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# Identification of The Structure of The Subsurface Layer Using The Seismic Refraction Method in Nagari Malampah

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**Abstract:** The frequent landslides in Nagari Malampah are caused by the location of the area near an active fault zone and the effects of the 2022 earthquake centered in Pasaman Barat Regency. The study aims to identify subsurface layer structures related to landslide susceptibility using the seismic refraction method. Field data were acquired along three survey line and processed using the Time-Term Inversion method. The results indicate the presence of two main subsurface layers. The first layer exhibits P-wave velocities ranging from 277.45 to 581.85 m/s at depths of approximately 3-6 m, interpreted as unconsolidated alluvial deposits consisting of sand, slit, and clay. The second layer shows higher velocities ranging from 499.49 to1093.12 m/s at depths of 12-32 m, suggesting denser materials such as compact clay, dense sand, and weathered bedrock. The significant velocity contrast between these layers indicates the presence of potential weak zones that may act as slip surfaces under conditions of high rainfall and seismic activity. These findings provide important information for landslide hazard assessment and mitigation planning in Nagari Malampah.

**Keywords:** Seismic refraction, time-lapse inversion, landslide, Nagari Malampah.



## 1. Introduction

West Sumatra Province is located along the equatorial line and lies adjacent to the Semangko Fault Zone, making it highly susceptible to geological hazard such as landslides [1]. In addition, the region is characterized by hilly topography, steep slopes, and high annual rainfall, which further increase landslide susceptibility. In 2022, a magnitude 6.1 earthquake occurred in Pasaman Barat Regency, causing damage to infrastructure and potentially affecting the stability of subsurface materials. Geographically, Pasaman Regency is located at coordinates $0°55'LU - 0°06'LS$ dan $99°45'BT - 100°21'BT$. Based on the geological conditions in Malampah Village, the types of

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rock formations consist of the Tmv Formation, which comprises volcanic rocks, and the Qat Formation, formed from soil dominated by alluvium or soft soil [2]. The types of volcanic rocks, young alluvial river deposits, soil types, and rock structures significantly influence the potential for landslides [3].

Landslide are the movement of soil, rock, or a mixture of both along a slope as a result of gravitational forces. Landslides occur due to instability in the soil and rocks that make up the slope. Soil instability is influenced by several factors, including soil morphology, rock conditions, and soil composition [3]. Landslides cause serious impacts, ranging from environmental damage, material losses such as property and infrastructure, to the loss of many lives [4]. Given these issues, mitigation efforts are needed to minimize the impacts of landslides. One such effort involves identifying the subsurface layer structure to determine areas prone to landslides [5].

Several previous studies have employed seismic refraction methods to identify lithological variations and subsurface structures in landslide prone areas. However, studies focusing on subsurface conditions of Nagari Malampah remain limited, particularly following the 2022 Pasaman earthquake. Most previous investigations were conducted in deferent geological settings, and information regarding the relationship between subsurface layer characteristics and landslide susceptibility in Nagari Malampah is still insufficient. Consequently, a research gap exists in understanding the subsurface conditional that may contribute to landslide hazard in this area. Therefore, this study aims to identify the subsurface layer structure in Nagari Malampah using the seismic refraction method and Time-Term inversion analysis. The study focuses on determining seismic wave velocities, layer depth, and thicknesses to characterize subsurface materials and evaluate their relevance to landslide susceptibility. The result are expected to provide scientific information that can support landslide hazard assessment and contribute to disaster mitigation planning in Nagari Malampah and surrounding area. Given the high potential for landslides due to geological conditions and seismic activity, mitigation efforts are essential. Landslide disaster mitigation focuses not only on post-event response, but also on preventive measures taken before an event occurs. One form of mitigation is to understand the characteristics of the subsoil, as landslide movement is influenced by the type and composition of the material within it. Mitigation measures consist of structural and non-structural mitigation. Non-structural mitigation focuses on educational and socialization efforts to the community to reduce the impact of disasters [6].

