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INTERDISCIPLINARY INVESTIGATION OF DEEP-SEATED COMPLEX LANDSLIDE ON THE PONOROGO – PACITAN ROAD, EAST JAVA PROVINCE, INDONESIA

*Arief Rachmansyah[1], Mayang Bunga Puspita[2], Faridha Aprilia[2]

[1]Civil Engineering Department, Brawijaya University, Malang, Indonesia
[2]Physics Department, Brawijaya University, Malang, Indonesia

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ABSTRACT: Road transportation plays an important role in driving economic growth in remote areas. Pacitan Regency, located in the southwest corner of East Java Province Indonesia, is an area with low economic growth. One of road transportation infrastructures that reach Pacitan Region is the Ponorogo - Pacitan Roads. However, along this route, there are some mass movements. Previous investigations have successfully identified dozens of landslide and rockslide points, which can be classified into three types: planar rockslides, wedge rockslides, and complex landslides. One significant landslide has been observed at 226 km, with the potential to shift the highway. Geodetic survey in 2021 using aerial mapping methods showed that the landslide zone had moved by 20 cm over 3 years. This landslide not only buried the road under debris but also shifted a 200-meter segment of the road. Later investigations in 2023 utilized the resistivity geoelectric method to determine the slip plane of the landslide. The results of the geoelectrical investigation concluded that the slip plane is located approximately 30 meters beneath the existing road. Based on the initial and follow-up investigations, that landslide can be classified as a deep-seated complex landslide. Numerical stability analysis, both using limit equilibrium and finite element method, showed that the number of safety factors of slope stability was low to very low. Landslide mitigation using retaining pile methods has only a small effect on the factor of safety number and is very costly. Therefore, non-conventional methods are needed to mitigate the landslide.

Keywords: Deep seated complex landslide, Interdisciplinary investigation, Hazard mitigation, Non-conventional method

1. INTRODUCTION

Road transportation infrastructure plays an important role in driving the regional economic growth, especially for the remote area. Pacitan Region, located in the southwest corner of East Java Province, Indonesia, is characterized by low economic growth [1]. The primary road transportation infrastructure serving to the Pacitan Region is the Ponorogo – Pacitan Road. However, along this road there are some mass movements, both landslides and rockslides. These slides are a common form of natural disaster in Indonesia, that exhibiting diverse scales, driving factors, complex triggers, and mechanisms [2].

Landslides occur across all continents and play a significant role in landscape evolution. Furthermore, they pretense a serious hazard in many parts of the world [3]. The key objective of landslide investigation is zoning, prediction, and mitigation, utilizing a combination of appropriate modern methods [4]. The geometry of landslides is crucial for stability and failure analysis models, as well as influencing the mitigation process. However, there is a lack of understanding regarding the factors that affect the 3D geometry of a landslide [5].

Detailed information about landslides, such as geological structure, soil or rock characteristics, groundwater, and their relationships, can be represented as a bulk model [6]. The overall model is derived from surface and subsurface investigations. Surface investigations aim to obtain topographic or 2D models for calculating the moving masses of the landslide. The use of UAVs as a means to update topographic data by performing aerial survey has proven to be efficient in terms of safety, time, and cost [7,8].

Information regarding the material and conditions beneath the ground surface can be obtained through geotechnical investigations involving drilling or geophysical methods [9]. The common method of geophysical investigation for subsurface characterization of landslide areas are Vertical Electrical Sounding and the Electrical Resistivity Tomography [10, 11,12].

Assessing a slope's stability is a challenging yet important aspect of mass movement mitigation. In its simple form limit equilibrium methods are used, stability is determined by the equilibrium of shear stress and shear strength. Factor of safety (*FoS*) is calculated by dividing the resistance by the driving forces [13]. Limit equilibrium method is the most common and practical used, but it should not be applied when the slope categorized as complex failure mechanisms [14].

The slope stability analysis techniques include limit equilibrium, empirical approaches for rocks slopes (SMR, Q-slope), finite element, district elements codes [15]. In Finite Element Method, slope stability analysis utilizes the shear strength reduction which involves calculating the safety factor by reducing the parameters that influence soil shear strength, namely cohesion and soil friction angle.

The main objective of the research that has been conducted is to find out a mitigation method for deep-seated complex landslide on Ponorogo – Pacitan Road km 226 which is effective (increases the slope stability) and efficient (low cost and easy to implement). This paper presents the results of a time-variant surface model of mass movement, 3D models with accurate depth of slip plane, and numerical analysis to increasing slope stability.

2. RESEARCH SIGNIFICANCE

This study offers a novel and original framework for mitigating deep-seated complex landslides threatening critical road infrastructure in low-growth regions. Unlike conventional approaches, it integrates long-term geodetic data to show deformation area, geoelectrical resistivity imaging, geotechnical drilling and advanced numerical analyses to construct a realistic 3D landslide model that closely represents field conditions. The originality lies in demonstrating the limitations of traditional retaining pile solutions for deep slip plane and proposing the need for non-conventional mitigation strategies base on interdisciplinary evidence. This research advances landslide hazard assessment by linking surface displacement, subsurface condition, and economic feasibility into a unified decision-making model.

3. METHODES

To obtain topographic map of the landslide area and surrounding and dangerous area was acquired through aerial survey techniques. It is crucial to calculate the volume of the moving mass within the landslide for numerical analysis. This map was useful for comprehensive subsurface data by engineering geology investigation, geotechnical drilling and resistivity geoelectric survey. After a geotechnical standpoint, determining the sliding plane and mapping crack distribution are important roles. The safety factor of slope stability is calculated using software based on limit equilibrium and finite element. With the same software simulations are also carried out for reinforcement of slope stability by modifying of slope geometry and retaining piles.

3.1 Topographic Mapping

The aerial survey was conducted at a height of 100 meters from the take-off point as existing roads. Data processing was carried out using the Open Drone Map facility to generate ortho-mosaic-photos and digital terrain models (DTM) [8]. The UAV used for the survey was the DJI Mavic Air 2.

