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Analysis of Liquefaction Potential in Sungai Limau District Padang Pariaman Regency Using the Multichannel Analysis of Surface Wave (MASW) Method

Angeline Chika Rorensia [1], Syafriani [1*], Hamdi [1], Akmam [1], Letmi Dwiridal [1]

[1] *Department of Physics, Universitas Negeri Padang, Jl. Prof. Dr. Hamka Air Tawar Padang 25131, Indonesia*
Corresponding author. E-mail: syafri@fmipa.unp.ac.id

ABSTRACT

Sungai Limau is one of the sub-districts in Padang Pariaman Regency which was badly damaged by the earthquake on 30 September 2009. Geologically, the Sungai Limau area is included in the category of cambisol soil types in the form of layers of sand, making it vulnerable to liquefaction due to earthquakes. This research was conducted to analyze the liquefaction potential using the Multichannel Analysis of Surface Wave (MASW) method. The MASW method can produce 2D Vs profiles to describe the structure and types of rock-forming materials at each depth and layer. This method can detect underground surfaces Vs to a depth of 30 meters. Data collection was conducted at Sungai Limau using the sysmatrack-MAE tool with 4 observation tracks. Each measurement uses a distance between geophones of 4 meters. The Vs results from MASW will be compared with the classification of soil types from UBC 1997. The average results of the shear wave velocity at a depth of 30 m (Vs30) in this study are 322.9 m/s for the first track, 303 m/s for the second track, 311 m /s for the third and fourth track. The four tracks fall into the same classification, namely medium soil type (class D). The results of the liquefaction potential analysis using the MASW method show that the first line has a high level of liquefaction potential in the third layer with a value of Vs 337 m/s (class D). The second track has a high level of liquefaction potential in the third layer with a value of Vs 314 m/s (class D). The third track has a fairly high level of liquefaction potential in the second layer with a value of Vs 209 m/s (class D). The fourth track has a high level of liquefaction potential in the second layer with a value of Vs 198 m/s (class D). The fourth and fifth layers on the entire track have no liquefaction potential with Vs ranging from 400-550 m/s (Class C).

Keywords : Earthquake, Liquefaction, MASW

I. INTRODUCTION

West Sumatera is an area with a high level of earthquake occurrence. This is because West Sumatera is at the confluence of the Indo-Australian plate which subducts under the Eurasian plate, causing oblique subduction, and giving rise to the Sumateran Fault and the Mentawai Fault. West Sumatera has seven active fault segments which are part of the Sumateran fault system, namely the Siulak segment, Sumpur segment, Sianok segment, Sumani segment, Barumun segment, Angkola segment, and Tutup segment [1]. In February 2022 the Meteorology, Climatology and Geophysics Agency (BMKG) discovered a new fault in West Sumatera, namely the Talamau segment which was discovered after the West Pasaman earthquake on February 28, 2022.

The spread of these fault segments has caused West Sumatera to have experienced several occurrences of damaging natural disasters due to earthquakes. One of the devastating earthquakes in West Sumatera was the 30 September 2009 earthquake with a magnitude of 7.6 with an epicenter 57 km southwest of Pariaman City at a depth of 71 km. Sungai Limau Subdistrict is one of the subdistricts in Padang Pariaman Regency which was badly damaged by the earthquake [2]. The high level of damage is because the Sungai Limau is geologically included in

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the category of cambisol soil types in the form of layers of sand [3]. Therefore, this area is vulnerable to geological disasters due to earthquakes, one of which is liquefaction.

Liquefaction is an event of liquefaction of saturated granular soil due to earthquake loads or other dynamic loads caused by an increase in the effective pressure of soil pore water. Liquefaction usually occurs in granular soils such as loose sandy soils and can cause significant settlement [4]. The liquefaction potential in granular soils due to earthquakes is influenced by seismic factors, namely the magnitude of the earthquake, the seismic acceleration of the ground surface, and the distance of the epicenter [5]. In the process of liquefaction, the cyclic load transfers the stress in the pores to become the effective stress of the soil. In this way, the pore pressure increases for a short time, while the effective stress between the soil particles is constant [6].