Through seismic refraction, it is possible to characterize the subsurface by estimating the depth and nature of geological materials beneath the earth’s surface [7]. The initial assumption used is that the subsurface is considered to have multiple layers or is layered. Seismic waves propagating through the subsurface depend on the rock's hardness scale. Seismic refraction is based on the physical principles of waves, namely Fermat's principle, Huygens' principle, and Snell's principle [8]. The seismic refraction method is used to investigate low subsurface conditions. This method uses P-wave propagation because it has a higher wave velocity than S-waves [9]. Waves propagating through soil and rock media will be partially reflected to the surface and partially refracted. This refraction occurs due to differences in rock density [10]. In the seismic refraction method, by knowing the distance between geophones and the travel time of seismic waves, the thickness of the subsurface layer can be estimated based on the wave propagation velocity [11]. Each rock layer with a different hardness level will cause the wave to propagate through the rock layer at a different speed [12].

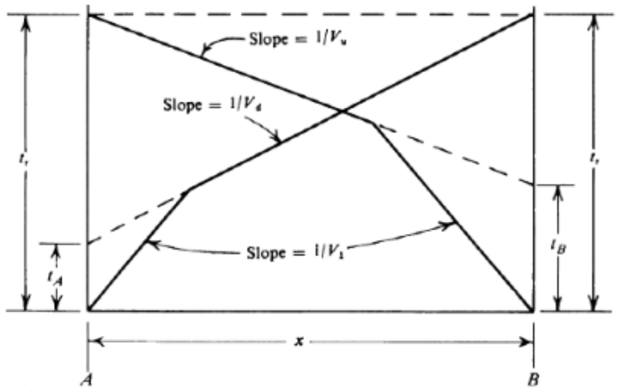


Figure 1. Seismic wave travel as represented on the travel-time curve

By analyzing a travel time curve, seismic wave velocity may be determined to estimate the depth and rock composition of each subsurface layer. Seismic wave velocity data for various types of materials can be seen in Table 1. [13].

| Material | | Propagation speed (vp) (m/s) |
|---|---|---|
| Land | Alluvial | 500-2100 |
| | Clay | 1100-2500 |
| | Loss | 300-600 |
| | Sand | 200-2000 |
| | Boulders | 400-1700 |
| Stone | Granite | 4600-6000 |
| | Gabro, dolerite, basalt | 5000-6700 |
| | Sandstone, shale | 1400-4500 |
| | Limestone, soft | 1700-4200 |
| | Limestone, hard | 2800-6400 |
| | Marble | 5700-6400 |
| | Slate | 3600-4400 |
| | Schist, gneiss | 3500-7500 |

Source: (Ayub et al., 2020)

The physical properties of rocks beneath the earth's surface vary due to differences in hardness, which indicates how strongly the rocks can withstand pressure without cracking. Landslides occur due to the movement of soil masses on a specific plane called a slip plane [14]. In Nagari Malampah, the undulating topography and steep slopes, combined with high rainfall, are factors that contribute to the high potential for landslides. Areas with high rainfall are prone to landslides, especially in hilly areas [15].

The analysis involves three principal methods for analyzing seismic data: *Intercept Time, Delay Time dan* method W*ave Front*. In addition, there are several methods for interpreting the topography of a boundary field, namely the *Reciprocal Hawkins, Time-Term Inversion, Time Plus-Minus, Hagiwara* and *Masuda* [16]. The Time-Term Inversion method is a special technique in seismic refraction methods to determine shallow subsurface conditions. The main principle of this method is to utilize direct waves and refracted waves [17]. The wave velocity obtained from the travel-time analysis from the first arriving wave of the first wave recorded using the geophone is used to create a travel-time vs. distance curve, which represents the subsurface conditions.

## 2. Materials and Method

This study uses descriptive quantitative research methodology. The data used is data obtained based on direct observations in the area to be studied. The seismic refraction technique was employed to determine the velocity of seismic waves within the subsurface layers.

