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Analysis of S-Wave Propagation and Resistivity Value in Porous Medium for Conjecture Potential of Groundwater in Lempuing Village, Bengkulu City

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Abstract: Bengkulu city is facing groundwater problems where some of the groundwater is brackish. The study aimed to determine the structure of the subsurface layer through the propagation velocity of secondary wave (Vs) in a layer of porous medium in estimating the potential for groundwater. This research supported by resistivity data and will be validated based on the depth of the well. MASW data was processed using WinMASW Professional 5.0 software to obtain a 1D profile of the Vs value, and Res2dinv software was used to obtain a 2D cross-section of the resistivity value. The results showed a decrease in the value of Vs in the porous medium layer from 133 to 358 m/s in the first path, and from 149 to 314 m/s for the second path. The decrease in the value of Vs is in the range of groundwater potential which is close to the depth of the resident's well, with the type of porous medium layer being sands and intact clays. The subsurface profile from the Vs measurement shows a good agreement with the resistivity value profile from the Geoelectric method. So, secondary wave propagation can be used in determining groundwater potential for a depth of < 10 m.

Keywords: Secondary wave; Resistivity; Porous medium; Groundwater; Bengkulu

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Introduction

Groundwater is water that occupies rock pores below the soil surface in the water-saturated zone (Santosan & Adji, 2018). Aquifers composed of sand. The sandy aquifer layer was typically found at relatively shallow (Nugraha et al., 2021). Aquifers have the same lithologic compositions, those are alluvium deposits, but they have different electrical conductivity (Putranto & Rude, 2016). Groundwater is naturally renewable because it is an integral part of the hydrological cycle (Asrifah, 2013). Groundwater that has undergone a gravitational infiltration process through rock/soil pores originates from the evaporation of seawater. The steam produced is carried by moving air. The water vapor then condenses to form clouds, which in turn produces rain. Precipitation that falls on the earth's surface spreads in several ways. The precipitation is mostly temporarily held on the ground near where the rainwater falls, which is eventually returned back to the atmosphere by evaporation and transpiration by plants. Some precipitation moves through the land surface, towards rivers, lakes, seas, and some seep into the ground to become ground water. In the hydrological cycle, the cycle of water is not always evenly distributed due to the influence of meteorology (temperature, pressure, atmosphere, wind) and topographic conditions. Irayani and Prabowo (2021) shallow aquifer potential is estimated to be the release of groundwater from mountain slopes or highlands.

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The topographic parameters that affect groundwater flow are elevation and slope of landscape with a moderate - very strong correlation. The relationship between elevation and groundwater gives a correlation coefficient (r) of 99.99% (very strong), while the slope makes r-value of 54.16% (moderate) (Listyani et al., 2019).

Groundwater has an essential role for humans because it is one of the water sources for daily life, including in Bengkulu Province. However, Bengkulu Province faces groundwater problems where some groundwater is brackish, including in Bengkulu City. Some areas in Bengkulu City have brackish groundwater, especially in areas adjacent to the beach, including the Bengkulu University area, which is ± 1 km from the beach. The level of brackish water in the area based on measurements of TDS and EC Meter E-1 shows the total dissolved solids with a salinity level (salt content) of 1720 ppm - 1967 ppm. The resistivity of the VES (Vertical Electrical Sounding) Geoelectrical measurement shows that the brackish water layer has a resistivity value between 1.38 – 4.90 Ωm. This value is lower than the resistivity of the aquifer layer in the form of groundwater, which is in the range of 5.20 – 98.87 Ωm (Suhendra et al., 2021). The VES Geoelectric method has also been used to measure the volume and discharge of groundwater found on the Bengkulu University campus and obtained a groundwater volume of 147,375 m^3 with a groundwater discharge of 26,645.3 m^3/day (Widiasari et al., 2020)