Measurement of liquefaction potential requires shear wave velocity (Vs) to determine a mapping of subsurface conditions against earthquake shock strength, soil amplification, liquefaction, and engineering needs [7]. This can be studied using the *Multichannel Analysis of Surface Wave* (MASW) method which can produce 2D Vs profiles.

The calculation of the factor of safety against liquefaction was conducted using the method developed by Andrus and Stokoe [8]. FS is a comparison of the ratio of cyclic stress or Cyclic Stress Ratio (CSR) to the ratio of cyclic resistance or Cyclic Resistance Ratio (CRR) [9]. The calculation of CSR using the Seed and Idriss formulation is as follows.

$$\mathrm{CSR} = \frac{\tau_{\mathrm{av}}}{\sigma'_{\mathrm{vo}}} = 0.65\left(\frac{a_{\max}}{g}\right).\left(\frac{\sigma_{\mathrm{v}}}{\sigma'_{\mathrm{v}}}\right).r_d \qquad (1)$$

where $a_{\max}$ is the peak ground acceleration, σv is the total vertical stress (Mg/m^2), σ 'v is the effective (Mg/m^2), and rd is the reduction factor.

The Cyclic Resistance Ratio value that applies to earthquakes with a magnitude of 7.5 ($CRR_{7.5}$) based on shear wave velocity data (Vs) is calculated using the Andrus and Stokoe formula as follows:

$$CRR = \left\{a\left(\frac{Vsk}{100}\right)^2 + b\left(\frac{1}{V^*sk - Vsk} - \frac{1}{V^*sk}\right)\right\}\left(\frac{Mw}{7.5}\right)^{-2.56} \qquad (2)$$

where Vsk is the corrected shear wave velocity, a,b are adjustment curves, Mw is the magnitude of the earthquake, and V*sk is the upper limit value of the corrected shear wave velocity for liquefaction events.

Calculation results from CSR and CRR are used as a ratio in determining the factor of safety (FS) which is a factor for determining liquefaction potential. The factor of safety against liquefaction can be defined as:

$$FS = \left(\frac{CRR}{CSR}\right) \qquad (3)$$

Determination of liquefaction potential can be seen in the FS value, if FS < 1.0 then liquefaction will occur, and if FS > 1.0 then liquefaction will not occur [8].

II. METHODS

The MASW method is based on the theory of Rayleigh wave propagation in which waves are generated by the interaction of shear waves with the surface soil layers. The MASW method used in this study is the Active MASW method, where the wave source used must be of high frequency, namely hammer or weight drop. Rayleigh waves are generated from a vertical mechanical source with a large hammer (sledgehammer) weighing 12 lb or the equivalent of 5.4 kg which is used to generate the waves. Nonetheless, variations in the weight of the hammer are required to perform the spectral characteristics of the soil at the desired target depth [10].

The configuration used in this study is a cross configuration with a distance between geophones of 4 meters. 12 geophone sensors must be placed (plugged in) above the ground in an imaginary straight line. The beating was conducted with three different source positions (Figure 1).

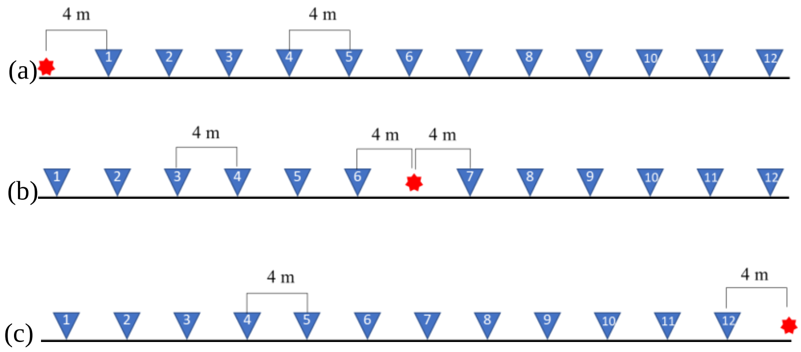


Fig 1. *Wave Source Layout (a) Beginning of Geophone (b) Middle of Geophone (c) End of Geophone*

