

Mapping Subsurface and Surface Characteristics of the Recent Pesanggrahan Landslide, Central Java, Indonesia, for Landslide Hazard Management

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ABSTRACT

Regions prone to deep landslides are characterized by thick materials exceeding 10 m and frequent natural disasters. This research aims to analyze the recent occurrence of Pesanggrahan landslide in Central Java, Indonesia, which is a region consisting of both settlements and rice fields. Surface mapping was conducted using aerial photos and direct field observations. Additionally, subsurface conditions to identify the unconsolidated material layers below the landslide surface have been analyzed using the seismic refraction method. The primary velocity (V_p) values are represented in 2D subsurface cross sections. Differences in V_p values corresponded to different geological layers. There were four distinct layers: Top Soil (TS), Clay (CL), Weathered Bedrock (WB), and Tuff Breccia (TB) within the 2D seismic refraction cross-section with V_p values ranging from 150 to 1,800 m/s. The ranges of V_p are: 150-600 m/s for Top Soil (TS), 600-1,200 m/s for Clay (CL), 1,200-1,800 m/s for Weathered Bedrock (WB), and values exceeding 1,800 m/s for Tuff Breccia (TB). The material layer is critical for sustainable land management strategies aimed to control landslides. Furthermore, the potential depth of the sliding plane was managed through effective environmental management practices, including proper disposal of household waste and minimizing the cutting of steep slopes.

1. INTRODUCTION

Landslide is a natural disaster that often occurs in Indonesia (Ariyanto et al., 2019; Usman et al., 2020; Sadisun et al., 2021), comprising several types based on mass movement and direction of materials such as rock, earth or debris down a slope (Lee and Jones, 2004). This natural disaster is also divided into shallow and deep landslides, depending on the thickness of the material (Pratiwi et al., 2019). However, the research location characterized by the appearance of an outcrop with a material thickness greater than 10 m tend to encounter deep landslide.

Residents at the base have diverse agricultural lands covered by the extremely thick material from the natural disaster. Although it remains in the transition zone, the materials mainly possesses Clay (CL) texture (Pulungan and Sartohadi, 2017; Sartohadi et al., 2018; Noviyanto et al., 2020). Therefore, to properly assess the impact of landslide, it is crucial to identify and understand the thickness of the materials.

In landslide environment, both surface and subsurface components can be investigated and identified by testing soil samples or mapping for risk disaster with Geographic Information System (GIS)

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(Iscan and Guler, 2021; Budha et al., 2020; Ming and Zawawi, 2021; Putra et al., 2021; Thongley and Vansarochana, 2021; Intarat et al., 2024), and the use of geophysical methods, respectively (Sana et al., 2021; Galone et al., 2024; Jin et al., 2024). In addition, the methods often used to identify subsurface layers include geoelectric (electrical resistivity tomography/ERT), seismic refraction tomography (SRT), and multichannel analysis surface wave (MASW) (Zainal et al., 2021; Amanatidou et al., 2022; Butchibabu et al., 2023; Karaaslan et al., 2023). Seismic refraction can be used to identify geological faults and fractures beneath the surface (Sichugova and Fazilova, 2024). Subsurface mapping in the form of cross-sections showing the layers is often used in environmental applications. Besides from landslide, it can also be used for mining and petroleum geology analyses (Jaysaval et al., 2021; Punzo et al., 2021; Rahimi et al., 2021), resulting in the generation of both 2D and 3D visualizations of subsurface cross-sectional results (Imani et al., 2021b; Sana et al., 2021; Whiteley et al., 2021).

This present research used seismic refraction to obtain a cross-section of the surface beneath landslide. According to Telford et al. (1990), and Reynolds (1997), the waves in various soil or rock layers with varying densities were refracted. Meanwhile, dissimilarities in the density of material layers tend to show differences in Vp values. Preliminary research used seismic refraction method to determine subsurface characteristics of landslide and the volume of materials (Samyn et al., 2012; Whiteley et al., 2020; Imani et al., 2021a).

The occurrence of landslide posed potential risk to the surrounding environment, caused by the unconsolidated super thick materials. Therefore, the current research focused on the layers, which tended to transition into slip areas, considered a major cause of landslide.

The subsurface cross-section was interpreted into multiple strata connected to geological and geomorphological data, through direct field observations and information from prior research. Layer interpretation was used to determine the characteristics of landslide materials, while differentiating Vp values from the results of seismic refraction measurement helped to identify the properties of diverse material layers. Furthermore, landslide was controlled through sustainable land management based on the properties of the materials.

2. METHODOLOGY

Surveys were carried out to determine the research location and geophysical measurement trajectories. Furthermore, three geophysical trajectories were determined after conducting direct field observations. Measuring the length of a possible path in landslide depended on whether the surface had undulations.

Direct field observations were carried out to obtain geomorphological and geological data to support seismic refraction interpretation. The outcrops or open material were carefully analyzed to obtain the actual appearance of the layer beneath the surface. These were found under large landslide and in several other parts.

