

Application of Spectral Analysis of Surface Waves (SASW) Method: Rock Mass Characterization

(Aplikasi Kaedah Analisis Spektral Gelombang Permukaan (SASW):
Pencirian Jasad Batuan)

T. L. GOH*, ABDUL RAHIM SAMSUDIN & ABDUL GHANI RAFEK

ABSTRACT

A geotechnical study needs to be carried out to determine the engineering parameters of the rock mass at the project site in executing construction projects such as tunnels, dams, highways and buildings. Design and safety factor of the construction are highly dependent on soil and rock engineering parameters which are usually determined by in-situ test such as Standard Penetration Test (SPT) and seismic tests. The SPT test which normally involves drilling and laboratory works always incur high operating cost, while seismic tests on the other hand are fast, cheap, non-destructive and an easy to operate method for rock mass characterization. The spectral analysis of surface waves (SASW) method is an in situ and non-destructive measurement that is rapid and cost effective. The aims of this study were to determine Rock Quality Designation (RQD) value, excavation classification analysis as well as site characterization by using the SASW method. WinSASW 3.1.3 was used for inversion processing of the SASW data to produce shear wave velocity (Vs) versus depth profiles. The profiles were then analyzed and correlated with rock mass engineering geological parameters such as RQD and site characterization as well as excavation classification of rock mass. Twenty (20) SASW tests were conducted on the granitic rock mass and four (4) SASW tests were conducted on a cut hill slope of metasedimentary rocks. RQD values were computed based on shear wave velocities and ultrasonic velocities of intact (fresh) rock. The differences between RQD obtained from SASW method and those from discontinuity survey were found to be less than 10%. Excavation classification for granitic rock mass at JKR Quarry was empirically determined using both SASW and ultrasonic velocities as well as RQD value of the rock mass. Site characterization for metasedimentary rocks mass at Bukit Tampoi was determined based on shear wave velocities from SASW method.

Keywords: Excavation classification; rock quality designation; SASW method; site characterization

ABSTRAK

Kajian geoteknikal perlu dijalankan untuk menentukan parameter kejuruteraan jasad batuan semasa menjalankan projek pembinaan seperti terowong, empangan, lebuh raya dan bangunan. Reka bentuk dan faktor keselamatan bergantung kepada parameter kejuruteraan tanah dan batuan dan selalu ditentukan dengan menggunakan ujian in-situ seperti ujian penusukan piawai (SPT) dan ujian seismos. Ujian SPT melibatkan kerja penggerudian dan makmal yang mahal. Ujian seismos ialah kaedah yang cepat, murah, tidak memusnah dan senang dikendalikan dalam pencirian jasad batuan. Kaedah analisis spektra gelombang permukaan (SASW) adalah kaedah seismos baru yang in-situ, tidak memusnah, cepat dan murah. Tujuan kajian ini ialah untuk menentukan nilai penanda mutu batuan (RQD), pengelasan pengorekan dan pencirian tapak dengan menggunakan kaedah SASW. WinSASW 3.1.3 telah digunakan untuk menyongsang data SASW dan menghasilkan profil halaju gelombang ricih (Vs) melawan kedalaman. Profil ini kemudian dianalisis dan dikaitkan dengan RQD, pencirian tapak dan pengelasan pengorekan jasad batuan. Dua puluh (20) ujian SASW telah dijalankan pada jasad batuan granit dan empat (4) ujian SASW dijalankan pada cerun potongan batuan sediment. Nilai RQD dihitung berdasarkan halaju gelombang ricih dan halaju ultrasonik batuan utuh (segar). Didapati perbezaan antara RQD yang diperolehi daripada kaedah SASW dengan survei ketakselajaran adalah kurang daripada 10%. Pengelasan pengorekan untuk jasad batuan granit di Kuari JKR ditentukan secara empirik dengan menggunakan halaju SASW dan ultrasonik serta nilai RQD jasad batuan. Pencirian tapak di Bukit Tampoi dihasilkan berdasarkan halaju gelombang ricih daripada kaedah SASW.