Research on groundwater is generally carried out using several methods, namely the Geoelectric method and Multichannel Analysis of Surface Wave (MASW) using primary waves. These methods can be used to determine the water-carrying layer or the aquifer layer. Measurements with the seismic refraction method get the aquifer layer having a primary wave velocity value of 2300 m/s (Pesma et al., 2020). In addition, research using the Geoelectric method with the Wenner-Schlumberger configuration obtained a resistivity value of the water-carrying layer of 0.12 – 0.64 Ωm (Saranga & Tongkukut, 2016). The geoelectric method of the Schlumberger configuration shows that the groundwater prospect area has a resistivity of 16 - 34 Ωm (Hadi et al., 2012). Karunianto (2013) showing a shallow aquifer in the form of alternating sandstone and silt with a resistivity of < 30 Ωm. Groundwater conditions in dug wells and drilled wells in housing have an average minimum WQI value in dug well waters of 76.9 and an average maximum WQI value of 92.3 (Prabowo et al., 2021). Sihotang et al. (2018) classify the type of aquifer not potential because it is influenced by rock conditions in the region research dominated by claystone and siltstone. The condition of the aquifer has a classification of humidity levels including moderate wetness which indicates good continuity of the geothermal system (Wowor et al., 2021).

Maemuna et al. (2017) conducted research using the Schlumberger configuration found the presence of an aquifer at a depth of 7.57 - 23.8 m with sand type. The aquifer zone is interpreted as Tuffaceous lapillistone with petrographic analysis is composed by glass. The resistivity value of tuffaceous lapillistone is about 43.63 and 340.11 Ωm (Sugarbo & Rizqi, 2021).

$$\beta = \sqrt{\frac{\mu}{\rho}} \quad (1)$$

In theory and proven by Equation 1, secondary waves cannot propagate in a fluid medium. However, when a vibration occurs, the secondary wave continues to propagate in a porous medium. A porous medium is a medium that contains groundwater and does not contain groundwater. In *V*s propagation, when passing through a porous medium that does not contain groundwater, the wave propagation will increase with increasing depth. A porous medium is a material consisting of a dense matrix with a vacuum that is interconnected. A solid matrix is rigid or undergoes small deformation. The interconnectedness of the voids (pores) allows the flow of one or more fluids through the material.

Based on the motion of the particles, waves are divided into P waves and S waves (Kearey et al., 2002). This study estimates the groundwater potential using secondary waves using the MASW method. In addition to the MASW method, this study also uses the Wenner-Schlumberger configuration Geoelectric method. Because the geoelectric method is a very stable method in determining groundwater potential. Thus, the boundary and direction of the stretch as well as the continuity of the aquifer layer can be known vertically and horizontally. From these measurements, information about groundwater reserves can be obtained, which can be used as a reference in groundwater management (Naryanto, 2018). The resulting parameter is the resistivity value used to validate the presence of a porous medium layer obtained from MASW method. The research was carried out in the village of Lempuing, Bengkulu City, which is one of the areas directly adjacent to the Indian Ocean. The village is close to the coast, causing the aquifer layer in this area to be estimated to be relatively shallow. Lempuing Village, Bengkulu City, is located around residential areas, so we can use the depth of the residents' wells as supporting data. This article provides information about groundwater's potential in the Village of Lempuing, Bengkulu City, by analyzing the subsurface structure of the secondary wave velocity (*V*s) propagation in a layer of a porous medium in 1D form and through a 2D cross-section of resistivity values.

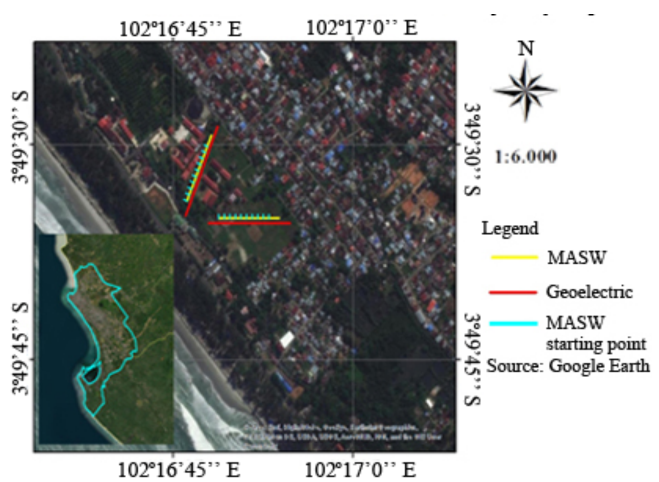

Figure 1. Map of study area.