Surface mapping was carried out using aerial photography taken above Pesanggrahan landslide with DJI Phantom. This landslide is located in Bogowonto watershed, with Sumbing Volcano situated upstream. Meanwhile, the surface morphology around Bogowonto watershed was characterized by several thick deposits of material and erosion (Maulana et al., 2023), leading to frequent landslide in Ngasinan research location. Direct field observations carried out in Ngasinan showed many creeps, dormants and landslide outcrops. Furthermore, super thick soil material was observed in this transition area, impacted by tertiary and quarter zones (Pulungan and Sartohadi, 2017; Pulungan and Sartohadi, 2018; Sartohadi et al., 2018; Prayitno et al., 2019). Thick layered soil properties were produced due to the formation of materials from many geological periods and sources.

Landslide outcrops, including those influenced by human activities such as cutting hillsides, showed layers of extremely thick soil material. Furthermore, layers originating from volcanic eruption deposits of Sumbing and weathering of parent rock have different characteristics. Figure 1 shows the exact location of landslide outcrops, in Bogowonto Watershed Basin in Ngasinan Village.

Seismic refraction is a geophysical method that can be used to determine differences in deeper layers. The principle of this method depends on the propagation of refracted seismic waves at the boundary of the layer, thereby depicting the difference in primary velocity (Vp) (Reynolds, 1997). Additionally, seismic refraction was obtained using the Snell's law formula in equation (1) (Telford et al., 1990).

$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2} = p \quad (1)$$

The quantity p is called the raypath parameter. Seismic refraction method was used to describe subsurface conditions in accordance with the V_p

model. However, in the case of landslide, the existence of field boundaries was identified through the contrast in V_p between the solid and weathered material.

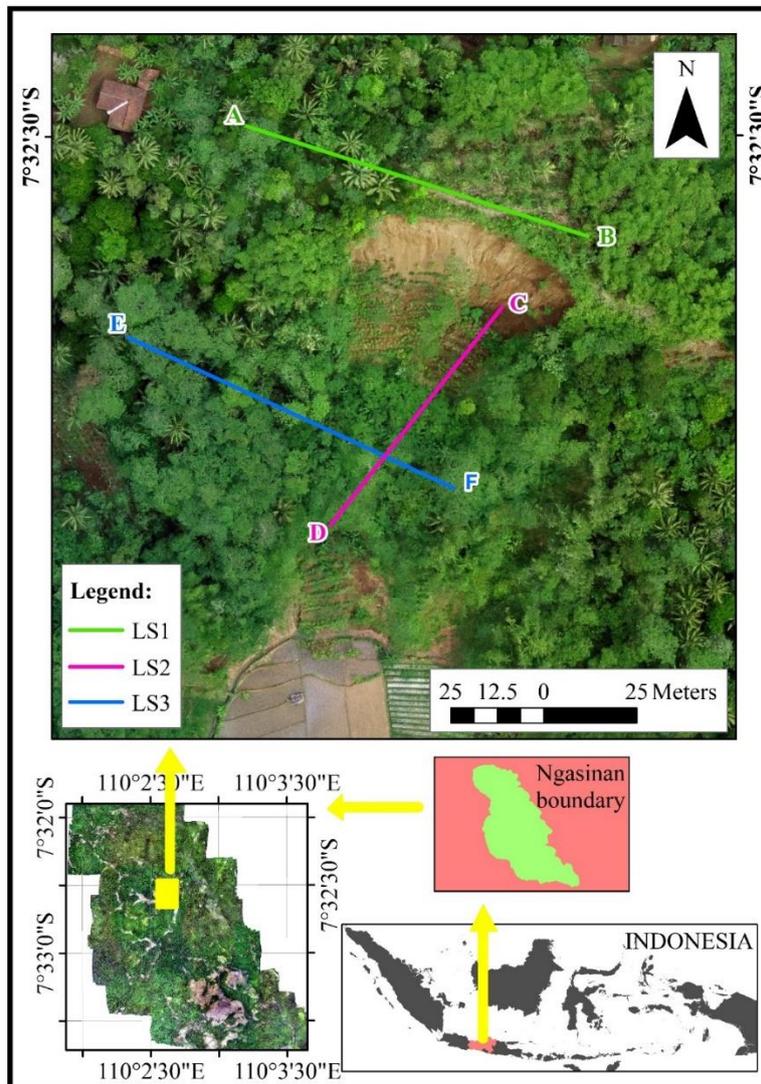


Figure 1. Research location and seismic refraction trajectory in the landslide area

Seismic refraction was measured using three trajectories in the landslide area. The first trajectory LS1 was positioned at the crown of the landslide, tending towards the West-East. The second trajectory LS2 was positioned on the body, heading North-South, in the same direction as the landslide movement. While, the third trajectory LS3 was

positioned at the foot of landslide tending towards West-East. Detailed seismic refraction measurement parameters are shown in Table 1. Additionally, field acquisition activities in Figure 2 show seismic trajectory and the tool used, namely Doremi 24 channels.