The DTM generated from this aerial survey is used to estimate the mass that moved during the landslide. Volume calculations are performed using DEMNAS as the initial topographic data. DEMNAS refers to the national topographic data of Indonesia, which was publicly released in 2018.

3.2 Engineering Geology Investigation

Two distinct soil and rock investigation methods were conducted in this study: field investigation and laboratory testing [16]. Geotechnical drillings to determine soil and rock profiles were carried out by the East Java Province Highways Service. Relevant soil parameters, such as specific gravity, water content, porosity, and clay content, were measured on laboratory.

3.3. Resistivity Geoelectrical Investigation

Resistivity geoelectric investigation, type Vertical Electrical Sounding (VES), and Electrical Resistivity Tomography (ERT) have been conducted. The VES method utilizes electrodes through which a direct current (DC) is passed to penetrate the layers of soil and rock structures. The difference between ERT and VES lies in the electrodes array and obtained results. The VES method generates apparent resistivity profiles of materials in a vertical one-dimensional format. VES geoelectrical investigations were conducted using the Schlumberger method at four points distributed within the estimated moving area. The advantage of using this VES method lies in its ability to penetrate deeper than ERT array within the same maximum distance between electrodes [17,18].

This study employs ERT survey with Dipole-dipole array. Three line-arrays of ERT survey were carried out across the landslide both from its crest to the toe and from side to side. However, the obtained results have certain limitations in accurately describing information pertaining to the depth of the sliding plane and the estimated volume of the moving masses. Consequently, additional measures are taken, including VES and ERT surveys, to acquire more precise and comprehensive data on these aspects.

3.4 Numerical Analysis of Slope Stability

Numerical slope stability analysis was carried out using software based on limit equilibrium and finite elements. An analysis with the limit equilibrium approach used the Morgenstern-Price formulas. In this analysis, the surface geometry is based on topographic measurements by UAV. The slip plane is based on the results of geoelectrical resistivity investigations and drilling data, then the slip plane generated by the software is automatically adjusted. The results of calculations with this approach are in the form of collapse areas and safety factor values.

Calculation of slope stability with the Finite

Element Method is carried out only for 2-dimensional models. The slope condition model is the same as the calculation with LEM. Calculations with FEM also produce safety factor values, both on slopes without and with reinforcement. Slope reinforcement simulation was chosen with pile driving, because this structural mitigation is the most likely to be carried out in the field [19].

4. STUDY AREA

4.1 Location of The Complex Landslide

The Ponorogo – Pacitan Road is situated in the southwest part of East Java Province, Indonesia. The landslide is located at kilometer 226, specifically within Slahung District, Ponorogo Regency. The responsibility for managing the road lies with the East Java Highways Services (Fig 1).

4.2 Geological Overview

The Ponorogo – Pacitan Road is situated in the eastern part of the Southern Mountains Zone. Generally, it exhibits undulating morphology and is composed of Early Miocene volcanic rocks, specifically a member of the Watupatok Formation (Fig.1), which contains andesitic lava interbedded with sandstone-claystone and chert [20].

The geological structures in the eastern part of the East Java Southern Mountains consist of folds and faults. These faults can be categorized into four groups based on their orientation: northeast-southwest, west-east, northwest-southeast, and north-south trending faults. Dacitic and andesitic intrusive rocks can be found in several areas, and the presence of these faults and intrusive rocks has resulted in gold-copper mineralization in several locations [20].

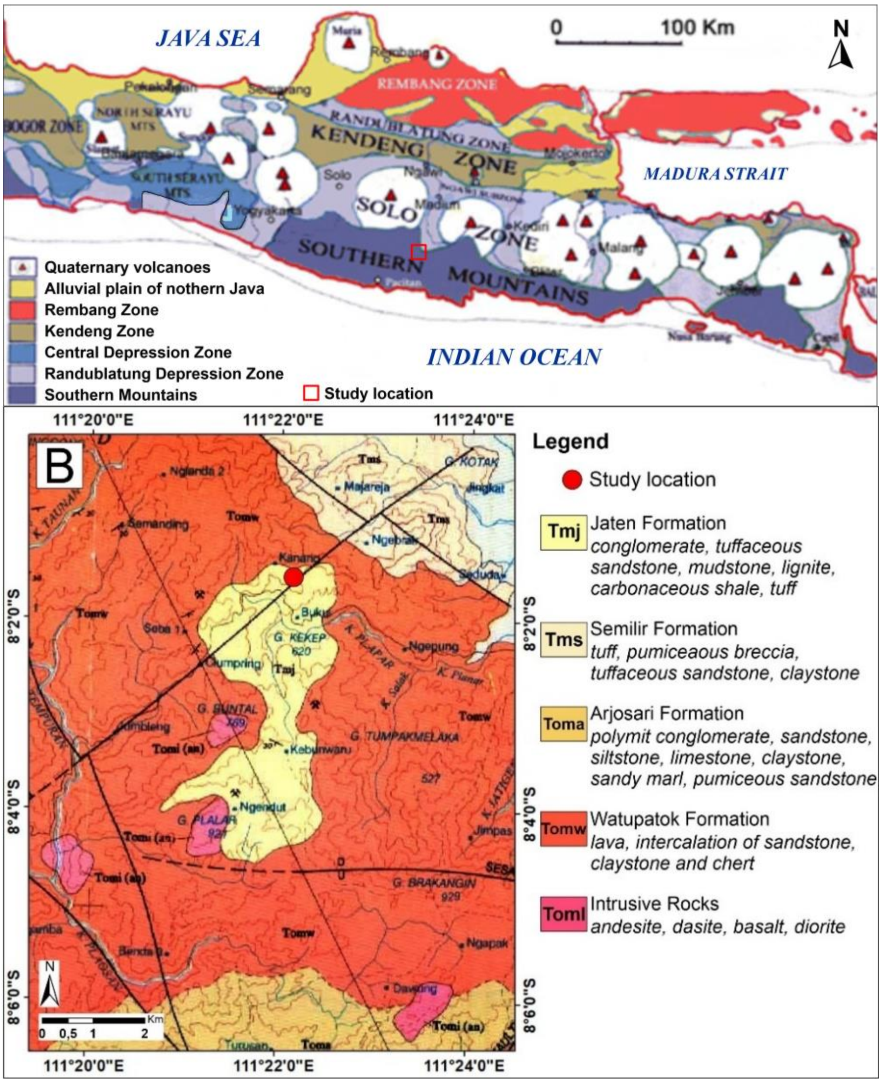

Fig. 1. Physiographic map (A) and Geological map (B) of study area [20]