Kata kunci: Kaedah SASW; penanda mutu batuan; pengelasan pengorekan; pencirian tapak

INTRODUCTION

Spectral analysis of surface waves (SASW) had been introduced since the 1980's and has attracted the attention of researchers because it is a fast, cheap, non-destructive and

an easy to operate method in rock mass characterization. SASW method had been applied in excavation classification by Suharsono (2006), rock quality designation (RQD) determination (Suharsono et al. 2004), determination of

flexible pavement and rigid pavement profiles (Mohd Azmi Ismail et al. 2001) and evaluation of concrete structures (Rix et al. 1990) as well as non-destructive evaluation and characterization of pavement systems by Nazarian & Stokoe (1984). Recently, SASW method also had been applied in rock mass characterization by Abdul Rahim Samsudin et al. (2009) as well as determination of rock mass Poisson's ratio by Goh et al. (2010). The study of SASW is being emphasized currently because in the application of shallow seismic method, two thirds (67%) of the energy of wave sources are transformed into surface waves. The aims of this paper were to determine Rock Quality Designation (RQD) value, excavation classification analysis as well as site characterization by using the SASW method.

struck at the two opposite sides of the receivers as shown in Figure 1. For sampling shallow material, short receiver spacing with high frequency receivers and high frequency sources were utilized. For sampling deeper material, low frequency receivers were used with long receiver spacing and low frequency sources. The common receiver midpoint geometry (CRMP) introduced by Cho & Lin (2001), Joh (1996), Suharsono and Abdul Rahim Samsudin (2003) was used as shown in Figure 2 for the receiver spacing configuration. The Rayleigh wave data were collected and transformed to frequency domain by a dynamic signal analyzer. WinSASW 3.1.3 (Joh 1996) geophysical software was used for inversion process to produce shear wave velocity versus depth profiles.

MATERIALS AND METHOD

SASW METHOD

Rayleigh waves are generated into the ground by hammering, detected by two receivers and recorded by a spectrum analyzer in the SASW method. Two receivers were placed on the surface and a hammer impact was used to generate Rayleigh waves. Forward and reverse configuration which will generate forward and reverse SASW profiles are normally obtained by the hammer

DETERMINATION OF RQD

Rock quality designation (RQD) represents the overall rock mass quality. Deere (1968) proposed a rock mass classification scheme based on relationship between RQD and rock mass quality as shown in Table 1. According to Deere (1964), value of RQD is calculated as:

$$RQD = \frac{\text{Cumulative core length} > 100 \text{ mm}}{\text{Total Drilling Length}} \times 100\% \tag{1}$$

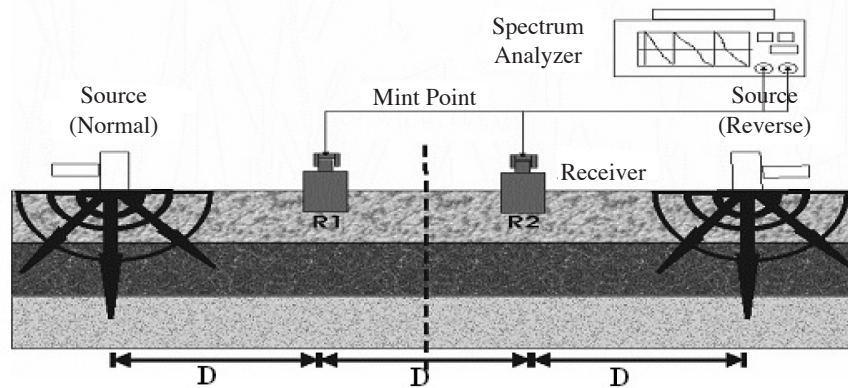


FIGURE 1. Field configuration of SASW method

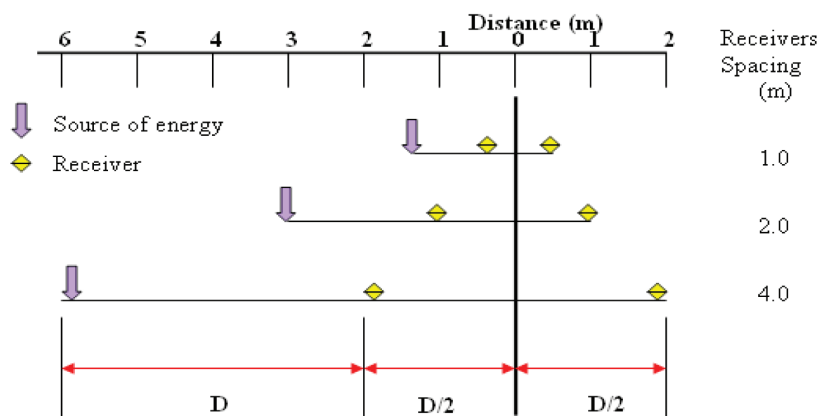


FIGURE 2. Common receivers midpoint geometry (CRMP)

