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INTEGRATED GEOPHYSICAL ANALYSIS FOR LANDSLIDE RISK MITIGATION: A CASE STUDY ON THE WEAK ZONE AREA OF JANTHO-LAMNO ROUTE, ACEH, INDONESIA

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ABSTRACT: A study was conducted along the Jantho-Lamno road to identify and mitigate landslide risks by analyzing the relationship between seismic wave propagation velocity and rock resistivity. The research aimed to assess geological conditions and pinpoint areas prone to slope failure, employing both seismic and resistivity methods on three selected lines (L1, L2, L3). Seismic wave propagation velocity (Vp) and resistivity (ρ) values were analyzed using ZondST2D and Res2Dinv software. The results revealed a distinct weak zone characterized by contrasting layers: a soft first layer and a denser second layer. Within this zone, Vp ranged from 0.3 to 0.9 km/s, with resistivity measuring less than 10 Ωm, mainly comprising sandstone and clay. This weak zone acted as a slip plane, driven by a water-saturated layer's pushing force, making it susceptible to structural instability due to gravitational pressure. To mitigate land creep, the proposed strategy involved constructing retaining walls, piles, shotcrete, wire mesh, net rock bolting, and rock removal techniques, tailored to the geological conditions of L2 and L3 Jantho. Similar measures would be implemented at L1 Lamno. L1 Lamno was identified as an ideal location for studying slope stability mitigation measures. Landslides in Aceh Province result from factors such as active tectonic movements, intense rainfall, geological structures, weathering processes, and seismic activity. Implementing slope stabilization and protection methods effectively reduces landslide risks, benefiting the region's safety and infrastructure.

Keywords: Weak zone, Resistivity, Seismic wave, Landslide, Mitigation

1. INTRODUCTION

The Aceh Province is susceptible to tectonic activity, which can cause weathering and rock mass fracturing. This poses challenges in road construction, particularly on slopes cut for road development. The Aceh government has been working to improve road infrastructure, including the Jantho-Lamno Road, to enhance access to remote communities and reduce travel distances between regions. However, the undulating topography, with hills ranging from 800 to 1,200 meters in height, makes road construction difficult and prone to landslides caused by rainfall-induced soil erosion [1,2,3]. Therefore, when building road infrastructure in disaster-prone areas like the Aceh Province, it is essential to consider the existing geological and topographical conditions to minimize the risk of natural disasters such as landslides.

This study addresses these gaps by presenting an integrated geophysical analysis specifically designed for landslide risk mitigation [4, 5], with a focus on the weak zone area of the Jantho-Lamno Route in Aceh, Indonesia. The key difficulties in assessing landslide susceptibility in such terrains are met with an innovative combination of seismic refraction and geoelectric resistivity methods. This integration allows for a nuanced evaluation of seismic wave propagation velocity and rock resistivity values, providing a detailed characterization of the subsurface.

Our original achievement lies in the precise differentiation of rock layers and the identification of both weakened upper layers and potential slip planes in deeper formations. By correlating seismic [6, 7, 8] and resistivity data [9, 10, 11], the study predicts landslide-prone zones and contributes to a deeper understanding of geological features that contribute to slope failures [12]. This integrated approach not only surpasses the limitations of singular geophysical techniques but also offers a more effective means of formulating targeted protective measures to enhance the resilience of critical transportation routes.

The choice of Jantho-Lamno Road is motivated by its status as a newly constructed route that connects eastern and western Aceh Province. Road deterioration issues in Aceh have been attributed to factors like insufficient knowledge of subsurface geological materials and subpar construction practices. This study uses geophysical methods to assess subsurface properties for geological characterization during road construction, ultimately improving awareness of landslide vulnerability in the region.

This research distinguishes itself by employing a novel combination of seismic refraction and geoelectric resistivity methods to comprehensively assess landslide susceptibility along the Jantho-Lamno Road in the Aceh Province of western Indonesia. Unlike previous studies that predominantly focused on the general vulnerability of Aceh to geological hazards, our research significantly advances the field by introducing an integrated geophysical approach tailored for landslide risk mitigation along the Jantho-Lamno Route. By combining seismic refraction and geoelectric resistivity methods, our study not only predicts landslide-prone zones but also provides a detailed characterization of subsurface conditions, surpassing the limitations of singular techniques. This nuanced understanding enables the formulation of targeted protective measures, establishing our work as a pioneering contribution in enhancing the resilience of critical transportation routes in geologically complex regions.

