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Subsurface Lithology Analysis Using HVSR Method in Jorong Ranah, X Koto Singkarak District

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Abstract: Jorong Ranah bordered Sumani segment and the Sianok segment. Both of these segments had experienced demaging earthquakes that affected Jorong Ranah. The damage caused could be determined by analyzing the subsurface lithology. This study aimed to determine the value of dominant frequency (f_0) and amplification factor (A_0) as well as the shear wave velocity (Vs) and subsurface lithology. Microtremor research was conducted at 8 measurement points. Microtremor signals were analyzed using the HVSR method to obtain data in the form of f_0 and A_0 presented in the form of H/V curves. The values were analyzed using Easy HVSR software to obtain a curve of shear wave velocity values against depth. 2D modeling of subsurface lithology was conducted using Rockworks software. The results showed that the f_0 value in Jorong Ranah ranged from 1.25 - 14.75 Hz and the A_0 value ranged from 3.26 - 6.92. The shear wave velocity (Vs) values ranged from 100 m/s - 1,604 m/s at depths ranging from 0 - 116.67 meters. In the first layer, the dominating subsurface lithologies were silt, hard sandy loam, breccia tuff, red soil, and gracefully sandstone. In the second layer, the dominating subsurface lithologies were silt, hard sandy loam, tuff, and volcanic breccia. In the third layer, the dominating subsurface lithologies were red soil, volcanic breccia, tuff, and tuff breccia. And in the fourth layer, the dominating subsurface lithologies were red soil and tuff breccia. Subsurface lithology affected potential damage, with high shear wave velocity (Vs) indicating stable, dense rocks and lower damage potential, while low Vs values suggested soft rocks that were more prone to deformation and higher damage risk.

Keywords: Subsurface Lithology; Shear Wave Velocity; Microtremor, HVSR

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Introduction

West Sumatra is one of the areas with very high earthquake intensity, because it is located on the Sumatra fault system and the Mentawai fault system. The Sumatra fault system is known as the Sumatra Faulth Zone [1]. The Sumatran fault zone is a major earthquake that has claimed many victims. One of these large earthquakes was the 6.3 SR earthquake in the Sianok and Sumani segments. These two segments pass through Jorong Ranah, X Koto Singkarak sub-district, so that destructive earthquakes often occur, causing many victims and considerable damage in this area [2]. So that mitigation efforts are needed by knowing the subsurface lithology in the area in order to minimize the consequences caused.

The lithology of an area needs to be identified to determine the permeable and impermeable rock materials that make up the affected area, as this will determine which rocks are likely to influence the damage and their distribution in the subsurface [3]. The geophysical survey is a key method for assessing subsurface structures, with the microtremor survey

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being one of the primary techniques often used as an initial step. This survey is carried out to evaluate how the ground responds to seismic vibrations. Microtremors are continuous, low-magnitude ground vibrations caused by both natural phenomena and human activities, and their characteristics are influenced by the local geological conditions [4]. The Horizontal-to-Vertical Spectral Ratio (HVSR), also known as H/V or the Nakamura method, was used to analyze microtremor signals. Nakamura stated that the main frequency and peak value of HVSR, often called the soil amplification factor, are related to the H/V ratio component in the microtremor recordings [5]. Microtremor data using the HVSR (Horizontal to Vertical Spectral Ratio) method can be used to determine dominant frequency and amplification values as well as seismic susceptibility indices that describe the dynamic characteristics of the soil [6]. This method is an effective, inexpensive and environmentally friendly method that can be used in residential areas [7]. Microtremors are short-period noise that originates from artificial sources. These waves come from all directions and resonate with each other [8].

Various studies have applied the HVSR method to assess earthquake risk. Lermo & Chávez-García (1994) investigated regions of Mexico City that were repeatedly affected by the major earthquakes of 1957, 1979, and 1985 [9]. Other studies have also applied the HVSR method to assess cities with a high earthquake disaster risk, including Jammu Barat and Vishakhapatnam in India [10], [11], Bandar Lampung and Jakarta, Indonesia [12] [13], and Ivanec, Croatia [14] [15]. The HVSR method was also employed to assess local effects during the Ezgeleh earthquake on November 12, 2017, with a magnitude of 7.3, as well as the Albania earthquake on November 26, 2019, which had a magnitude of 6.4 [17], the Changning earthquake in 2019 [18], and the Izmir, Turkey, earthquake on October 30, 2020 [19].

