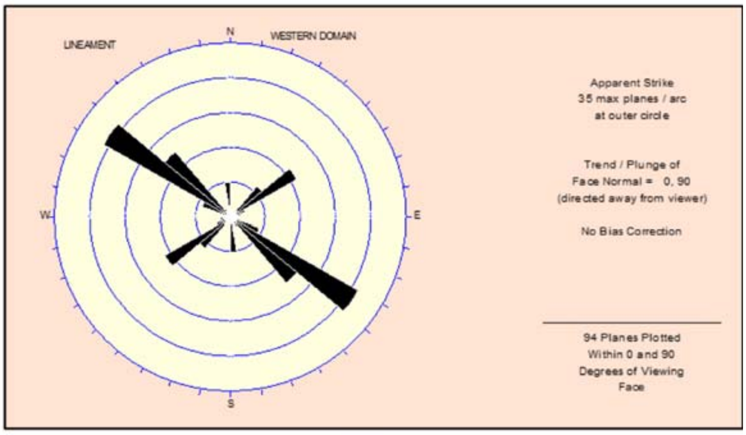
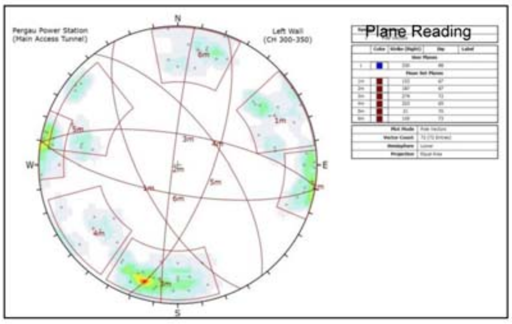
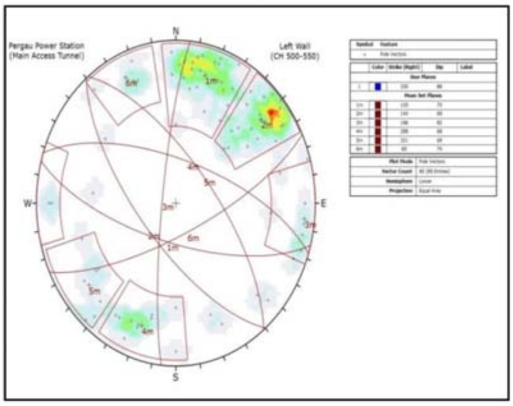


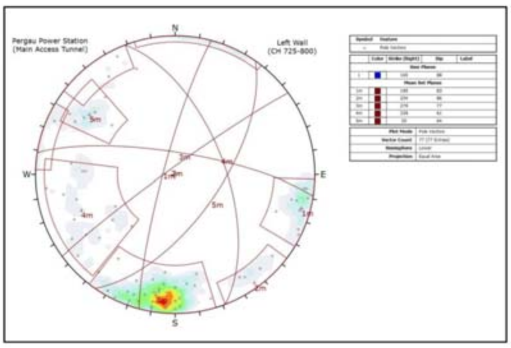
Figure 4. The Rose diagram of the lineaments from the study area.



(i)



(ii)



(iii)

Figure 5. Major planes plots of discontinuity in the data from the outcrops between; i) CH 300-350 at left wall in MAT., ii) CH 500-550 at left wall in MAT., and iii) CH 725-800 at left wall in MAT.

3.2 Low and High Electrical Resistivity Response

Base on the results from more than 30 electrical resistivity survey lines in this study, values less than 100 Ωm are classified as a weak zone with water and matched with the geological mapping results. An example of electrical resistivity result is shown in Figure 6, which has low resistivity value for the weak area, containing watery. The high resistivity values (>1000 Ωm) were classified as less fractured and dry. Low and high electrical resistivity responses are also integrated with GPR results.

