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Delineation of shallow structures in the vicinity of Ulu Slim hot spring using seismic refraction and MASW techniques

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ABSTRACT

Ulu Slim hot spring possesses the highest surface temperature with a reported temperature of 104° C. Hence, the site may be suitable for electric power generation from the geothermal aquifer. In the present work, two seismic techniques are used for shallow structures investigation. The methods are the seismic refraction and the Multi-Channel Analysis of Surface Waves (MASW). The delineation of superficial structures will aid in developing the area without affecting the geothermal system. The instrumentation used for both is similar to a large extent. The main differences are the natural frequencies of geophones used. MASW requires a low natural frequency geophone, whereas seismic refraction uses high-frequency ones. Both techniques are applied at five locations distributed in the 5 km x 5km area. The results obtained from both methods are also tending to confirm with each other. From all profiles, three layers are delineated in the vicinity of the hot spring. The top layer is impermeable clay with an average Vp of 500 m/s and Vs <200 m/s. Underneath this surface layer, the possible aquifer unit characterised by sand, with Vp in the range of 1000 to 2800 m/s and Vs between 200 m/s and 300 m/s. The final layer is the bedrock characterised by a Vp higher than 3700 m/s and Vs greater than 300 m/s. A particularly striking feature of the bedrock structure obtained from our results shows that the bedrock is relatively close to the surface of the vicinity of the hot spring, with a depth of about 5 m. These results confirm the conceptual model proposed for the Ulu Slim hot springs as of granitic origin. Moreover, a plot of the Poisson ratio indicated regions of high water saturation that may represent the hot water pathway to the surface.

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Hot spring; multichannel analysis of surface waves; seismic refraction; Vp/Vs ratio

1. Introduction

Hot springs in Malaysia have been a source of continued interests due to its tremendous potential as a source of energy, recreation, therapeutic properties, tourism and a possible resource of drinking/mineral water (Chow et al. 2010; Hamzah et al. 2013). About seventy hot springs have been reported to exist in Malaysia, with a large chunk of these located along the major fault zones in the western flank of the Main Range Granite Batholith of the Malay Peninsula (Baioumy et al. 2015). A reasonable number of study on the hot springs have been geared towards an understanding of the geochemical and physical parameters of the hot springs (chemical composition, temperature, flow rate, etc.), and its economic viability (Bach 1991; Samsudin et al. 1997; Chow et al. 2010; Hamzah et al. 2013; Baioumy et al. 2015; Chan et al. 2017). However, there is a need for a proper understanding of the source of these hot springs and their geological settings.

Furthermore, given the interest in developing the hot spring areas like tourist attractions and other developmental plans, there is a need for an understanding of the geology of the near-surface, which would be useful in any infrastructural development within and around the site. This work, therefore, represents an attempt to provide an understanding of the near-surface geological settings of the hot spring in Kampung Ulu Slim using a combination of both the seismic refraction and multichannel analysis of surface waves (MASW) techniques. The main objective of this work is to characterise the near-surface within and around the hot spring area of Kampung Ulu Slim. This objective would involve the determination of the geometry of the bedrock, seismic velocities of the underlying near-surface materials, and stratigraphy configuration of the near-surface geology.

Geophysical techniques such as gravity magnetics, resistivity and seismic methods have been routinely utilised in the mapping of geothermal systems (Georgsson 2009; Colwell et al. 2012; Rodríguez et al. 2015). The seismic method is regarded as an indirect method, as it is capable of providing information about the geological settings and structures that are important in understanding the geothermal system (Shah et al. 2015). It involves the generation and measurement of elastic waves, whose propagation and velocity are dependent on the mechanical properties of the medium through which it travels. Some of the features that govern the movement of the waves are the composition, density, elasticity moduli, and temperature of the medium. The sole aim of the various seismic methods, such as seismic refraction, seismic reflection, and surface wave analysis, is to determine

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how the velocities of the subsurface are distributed. The present work will, in turn, enhance the knowledge of the subsurface structure.

The seismic refraction method utilises the seismic energy that travels in the body of the earth and returns to the surface after undergoing critical refraction (Kearey et al. 2002). The propagation obeys Snell's law and the critical angle of incidence. The parameter of interest is the first arrivals of the P-wave, which leads to the construction of the travel-time graph. The processing of the travel-time chart is capable of producing the variation of P-wave velocity (Vp) with depths for the subsurface. For the multichannel analysis of surface waves (MASW) technique, on the other hand, the dispersive characteristics of surface waves are utilised to infer the properties of the medium by inverting the dispersion curve to obtain the shear wave velocity model. Any of the different types of surface waves can be deployed for such investigations, however, the Rayleigh wave is commonly utilised due to its ease of generation and detection (Socco et al. 2010; Foti et al. 2015), as well as its effectiveness and reliability. The investigated parameter is shear wave velocity, Vs, which indicates the stiffness of the material. The MASW technique has been successful in the mapping of bedrock (Miller et al. 1999; Boiero et al. 2013; Sundararajan and Seshunarayana 2014), fault detection amongst other applications.

