Geoelectrical Prediction for Sliding Plane Layers of Rotational Landslide at the Volcanic Transitional Landscapes in Indonesia

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Abstract. The transitional between Quaternary and Tertiary volcanic landscapes is characterized by very deep interlayered clays. The the study of clay occurrence at certain depth through geophysical application is not intensively studied yet. Our sampling site is located at Bompon Sub-watershed where the rotational landslide are frequently occurred. This research aims to investigate the characteristics of clay layer that potentially become sliding surface of landslides using two-dimensional (2D) resistivity method. Resistivity survey using dipole-dipole configuration was conducted above three types of rotational slides typically occurred in the study area. We also did field observation as well as laboratory measurement for supporting data interpretation. Three kinds of interlayered clay materials are clearly detectable from 2D resistivity sections under all bodies of landslides. Those materials are entirely categorized as clay but different on cracks structure and cracks density, soil moisture, total porosity, bulk density, and specific gravity. Based on its physical characteristics, the saturated clay located around 10 up to 20 meters in depth is the most likely becoming sliding surface of landslides. This result is useful for understanding the nature of rotational slides commonly occurred in the volcanic transitional landscapes in Indonesia.

1. Introduction

Rotational landslide is a typical at the very deep clayey soil layers. The common situation of very deep clay layers formation is coming from the weathering of a series of volcanic ash deposition [1][2][3]. In a specific location those weathered interlayer volcanic ash is laying on the older clay formation which derived from hydrothermal alteration of volcanic rocks. The occurrence of those two different genetic clay in our sampling site of Bompon Sub-watershed may have different behavior in relation to rotational landslide processes.

The study of landslides in the study area has been initiated by identifying potential disaster at the regional scale [4]. It then evolved toward landslide susceptibility mapping with qualitative to semi-quantitative methods in some part of Tertiary Mount Menoreh [5][6][7]. The susceptibility studies have been performed in general regardless of the different characteristics and parameters of each type of landslide. The only detailed research on the aspects of a specific type of landslide was about rock fall at the top of mountains that had experienced a process of denudation [8]. Thorough research related to the characteristics of the rotational slide has never been conducted before in the study area shows in the figure 1.
The availability of subsurface data is an essential factor in examining the characteristics of landslides, especially the existence of a sliding plane. The widely used technology for identifying the subsurface of a slide is geophysical methods because the operation is easier, cost and time efficient, and capable of producing better spatial features than the boring or coring method [9][10][11]. One of the suitable geophysical techniques for landslide studies in clay terrain is the geoelectrical method since the resultant value of electrical resistivity has a relatively strong correlation to some soil geotechnical parameters, namely texture, coating structure, salinity, and water content [12][13]. The two-dimensional resistivity method has been successfully applied to detect various clay layers becoming as sliding plane of rotational slide, such as groundwater-leached marine clay deposits [14][15][16], clay intercalations in sedimentary rocks [17], and clay layers developed from weathered parent rock [18].

This research aimed to investigate the characteristics of clay layer that could became a potential slip plane of rotational landslides in transition volcanic zone using two-dimensional resistivity method. The locations of the landslide events were sampled according to the types of landslides observed from UAV-derived photo interpretation, Digital Elevation Model (DEM) and field check (validation) in the Bompon Watershed. The nature of subsurface bedding was interpreted by correlating 2D resistivity data with soil profile obtained from field observation and laboratory analysis. The interpretation results, i.e., the physical structure of bedding, were then analyzed together with DEM to determine the clay layer as a potential sliding plane of rotational slides in the study area.