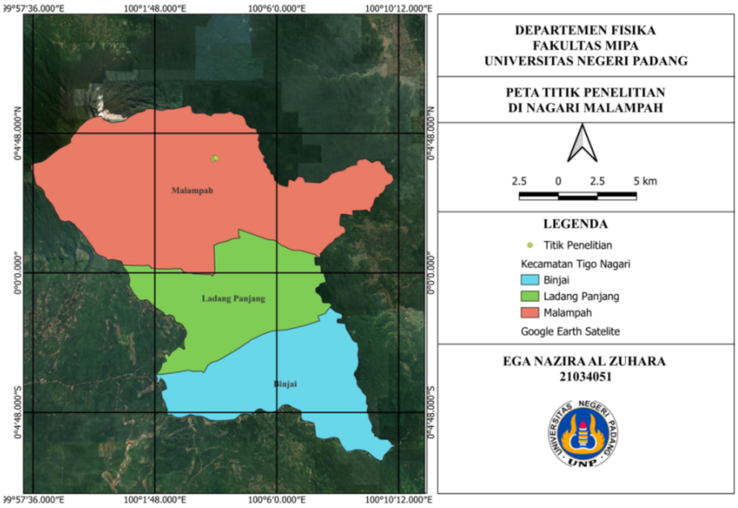



Figure 2. Map of the research location in Nagari Malampah, Tigo Nagari District

The data acquisition process utilized a seismograph device, specifically the SysmaTrack-MAE model, trigger cables, geophone cables, a measuring tape, a seismic hammer, iron plates, geophones, a GPS, a laptop, and USB cables. Data collection was conducted along three transects using an in-line configuration. "The initial line, beginning at the 0-meter mark, is positioned at coordinates $0°4'24$N-100°3'39$E$, extending to the 52-meter point at coordinates $0°4'25$N-100°3'39 $E$sampai. The second transect for the 0-meter point was located at coordinates $0°1'36"$N-100°6'8"$E$ to the 39-meter point at coordinates $0°1'37"$N-100°6'8"$E$. The third transect for the 0-meter point was located at coordinates $0°1'37"$N-100°6'2"$E$ to the 39-meter point at coordinates $0°1'38"$N-100°6'2"$E$. The length of the first track is 52 meters with a spacing of 4 meters between geophones, while the second and third tracks are 39 meters long with a spacing of 3 meters between geophones. The design of the track layout for data measurement is presented in Figure 3.

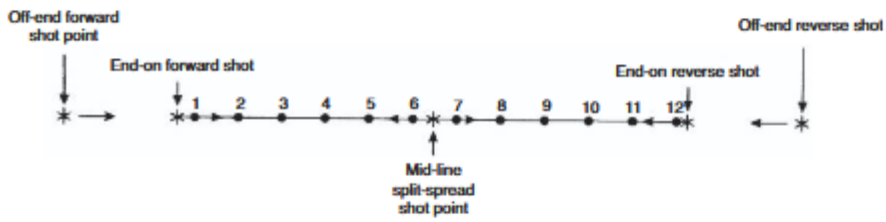
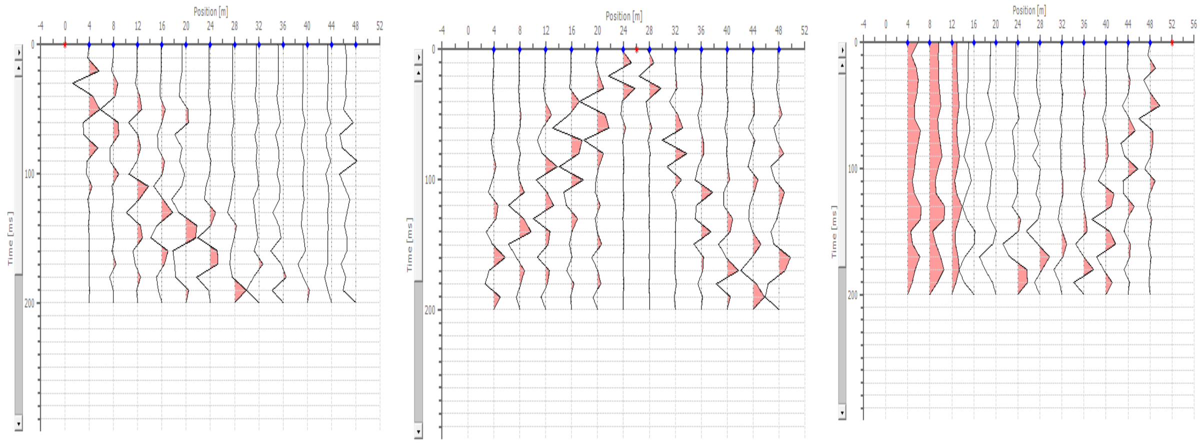