TABLE 1. Rock mass classification based on RQD

No	RQD (%)	Rock Mass Quality
1	0-25	Very poor
2	25-50	Poor
3	50-75	Fair
4	75-90	Good
5	90-100	Excellent

Suharsono et al. (2004) proposed that the RQD value can be calculated using shear wave velocity derived from SASW method and the ultrasonic shear wave velocity of intact rock. RQD value can be empirically related to the relative frequency of discontinuities and condition of weathering of the rock mass. Based on the dispersion of shear wave velocity and ultrasonic test, the empirical relationships of RQD with shear wave velocity proposed by Suharsono et al. (2004) is:

$$RQD (\%) = 100^{(1-\delta)}, \quad (2)$$

where, $\delta = \left[\frac{(Vs\mu - Vs\beta)^2}{(Vs\mu + Vs\beta)^2} \right]^2$, $Vs\mu$ is shear wave velocity of intact rock from ultrasonic test and $Vs\beta$ is shear wave velocity from SASW test.

SITE CHARACTERIZATION

Site characterization was carried out based on relationship between geological material and shear wave velocity of rock mass by using SASW method which is proposed by Bay (2000) as shown in Table 2.

TABLE 2. Relationship between geological material and shear wave velocity (V_s) based on SASW measurement

Classification of geological material	Shear wave velocity, V_s (m/s)
Very soft	84 – 107
Soft soil	107 – 137
Moderately soft soil	137 – 183
Hard soil	183 – 274
Very hard soil	274 – 366
Highly weathered rock	366 – 610
Slightly/Moderately weathered rock	610 – 2743

EXCAVATION CLASSIFICATION

Bedding planes, joints, faults and fractures are among parameters that control excavation classification. Caterpillar (2006) established more systematic and accurate approach to predict excavation classification. Suharsono (2006) proposed an alternative method by using SASW method and ultrasonic test in determination of excavation

classification for rock mass. According to Suharsono (2006), the boundaries of excavation classification for rock mass can be calculated based on RQD classification (Deere 1968), shear wave velocity from SASW test and ultrasonic test and are derived as:

$$\text{Boundary equation at RQD 25\% : } Y = 8.8384X^{-0.5031}, \quad (3)$$

$$\text{Boundary equation at RQD 50\% : } Y = 10.969X^{-0.5005}, \quad (4)$$

$$\text{Boundary equation at RQD 75\% : } Y = 14.53X^{-0.5008}, \quad (5)$$

$$\text{Boundary equation at RQD 90\% : } Y = 19.001X^{-0.4973}, \quad (6)$$

where Y is the ratio of shear wave velocity of rock mass obtained from SASW test and intact rock shear wave velocity from ultrasonic test ($Vs\beta / Vs\mu$) and X is intact rock shear wave velocity obtained from ultrasonic test ($Vs\mu$). The excavation classification is shown in Figure 3.

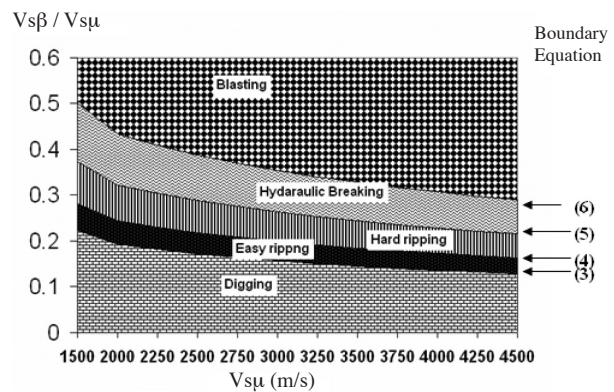


FIGURE 3. Excavation classification for rock mass

RESULTS AND DISCUSSION

Two different sites were selected for this study. The first site is the JKR Quarry, Bukit Penggorak, Kuantan, Pahang and the second site is meteorological station at Bukit Tampoi, Dengkil, Selangor. The JKR Quarry at Bukit Penggorak, Kuantan Pahang comprises light colored coarse granite (Arnie 2005). The rock at the Dengkil site is part of Kenny Hill Formation which comprises of weathered phyllite and quartzite (Rosly 1980).