The dominant frequency (f_0) is the frequency value that appears frequently in a time range. The dominant frequency value is obtained from the peak horizontal axis of the H/V curve. The dominant frequency value from HVSR processing states the natural frequency found in the area. Through this parameter, the nature and characteristics of the rocks can be known. This states that in the event of an earthquake or disturbance in the form of vibration that has the same frequency as the natural frequency, resonance will occur resulting in amplification of seismic waves in the area. The value of the dominant frequency (f_0) of an area is supported by several factors, namely the thickness of the weathered layer and the subsurface average velocity (Vs), so it can be written with f_0 is the natural frequency, Vs is the average value of shear wave velocity at a depth of up to 30 meters from the surface, and H is the thickness of the weathered layer [20]. The dominant frequency value is obtained from Equation 1 [21].

$$f_0 = \frac{V_s}{4H} \tag{1}$$

Where f_0 is the dominant frequency (Hz), Vs is the S-wave velocity (m/s) and H is the sediment thickness (m). Soil Classification Based on the Dominant Frequency Value of Microtremor by Kanai can be seen from Table 1.

Table 1. Soil Classification Based on the Dominant Frequency Value of Microtremor by Kanai

Soil Classification		Dominant Frequency (f_0)	Kanai Classification	Desription
Type	Kinds Of			
Type IV	I	6.667 - 20	Tertiary or older rocks. Consists of hard sandy rocks, gravel and others.	The thickness of the surface sediments is very thin, dominated by hard rocks.
	II	4 - 10	Alluvial rocks, with a thickness of 5 meters. Consists of cipher, gravel, sandy hard clay, loam, etc.	Its surface sediment thickness falls into the medium category of 5-10 meters
Type III	III	2.5 – 4	Alluvial rocks, with thickness > 5 meters. Consists of cipher, gravel, sandy hard clay, loam, etc.	The thickness of its surface sediments falls into the thick category, 10-30 meters.
Type II Type I	IV	<2.5	Alluvial rocks, which are formed from delta sedimentation, top soil, mud with a depth of 30 meters or more.	The thickness of the surface sediments is very thick.

(Source: Ref [22])

Amplification is the amplification of a wave when it passes through a certain medium. Amplification in seismic waves can be caused when an object that has its own frequency is disturbed by another wave with the same frequency. Amplification can occur when waves propagate to the ground surface where the natural frequency (f_0) of the ground has a frequency value that is almost the same or equal to the frequency of the incoming earthquake. The amplification factor value of a place can be known from the peak height of the HVSR amplitude spectrum of the microtremor measurement results in that place [4]. Soft sedimentary rocks are known to amplify ground motion during earthquakes and therefore cause more damage on average than hard layers. Amplification factor values can be classified into 4 zones according to the Japan Road Association 1980 in Table 2.

Table 2. Amplification Factor Values in 4 Zones

Zona	Classification	Amplification Factor Value	Color in Mapping
1	Low	fa < 3	Green
2	Medium	3≤fa <6	Blue
3	High	6 ≤fa <9	Yellow
4	Very High	≥ 9	Red

(Source: Ref [23])

The seismic vulnerability index describes the condition of the earthquake hazard vulnerability level based on the local rock geology. The seismic vulnerability index (Kg) of an area describes the level of vulnerability of a layer of soil that is deformed by an earthquake. The level of damage to buildings is directly proportional to the seismic vulnerability index (Kg). The seismic vulnerability index can be seen in the Equation 2 [24].

$$Kg = \frac{A0^2}{f_0} \tag{2}$$

Where Kg is the seismic vulnerability index, A_0 is the amplification factor and f_0 is the natural frequency. Based on the mathematical calculations that have been used, the value of the seismic vulnerability index is strongly influenced by the maximum amplitude and natural frequency. When the amplitude value is large and the natural frequency value is small, the value of the seismic vulnerability index will be greater. Conversely, if the amplitude value is small and the natural frequency value is large, the value of the seismic vulnerability index will be smaller. The classification of the seismic vulnerability index (Kg) can be seen in Table 3.

Table 3. Classification of the Seismic Vulnerability Index (Kg)

Zona	Classification	Seismic Vulnerability Index
1	Low	Kg <3
2	Medium	3≤ Kg ≤ 6
3	High	Kg > 6

(Source: Ref [25])

High Kg values are found in soils with soft sedimentary rock lithology. These high values describe that the area is vulnerable to earthquakes. Conversely, small Kg values are generally found in soils with strong and stable constituent rocks so that when an earthquake occurs, the area has a low risk, experiencing only small shocks.