After a engineering geology perspective, the presence of faults and mineralization increases the potential for landslides. In 2019, investigations successfully identified dozens of landslide locations, which can be classified into three types: planar, wedge, and complex. One of the large-scale landslides is situated at kilometer 226 and poses a risk of cutting off the highway. After the topographyc map of the study area and its surrounding (Fig 2) this landslide not only buried the road with debris but also shifted a 200-meter-long section of the road [2].

The landslide became a complex landslide because of the existence of boulders of basaltic rocks besides the silt-clay-sand as the main material on the area landslide. There is a high probability for the landslide to occur because of the alterated basaltic bedrock material. The existence of the alteration zone indicates the existence of a geological structure such as fault and or fracture. At the western boundary of the moving material, fractured and low-altered dacite is found [22]. Judging from the regional geological map, the moving material is likely sandstone and basalt from the Watupatok Formation, altered by dacite intrusion.

Furthermore investigations employing geomagnetic methods are necessary to determine the that assess the influence of surrounding geological structures showed, that the landslide at the research location is expected to spread eastward [23].

5. RESULTS AND DISCUSSION

5.1 Surface Topography and Deformation

The topographic contour (Fig. 2) based on the Digital Terrain Model (DTM) data that processed from the aerial survey results in August 2021. The research location and its surrounding covers an area of 287×470 m². Surface deformation analysis was carried out by comparing elevation between initial topographic data after Indonesian DEMNAS that published 2018.

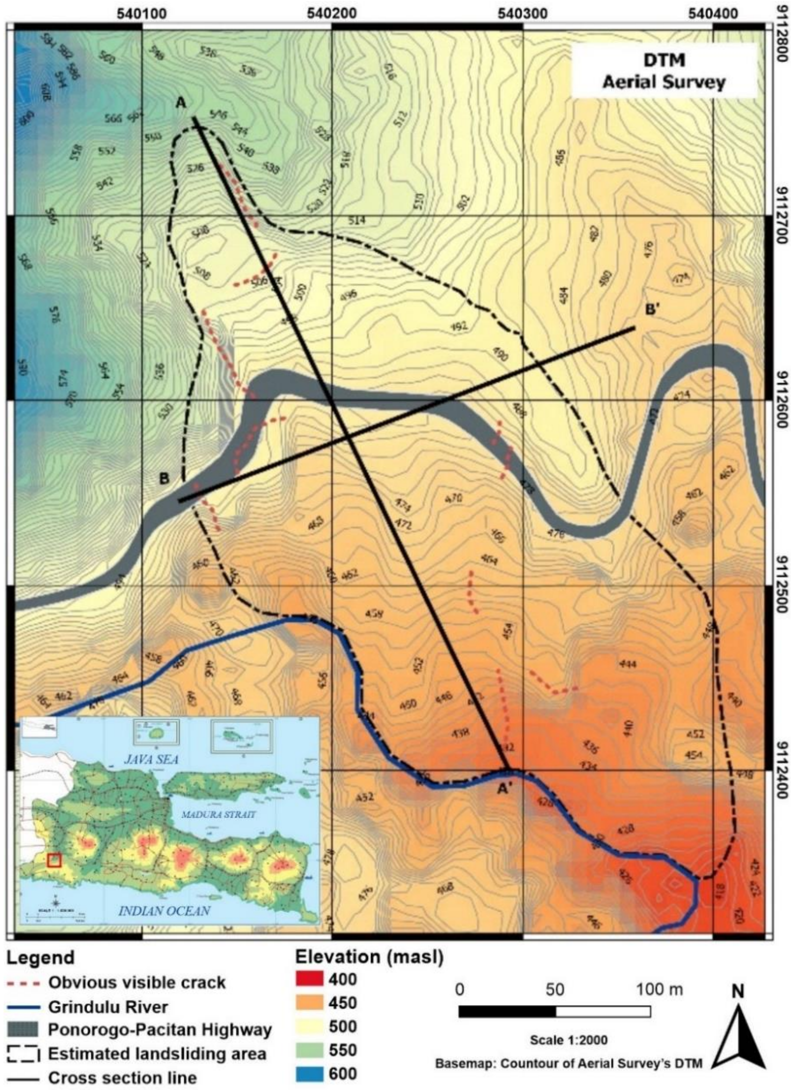

Fig. 2 Topographyc map of landslide area and its surrounding.

The estimated area affected by the mass movement event is 4.21 hectares. Figure 3 shows the elevation profile from both topographic data at line AA’ and BB’ The AA" line from Northwest to Southeast is considered to represent the moving slope, while the BB' line from East to West is chosen to represent the highway route. By comparison of AA’ profiles before and after the landslide incident, it shows that the upper part tends to move downwards, while the lower part moves upwards. At the location of the BB profile represent uplift.

