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# Integral Analysis of Seismic Refraction and Ambient Vibration Survey for Subsurface Profile Evaluation

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**Abstract.** Geotechnical site investigation as known as subsurface profile evaluation is the process of subsurface layer characteristics determination which finally used for design and construction phase. Traditionally, site investigation was performed using drilling technique thus suffers from several limitation due to cost, time, data coverage and sustainability. In order to overcome those problems, this study adopted surface techniques using seismic refraction and ambient vibration method for subsurface profile depth evaluation. Seismic refraction data acquisition and processing was performed using ABEM Terraloc and OPTIM software respectively. Meanwhile ambient vibration data acquisition and processing was performed using CityShark II, Lennartz and GEOPSY software respectively. It was found that studied area consist of two layers representing overburden and bedrock geomaterials based on p-wave velocity value ($v_p$ = 300 – 2500 m/s and $v_p$ > 2500 m/s) and natural frequency value ($F_o$ = 3.37 – 3.90 Hz) analyzed. Further analysis found that both methods show some good similarity in term of depth and thickness with percentage accuracy at 60 – 97%. Consequently, this study has demonstrated that the application of seismic refractin and ambient vibration method was applicable in subsurface profile depth and thickness estimation. Moreover, surface technique which consider as non-destructive method adopted in this study was able to compliment conventional drilling method in term of cost, time, data coverage and environmental sustainaibility.

## 1. Introduction

Site investigation obtained the information about the characteristic of the geomaterials to provide design and construction suitability. The entire process of information gathered on site for the purpose of engineering design and construction was defined as site investigation [1]. Site investigation was performed to determine the cross-section of subsurface profile (profiling), number of layers, thickness and depth of the geomaterials, description, properties and stiffness of geomaterials, groundwater level, etc.

Generally, site investigation was performed based on conventional or alternative method. Conventional method was performed based on destructive test particularly using drilling approaches via boring, probing and trial pitting methods. In the past, several limitations of conventional method raised involving challenging and difficult sites due to expensive, time consuming, limited data coverage and less environmental friendly. For example, high number of borehole point was required in order to obtain detail subsurface information thus able to influence the increment of cost and time of the investigation [2] – [4]. Moreover, mobilization and demobilization of conventional method has experienced difficulty when working in most of difficult sites such as hilly terrain, thick forest, soft ground, rural areas, disaster areas, etc. As reported by [5], conventional methods experience limitations during the application at complex terrains, steep hills, marshy and swampy areas, coastal regions and areas consists of variation of soil and rock materials. Furthermore, most of conventional drilling method provides limited data coverage particularly at actual drilling point location in one dimensional (1-D) perspective. Consequently in complex geological sites, interpolation between boring data may expose to high degree of uncertainties thus reduce the results reliability of the subsurface profile. The information obtained from conventional drilling method was a single point data and the interpolation between a large boreholes spacing can lead to increase the degree of uncertainties of the subsurface profile investigated [6] – [8]. Lots number of drilling point was required in order to obtain higher accuracy of the subsurface results thus increasing cost and time of the project [9-10]. In addition, destructive approach adopted in conventional drilling method can be considered as non-sustainable to our environment due to its encouragement of site damageability.

In multidisciplinary era, most researchers diversify their research area with an alternative method to improve the existing conventional method [11]. Surface investigation using alternative method via geophysical method has increasingly adopted various application related to engineering, environmental, mining and archeological studies [12] – [14]. Studying an earth based on physics properties states the definition of geophysics. Common properties of physics used in geophysical method were wave velocity, natural frequency, electrical resistivity, density, magnetic susceptibility, etc. Sophisticated geophysical instrument such as seismic refraction, ground penetrating radar, ambient vibration, electrical resistivity, gravity, magnetic, etc. was invented due to the rapid development of electric and electronics engineering. Geophysical method has been widely known as its ability to compliment conventional methods in subsurface profile evaluation efficiently in term of cost, time, data coverage and sustainability. Data acquisition can be performed rapidly with fewer workers thus consider cost-effective in site investigation. Moreover, geophysical method was capable to obtained large data coverage in two and three dimensional (2-D and 3-D) perspectives thus able to assist conventional drilling method for the decision making regarding the suitable number and location of drilling point. Furthermore, most of geophysical methods adopted surface techniques in data acquisition thus consider sustainable to our environment due to its nature of non destructive test. Geophysical method can be performed more quickly and less expensively and has the ability to cover larger areas more thoroughly [5,15,7,16,17]. Physical properties can be obtained in a large scale characterization under undisturbed conditions [7]. According to [18], geophysical method offers the chance to overcome some of the problems inherent in more conventional ground investigation techniques. However, the standard performance of individual geophysical method were still depends on fundamental physical constraints, e.g. penetration, resolution, and signal to-noise ratio [8,19].