At JKR Quarry, Bukit Penggorak, Kuantan, Pahang, five (5) survey points (P1, P2, P3, P4 and P5) comprising twenty (20) SASW tests were carried out. A total of four (4) SASW tests with different direction of sources of energy were run at each survey point as shown in Figure 4. SASW test for survey points 1 and 2 were conducted on different granite cut terraces, where rock mass beneath each of the terraces can be clearly measured by vertical discontinuity surveys. The RQD values measured from direct vertical

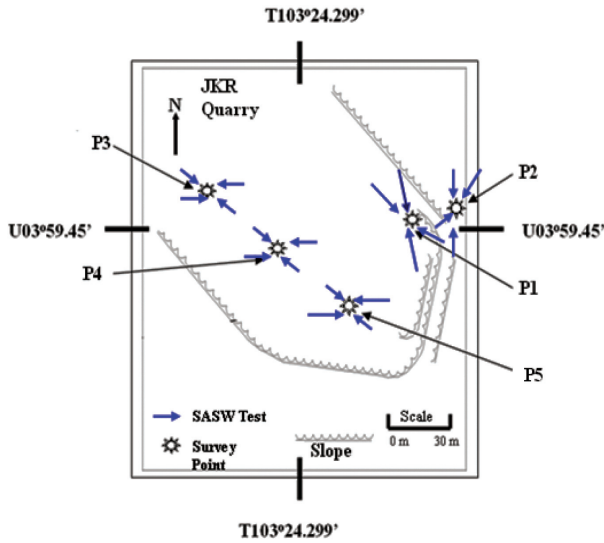


FIGURE 4. Twenty SASW tests were carried out at JKR Quarry, Bukit Penggorak, Kuantan, Pahang

discontinuities are compared to RQD values obtained from SASW tests. SASW tests for survey point 3, 4 and 5 were conducted at the base level of quarry, where measurement of rock mass discontinuities under the survey point are not possible. Intact rock shear wave velocity obtained from ultrasonic test was 3365 m/s. The SASW tests were carried out to determine the values of RQD and excavation classification for granitic rock mass in this study area.

At Bukit Tampoi, Dengkil, Selangor, two (2) survey points with four SASW measurements were tested at the meteorological station. Two (2) SASW measurements were carried out for each survey point. The SASW tests were carried out on the top soil of the metasedimentary formation to determine site characterization.

DETERMINATION OF RQD

For JKR Quarry, Bukit Penggorak, Kuantan, Pahang, the RQD values obtained from vertical discontinuities survey for P1 and P2 were 98% and 97%, respectively. The vertical discontinuities survey lengths for P1 and P2 were 7.5 m and 17 m, respectively. The SASW survey lines for P1 were conducted in four different directions and marked as BP163, BP343, BP115 and BP295. The SASW survey lines for P2 were named as BP193, BP233, BP053 and BP013. The comparison between RQD values obtained from discontinuity survey and SASW tests for P1 and P2 in four different directions are shown in Figures 5 and 6.

For P1, the average values of RQD obtained from SASW tests for BP163, BP343, BP115 and BP295 were 92%, 97%, 98% and 96%. For P2, the average RQD values obtained from SASW measurement for BP193, BP233, BP053 and BP013 were 99%, 97%, 97% and 97%, respectively. The results indicate that the RQD values obtained from SASW measurement were significant, where the differences between RQD discontinuity survey and RQD SASW method were less than 10%.

