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IDENTIFYING SHALLOW SUBSURFACE CHARACTERISTICS VIA COMPRESSIONAL TO SHEAR WAVES VELOCITY RATIO (VP/VS) FROM SEISMIC REFRACTION TOMOGRAPHY

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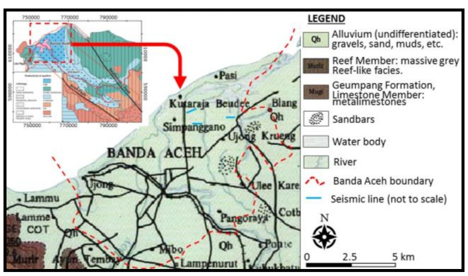
Graphical abstract



Abstract

This study was conducted in Banda Aceh district by utilizing seismic refraction P- and S-waves methods on three similar profile lines, with the aim to identify subsurface characteristic. The seismic data were acquired using ABEM TERRALOC MK8 system with 28 Hz vertical and 6 Hz horizontal geophones, and suitable seismic sources. Software used for processing to produce 2-D tomography sections and interpretations are IXRefract, Microsoft Excel, SeisOpt@2D v6.0 and Surfer 8. The results show the study area comprises of four subsurface layers with strong to very strong relation between Vp and Vs (R^2 is >0.7509) for each layer. Ratio value of Vp and Vs (Vp/Vs) for each layer (1st to 4th) was calculated to be 4.75 – 5.79; 6.50 – 8.89; 6.57 – 12.17 and 6.08 – 8.21 respectively. This study concluded that the ground subsurface in Banda Aceh district is made up of water saturated unconsolidated sediments that was identified to be a mixture of clay and silt at depth up to 55 m.

Keywords: Seismic refraction, velocity, ratio, tomography, coefficient of determination

Abstrak

Kajian ini dijalankan di daerah Banda Aceh dengan menggunakan kaedah sismik pembiasan gelombang-P dan -S ke atas tiga garis profil yang sama, bertujuan untuk mengenal pasti ciri subpermukaan. Data sismik ini diperolehi menggunakan sistem ABEM TERRALOC MK8 bersama geofon menegak 28 Hz dan mendatar 6 Hz, serta sumber sismik yang sesuai. Untuk menghasilkan keratan 2-D tomografik dan penafsiran, perisian digunakan adalah IXRefract, Microsoft Excel, SeisOpt@2D v6.0 dan Surfer 8. Keputusan menunjukkan kawasan kajian terdiri daripada empat lapisan subpermukaan dengan hubungan yang kuat dan sangat kuat antara Vp dan Vs (R^2 adalah >0.7509) bagi setiap lapisan. Nilai nisbah antara Vp dan Vs (Vp/Vs) bagi setiap lapisan (1 hingga 4) adalah 4.75 – 5.79; 6.50 – 8.89; 6.57 – 12.17 dan 6.08 – 8.21 masing-masing. Kesimpulan kajian menunjukkan subpermukaan tanah di daerah Banda Aceh terdiri daripada sedimen takterkonsolidasi bercampur lempung dan lumpur yang tepu air dengan kedalaman sehingga 55 m.

Kata kunci: Sismik pembiasan, halaju, nisbah, tomografik, pekali penentuan

1.0 INTRODUCTION

Shallow seismic refraction processing procedures started with the Intercept Time method in the year 1930s [1]. The data acquisition and processing procedures have developed since 1980s to fulfil the engineering and environmental requirements [1, 2]. Seismic refractions sometimes fail to resolve geological layers due to thin layer problem or insufficient velocity contrast [3].

The accessing of surface waves for shallow application including Spectral Analysis of Surface Waves (SASW) [4] and Multichannel Analysis of Surface Waves (MASW) [5, 6, 7, 8] provide great contributions to the engineering, environmental and archaeology applications [3, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19].

Velocity ratio of compressional wave to shear wave (Vp/Vs) is widely and effectively used to investigate engineering site and seismic wave propagation in porous media including sea-floor sediments, groundwater and hydrocarbon bearing formations. Characteristics such as porosity, lithology, mineralogy, consolidation and fluid saturation contribute to the elastic moduli variations. Clay content and water saturation are factors that contribute to the changes in Vp/Vs ratio. Thus, the Vp/Vs ratio can be used to model and evaluate lithological properties and petrophysical parameters of sediments and rocks [20, 21, 22, 23, 24, 25, 26, 27]. The Vp/Vs are also used to identify fluid saturation for porous media, and the influence of water saturation and clay content [28, 29, 30, 31, 32, 33, 34, 35]. Table 1 shows the research outcome using Vp/Vs ratio.