Hence, the aim of this study was to demonstrate the applicable of geophysical methods in site investigation thus promoting to related parties regarding its good prospect in subsurface profile evaluation. Consequently, this study performed an integral analysis of seismic refraction (p-wave velocity) and ambient vibration (natural frequency) methods in subsurface profile evaluation.

## 2. Materials and Methods

*2.1 Study area and geologic setting*

Generally, site study was located at hilly terrain surrounded by forest, developing town, golf course, private and government building and residential area as shown in Figure 1. This study was performed at Kluang, Johor area specifically at Meteorological Station, Kluang Johor. Study area can easily access using common types of vehicles such as car, van, pickup, motorcycle, bicycle, etc. Site study was located at the top of the hills and considered quite isolated with surrounding human activities due to its necessity to collect sensitive meteorological data such as precipitation and seismicity.

General geology of Peninsular Malaysia area has been well documented by Mineral and Geoscience Department Malaysia [20]. Based on geological map shown in Figure 1, the study area was located in acid intrusive area (granitic rock) and near to the boundary of Triassic period (volcanics and sedimentary rock) and continental deposits. In general, the present of this type of rock will exhibits geology structures, namely faults, joints and bedding plane. The fractures created from these structures were suitable for groundwater carriage and storage in existing rock formation. Shallow or deep residual soil of granite can be found at site studied. Based on site observations, weathered granitic rock related to residual soil and boulder can easily found in this area. In addition, the presence of relicts geology structure (texture and discontinuity) from weathering process acts into fresh granitic rock at the past was clearly can be observed in many places in study area. This evidence has indicated that studied area may consist of heterogeneous geomaterials derived from weathering of granitic rock formation.