Based on Figure 1, beatings are conducted at (a) the beginning, (b) the middle, and (c) the end of the track. Wave generation and recording are done repeatedly to obtain an average signal in the frequency domain. The average signal obtained through repeated measurements can eliminate the effect of random noise and unclear signals on the data recording process [11].

Analysis of shear wave velocity on the soil profile can be processed using SeisImager software version 4.2.0.0. There are 3 stages of data processing to obtain the Vs profile, namely dispersion curve extraction, dispersion curve picking, and inversion. In the extraction process, a wave in the time domain form is converted into a curve spectrum between the phase velocity and frequency. The extraction process produces a dispersion curve that will be picked. Picking the spectrum of the dispersion curve is the process of picking the blue or color fundamental mode point that shows a high amplitude correlation. The inversion results will form several layers that are adjusted to the results of the picking or synthetic model that is entered.

III. RESULTS AND DISCUSSION

Analysis of liquefaction potential requires data on shear wave velocity and groundwater depth data. The Vs data processing process is processed through the SeisImager application and groundwater depth data obtained through research by Monica et al. with a depth of 5.45 m [12].

The wave extraction process is conducted by utilizing the fast fourier transform (FFT) process, to obtain dispersion curve results from the time domain to the frequency domain at each point of the path [13]. The blue color shows the amplitude value, the thicker the blue color, the greater the amplitude value. Picking the dispersion curve is done when there is the dispersion or a large deflection of the amplitude value to determine the value of Vs (Figure 2).

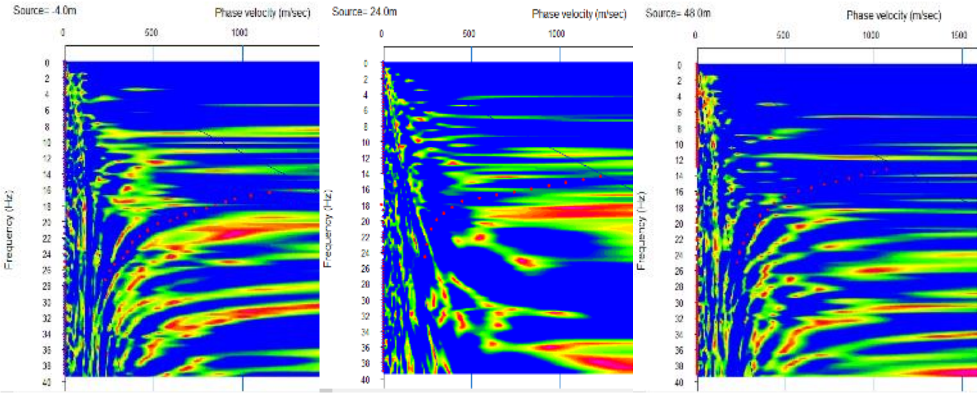
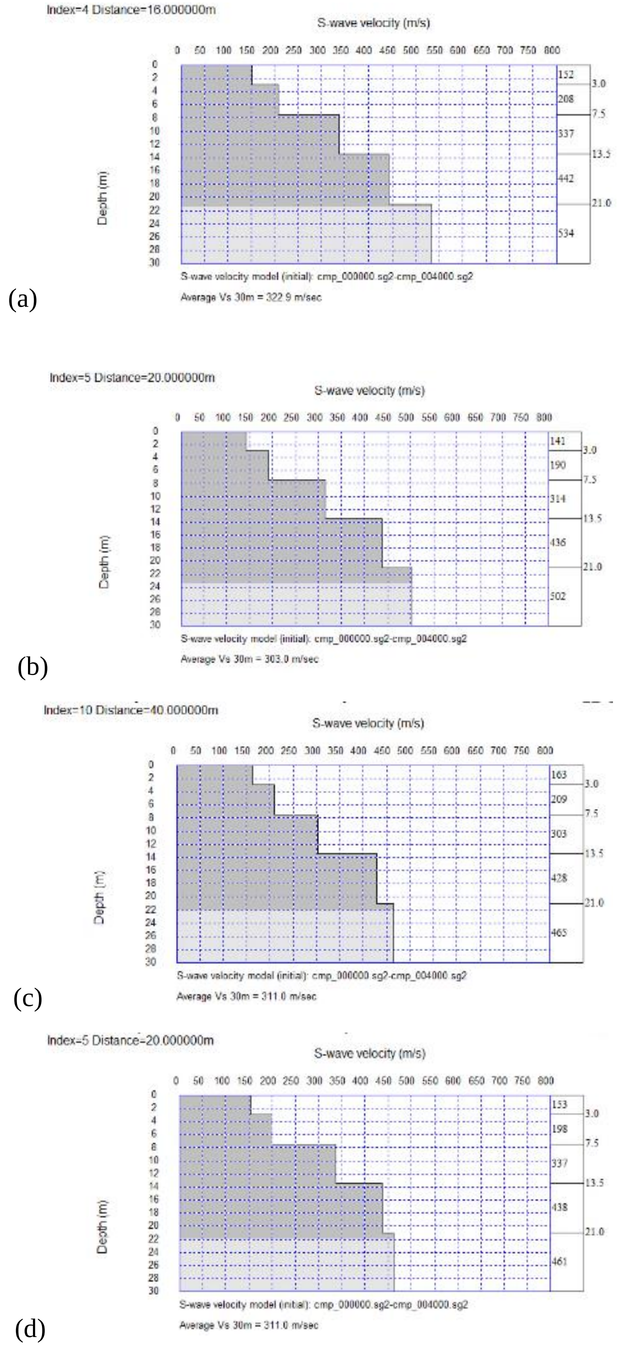