Method

Data Acquisition

Data collection was carried out in the area of Lempuing Village, Ratu Agung District, Bengkulu City (Figure 1), using Seismograph Digital PASI 16S24-P and Resistivity & IP M MAE X612-EM. Vs data was obtained based on MASW method and resistivity data obtained from measurements using the Geoelectric method. Paths for both measurements can be seen in Figure 2. MASW measurement used 24 geophones with a distance between geophones of 2 meters. The seismic source is a hammer struck on an iron plate. For Geoelectric measurement, data collection used 48 electrodes with a distance between the electrodes of about ± 2 m. For every 1 geoelectric path, 2 measurements are made, so the number of electrodes is 84 with a path length of 166 m (Figure 2).

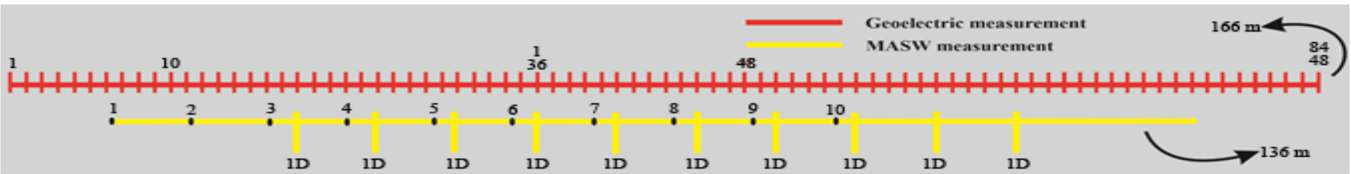

Figure 2. Paths for Geoelectric and MASW measurements

Data Processing

- *MASW*

The MASW data was processed using WinMASW Professional 5.0 software, and filtered to remove noise in the data by activating the data selection column. Then, the seismic waves are selected to be used for the next processing stage. The data recorded by the MASW method in the time-distance domain is transformed into the phase velocity-frequency domain using Fast Fourier Transformation (FFT) which produces a dispersion curve. After that, the data picking process is carried out on the dispersion curve, then an inversion process is carried out to get the Vs profile to the 1D depth. The level of accuracy of the inversion process is assessed and evaluated through the value of misfit error. The smaller the misfit error value and the minimum RMSE, the better the Vs profile. The results of the 1D Vs profile are interpolated into 2D using Surfer 13 software and a 2D subsurface section is obtained.

- *Geoelectrical*

The recorded data were processed using the Res2dinv software to obtain the actual resistivity value (ρ). The inputted data is inverted repeatedly to get the smallest RMS error value. Then obtained a 2D cross-section of the subsurface structure in the form of a relationship between the resistivity value and depth. The 2D cross-section is used to determine the structure of the subsurface layer in the study area.

Data Analysis

Each value was analyzed and interpreted to determine the condition of the subsurface structure in the village of Lempuing. The Vs value in the 1D profile is used to obtain the weight value of the soil volume (γ_{sat}) using Equation 2. The subsurface layer is classified based on the value of Vs using Figure 3 and the decrease in the value of Vs is analyzed based on the soil site class in Table 1.

$$\gamma_{sat} = 8.32 \log V_s - 1.61 \log z \quad (2)$$

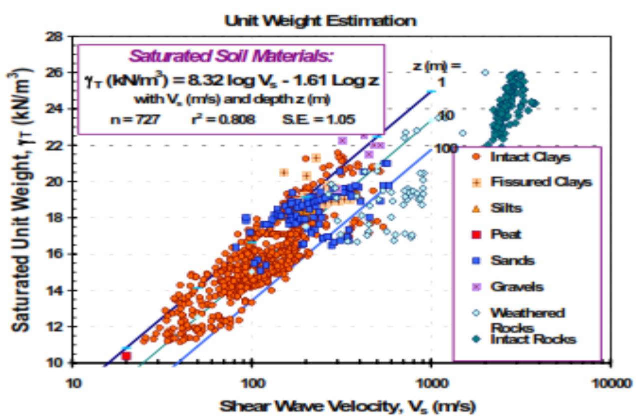

Figure 3. Correlation between soil volume weight and Vs (Mayne, 2001)