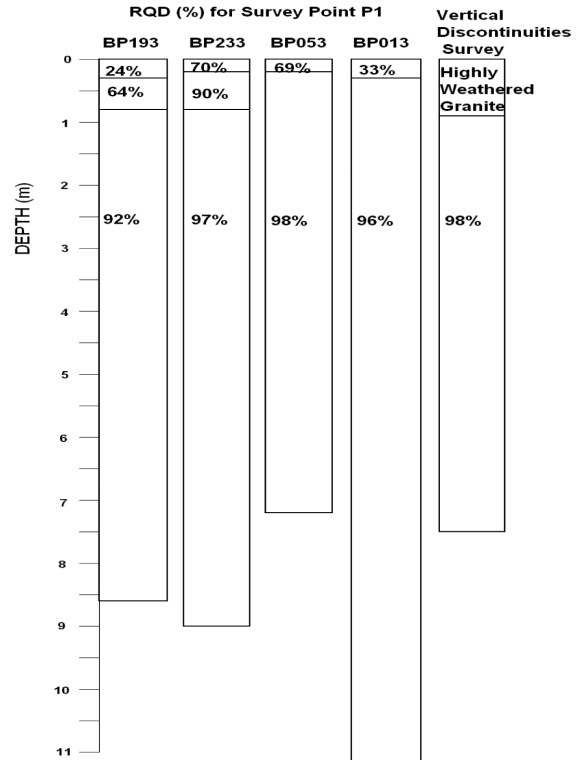


FIGURE 5. Comparison between RQD values obtained from discontinuity survey and SASW test for P1, JKR Quarry, Bukit Penggorak, Kuantan, Pahang

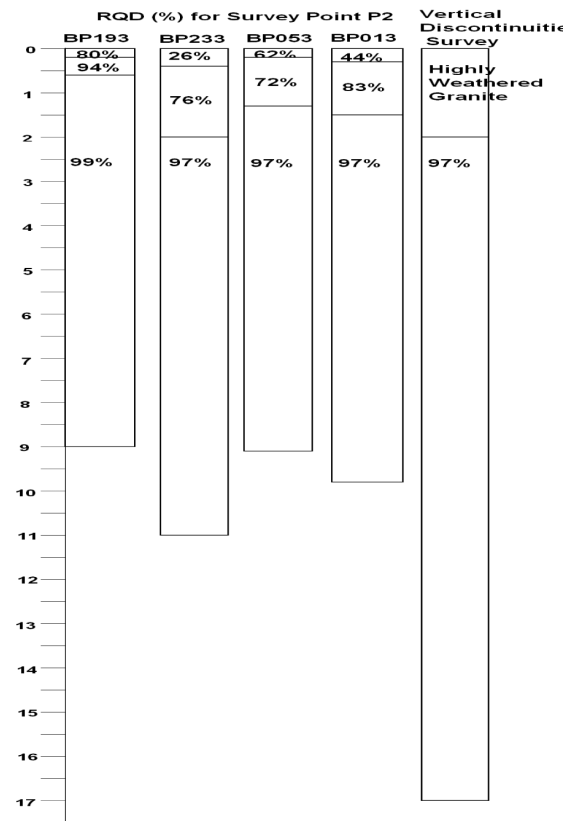


FIGURE 6. Comparison between RQD values obtained from discontinuity survey and SASW test for P2, JKR Quarry, Bukit Penggorak, Kuantan, Pahang

EXCAVATION CLASSIFICATION

From the SASW test results, Figure 7 shows the outline of excavation classification at P3, P4 and P5. This site was divided into 3 layers. The first layer was classified as digging with range of shear wave velocities of 0 m/s to 500 m/s; second layer is easy ripping with range of shear wave velocities of 500 m/s to 634 m/s and third layer is hard ripping with range of shear wave velocities of 634 m/s to 837 m/s.

SITE CHARACTERIZATION

At meteorological station at Bukit Tampoi, Dengkil, Selangor, SASW tests on two survey points (D1 and D2) indicated that this site can be characterized into 3 layers according to the classification method proposed by Bay (2000) as shown in Figure 8. The top layer consists of soft and very soft soil with shear wave velocities range from 67 m/s to 137 m/s. The shear wave velocities for

second layer were from 137 m/s to 610 m/s, which were interpreted to consist of hard soil, moderately hard soil, very hard soil and highly weathered rock. Meanwhile, the third layer was interpreted to consist slightly or moderately weathered rock with shear wave velocities of 610 m/s to 1152 m/s.

CONCLUSIONS

The difference between RQD values derived from SASW tests and those of discontinuity surveys are less than 10% illustrates that the SASW test is valid in seismic survey application for RQD measurement. SASW test is a non-destructive method that is cheap and easy to operate for earth material characterization especially in determination of stiffness and excavatability properties of the rock mass.