Subsurface lithology is influenced by natural frequency, amplification factor and seismic susceptibility index as well as the depth of sedimentary layers. Lithology is also defined as the description of rocks in outcrop based on their characteristics, such as color, mineral composition, synonym grain size and petrography. Each rock has a different shape, hardness, roughness and smoothness of surface. This is due to the different materials that make up the rock. Interpretation of subsurface lithology is influenced by shear wave velocity (Vs). Rocks or materials that are soft will have a relatively smaller Vs value compared to hard rocks, because the shear wave velocity value is directly proportional to the density of the rock. Shear wave velocity (Vs) is an important parameter to evaluate the dynamic condition of the soil and can be used to estimate the subsurface lithology in a region. One way that can be used is by averaging the Vs values based on the time of propagation from the surface to a depth of 30 m or Vs30 [26]. Vs30 is a key indicator of the ground response that generally dominates the ground motion amplification due to earthquakes [27]. Site classification based on SNI 1726 Vs value can be seen in Table 4.

Table 4. Site classification based on SNI 1726 Vs value

Site Classification	Shear Wave Velocity (m/s)
Hard Rocks	Vs ≥ 1.500
Rocks	750 < Vs ≤ 1.500
Very Compact Soil and Soft Rock	350 < Vs ≤ 750
Medium Soil	175 < Vs≤ 350
Soft Soil	Vs < 175

(Source: Ref [28])

Method

Microtremor signal measurements were conducted in Jorong Ranah, X Koto Singkarak District. Primary data collection in the form of direct microtremor signal measurements in the area as many as 8 measurement points. The microtremor signals taken are in the area located at geographical coordinates 0°42'48 - 0°43'26.2″ N-S and 100°36'10″ - 100°36'59.4″ west. The following is a map of the research location shown in Figure 1.

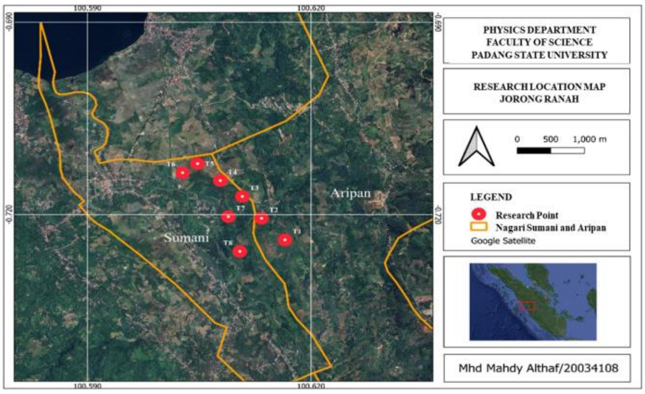


Fig 1. Microtremor Data Collection Location Map

The research was carried out through several stages as shown in Figure 2.