The combination of both seismic techniques is capable of providing a more holistic view of the subsurface, as we will be determining both the Vp and Vs of the subsurface structure. This informatoin can be used to determine estimates of the Poisson ratio that can be used to delineate the status of the subsurface structures. Furthermore, the integration of both methods in the study of the near-surface is capable of reducing the ambiguity associated with the use of just one geophysical tool, resulting in a more accurate subsurface model (Ivanov et al. 2010).

2. Geology and site description

Geothermal systems are governed by structural concepts that are related to basement tectonics, irrespective of whether the geothermal source is in a sedimentary or volcanic environment (Hochstein and Hunt 1970). For Peninsula Malaysia, the locations of the hot springs are closely associated with granitic intrusions, major fault zone and in some cases small fractures (Baioumy et al. 2014). Kampung Ulu Slim plays host to one of the promising hot springs sites in the Malay Peninsula, given its high subsurface temperature of about 104 °C when compared to other hot springs within the peninsula (Javino 2016). Located in the state of Perak, Malaysia, with a geographical coordinate of 3°53′55.79”N and 101°29′52.44”E, the geology of the area is characterised mainly by granitic rocks intrusion (Figure 1). The general conceptual model for the hot spring source for Ulu Slim, as postulated by Javino (2016), is presented in Figure 2. This model assumes that the hot springs are located within fault planes and the contact zone of the granitic intrusion and the metasediments.

3. Methodology

3.1. Seismic refraction

3.1.1. Acquisition

Seismic refraction was carried out along five different strips (Figure 1) surrounding the location of the Kampung Ulu Slim hot spring. The minimum length of the refraction line utilised is 57.5 m for geophone

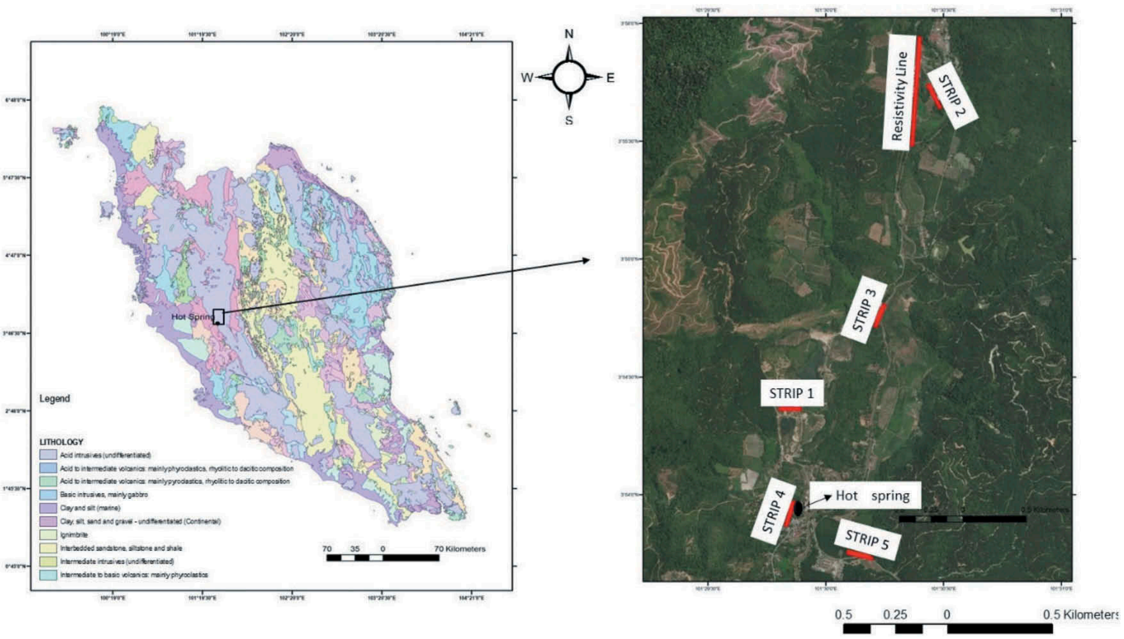

Figure 1. Geological map of Peninsular Malaysia with an inset of the map showing the seismic lines conducted in the study area.