In the subsequent sections, we detail the methodology employed in our integrated geophysical analysis, present the findings, interpret the results, propose mitigation strategies, and discuss the long-term effectiveness of these measures. Additionally, we provide a comparative analysis with other regions facing similar geological challenges, enriching our understanding of landslide dynamics and risk mitigation on a global scale.

2. RESEARCH SIGNIFICANCE

This study is of utmost importance in geotechnical engineering and disaster risk mitigation, particularly in regions with intricate geological landscapes like the Aceh Province in Indonesia. The integrated geophysical analysis, utilizing seismic refraction and geoelectric resistivity methods, significantly advances our understanding of landslide susceptibility along the Jantho-Lamno Route. This in-depth evaluation allows for the identification of weakened upper layers and potential slip planes in deeper formations, providing a nuanced understanding crucial for formulating targeted protective measures. By addressing the challenges faced in road construction in disaster-prone areas, specifically focusing on the newly constructed Jantho-Lamno Road, the research contributes to the resilience of critical transportation routes and directly informs improvements in road infrastructure. Additionally, the study's insights into subsurface geological materials and identification of critical features have broader implications for geological studies and hazard assessments in similar regions globally. Furthermore, the research informs policy and planning processes, aiding in the development of targeted measures to enhance the resilience of critical transportation routes, with potential applications in sustainable development practices for areas prone to geological hazards.

3. GENERAL GEOLOGY OF STUDY AREA

The Lamno region in Aceh Jaya has diverse geological formations, including the Lhoong (Mulh) Formation. This formation is characterized by mafic volcanic rock, limestone, claystone, siltstone, and a minor sandstone (Fig. 1). The rocks in question have undergone a weathering process, transforming into sedimentary clastics. These clastics are subsequently deposited inside terrestrial environments [2].

The research site in the Jantho-Aceh Besar area is characterized by raba limestone formations (mulr), as depicted in Fig. 1 of the regional geological map. Aceh Besar is a geographical region encompassing multiple rock formations, specifically the Raba Limestone Formation. This formation is characterized by its dark hue, thin layering, and composition of clayey limestone and silicates. The rocks have experienced a weathering process resulting in sedimentary plastics forming, which are subsequently deposited in terrestrial environments [2]. The estimated ages of the Meucampli Formation, Lhong Formation, and Indapuri Formation range from the Middle Miocene to the Pliocene. In contrast, the Raba Limestone Formation is believed to have originated during the Jurassic to Cretaceous period, making it potentially the oldest formation [2, 3].

Aceh Province is situated inside the Sumatran Fault zone, extending from Teluk Semangko to the Andaman Sea, in a regional geological context. The western region of Aceh Province is Indo-Australian Plate converges with the Eurasian characterized by a subduction zone, where the Plate. The subduction rate beneath the Eurasian plate is around 5 centimeters per year, while the Indo-Australian plate exhibits a northward.

