Integrated Geophysical Methods to Determine Subsurface Structure of PSK-1 Mini Hydro Power Plant, Citeurep Creeping Area

Darrian¹, Gregorio Adri Prawira¹, Frankstein Arphan¹, D D Warnana¹, Sugiyono²

¹Department of Geophysical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
²Medco Hidro Indonesia, The Energy Building, Jenderal Sudirman Lot 52-53, Jakarta, Indonesia

*Corresponding author e-mail: Darrianalisantoso14@gmail.com

Abstract. Citeurep area of PSK-1 mini hydro power plant is one of the areas passed by waterway to flow water into the power plant turbine and it resides on a foothill with some natural water springs. As time passes, this waterway suffered continuous damage due to continuous slow movement of land mass (creeping). Therefore, integration of geological data, drill data, remote sensing (drone data), Vertical Electrical Sounding (VES), Electrical Resistivity Tomography (ERT), and Very Low Frequency (VLF) were carried out, creating a 3D VES model, 2D ERT model, and 2D VLF model. Geological data, drill data, and the drone data are used for elevation model and utilized as supporting data to create a better electrical and VLF model to determine the subsurface lithology. VES and ERT models show a subsurface structure that formed an appearance of a natural “weir” from breccia rock of Koleberes Formation (140-380 Ωm) and thick low resistivity zones that contain sandy grains up to 50 meters deep (6-11) Ωm in the Citeurep area. VLF model shows some conductive zones that are interpreted as a flow of underground water. All processed data indicates that Citeurep area is an alluvial that is dominated with breccia as a bedrock. It can be concluded that the causes of creeping are due to: 1) heavy load from the top of the hill coupled with thick sedimentary layers saturated with water which influence the addition of mass and 2) lack of layer cohesion. The absence of sudden landslides is largely caused by hard breccia rocks that form a structure in appearance of a natural “weir

1. Introduction
Landslide is a downhill movement of slope-forming material under the influence of gravity and water [1]. PSK-1 mini hydro waterway resides on the foothill of Citeurep and has a steep slope and water springs in this area. This condition makes the ground creeping and continuously damaging the waterway.
Figure 1. Regional Geology Map Near PSK-1 Powerplant. Reprinted from “Peta Geologi Regional Sindang Barang dan Bandar Waru” by Koesmono, Kusmana & Suwano, 1996, Copyright by Geological Research and Development Center, Reprinted with Permission.

Based on Regional Geology Map of Sindang Barang and Bandar Waru from Koesmono, Kusmana & Suano (1966), PSK-1 Powerplant have four geological units [Figure 1] which are comprised of:

- Mount Patuha lava and volcanic mudflow [Qv(p, l)], consists of andesite lava from Mount Patuha. This geolocal unit is deposited at the surface, estimated from the Holocene era.
- Lava and volcanic mudflow Mount Kendeng [QL(K, W)], consists of lava flow interspersed with lava mudflow deposits like andesite breccia and tuff breccia. This unit was deposited in the Pleistocene era.
- Inseparable pyroclastic deposited [QTv], consists of breccia andesite, breccia tuff, and lapilli tuff. This unit is deposited in the Pleistocene – Pliocene era.
- Koleberes Formation [Tmk] consists of finely laminated tuff sandstone, crystal tuff, breccia tuff and breccia with andesite and deposited during the Late Miocene era.

Citeurep area itself located in a rice field terracing flooded with water that originates from water springs in the area. Based on the previous geological analysis by Mucoindo in 2014, Citeurep consists of three main lithologies: alluvial, pyroclastic deposit and Breccias from Koleberes Formation. This area has suffered ground creep in December 2017 and October 2018, damaging the waterway along this area. Until now, there are still some indication of soil creeping.

The goal of this study is to interpret the subsurface of Citeurep area to determine the cause of creeping. To achieve this, we use Vertical Electrical Sounding or known as one-dimensional resistivity (VES), Electrical Resistivity Tomography or known as two-dimensional resistivity (ERT), and Very Low Frequency (VLF) method integrated with remote sensing data. VES method is used to make a 3D subsurface model while ERT method serve as validation for 3D VES model and a 2D subsurface model with the aim of giving a clearer view of the subsurface lithology. Resistivity method still requires calibration results from other geophysical or geological data, especially when a very wet material is investigated [2]. VLF method is added to compensate the flaw of resistivity method, this method will produce a 2D resistivity inversion model.
2. Methods

2.1 Resistivity Method

Resistivity is one of the natural rocks parameter which explains the ability of rocks to conduct electricity. The greater the resistivity, the smaller the rock's ability to conduct electricity. In contrast to resistance, resistivity is invariant, meaning that it does not depend on the shape of the rock. Resistivity measurements is an active geophysical method by measuring the potential difference generated due to electric injection. The electric current will follow the path of least resistance, concentrating in conductive material [3] such as water content in the soil [4]. One of Resistivity variation of below the measurement point can be determined from the difference of electrical potential and the strength of injected current, However, the homogeneity of the subsurface depth is very rare so that electric current will follow or go through path with smallest resistance.