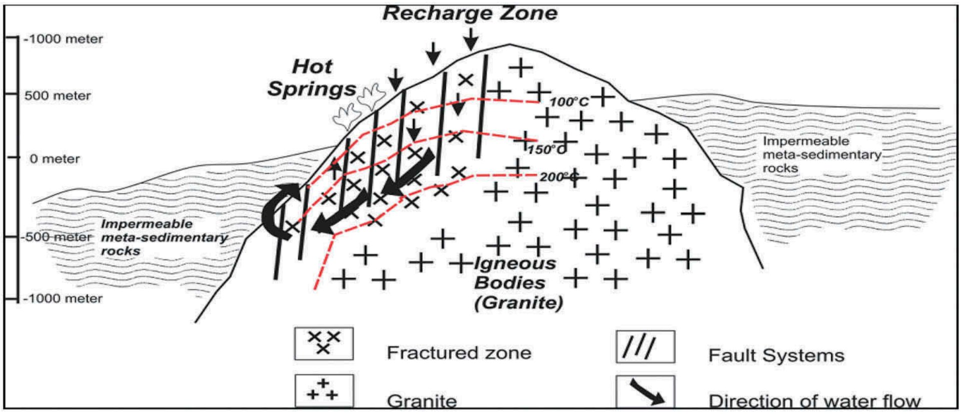

Figure 2. General conceptual model for Ulu Slim, Perak hot spring (Javino 2016).

spacing of 2.5 m and a maximum of 115 m for geophone spacing of 5 m (Table 1). We deployed twenty-four 28 Hz geophone for each survey, with five inline shots and offset shots at both sides of the survey line. The Terraloc Mk 8 seismograph and a sledgehammer source of 12 kg were used.

3.1.2. Data processing

The data were processed following the steps outlined below:

- Picking of the first arrival times;
- Plotting of the travel-time graph;
- Assigning of layers and implementation of the time – term inversion;
- Seismic tomography with the result from the time – term inversion used as the initial model parameters;
- Inversion of the P-wave seismic velocity to obtain the (Vp) model of the subsurface.

3.2. Multichannel analysis of surface waves

3.2.1. Data acquisition

Twenty-four 4.5 Hz geophones mounted on a land-streamer set-up with 1 m spacing and a sledgehammer as a source were used for the present survey. The roll-along configuration was used, the parameters for the source offset and array movement is presented in Table 1.

3.2.2. Data processing

The SurfSeis software was used in the analysis of the obtained shot gather according to the following schemes:

- Transforming the data from the time-distance (t-x) domain to frequency – phase velocity (f-c) domain (f-c spectra);
- Identification and picking of the dispersion curve corresponding to the fundamental frequency from the f-c spectra;
- Inversion of the picked dispersion curve to obtain a model 1D Vs for the subsurface. The inversion was run using the Levenberg-Marquardt least-squares algorithm (Xia et al. 1999). This algorithm requires the specification of an initial model for Vp, Vs, thickness, density, and Poisson's ratio, of which the Vp obtained from the seismic refraction measurement was utilised.
- The best model for the subsurface was selected based on the evaluation of the root mean square error (RMSE) obtained between the observed dispersion curve and the theoretical dispersion curve. A low RMSE is ideal.
- Generation of a pseudo-2-D Vs model of the subsurface by the combination of a series of 1-D Vs model obtained along the line.

A sample of the seismic data collected along strip 5, the picked first arrival, and the travel-time graph is presented in Figure 3. Figure 4 shows an example of the

Table 1. Data acquisition parameters for both seismic methods.

	Survey	MASW				Seismic Refraction	
Location	Line	Geophone Spacing (m)	Offset (m)	Source Movement (m)	Total Records	Survey Line	Geophone Spacing (m)
Strip 1	Line 1	1	4	5	19	Line 1	2.5
						Line 2	2.5
Strip 2	Line 1	1	1	10	15	Line 1	5
Strip 3	Line 1	1	1	10	11	Line 1	5
Strip 4	Line 1	1	1	23	3	Line 1	2.5
	Line 2	1	1	23	4	Line 2	5
Strip 5	Line 1	1	1	5	20	Line 1	2.5
	Line 2	1	1	5	26	Line 2	2.5

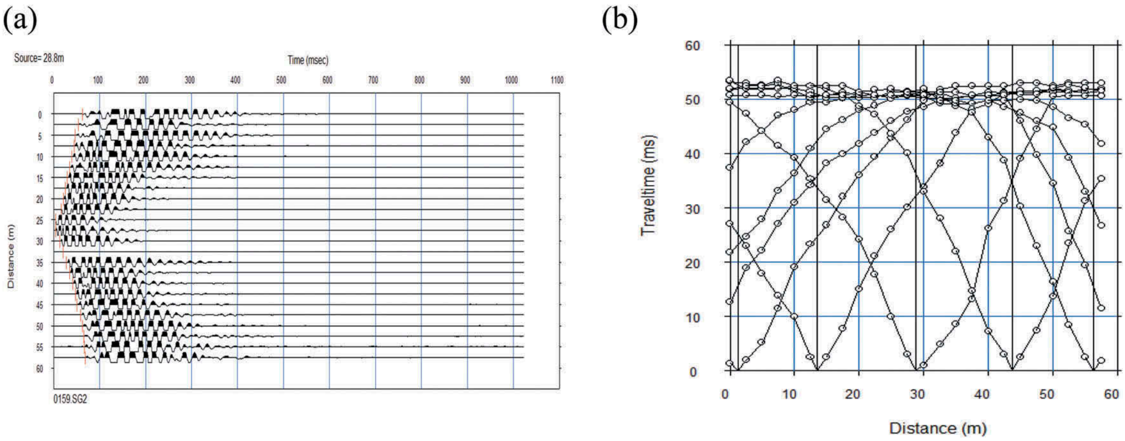

Figure 3. Sample seismic refraction seismogram and the resulting travel-time graph for the line.