Figure 3. Measurement track design using seismic refraction

Data collection begins with defining the orientation and extent of the measurement line, and then specifying the interval between geophones. After the path is laid out, continue by planting 12 geophones into the ground at the predetermined spacing. Next, record the coordinates and elevation of each geophone, which can be viewed using GPS. Connect the Sysmatrack-MAE seismograph to the laptop using a USB cable, and connect the trigger cable linking the trigger embedded in the ground to the laptop to read the propagating waves. Lay out the geophone cables and connect them to each geophone, then run the Sysmatrack software. After all equipment is installed, calibrate the geophones by performing a geophone test to ensure all 12 geophones are functioning properly. After completion, proceed with data acquisition for the three survey lines, each line having three shot points. For the first track, the first shot point is 4 meters from geophone 1, the second shot point is between geophones 6 and 7, and the third shot point is 4 meters after geophone 12. For the second and third tracks, the first shot point is 3 meters from geophone 1, the second shot point is at the point between geophones 6 and 7, and the third shot point is 3 meters after geophone 12. Data processing using Easy Refract software begins with inputting data into the software, then picking the arrival time of the first wave from the refraction waves recorded by the geophone. After the picking stage, the travel-time curve is constructed and examined through the time-term inversion approach to determine the velocity of seismic waves in each subsurface layer.

## 3. Results and Discussion

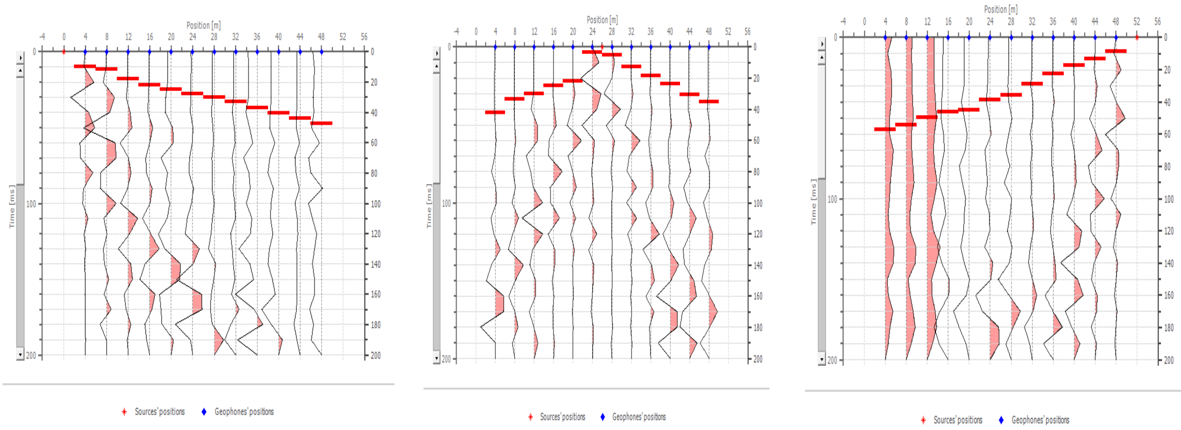
The seismic wave data presented in Figure 4 were subsequently processed by picking, in which the arrival time of the first wave was identified recorded, using Easy Refract software.




(a) (b) (c)

Figure 4. Waves recorded by the geophone on the first traverse (a) shot point at 0 meters (b) shot point at 26 meters (c) shot point at 52 meters

Figure 4 present the seismic wave recordings obtained from three shot point positions along the first survey line. The recorded waveforms exhibit generally good signal quality, with clear first-arrival events observed across most geophones. The amplitudes of the seismic signals gradually decrease with increasing distance from the shot point due to energy attenuation during wave propagation through subsurface materials. In additional, slight variations in waveform patterns and arrival times can be observed among the three-shot point, indicating lateral heterogeneity in subsurface conditions. The first arrivals times tend to increase with geophone distance, reflecting the propagation of seismic waves through layers with different physical properties. The relatively clear first arrivals and acceptable signal-to-noise ratio suggest that the acquired data are suitable for travel-time analysis and velocity estimation. Differences in arrival-time patterns between shot point may indicate variations in subsurface material properties along the survey line. Areas showing relatively faster arrivals are interpreted as containing denser or more compact materials, whereas slower arrival may represent unconsolidated and weathered deposits. These velocity contrasts provide preliminary evidence of subsurface layering, which is further analyzed through travel-time inversion to obtain detailed velocity models and layer geometries. Picking was performed on all traces and each source, as shown in Figure 5.