Table 1. Classification of site classes based on the correlation of field and laboratory soil investigations (Wangsadinata, 2006)

Site Class	Type of Soil	*Vs* (m/s)
A	Hard rock	*Vs* > 1500
B	Medium rock	750 < *Vs* ≤ 1500
C	Very dense soil and soft rock	350 < *Vs* ≤ 750
D	Medium ground	175 < *Vs* ≤ 350
E	Soft soil	*Vs* < 175

The Vs was calculated by analyzing the dispersion properties of Rayleigh waves contained in the seismic data recorded during the survey (Rusydy et al., 2016). The resistivity value was analyzed based on the resistivity value of each layer obtained with respect to depth. The resistivity value is used to support the Vs data in determining the porous medium layer in the study area and is matched based on the depth of the wells around the study area. The value of Vs and resistivity were classified to determine the subsurface layer and correlated with the geological map of the study area. The porous media layer from the two methods was compared, to obtain the percentage of conformity between the two methods.

Result and Discussion

• 1D Vs Profile

Figure 4a shows one of the dispersion curves from the MASW measurement used to obtain a 1D Vs profile. The relations between Vs and depth are given in Figure 4c. There are two types of lines: the results of picking (red line) and the best picking model (blue line). The closer together these two lines indicate the smaller the value of the misfit curve shown in Figure 4b.

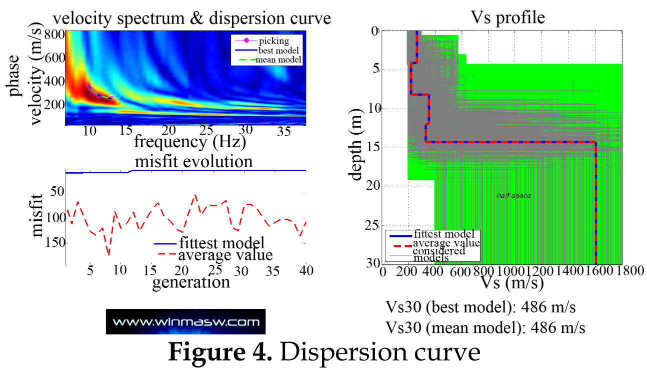

Figure 4. Dispersion curve

Figure 5 shows a 1D profile of the Vs value against depth which is obtained for one measurement based on the dispersion curve in Figure 4. The values shown in the 1D profile consist of depth, Vs, density, and thickness. The value of Vs in the subsurface layer found in Lempung Village varies due to different materials in the propagation of Vs. As the depth increases, the value of Vs also increases.

Theoretically, Vs cannot propagate in a fluid medium because the fluid does not have a modulus of elasticity to return to its original shape. This theory is proven by Equation 1 proposed by Sheriff and Geldart (1995), that the water elasticity constant in the secondary wave is zero. Based on this theory, fluid (water) has an effect on the propagation of secondary waves below the earth's surface, as shown in Table 2. The softer a layer of soil, the greater the groundwater content. Figure 5 shows a decrease at a depth of 4.2 m with a Vs of 220 m/s.

Density containing groundwater is equal to or less than the density in the first layer. Figure 5 shows the groundwater density of 1.9 g/cm³. The decrease in the value of Vs and density indicates the influence of groundwater that affects the propagation of secondary waves. The density of groundwater contained in the measurement results is not worth 1 g/cm³ because what is measured is the density of the layer (water and material). This is because groundwater below the surface is between the pores of the rock/ material.