This article aims to study the Vp/Vs ratio for shallow subsurface in Banda Aceh district (Pasi, Kutaraja Beudee, Simpanggano, Ujong Krueng, Blang Krueng, Tiibang and Syiah Kuala) which dominated and overlaid by undifferentiated alluvium such as gravels, sand, muds, etc. [36]. The study outcome is expected to provide the Vp/Vs ratio values in shallow subsurface by using seismic refraction P- and S-waves methods.

Table 1 Study outcome by researchers on Vp/Vs ratio for sediments and rocks

Authors	Outcome
Pickett, 1960; 1963	The Vp/Vs values; 1.65-1.75 for sandstones, 1.75-1.85 for dolomites and 1.85-1.95 for limestone.
Benzing, 1978; Benzing *et al*., 1983; Hamilton, 1979	Presence of mud or shale in carbonates and sandstones causes an increase in Vp/Vs up to 13-46 for sea floor muds.
Salem, 1993	Shales (clays) rich zones show greater values of Vp/Vs than zones of lesser amounts of shales or zones that are composed of other kinds of lithology, such as sandstones, carbonates or conglomerates.
Gardner and Harris, 1968	The Vp/Vs values less than 2 for unconsolidtaed sediments saturated with gas or oil and more than 2 for unconsolidated sediments saturated with oil or water.
Gregory, 1977	Vp/Vs values of ~1.5 for gas-saturated sandstone, 1.62-2.02 for oil saturated reservoirs and 1.63-2.18 for brine-saturated reservoirs.
Tatham, 1982	Vp/Vs values: 1.78-2.4, corresponds to highly hetereogenous shaly sandstone reservoirs saturated with mutiphase fluids (oil, gas and brine).
Eastwood and Castagna, 1983	Vp/Vs values: 1.8 for quartz-rich, >5 for loose, water-saturated sediments.
Stuempel at al., 1984; Meissner *et al*., 1985	Vp/Vs values of up to 9, corresponds to water-saturared sediments having clays.
Castagna *et al*., 1985	Vp/Vs values of 1.45 for quartz spheres, velocity ratio decreases with increasing degree of sphericity of grains (or increase with increasing degree of grain angularity).
Tatham, 1985	Silts and sands with similar grain shapes show greater values of Vp/Vs than sands, eventhough both silts and sands have the same porosity.
Juneja and Endait, 2017	Vp/Vs values for basalt is 1.89 based on lab experiments

2.0 GENERAL GEOLOGY

The study was conducted in the northern part of Banda Aceh district (Figure 1). Generally, Banda Aceh district is dominated and overlaid by undifferentiated alluvium which consists of gravels, sands, muds, etc. This region is in the Krueng Aceh valley zone which is flanked by Tertiary and Quaternary volcanic mountains. On the other hand, sandbars are rarely found in this district. The Reef Member with massive grey Reef-like facies can be found in the western part of this district. A mountain ridge of limestone is laying from southwest to southeast part of this district, known to be the Geumpang Formation, with Limestone Member of metalimestones [36, 37].

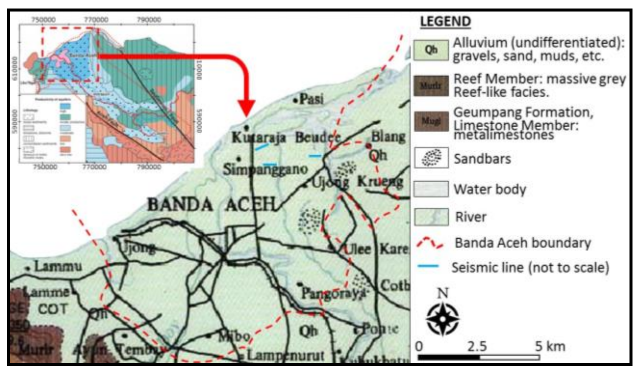


Figure 1 Geology map of Banda Aceh, Sumatra [36, 38, 39, 40]

3.0 METHODOLOGY

Three seismic refraction survey profile lines (Table 2) were conducted to cover the area of Pasi, Kutaraja Beudee, Simpanggano, Ujong Krueng, Blang Krueng, Tiibang and Syiah Kuala which represent the soil subsurface of the study area (Figure 2).