(a) (b) (c)

Figure 5. Results of the first wave picking (a) shot point at 0 meters (b) shot point at 26 meters (c) shot point at 52 meters

Figure 5 shows the first-arrival picking results used for travel-time analysis. The first-arrival event is clearly identifiable on most traces, indicating good data quality and reliable travel-time measurement. Accurate picking is essential because the calculated seismic velocities and layer depths are directly dependent on the precision of first-arrival identification. These results are then utilized to construct a travel-time curve, which depicts the correlation between time and distance, as shown in Figure 6.

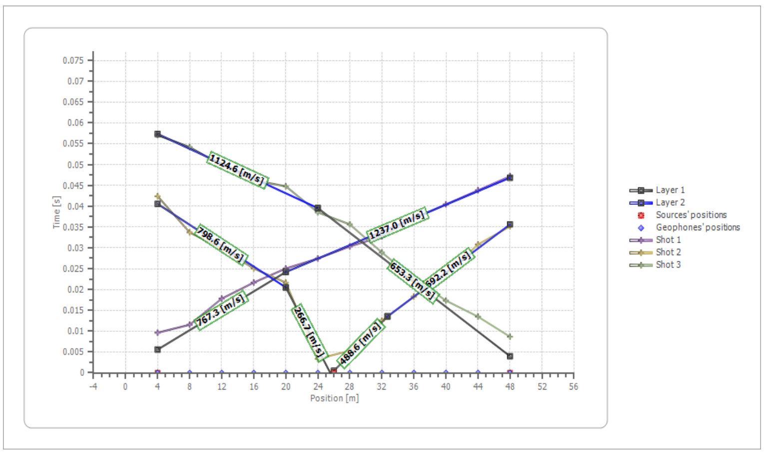



Figure 6. Travel-time curve for the first route

Figure 6 illustrates the travel-time curve obtain from the picked first-arrival data. The curve exhibits changes in slope that indicate variations in seismic wave velocity within the subsurface. The initial segment with a steeper slope corresponds to low-velocity near-surface layer, while the subsequent segment with a gentler slope indicates the presence of a higher-velocity underlying layer. This velocity contrast suggests the existence of distinct geological materials and confirms the presence of at least two subsurface layers along the survey line. Based on the slope values, the first has a velocity of approximately 581.85 m/s, while the second layer has a velocity of approximately 1093.12 m/s. The velocity increase with depth suggests a transition from unconsolidated surface materials to more compact subsurface deposits. Next, the Easy Refract software performs an inversion process on the travel-time curve to calculate the thickness of each layer. The result is a two-dimensional cross-section model as shown in Figure 7.

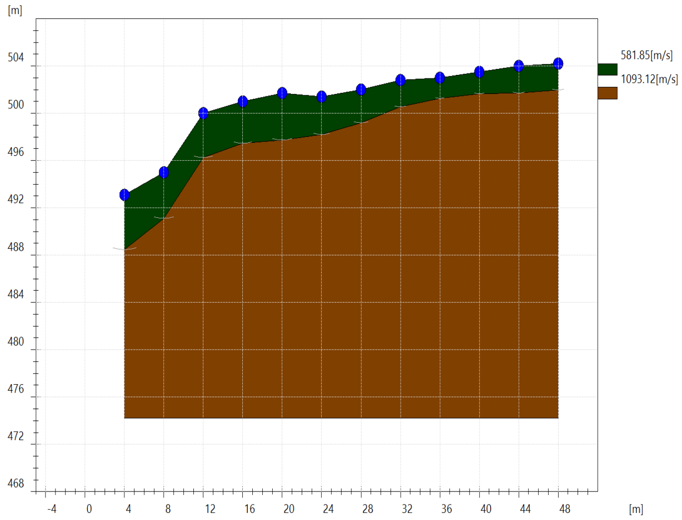



Figure 7. Subsurface model for the first trajectory

Figure 7 presents a cross-sectional representation of the subsurface layers. This cross-section consists of two main layers. The first layer has a velocity of 581.85 m/s at a depth of 4 m to 6 m, based on reference velocity values reported by Ayub et al. (2020), this layer is interpreted as unconsolidated alluvial deposits consisting of sand, slit, and clay with relatively high moisture content. First layer is composed of soft, water-saturated alluvial soil and sand. The velocity of the second layer is 1093.12 m/s at a depth of 20 m to 32 m, and is composed of water-saturated sand, dense clay, and dense alluvium. This velocity range suggest denser and more consolidated materials, such as compact clay, dense sand, or weathered bedrock materials. The significant velocity contrast between the two layers indicates a mechanical discontinuity that may influence slope velocity.