***Fig 2**. Picking Spectrum Dispersion Curves*

Based on Figure 2, surface waves are at a frequency of 5-40 Hz so picking is done at that interval. The red dot is the fundamental mode picking point which is the dispersed part of the curve. The blue line is the boundary of the picking zone which is adjusted to the spacing and stretch used. The longer the stretch and density of a geophone, the wider the graph will be, conversely the shorter the stretch and the larger the spacing of a geophone, the narrower the graph will be.

The inversion results will form several layers that are adjusted to the results of the picking or synthetic model that is entered. In the inversion process, the depth is set to 30 meters which aims to determine the value of Vs30. The Vs30 value can provide information about areas that tend to experience greater wave amplification than other areas [14]. Layers are defined as 6 layers based on the UBC classification table [15]. The inversion process produces a Vs curve model which displays different shear wave velocity values at each depth. The combination of these Vs curve models produces a 1D Vs profile (Figure 3).



(a)

(b)

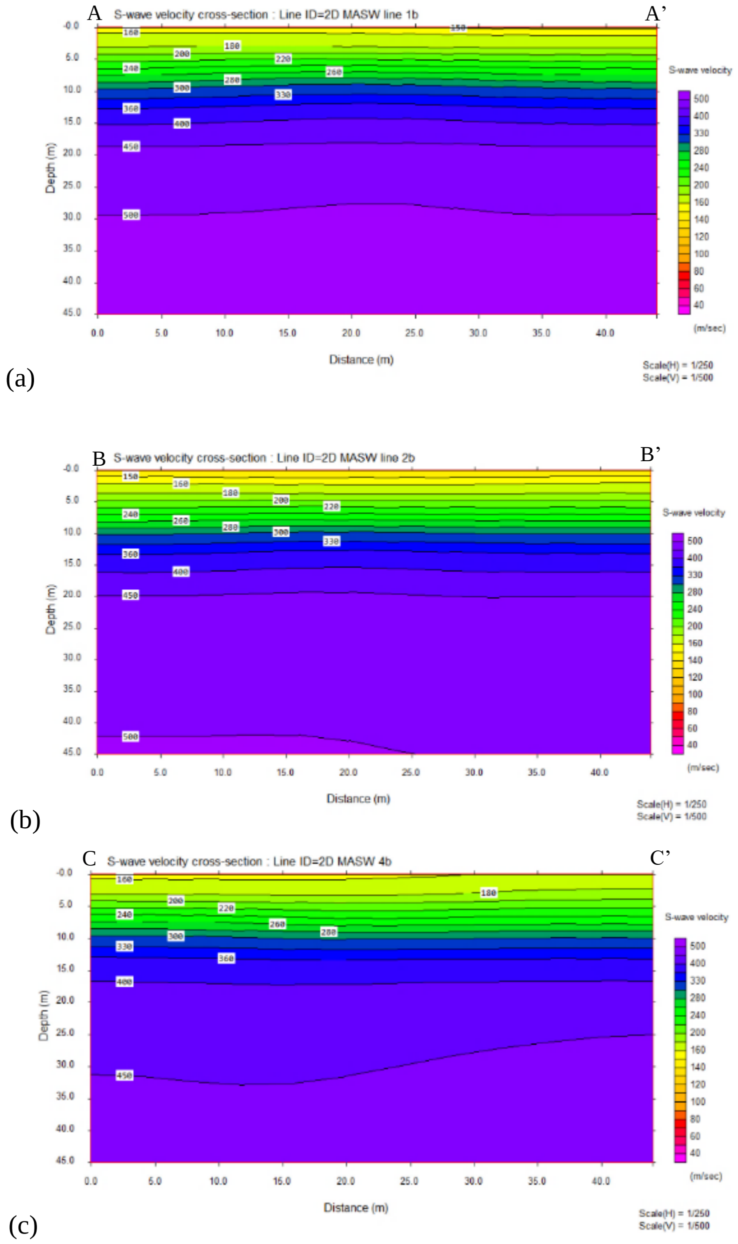
(c)

(d)

Fig 3. *Profile 1D Vs (a) First Track (b) Second Track (c) Third Track (d) Fourth Track*