Table 2 Coordinate of the seismic refraction profile lines at Banda Aceh study area

Profile name	Distance (m)	Latitude (°N)	Longitude (°E)
S1	0	5.590133	95.331412
	115	5.590187	95.332447
S2	0	5.581190	95.336462
	115	5.581344	95.337497
S3	0	5.584987	95.348244
	115	5.585015	95.349320

Figure 2 Seismic refraction profile lines of P- and S-waves at study area [36, 41]

The seismic refraction P-wave was conducted on the three profile lines using 24 channel seismograph ABEM TERRALOC MK8 system which was connected to 28 Hz vertical geophones using a pair of seismic cables. The geophones were placed in a straight line with the geophone spikes planted on the ground surface with a constant 5 m geophone spacing. A series of vertical strikes on a metal plate using a 5 kg sledgehammer produces seismic P-waves, which will then be detected by the geophones and recorded/saved by the seismograph (Figure 3). The location of the strike (shot) points were arranged in such a way that they are laid along the seismic profile line (Table 3).

Seismic refraction S-wave was conducted on the same three profile lines using the same seismograph system. The 28 Hz vertical geophones were replaced with 6 Hz horizontal geophones. The geophones were placed in a straight line on the ground surface with constant geophone spacing of 5 m with the consideration of the geophone vibration axis is perpendicular to the profile line. A wooden plank was placed under the vehicle front or back tyres in order to have its weight providing good friction contact with ground surface. The wooden plank was strike at the end of both sides to generate shear wave (Figure 3). The location of the strike (shot) points were arranged in such a way that they lay along the seismic profile line (Table 4).

Table 3 Shot point location for P-wave seismic refraction

Profile name	Length (m)	Shot points refer to 0 m as geophone 1 (m)
S1	115	-61, -40, -20, 2.5, 27.5, 57.5, 87.5, 112.5, 135, 155, 175
S2	115	-45, -30, -15, 2.5, 27.5, 57.5, 87.5, 112.5, 130, 145, 160
S3	115	-38, -15, 2.5, 27.5, 57.5, 87.5, 112.5, 130, 145, 160

Table 4 Shot point location for S-wave seismic refraction

Profile name	Length (m)	Shot points refer to 0 m as geophone 1 (m)
S1	115	-30, -20, -10, 2.5, 27.5, 57.5, 87.5, 112.5, 125, 135, 145
S2	115	-30, -20, -10, 2.5, 27.5, 57.5, 87.5, 112.5, 125, 135, 145
S3	115	-30, -20, -10, 2.5, 27.5, 57.5, 87.5, 112.5, 125, 135, 145

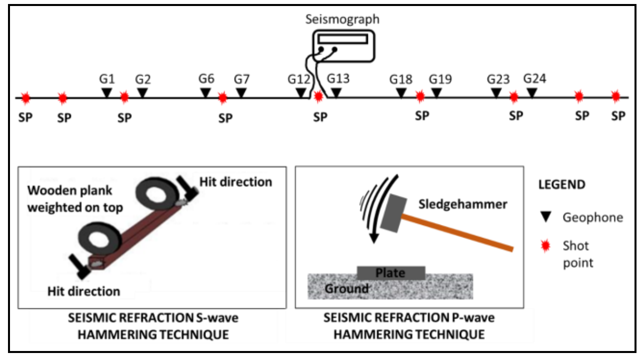


Figure 3 Seismic refraction layout and hammering technique for P- and S-wave [42, 43]

The data (P- and S-waves) collected and saved in the seismograph were transferred into a computer for processing and interpretations following the flow chart shown in Figure 4 using several software (IXRefract, Microsoft Excel, SeisOpt@2D v6.0 and Surfer 8). The direct current (DC) effect in the data was removed for better signal to noise ratio (S/N) quality. For the poor S/N ratio, further processing steps were applied which include band pass/ low pass/ high pass to improve the ratio. The acceptable S/N ratio data are saved as *.sg2 format for further processing using SeisOpt@2D v6.0 software to produce 2-D tomography section of subsurface for interpretation using Surfer 8 software.