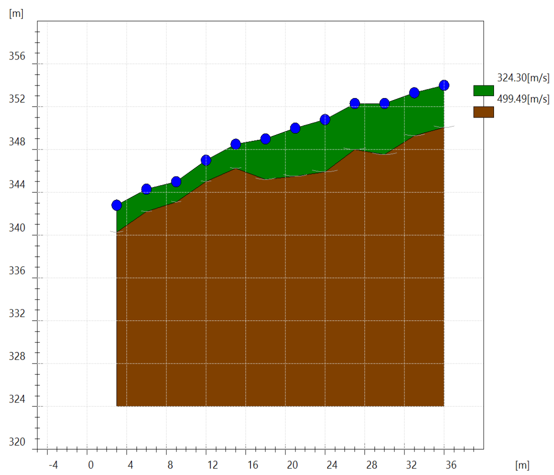



Figure 8. Subsurface model for the second trajectory

Figure 8 shows that the cross-section model has two layers. The initial layer, characterized by a velocity of 324.3 m/s between depths of 3 to 6 meters, is composed of soft alluvial soil and sand. The second layer, with a velocity of 499.49 m/s at a depth of 12 m to 20 m, is composed of hard clay soil and weathered soil. Compared with line 1 the lower velocities observed along line 2 indicate weaker subsurface materials and a higher degree of weathering. Such conditions may reduce shear strength and increase susceptibility to slope failure during periods of intense rainfall.

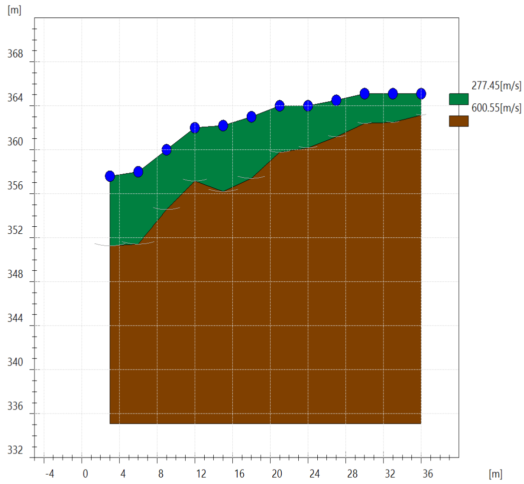



Figure 9. Subsurface model for the third trajectory

Figure 9 present the subsurface velocity model for the third survey line, revealing two main layers with contrasting seismic velocities. The upper layer occurs at depths of approximately 4-6 m and exhibited a P-wave velocity of about 277.45 m/s. Based on published seismic velocity references; this layer is interpreted as unconsolidated near-surface material that may consist of soil, weathered deposits, and loose sediments. The lower layer is identified at depths ranging from approximately 16-28 m and exhibits a higher velocity of about 600.55 m/s, suggesting relatively denser and more compact subsurface materials. The increase in seismic velocity with depth indicates a transition from weak surface deposits to more consolidated materials beneath.

The observed velocity contrast between the upper a lower layer may indicate a mechanical discontinuity within the subsurface. Such discontinuities can influence the distribution of stress and groundwater infiltration within slope materials. Under conditions of prolonged rainfall, increased pore-water pressure may reduce the shear strength of the overlying materials, thereby increasing the likelihood of slope instability and landslide initiation. Similar relationships between low-velocity weathered layers and landslide susceptibility have been reported in previous seismic refraction studies of landslide-prone areas.

## 4. Conclusion

This study successfully identified the subsurface structure of Nagari Malampah using the seismic refraction method and Time-Term Inversion analysis. The result indicates the presence of two layers characterized by contrasting seismic velocities, suggesting differences in material properties and degrees of consolidation. The observed velocity contrast may represent a mechanical discontinuity that can influence groundwater movement and slope stability. Under conditions of intense rainfall, such subsurface conditions may promote increased pore-water pressure and reduced shear strength, which are important factors in landslide initiation.

These findings provide valuable information for understanding subsurface conditions associated with landslide susceptibility in Nagari Malampah. The study demonstrates that seismic refraction is an effective method for identifying potential weak zones and supporting landslide hazard assessment. The resulting subsurface model can serve as a scientific basic for future geotechnical investigations, landside risk evaluation, and disaster mitigation planning in the study area.

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