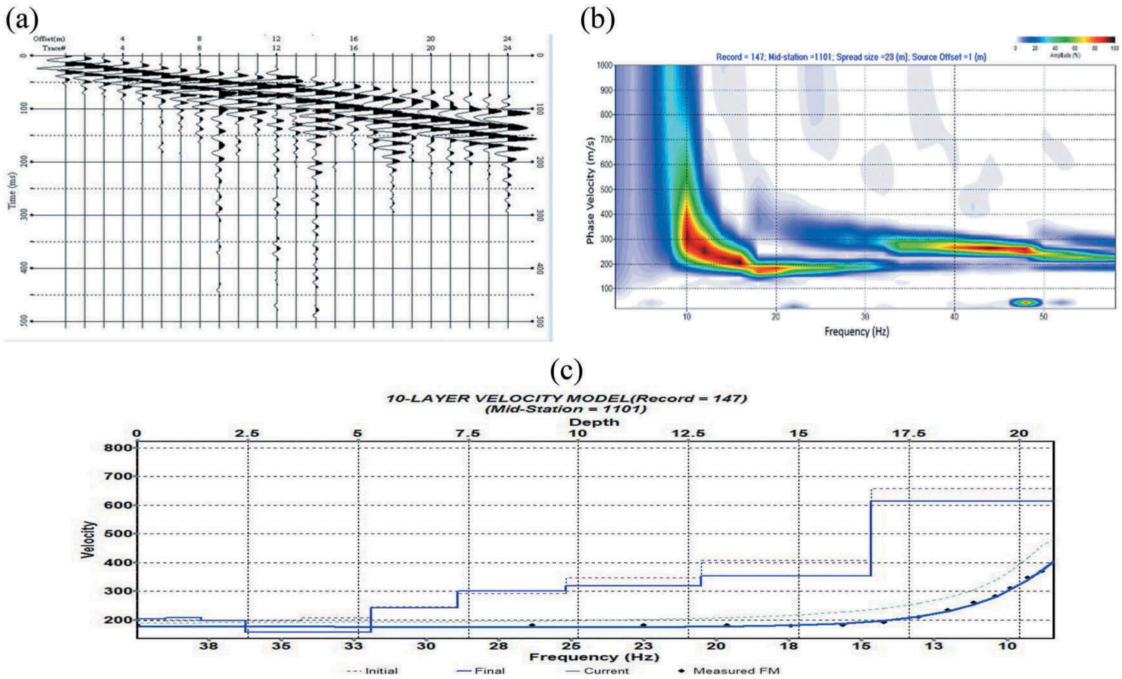

Figure 4. Processing steps involved for the MASW (a) Seismic shot gather (b) f-c spectra for the shot-gather (c) Vs model of the inverted dispersion obtained from the dispersion curve.

seismogram observed in the area, its corresponding f-c spectra, and inversion; there were detected differences in the frequency content and phase velocity obtained from the f-c spectra obtained from the different strips. These processing steps highlighted above resulted in Figures 3 and 4, forming the basis for the generation of the 2-D Vp and Vs model of the subsurface.

4. Result and discussion

The measurements on Strip 1 were carried out on a flat surface covered by muddy clay, about 700 m northwards from the surface occurrence of the largest hot spring. The SR measurements consisted of two lines (Figure 5), combined together during processing to achieve a total length of 115 m. A full range of 110 m coverage of the MASW was obtained along the same line for the SR measurements also.

Both the Vp and the Vs model indicates a three-layers stratigraphy, a top layer with Vp less than about 460 m/s and Vs 130 m/s to a depth of about 5 m. These velocity values are typical of clay (Reynolds 2011; Foti et al. 2015), which is observed to characterise the topsoil ((Figure 5). The second layer has Vs that ranges from 200 m/s to 300 m/s and corresponding Vp values also ranging from 1000 m/s to 3000 m/s, from a depth of about 5 m to 20 m. The much larger increase in the values of Vp for the second layer, as compared to the first suggest that the soil is saturated with the corresponding Vs values ranging from about 200 m/s to 300 m/s suggestive that the layer is probably made up of sand or silt (Reynolds 2011; Foti et al. 2015). The last layer identified for this line occurs at