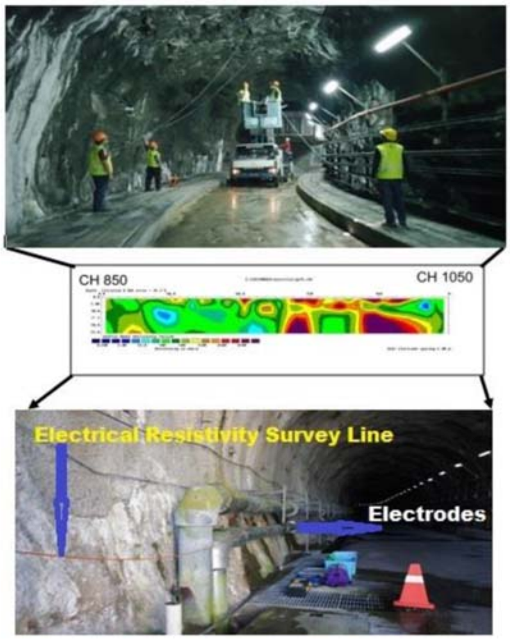


Figure 6. Electrical resistivity result with low and high resistivity value along the survey line shown inside the Tunnel.

3.3 Low and High Reflection of Radar Wave

The GPR shows the high reflection signal associated with the wet area while low reflection at dry region and with fewer fractures in the rock mass. In the study results (Figure 7), the areas with saturated fracture have a higher intensity of reflection ,which indicates that the area is wet and highly contaminated with fine clayey particles. Areas marked with less fractured (dry) interpreted as relatively much drier compare with highly fractured [19] areas.

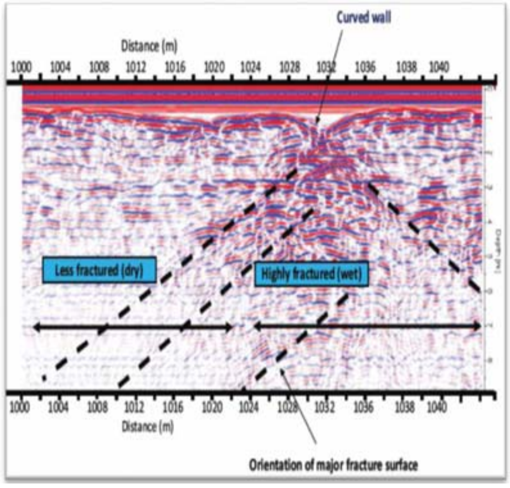


Figure 7. GPR result with low and high reflection signal observed at different rock mass condition.

4. Discussion

Groundwater intrusion is a common issue and problem inside the tunnels. The concrete-lined sections of the tunnel have been the main concern of water trapped behind the shotcrete. Once the water pressure builds up, it induces cracks and may also trigger failure (roof or wall collapse) in the tunnel. Continuous wetting of the bedrock encourage chemical weathering or mineral decomposition and hence reduces the rock mass strength in the long run. Concrete spalls, cracking in the shotcrete lining and corrosion of the steel support structures (bolts, dowels, and anchors) are used as indicators of the weak zone and suspected highly fractured zone.

4.1 Comparison Between Methods

The electrical resistivity and the GPR geophysical methods used in the work showed that low resistivity and high intensity of reflection signal areas could be correlated with weak and groundwater-filled in fractured/faulted bedrock zones. Regional and in-situ mapping helped to identify the directions of fractures/faults and the major joints present in the bedrocks. The study areas with a total length of the tunnels used is about 2 km.

4.2 Tunnel Stability Rating System (TSRS)

Once all the parameter from geological mapping and geophysical survey were obtained, a Tunnel Stability Rating System (TSRS) was proposed. These methods used five parameters to establish this rating system with the summary of the results as presented in Table 1. In this stability rating system, geophysical parameters contribute 30%, and the rating value is given based on their classification of groundwater accumulations and the degree of bedrock fractures. Meanwhile, structural or mechanical defect (concrete spall and corrosion on support structures) contribute 20%. Geological mapping includes the geological defects and discontinuity data recorded in term of the intensity of these parameters. Rock material strength from point load test and converted value from Schmidt hammer test (uniaxial compressive test, USC) used with 10%. Groundwater occurrence also gave a percentage of 10. Rock Mass Geomechanical Properties contributed the balance of 30%. All the parameters observed, i.e., geological mapping and a geophysical study conducted in the survey area are in-situ. Normally, the Rock Mass Rating (RMR) by [20], and the Q-System by [21], was adopted for this study and used to evaluate the rock mass inside the tunnels as shown in Figure 8.