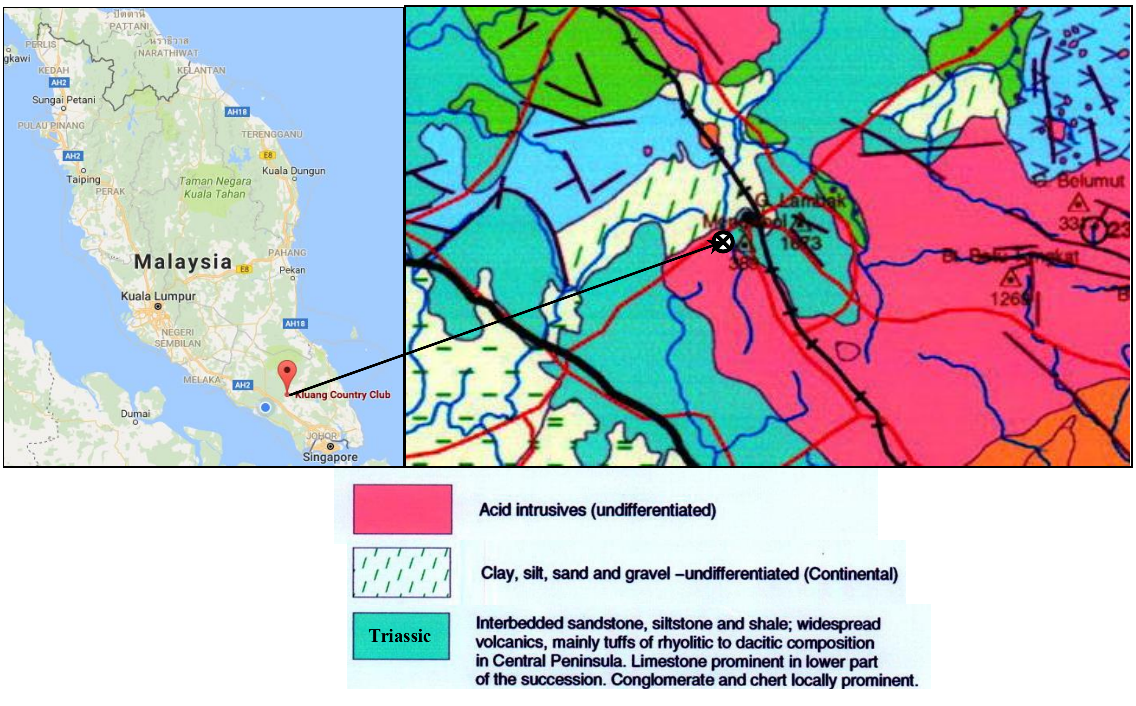


**Figure 1.** Site location (Left) and geology (Right) of the study area [20].

*2.2 Seismic refraction survey*

Seismic refraction survey (SRS) was performed using the ABEM Terraloc MK8 equipment set consists of source, receiver and record. Seismic source was generated using 12 pound of sledge hammer. 28 Hz of vertical geophone was used as seismic wave receiver while ABEM Terraloc MK8 seismograph was used as seismic recorder. Other important components used in SRS were seismic land cables (2 set), trigger cable, striker plate and 12 Volt of battery. Complete equipment set of ABEM Terraloc MK8 used in this study was given in Figure 2. A single spread of SRS line (total distance = 80.5 m) was performed across the studied area aligned in west-east direction as shown in Figure 3. Field configuration was based on 3.5 m equal geophone spacing interval, 20 m offset distance and 7 seismic shot point (2 offset shot plus 5 inline shot point). Each seismic record has been stacked at 20 – 30 numbers of shot point in order to obtained best possible seismic record. Field arrangement of SRS was given in Figure 4. Seismic raw data was processed using commercialized OPTIM software specifically via SeisOptPicker and SeisOpt@2D software. OPTIM software has widely used in seismic refraction analysis [21,22,4] since its ability to generate detail tomography outcome and user friendly package. SeisOptPicker was performed to pick the first arrival (p-wave velocity) and entering the geometry data input while SeisOpt@2D was used to generate tomography of the subsurface profile analyzed based on primary velocity distribution output.

