BERKALA FISIKA INDONESIA
Jurnal Ilmiah Fisika, Pembelajaran dan Aplikasinya
http://journal.uad.ac.id/index.php/BFI/index
2085-0409 (Print) │2550-0465 (online)

Analysis of subsurface structure in ulakan tapakis district Padang Pariaman regency using refraction seismic method

Syafriani*, Nadilla Adzura

Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Negeri Padang, Indonesia
Email: syafri@fmipa.unp.ac.id
* Corresponding author

Informasi artikel

Sejarah artikel:

Dikirim	26/10/23
Revisi	15/12/23
Diterima	16/01/24

Kata kunci:
Gempa Bumi
Struktur Bawah Permukaan
Seismik Refraksi

ABSTRAK

Penelitian ini bertujuan untuk menganalisis struktur bawah permukaan di Kecamatan Ulakan Tapakis Kabupaten Padang Pariaman menggunakan metode seismik refraksi. Akuisisi data dilakukan menggunakan teknik konfigurasi peralatan *in-line* pada delapan lintasan. Data yang diperoleh berupa waktu rambat gelombang sebagai fungsi jarak. Pengolahan data pada metode seismik refraksi didasarkan pada waktu tiba gelombang pertama, melalui *picking first break* untuk mendapatkan grafik *travel time* dan menggunakan *time-term inversion* untuk mendapatkan penampang seismik 2-D. Hasil penelitian menunjukkan struktur bawah permukaan di daerah penelitian terdiri dari 2 lapisan berdasarkan perbedaan kecepatan rambat gelombang pada lapisan tiap-tiap lintasannya. Kecepatan gelombang pada lapisan pertama 252 m/s hingga 425 m/s diinterpretasikan sebagai lapisan batuan dasar lapuk, *top soil*, campuran pasir dan kerikil tak jenuh pada kedalaman 1 hingga 6 meter. Lapisan kedua memiliki kecepatan gelombang 503 m/s hingga 665 m/s diinterpretasikan sebagai lapisan aluvium, pasir dan kerikil jenuh pada kedalaman lebih dari 6 meter. Struktur bawah permukaan di daerah ini termasuk dalam struktur primer dengan satuan formasi batuan berupa endapan permukaan Aluvium (Qal) yang diduga mengalami pelapukan pada bawah permukaannya. Penelitian ini memberikan kontribusi signifikan dalam mitigasi risiko bencana gempa bumi dengan memberikan pemahaman tentang potensi bahaya terkait.

Keywords:
Earthquake
Subsurface Structure
Refraction Seismic

ABSTRACT

Analysis of Subsurface Structure in Ulakan Tapakis District, Padang Pariaman Regency Using Refraction Seismic Method. This study aims to analyse the subsurface structure in Ulakan Tapakis District, Padang Pariaman Regency using the seismic refraction method. Data acquisition used the in-line configuration technique on eight passes. The data obtained form of wave traveltime as a function of distance. Data processing the refraction seismic method is based on the arrival time of the first wave, by picking the first break to obtain a travel time graph and using time-term inversion to obtain a 2-D seismic cross section. The results showed that the subsurface structure in the study area consisted of 2 layers based on differences in wave propagation velocity on each path. Wave velocities in the first layer of 252 m/s to 425 m/s are interpreted as layers of weathered bedrock, topsoil, unsaturated sand and gravel mix at depths of 1 to 6 meters. The second layer has wave velocities of 503 m/s to 665 m/s interpreted as layers of alluvium, saturated sand and gravel at depths greater than 6 meters. The subsurface structure in this area is included in the primary structure with rock formation units in the form of surface Alluvium (Qal) deposits which are suspected of experiencing subsurface weathering. This research makes a significant contribution to mitigating the risk of earthquake disasters by providing an understanding of the potential associated hazards.

How to Cite:

Syafriani, & Adzura, N. (2024). Analysis of subsurface structure in ulakan tapakis district Padang Pariaman regency using refraction seismic method. *Berkala Fisika Indonesia: Jurnal Ilmiah Fisika, Pembelajaran Dan Aplikasinya*, *15*(1), 33–43. https://doi.org/10.12928/bfi-jifpa.v15i1.27448

Introduction

West Sumatra is one of the most seismically active provinces in Indonesia. This is because West Sumatra is located in three seismically active zones, namely the meeting point of two of the world's major tectonic plates, the Eurasian and Indo-Australian plates, which form a subduction zone (Douglas, 2007). The meeting of these two plates has a direction and type of subduction that is not uniform (Prawirodirdjo et al., 2000). This non-uniform subduction causes oblique subduction and gives rise to the Mentawai fault zone and the Sumatra fault zone. These three zones are the main sources that make the West Sumatra region very vulnerable to the threat of earthquakes (Sieh & Natawidjaja, 2000). One of the most devastating earthquakes occurred on 30 September 2009, which shook the west coast of Sumatra with a magnitude of 7.6, and the epicentre was located about 57 km southwest of Padang Pariaman at a depth of 71 km. This earthquake caused a lot of damage to buildings and infrastructure and resulted in casualties (Setyonegoro, 2013).