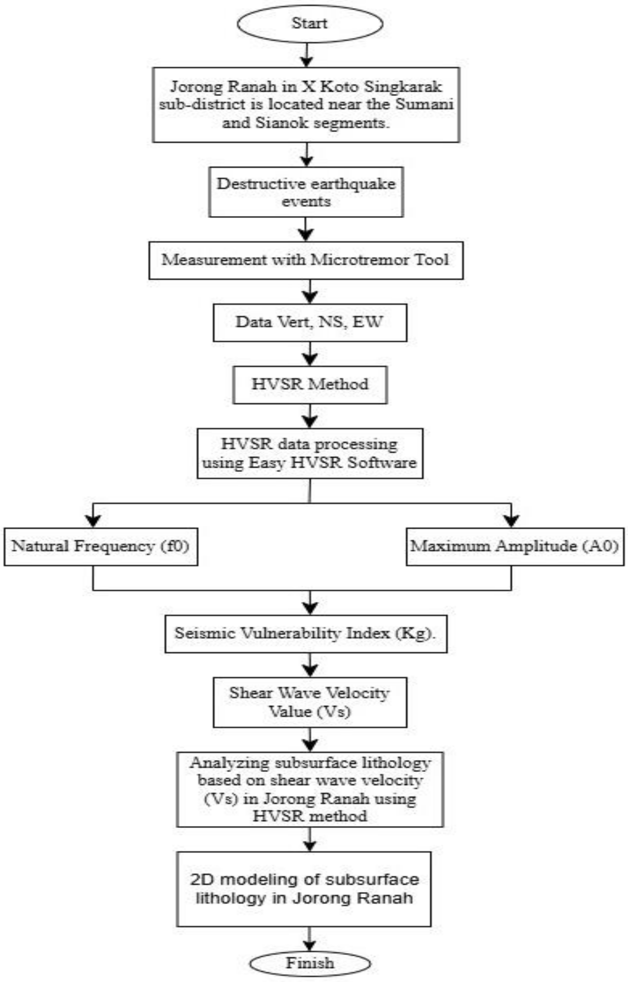


Fig 2. Data Processing Techniques for Subsurface Lithology

This research began with determining the research area, namely Jorong Ranah, X Koto Singkarak District. This is because Jorong Ranah is close to Sumani segment and Sianok segment. Where on March 6, 2007 occurred within 2 hours and there were 2 destructive earthquakes with magnitudes of 6.4 SR and 6.3 SR which had claimed 67 lives and 826 people injured and 43,719 building damages that occurred in Bukittinggi, Padang Panjang, Payakumbuh and Solok [29].

Measurements were made using the S3S Seismometer, Sysmatrack - M. AE and some other hardware. The research was conducted by conducting a site survey and making a survey design of the data collection location. Microtremor measurements were carried out at 8 measurement points with a distance of 500 meters between points. With each measurement point carried out for 40 minutes of measurement time if there is noise and 20 minutes if there is no noise. The resulting data are Vert, NS, and EW data. Furthermore, the data were analyzed using the HVSR method using Easy HVSR software. The HVSR method can be seen in Equation 3 [30]:

$$HVSR = \frac{\sqrt{(AE(f)^2 + AN(f)^2}}{AZ(F)} \quad (3)$$

Where HVSR is the H/V component spectrum ratio, Ae (f) is the spectrum of the east-west horizontal component in the frequency domain, AN (f) is the spectrum of the north-south horizontal component in the frequency domain and AZ (f) is the spectrum of the vertical component in the frequency domain.

So that the value of natural frequency (f_0) and maximum amplitude (A_0) are obtained. From these two variables, the seismic vulnerability index (Kg) is calculated to estimate the damage that may occur in an area during an earthquake. The calculation of the seismic vulnerability index (Kg) can use Equation 4:

$$Kg = \frac{A0^2}{f0} \quad (4)$$

Where Kg is the seismic vulnerability index, A_0 is the amplification factor and f_0 is the dominant frequency (Hz). Furthermore, the shear wave velocity (Vs) value was obtained from Easy HVSR software. The shear wave velocity (Vs) value is obtained for each subsurface layer. After the shear wave velocity value is obtained, the shear wave velocity value is analyzed. The analysis was carried out using site classification based on SNI 1726 to estimate the subsurface lithology in an area in accordance with the Jorong Ranah formation, namely the Qtau formation (undecomposed flow). And the mapping of subsurface lithologic structure is done by using Rockworks software.

Result and Discussion

Measurements were made at 8 measurement points with a distance of ±500 meters between points. Microtremor data is analyzed with Easy HVSR software by cutting to select signals without noise. The dominant frequency value (f_0) in Jorong Ranah, X Koto Singkarak District ranges from 1.25 Hz - 14.75 Hz. The distribution of the dominant frequency value (f_0) can be seen in Table 5.

Table 5. Data Analysis Results of Dominant Frequency Values

Point	Longitude	Latitude	Dominant Frequency	Category
1	100,616509	-0,723943	14,75	
2	100,613370	-0,720582	14,75	
4	100,607833	-0,714698	11,75	Type 1
6	100,602779	-0,713477	14,75	
8	100,610458	-0,725738	14,75	
5	100,604789	-0,712063	5,3	Type II
7	100,608909	-0,710328	6,2	
3	100,610785	-0,7171765	1,25	Type IV

Table 5 is the result of the analysis of the dominant frequency value based on the Kanai 1983 classification, then obtained varying values in microtremor measurements in the study area which can be seen in Figure 3.

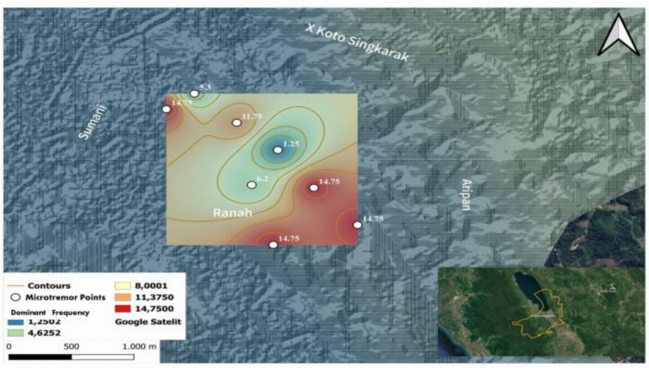


Fig 3. Results of Dominant Frequency Mapping (f_0) in Jorong Ranah, X Koto Singkarak District

