Landslide investigation using electrical resistivity tomography (ERT) technique at the location of water channel PLTM Lambangan, Pagimana, Central Sulawesi

Asrafil¹, I Uno¹, H Jayadi¹, S Rugayya²

¹Geological Engineering Study Program, Tadulako University, Indonesia
²Department of Physics, Tadulako University, Indonesia

E-mail: asrafil@untad.ac.id

Abstract. Mass movement phenomena that occur in the research area affect the destruction of water channel in the area of PLTM Lambangan that located at the location. This research aimed to investigate soil movement phenomena in order to determine control factors that causing soil prone to move, especially in the surface geological aspect and underground lithology condition in the research area. Investigation method applied is by underground geologic and geophysical surveys using electrical method, that is Electrical Resistivity Tomography (ERT) with Wenner Configuration. Results of investigation show that geological factors are quite related to the soil movement. Movement phenomena occur in the surface with hilly to steep cut topography (21-55%) with material sourced from alluviation of clastic sediment dan carbonatic rocks. The damaged area is people farming area where fibre root of plant adds water absorption capacity of the soil. Also, sliding materials show water seepage that indicates that the moving slope has been saturated. This condition supported by information from geoelectric survey which indicates that in general the under surface material potent to slide or move because of unconsolidated material with its resistivity values in the order of 16 – 43 m that estimated related to alluvial or saturated residual soil.

1. Introduction

In the village area of Lambangan, a power plant was built by PT. Lembongan Energi Utama by utilizing the potency of water resources from the Lambangan river in which the formal name to be known as the Mini Hydro Power Plant (PLTM) Lambangan. However, operational of PLTM Lambangan was stopped due to the disruption of water channels toward to the powerhouse since July 2016. This was caused by the mass movement events (landslide) that occurred on the slopes near the water channel of PLTM Lambangan. The landslide brought material which then closed some of the canals and destroyed part of the Lambangan Power Plant's waterway network. It is therefore important to investigate the mass movement activities.

The phenomenon of soil movement (which is often termed landslides) is defined as the movement down the mass of the soil or rocks that making up the slope, or mixing both of them, as a result of disruption to the stability of the soil or rocks in the slope[1]. This phenomenon is one of the most widespread and frequent natural hazards compared to other geological disasters (such as earthquakes, volcanic eruptions, and tsunamis) [1, 2]. As the precaution, investigation of this phenomenon cannot be ignored.
In a landslide investigation the particular geophysics method is Electrical Resistivity Tomography (ERT) technique[3, 4, 5]. The ERT is an active geophysical method which can provide 2D or 3D images/models of the distribution of the electrical resistivity in the subsurface geo-materials[5], which is often used as a tool for investigating and characterize shallow landslides in lithologically and/or structurally complex rock types[4]. For better correlation and validation of ERT results, ground (surface & subsurface) information from various sources must be used [6], therefore a surface geological survey has been carried out.

The PLTM Lambangan area is located in Banggai Regency, the Eastern part of Central Sulawesi, Indonesia (figure 1). This research aims to investigate mass movement events (landslide) to find out the controlling factors that cause the soil material to be susceptible to moves, especially on aspects of surface geology and subsurface lithology in the study area.

![Figure 1](image_url)

**Figure 1.** Map of research locations in Lambangan Village, the red rectangle shows the area of investigation for this research.

2. Geologic Setting

2.1. Geomorphology

The study area is in the district of Pagimana, which in regional physiography consists of morphological forms of mountains and karst, hills and lowlands [7]. The study area is located on the surface (relief) with the dominant form of hilly topography - steep/steepest slope (slope of 21-55%, see figure 2. Genetically, the study area is a hilly area, which is part of the deposition of material (alluviation) of weathering clastic sedimentary rocks and carbonation of Poh Formation. The study area entirely surrounded by gentle to very steep slopes, and morphographcally hilly landform cover almost all study area.
2.2. Stratigraphy
Based on the regional stratigraphic setting of Luwuk's Area [7], the study area consists of several rock formations (see figure 3). The oldest or basement of the area is Ultramafic rock with the age of Cretaceous. This unit underly the sequence of sedimentary formations include Cretaceous Matano, Tertiary Formations of Salodik and Poh. The youngest units that formed in this area are Quartenary deposits of Coral Reef and Alluvium [7].