Ulakan Tapakis is one of the 17 (seventeen) subdistricts in Padang Pariaman district that were severely damaged by the earthquake. The high damage to buildings or infrastructure is due to Ulakan Tapakis, which is geologically located in an earthquake-prone area. In addition, the potential for damage to buildings and infrastructure due to the release of seismic energy is inextricably linked to the large number of buildings that have been constructed without considering the structure of the subsurface. One of the disaster mitigation efforts that can be made to minimize the impact of damage to buildings and infrastructure caused by this earthquake event is to study the subsurface layer's characteristics.

The structural characteristics of the subsurface layer can be seen from the different values of its physical parameters. The values of these physical parameters can be determined by making measurements above the ground. The method used in such measurements is the refraction seismic method (Enikanselu, 2008). The refraction seismic method is one of the active seismic geophysical methods that uses the refraction properties of seismic waves to determine the subsurface structure by clearly knowing information about the geological structure or material structure of the earth's subsurface layer (Adnyawati et al., 2012).

This method is based on the nature of wave propagation, which undergoes refraction with a critical angle, namely when the wave in its propagation passes through a boundary plane that separates one layer from the layer below, which has a more incredible wave speed (Jamal & Maria, 2019). The research of Nurdiyanto et al. (2011) revealed the basic assumptions about the speed of seismic waves traveling in each layer vary depending on the medium through which they travel in the boundary plane between layers of seismic waves traveling at the speed of waves in the layer below, the deeper a layer, the more compact the supporting material and the density of the rock layer will also be greater, the greater the speed of seismic wave propagation in the rock layer.

The parameter observed in this refraction seismic method is the characteristic arrival time of the wave at each receiver (Wahyuningsih et al., 2006). The main principle is to use the first arrival time of seismic waves in the calculation. The time required for seismic waves to propagate through rock layers depends on the speed of the medium through which they travel (Nurcandra & Koesuma, 2013). Data on the velocity of seismic wave propagation in each layer of rock and soil material are shown in Table 1.

Table 1. Primary wave velocity (Vp) in earth materials (Burger et al., 1992)

Material	Vp (m/s)
Granit	5000 – 6000
Basalt	5400 – 6400
Metamorphic rock	3500 – 7000
Sandstone and shale	2000 – 4500
Limestone	2000 – 6000
Weathered layered	300 – 900
Top Soil	250 – 600
Alluvium	500 – 2000
Clay	1000 – 2500
Sand (unsaturated)	200 – 1000
Sand (saturated)	800 – 2200
Sand and gravel unsaturated	400 – 500
Sand and gravel saturated	500 – 1500
Gracial till unsaturated	400 – 1000
Gracial till (saturated)	1500 – 2500
Air	331,5
Water	1400-1600

Based on Table 1, it can be seen that the speed of seismic wave propagation in each subsurface layer is different. This is influenced by several physical properties of the rock layer or medium through which the seismic waves travel (Sismanto, 1999). Firnanza (2017) revealed that factors affect the transmission of seismic waves in the subsurface layer, including lithology, density, porosity, depth, pressure, rock age, and temperature.

In general, there are three main types of seismic data interpretation methods: time delay method, wavefront reconstruction method, and intercept time method (Julius et al., 2020). Intercept time is one of the most basic, effective, and efficient interpretation methods in refraction seismic data analysis. *Intercept time* is a T-X method derived from the traveltime curve. The travel time curve is a curve that shows the relationship between the distance of each geophone from the seismic wave source and the arrival time of the first wave at each geophone). By analyzing the traveltime curve, information about the velocity of the seismic waves in each layer can be obtained, and the depth and type of rock and material in each layer can be determined (Telford et al., 1990).

Method

This research is a type of descriptive research that aims to obtain a description of the subsurface structure of the research area based on the form of seismic wave velocity propagation using the refraction seismic method with an estimate based on a 2D seismic cross-section model. This research uses primary data from direct measurements in the study area, as seen in Figure 1.