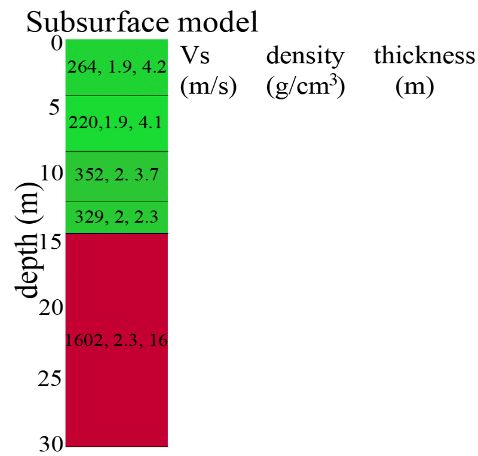

Figure 5. 1D Vs Profile

The distribution of the 1D profile MASW measurement points in Figure 5 can be seen in Figure 6. There is 1 MASW measurement point with a depth of 14.3 m on a 2D Geoelectric cross section. Therefore, the 10-point 1D MASW profile uses a depth of up to 14.3 m as shown in Figure 6.

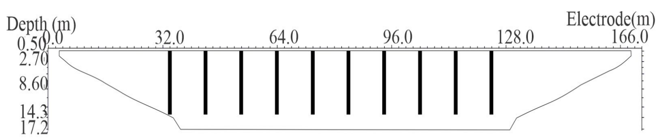

Figure 6. MASW measurement point (black vertical line) on Geoelectric track (trapezoid shape)

Table 2. Classification of subsurface types based on the value of *Vs* against γ_{sat}

Layer	Depth (Z) (m)	Vs (m/s)	γsat (kN/m3)	Description	Site Classs
1	0 – 4.2	264	19.14	Intact clays	
2	4.2 – 8.3	220	18.01	Sands	Medium soil
3	8.3 – 12	352	19.45	Intact clays	
4	12 – 14.3	329	19.08	Sands	
5	Half space	1602	Half space	Half space	

- *2D Cross Section of Resistivity Value*

Figure 8 shows a 2D cross - section of the resistivity values at location 1 and location 2. The resistivity values ranged from 0.492 Ωm – 699 Ωm with an RMS of 25% at location 1 measurements and 1.62 Ωm – 995 Ωm with an RMS of 18.9% at site measurements 2. The depth of each measurement location reaching 17.2 m. The results of the classification of subsurface structures based on geological maps of Gafoer et al. (1992) are shown in Table 3 and Table 4. The relations between the value of Vs and the value of the weight of the soil volume (γsat) is used in classifying the type of subsurface layer as obtained in Table 2.

The 1D Vs value profile data is interpolated into 2D form to determine the distribution of the Vs with respect to depth. The 1D profile is interpolated based on the value of Vs, depth, and longitude (Figure 7). The results of 2D interpolation are shown in Figure 7, where the x-axis is the longitude, and the y-axis is the depth of the 1D profile of the MASW method. The figure shows the distribution of the decrease in the value of Vs that occurred at both locations. Some part of the decrease in the value of Vs has occurred from the surface spreading down to a depth of 10 m in Figure 7b, which is marked (blue circle). This is due to the potential for a porous medium with high porosity in the layer.

The distribution of the decrease in the value of Vs occurs due to the influence of density, porosity and fluid content (water). The lower or smaller the value of Vs, the softer the soil condition. The types of subsurface layers that are grouped based on the value of the Vs profile can be seen in Table 2. The value of Vs in the 1D profile is used to calculate the value of the weight of the soil volume (γ_{sat}) (Equation 2), as shown in Table 2

Table 1 to determine the site class of the soil layer type. The decrease in the value of Vs that occurs in Table 2 (yellow) indicates the type of medium soil layer, which means that the decrease in the value of Vs has soil water content that affects its propagation obtained in Table 2. The subsurface layers are classified according to the value of Vs using Figure 3.