Based on Figure 3, the 1D Vs profile shows the shear wave velocity information at each depth. On the first track (Figure 3a), the Vs value obtained was 152 m/s at a depth of 0-3.0 meters, a depth of 3.0-7.5 meters obtained a Vs value ranging from 208 m/s, a depth of 7.5-13.5 meters obtained a Vs value of 337 m /s, a depth of 13.5-21.0 meters obtained a Vs value of 442 m/s, and a depth of 21.0-30.0 meters obtained a Vs value of 534 m/s. The average value of Vs30 obtained on the first track is 322.9 m/s. Then on the second track (Figure 3b), a Vs value of 141 m/s was obtained at a depth of 0-3.0 meters, a depth of 3.0-7.5 meters obtained a Vs value of 190 m/s, a depth of 7.5-13.5 meters obtained a Vs value of 314 m/s s, a depth of 13.5-21.0 meters obtained a Vs value of 436 m/s, a depth of 21.0-30.0 meters obtained a Vs value of 502 m/s. The average value of Vs30 obtained on the second track is 303 m/s. Furthermore, on the third track (Figure 29c) the Vs values obtained ranged from 163 m/s at a depth of 0-3.0 meters, a depth of 3.0-7.5 meters obtained a Vs value ranging from 209 m/s, a depth of 7.5-13.5 meters obtained a Vs value of 303 m/s, a depth of 13.5-21.0 meters obtained a Vs value of 428 m/s, and a depth of 21.0-30.0 meters obtained a Vs value of 465 m/s. The average value of Vs30 obtained on the third track is 311 m/s. Finally, on the fourth track (Figure 29d) a Vs value of 153 m/s was obtained at a depth of 0-3.0 meters, a depth of 3.0-7.5 meters obtained a Vs value of 198 m/s, a depth of 7.5-13.5 meters obtained a Vs value of 337 m/s s, a depth of 13.5-21.0 meters obtained a Vs value of 438 m/s, a depth of 21.0-30.0 meters obtained a Vs value of 461 m/s. The average Vs30 value obtained on the fourth track is 311 m/s.