Table 1. Seismic refraction measurement parameters

Trajectory	Length (m)	Interval (m)	Shot number	Geophone number	Record time (s)	Sampling rate (Hz)
LS1 (AB)	98.5	4.5	5	22	0.25	5,000
LS2 (CD)	76.5	3.5	5	22	0.25	5,000
LS3 (EF)	98.5	4.5	5	22	0.25	5,000

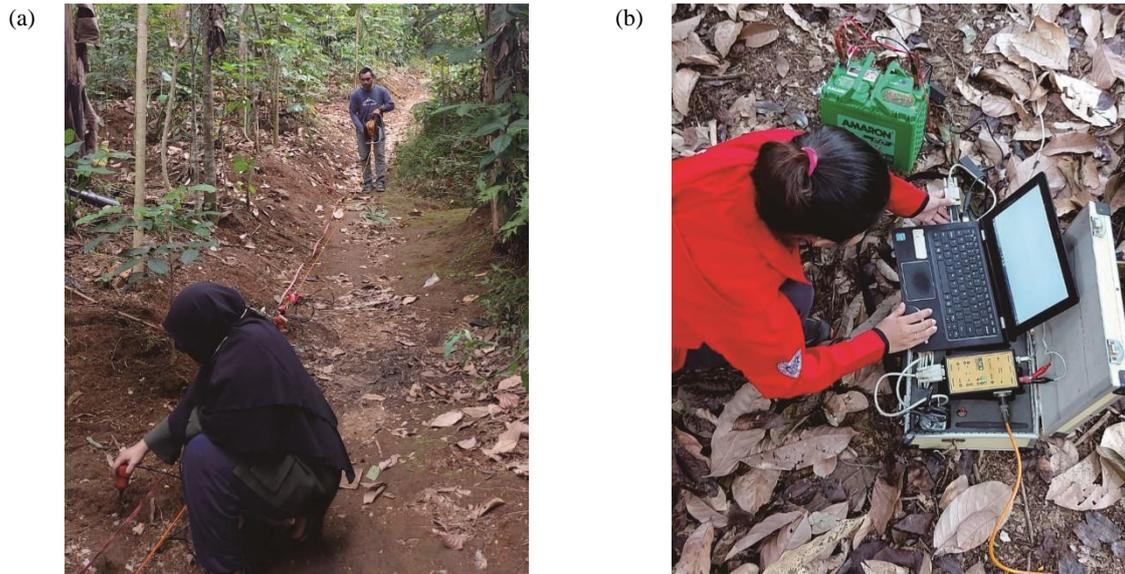


Figure 2. Seismic refraction measurement: (a) one of seismic trajectories, and (b) measurement tools Doremi 24 channels

Seismic refraction data processing flowchart and method are shown in Figures 3 and 4. In addition, three seismic trajectories produced a 2D cross-section of V_p values. Data was processed with Seisimager package software, comprising Pickwin and Plotrefa programs (Figure 4). The main task of the Pickwin program is to pick the first arrival time, including editing the geometry, and turning off bad traces. The picked data is saved and opened in the Plotrefa program, where the T-X curve tends to be displayed (Figure 3). Furthermore, data quality control was performed by editing the position of the picking point to comply with the rules of refraction. Elevation data were inputted in this program, whose main task was to perform tomographic inversion. In this research, an initial model of 10 layers, maximum depth of 30 m, and five iterations served as the parameters of the inversion process.

3. RESULTS AND DISCUSSION

3.1 Material layers interpretation

Seismic refraction measurements were used to generate 2D cross-sectional V_p values from the subsurface of the Pesangrahan landslide. Layered variations in V_p values were shown in 2D cross-section, depicting various material deposit layers, as proven by the results of the inversion in Figure 5. Seismic refraction data on 2D cross-section of LS1, LS2, and LS3 trajectories suggested that each had a depth of approximately 25 to 30 m.