2.3. Geological Structure
Based on Regional Geological Maps of Luwuk [7], the geological structure of the study area is strongly related to regional effect that result to the presence of faults, lineament, and folds structures. The main structures that formed in the study area are strike-slip and thrust or reverse fault. Both structure tend to have a similar orientation in Northeast-Southwest direction. Reverse fault is represented by the Pasini fault, the Poh fault, and the Batui fault. The Pasini fault is part of a regional structure that borders the Poh Formation with the Salodic Formation. The lineament and fold structure that forms the anticline and syncline also have the same orientation, in Northeast-Southwest direction, similar to reverse fault pattern in the Study area.

Figure 2. Map of Study Area Slope Class
3. Methods
The research method was carried out through two stages of investigation, starting with a survey of geological conditions and then followed with subsurface survey conditions using the geoelectric method. The following are the stages of the research that have been conducted to investigate mass movement (landslide) in the study area.

3.1. Geologic Survey
The geologic survey is intended to determine the surface geological conditions in and around the study area. Information on geological conditions in the study area mainly to review the geological aspects of landslides in the study area (existing conditions). The acquisition of geological data is carried out in the orientation and observation of the study area, in order to determine engineering geological condition related to the mass movement event.

3.2. Geoelectrical Survey
The geoelectric survey method that applied in this study is was ERT technique or Electrical Resistivity Tomography. ERT is a geoelectric technique that can be used to determine the spatial conditions of subsurface material. The spatial condition of the underground material can be observed from the
spatial distribution pattern of the resistivity value of the material. The resistivity value ($\rho$) is calculated based on electric current data ($I$) and potential difference ($V$) that obtained from field measurement, in which data of electric current and potential difference are obtained from the injection of electric current into the earth surface through the pair of current electrodes (C1, C2) and potential electrodes (P1, P2) [8].

For field investigations in the study area used the geoelectric measurement method of the ERT technique apply with the Wenner electrode configuration (figure 4). The geometry factor for this configuration is given by the equation:

$$K = 2\pi na$$

(1)

While the apparent resistivity value is obtained through equation [9]:

$$\rho = K \frac{\Delta V}{I}$$

(2)

Relationship between measured rock resistivity and pore filler water resistivity measured from formation water, is reflected by the formation factor (F) value, namely[10]:

$$F = \frac{\rho}{\rho_w} = \frac{a}{\phi^m}$$

(3)

Formation factors can be used for estimating wet zones (saturation of water) because this magnitude reflects porosity in sedimentary and igneous rocks that have fractured[10]. Resistivity water to pore filler $\rho_w$, besides can be measured directly, it can also be calculated using the equation[10]:

$$\rho_w = \frac{10000}{\text{Conductivity}}$$

(4)

Where conductivity ($\mu_s$) is the conductivity of groundwater electricity[10]. Some conclusions about the value of the Formation Factors (F) from several hydrological studies obtained by Boehmer [10], shown in table 1.

The acquisition of geoelectric data begins with the installation of geoelectric equipment at a location determined from the result of the geological survey. Geoelectric measurements begin with the injection of an electric current through an electrode arrangement in the Wenner configuration. The magnitude of the electric current and the potential difference for each distance of the electrode current and the potential electrode are recorded to calculate the apparent resistivity value of the subsurface material. Geoelectric data acquisition was carried out on three lines from the recomendation of geological survey orientation in the study area. Each geographic coordinate noted through the GPS device and the geoelectric direction (azimuth).
Table 1. Classification of Formation Factors for Sedimentary Rocks.

| F   | Formation                              | Aquiver/Aquiclude          |
|-----|----------------------------------------|-----------------------------|
| ≤ 1 | Clay                                   | Aquiclude                   |
| 1 – 1.5 | Peat, clayey sand or silt               | Aquiclude                   |
| 2   | Silt–fine sand                         | Poor to medium aquiver      |
| 3   | Medium sand                            | Medium to productive aquiver|
| 4   | Coarse sand                            | Productive aquiver          |
| 5   | Gravel                                 | Highly productive aquiver   |

3.3. Data Processing and Analysis

The results from field geological survey further analyzed by examining field conditions that were combined with literatures or references related to geological conditions including geomorphology aspects, lithology and geologic structure in the study area. The results of the analysis will provide a descriptive geological aspect review of landslides related to surface geological conditions in the study area. This information is then used as a reference in interpreting the nature of subsurface geologic in geoelectric surveys.