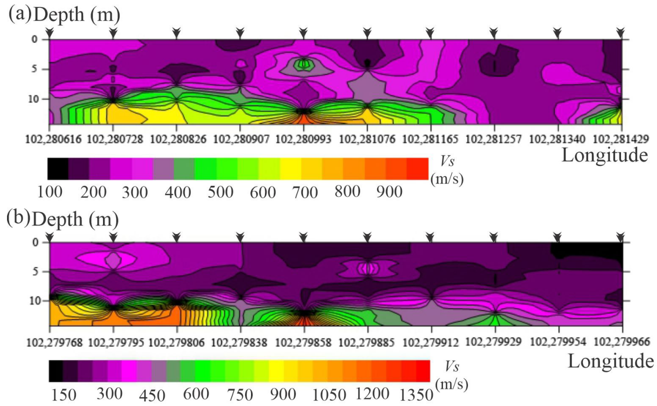

Figure 7. 2D cross section of Vs value

Table 2 observes a decrease in Vs with values of 220 m/s and 329 m/s, which may indicate a sand layer. However, because there are several factors that affect the decrease in the value of Vs in the study area, the classification of the subsurface layer is assisted by In Figure 8, groundwater is marked in blue, brackish water is marked in black, clay is marked in brown, sand and gravel are marked in red and the sand layer is marked in yellow. The type of subsurface layer in Lempuing Subdistrict, Bengkulu City, consists of sand, gravel, clay, brackish water and ground water. The brackish water found at location 1 shown in Table 3 is caused by 2 factors, namely from swamps and beaches.

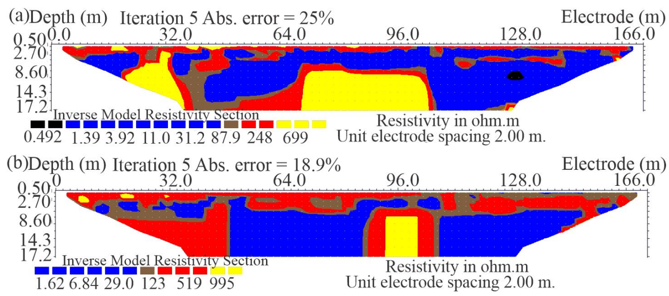

Figure 8. 2D cross-section of resistivity values (a) location 1 and (b) location 2

The RMSE value obtained from the 1D value Vs is the error value for each measurement layer. The smaller the RMSE value, the higher the level of accuracy obtained at each layer. RMSE on the MASW method reached 0 and the lowest misfit obtained was -0.91. Thus, the accuracy of the MASW method is quite high in determining the subsurface layer.

Table 3. Classification of subsurface type at location 1

Layer	Resistivity Value (Ωm)	Description
1	0.492	Brackish water
2	1.39 – 87.9	Groundwater
3	(> 87.9) – 100	Clay
4	248	Gravel and sand
5	699	Sand

Table 4. Classification of subsurface type at location 2

Layer	Resistivity Value (Ωm)	Description
1	1.62 - 29	Groundwater
2	< 123	Clay
3	123 - 519	Gravel and sand
4	995	Sand

The layers of the earth are composed of various types of rock that have different conductivity values. The conductivity value is inversely proportional to the resistivity value. The greater the conductivity value, the lower the resistivity value and vice versa. The greater the value of the resistivity of a rock, the more difficult it is for the rock to conduct electric current. This causes the Geoelectric method to be very sensitive to water, due to the high conductivity of water. Therefore, the results shown in Tables 3 and 4 obtain resistivity values for groundwater ranging from 1.39 – 87.9 Ωm and 1.62 – 29 Ωm.

The presence of groundwater is characterized by a layer bounded by clay. This is also observed in Figure 8. The clay layer is a brown layer. Geoelectrical measurement results show that the clay layer surrounding the groundwater is at resistivity values (>87.9) Ωm - 100 Ωm for measurements at location 1 and < 123 Ωm for measurements at location 2.

- *Comparison of 1D Vs Profile and Resistivity Value*

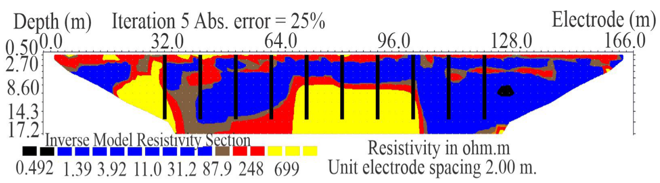

Figure 9. The 1D MASW measurement point (black vertical lines) on the Geoelectrical trajectory.