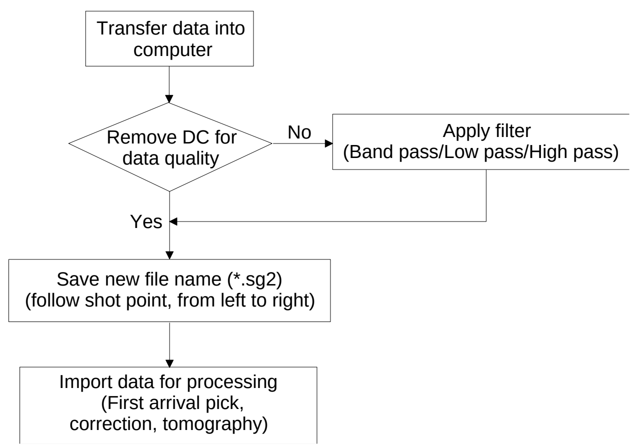


Figure 4 Seismic refraction P- and S-waves flow chart

4.0 RESULTS AND ANALYSES

Figure 5 shows an example of the seismic data with acceptable S/N ratio including first arrival pick for the P- and S-waves. The first arrival times (refer to appropriate shot point) are plotted against geophone distance for validation of the picking of the first arrival time for profile lines S1 – S3 respectively (Figure 6 – 8).

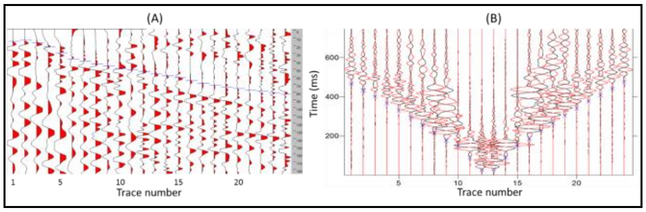


Figure 5 Seismic data with first arrival pick; (a) P-wave, and (b) S-wave

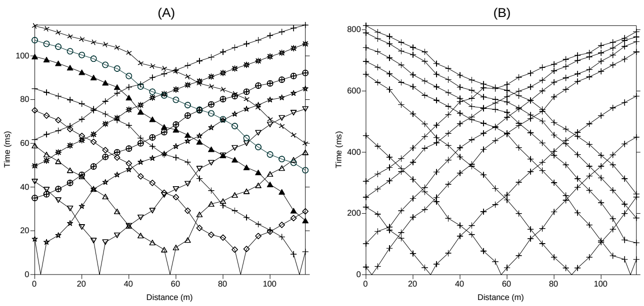


Figure 6 First arrival time vs distance graph for profile line S1; (a) P-wave, and (b) S-wave

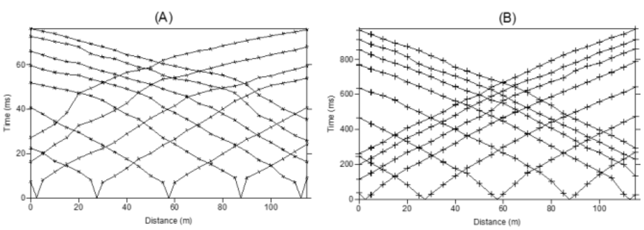


Figure 7 First arrival time vs distance graph for profile line S2; (a) P-wave, and (b) S-wave

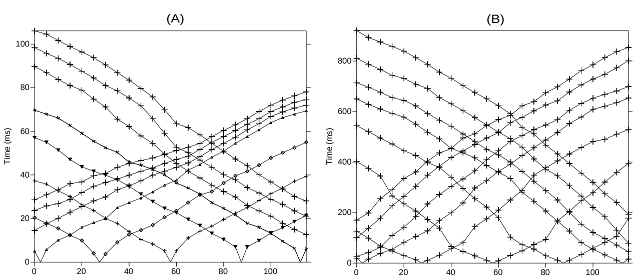


Figure 8 First arrival time vs distance graph for profile line S3; (a) P-wave, and (b) S-wave

Figure 9 – 11 show the 2-D tomography section of the seismic refraction P- and S-waves for the profile lines of S1 – S3 respectively. Each profile line of the P- and S-waves show a significant tomography in identifying variations of seismic velocity due to lithology and subsurface characteristics (density, moduli), and its very significant to interpret the boundary of interest in the study area.

The seismic refraction P-wave tomography (Figure 9a, 10a and 11a) indicate the study area is divided into four layers. The first layer (top layer) with P-wave velocity (Vp) of <750 m/s; second layer with depth of 0 – 5 m and velocity (Vp) of 750 – 1275 m/s; the third layer with depth of 0 – 12 m and velocity (Vp) of 1275 – 1684 m/s; and the forth layer with depth of 3 – 55 m and velocity (Vp) of >1684 m/s. The highest value of Vp layer (1684 m/s) is within the related range of compressional velocities for saturated soil and was probably indicative of unconsolidated sediment, and the change in Vp at this boundary is 1275 m/s. The variation of the Vp is due to bulk modulus and subsurface strength.