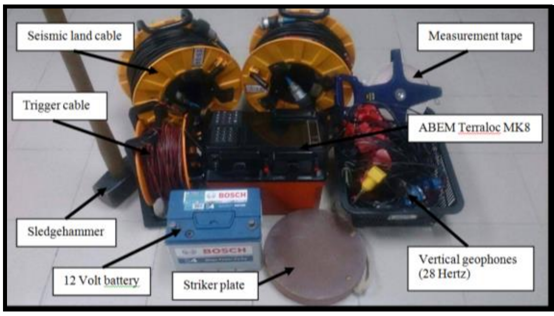


**Figure 2.** Seismic refraction equipment set.


**Figure 3.** Spread line performed at site studied.

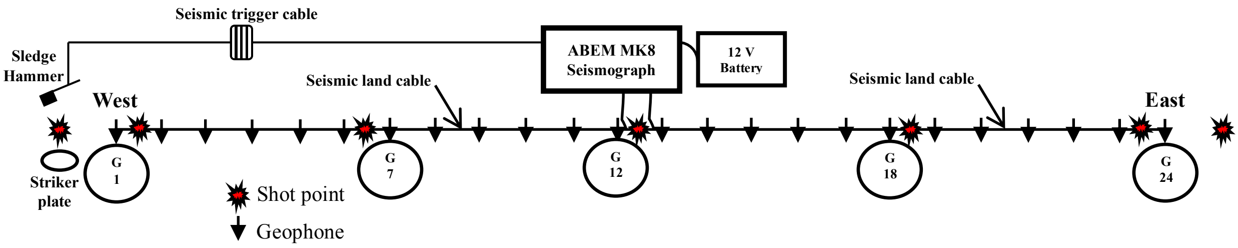


**Figure 4.** Field arrangement of seismic refraction survey (SRS).

*2.3 Ambient vibration survey*

Ambient vibration method was performed using Lennartz CityShark II equipment set consists of receiver and recorder. Ambient vibration receiver and recorder were based on three units of Lennartz portable tri-axial seismometer and CityShark II data logger respectively. Other component of the equipment were geophone reinforced cable, memory card and 12 volt battery. Complete equipment of ambient vibration was given in Figure 5. Three sensor of seismometer were placed in seismic spread line which aligned in north direction as shown in Figure 6. During the data acquisition, position of sensor 1 was located at center (datum) while the other two sensors were placed at both ends of different sides. Ambient vibration measurement was collected using similar three major components of seismometer of North-South, East-West and Vertical. The sensor was placed closed to seismic refraction geophone location at geophone 1 (G01), geophone 7 (G07), geophone 12 (G12), geophone 19 (G19) and geophone 24 (G24) due to complete data coverage based on seismic spread line performed. Ambient vibration data acquisition was repeatedly recorded for two times due to result consistency purposes. Ambient vibration raw data obtained from data acquisition was finally analyzed using GEOPSY software for interpretation purposes. GEOPSY software has widely used in ambient vibration data processing [23] – [26] due to its good ability and user friendly package in order to produce natural frequency ($F_o$) of site studied. As reported by [25], GEOPSY package has widely known as novel programming software in ambient vibration processing due to its updated and powerful algorithm processing ability.

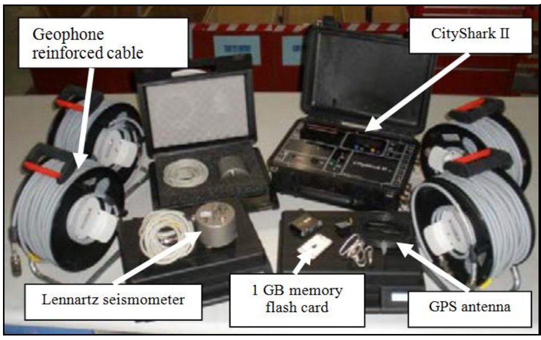


**Figure 5.** Ambient vibration equipment set.

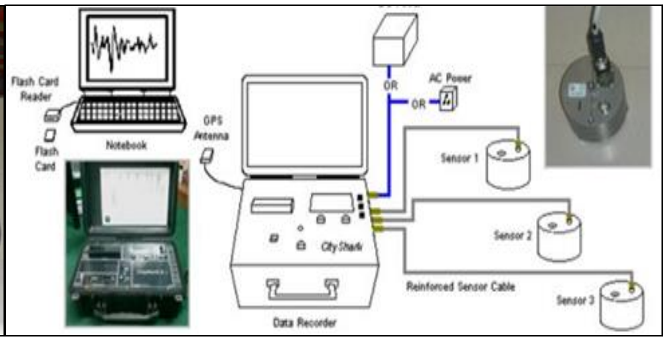


**Figure 6.** Ambient vibration component arrangement.

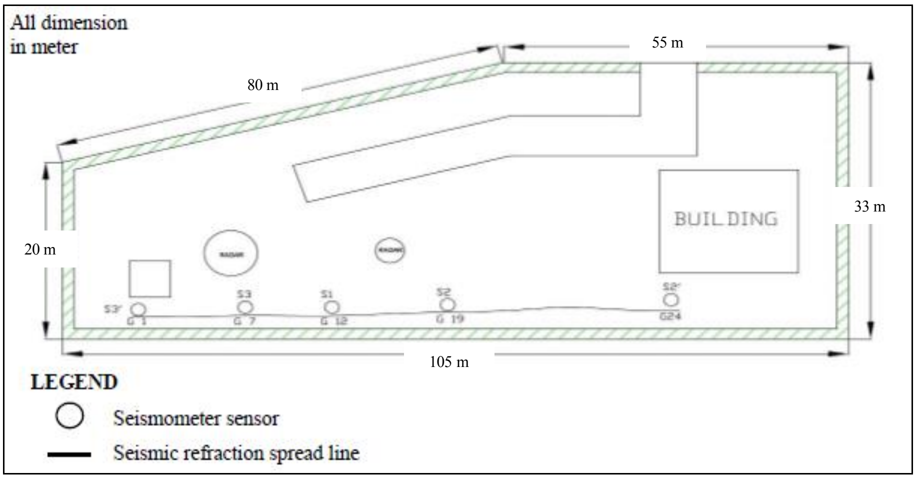


**Figure 7.** Layout of ambient vibration data acquisition.

## 3. Results and Discussions

All results were discussed based on seismic refraction, ambient vibration and subsurface profile evaluation between both methods as given in subsection 3.1 – 3.2.