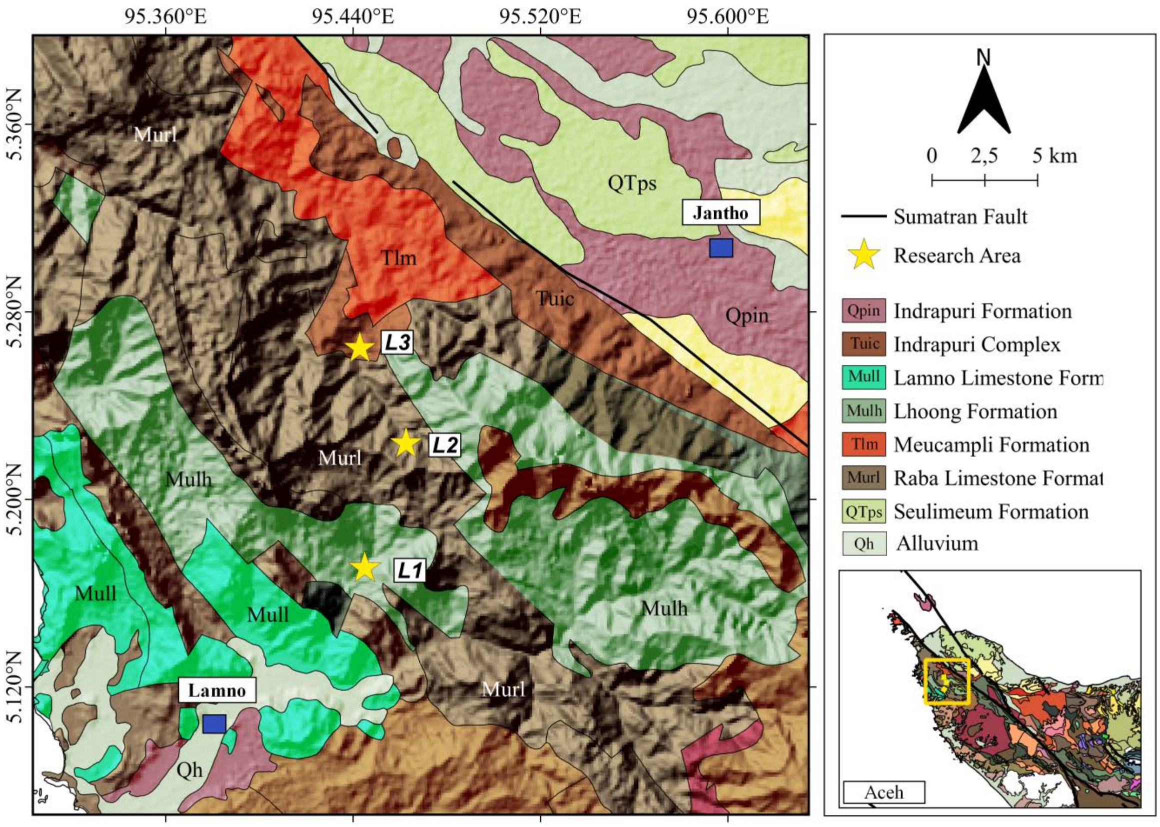

Fig.1 Geological Map of the Research Area, Modified from [2]

movement [2, 13, 14, 15].

Concerning the research area, the rock composition mentioned above has experienced weathering to become sedimentary clastics, which were then deposited in a terrestrial setting. Due to the complex geological setting and structure, this research area requires special slope stability studies. Landslides are triggered mainly by several key factors: high frequency and high strength earthquakes and high rainfall intensity. This conclusion is drawn from an analysis of secondary data and information gathered [2, 13, 14]. Applying slope stability and protection strategies is crucial for addressing slope-related concerns. However, researchers need to identify appropriate approaches for this purpose. The formation of landslides in [1] is primarily influenced by geological conditions and slope structure, as indicated by previous research [16, 17].

4. METHODOLOGY

This research comprises two main phases: field data collection and data analysis. The field data collection occurred in areas with potential slopes, utilizing the seismic method (3 lines) and the geoelectric method (3 lines) in the road construction area on the Jantho-Lamno Route. The data used in this study include recorded data from the PASI 16S – 24P seismograph, facilitating the determination of primary wave travel time in each layer of the measurement lines. Rock resistivity data were collected using the Wenner-Schlumberger configuration from the Naniura NRD-300 HF resistivity meter. Fig. 2 illustrates the study area of geophysical survey.

The research employs advanced geoelectric methods to measure resistivity values in the field, utilizing a multi-electrode configuration that enhances productivity and reduces operational costs. Specifically, the Wenner-Schlumberger electrode configuration is adopted, providing a hybrid approach that combines elements from both configurations and is tailored for setups with constant-spaced electrode lines. The study systematically varies the electrode distance factor (n) to comprehensively assess potential changes in resistivity values. The measurement process involves a step-by-step procedure, commencing with the establishment of a central reference point and extending the apparatus to cover a distance of 230 m. The Naniura NRD-300 HF resistivity meter, connected to potential and current electrode cables, is powered with a 12-volt DC battery, and measurements are conducted with 5 m electrode distances.

The Wenner-Schlumberger electrode configuration is a key method in geophysical surveys, measuring electrical resistivity through strategic steps. It starts with selecting electrode spacing, establishing a central reference point, and injecting current between outer electrodes. Varying spacings cover different depths, and recorded data create a resistivity sounding curve. Apparent resistivity is calculated for each configuration. The final step involves data inversion, interpreting the curve to generate a detailed subsurface resistivity model. This methodology effectively unveils geological insights.