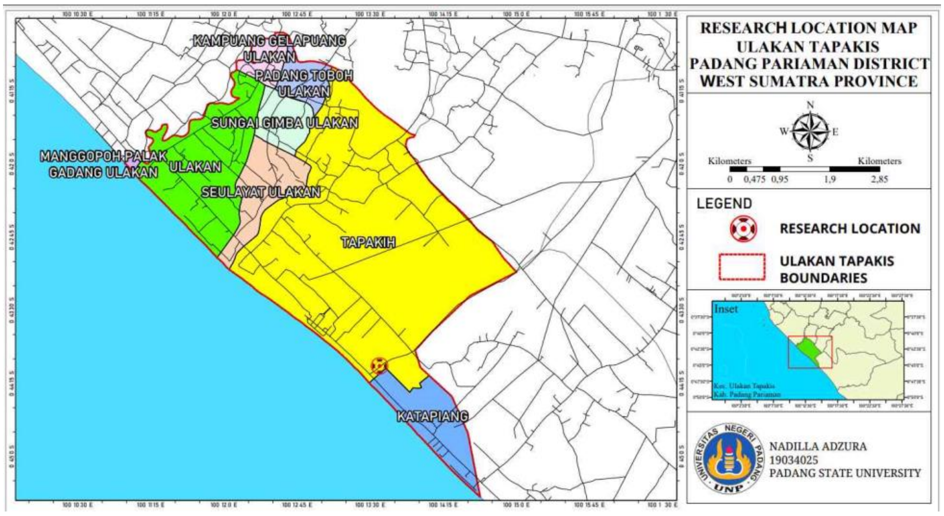


Figure 1. Map of the study area

The field data collection consists of eight tracks with the equipment used: the Sysmatrack-MAE seismograph, 12 geophones, trigger cables, geophone cables, laptops, meters, vibration sources in seismic hammers, and iron plates. The field technique used for data collection is an in-line configuration.

Point 0 meters on the first section is located at 0°44'4.24"S and 100°13'35.64"E to point 39 meters at coordinates 0°44'3.35"S and 100°13'34.75"E. The second section is located at point 0 meters at coordinates 0°44'3. 35"S and 100°13'34.75"E to point 39 meters at coordinates 0°44'2.38"S and 100°13'33.93"E. The third track section point 0 meters at coordinates 0°44'2.38"S and 100°13'33.93"E to point 39 meters. The third bearing 0 meter point is located at coordinates 0°44'2.38"S and 100°13'33.93"E to bearing 39 meters at coordinates 0°44'1.46"S and 100°13'33.06"E. The fourth bearing 0 meter point is located at coordinates 0°44'1.46"S and 100°13'33.06"E to bearing 39 meters at coordinates 0°44'00.54"S and 100°13'32.20"E. The fifth section of track point 0 meters is located at coordinates 0°44'0.57"S and 100°13'33.29"E to point 39 meters at coordinates 0°44'01.23"S and 100°13'32.21"E. The sixth section of track point 0 meters is located at coordinates 0°44'01.23"S and 100°13'32.21"E to point 39 meters at coordinates 0°44'01.92"S and 100°13'31.16"E. The seventh section of track point 0 meters is located at coordinates 0°44'01. 23"S and 100°13'32.21"E to point 39 meters at coordinates 0°44'01.92"S and 100°13'31.16"E. The seventh section of track point 0 meters is at coordinates 0°44'03. 17"S and 100°13'35.90"E to point 39 meters at coordinates 0°44'03.94"S and 100°13'34.85"E. The eighth stretch of track point 0 meters is located at coordinates 0°44'03.94"S and 100°13'34.85"E to point 39 meters at coordinates 0°44'04.69"S and 100°13'33.88"E. The length of each stretch of track is 39 meters with a geophone spacing of 3 meters. The data acquisition configuration is shown in Figure 2.