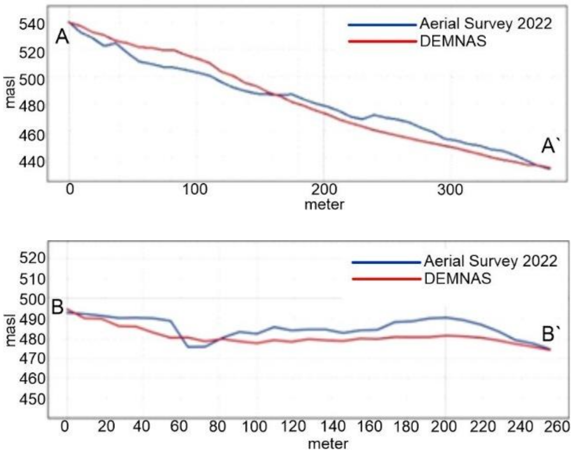

Figure 3. Topographic deformation at landslide area base on DEMNAS (2018) and DTM (2021).

Surface deformation in the form of ground subsidence and uplift, with a total deformation value ranging from -4.7 m to 6.58 m during the period of November 2017 (published 2018) to August 2021 (UAV survey). Factors influencing the occurrence of deformation at the research site include morphological conditions, landslides, river erosion, and land use. After figure 3 indicates that the average deformation velocity at the research location ranges from -0.554 m/year to 0.211 m/year during the observation period from November 2017 to August 2021.

The estimated volume of the moving masses obtained by comparing the DEMNAS and DTM from aerial survey is up to 160,000 m^3. The volume estimation was carried out by multiplication of landslide area based on updated topographic data that obtained using Aerial Survey and depth of slip plane as the result of subsurface investigation.

5.2 Sub-Surface Landslide Model

To construct subsurface model of landslide was carried out resistivity geoelectric survey on 4 points for VES, 3 lines for ERT, and 2 point for geotechnical drilling (fig 4). Locations were selected based on easiness of implementation in the field and the lowest error in calculations. Data processing was performed using IPI2WIN and Progress sofware, and RockWorks to create profiles and 3D models.

5.2.1 VES Geoelectric Survey

Figure 5 shows cross-sectional profiles of the VES results at four points scattered around the landslide site, projected parallel to Line AA' of the topographic profile. This aims to visualize the subsurface conditions and the deeper distribution of materials beyond what is captured by ERT, reaching depths of up to 90 meters from the ground surface. In the cross-sectional VES profiles, it can be interpreted that the bedrock (dasitic lava) depth ranges around 60 meters from the surface, with tuff dominating between depths of 20 to 60 meters compared to Clay and Clayey-Tuff materials.

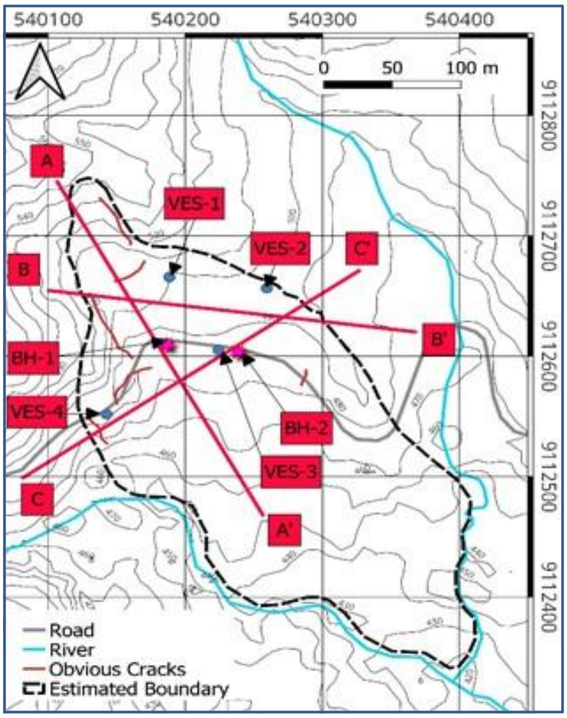

Fig 4. Landslide area and VES geoelectric point, ERT lines, and borehole points.

The sliding plane in the VES profiles is interpreted to be located at the contact area between the Clay and Tuff materials at depths of 20 to 30 meters from the ground surface. The lower cohesive properties of the clay material allow for mass movement if there is a significant increase in water content. The sliding plane pattern indicates that the slip plane of the landslide is stepped.

5.2.2 ERT Geoelectric Survey

The ERT method provides a cross-section profile of apparent resistivity that can be interpreted to determine subsurface materials. The ERT profiles were interpreted using lithology indexes derived from borehole data analysis. The optimal depth of the apparent resistivity profile obtained by ERT is 25 meters below the surface (Fig 6).