2. Physiographic Setting

Every deposition area of Tertiary and Quaternary volcanos created their own unique physiographic setting. Both tertiary old Andesite Formation and quaternary old Sumbing Formation fashioned an mountainous range topography with East-West and North-South orientation respectively, while the young Sumbing Formation shaped a cone morphology characterized by radial centrifugal river pattern (Figure 2). The old Andesitic Formation product of ancient Mount Menoreh underlid the Bompon watershed and composed of andesitic breccia, tuff, tuff lapilli, agglomerate, and lava intercalation [19]. The hydrothermal rocks which is transformed into clay could be found in part of this formation as well. Almost all tertiary rocks in the study area were covered by clay-dominated soil which is estimated to have developed from the volcanic ash of both Old and Young Sumbing Volcano (see fig. 2).
The hilly landscape of Bompon Sub-watershed has been performed by a series of erosion and landslide processes. The elevation of Bompon Sub-watershed is between 413 – 539 mmsl. The slopes are mainly 8° to 15°, but steep slopes (> 25°) are also identified in the upper and lower parts of the watershed. The main valley of Bompon Sub-watershed has orientation of North-South direction that parallel with Quaternary Sumbing Volcanic systems, while the sub-valley systems has orientation of Northeast – Southwest direction that parallel with Tertiary Kulonprogo Volcanic systems. In the middle part of watershed, the valley become wider with a gradient of 0-8°. The perennial Bompon River flows along the foothills and it is wetting of the foothills that may increase slope instability.

The high rainfall intensity in the Bompon Sub-watershed occurs during October-April. The orographic rain caused by the presence of Young Sumbing Volcano on the north is also a contributing factor to the rainfall events in Bompon Watershed. The record shows that the average annual rainfall in the area is more than 3,000 mm. Extreme rains with an intensity of more than 50 mm/hour with duration of 2 hours frequently occur and occasionally trigger intensive soil erosion that initiate landslides in the study area.

3. Methods

This research started with sampling the location of the rotational slides for the 2D resistivity measurement. The site selection was performed by manually interpreting the landslide area using small format UAV-derived photographs and Digital Elevation Model. The landslides identified in this process were then validated through field survey. The sample size is expected to represent the magnitude/extent and the degree of landslide activity.

The 2D resistivity method was designed to show the structure of the underlying rock layers of landslide body. The concept of resistivity method is to measure the potential difference of subsurface materials through a pair of electrodes after injecting an electrical current from another pair of electrodes. In this research, some electrodes array using dipole-dipole configuration were designed across the

![Figure 2. The position of Bompon Watershed within the Transitional Volcanic Landscape between Quaternary (Mt. Sumbing) and Tertiary (Mt. Menoreh) Systems in Central Java Province, Java Island.](image)
contour elevation and spaced by 20 m. The length of the electrode array depended on the length of the slope at which the landslide occurred. The resistivity meter used in this research was Syscal Junior with specific generated current, measured voltage, and electric power of 1250 mA, 400 V, and 200 W, respectively. The raw data was processed using RES2DINV software with inverse modeling technique that relied on the concept of smoothness-constrained least square introduced in the equation of deGroot-Hedlin and Constable [20].

Some soil samples were collected from the outcrops of landslide body to provide thorough geophysical data analysis. The soil was sampled from every observable physical difference in the field, such as from the color, structure, compaction, and the presence or absence of cracks. The laboratory measurements were conducted to the soil samples to gain the physical properties such as texture, moisture content, bulk density, specific density, and total porosity.

4. Results and Discussion

The results of aerial photo interpretation and analysis revealed that the majority of Bompon Watershed was the depletion and deposition area of rotational landslides. The rotational slide can be differentiated by magnitude into two types, namely shallow landslide and deep-seated landslide. Meanwhile, in terms of activity, it is categorized into active landslide and inactive (dormant) landslide. Based on the characteristics of the landslides occurring in the study area, the 2D resistivity measurement was performed on three rotational slide bodies. Each of which had the following characteristics: 1) an active deep-seated landslide; 2) a dormant deep-seated landslide, and 3) an active shallow landslide (Figure 3).