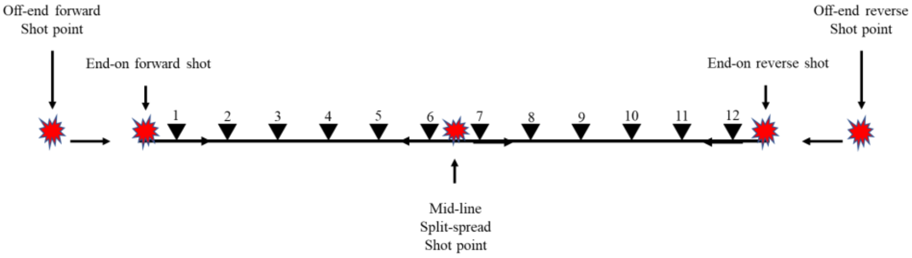


Figure 2. Configuration of refraction seismic data acquisition

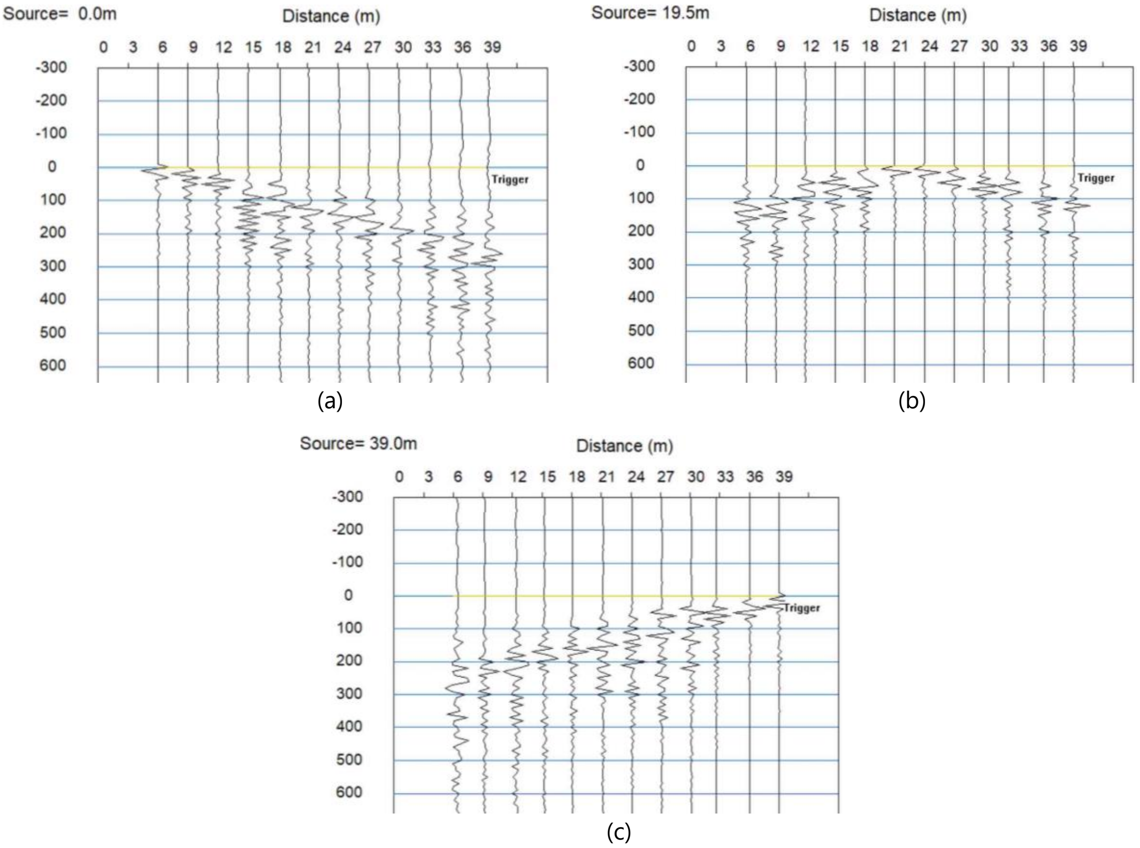
Based on Figure 3, refraction seismic data acquisition begins with determining the measurement path, measuring the length of the path and determining the coordinates of each measurement, inserting geophones into the ground and selecting the interval between geophones, arranging the equipment configuration as shown in Figure 3, where the geophone and the wave source (shot point) are placed in a straight-line extension. Then connect some connection cables (trigger cable and geophone cable) to the equipment. Then operate the seismograph and collect data by giving a shot point disturbance three times in a row, starting from a point 3 meters in front of geophone 1, in the middle of geophones 6-7, and 3 meters behind geophone 12.

The seismograph automatically records the wave response through travel time data. The data are then processed using the SeisImager software (pickwin and plotrefa programs) (Febrianti, 2020). The pickwin program is used to determine the arrival time of the first wave arriving at each geophone to obtain travel time curve data, while the plotrefa program is used to model the structure of the subsurface layer in the form of a 2-D seismic cross section (Febrianti, 2020; Hadi et al., 2021).

Results and Discussion

The results obtained from the field data acquisition in the form of seismic wave propagation recorded by 12 geophones with the length of each track 39 meters and the distance between geophones 3 meters, as can be seen in Figure 3. The seismic waves obtained in Figure 3 were then used to pick the arrival time of the first wave using the Pickwin program. The first wave arrival time is picked for all trajectories and each source, as seen in Figure 4.