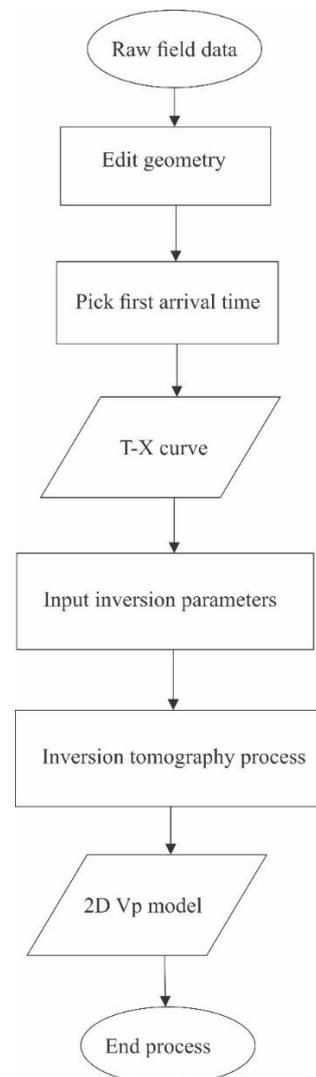


Figure 3. Flowchart of seismic refraction data processing

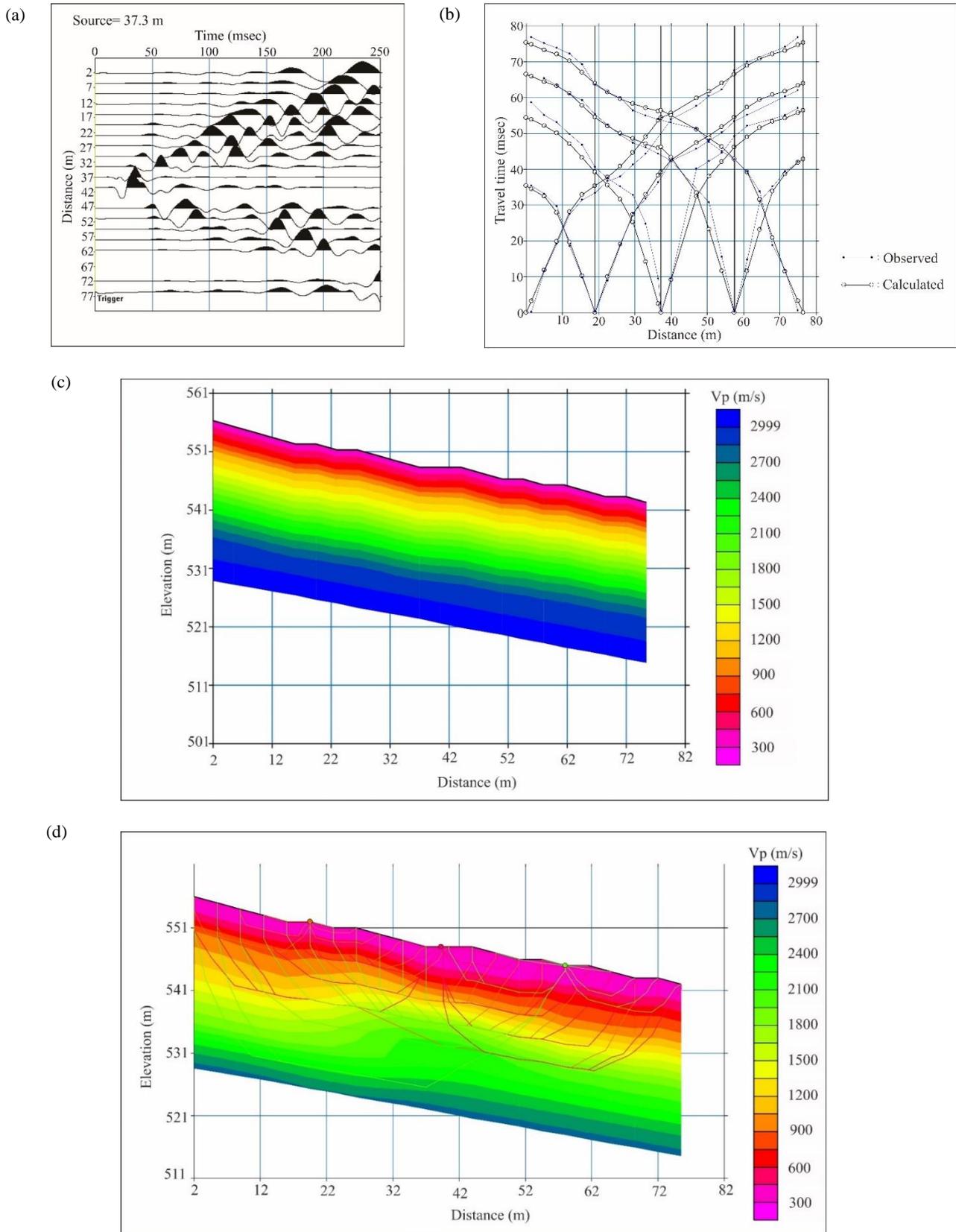


Figure 4. Seismic data processing: (a) raw data, (b) traveltime graphic, (c) initial model, and (d) inversion result