Table 1. Tunnel stability rating system proposed to quantify the tunnel integrity, after [20, 21].

Parameter	Range value				
A) Geophysical Properties (30%)					
• Resistivity Value (% of interpreted water accumulations in single pseudo section)	80-100	60-79	40-59	20-39	< 19
Rating Value	15	12	10	5	0
• Ground Penetration Radar (Degree of saturation)	Unsaturated @ dry	Slightly saturated	Moderately saturated,	Highly saturated	Completely saturated
Rating Value	10	8	6	3	0
• GPR(degree of fracturing with water accumulations)	Massive	Low fractured	Moderately fractured	Hifhly fractured	Intensely fractured
Rating Value	5	3	2	1	0
B) Structural/Mechanical Defects (20%)					
• Cracks/Concrete Spall	None	Minor	Moderate	Substantial	Extensive
Rating Value	5	4	3	2	1
• Corroded/Defective Support Structures (Bolts/Anchors/etc)	None	Minor	Moderate	Significant	Severe
Rating Value	15	12	10	7	3

Table 1. Continued.

Parameter	Range value				
C) Rock Mass Geomechanical Properties (30%)					
• Geological Defects & Instabilities	Absent	Minor	Moderate	High	Intense
Rating Value	30	25	15	10	5
D) Rock Material Strength (10%)					
• UCS/Point Load Index (MPa)	> 200	200-100	99-50	49-10	< 10
Rating Value	10	8	5	3	0
E) Ground Water Intrusions (10%)					
• Inside tunnel conditions	Dry	Damp/Minor	Mod. Wet	Wet	V. Wet
Rating Value	10	7	5	3	0
Classification Of Tunnel Stability Rating System (TSRS, 2015)					
Total of Rating Value	100-81	61-80	41-60	21-40	< 20
Class	I Very good	II Good	III Fair	IV Poor	V Very Poor

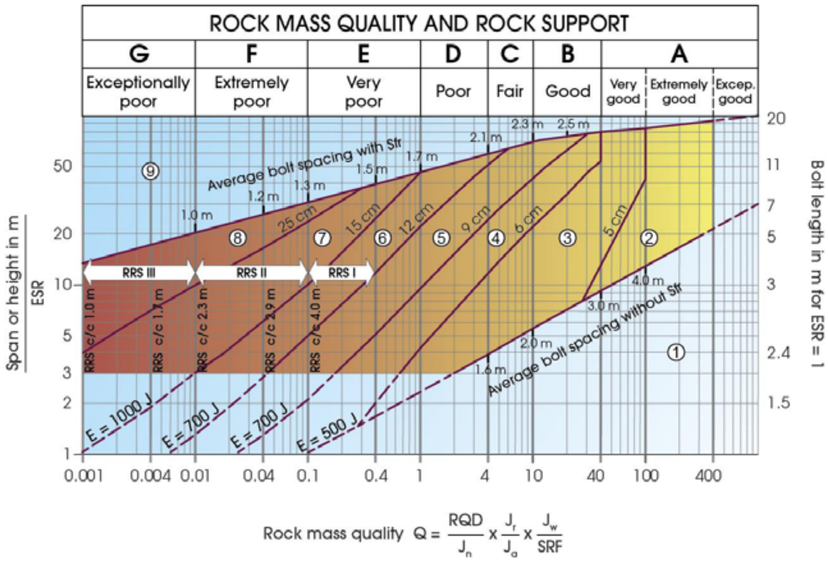
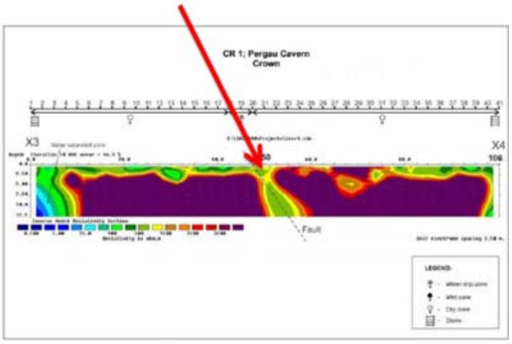