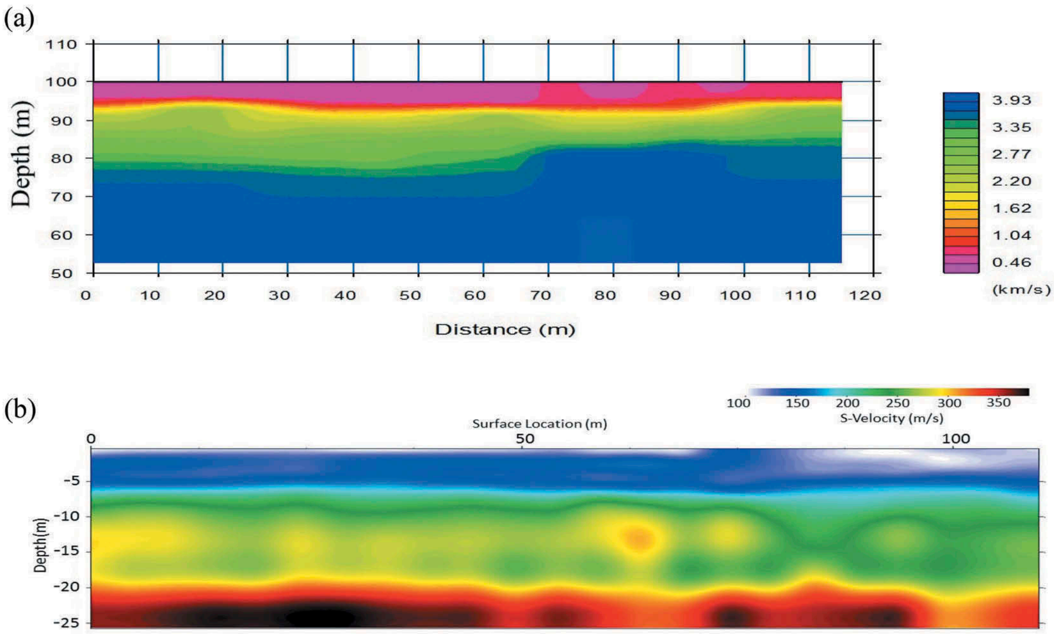

Figure 5. Seismic Velocity model for the subsurface in strip 1: (a) Vp model (b) Vs model.

a depth of 20 m and below. The high values for Vp and Vs (above 3000 m/s and 300 m/s respectively) suggest that the bedrock occurs at this depth and composed of granite as suggestive from the geology of the area and from the range of values of Vp and Vs of rock materials (Dal Moro 2014; Aziman et al. 2016) . The low Vs values obtained for the granite layer can probably be attributed to the low resolving power of the MASW technique at depths (Anukwu et al. 2018).

The Vp model, Vs model, and Poisson model for Strip 2 is presented in Figure 6, and this location is about 3.5 km away from the Kampung Ulu Slim hot spring. The area is characterised by the presence of weathered granite boulders. The seismic survey was established on a flat surface, low ground from one end, and a hilly terrain towards the east and west side of the line. In general, higher seismic velocities (Vp and Vs) were obtained for this strip compared to the other strips, an indication of not very weathered subsurface, the presence of surface boulders characterises the area. A three-layers stratigraphy is inferred for this strip is revealed from the Vs and Vp model (Figure 6). A top layer with Vs of about 200 m/s and Vp higher than 1000 m/s but less than 2000 m/s, which is suggestive of a weathered layer, this is closely followed by a stratigraphy with Vs higher than 300 m/s and Vp with an average of 3000 m/s, suggestive of moderately weathered layer. The bedrock for this strip possesses Vp higher than 4000 m/s, and Vs greater than 400 m/s, values suggest a fresh bedrock, in line with the typical weathering profile for granitic soil (Salih 2012), and occurs at a depth of about 32 m. The Poisson model shows that the area is characterised by the presence of water with different saturation levels. The deeper layer represents the highest saturation with Poisson's ratio close to 0.5

The seismic measurements for Strip 4 were carried out along a pathway, close to the hot spring site (about 50 m from the hot spring); it consisted of two lines of SR and MASW, respectively. The values for the seismic velocities obtained from the area also indicate three distinct layers, with the depth to bedrock for line 1 identified from the Vp model to occur at about 15 m, with a Vp value higher than 5000 m/s. However, this layer's depth coincides with the Vs model, with Vs value higher than 300 m/s (Figure 7). The top layer is relatively thin of about 3 m, followed by a probably saturated zone of a thickness of about 12 m. Line 2 shows an intrusion of the bedrock (possibly granitic body) up to a depth of about 10 m, between line position 40 and 60 on the Vp model, with a Vs higher than 4000 m/s. The depth to the bedrock here is the shallowest obtained for this study and fits the geological model proposed for the area (Javino 2016). Table 2 gives a breakdown of the Vp and Vs values and geometry of the stratigraphy of the near-surface for all the strips.

Furthermore, the soil's dynamic properties such as density, Poisson's ratio, rigidity modulus, Young's Modulus, Bulk modulus, ultimate bearing capacity, and stress ration are estimated. These parameters showed a dependency on Vs and Vp (Table 3) and were obtained from the 2-D profiles for Vs. and Vp for the individual strips. The geotechnical parameters are essential for any future infrastructural development plan for the area.