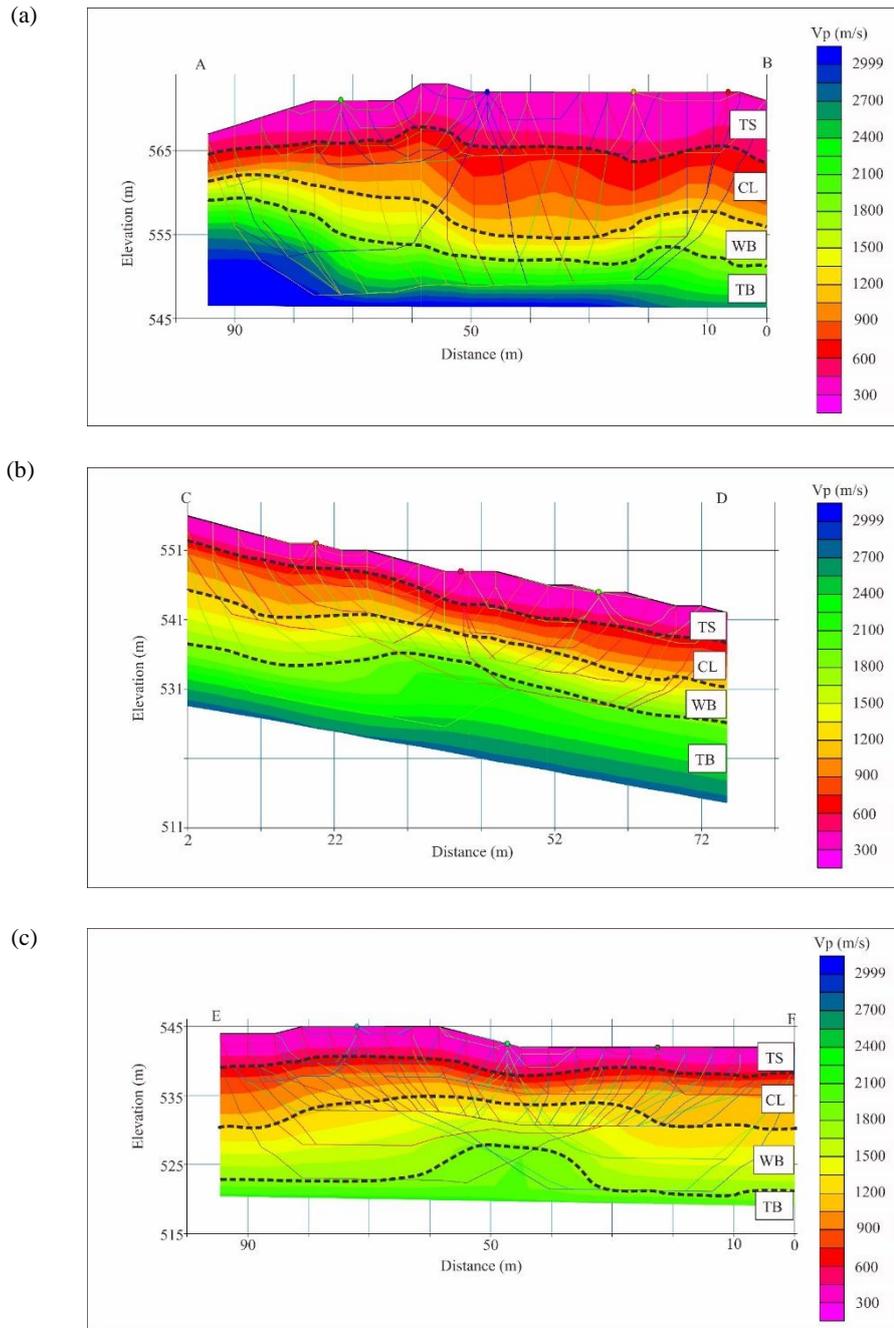


Figure 5. Inversion results: (a) LS1, (b) LS2, and (c) LS3 trajectories

2D seismic refraction sections obtained V_p values between 150 m/s and 2,999 m/s. Patanduk (2020), conducted a research on the transition zone, and reported that V_p within the range of 200 and 700 m/s were categorized as Top Soil (TS), while values between 700 and 1,000 m/s, 1,000 and 1,800 m/s, and greater than 1,800 m/s were referred to as CL, Weathered Bedrock (WB), and Tuff Breccia (TB), respectively. In accordance with previous research (Patanduk, 2020) and direct geomorphological observations conducted in the field, the interpreted seismic section contained four large layers. TS

constituted the top layer, followed by CL, WB, and TB with V_p values within the range of 150 to 600 m/s, 600 to 1,200 m/s, 1,200 to 1,800 m/s, and greater than 1,800 m/s, respectively.

Direct field observation led to the discovery of WB outcrop at the foot of landslide, characterized by soft hardness, mixed lump structure, and red appearance. WB originated from breccia material altered as a result of weathering. Figure 6 shows WB outcrop at the foot of a landslide, approximately 20 m below LS3 trajectory. When viewed from an elevated position, WB outcrop was approximately 50 m below

LS1 track. This direct observation data strengthened the interpretation of 2D seismic refraction layer.

Although landslide has not yet covered TB outcrop, this structure was discovered in nearby areas. TB outcrop has an elevation of 517 m, implying that the interpretation of 2D seismic refraction section was correct because TB was below WB layer. Furthermore, TB outcrop was characterized by a grayish-white color, sand-border texture and softness, with the location shown in Figure 7.