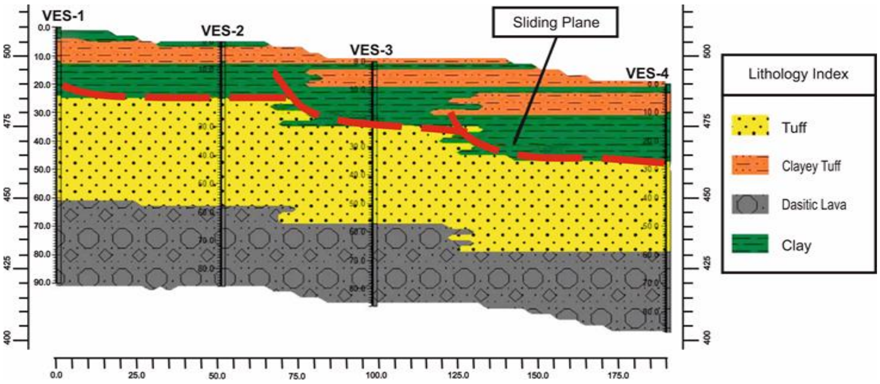

Fig. 5 Cross-section from combines VES Profiles

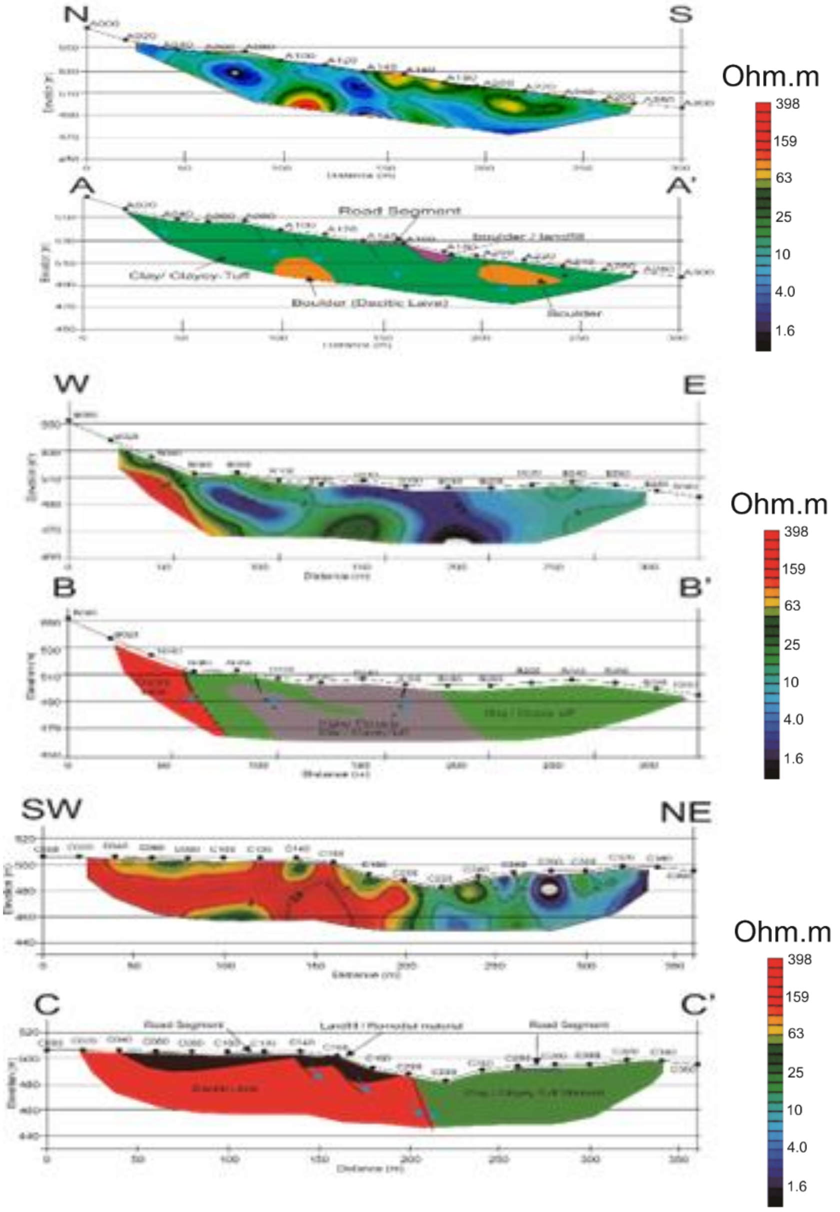

Fig. 6 Subsurface profiles from ERT geoelectric survey and its interpretation (ERT Line AA', BB', and CC')

Figure 6a illustrates the contrasting resistivity observed along Line AA', delineating a distinct boundary between the low resistivity zone (<10 Ohm.m) and the high resistivity zone (>10 Ohm.m). Resistivity values below 10 ohm.m signify the presence of clay resulting from the weathering of the tuffaceous mudstone material. Additionally, resistivity values ranging from 15 to 20 ohm.m indicate the existence of a porous zone filled with water. The Clayey-Tuff layer beneath Line AA' exhibits a southern inclination. Moreover, the measured fracture orientation at the surface aligns parallel with the distribution pattern of the Clayey-Tuff material.

Figure 6b shows contrasting resistivity along Line BB' occurs between the high resistivity zone (>80 Ohm.m), the moderate resistivity zone (10 - 40) Ohm.m), and the low resistivity zone (<15 Ohm.m). The geological significance of the high resistivity contrast with the low resistivity zone in the western part of Line BB' indicates the presence of a contact between Dacitic lava and soil or Clayey-Tuff material. The measured surface fractures exhibit an orientation parallel to the inclination of the weathered.

Figure 6c shows contrasting resistivity along Line CC' occurs between the high resistivity zone (>80 Ohm.m), the moderate resistivity zone (10 - 40 Ohm.m), and the low resistivity zone (<15 Ohm.m). The high resistivity zone to the west of Line CC' suggests the presence of dacitic lava at depths of 10-20 m. The high and low resistivity contrasts within the dacitic lava and soil in the central part of Line CC' indicate a distinct vertical pattern. The resistivity contrast in the middle section of Line CC' signifies a vertical contact between the dacitic lava and the soil or clayey-tuff, which can be interpreted as a sliding plane. The measured surface fractures show an inclination parallel to the contact pattern of the basaltic rock and soil/ clayey-tuff, specifically towards the east.

5.2.3 Three Dimensional Model

The three-dimensional model is created by combining the previous data and cross-sections into a comprehensive model, as shown by Figure 7. From the results of the three-dimensional model, it can be observed that there is a transition between the clay layer and the sandstone layer starting at a depth of 20 meters. Clay typically exhibits lower cohesion due to its fine particle size and composition, whereas sandstone demonstrates higher cohesion owing to its larger particle size and the cementation of sand grains. The non-uniform distribution of the clay layer and the presence of surface fractures facilitate water infiltration into the sandstone layer, resulting in the formation of a sliding plane. The three-dimensional model also indicates that the material moving towards the southeast exhibits a relatively massive nature and will continue its movement due to the lower cohesion of clay materials.