As part of the geophysical investigations for the study area, resistivity measurements were carried out using the Wenner-Schlumberger array along the line shown in Figure 1, close to the seismic lines of strip 2. The electrode spacing was 20 m for the two outer

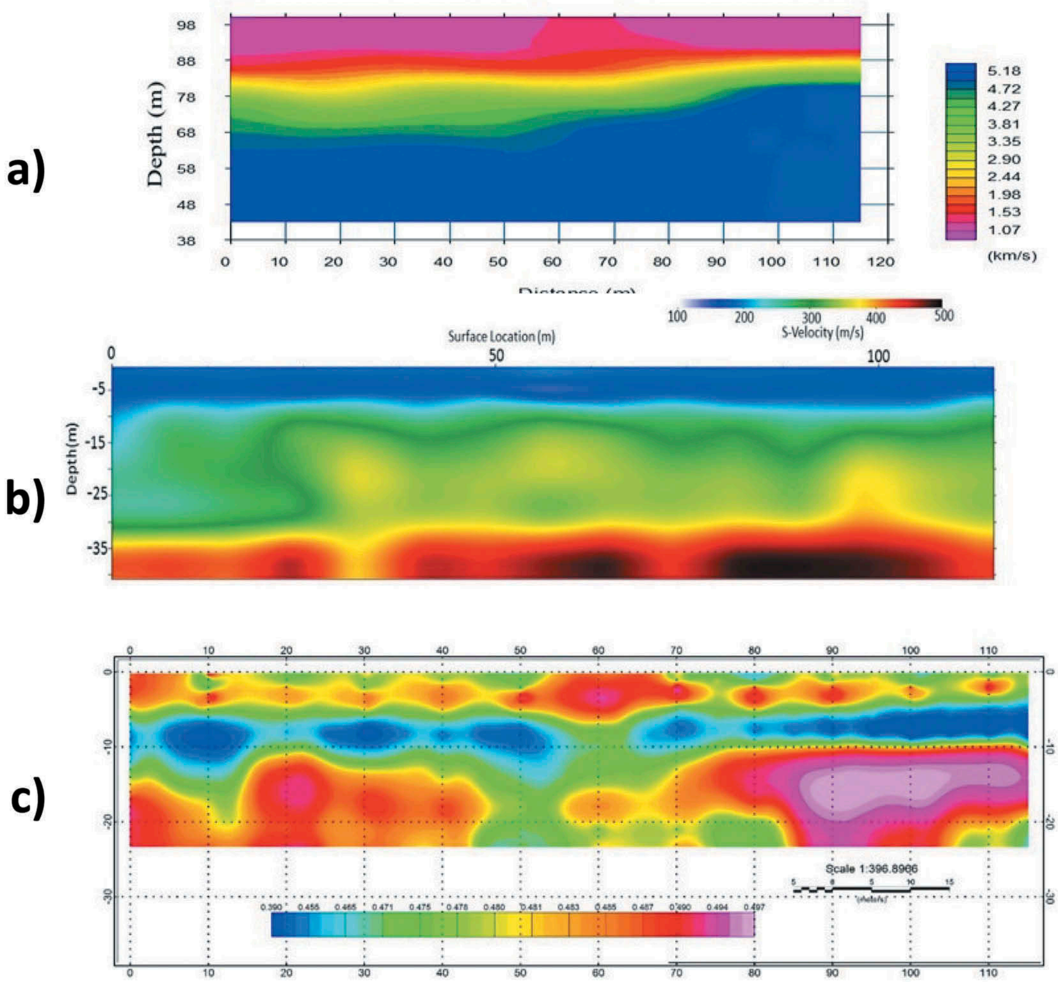

Figure 6. Seismic Velocity model for the subsurface in strip 2: (a) Vp model (b) Vs model c) Poisson ratio.