Resistivity data processing using Res2Dinv involves inputting organized data, configuring the survey parameters, and creating an initial resistivity model. The Res2Dinv program is employed for data processing and modeling, utilizing measurements as input parameters to establish a 2-D resistivity model beneath the Earth's surface. This program efficiently handles up to 650 electrodes and 6500 points simultaneously [18] The software's inversion process iteratively refines the model to fit measured resistivity values, with careful parameter selection for optimal results. A thorough review and refinement loop may be employed, followed by cross-validation for model reliability. The final step involves presenting the resistivity models visually, enhancing the communication of subsurface resistivity distributions and geological insights. Always refer to the software documentation for version-specific guidance.

Refraction seismic data acquisition measures travel time of seismic waves to reveal geological layers. With a well-designed survey, shot points induce waves, and travel times are recorded at receiver stations. Analysis unveils depth and velocity insights. Velocity inversion constructs a subsurface model, aiding geological interpretation. Verification with field data ensures reliability, and visual presentations facilitate a comprehensive understanding. This method is crucial for applications like engineering site investigations and resource exploration.Simultaneously, the study determines the velocity of seismic waves using a PASI 16S–24P Seismograph equipped with 24 geophones. Seismic measurements are conducted along three lines (1, 2, and 3), each spanning 230 m with a uniform spacing of 10 m between each path. The seismic refraction measurements include a specific shot point configuration with seven shots on L1 and five shots each on L2 and L3.

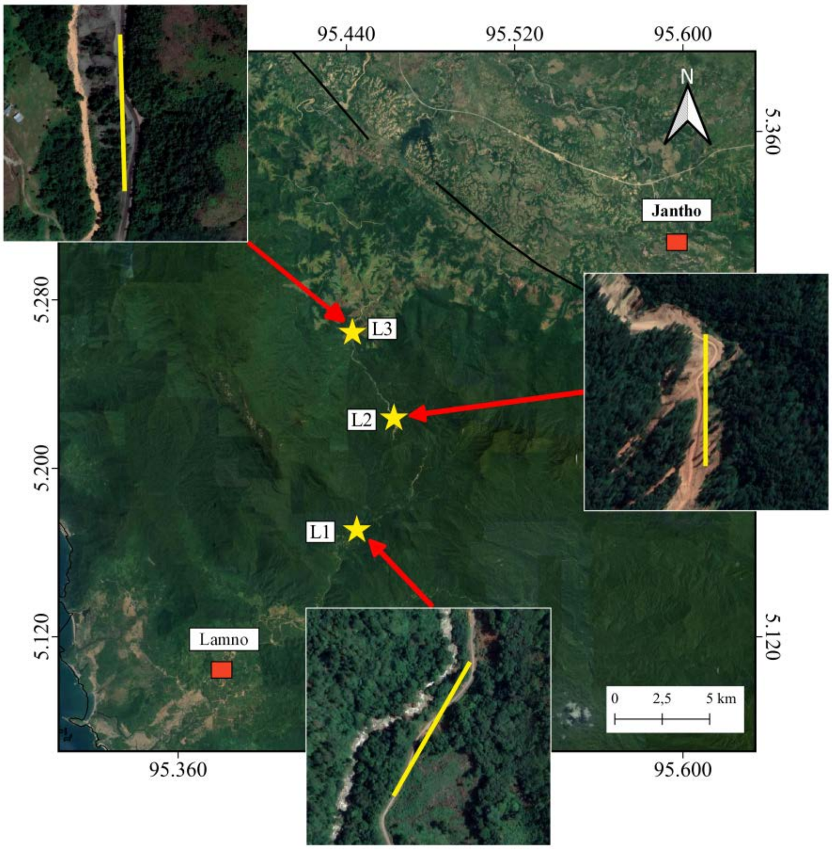

Fig. 2 The study area of geophysical survey in the road construction area on the Jantho-Lamno Route.