### *3.1 Seismic refraction survey*

A single (1) profile of two-dimensional (2-D) seismic refraction result was obtained from data acquisition at selected area in Meteorological Station, Kluang Johor. Seismic refraction result analyzed using OPTIM software was presented as seismic refraction tomography (SRT) given in Figure 8. Spread line of seismic refraction survey was aligned based on west-east direction. The SRS results which align based on west-east direction was performed using 3.5 m of equal geophone spacing with total spread line length of 80.5 m. According to Figure 8, maximum penetration depth obtained was up to 30 m. Generally, SRT obtained from Figure 8 has revealed that there are two (2) major types of geomaterials present at site studied which interpreted based on domination of different P-wave velocity contrast. The first and second layer of the subsurface profile studied was interpreted as overburden ($v_p$ = 300 – 2500 m/s) and bedrock ($v_p$ > 2500 m/s) respectively. According to [27], primary velocity for soil was varied at 244 – 1219 m/s relative to variations of denseness and saturation condition. Moreover as reported by [28], primary velocity for weathered rocks was varied at 609.6 – 3048.6 m/s. Furthermore, [28] has reported that primary velocity value for hard rocks and granite was varied at 2400 – 6000 m/s. Consequently, SRT result interpretation has been verified based on stated established references. Overburden layer may possibly consist of weathered granitic rock (e.g. Grade VI, V, IV and III) with heterogeneous condition due to its low-medium-high primary velocity values. Heterogeneous layer of overburden layer was possibly composed from residual soil, soil with corestones and poor to moderate quality of rock mass. Bedrock layer may possibly consist of massive and hard rock mass derived from granitic rock of Grade II and I due to its high to very high primary velocity values. Based on Figure 8, boundary layer between overburden and bedrock was varied (18 ~ 30 m) with undulation condition. Seismic velocity of earth materials may be influenced by several factors such as lihology, denseness, void ratio or porosity, concentration of fluid, lithification, pressure and isotropy condition level. According to [29], lithology, porosity and interstitial fluids of geomaterials can influenced the success of interpretation of subsurface profile based on the seismic P-wave velocity contrast. As reported by [30], seismic velocity parameter was influenced by density, lithology, porosity, cementation and compaction, pressure, nature of fluid saturation (air, gas, water or petroleum) and isotropic.