The classification of the dominant frequency (f_0) value in Table 5 has a range of f_0 values from 1.25 Hz - 14, 75 Hz. Type I soil classification with a value range of 6.67 Hz - 20 Hz is found at point 1, point 2, point 4, point 6 and point 8. Areas with this dominant frequency (f_0) are assumed to have a very thin thickness of surface sediments and are dominated by hard rock, smaller than 5 meters. Generally consisting of hard sandy rocks, gravel and others. The f_0 value of Type II soil classification with a value range of 4 Hz - 6.67 Hz is found at point 5 and point 7. The area with this dominant frequency (f_0) is assumed to have a surface sediment thickness in the medium category of 5 - 10 meters. Which consists of alluvial rocks in the form of sandy gravel, sandy hard clay, loam and others. The f_0 value of Type IV soil classification with a value range of <2.5 Hz is found at point 3. The area with the dominant frequency (f_0) is assumed to have a very thick surface sediment thickness, more than 30 meters consisting of alluvial rocks in the form of delta sediments, top soil, mud with a depth of 30 meters or more. The dominant frequency value in an area is influenced by the thickness of the sediment layer and the average wave propagation speed below the ground surface. This means that the difference in the depth of the wave reflection field below the ground surface causes differences in the dominant frequency value at each research location point. If the wave bounces on a thick sediment layer, the dominant frequency value will be small. Vice versa, if the wave bounces on a thin sediment layer, the dominant frequency value will be greater.

The amplification factor (A_0) in Jorong Ranah, X Koto Singkarak District ranges from 3.26 - 6.92. The following data analysis results of the amplification factor value at each measurement point can be seen in Table 6.

Table 6. Data Analysis Results of Amplification Factor Value (A_0)

Point	Longitude	Latitude	A_0	Category
1	100,616509	-0,723943	5,24	
2	100,613370	-0,720582	3,26	
3	100,610785	-0,717165	3,72	
4	100,607833	-0,714698	4,09	Medium
5	100,604789	-0,712063	4,38	
6	100,602779	-0,713477	3,97	
8	100,610458	-0,725738	4,03	
7	100,608909	-0,720328	6,92	High

Table 6 is the result of data analysis of the amplification factor value, then obtained varying values in microtremor measurements in the study area which can be seen in Figure 4.

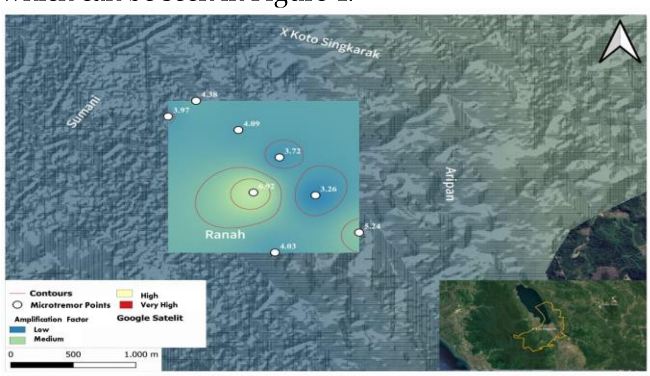


Fig 4. Amplification Factor (A_0) Mapping Results in Jorong Ranah, X Koto Singkarak District

The amplification factor is inversely proportional to the shear wave velocity (Vs). Shear wave velocity (Vs) is affected by the density (ρ) of the study area. The decreasing density (ρ) of an area causes the waves passing through it to have a small speed so that it has a large amplification factor. In Table 6, the value of the medium amplification factor is in the range of values 3, 26 - 5.24. The low amplification factor indicates that there are more compact rocks or less contrasting impedance changes, while the high amplification indicates that there are softer rocks with contrasting impedance changes.

When viewed from the geological formation, the research area with a moderate amplification factor value is in the young Merapi formation which is mostly volcanic lava deposits and volcanic breccia. Point 7 has the highest amplification value compared to other points in the study area. This is because there is an alluvial formation consisting of sandstone and claystone, in the condition of soft soil types or soil conditions with low rock density has a small inertia, so the soil is easily moved and experiences a large shock during an earthquake.