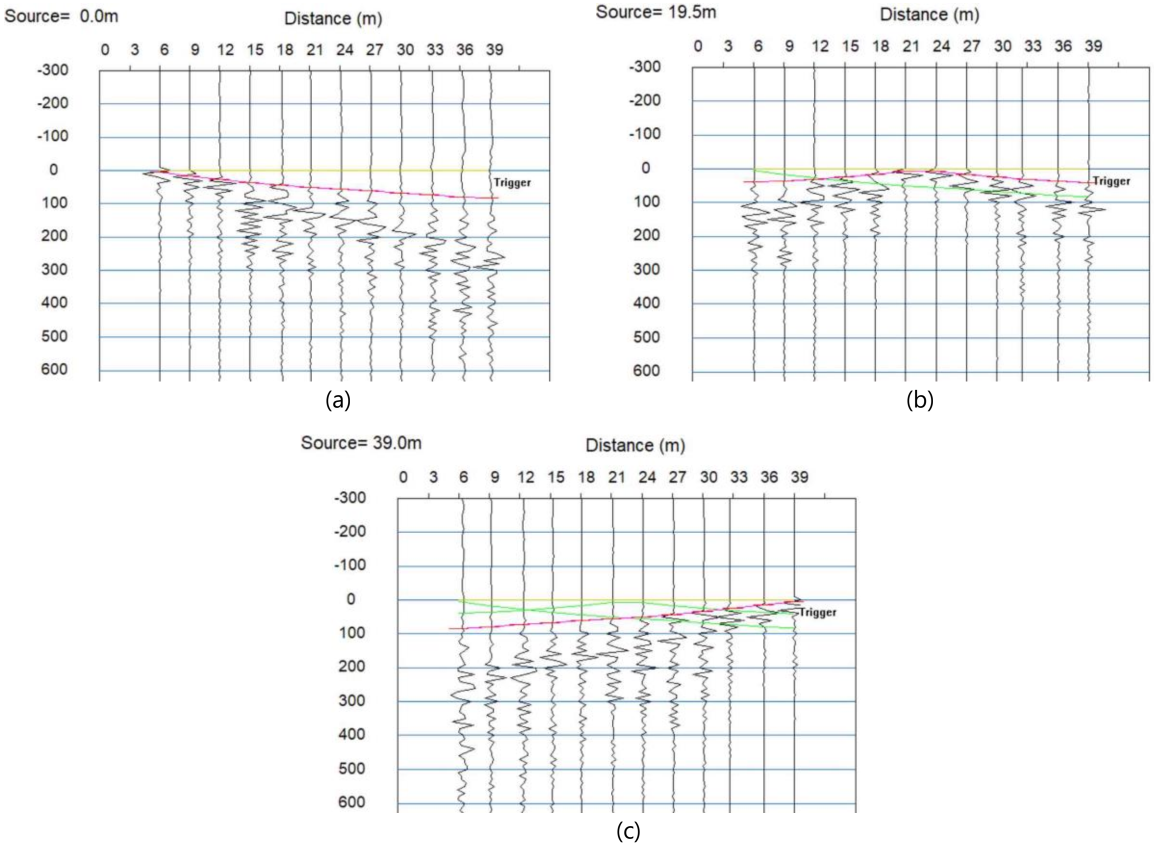
Figure 4 shows the results of picking the arrival time of the first wave on one of the tracks, track 1, which consists of 3 shot points. The first shot point is 0 meters away, the second is 19.5 meters away, and the third is 39 meters away. The results of picking seismic wave propagation records are then displayed on the traveltime curve data graph (T-X curve) in the form of multiple points, which are then analyzed using the plotrefa program. The T-X curve is a curve that describes the relationship between time and distance, as shown in Figure 5.



(a) (b)

(c)

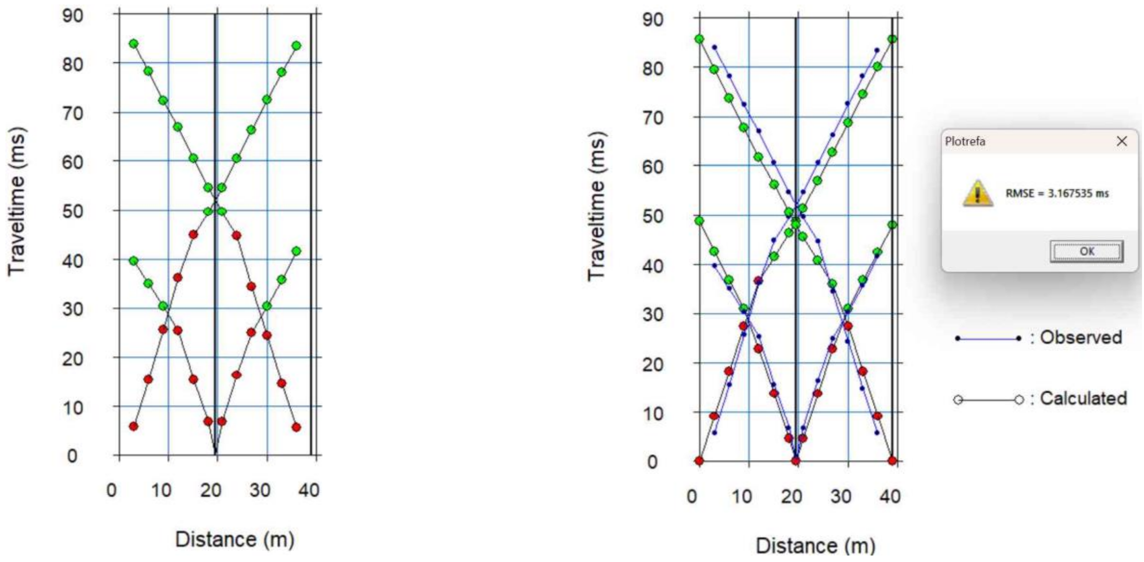
Figure 3. Geophone on track 1 recording seismic waves (a) shot point 0 meters (b) shot point 19.5 meters (c) shot point 39 meters



(a) (b)

(c)

Figure 4. Seismic wave picking results for track 1 (a) Shot point 0 meters (b) Shot point 19.5 (c) Shot point 39 meters



RMSE = 3.167535 ms

(a)

(b)

Figure 5. Traveltime (T-X) curve for track 1 (a) Based on field measurements (b) Based on plotrefa program calculation

Figure 5(a) shows the traveltime curve based on the results of picking the arrival time of the first wave recorded by the geophone in the field measurement of track 1 consisting of 3 shot point variations. Figure 5(b) shows the traveltime curve comparing the results of picking the arrival time of the first wave with the calculation results of the Plotrefa program on track 1 with an RMSE of 3.167535 ms. For track 2, the RMSE is 2.850987 ms. For trajectory 3, the RMSE is 3.417317 ms. For trajectory 4, the RMSE is 4.461137 ms. For trajectory 5, the RMSE is 5.820944 ms. For trajectory 6, the RMSE is 2.979994 ms. For trajectory 7, the RMSE is 2.651409 ms. For trajectory 8, the RMSE is 5.1242952 ms.