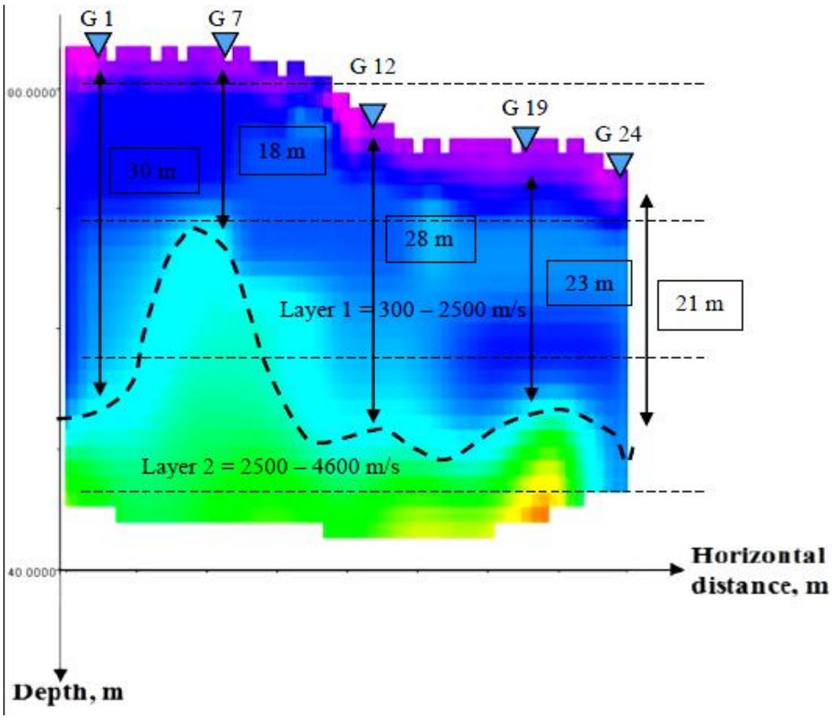

**Figure 8.** Seismic refraction tomography at Meteorological Station, Kluang Johor.

*3.2 Ambient vibration survey*

Basically, ambient vibration survey was performed to obtain the properties of peak natural frequency of material. Peak natural frequency was obtained from horizontal vertical spectral ration (HVSR) curves as given in Figure 9. According to Figure 9, single peak of HVSR was obtained from all measurement of ambient vibration method thus describes the existence one significant layer (overburden materials) to reach the hard layer (bedrock). Peak natural frequencies values for every sensor obtained are 3.90 Hz (G12), 3.42 Hz (G24 & G 19), 3.67 Hz (G01) and 3.54 Hz (G07) as tabulated detailed in Table 1. As referred to [31], subsurface profile evaluation with particular reference to overburden depth was estimated using empirical relationships (1). This equation was used to estimate subsurface profile depth based on ambient vibration properties. Overburden depth obtained from the empirical relationship (1) was estimated and illustrated in Figure 10.

$$H = 137 f_r^{-1.190} \tag{1}$$

Where:
Fr = Peak natural frequency, $F_o$ (Hz)
H = Overburden depth, y (m)

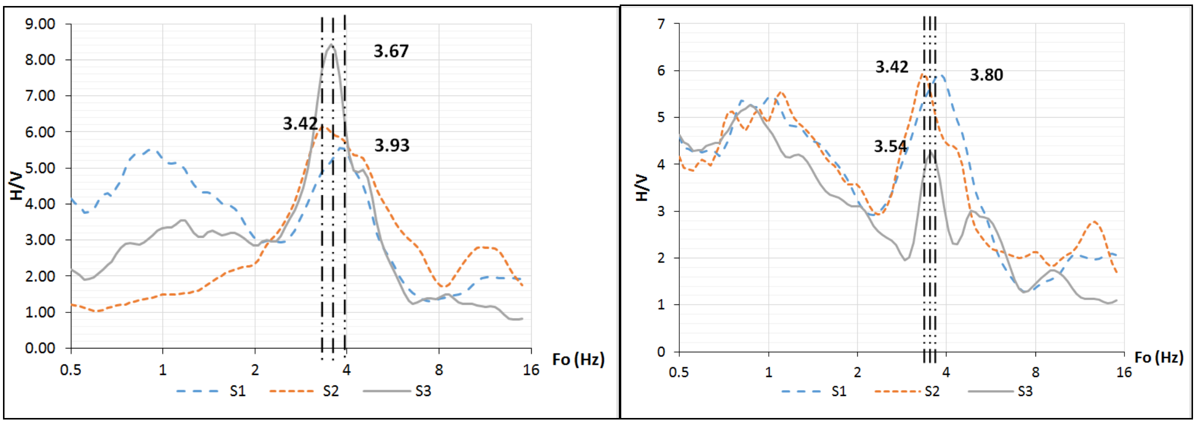


**Figure 9.** HVSR curve for measurement 1 (Left) and measurement 2 (Right).

**Table 1.** Natural frequency ($F_o$) results at every seismometer sensor.

| File / Measurement No. | Sensor 1 (Reference) $F_o$ (Hz) | Location | Sensor 2 $F_o$ (Hz) | Location | Sensor 3 $F_o$ (Hz) | Location |
|---|---|---|---|---|---|---|
| 16/1 | 3.93 | G 12 | 3.31 | G 24 | 3.42 | G 1 |
| 17/1 | 3.93 | G 12 | 3.80 | G 24 | 3.54 | G 1 |
| Average M1 | 3.93 | | 3.42 | | 3.67 | |
| 18/2 | 3.80 | G 12 | 3.31 | G 19 | 3.54 | G 7 |
| 19/2 | 3.93 | G 12 | 3.42 | G 19 | 3.67 | G 7 |
| Average M2 | 3.80 | | 3.42 | | 3.54 | |
| Sensor 1 Average | 3.90 | | | | | |