Furthermore, the dominant frequency (f_0) and amplification factor (A_0) are calculated so that the value of the soil susceptibility index (Kg) is obtained using Equation (4). The following results of the calculation of seismic susceptibility index data at each measurement point can be seen in Table 7.

Table 7. Data Analysis Results Seismic Vulnerability Index Value (Kg)

Point	Longitude	Latitude	Kg	Category
1	100,616509	-0,723943	1,861532203	
2	100,613370	-0,720582	0,720515254	
4	100,607833	-0,714698	1,423668085	
6	100,602779	-0,713477	1,068535593	Low
8	100,610458	-0,725738	1,101077966	
5	100,604789	-0,712063	3,619698113	Medium
3	100,610785	-0,717165	11,07072	High
7	100,608909	-0,720328	7,723612903	

Table 7 is the result of data processing from the seismic vulnerability index value, then obtained varying values in microtremor measurements in the research area which can be seen in Figure 5.

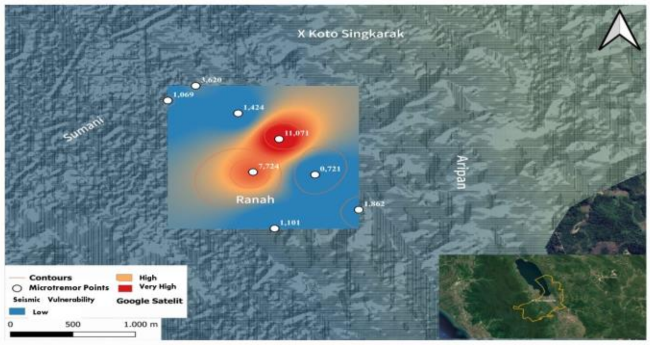


Fig 5. Seismic Vulnerability Index (Kg) Mapping Results in Jorong Ranah, X Koto Singkara District

The seismic vulnerability index parameter (Kg) can reflect local effects and can be used as an indicator in determining earthquake prone points. In Table 7, low seismic susceptibility index values are obtained at point 1, point 2, point 4, point 6 and point 8. Medium seismic susceptibility index values at point 5, and high seismic susceptibility index values at point 3 and point 7. High seismic susceptibility index levels are usually found in areas with low natural frequencies (f_0). This means that relatively thick sedimentary layers covering the bedrock have a high seismic susceptibility index. In thick sedimentary layers, if accompanied by high seismic shear wave amplification (amplification factor), it will result in a high seismic susceptibility index as well. A low seismic susceptibility index has a more stable soil layer and therefore less potential for earthquake impacts. A moderate seismic vulnerability index has a diverse soil layer, some of which have a moderate potential for earthquake impacts, so the potential impact of an earthquake is also moderate. A high seismic vulnerability index has a soft soil layer that is easily affected by earthquake vibrations, so the potential for earthquake impacts is quite large.

The presence of Vs values in each soil layer will facilitate the reading of subsurface lithology and classification of rock types. Basically, the Vs value is related to the stiffness level of a layer. The greater the Vs value, the higher the stiffness of the layer. The research points carried out are only in one zone, namely the Qtau formation (undecomposed flow). Identification of the distribution of subsurface lithology is carried out by modeling the shear wave velocity value interpreted with the constituent lithology in the geological formation of the study area. The following is a cross section view of the subsurface lithology in Jorong Ranah, District X Koto Singkarak. Figure 6 provides a visual representation of the cross section between points in the study area.

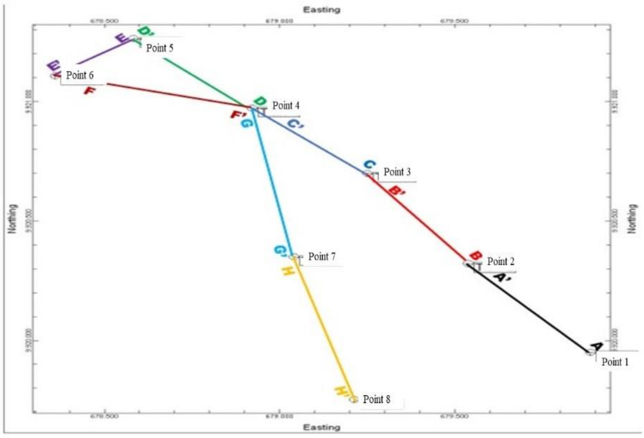
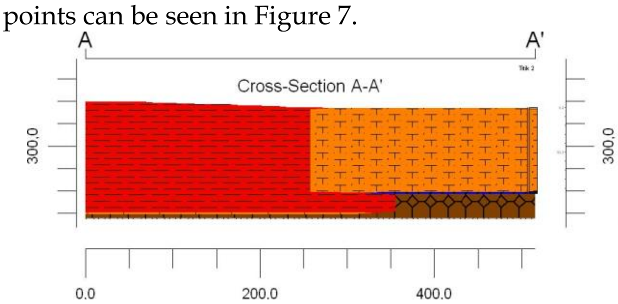
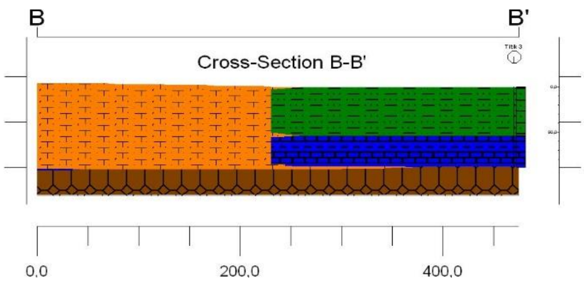