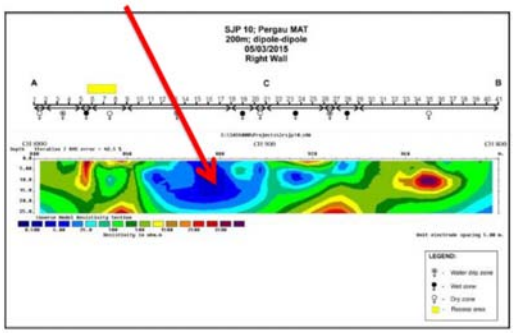
Figure 8. Rock Mass Rating (RMR) and Q-System, after [20, 21].

5. Conclusion

This study has shown the advantages of the use of integrated geophysical, geological and geomechanical methods as a better approach for the determination of tunnel stability assessment. Hidden information on the fractured /faulted bedrock units and the groundwater flow system internal of the shotcrete lined walls could be determined by this approach without damage to the walls as demonstrated in this work and presented in Table 1 and Figure 9. The characteristics of the tunnel rating system adopted in this study are;



(a)



(b)

Figure 9. Some results from the Electrical Resistivity Survey; a) Evidence of faulted/fractured bedrock unit, but dried as shown by the red arrow; b) Seepage at shotcrete and groundwater flow out as observed during the data acquisition as confirmed by the Electrical Resistivity results as demonstrated by the red arrow.

a) Very good. For a tunnel to be adjudged as a very good class, the bedrock conditions must be massive and dry. It must not show any significant signs of distress, mechanical or structural defects in the shotcrete lining. The bedrock must be solid, less jointed structures, unweathered or slightly weathered (most importantly, Gneissic bedrock materials), and no visible signs of instability. The supporting structures for the tunnel must also be in excellent or excellent conditions. Usually, highly strong bedrock materials, especially Granitic materials are most recommended. There must be no signs of groundwater intrusions. In situations of minor groundwater intrusions, it must be well managed through the adequate drainage system. Routine maintenance is at this moment recommended to keep a tunnel in a very good class.

b) Good. A tunnel is termed to be in a good class if the bedrock conditions are less jointed but slightly wet and show some minor defects in the shotcrete lining such as; light cracks, a small degree of fractured/faulted bedrocks and minor or localised corrosions in the shotcrete walls. The exposed bedrock units are widely spaced or jointed, slightly weathered, but no signs of alterations and evidence of instability in the exposed rocks mass that was adequately taken-care-of. In situations of groundwater seepages, it must be well managed through adequate drainage system and routine maintenance systems.

c) Fair. A fair tunnel rating system gives the following characteristics; when the bedrock units of a tunnel are riddled with some discontinuities structures that are significantly wet through seepages of groundwater intrusions, some significant amount of mechanical defects, i.e., cracks and spalls were observed in the bedrock units. If the exposed bedrock units are well jointed, but show some localised wedges and joints, with seepages of from the walls and roof but insufficient drainage control systems. The bedrock materials must be unyielding to supporting tunnel systems. Adequate routine maintenance must be carried out to arrest the situations.