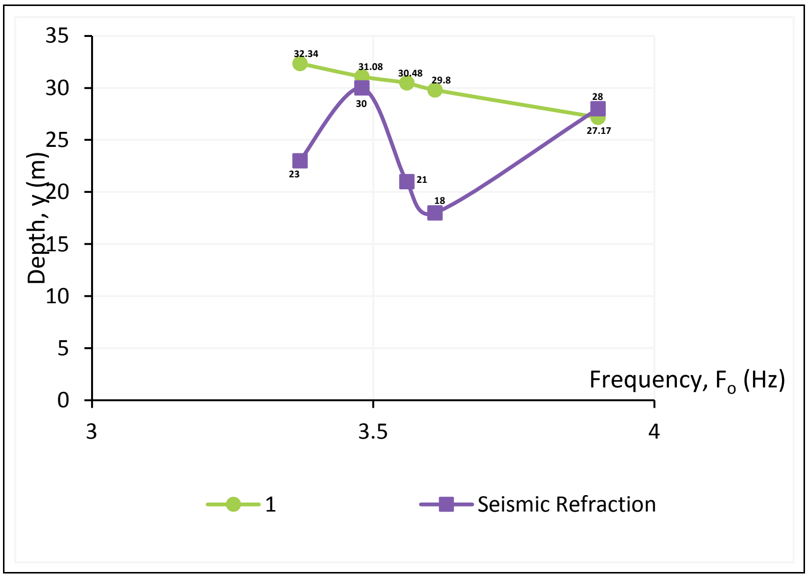


**Figure 10.** Overburden depth outcome based on peak natural frequency and primary velocity value.

*3.3 Subsurface profile evaluation based on seismic refraction and ambient vibration survey*

The evaluation of subsurface profile was specifically focused on overburden depth of site studied. Overburden depth obtained using both method was compared to conclude its efficiency in subsurface evaluation depth prediction. Depth evaluation was based on comparison between both methods specifically located at G01, G07, G12, G19 and G24 as explained in section 2.2 and Figure 7. The result (overburden depth) from seismic refraction and ambient vibration were analyzed and presented in Table 2 and Figure 11. It was found that overburden depth obtained from seismic refraction and ambient vibration survey shows some positive promising outcome due to its moderate depth differences ($\Delta y = 1.0 - 11.80$ m). Based on Figure 11, percentage accuracy of overburden depth was varied at 60 – 97% thus demonstrate that this technique was applicable in subsurface profile evaluation. Integration of seismic refraction and ambient vibration survey may compliment each strength and weakness in subsurface profile evaluation. For example, ambient vibration method was unable to define types of earth materials based on its outcome despite its ability to estimate overburden depth and thickness. However, seismic refraction method may able to compliment those weaknesses by interpretation of earth materials based on primary velocity obtained. Combination of both geophysical outcomes may also verify its reliability in term of depth accuracy in subsurface profile evaluation.

Those depth differences may occur due to the influence of noise. Geophysical equipment such as seismic refraction and ambient vibration has being widely known regarding to noise sensitivity. Generally, noise can be controlled or uncontrolled relative to situation. Example of controlled noise was a traffic noise. Traffic noise may derive from movement of any types of vehicles thus able to reduce quality of seismic and ambient vibration data. Consequently, data acquisition need to be carefully planned (e.g. performing data acquisition at the lowest traffic volume) in order to obtained high quality of seismic refraction and ambient vibration data. Uncontrolled noise may occur due to the highly geological complexity of site studied. Therefore, equipment operator needs to performed data acquisition with his best which finally require very high experiences of experts in order to process the data and interpret the outcome. Moreover, noise also can be influenced by wind, vegetation, insects, electronics devices, etc. Noise influences cannot be totally eliminated since the sensitivity of geophysical equipment was very high from any types of physics properties. However, noise can be minimized subjected to operator expertise and experienced. High quality of geophysical data obtained from data acquisition will influence the ease of data processing thus able to producing good result reliability for interpretation stage.