The data processing requires pseudo resistivity data. The apparent resistivity value \( \rho_a \) is calculated based on electric current data and the potential difference using the following formula:

\[
\rho_a = R \cdot k
\]  

(5)

To obtain the value of \( \rho \) (true resistivity) is done by inversion modelling techniques. This inversion processing uses Res2Dinv software[8, 11] for modelling technique to converts the apparent resistivity value into the true material resistivity value[11, 12].

3.4. Interpretation of geoelectrical data

Interpretation is done by comparing the resistivity values of the inversion process results with the table of general material resistivity values presented in figure 5. The data in the figure is not an exact value but is a range value of a material. A resistivity value can indicate the resistivity value of various materials in the table so that reference information is needed from geological, hydrogeological conditions and other supporting data to find out the exact type of material related to resistivity value.

4. Results and Discussion

4.1. Surface Geological Analysis

Orientation work on the study area not only to determine the presence of lithologies and structures on the surface, but also to observe the condition of landslide slopes and surrounding areas that are vulnerable to movement. According to Karnawati [1], there are three main keys to see the characteristics of slopes that are vulnerable to movement, include:

1. The slope is composed of loose soil or thick material.
2. The slope is composed of layers dipping with slope.
3. The slope is composed of rocks or material that is easily slid or cracked.

Furthermore, the results of the analysis of surface geological conditions by describing various controlling factors that trigger the occurrence of mass movements (landslides) in the study area.

4.1.1. Morphological Conditions (Slope). Based on field investigations and the results of the geological analysis, it has been found in general the study area has a steep slope in the hilly
topography. The study area has a slope of >15°, with the highest elevation of ± 216 meters above sea level. The landslide point itself at an elevation of ± 176 meters above sea level.

Land with a steep slope is an area that is naturally prone to erosion and landslides. Landslides or mass movement phenomena can occur slowly following a reduced of slope stability. Because the slope is one of the geomorphological formations that determines landslides, so the higher the percentage/degree of slope, the more the risk of landslides.

![Resistivity Values of Some Rocks, Soils, and Ore Minerals](image)

**Figure 5.** Resistivity Values of Some Rocks, Soils, and Ore Minerals [13]

4.1.2. **Geological condition.** Two aspects to overview and describe the geologic conditions in the study area can refer to two aspects, namely stratigraphy and the presence of geological structures. The existence of these two aspects strengthens each other in controlling the causes of mass movements/landslides in the study area [1].

The controlling factor of stratigraphic the study area refers to the position of the layer and the type of lithology that makes up the layering. The results from the field investigation show that sandstone and limestone units dominate in the landslide study area, with the top part in the form of thick alluvial material. The lithology of slopes outcropped in the study area appears to have been composed of weathered rock material, and some have even been alluvial material or residual / topsoil layers (figure 6).
Figure 6. Existing Lithology in landslide area; (a) layered sandstone outcrops; (b) outcrops of sandstones weathered and debris on landslide material have become residual soil; (c) outcrops of weathered limestone on landslides, (d) fractured outcrops on sandstones; (e) fractured outcrops on limestone; and (f) Seepage appears to come out of the weathered rock in the overburden.

The fault structure found in the study area in the form of the reverse fault has a one-way orientation, which is Southwest-Northeast. The existence of this structure makes slope lithology can be subjected to pressure, disjointed by faults so that it is easy to crack, and released. Therefore, rocks that have cracked by the structure have relatively low stability, and become a weak field that is relatively easy to move as a landslide with slide mechanism or flow of material. Field observations show rocks with sandstone and limestone lithology found in the study area have shown cracks (disjointed) on the rock (figure 6 (d) and figure 6 (e)).

Joints in rock bodies have a paired appearance, characterized by slight shifts. Joints in the rock in the study area is a type of shear joints, where compression forces that tend to shift the rock cause it. This analysis of joints shows that the compression force is relatively in the same direction as the tectonic force that is oriented toward the Southeast-Northwest direction (figure 7).