The RMSE (Root Mean Square Error) value is obtained by comparing the field data (observed) to the model data (calculated). The smaller the RMSE, the closer the model is to the field data. This indicates that the quality of the data produced is improving (Hadi et al., 2021). After obtaining the RMSE value from the analysis of the traveltime curve data on each track, the inversion process is then performed using the time-term inversion method in the Plotrefa program to obtain a 2-D cross-sectional model of the subsurface structure based on the wave propagation velocity value on each track, one of which is shown in Figure 6.

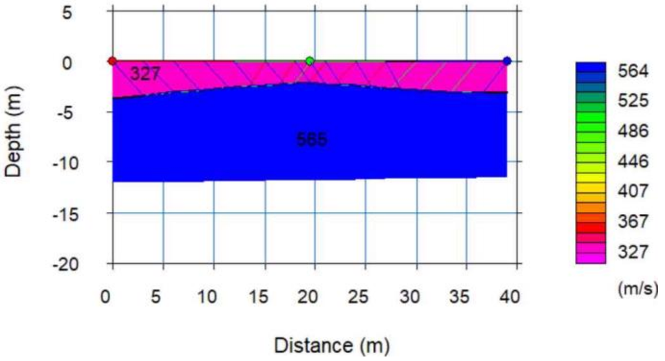


Figure 6. 2-D cross-sectional model of the subsurface structure on track 1

Figure 6 shows a 2-D cross-sectional model of the subsurface structure on track 1 from the inversion process consisting of 2 layers. The second layer is a layer of alluvium, topsoil, weathered bedrock, saturated sand and gravel, unsaturated sand, and gravel with a wave propagation velocity value of 565 m/s at a depth of > 3 m. The interpretation of the modeling results of the weathering zone (Jamal & Maria, 2019). The interpretation of the results of the 2-D modeling of the subsurface structure cross-section on each track, as shown in Table 2.

Table 2. Interpretation of subsurface structural data of each track

Line	**Layer**	**Speed (m/s)**	**Depth (m)**	**Material Type**
1	1	327	1 - 3	Topsoil, weathered bedrock and unsaturated sand.
	2	565	> 3	Alluvium, saturated sand and gravel.
2	1	425	1 – 4	Topsoil, weathered bedrock, unsaturated sand and gravel.
	2	520	> 4	Alluvium, saturated sand and gravel.
3	1	304	1 - 3	Topsoil, weathered bedrock and unsaturated sand.
	2	467	> 3	Mixture of unsaturated gravel, sand and unsaturated gravel.
4	1	252	1 - 3	Topsoil and unsaturated sand.
	2	495	> 3	Mixture of unsaturated gravel, sand and unsaturated gravel.
5	1	338	1 - 3	Topsoil, weathered bedrock and unsaturated sand.
	2	503	> 3	Alluvium, saturated sand and gravel.
6	1	293	1 - 3	Topsoil and unsaturated sand.
	2	572	> 3	Alluvium, saturated sand and gravel.
7	1	335	1 – 4	Topsoil, weathered bedrock and unsaturated sand.
	2	483	> 4	Mixture of unsaturated gravel, sand and unsaturated gravel.
8	1	350	1 – 6	Topsoil, weathered bedrock and unsaturated sand.
	2	665	> 6	Alluvium, saturated sand and gravel.

Based on Table 2 to illustrate the results of a more straightforward interpretation of the model on each measurement line, the formation of a 3-D cross-sectional model of the entire line is arranged based on the coordinates determined during the measurement, as shown in Figure 7.