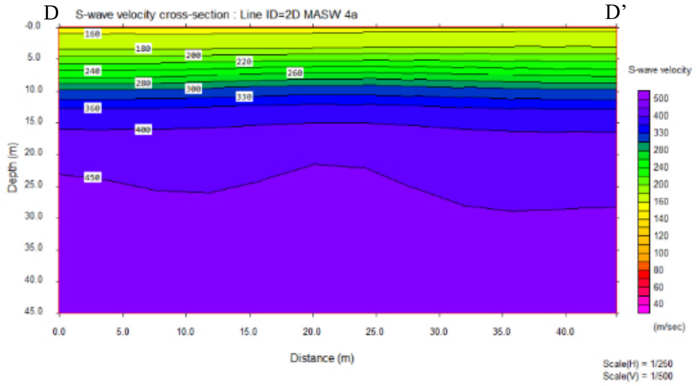
The process is continued with tomographic analysis which can produce 2D Vs profiles, by combining and interpolating pixels between 1D Vs profiles. The 2D Vs profile shows different colors at each depth, which are classified based on the shear wave velocity (Figure 4).



(a)

(b)

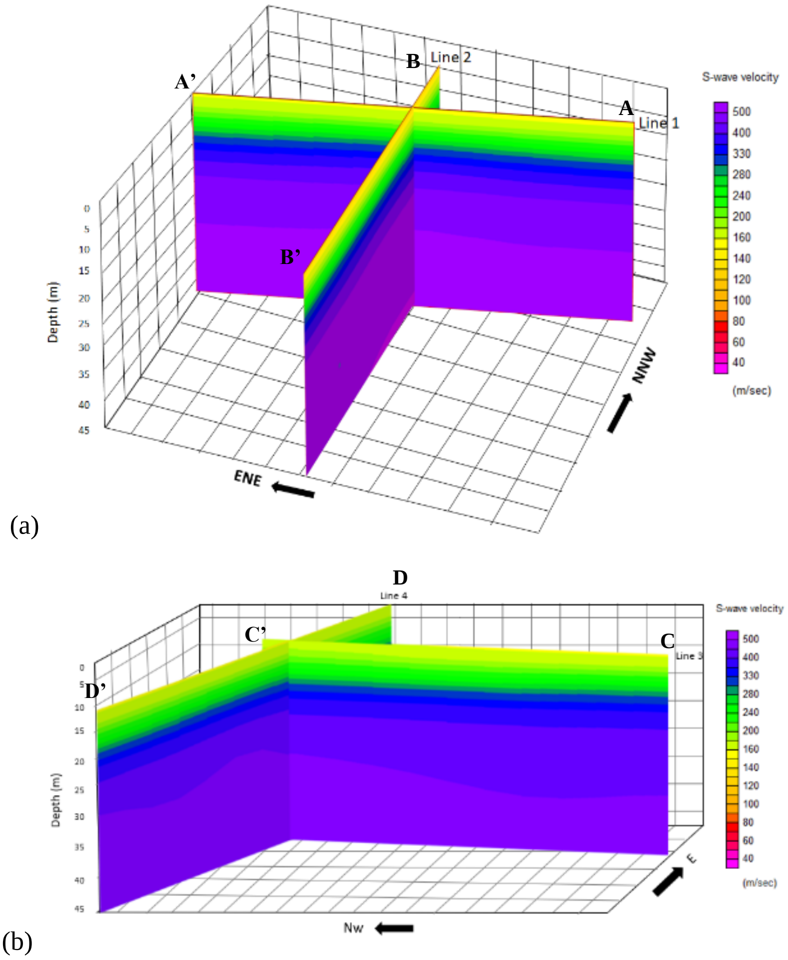
(c)