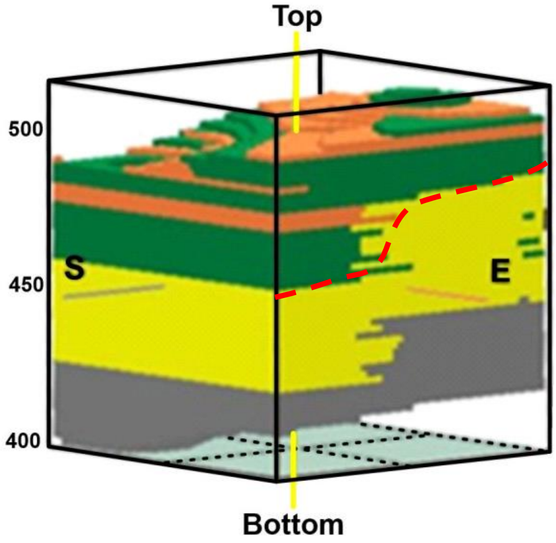

Fig. 7 The three-dimensions subsurface model for the study area.

5.2.4 Characteristic of Material

There are two boreholes being sampled for performing geotechnical investigation. Both boreholes are located next to the road, as shown by Figure 3. The first has maximum depth at 15m, while the second has maximum depth at 30m. From both borehole there are four lithology indexes that can be derived, i.e Clay, Tuff, Clayey-Tuff, and Dacitic Lava. The maximum depth of the sliding plane located from 20 to 30 m below the current road surface. It is classified as a deep-seated landslide. It has higher probability for become chronic landslide, that occurs when the material absorbs enough rainfall water.

Data on the physical and mechanical properties of the material were obtained from laboratory test results. Soil samples were obtained from drilling data, while rock samples were obtained from outcrops (Table 1).

Table 1. Physical and mechanical characteristic of material

Material	Unit Weight	Cohesion	Friction Angle	Modulus Elastisity
	(γ')	(c)	(ϕ)	(E)
	kN/m^3	kPa	°	kPa
Topsoil (Silty sand)	19,97	22,55	22	20000
Debris material (gravelly clay)	16,04	33,34	13	30000
Water saturated silty clay	19,05	31,38	15	25000
Tuff	17,6	90	38	40000
Dacitic Lava	20	100	50	50000

5.3 Slope Stability

5.3.1 Slope Profile

The shape and size of the slope play an important role in calculating the stability, because both parameters affect factor of safety value. In this study, the slope surface profile was obtained from the results of a topographic mapping using the aerial method (Fig. 8).

The subsurface profile is based on the results of drilling and resistivity geoelectric investigations. The slip plane is based on the presence of a layer of soil or rock with a high-water content [19], while the pattern of rock stratigraphic is adjusted to the results of geoelectric profiling.

5.3.2 Slope Stability by Limit Equilibrium Method

Almost all slope stability analysis with limit equilibrium-based software produces a theoretical slip plane in the arch form that arc according to the specified approach. In this modeling, the slip plane is simulated until it approaches the plane of the subsurface investigation results (Fig. 9).

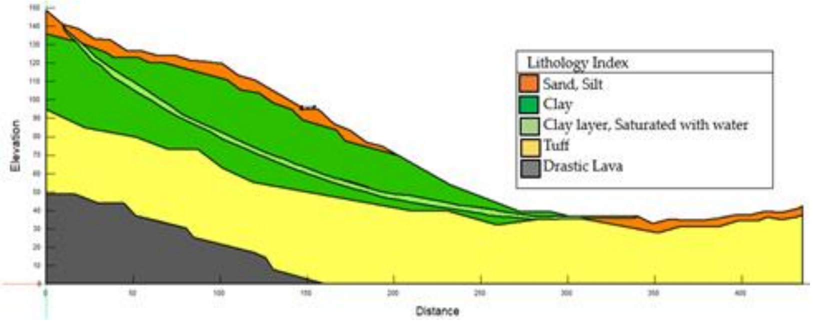

Fig. 8 Slope profile of moved mass

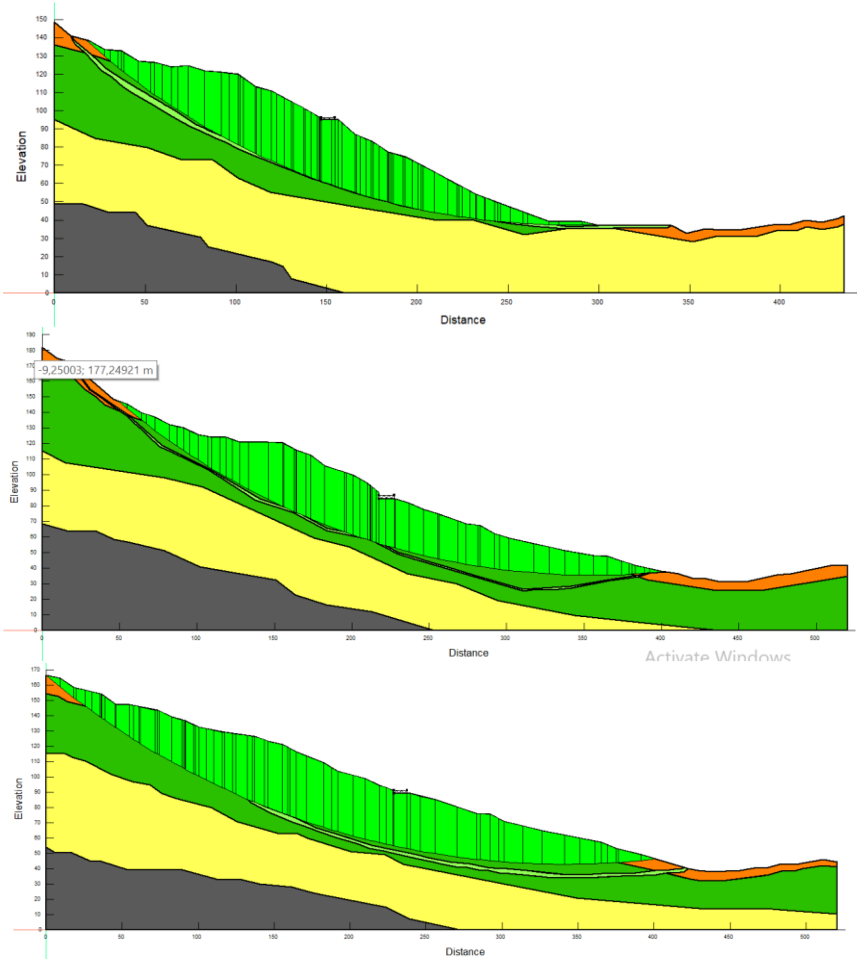

Fig. 9 Slope profiles and moving material as simulation results using the limit equilibrium method.