The seismic refraction S-wave tomography (Figure 9b, 10b and 11b) indicate the study area is also divided into four layers. The first layer (top layer) with S-wave velocity (Vs) of <121 m/s; second layer with depth of 0 – 12 m and velocity (Vs) of 121 – 196 m/s; the third layer with depth of 15 – 42 m and velocity (Vs) of 196 – 265 m/s; and the forth layer with depth of 25 – 45 m and velocity (Vs) of >265 m/s. Generally, it was identified that the Vs value is about 15% of the Vp value, with relatively small variation of Vs. At a depth of 35 m where the unconsolidated sediment was found, the Vp and Vs values were greater than 1680 m/s and 260 m/s respectively. Increase in Vs value occurred in the water saturated unconsolidated sediments such as shown in the time-distance graph. This could occur if Vs variations and values was too low in relation to the depth due to shear modulus and Poisson's ratios for the lithological units.

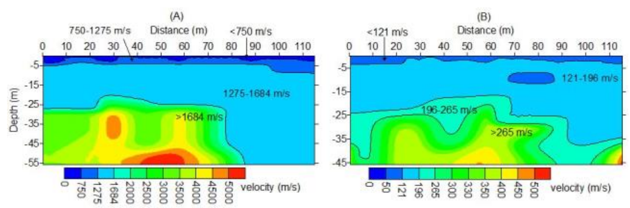


Figure 9 Refraction tomography for spread line S1; (a) P-wave, and (b) S-wave

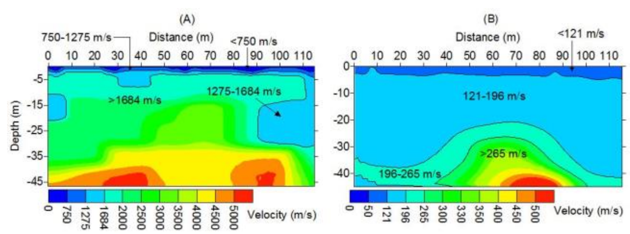


Figure 10 Refraction tomography for spread line S2; (a) P-wave and (b) S-wave

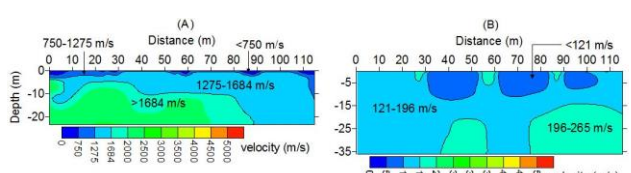


Figure 11 Refraction tomography for spread line S3; (a) P-wave and (b) S-wave

The Vp and Vs were analysed to identify the relation. The Vp and Vs for each layer were identified using 2-D tomography section of the seismic refraction P- and S-waves were plotted as shown in Figure 12 – 14. The relation for each layer shows a high value of coefficient of determination (R^2) between Vp and Vs with values of >0.7509 (strong to very strong relation) except for the first layer of profile line S3 with R^2 value of 0.2208 due to subsurface heterogenity in the layer [44, 45]. The Vp/Vs ratio for each layer were also calculated. Table 5 shows the summary of the R^2 values and Vp/Vs ratio for the three profile lines and related layer respectively.

The results indicate that Vp/Vs varies from 4.75 to 5.79 at first layer representing the top soils. Second and third layer with Vp/Vs variation of 6.50 to 8.89 and 6.57 to 12.17 respectively, representing the highly saturated sediments. The bottom layer with a Vp/Vs range of 6.08 - 8.21, exhibit the partially saturated sediments. This Vp/Vs variations, laterally and vertically, are interpreted as unconsolidated sediments which are saturated with water [28, 32], and its related to the high degree of heterogenity of the sediments investigated.

The results gained by seismic refraction method is very significant in determination of shallow subsurface characteristics. The compressional to shear waves velocity ratio (Vp/Vs) can indicate variations in lithology and the presence of clay and silt in sediments causes an increase in Vp/Vs. By increasing the degree of water saturation at the pore spaces, will affect the nature of the sediment, which results in an increase in the velocity ratio, that are characterizing the subsurface deposits, both horizontally and vertically.