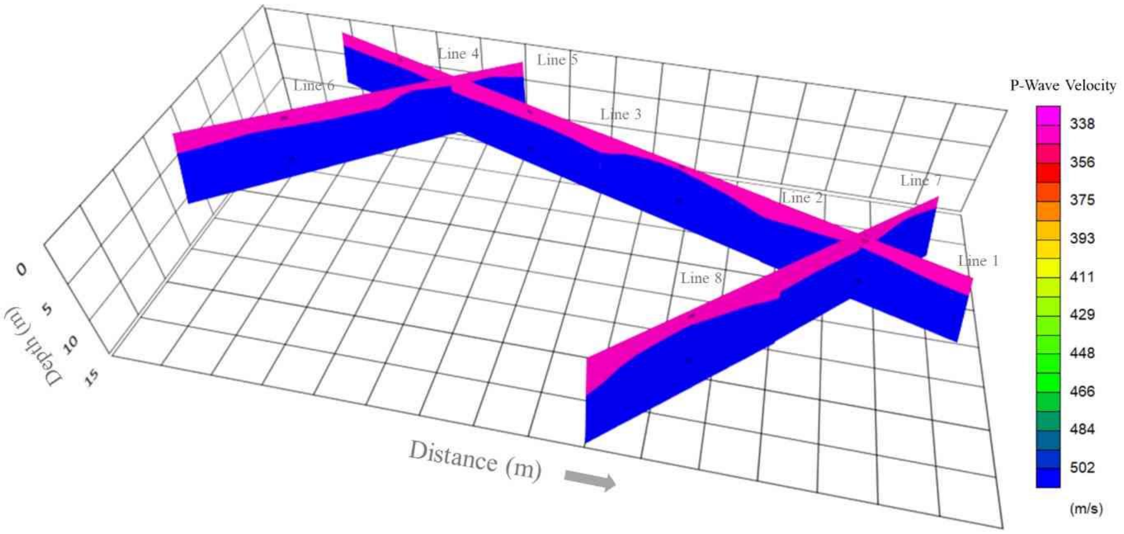


Figure 7. The final result of the interpretation of the 3-D subsurface structure cross-section model

Based on Figure 7, the final results of the data interpretation of the 3-D subsurface structure cross-section model that has been carried out show that the subsurface structure in the Ulakan Tapakis area is composed of alluvium (Qal) surface deposits consisting of loose material, namely saturated sand, and gravel, unsaturated sand, and gravel, which are generally found on the coastal plain, and weathered bedrock layers in the form of topsoil. Topsoil is the uppermost layer of soil (formed by the weathering of the underlying material) or what is often referred to as the weathered zone. Based on the type of material that makes up the rock layer, the area has undergone a weathering process.

The results of the data analysis are consistent with the geological data of the study area. This is shown based on the final results of data interpretation seen in Figure 7. The data analysis shows that the subsurface structure in the Ulakan Tapakis area consists of 2 layers of rock or material lithology based on the differences in the speed of seismic wave propagation in each layer. The difference in velocity in each layer is characterized by the slope of the travel time curve (Febrianti, 2020). The difference in the slope of the P-wave propagation on the travel time curve indicates the difference in the rock layers (Artono et al., 2017). It is assumed that the first layer is a soft layer with a lower hardness than the second layer because the first layer has a high porosity and a lower density or rock density than the second layer. This is consistent with the fundamental assumptions from the data processing results, which show that each subsurface layer has a different wave propagation speed and thickness. The greater the wave propagation speed in the subsurface, the greater the depth and the greater the density or hardness of the rock so that the individual rock layers are more compact (Zulhelmi et al., 2018).

Conclusion

Based on the research results, the subsurface structure in the Ulakan Tapakis area consists of 2 layers based on the difference in wave propagation velocity in the layers at each cross-section. The wave velocity in the first layer of 252 m/s to 425 m/s is interpreted as a layer of weathered rock, topsoil, unsaturated sand, and gravel mixture at a depth of 1 to 6 meters. The second layer has a wave velocity of 503 m/s to 665 m/s and is interpreted as a layer of alluvium, saturated sand, and gravel at a depth greater than 6 meters. The subsurface structure in this area is included in the primary structure with a rock formation unit in the form of surface alluvium (Qal) deposits that are thought to have been weathered below the surface.

Although analysis of subsurface structures in the Ulakan Tapakis area of Padang Pariaman Regency provides valuable insights, several limitations need to be addressed for future research efforts. First, this study may face challenges in accurately determining deeper structures due to the limited depth resolution inherent in refraction seismic methods. To address this, future research could explore alternative geophysical methods or modify existing techniques to penetrate deeper layers with better accuracy. Additionally, lateral variations in subsurface structure can impact the reliability of interpretations, emphasizing the need to integrate data from multiple geophysical methods for a more comprehensive understanding and improved lateral resolution. Additionally, assumptions and simplifications made in interpreting seismic data can introduce uncertainty, underscoring the importance of validating interpretations through direct geological observations. Advanced data processing techniques, such as full waveform inversion, can also be used to reduce limitations and increase the accuracy of subsurface imaging. Finally, longitudinal studies conducted over time can monitor changes in subsurface structures, providing insight into dynamic geological processes and associated hazards, thereby contributing to more robust risk assessments and mitigation strategies in earthquake-prone regions such as West Sumatra.

References

Adnyawati, N. K., Efendi, R., & Sabhan, S. (2012). Analisis Struktur Bawah Permukaan Dengan Menggunakan Metode Seismik Refraksi Di Universitas Tadulako. *Natural Science: Journal of Science and Technology*, *1*(1), 17–26. https://doi.org/10.22487/25411969.2012.v1.i1.1014

Artono, V. Y., Efendi, R., & Sandra, S. (2017). Identifikasi Lapisan Lapuk Bawah Permukaan Menggunakan Seismik Refraksi di Desa Lengkeka Kecamatan Lore Barat Kabupaten Poso. *Natural Science: Journal of Science and Technology*, *6*(3), 291 – 300. https://doi.org/10.22487/25411969.2017.v6.i3.9204

Asrul, A. M., Efendi, R., & Sandra, S. (2019). Pemodelan Reservoar Panasbumi Menggunakan Metode Geomagnet di Desa Lengkeka Kecamatan Lore Barat, Kabupaten Poso. *Gravitasi*, *17*(2), 1–9. https://doi.org/10.22487/gravitasi.v17i2.12417

Burger, H. R., & Burger, D. C. (1992). *Exploration geophysics of the shallow subsurface* (Vol. 8). Prentice Hall.