(d)

Fig 4. 2D profile _ Vs (s) First Pass (b) Second Pass

Based on Figure 4, the 2D Vs profile obtained shows the condition of the subsurface layers more clearly and accurately. The results of the 3D Vs profile were also obtained through tomographic analysis of the 2D Vs profile. The point of intersection in the formation of the 3D Vs profile is set at the coordinates lat -0.556635, long 100.089563. The 3D Vs profile can be seen in Figure 5.



(a)

(b)

***Fig 5.** Final 3D profile results Vs (a) First Location (b) Second Location*

Based on Figure 5. The results of the 3D Vs profile show that the research conducted is correct because the profiles of tracks 1 and 2 and tracks 3 and 4 are connected at their intersection points. Based on data processing, 3 classifications of soil types were obtained which were categorized based on site classification by UBC [15], namely soft soil, medium soil, and very dense soil with soft rock. Liquefaction events usually occur in alluvium soils with a Vs value of fewer than 360 m/s and shallow groundwater depths [4].

On the first track, the average value of Vs30 is 332.9 m/s (class D). Where the first layer at a depth of 0-3.0 meters is included in the category of soft soil (class E) with a value of 152 m/s Vs. The type of material in this layer is soft clay with a low level of liquefaction potential. The second layer at a depth of 3.0-7.5 meters with a value of Vs 208 m/s is included in the moderate soil category (class D). This layer is above the MAT, so the level of liquefaction potential in this layer is moderate with the type of material in the form of soft clay, sand deposits, and alluvium. The third layer at a depth of 7.5-13.5 meters with a Vs value of 337 m/s is included in the moderate soil category (class D) with the types of materials in the form of soft clay, sand deposits, and alluvium. The groundwater table is in this layer, so the liquefaction potential is high. The fourth layer at a depth of 13.5-21.0 meters with a value of Vs 442 m/s belongs to the category of very dense soil with soft rocks (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium. The fifth layer at a depth of 21.0-30.0 meters with a value of Vs 534 m/s belongs to the category of very dense soil with soft rocks (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium.

On the second track, an average Vs30 value of 303 m/s (class D) is obtained. Where the first layer at a depth of 0-3.0 meters is included in the category of soft soil (class E) with a value of 141 m/s Vs. The type of material in this layer is soft clay with a low level of liquefaction potential. The second layer at a depth of 3.0-7.5 meters with a Vs value of 190 m/s is included in the moderate soil category (class D). This layer is above the MAT, so the level of liquefaction potential in this layer is moderate with the type of material in the form of soft clay, sand deposits, and alluvium. The third layer at a depth of 7.5-13.5 meters with a Vs value of 314 m/s is included in the moderate soil category (class D) with material types in the form of soft clay, sand deposits, and alluvium. The groundwater table is in this layer, so the liquefaction potential is high. The fourth layer at a depth of 13.5-21.0 meters with a value of Vs 436 m/s belongs to the category of very dense soil with soft rock (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium. The fifth layer at a depth of 21.0-30.0 meters with a value of Vs 502 m/s belongs to the category of very dense soil with soft rock (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium.

On the third track, the average value of Vs30 is 311 m/s (class D). Where the first layer at a depth of 0-3.0 meters is included in the category of soft soil (class E) with a value of 163 m/s Vs. The type of material in this layer is soft clay. The level of liquefaction potential in this layer is moderate because it is above the MAT. The second layer at a depth of 3.0-7.5 meters with a Vs value of 209 m/s is included in the moderate soil category (class D) with the types of materials in the form of soft clay, sand deposits, and alluvium. The groundwater table is in this layer, so the liquefaction potential is quite high. The third layer at a depth of 7.5-13.5 meters with a value of Vs 303 m/s is included in the moderate soil category (class D). The level of liquefaction potential in this layer is low because the soil type is starting to become denser with material types in the form of soft clay, sand deposits, and alluvium. The fourth layer at a depth of 13.5-21.0 meters with a value of Vs 428 m/s belongs to the category of very dense soil with soft rock (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium. The fifth layer at a depth of 21.0-30.0 meters with a value of Vs 465 m/s belongs to the category of very dense soil with soft rock (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium.