In the seismic refraction data processing using ZONDST2D [6], the initial step involves acquiring raw data through a survey along the Jantho-Lamno Road, recording travel times of refracted seismic waves. Subsequently, the data undergoes preprocessing to eliminate noise and enhance quality before being imported into ZONDST2D. Within the software, the survey geometry is defined, specifying the positions of the seismic source and geophones for accurate modeling. The construction of an initial velocity model precedes the forward modeling process, simulating expected travel times and aiding in the inversion to estimate subsurface velocities. Quality control checks ensure the reliability of the inverted model, which is then interpreted to unveil geological features beneath the road. Visualization tools within ZONDST2D assist in creating depth-velocity profiles or contour maps for a clearer representation of the subsurface structure. The final step involves comprehensive reporting, documenting processing steps, parameters, and interpreted results, providing valuable insights into the geological conditions of the Jantho-Lamno Route.

5. RESULTS AND DISCUSSION

The study identified distinct layers with varying characteristics along these lines, including alluvium, sandstone, clay, and limestone, with associated velocity and resistivity ranges. In Lamno (L1), three distinct geological layers were identified using seismic and resistivity methods. The initial alluvium layer, with a velocity range of 0.3 – 0.9 km/s and ±10 m thickness, was found to be vulnerable to landslides as illustrated in Fig. 3. The subsequent layer, consisting of sandstone and clay (velocity: 0.9 – 1.9 km/s, thickness: ±10 m), was identified as the landslide-prone area. A positive correlation between wave velocity and rock density was observed. The resistivity analysis of L1 revealed three layers with a penetration depth of ±50 m. The alluvium layer exhibited low resistivity (10-130 Ωm), and the second layer was a composite of sandstone and clay (130-250 Ωm). The third layer was composed of limestone (250-600 Ωm) as illustrated in Fig. 4. Visible boulders, likely derived from andesite igneous rock, were observed on the surface.

The slip plane at L1, in the Lamno area, was determined using seismic and resistivity data, showing consistent dimensions (40-90 units) within layers of sandstone and clay. Slope instability was influenced by mild to undulating topography with a slope range of ±40 degrees, characterized by a rotating slip type. Various slope protection methods were proposed for this sedimentary rock site, including shotcrete, wire mesh, net rock bolting, and targeted rock removal. Implementing a drainage system with proper gradient, asphalt layer application, and biotechnical slope protection were also suggested strategies [18, 19, 20]. These measures aimed to mitigate potential slope hazards and improve stability.

In Jantho (L2), the study identified three geological layers through seismic analysis. The initial alluvium layer, saturated with water, had a velocity range of 0.3–0.9 km/s and a thickness of ±5 m. The second layer, composed of sandstone and clay, had a velocity range of 0.9–1.9 km/s and a thickness of ±15 m. The third layer, limestone, had a velocity range of 1.9–2.9 km/s and a thickness of ±50 m. Landslide susceptibility was found in the alluvium layer, with a velocity range of 0.3–1.3 km/s, while the landslide-prone area was in the sandstone and clay layer, with a velocity range of 0.9–1.9 km/s as illustrated in Fig. 5. A positive correlation existed between wave velocity and rock density.

The resistivity analysis for Jantho (L2) showed three layers with a penetration depth of ±55 m