d) Poor. A tunnel system is judged poor when the bedrock units are heavily jointed with localised sheared structures. The supporting steel materials are heavily affected by groundwater intrusions leading to corrosions. The bedrock is heavily weathered, altered and shows high degrees of instabilities, and the presence of weak rock materials with a substantial amount of groundwater intrusions leading to wet ground and calcite deposition. This class of tunnel needs urgent attention and structural repair with additional drainage systems to arrest the situation.

e) Very Poor. In situations where the bedrock units in a tunnel system are heavily jointed and sheared, widespread defects, direct contacts with the groundwater intrusions, and heavily weathered with steel supporting materials corroded, such tunnel systems are classified as very poor. The presence of feeble rock materials causes excessive groundwater seepages, highly wet ground, roofs and walls conditions with calcite deposits due to poor drainage systems. This situation calls for an immediate shutdown of the system for urgent repairs or replacement of all the supporting mechanical, structural steel materials and the drainage systems. Reinforcement of the shotcrete lining walls must be carried out.

The tunnel stability rating system, (TSRS), offer a better alternative to the identification of the stability of tunnels. This study clearly correlated well with the previous studies as shown.

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References

[1] Genter A., Guillou-Frottier L., Feybesse J.L., Nicol N., Dezayes C. and Schwartz S., *Geothermics*, 2003; **32**: 701-710.

[2] CuenotN., Charléty J., Dorbath L. and Haessler H., *Geothermics*, 2006; **35**: 561-575.

[3] Sausse J., Fourar M. and Genter A., *Geothermics*, 2006; **35**: 544-560.

[4] Archie G.E., *Transactions of the AIME*, 1942; **146**: 54-62.

[5] Griffiths D. and Barker R., *J. Appl. Geophys.*, 1993; **29**: 211-226.

[6] Dahlin T., *First Break*, 1996; **14**: 275-283.

[7] Baines D., Smith D.G., Froese D.G., Bauman P. and Nimeck G., *Sedimentology*, 2002; **49**: 441-449.

[8] Lee S.G., Lee D.H., Kim Y., Chae B.G., Kim W.Y. and Woo N.C., *Appl. Geochemist*, 2003; **18**: 135-143.

[9] Chambers J.E., Kuras O., Meldrum P.I., Ogilvy R.D. and Hollands J., *Geophysics*, 2006; **71**: B231-B239.

[10] Panthulu T., Krishnaiah C., Shirke J., *Eng. Geol.*, 2001; **59**: 281-295.

[11] Rabemanana V., Durst P., Bächler D., Vuataz F.D. and Kohl T., *Geothermics*, 2003; **32**: 645-653.

[12] Lee S.G., Kim Y., Chae B.G., Koh D.C. and Kim K.H., *Appl. Geochemist*, 2004; **19**: 1711-1725.

[13] Kayode J., Adelusi A., Nawawi M., Bawallah M. and Olowolafe T., *J. Afr. Earth Sci.*, 2016; **119**: 289-302.

[14] Airo M.L., Regional interpretation of aerogeophysical data: extracting compositional and structural features, Aerogeophysics in Finland 1972-2004.

[15] Attewel P.B., *Comprehensive Rock Engineering 1*, Pergamon Press. Oxford, 1993.

[16] Loke M.H., *The 62nd EAGE Conference and Technical Exhibition*, Extended abstracts. 2000; D-2.

[17] Standard guide for using the direct current resistivity method for subsurface investigation. http://www.astm. org/ standards/D6431.htm.Retrieved December 15, 2015.

[18] Standard guide for using the surface ground penetration radar method for subsurface investigation. http://www. astm.org/standards/D6432-99.htm. Retrieved December 15, 2015.

[19] JMG, *Geological Map of Peninsula Malaysia*. (ed.) Jabatan Malaysian Mineral and Geosciences, Kuala Lumpur, 2016.

[20] Bieniawski Z.T., *Proceedings of the 3rd International Congress on Rock Mechanics*, 1974; 27-32.

[21] Barton N., Lien R. and Lunde J., *Rock Mech.,* 1974; **6**. DOI 10.1007/BF0123 9496.