Fig 6. Cross Section of the Research Area

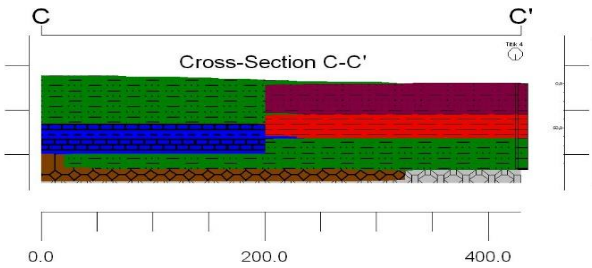
Figure 6 shows the cross section at points in the study area. Where in Figure 6 it can be seen that the relationship between point 1 to point 2 is expressed in cross section A - A', the relationship between point 2 to point 3 is expressed in cross section B - B', the relationship between point 3 to point 4 is expressed in cross section C - C', the relationship between point 4 to point 5 is expressed in cross section D - D', the relationship between point 5 to point 6 is expressed in cross section E - E', the relationship between point 6 to point 4 is expressed in cross section F - F', the relationship between point 4 to point 7 is expressed in cross section G - G', and the relationship between point 7 to point 8 is expressed in cross section H - H'. To provide a clearer picture of the cross section at these points can be seen in Figure 7.



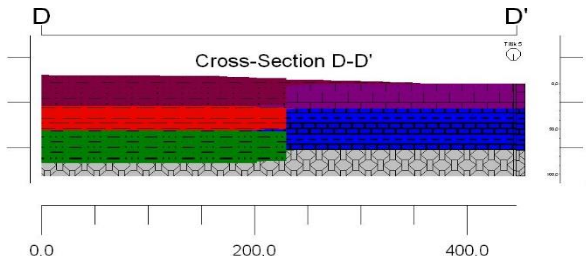
(a)



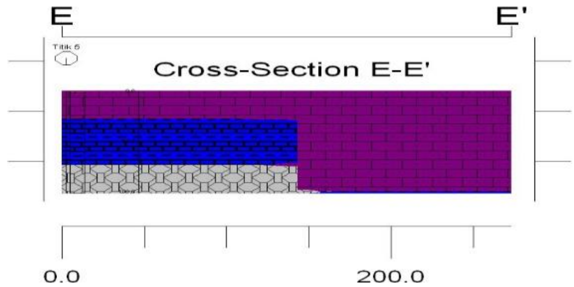
(b)



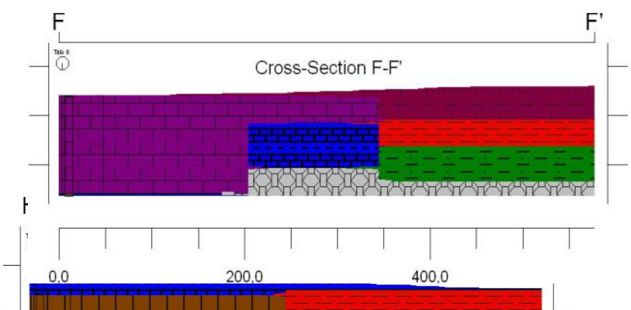
(c)



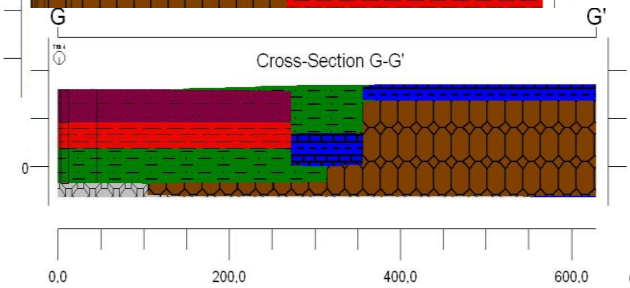
(d)