![Figure 3. Rotational landslide inventory map of Bompon Watershed and the location of 2D resistivity survey area.](image-url)
Figure 4. 2D Resistivity sections recovered that all types of rotational landslides in Bompon Watershed have same subsurface material pattern. High resistivity interpreted as dry clay layer covered the landslides surface (25-300 Ωm), very low resistivity interpreted as saturated clay layer occurred dominantly below the dry clay (<25 Ωm), and slightly high resistivity interpreted as altered clay was locally found at the bottom of body landslides (25-00 Ωm). a) an active deep-seated landslide. b) a dormant deep-seated landslide, and c) an active shallow landslide.
The three sections of the 2D resistivity measurement showed on figure 4 that all types of the rotational slides had the same pattern of resistivity, either horizontally or vertically (Figure 4). The surface layer covering the landslide body had relatively higher resistivity values ranging from 25 to 300 Ωm. This layer was identified as dry clay which has variety in depth (10 up to 20 m). The second layer with a very low resistivity (<5 Ωm) was identified as saturated clay layer. This layer has an average thickness of 25 meters, moreover it could be more than 30 meters thick. Whereas the lowest layer showed a trend of high resistivity within the range of 25-100 Ωm which was predicted to be an altered clay layer commonly occurred in the landslide scarp within this area. This altered clay layer was captured 25 meters under the surface at the dormant deep-seated landslide and an active shallow landslide, but it appeared in shallower depth around 8 meters at the active deep-seated landslide.

The soil samples collected from lateral scarp of first landslide (Figure 5) confirmed that the three layers detected from the 2D resistivity method had similar texture (clay) but different physical characteristics, namely total clay, fluid content, total porosity, bulk density, specific gravity, structure, and the presence or absence of cracks shown at table 1. The first layer appeared to be a layer of dry clay because there were many visible cracks with 1-2 cm wide and 1-2.5 m deep. However, this layer had the highest moisture content among the identified layers because, in addition to its position (i.e., near the surface), plant roots, which can absorb water in the soil, were found in a large number. This layer had a loose structure and sizeable total porosity; therefore, the bulk density tended to be smaller than the two clay layers beneath it.

The second layer, sampled at 12 m below the surface, showed the same condition as a saturated clay layer due to its compact structure. Its clay content (%) was similar to the first layer. However, lying deep below the surface, it received considerable lithostatic pressure and, thereby, reduced the total pores to only 5.6. Furthermore, it did not have micro or macro plant roots. Both dry clay and saturated clay layers were estimated to have developed from the ash of Quaternary Sumbing Volcano that had been deposited in the study area.

The third layer, underlying the saturated clay layer, was not visible in the soil profile that was exposed at the lateral scarp. Nevertheless, the layer suspected as the base of the landslide body in Bompon Watershed was observable from the one exposed at the foot of the first landslide (A-A’). The third layer

![Figure 5. Three clay layers exposed at the lateral scarp and foot of active deep-seated landslide were clearly distinguished in the field from its physical appearance such as color, texture and structure. 1) dry clay layer. 2) saturated clay layer. 3) altered clay layer.](image-url)
was a weathered rock material that had experienced heavy alteration and formed 45% clay. It had a variety of colors ranging from red brick, yellow to white. In dry conditions, it had a compact, blocky, and firm structure with no cracks. The source rock of this clay alteration was estimated to have come from the andesitic breccia that is product of Tertiary Menoreh Volcano.

Table 1. Physical characteristics of clay layers under the rotational landslides body at Bompon Watershed resulted from laboratory measurements

| Physical characteristics | Dry Clay | Saturated Clay | Altered Clay |
|-------------------------|----------|----------------|-------------|
| Texture (% )            |          |                |             |
| Sand                    | 5.13     | 3.12           | 6.57        |
| Silt                    | 29.14    | 27.73          | 48.13       |
| Clay                    | 65.72    | 69.15          | 45.3        |
| Total Porosity (%)      | 66.12    | 56.04          | 58          |
| Bulk Density            | 0.91     | 1.01           | 0.99        |
| Specific Gravity        | 2.69     | 2.3            | 2.35        |
| Soil Moisture           | 13.88    | 5.6            | 4.75        |
| Structure               | crumbly  | Granular       | blocky      |
| Cracks occurrence       | abundant | Absence        | absence     |