TS, CL, WB, and TB layers were depicted in the interpretation of 2D seismic refraction cross-section. Each of the four layers had a different thickness, for example TS, CL, WB, and TB ranged from 2 to 8 m, 3 to 10 m, 2 to 12 m and greater than 15 m. Sequentially, each layer had a depth surface of 0-5 m, 5-15 m, 15-20 m and greater than 20 m. Table 2 shows the layers derived from seismic refraction findings and direct field observations.

The loose uppermost layer, TS was found on both the surface and crown of landslide, covered with many types of plants. CL layer was characterized by

CL texture based on the outcrops surrounding landslide. Meanwhile, the red WB layer is loose, having a similar appearance to the outcrop in Figure 6. This layer is formed from a combination of previously occurring landslide material and weathering of subsurface rock. TB layer contains material impacted by volcanic eruptions (tuff), including rock deposit from pre-existing outcrops as shown in Figure 7. The prior material was moved and deposited by river currents, forming breccia rock units. Furthermore, WB and TB layers were characterized by the CL texture and ability to hold large quantity of water when tested. This implied that the material had weathered, proven by the altered physical and chemical qualities.

Table 2. Super thick material layers in deep landslide

Layer	Depth (m)	Vp (m/s)	Thickness (m)
TS	0-5	150-600	2-8
CL	5-15	600-1,200	3-10
WB	15-20	1,200-1,800	2-12
TB	>20	>1,800	>15

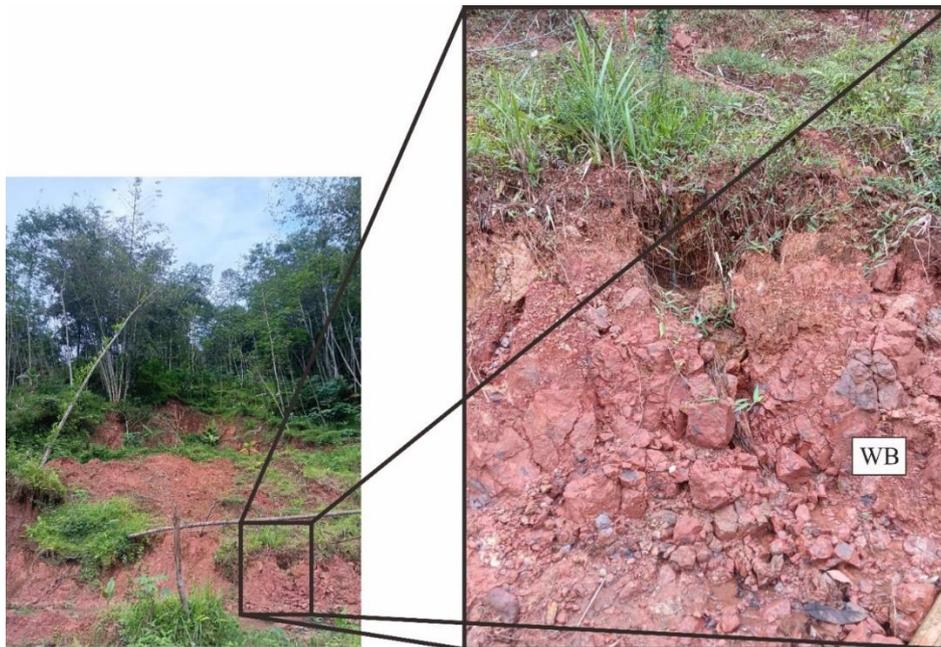


Figure 6. WB at the foot of landslide

In geology, weathered or altered material is related to hydrothermal variations around volcanoes (Kereszturi et al., 2021; Douglas et al., 2022; Kanakiya et al., 2022; Heap et al., 2023). The altered material was produced as a result of magma activity, generating heat beneath the surface. However, this

volcanic activity occurred earlier leading to the formation of younger eruption strata (Sambodo and Arpornthip, 2021). Material from several eras formed layers that were deposited into super thick material, such as at the research location.



Figure 7. TB in Ngasinan research area

The distinct properties of the layers make thick materials prone to landslide. However, the susceptibility to this natural disaster was controlled by the thickness, and characteristics of the material, including varying physical and chemical contents. Texture is a physical quality, as well as fissures and the loose materials found at the research location (Teh et al., 2023). The chemical features include the mineralogical content influenced by the rapid occurrence of the weathering process (Pandarinath, 2022). Furthermore, the altered material contains CL minerals namely smectite, illite, quartz, etc (Weisenberger et al., 2020; González-Partida et al., 2022), leading to the formation of a pseudo-sliding plane. The characteristics of a super thick material

layer that can form a pseudo-sliding plane include CL texture, high CEC value, easy absorption of water and low resistivity value (Purnamasari et al., 2024).

A specific finding of this research is the identification of layers in unconsolidated super thick material. The finding differs from previous recent investigations that adopted seismic refraction methods. Table 3 shows the differences between the present findings and past research. Meanwhile, layers of super thick material interpreted in detail at deep landslide locations are critical for environmental management. The combination of subsurface, and surface mapping, as well as direct field observation is a research method that integrates numerous scientific disciplines.