Slope stability calculations were performed using Geostudio 2018 Slope/W. Slope stability was calculated during the dry season and the rainy season when the slip plane is saturated. Calculations were made using the Morgenstern-Price limit equilibrium method. The analysis was carried out on three different profiles that Northwest – Southeast direction. The factor of safety (FoS) is presented in Table 2. The results of the limit equilibrium calculation indicate that the slope is unstable and will move during the rainy season.

Table 2: Resume Factor of Safeties and its stability

Profile of Slope	Factor of Safety (FoS)		Decreasing of FoS	Stability
	Dry season	Rainy Season		
A-A	0,941	0,609	35,28%	Unstable
B-B	1,084	0,726	33,03%	Unstable
C-C	1,102	0,7	36,48%	Unstable

5.3.3 Slope Stability by Finite Element Method

The result numerical analysis by using FEM is presented on Figure 10. The slip plane in 2D finite element-based software is represented by a very contrasting deformation difference. In the analysis with the finite element method, the deformation limit is greater than the slip plane of the subsurface investigation results, these consequences the factor of safety value is lower than the result of limit equilibrium calculation. This is likely due to the greater amount of material movement. In the LEM analysis, the landslide slip plane can be adjusted to approximate the 2D model resulting from the subsurface investigation, while in the FEM analysis the deformation boundary considered as the slip plane is automatically generated by the software.

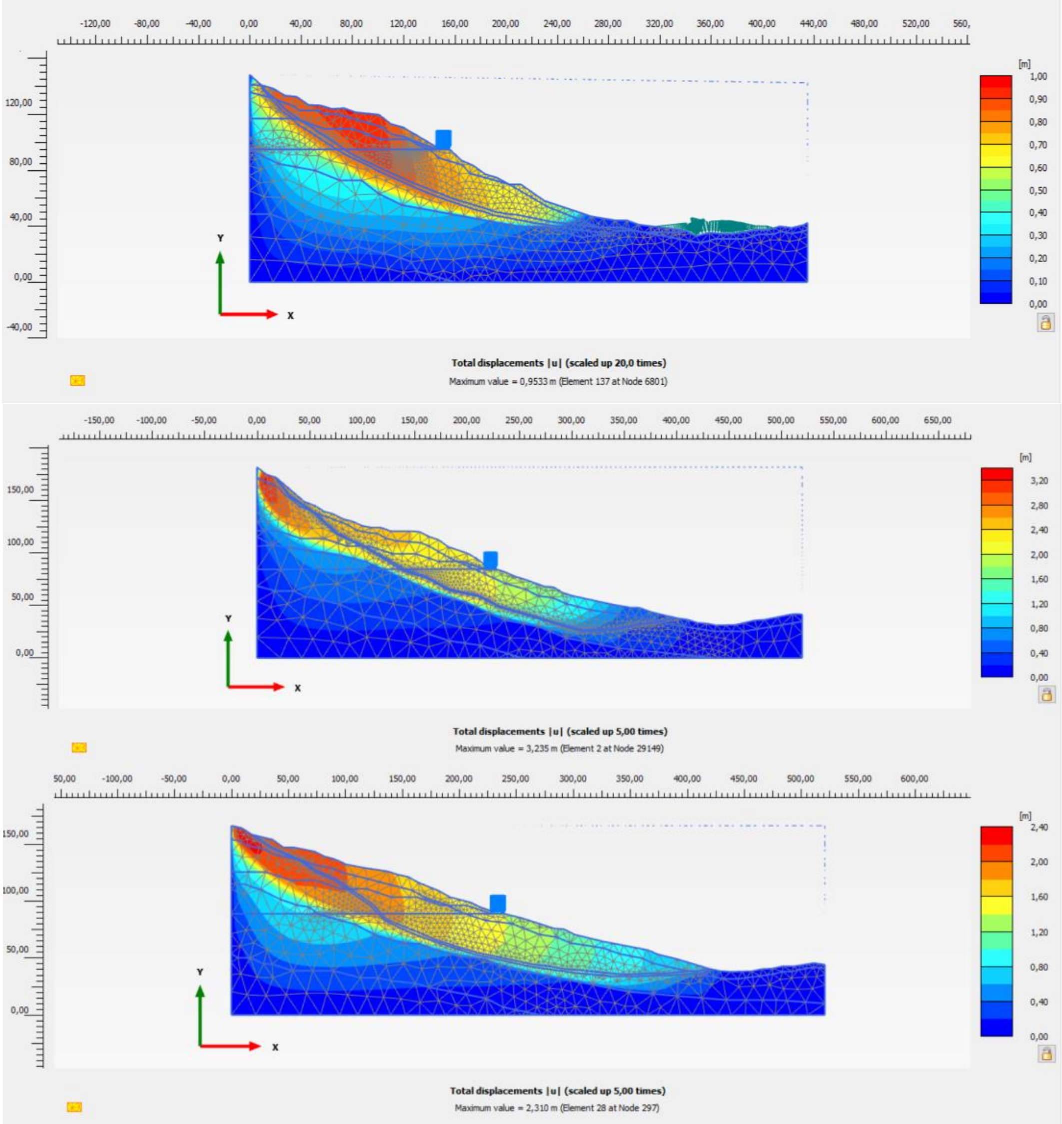

Fig.10 Results of slope stability analysis with 2D finite element-based software.

5.4 Reinforcement of Slope Stability

Slope stability reinforcement modeling was carried out by modifying the geometry of the upper slope with a ratio of 1:3 which aims to reduce the soil load and the addition of 0.8 m diameter piles with a depth of 50 m with a distance between piles of 8.5 m. This very long pile is needed so that the piles can intersect the landslide slip plane (Fig. 11). Modifying slope geometry by altering the slope angle can increase the slope's safety factor [25]. Steeper slopes and smaller mesh sizes make slopes more sensitive and result in lower safety factors [26].