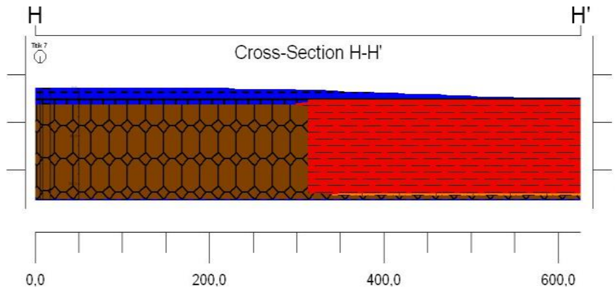
(e)



(f)



(g)



(h)

Fig 7. Cross Section (a) Point 1 - 2, (b) Point 2-3, (c) Point 3-4, (d) Point 4-5, (e) Point 5-6, (f) Point 6-4, (g) Point 4- 7, (h) Point 7-8

Figure 7 shows the cross section from the first point to the second point. In Figure 7 (a) is a cross section from point 1 to point 2. The rock layers identified include red soil, tuff and volcanic breccia. The dominating constituent rocks are red soil and tuff. In Figure 7 (b) is a cross section from point 2 to point 3. The identified rock layers include tuff, silt, tuff breccia and volcanic breccia. The dominating constituent rocks are tuff and silt. Figure 7 (c) is a cross section from point 3 to point 4. The identified rock layers include silt, tuff breccia, gravelly sandstone, red soil, volcanic breccia and fanglomerate. The dominating constituent rock is silt. Figure 7 (d) is a cross section from point 4 to point 5. The rock layers identified include silt, tuff breccia, gravelly sandstone, red soil, sandy hard claystone and fanglomerate. The dominating constituent rock is tuff breccia. Figure 7 (e) is a cross section from point 5 to point 6. The rock layers identified include sandy hard clay, tuff breccia and fanglomerate. The dominating constituent rock is sandy hard clay. Figure 7 (f) is a cross section from point 6 to point 4. The rock layers identified include silt, tuff breccia, sandy hard clay, pebbly sandstone, red soil and fanglomerate. The dominating constituent rock is sandy hard clay. Figure 7 (g) is a cross section from point 4 to point 7. The rock layers identified include gravelly sandstone, silt, tuff breccia, red soil, volcanic breccia and fanglomerate. The dominating constituent rock is volcanic breccia. Figure 7 (h) is a cross section from point 7 to point 8. The rock layers identified include tuff breccia, red soil and volcanic breccia. The dominating constituent rocks are volcanic breccia and red soil. Areas with high values of shear wave velocity (Vs) indicate that hard and dense rocks are present and that the rocks are more stable and less susceptible to deformation, resulting in lower potential damage. On the other hand, areas with low values of shear wave velocity (Vs) indicate that there are soft rocks and rocks are easily deformed so that the potential for damage is higher.

Cross sections of subsurface lithology are very important visual representations especially in the field of geophysics. Cross sections make it possible to identify the different types of soil and rock present in the subsurface. Cross sections can also identify the sequence of soil or rock layers and the geological structure of an area. So that by knowing the constituent layers of soil or rock, the potential for damage due to earthquakes can be minimized as a form of disaster mitigation in the future.

Conclusion

Based on the results obtained, it is concluded that the dominant frequency value (f_0) in Jorong Ranah, X Koto Singkarak District ranges from 1.25 - 14.75 Hz and the amplification factor value (A_0) ranges from 3.26 - 6.92. The value of shear wave velocity (Vs) based on microtremor data at the measurement point in Jorong Ranah, X Koto Singkarak District can be seen from the formation. The distribution of shear wave velocity (Vs) values has a range of values of 100 m/s - 1,604 m/s. Jorong Ranah, X Koto Singkarak Subdistrict has a lithology that composes the subsurface structure dominated by tuff breccia. The condition of subsurface lithology has a significant influence on the potential level of damage. Areas with high values of shear wave velocity (Vs) indicate the presence of hard and dense rocks and rocks are more stable and less susceptible to deformation so that the potential for damage is lower. Conversely, areas with low values of shear wave velocity (Vs) indicate that soft rocks are present and rocks are easily deformed, resulting in higher damage potential

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