Table 3. Previous research that used seismic refraction method

Tittle	Research result
Engineering geotechnical evaluation of soil for foundation purposes using shallow seismic refraction and MASW in 15 th Mayo, Egypt.	Subsurface mapping with massive materials for building construction (Mohammed et al., 2020).
Landslide monitoring using seismic refraction tomography - The importance of incorporating topographic variations.	Determination of the near-surface soil layer below landslide with a thin soft layer (Whiteley et al., 2020).
Electrical resistivity and refraction seismic tomography in the detection of near-surface Qadimah Fault in Thuwal-Rabigh area, Saudi Arabia.	Subsurface identification of structures such as faults (AlQahtani et al., 2021).
Determination of Weathered Layer Thickness Around the Landslide Zone using Seismic Refraction Method.	The refraction method used was simple, only two layers were obtained, namely weathered and massive (Hadi et al., 2021).
Application of combined electrical resistivity tomography (ERT) and seismic refraction tomography (SRT) methods to investigate Xiaoshan District landslide site Hangzhou, China.	The slip interpretation of landslide area with contact boundary characterized by clearly thin weathered material (Imani et al., 2021b).

Table 3. Previous research that used seismic refraction method (cont.)

Title	Research result
Assessment of spatiotemporal changes in water contents of landslide zone by geophysical methods: a case study.	Integration of geological and geophysical data to determine water content under landslide (Imani et al., 2021a).
Characteristics and rippability conditions of near-surface lithologic units (Penang Island, Malaysia) derived from multimethod geotomographic and geostatistics models.	Subsurface ground water and infrastructure (Akingboye and Bery, 2022).
Hydromechanical assessment of a complex landslide through geophysics and numerical modeling toward an upgrade for the Villerville landslide (Normandy, France).	Identify the subsurface geology of landslide on a large scale enabling the visibility of the structural extent (Thirard et al., 2022).
Integrated analysis of geophysical methods for slope failure characterization.	Geophysical method for measuring the subsurface characterized by the massive nature, creep landslide type, and rock borders found in the research area (Zakaria et al., 2022).
Identification of surface layer structure using seismic refraction for landslide reduction in Tandikek region, West Sumatra Indonesia.	The simple seismic method was used to obtain two layers with clear boundaries between the weathered and massive layers (Draini et al., 2023).
Integrated geophysics for investigation of landslide-affected site located near Alemketema Town, Central Ethiopia.	Large-scale subsurface mapping showed massive rock layers (Genetu and Mewa, 2023).
Landslide assessment through integrated geoelectrical and seismic methods a case study in Thungsong Site, Southern Thailand.	Subsurface mapping of landslide area containing massive material, distinguished by three layers with thin weathered material, in addition, sandstone was found at a depth of less than 5 m (Sujitapan et al., 2024).

3.2 Hazard environment management

Data on thickness and depth of subsurface layers are useful for managing the environment around the landslide. Different V_p values representing material density were found in layers determined by seismic refraction measurements. This parameter is related to porosity, which was used to determine whether fluids such as water could easily pass through the material (Schaetzl and Anderson, 2005). Additionally, porosity is also associated with the vegetation on the surface (Birkeland, 1984), including the type of roots, as well as the appropriateness to the properties of the deposited material (Purwaningsih et al., 2020). Direct field observations showed that the vegetation type commonly found around landslide was characterized by tap roots and fibers. Therefore, the reinforcement of soil by roots is a complex synergy of root-soil mechanical properties, and morphology, including plant-induced alterations, leading to a considerable enhancement in slope stability (Lann et al., 2024).

Direct field observations were also used to identify the environment around landslide. Based on Figure 8, the area surrounding landslide was characterized by mixed vegetation, rice fields, and settlements, found in elevated position above landslide. Meanwhile, the rice fields were located below the landslide (Figure 8). Settlements, rice fields and mixed vegetation exposed lands to this natural disaster.

Some causes of landslide are sedimentary material characterized by low density (not massive), thick material deposits, sliding plane, varying surface undulations that tend to be steep and high rainfall (Jäger et al., 2013; Chae et al., 2017; Abdullah et al., 2020). Furthermore, the rainfall were projected and used to evaluate subsequent alterations in landslide susceptibility, and the frequency of these events exceeded the empirical thresholds (Lin et al., 2022). The sliding plane was identified based on the layers resulting from the interpretation of geophysical measurements. The morphology was determined by directly observing the location of settlements and rice fields on undulating land.

Based on this perspective, an increase in population growth, enlarges the settlement area. Furthermore, the surrounding area of landslide tends to be affected by the increasing quantity of settlements. Land used as settlement may be vulnerable or have an impact on existing landslide (Servanzi et al., 2023). The material deposits underneath will also be affected by water from household waste. When this wastewater directly enters the sedimented material or soil, it tend to hinder vegetation growth. Many fruit plants with mixed vegetation in Ngasinan do not bear fruit even though the plants are healthy, due to the inappropriate chemical content of the soil (Birkeland, 1984). In addition, non-fruiting of local vegetation has an economic impact on the community.