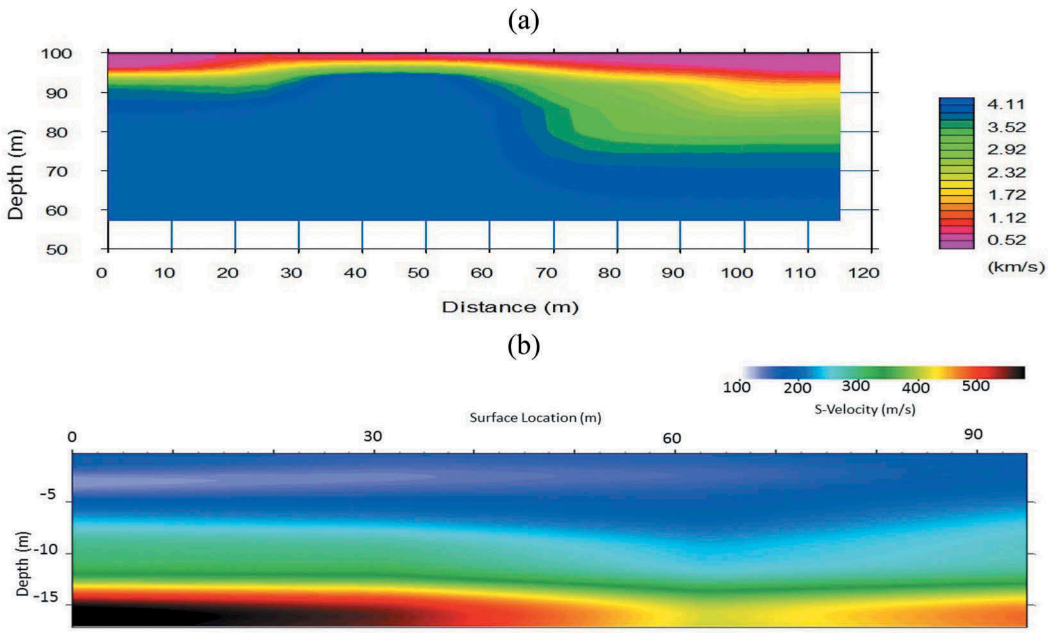

Figure 7. Seismic Velocity model for the subsurface in strip 4 close to the hot spring location: (a) Vp model (b) Vs model.

electrode reels and a 10 m spacing for the two inner electrode reels, with a total length of 800 m. The inverted resistivity section is as shown in Figure 8.

The seismic survey for strip 2 corresponds to the distance from about distance 340 m to 470 m (points A to B) of the resistivity line. The depth to bedrock

Table 2. Soil dynamic parameters as obtained from the MASW and seismic refraction results.

Location	Layer	Depth (m)	Vp (m/s)	Vs (m/s)	Density (g/cm^3)	Poisson Ratio	Ridgidity Modulus (Dyn/cm^2)	Young's Modulus (Dyn/cm^2)	Bulk Modulus (Dyn/cm^2)	Ultimate Bearing Capacity (Kg/cm^2)	Stress Ratio
Strip1	Layer 1	0-5	460	130	1.44	0.46	2.43E+10	7.07E+10	2.71E+11	10.74	0.84
	Layer 2	5-20	2500	250	2.19	0.49	1.37E+11	4.10E+11	1.35E+13	11.58	0.98
	Layer 3	>20	3740	350	2.42	0.50	2.97E+11	8.88E+11	3.35E+13	12.00	0.98
Strip2	Layer 1	0-10	1070	200	1.77	0.48	7.09E+10	2.10E+11	1.94E+12	11.29	0.93
	Layer 2	10-30	3200	350	2.33	0.49	2.86E+11	8.53E+11	2.35E+13	12.00	0.98
	Layer 3	>30	5180	400	2.63	0.50	4.21E+11	1.26E+12	7.00E+13	12.17	0.99
Strip3	Layer 1	4	590	100	1.53	0.49	1.53E+10	4.54E+10	5.11E+11	10.41	0.94
	Layer 2	4-10	3200	180	2.33	0.50	7.55E+10	2.26E+11	2.38E+13	11.16	0.99
	Layer 3	>10	4620	250	2.56	0.50	1.60E+11	4.79E+11	5.43E+13	11.58	0.99
Strrip4	Layer 1	0-7	590	150	1.53	0.47	3.44E+10	1.01E+11	4.86E+11	10.92	0.87
	Layer 2	3-30	2330	250	2.15	0.49	1.35E+11	4.02E+11	1.15E+13	11.58	0.98
	Layer 3	5 to >30	4060	500	2.47	0.49	6.19E+11	1.85E+12	4.00E+13	12.46	0.97
Strip5	Layer 1	0-9	460	200	1.44	0.38	5.74E+10	1.59E+11	2.27E+11	11.29	0.62
	Layer 2	9-20	2888	300	2.27	0.49	2.05E+11	6.11E+11	1.87E+13	11.81	0.98
	Layer 3	>20	4090	450	2.48	0.49	5.02E+11	1.50E+12	4.08E+13	12.32	0.98

Table 3. Definitions of the geotechnical parameters utilised in this study.

Geotechnical Parameters	Reference
Density; $\rho = 0.31V_P^{0.25}$	(Gardner et al. 1974)
Poisson's ratio; $\sigma = \left((V_p/V_s)^2 - 2\right)/2\left((V_p/V_s)^2 - 2\right)$	(Kearey et al. 2002)
Shear modulus; $\mu = \rho V_s^2$	(Kearey et al. 2002)
Young's modulus; $E = 2\rho V_s^2(1+\sigma)$	(Lowrie 2007; Tezcan and Ozdemir 2014)
Bulk modulus; $K = E/3(1-2\sigma)$	(Lowrie 2007)
Ultimate Bearing Capacity; $Q_a = 2.4(10^{-4})\rho V_S$	(El-Rahman and El-Werr 1992)
Stress Ratio; $S_i = 1 - 2\left(\frac{V_s^2}{V_p^2}\right)$	(Thomsen 1986)

corresponds to that obtained for the resistivity, which is at about 20 – 30 m from the line position of 360 m to the end of the line. This depth agrees with the depth to bedrock obtained from the seismic measurements of 30 m. An interesting anomaly is observed on the resistivity section, which is probably a fault that runs from the surface to the maximum depth of the profile. This anomaly is not found on the seismic sections because the lines did not get to that depth.