Douglas, J. (2007). On the Regional Dependence of Earthquake Response Spectra. *ISET Journal of Earthquake Technology*, *44*(1), 71–99. https://brgm.hal.science/hal-00557622/

Enikanselu, P. A. (2008). Geophysical seismic refraction and uphole survey analysis of weathered layer characteristics in the “Mono” Field, North Western Niger Delta, Nigeria. *The Pacific Journal of Science and Technology*, *9*(2). https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=051f026f3c439c76a8201ba5786b6b1f0c7d9907

Febrianti, N. R., & Jamidun. (2020). Aplikasi Metode Seismik Refraksi untuk Identifikasi Pergerakan Tanah di Perumahan Balaroa Palu. *Gravitasi*, *19*(2), 44–50. https://doi.org/10.22487/gravitasi.v19i2.15409

Firnanza, E. (2017). *Penentuan Litologi Lapisan Bawah Permukaan Berdasarkan Model Kecepatan 2D Tomografi Seismik Refraksi Untuk Geoteknik Jalan Tol* [Universitas Lampung]. https://digilib.unila.ac.id/29575/

Hadi, A. I., Refrizon, R., Halauddin, H., Lidiawati, L., & Edo, P. (2021). Interpretasi Tingkat Kekerasan Batuan Bawah Permukaan di Daerah Rawan Gempa Bumi Kota Bengkulu. *Indonesian Journal of Applied Physics*, *11*(1), 11. https://doi.org/10.13057/ijap.v11i1.46525

Jamal, J., & Maria, M. (2019). Identifikasi Lapisan Bawah Permukaan Daerah Bonto Tiro Menggunakan Metode Seismik Refraksi. *Jurnal Geomine*, *7*(2), 101–106. https://doi.org/10.33536/jg.v7i2.379

Julius, A. M., Taruna, R. M., Putra, S. Y. S., Negara, P. K. G. A., Rumy, B. F. A., Yullatifah, A., Nopianti, E., Akuba, N. S., Taufik, T., Subakti, H., & Widana, I. D. K. K. (2020). Pengukuran Kecepatan Gelombang Seismik Menggunakan Metode Refraksi Pada Lapisan Tanah Dangkal. *Geodika: Jurnal Kajian Ilmu Dan Pendidikan Geografi*, *4*(1), 22–31. https://doi.org/10.29408/geodika.v4i1.1915

Nurcandra, N., D, D., & Koesuma, S. (2016). Penentuan Tingkat Kekerasan Batuan Menggunakan Metode Seismik Refraksi di Jatikuwung Karanganyar. *Indonesian Journal of Applied Physics*, *3*(01), 29. https://doi.org/10.13057/ijap.v3i01.1212

Nurdiyanto, B., Hartanto, E., Ngadmanto, D., Sunardi, B., & Susilanto, P. (2011). Penentuan tingkat kekerasan batuan menggunakan metode seismik refraksi. *Jurnal Meteorologi Dan Geofisika*, *12*(3), 211–220. https://doi.org/10.31172/jmg.v12i3.103

Prawirodirdjo, L., Bock, Y., Genrich, J. F., Puntodewo, S. S. O., Rais, J., Subarya, C., & Sutisna, S. (2000). One century of tectonic deformation along the Sumatran fault from triangulation and Global Positioning System surveys. *Journal of Geophysical Research: Solid Earth*, *105*(B12), 28343–28361. https://doi.org/10.1029/2000JB900150

Setyonegoro, W. (2013). Gempabumi Padang 30 September 2009 dan Potensi Tsunaminya. *Buletin Meteorologi Klimatologi Dan Geofisika*, *7*(3), 164–171. https://www.academia.edu/download/34220525/Wiko_Buletin_Vol.7__No.3__Sept.__2011._ISSN__0215-

1952.pdf

Sieh, K., & Natawidjaja, D. (2000). Neotectonics of the Sumatran fault, Indonesia. *Journal of Geophysical Research: Solid Earth*, *105*(B12), 28295–28326. https://doi.org/10.1029/2000JB900120

Sismanto. (1999). *Eksplorasi dengan Menggunakan Seismik Refraksi*. Gadjah Mada University Press.

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (1990). *Applied Geophysics*. Cambridge University Press. https://doi.org/10.1017/CBO9781139167932

Wahyuningrum, S., Yulianto, G., & Nurwidyanto, M. I. (2012). Interpretasi Data Seismik Refraksi Menggunakan Metode Reciprocal Hawkins dan Sofware SRIM (Studi Kasus Daerah Sioux Park, Rapid City, South Dakota, USA). *Berkala Fisika*, *9*(4), 177–184. https://ejournal.undip.ac.id/index.php/berkala_fisika/article/view/3079