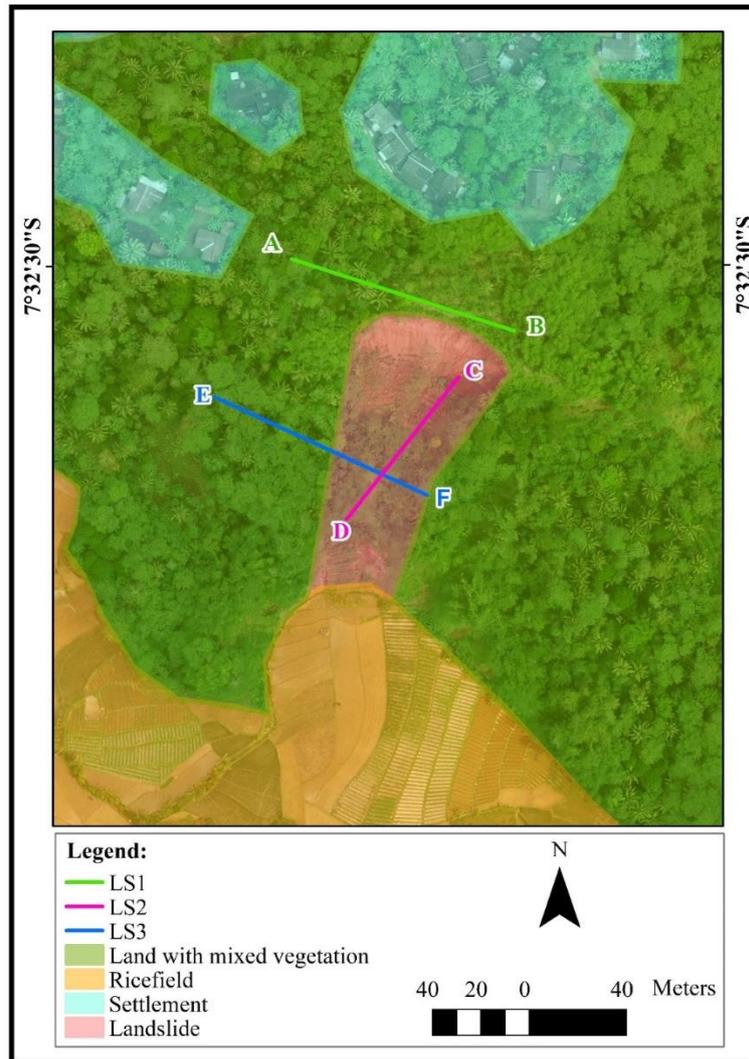


Figure 8. The surrounding environment of landslide

Landslide risk reduction depends on the perceptions of local communities in the affected areas, which is closely associated with the economic and social conditions (Qasim et al., 2018). Ngasinan people were unable to understand the geomorphological or subsurface conditions of the region. It is necessary to provide advice regarding proper land management to reduce or control the impact of landslide. Pipes or similar instruments must be used to convey the management of domestic waste flows. Furthermore, waste management needs to be carried out to prevent garbage from entering the soil or material deposits directly. Appropriate land management on slopes prone to landslide also needs to be conveyed to Ngasinan community, specifically those whose homes are located in landslide-prone locations. Land management can be started by planting vegetation that suits the characteristics of the subsurface material, and cuts on steep slopes also need

to be minimized. Appropriate land use such as afforestation, reforestation, and proper agricultural practices can help stabilize slopes, reducing the risk of landslide (Poddar and Roy, 2024). Therefore, comprehending the connection between land use and land cover alterations, as well as the vulnerability to landslide is crucial in managing the risk of this disaster in mountainous regions (Poddar and Roy, 2024).

4. CONCLUSION

In conclusion, seismic refraction data were used to identify subsurface layers that extend to a depth of approximately 25 to 30 m. Layers with varying V_p values were observed in 2D seismic refraction section showing dissimilar material layering. TS, CL, WB, and TB constituted the four major layers, arranged from top to bottom (surface). TS, CL, WB, and TB layers had V_p values in the range of 150-600 m/s, 600-1,200 m/s, 1,200-1,800 m/s, and greater than

1,800 m/s, respectively. Landslide minimization or the investigation of control methods was enhanced by the subsurface interpretation of seismic data. The selection of appropriate vegetation, an environmental management method helped prevent landslide. Determining the type of vegetation also required data on the characteristics, both physical and chemical properties of soil. Managing household waste and reducing the cutting of steep slopes should be performed to reduce the risk of landslides. The results proved effective for future research on landslide minimization applications. Additionally, the layering and thickness of the material could serve as a reference. In future research, ERT and other geophysics method should be used on all trajectories.

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