Figure 7. Analysis of joints data with a rose diagram.
4.1.3. Soil and Hydrogeology. Soil and rock conditions on the cliffs/slopes observed around the study area (landslides) have generally experienced weathering. Soil and rock as a covering material on the cliffs are loose and broken into alluvial deposits on the surface. Because the material is not well-consolidated (solid), this allows it to be able to pass water into the pore of material [14, 1]. This condition will be one of the trigger factors for the potential for landslides/mass movements.

Generally, slopes/cliffs that are part of the hills have natural channels for water absorption in the soil and its constituent rocks. These channels can be very sensitive to increase water pressure (if there is additional water catchment) [15, 16]. In addition, this can make water able to push rock mass to move and become a trigger for landslides. Seepage into the slope can weaken the bond between soil particles to increase the weight of the soil mass on the slope. As a result, the slope experiences mass movement (landslides) due to the reduced strength of the slope that makes the slope unstable.

Study areas that have experienced landslides are dominated by residual soil and loose material. From observations in the field in landslide areas, it shows seepage come out of the landslide material and rock weathering in the topsoil. This phenomenon shows that the landslide slope is a water-saturated or underground water accumulation zone [1]. Slope failure always occurred when the soil moisture content within a certain region near the toe of slope became nearly fully saturated, even if other parts of the sliding mass were still only partially saturated [17].

4.1.4. Land Use. The land use activity on the slopes in the study area is for build water channel networks from the dam(intake) to the power plant in Lambangan and some others area are used by residents as plantation land. The use of land for plantations by planting plants with fibrous root types will certainly result in loosening the soil where it is planted [1]. This will increase the ability of the soil to absorb water. The water can accumulate in the soil and eventually press and weaken the bonds between soil grains [16, 17]. Finally, when the amount of water infiltration increases and the soil becomes saturated with water, it can trigger landslides [1].

Another land use activity that cannot be avoided and make the slope potential for landslides is cutting slopes to build the Lambangan Hydroelectric Power Plant network. Slope cuts can result in the loss of the upright portion of the slope from the lateral direction. This then causes the slope to become unstable and can push/move the mass of soil and rocks that are on the slope, so that landslides will occur. Therefore, when a landslide occur, the construction is hit by landslide material.

4.2. Analysis of Subsurface Lithology Conditions (Geoelectrical Survey)

Data of geoelectrical measurements from Line 1 to Line 3 are analyzed using Res2Dinv software. The results of data analysis for each geoelectric pathway are presented in the form of 2D resistivity cross-section profiles.

Each measuring line provides a distribution of resistivity values in various ranges. In the geoelectric section on line 1, the resistivity value is produced in the range of 2.34-83.37 Ωm. In the geoelectric section on line 2, the resistivity value is produced in the range 1.32-42.28 Ωm. As for the geoelectric cross-section inline 3, the resistivity values in the range of 0.14-319.37 Ωm are generated. The distribution of subsurface resistivity values at each subsurface geoelectric measuring path is illustrated with varying color gradations.

Considering the geological conditions, the measurement line topography and the range of subsurface resistivity distribution values, a correlation between the resistivity value and the lithology of the study area is conducted. In general, the resistivity values obtained are interpreted as follows.

a. Subsurface material with a high resistivity value> 43 Ωm. Interpreted as a dense and massive material.

b. Subsurface material with medium resistivity values in the range 16 - 43 Ωm. Interpreted as an alluvial material or residual and water-saturated soil.

c. Sub-surface layers or materials with low resistivity values in the range of 3 - 16 Ωm. Interpreted as sandy clay material.
d. Subsurface materials with very low resistivity values with values <3 Ωm. Interpreted as a layer of sandstones that can function as groundwater aquifers.

To describe of the subsurface layer of the entire geoelectric measuring line is by correlating the resistivity values in the form a cross-section profile. Correlation refers to the resistivity value and the estimation of the material layer, assuming the value of water resistivity (ρw) is fixed to depth. The water resistivity value obtained from the calculation results is worth 16,935 Ωm, based on the average conductivity of water samples obtained at the seepage of water at the measurement location is 590.5 μS.