On the fourth track, an average Vs30 value of 311 m/s (class D) is obtained. Where the first layer at a depth of 0-3.0 meters is included in the category of soft soil (class E) with a value of 153 m/s Vs. The type of material in this layer is soft clay. The level of liquefaction potential in this layer is moderate because it is above the MAT. The second layer at a depth of 3.0-7.5 meters with a Vs value of 198 m/s is included in the moderate soil category (class D) with material types in the form of soft clay, sand deposits, and alluvium. The groundwater table is in this layer, so the liquefaction potential is quite high. The third layer at a depth of 7.5-13.5 meters with a value of Vs 337 m/s is included in the moderate soil category (class D). The level of liquefaction potential in this layer is low because the soil type is starting to become denser with material types in the form of soft clay, sand deposits, and alluvium. The fourth layer at a depth of 13.5-21.0 meters with a value of Vs 438 m/s belongs to the category of very dense soil with soft rock (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium. The fifth layer at a depth of 21.0-30.0 meters with a value of Vs 461 m/s belongs to the category of very dense soil with soft rock (class C). This layer has no liquefaction potential because the Vs value is more than 360 m/s with the type of material in the form of deposits of sand, gravel, clay, and alluvium.

As a reinforcement of the results of this study, calculations were conducted to determine the factor of regional safety using the method developed by Andrus and Stokoe [8]. This calculation requires a comparison of the CRR ratio and the CSR ratio. The value of the Cyclic Resistance Ratio (CRR) is the resistance of the soil to liquefaction, while the value of the Cyclic Stress Ratio (CSR) is the ratio between the average shear stress caused by an earthquake and the effective vertical stress in each layer. The calculation results at the first location obtained a CRR value of 0.063 and a CSR value of 0.209. A comparison of CRR and CSR produces a safety factor of 0.3. The calculation results at the second location obtained a CRR value of 0.194 and a CSR value of 0.202, so the safety factor value was 0.96. A safety factor value that is less than 1 has the liquefaction potential [8].

Research on liquefaction potential using the MASW method shows that the Sungai Limau District, Padang Pariaman Regency has different liquefaction potentials in each layer. The high liquefaction potential on the first and second lines is in the third layer (7.5-13.5 m) with Vs values of 337 m/s and 314 m/s (class D). This study was strengthened using the Andrus and Stokoe development methods with an observation point at a depth of 13.5 m obtained a safety factor value of 0.3. The factor that affects the high level of liquefaction in this layer is the small distance between the observation points and the depth of the MAT. The third and fourth tracks which have quite high liquefaction potential are in the second layer (3.0-7.5 m) with Vs values of 209 m/s and 198 m/s (class D). The observation point is determined at a depth of 7.5 m with a safety factor value of 0.96. The factor that affects the high rate of liquefaction in this layer is the small value of Vs. The value of the factor of safety is close to one because the distance of the observation points and the depth of the MAT are quite far.

IV. CONCLUSION

Based on research on liquefaction potential using the MASW method, it can be concluded that the first line has a high level of liquefaction potential in the third layer with a Vs value of 337 m/s (class D). The second track has a high level of liquefaction potential in the third layer with a value of Vs 314 m/s (class D). The third track has a fairly high level of liquefaction potential in the second layer with a value of Vs 209 m/s (class D). The fourth track has a high level of liquefaction potential in the second layer with a value of Vs 198 m/s (class D). The fourth and fifth layers on the entire track have no liquefaction potential with Vs ranging from 400-550 m/s (Class C).

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