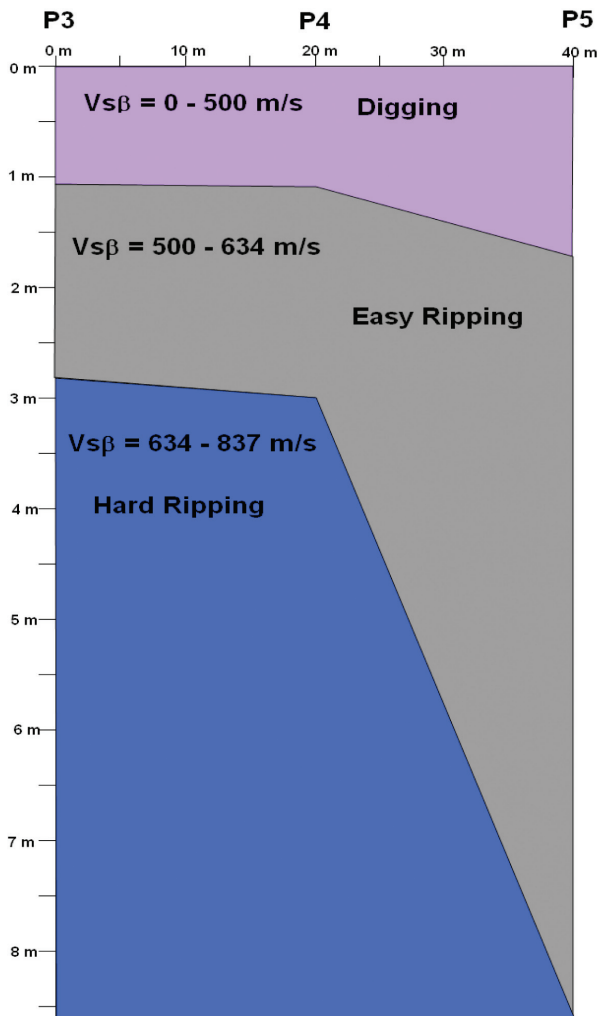


FIGURE 7. Excavation classification for P3, P4 and P5, JKR Quarry, Bukit Penggorak, Kuantan, Pahang

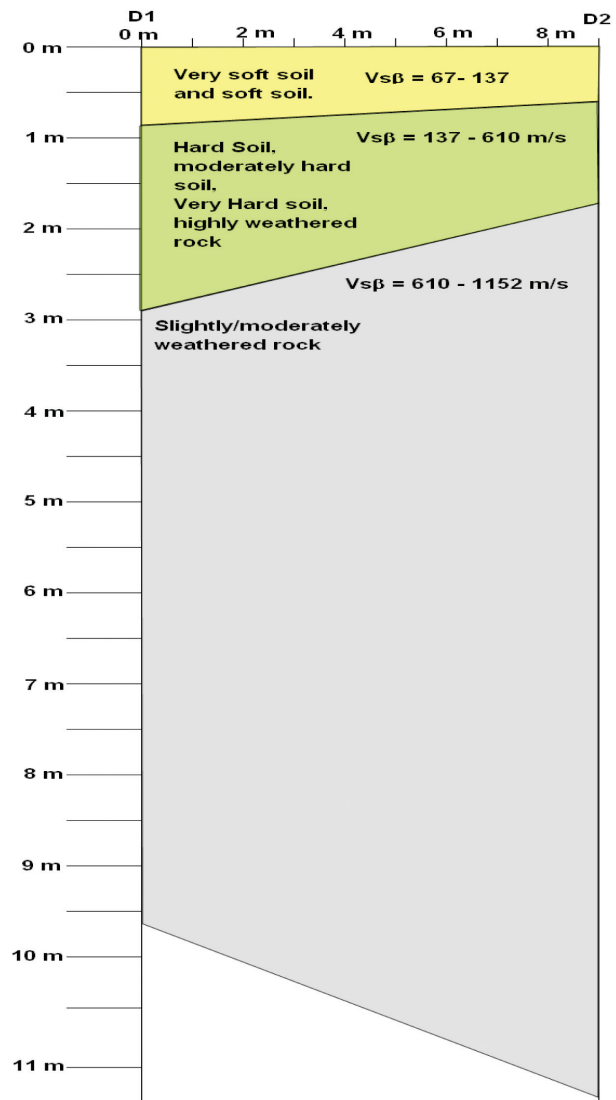


FIGURE 8. Site characterization for D1 and D2 at meteorological station, Bukit Tampoi, Dengkil, Selangor

ACKNOWLEDGEMENTS

The authors thank the Government of Malaysia for financial assistance through UKM-ST-01-FRGS0060-2006 and the lab staff of Geology Programme, UKM for their help in the field.