Cross-section profile 1 along ± 160 meters, with a relatively northeast-southwest track (N 206 ° E). Cross-section 1 profile with topographic shows the existence of layers that can potentially be the slip plane when there is mass movement/landslides. The slip plane was interpreted filled with sandy clay material. The clay content which is impermeable (difficult to pass water) is a factor why this layer can be a slip plane. This layer is at a depth of ± 11 m from the ground surface (mdpt). It also appears that the overburden, which is alluvial material and partially residual soil, shows wet zones (saturated of water) with thickness ± 8 m. This can be seen in the contrast color gradations of resistivity values in the overburden (figure 8). This situation is also marked by the appearance of water seepage on the surface land.

Cross-section profile 2 along ± 160 meters, with a relatively northeast-southwest track (N224 ° E). Cross-section profile 2 with topographic correction also shows the existence of layers that can potentially be as a slip plane when mass movement/landslide occur as well as cross-section profile 1. The slip plane is thought to contain sandy clay material which is impermeable (difficult to pass water) with a depth of ± 2-25 mdpt. It also appears that the overburden, which is alluvial material and partially residual soil, shows wet zones (saturated of water) in large quantities.

Cross-section profile 3 along ± 184 meters, with a relatively northwest-southeast path (N 320 ° E). The line geoelectric measurement cuts line 1 and line 2. In the cross-section profile, 3 with topographic correction has deeper depth penetration compared to measurement results inline 1 and line 2. From the illustration, the cross-section profile shows the existence of subsurface material with resistivity values height (> 43 Ωm), which is estimated to be a boulder of limestone at a depth above 25 mdpt. Around the material which is estimated limestone is likely to be a subsurface aquifer layer, because the contrast of resistivity is showing the wet zone. The sandy clay material is gradually in the aquifer layer with an estimated thickness of ± 5m. In the overburden, it is still dominated by alluvial material and residual soil. Most of these materials come from avalanches which contain sandstones, limestone, sandy clay material and overburden (residual soil) with thickness reaching ± 10 m. It is characterized by gradations of contrasting resistivity color in the cross-sectional profile and water seepage that appears on the surface in the field (figure 8).

Naturally subsurface material from the geoelectric investigation has the potential to become a landslide material. From the review of the three cross-section profiles of geoelectric measurements also obtained information that the subsurface layer generally at the top is still filled with a pile of unconsolidated material (not solid) and also the residue of the avalanche material. Therefore, special handling is needed in utilizing the land on this area. The need for consideration will be the handling of water originating from inside or outside the earth's surface which is infiltrated into the layers so that it does not become saturated with water so that the material becomes "pulp" and easy to move.

Based on information on the investigation of the phenomenon of mass movements (landslides) in the study area, a simple illustration of the landslide model was made (figure 9). The illustration tries to illustrate that a landslide due to the following aspects damaged the existence of a PLTM waterway network building that.

a. A layer of overburden that is derived from alluvial material that is not well-consolidated covers the lithology of the slope. In other words, those waterways were built on layers of material that are not solid.

b. Material layer that experience landslides (downward shifting) follow the natural slip plane, crashing/hitting waterway buildings. This resulted in the construction of a water channel building
at the landslide site which was damaged and carried along by landslide material, so that the water channel from intake to the Power House became clogged (disconnected).

Figure 8. Profile of Geoelectric Cross Section with Topography

As a result of the control by the steep slope conditions, lithology in the form of sedimentary rocks results alluvial material, the presence of disjointed rocks and the occurrence of water saturation on the slopes at the study location, then there was the phenomenon of mass movement (landslides) with a wedge shape in two places (figure 10).
Figure 9. Landslide Model in The Study Area

Figure 10. Geological Map of The Study Area
5. Conclusion
The study area dominantly has steep slope surface conditions, with rock units consist of limestone and sandstone in which both are part of Poh Formation. The formation partially show intense weathering that result in thick residual soil and covered by alluvial soil. From surface and slope view of material, structurally sandstone and limestone unit are strongly jointed, cracked, and easy to lose materials. All this together work as main agents responsible for the mass movement or landslide events. Therefore, to solve this problem, it needs to mentioned that complete geological and underground survey are strongly recommended in the line with government policy on strict regulation for land use.

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