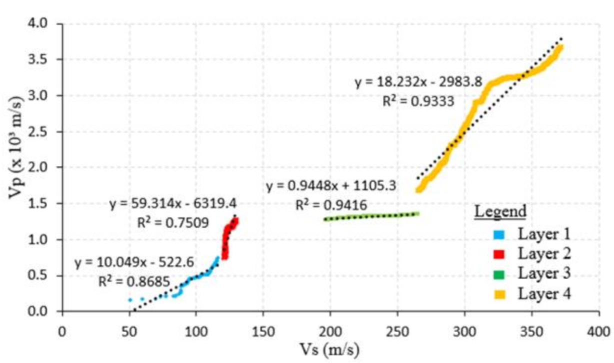


Figure 12 The Vp against Vs plot for each layer of profile line S1 at study area

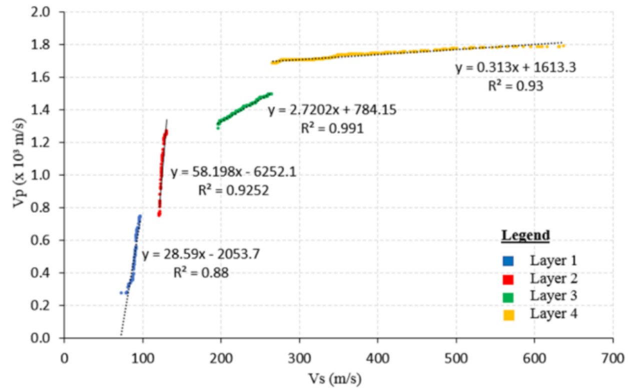


Figure 13 The Vp against Vs plot for each layer of profile line S2 at study area

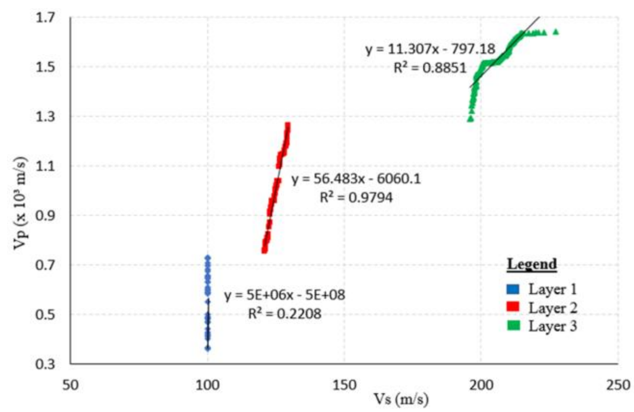


Figure 14 The Vp against Vs plot for each layer of profile line S3 at study area

Table 5 The R^2 values for the respective layer of profile lines of the study area

Profile name	Layer no.	Vp (m/s)	Vs (m/s)	R^2 values	Empirical relation	Vp/Vs
S1	1	<750	<121	0.8685	Vp = 10.049 Vs – 522.6	4.75
	2	750 – 1275	121 – 196	0.7509	Vp = 59.314 Vs – 6319.4	8.89
	3	1275 – 1684	196 – 265	0.9416	Vp = 0.9448 Vs + 1105.3	6.57
	4	>1684	>265	0.9333	Vp = 18.232 Vs – 2983.8	8.21
S2	1	<750	<121	0.88	Vp = 28.59 Vs – 2053.7	5.79
	2	750 – 1275	121 – 196	0.9252	Vp = 58.198 Vs – 6252.1	6.78
	3	1275 – 1684	196 – 265	0.991	Vp = 2.7202 Vs + 784.15	6.65
	4	>1684	>265	0.93	Vp = 0.313 Vs + 1613.3	6.08
S3	1	<750	<121	0.2208	Vp = 5 X 10^6 Vs – 5 x 10^8	5.54
	2	750 – 1275	121 – 196	0.9794	Vp = 56.483 Vs – 6060.1	6.50
	3	1275 – 1684	196 – 265	0.8851	Vp = 11.307 Vs + 797.18	12.17

5.0 CONCLUSION

The study area is classified into four layers according to the Vp and Vs values with strong to very strong correlation between the values. The Vp/Vs ratio value for the first to forth layer is 4.75 – 5.79; 6.50 – 8.89; 6.57 – 12.17 and 6.08 – 8.21 respectively. This ratio values indicate that these layers are unconsolidated sediments which are saturated with water [28, 32]. This study concludes that ground subsurface of Banda Aceh district is classified into four layers with total depth up to 55 m and Vp/Vs ratio value is 4.75 – 12.17, which indicate as water saturated unconsolidated sediments that mixed with clay and silt [33, 34].

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