The results of the 2D measurement resistivity value were compared with the 1D profile of the Vs value to determine the level of compatibility between the two methods in determining the porous medium layer in estimating the groundwater potential. The 2D cross-section of the resistivity values of Figure 9, was cut into a 1D profile (Figure 10) for comparison with the MASW method. Comparison of resistivity values and Vs values was carried out to a depth of 14.3 m. Figure 10a shows that the location of groundwater potential based on resistivity values is at a depth of ±3 m below the surface with a value of 1.39 – 87.9 Ωm which is marked in blue.

The decrease in Vs value occurred at a depth of 4.2 m with a value of 220 m/s and at a depth of 12 m with a Vs value of 329 m/s. The difference between the depths of the two methods, in determining the groundwater potential is 1.2 m. In the fourth layer of the MASW method, the decrease in the value of Vs is not too significant, so the decrease in the fourth layer indicates a very small potential for groundwater with the type of layer in the form of sand. This is consistent with the resistivity value where at depths > 10 m, there is no potential for groundwater with the type of layer in the form of sand marked in yellow.

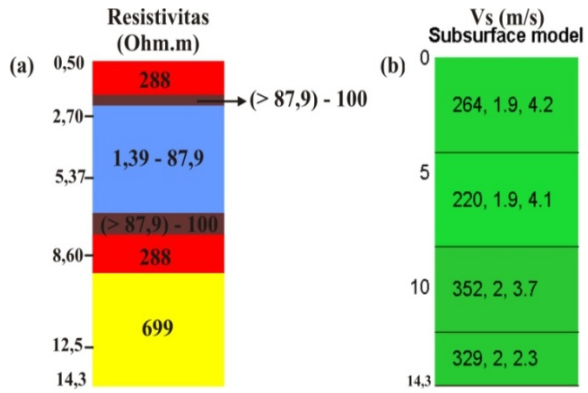

Figure 10. 1D profile (a) resistivity value and (b) Vs

Measurement of location 1 shows the suitability between the two methods in determining the layer of porous medium at a depth of < 10 m by 80%. This suitability is obtained based on the results of the two methods in determining the layer of porous medium that has groundwater potential. At a layer depth of > 10 m, the suitability between the two methods is around 40% because some data from the MASW method show a half space layer (the layer is considered homogeneous for a certain depth to infinity). At location 2, the suitability of the measurement results for layers with a depth of < 10 m is 90% and 40% for a depth of > 10 m. The decrease in Vs value at location 1 ranged from 133 – 358 m/s and at location 2 it ranged from 149 – 314 m/s. The Geoelectric method obtains a Root Mean Square (RMS) error which is quite high compared to the RMSE and the misfit in the MASW method is 18.9% to 25%. RMSE on the MASW method reached 0 and the lowest misfit obtained was -0.91. RMSE is the error obtained at each depth and the misfit is the value of the mismatch between the results and the actual layer. Thus, the accuracy of the MASW method is higher than the Geoelectric method, but the Geoelectric method is more stable in determining the potential for groundwater and groundwater content in the research area, because the resistivity and electrical properties of the Geoelectric method are very sensitive to water.

The Vs value and the resistivity value are then matched with the depth of the well in the study area. The depth of the wells in the study area ranges from 5 m to 6 m below ground level, but the potential for groundwater has been found at a depth of 4 m. The decrease in the value of Vs and the value of groundwater resistivity occurred from a depth of 2.7 – 2.9 m below the surface at both locations.

Conclusion

Secondary wave propagation in the porous medium layer decreases when passing through a medium containing water potential. In this study, a decrease in the value of Vs was observed through a layer of porous medium indicating the presence of groundwater between 133 to 358 m/s. The types of porous medium layers that have the potential to contain groundwater are sands and intact clays. The resistivity value of the brackish water layer is 0.49 Ωm. The subsurface profile from the Vs measurement using the MASW method shows a fairly good match with the resistivity value profile from the Geoelectric method. This shows that secondary wave propagation has the potential to be used in determining groundwater potential for a depth of < 10 m, especially in areas with shallow groundwater such as Bengkulu City.

Acknowledgements

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