Modeling was also carried out on 3 slope profiles which increased the safety factor value 1.34, 1.31 and 1.30, or with an average of 1.32. According to [24], the safety factor value is classified as stable. However, this method is difficult to do, because installing piles to a depth of 50 meters is difficult due to the very steep slope and high risk of accidents. In addition, the combination of the two slope reinforcement methods is estimated to be expensive. For this reason, a more efficient and effective mitigation method for deep seated complex landslide is needed.

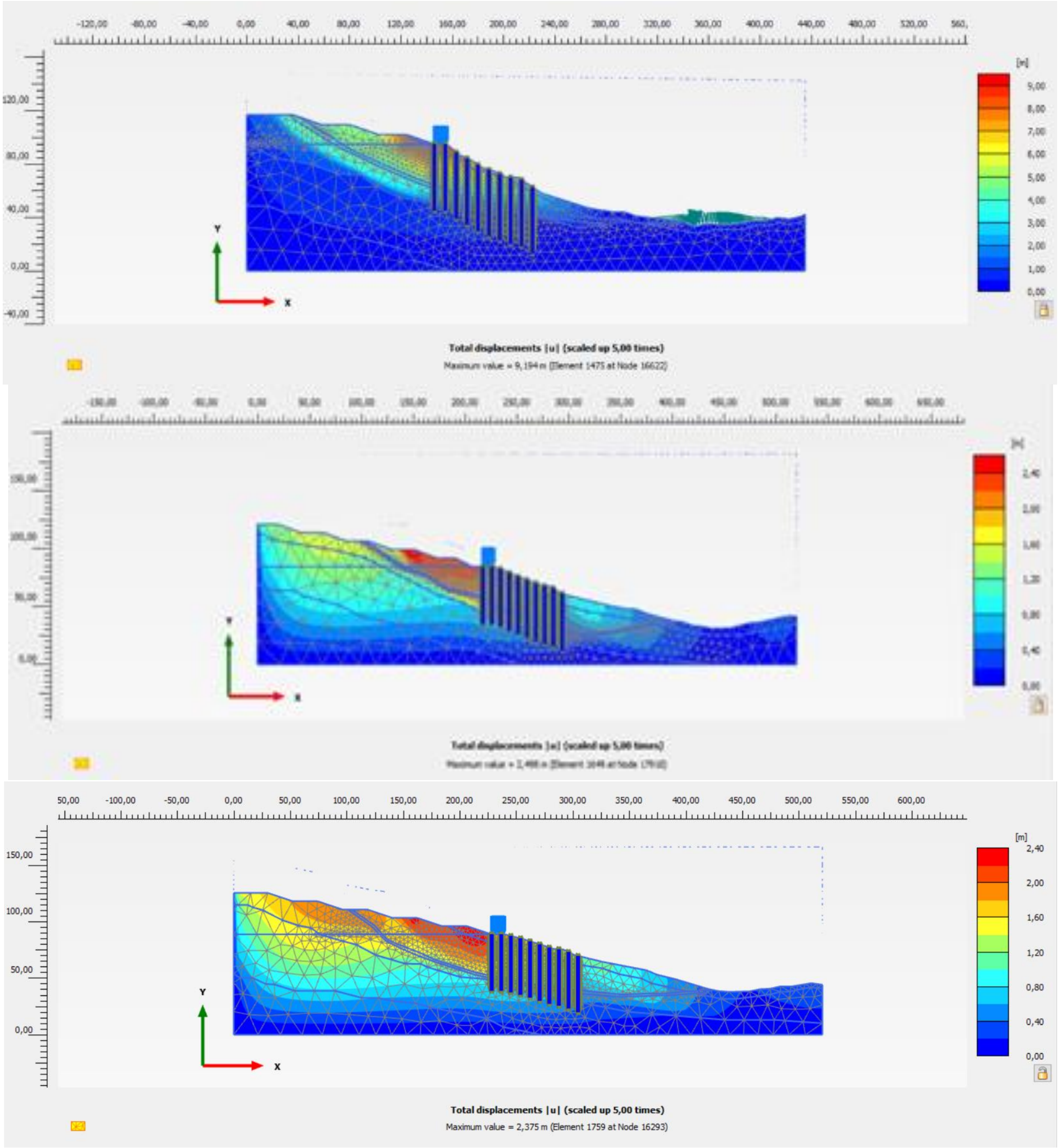

Fig. 11 Finite element model of reinforcement slope with slope geometry modifications and pile.

6. CONCLUSION

Landslides are a common hazard throughout the world, including in Indonesia, which experiences high rainfall. Landslide mitigation planning requires interdisciplinary research to obtain a 3D model that more closely approximates reality. Landslide disaster investigations with an interdisciplinary approach produce better models, especially the description of subsurface conditions. This model has an important meaning for structural landslide mitigation planning.

An interdisciplinary investigation of the landslide on the Ponorogo - Pacitan Highway at KM 226 provided the following information:

- Topographic mapping shown a 4.2-hectare area of movement with a volume of approximately 165,000 m3.
- Geoelectrical resistivity studies and geotechnical drilling exposed that the landslide slip plane was located at a depth of approximately 30 meters from the existing road at the time of drilling.
- Simulations using both the Limit Equilibrium and Finite Element approaches yielded a safety factor of less than 1.25, which is considered unstable. The safety factor resulting from the FEM method is lower than the analysis results using the limit equilibrium method, because the slip plane from the FEM analysis is deeper so that the volume of deformed material is greater.
- Landslide hazard mitigation using a combination of slope modification and pile can increase the safety factor to a stable level. However, this method is less feasible for implementation at the study area due to extreme topography caused to high risks of safety during construction and may be high-cost construction as consequence of using much of long piles.

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