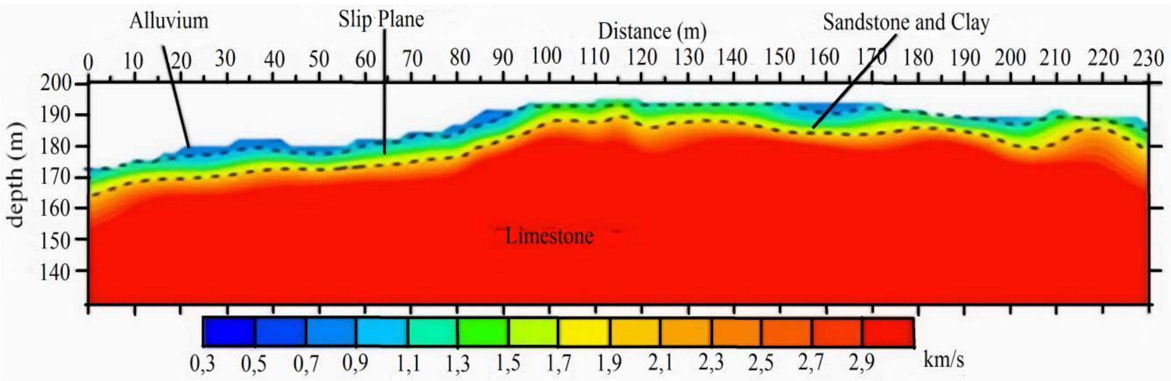

Fig. 3 Seismic Refraction Results at L1

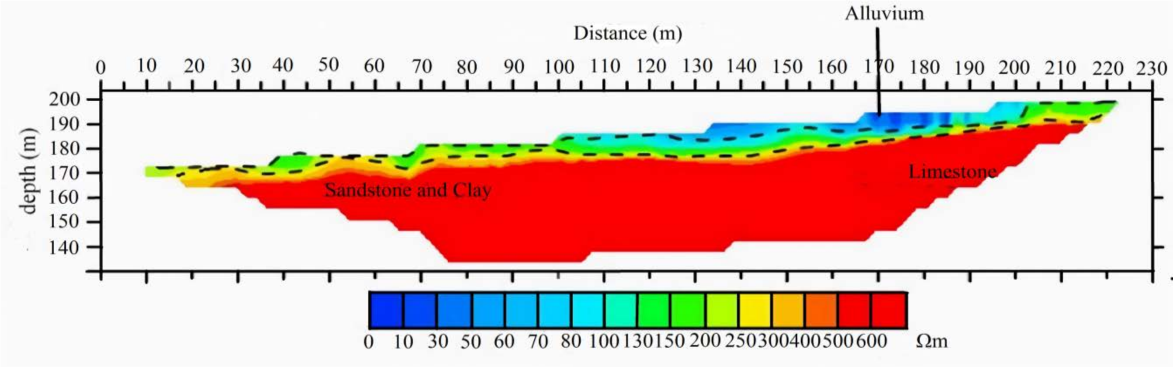

Fig. 4 Resistivity Results at L1

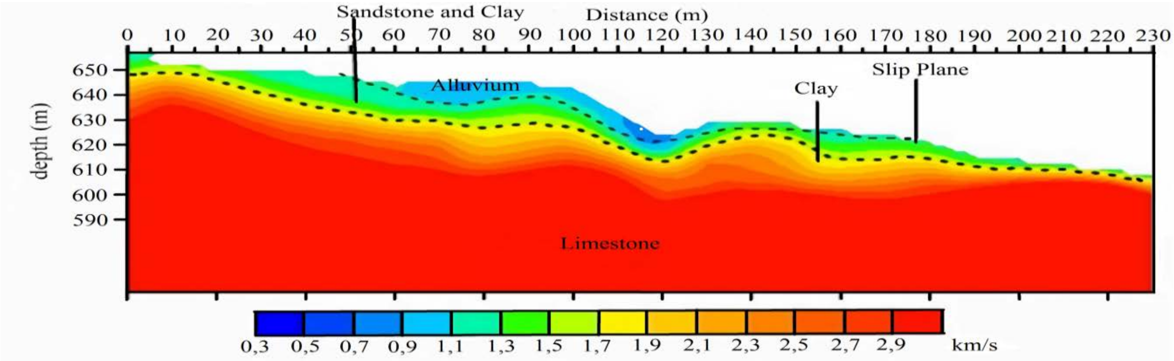

Fig. 5 Seismic Refraction Result at L2

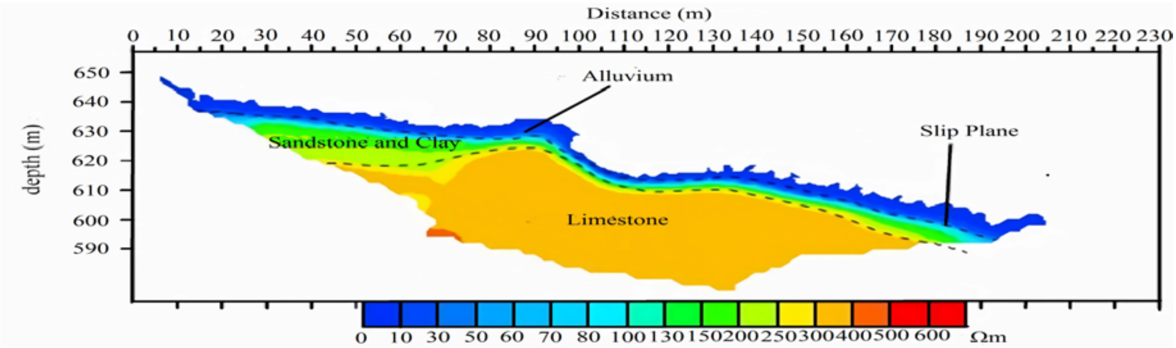

Fig.6. Resistivity Results at L2

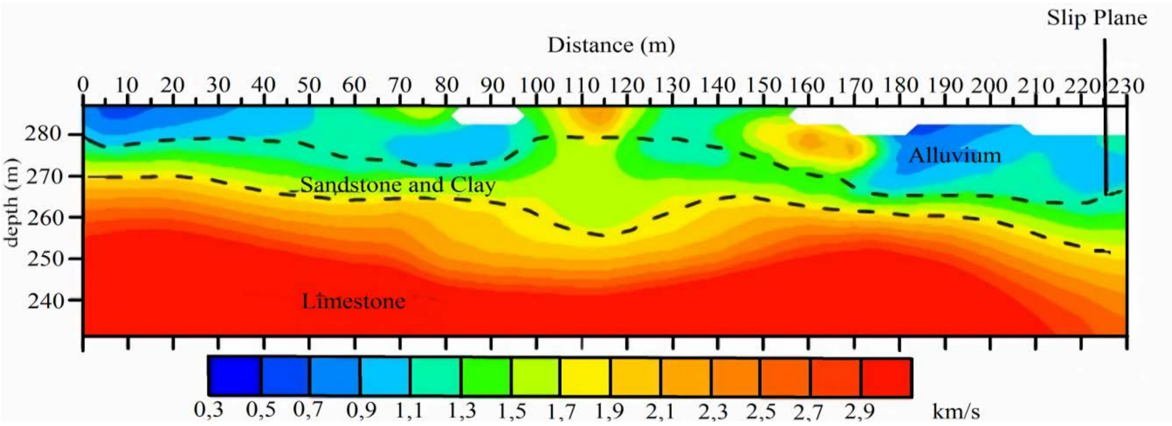

Fig. 7 Seismic Refraction Results at L3

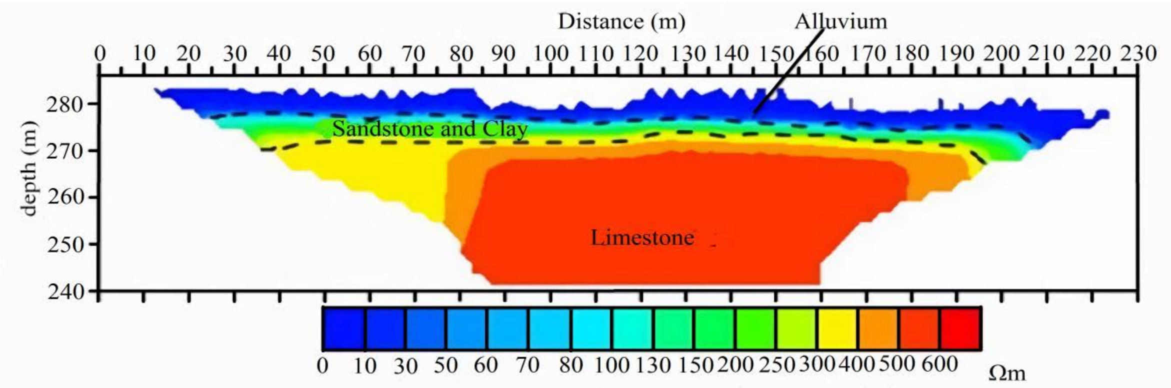

Fig. 8 Resistivity Results at L3

as illustrated in Fig. 6. The initial alluvium layer had resistivity values of 10–130 Ωm and a thickness of ±10 m. The second layer, a composite of sandstone and clay, had resistivity values of 130–250 Ωm and a thickness of ±15 m. The third layer, limestone, exhibited resistivity values of 250–600 Ωm and a thickness of ±30 m. The slip plane at L2 was determined to have comparable cross-sectional dimensions within the sandstone and clay layers. Jantho (L2) displayed slope instability due to a slope gradient of ±60 degrees, characterized by a curved Rotational Slip feature. Mitigation strategies for this steep site included retaining walls, gabions, drainage systems, and vegetation cover to prevent slope collapse and initial alluvium layer with a velocity range of 0.3–1.3 km/s, while the sliding area was within the subsequent layer of sandstone and clay, exhibiting a velocity range of 0.9–1.9 km/s. A positive correlation between wave velocity and rock density was observed