The density of the geological materials obtained for the study area shows a minimum of 1.44 g/cm^3 and a maximum of 2.63 g/cm^3. The values obtained for the density of the bedrock, i.e. layer 3, ranges from 2.42 g/cm^3 to 2.63 g/cm^3, and it corresponds to the values obtained for the dry densities of granite as reported in (Kong 1994). The density of the overburden materials ranges from 1.44 g/cm^3 to 2.27 g/cm^3, and the Poisson's ratio obtained is more than 0.4 typical values for clay soil and porous materials that are saturated materials (Bishop and Hight 1977; Bowles 1996).

It is also possible to obtain the seismic site classification for the study area, which is based on the average shear wave velocity of the top 30 m (Vs30). The MASW technique is suitable for such Vs30 calculation, and as such, the obtained Vs model for all the strips was utilised to obtain the Vs30. The Vs30 obtained for all the site is as presented in Table 4. The NEHRP site classification for seismic design is employed and it shows that in general, the study area falls under two classes, D and E. Only strip 3 falls under class E, while other strips are in class D.

5. Conclusion

Shallow seismic measurements involving seismic refraction and multichannel analysis of surface waves were performed at five strips around Kampung Ulu slim, Peak Malaysia, to provide information about the geology of the near-surface. This is of particular importance due to the hot spring found in the locality. The combined use of both seismic method provided a depth of penetration ranging from about 15 to 40 m. Both compressional wave velocity (Vp) and shear wave velocity model (Vs) obtained from the SR and

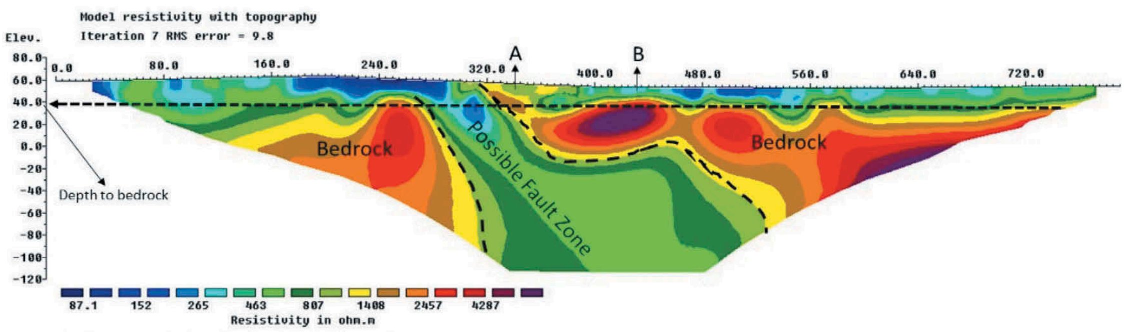

Figure 8. Inverted resistivity section along strip 2 of the study area.

Table 4. Seismic site classes based on the NEHRP classification.

Location	Vs30 (m/s)	Site Class
Strip 1	205 – 229	D
Strip 2	216 – 279	D
Strip 3	144 – 175.31	E
Strip 4 – Line 1	266 – 264	D
Strip 4 – Line 2	250 – 263	D
Strip 5 – Line 1	272 – 286	D
Strip 5 – Line 2	219 – 312	D

MASW method respectively complemented each other in the characterisation of the geological sequences down to the depth of penetration.

The conclusions from this work are as follows:

(1) The obtained Vp and Vs from both seismic refraction and MASW allowed for the estimation of the geotechnical parameters for the study area.
(2) The subsurface is characterised by three distinct layers, the first layer, possibly characterised by clay with an average Vp of about 500 m/s and Vs $\leq$ 200 m/s. A saturated second layer with Vp ranging from 1000 m/s to 2800 m/s and Vs between 200 m/s and 350 m/s, possibly composed of sand. The bedrock is characterised by high values of both Vp and Vs greater than 3700 m/s and 300 m/s, respectively, which we have inferred to be composed of granite.
(3) The density of the subsurface material ranges from about 1.44 g/cm^3 to 2.63 g/cm^3. The density of the bedrock is in the range of 2.42 g/cm^3 to 2.63 g/cm^3, which is in the range of for granite.
(4) The Poisson's ratio for the overburden (layers 1 and 2) materials is higher than 0.4.
(5) The NEHRP classification of the areas investigated shows the predominant site class of D class prevails for all of the sites except strip 3, which falls in class E.
(6) The structure of the bedrock in the strip close to the location of the hot spring indicates an intrusion of the bedrock to the surface. This feature correlates quite well with the conceptual model proposed for the Ulu Slim hot spring.
(7) We were able to show the similarity of the seismic models for the subsurface and that of the inverted resistivity to a depth obtainable from the seismic models.

Disclosure statement

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