Table 1 shows the 2D resistivity method is proven to be highly capable of detecting the clay layer developed in a volcanic landscape. Despite the very high clay content (>60%) in Bompon Watershed, each clay layer showed a different response of resistivity value. The first and second clay layers were detectable because they differed in structure, compaction, total porosity, and cracks. Many cracks in the soil, loose structure, and high total porosity are highly correlated with larger resistivity. In this research, the soil moisture was concluded to have a weak influence on increasing the conductivity value of the dry clay layer. On the contrary, the saturated clay layer had a very small resistivity (<25 Ωm) because its compact structure induced a strong inter-granular connection, which can conduct electrical current efficiently.

The third layer was estimated as a clay alteration with a relatively high resistivity. This resistivity was caused by the lower total clay content compared to the first and second layers. The different resistivity can also be attributed to differences in soil geochemical properties [21][22]. The third layer had different parent material from the other two layers, namely andesitic breccia with high content of silica. This silica was the primary cause for the rising of resistivity value.

The 2D resistivity data, supported by soil observation in the field, showed that the saturated clay layer (resistivity <25Ωm) was responsible to be the sliding plane of the landslides. It was found 10 to 20 meters below the surface with a thickness of more than 20 meters. The compact structure indicates that it is permeable. In the event of high-intensity rain, water can easily seep through the dry clay layer, which is composed of a loose structure and numerous cracks, but it tends to flow slowly within the soil and accumulate when in contact with the saturated clay layer. The clay layer is very thick, which increases the possibility of copious water accumulation and the formation of potential slip plane. This assertion is evidenced by the appearance of slickenside in the soil profile exposed beneath the lateral scarp of the landslide (figure 5).

Physically, the altered clay layer beneath the saturated clay layer also potentially forms into a sliding plane. In wet conditions, its soil consistency turns into very soft and poses a threat to slope stability. As seen in the 2D resistivity cross-section of dormant deep-seated landslide and active shallow landslide, the clay alteration layer is located lower than the valley (more than 30 meters in depth). Therefore, there
is a low possibility of this layer being the sliding plane of the landslides in the study area, but it will potentially form into a sliding plane if it is located at a shallower such as at the active deep-seated landslide case (8 meters in depth). When this layer loses its soil structure due to the wetting process, it turns into a very soft structure and has high possibility causing subsidence and strengthen the saturated clay above it. All of these conditions allow the formation of curve movement within altered clay layer and form a rotational landslide.

5. Conclusion

This research has revealed that 2D Resistivity method can produce a clear image of clay layers under the rotational slide bodies in the volcanic transitional landscape. All types of rotational slides commonly occurred in the Bompon watershed (active deep-seated, active shallow and dormant deep-seated landslide) are composed of dry clay (25-300 Ωm), saturated clay (<25 Ωm) and altered clay (25-00 Ωm). In addition, those clays could be distinguished from the laboratory data such as total of clay, fluid content, total porosity, bulk density, specific gravity, structure, and the presence of cracks. The saturated clay located around 10 up to 20 meters in depth is responsible creating sliding plane of rotational slides in the study area. Meanwhile, the altered clay layer also potentially becomes a sliding plane rotational landslide if it is located shallower than 30 meters in depth (smaller than relief amplitude).

Acknowledgements

The authors are very thankful to Wiwit Suryanto, Eddy Hartantyo and Ade Anggraini for their constructive criticisms and suggestions. This research is a part of “Genesis of Soil Parent Material for the Basis of Sustainable Land Use Strategy Formulation in Jebol Sub-Watershed, Magelang Regency, Central Java Province” study supported by postgraduate grant program from Indonesian Ministry of Research, Technology and Higher Education (Hibah Penelitian Pasca Sarjana 2016-2018).

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