REFERENCES

- Abdul Rahim Samsudin, Goh, T.L. & Abdul Ghani Rafek 2009. Application of spectral analysis of surface wave (SASW) for characterization of rock mass in engineering geology: case study in Malaysia. *Geosea 2009, 11th Regional Congress on Geology, Mineral and Energy Resources of Southeast Asia* pp. 62.
- Arnie Salfarina Arshad 2005. Classification and characterization of rock engineering geology at JKR Quarry, Bukit Penggorak Kuantan, Pahang Darul Makmur. BSc Thesis. Universiti Kebangsaan Malaysia, Bangi.
- Bay, J.A. 2000. *Site characterization using the spectral analysis of surface waves method*. Seminar at University of Alabama at Birmingham.
- Caterpillar, T.C. 2006. *Caterpillar Performance Handbook*. Ed. 36th: Caterpillar Inc.
- Cho, Y.S. & Lin, F.B. 2001. Spectral analysis of surface wave response of multi-layer thin cement mortar slab structures with finite thickness. *NDT&E Internationals* 34: 115-122.
- Deere, D.U. 1964. Technical description of cores for engineering purpose. *Rock Mech. Eng. Geol.* 1: 16-22.
- Deere, D.U. 1968. *Geological Considerations, Rock Mechanics in Engineering Practice*. New York: Wiley.
- Joh, S.H. 1996. Advances in interpretation and analysis techniques for spectral analysis of surface waves (SASW) measurements. Ph. D Thesis. University of Texas.
- Goh, T.L., Ghani Rafek, A., Rahim Samsudin, A., Hariri Arifin, M. & Baizura Yunus, N. 2010. Penentuan nisbah Poisson dengan menggunakan kaedah seismos. *Prosiding Seminar Geofizik Kejuruteraan dan Sekitaran* pp. 55-64.
- Mohd Azmi Ismail, Khairul Anuar Mohd Nayan, Abdul Rahim Samsudin & Abdul Ghani Rafek 2001. Spectral analysis of surface waves method: an initial assessment and its potential use in geology. *Geological Society of Malaysia Annual Geological Conference*: 185-190.
- Nazarian, S. & Stokoe II, K.H. 1984. In situ shear wave velocity from spectral analysis of surface waves. *Proc. of 8th World Conference on Earthquake Engineering* 3:31-38.
- Rix, G. J., Bay, J. A. & Stokoe II, K.H. 1990. Assessing in situ stiffness of curing Portland cement concrete with seismic tests, Paper presented to *Annual Meeting, Transportation Research Board*, Washington, D. C.
- Rosly Mohd. Nor. 1980. Geology of Kenny Hill formation Selangor, Peninsular Malaysia. MSc Thesis. Universiti Kebangsaan Malaysia, Bangi.
- Suharsono 2006. Application of spectral analysis surface wave as new technique for rock mass classification in engineering geology. Unpublished Ph. D Thesis. Universiti Kebangsaan Malaysia, Bangi.
- Suharsono & Abdul Rahim Samsudin 2003. The attenuation effects of surface wave propagations on rock mass using SASW method. *Bulletin Geological Society Malaysia* 46: 475-478.
- Suharsono, Abdul Rahim Samsudin & Abdul Ghani Rafek 2004. Computation or rock quality designation (RQD) using spectral analysis surface wave method. *Buletin Geological Society of Malaysia* 49: 51-55.

Geology Programme
School of Environmental and Natural Resource Sciences
Faculty of Science and Technology
Universiti Kebangsaan Malaysia
43600 UKM Bangi, Selangor D.E.
Malaysia

*Corresponding author; email: gdsbgoh@gmail.com

Received: 5 January 2010

Accepted: 19 May 2010