**Table 2.** Overburden depth comparison between seismic refraction and ambient vibration survey.

| Sensor Location | Seismic Refraction Method | Ambient Vibration Survey | Depth Differences $\Delta y$, (m) |
|---|---|---|---|
| | Depth, y (m) | Depth, y (m) | |
| G 01 | 30.00 | 29.16 | 1.08 |
| G 07 | 18.00 | 30.44 | 11.80 |
| G 12 | 28.00 | 27.12 | 0.83 |
| G 19 | 23.00 | 31.71 | 9.34 |
| G 24 | 21.00 | 31.71 | 9.48 |

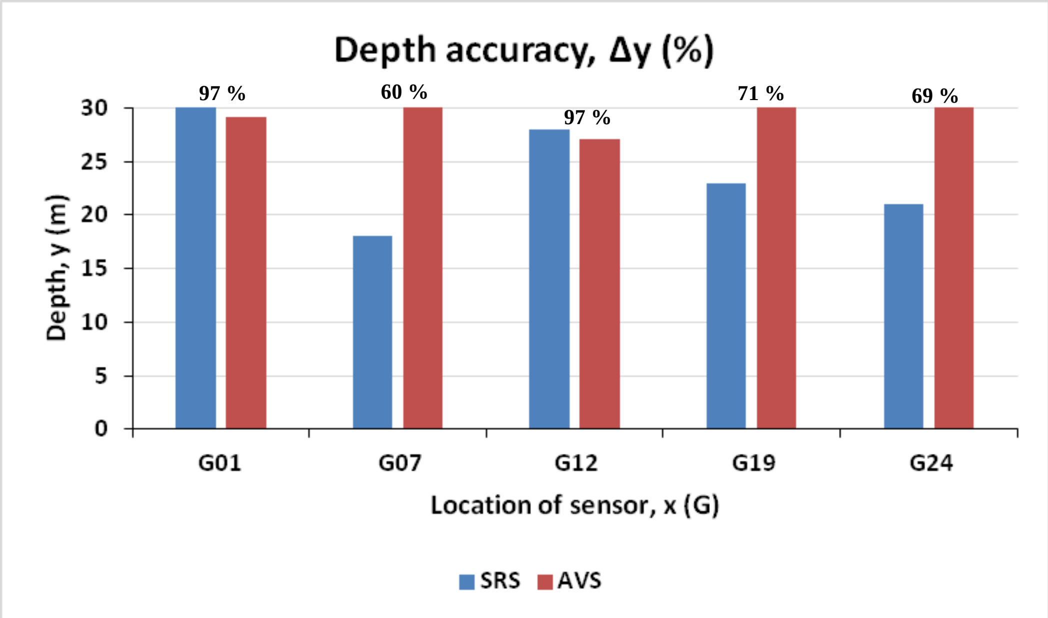


**Figure 11.** Percentage accuracy of overburden depth obtained using SRS and AVS.

## 4. Conclusion

The subsurface profile evaluation with particular reference to overburden depth and thickness was successfully being performed using seismic refraction survey (SRS) and ambient vibration survey (AVS). The geometry of subsurface profile has been determined by analyzing primary velocity and peak natural frequency data obtained along the seismic spread line and the results has shown a good similarity in term of boundary of overburden and bedrock. This finding has proved that this technique was applicable to estimate and predict thickness and depth of subsurface geomaterials thus able to compliment the conventional borehole data. The geometry and physical characteristics of subsurface profile can be easily recognized. Consequently, the determination of shape and depth of the subsurface profile material are easier and cheaper than with conventional borehole method. The information obtained from SRS and AVS was useful as a decision making regarding the suitability of subsurface profile which may perform afterward. The integration of SRS and AVM is suitable for our sustainable ground investigation due to its efficiency in term of cost, time and data coverage. Moreover, SRS and AVS were performed based on surface techniques (non-destructive test) thus able to prevent site damage which contribute to the environmental sustainable. Finally, this study has demonstrated that the integration of seismic refraction and ambient vibration survey can be a good alternative tool in geotechnical site investigation.

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