Resistivity data processing for Jantho Line (L3), with a penetration depth of ±50 m, showed three layers as illustrated in Fig. 8. The initial alluvium layer had resistivity values of 10–130 Ωm and a thickness of ±10 m, saturated with water, resulting in low resistivity. The layer immediately below, a combination of sandstone and clay, exhibited resistivity values of 130-250 Ωm and a thickness of around ±10 m. The third layer, classified as limestone, had resistivity values of 250-600 Ωm and a thickness of approximately ±30 m.

The slip plane's position at L3 was determined using seismic refraction and resistivity methods, showing similar cross-sectional dimensions. The slip plane was found within a stretch distance of 175-230 and corresponded closely to the sandstone and clay layer. Jantho Line (L3) exhibited slope instability with a relatively gentle slope ranging from 20-35 degrees, and the slip surface observed had the characteristics of a Translation Slip type, which is flat in shape.

regulate water movement. Vegetation's root systems enhanced shear strength and stability, particularly in weak or unstable areas [21, 22, 23].

In Jantho (L3), three distinct geological layers were identified through seismic analysis with a penetration depth of around ±50 m as illustrated in Fig. 7. The initial alluvium layer, exhibiting water saturation in various sections, had a velocity range of 0.3–0.9 km/s and a thickness of around ±10 m. The second layer, composed of sandstone and clay, had a velocity range of 0.9–1.9 km/s and a thickness of around ±10 m. The third layer, identified as limestone, had a velocity range of 1.9–2.9 km/s with a margin of error of ±30 m. The region prone to landslides was found in the

Mitigation strategies for Jantho Line (L3) included shotcrete, soil nails, re-profiling, and cutting techniques. Shotcrete and soil nails were emphasized due to the susceptibility of pyroclastic deposits to erosion. Shotcrete prevents rainfall infiltration into the slope, while soil nails enhance the interaction between soil [24] and shotcrete [25]. Re-profiling involved modifying the slope's configuration to establish a stable height and slope [26].

The study reveals a geologically vulnerable region prone to landslides, characterized by a soft upper layer and a hard lower layer. Factors like tectonic movements, precipitation intensity, and seismic activities contribute to landslide risks in Aceh Province. Implementing tailored slope protection measures such as shotcrete, wire mesh, net rock bolting, rock removal, and slope modification is crucial. Further studies, including rock mass assessment and kinematic analysis, will enhance mitigation efforts in similar regions.

6. CONCLUSION

In conclusion, this study has identified a distinct weak zone at the research site, characterized by a soft upper layer and a hard, dense second layer. The second layer exhibits low velocity and resistivity values, making it susceptible to sliding. This weak zone acts as a slip plane, facilitated by water-saturated layers, particularly in the case of Line 1 Lamno (L1) and Line 2 Jantho (L2), which consist of sandstone and clay, resulting in slightly curved Rotational Slip types. Line 3 Jantho (L3) displays a flat Translation Slip type due to the presence of sandstone and clay. These weak zones consist of rocks with low strength and poor compaction, making them prone to structural failure under the influence of gravity forces.

The main factors contributing to landslides and ground movements in Aceh Province include active tectonic movements, intense rainfall, geological structures, weathering, and seismic activity. Mitigation measures for landslides involve various slope stability and protection methods, which should be selected based on the specific composition and condition of the slope material. Different approaches are required for soil and rock slopes due to their distinct stability characteristics. In regions like L2 and L3 in Jantho, methods such as shotcrete, wire mesh installation, net rock bolting, and rock removal have been identified as suitable for slope stabilization. In areas with extensively weathered rock and soil debris, re-profiling and rock removal techniques are necessary. Loose debris observed on the slopes of L1 Lamno can be addressed with shotcrete, soil nails, or slope redesign methods to mitigate the risk of slope collapse.

Further research efforts should focus on assessing rock mass, slope mass, and kinematic analysis to better understand landslide risks in Aceh Province. These studies are essential for developing effective strategies to reduce the risk of landslides in the region.

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