![Illustration of electrical current propagation and its equipotential field when using 2 Current Electrodes. Reprinted from Geoelectrics, BGR, retrieved 21 October 2019, from https://www.bgr.bund.de/EN/Themen/GG_Geophysik/Bodengeophysik/Geoelektrik/geoelektrik_nede_en.html. Copyright by Ursula Noell. Reprinted with Permission](image)

When you acquired resistivity data in the field you will get apparent resistivity, this happens because subsurface rocks are not a homogeneous medium so the value obtained is no longer actual resistivity but is apparent resistivity ($\rho_a$) or known as pseudo resistivity. Apparent resistivity is not a physical property of the subsurface media and the resistivity value can be formulated as follows [5]:

$$\rho_a = \frac{\delta V_{MN}}{I} , \, K$$  \hspace{1cm} (1)

$$K = 2\pi \left\{ \left[ \frac{1}{AM} - \frac{1}{MB} \right] - \left[ \frac{1}{AN} - \frac{1}{NB} \right] \right\}^{-1}$$  \hspace{1cm} (2)

Where:
- $\rho_a$ = apparent resistivity (Ωm)
- $V_{MN}$ = potential difference of MN electrodes (Volt)
- $I$ = electrical current (ampere)
- $K$ = geometric factor
- AM,MB,AN,NB = length between electrodes (meter)

To find the value of true resistivity, apparent resistivity depends on a factor called geometry factor (K). Geometry factor has different value for different electrode configuration and each configuration has its own characteristics. There are some considerations for choosing a configuration: the depth of the
investigation, the sensitivity level of the electrode configuration to vertical and horizontal subsurface structure [6]. Our aim for VES and ERT method is to create a model where we can determine the weak zones and the landslide plane caused by water impermeable layer.

VES acquisition were carried out with 12-point VES measurements with one defect data that was discarded (VES 11w). The location of the VES point can be seen in Figure 3 along with ERT and VLF line. VES acquisition uses Wenner-Schlumberger configuration to obtain sufficient penetration depth as well as good vertical resolution. The length of VES measurement range is 50 m - 120 m, so that expected maximum depth can reach 25 m - 60 m. the measurement data were processed using Progress Software for inversion and to make one-dimensional resistivity modeling. This one-dimensional model will be processed further using Rockworks Software to create a 3D VES Model.

Three ERT line acquisition was carried out in Citeureup area as well to validate the VES 3D model. Measurements were made with a track length of 100 m and spaces between the electrodes is 4 m so the expected maximum depth is 20 m. Schlumberger configuration is used for measurements. The measured data are processed with Res2Dinv Software to create a two-dimensional resistivity cross section model. The two-dimensional model are combined in Rockwork Software to create a fence model.

2.2 Digital Elevation Model
Digital Elevation Model or DEM is obtained from remote sensing data (using drone) and it is a digital representation of land surface topography. DEM is the most widely used basis for making digital maps of the earth. In digital mapping, each part of the map is divided into several blocks. The slope of the land in each block is irregular so it is necessary to minimize the slope variability in one block. In theory, this variability can be reduced by reducing the slope angle intervals used for the block division criteria [7]. In remote sensing, image analysis is carried out on an image with an overhead perspective (top view perspective) represented digitally. Our aim for this method is to produce elevation data at each coordinate and integrated it to resistivity model to create three-dimensional model based on resistivity value.

Digital Elevation Model was processed from drone aerial photos taken by Medco Energi Lead Geologist using APS Menci Program. APS Menci produces DEM and Orthophoto. DEM was validated using Google Earth by converting it into .kml file. If the results are off, DEM is georeferenced using GlobalMapper by comparing landmark coordinates of an established map to the visible topography of that landmark. From this model, resistivity measurement points elevation can be known. Its elevation are used to correlating resistivity data.

2.3 Very Low Frequency
Very Low Frequency is a geophysical method based on electromagnetic principles with passive measurement techniques. The VLF-EM method utilizes electromagnetic fields from low frequency radio transmitters and usually used for submarine navigation purposes. The frequency used ranges from 15 KHz - 30 KHz. Main electromagnetic field comes from a radio transmitter with a vertical electric field component (EPz) and the horizontal component (HPy). HPy component penetrate into the ground and induce a secondary electrical component horizontally (ESx) in a conductive medium buried with a related magnetic field (HS), this secondary EM field has an oscillating parts, namely inphase and quadrature. Intensity of secondary EM field depends on the soil conductivity. Inphase (real) and quadrature (imaginary) are the results for VLF. Real and imaginary expressed as a percentage of terrain main total of VLF transmitters. The real part of tipper is sensitive to objects with low resistivity while the quadrature of the tipper is sensitive to variations in the electrical properties of the earth. VLF interpretation can be done through qualitative and quantitative interpretation. Qualitative interpretation uses the Fraser filter or K-Hjelt filter to identify locations (lateral) of the resistivity and conductive zone while the quantitative interpretation uses inversion method to get 2D resistivity subsurface using INV2DVLF Software. There are 3 VLF acquisition line and can be seen in Figure 3.
3. Results and Discussion

Aerial drone photos were used to produce Digital Elevation Model. All of the photos were merged and processed to produce Digital Elevation Model using APS Menci software. From the processed DEM, we know that Citeurep area has an elevation around 627 - 775 meter above mean sea level.

![Figure 3. Creeping area and Acquisition Map of VES Data Points, ERT Tracks, VLF Tracks, and drill data (BHT)](image)

Resistivity measurements are carried out during rainy season in a flooded rice field. Therefore, the resistivity value is estimated to have smaller value than normal resistivity value of rocks. This paper interprets the layer based on resistivity contrast with drilling data that is used for validation rather than standard resistivity value of rocks. In VES method, each VES point is interpreted and then correlated to form a 3D model. After all points are processed and interpreted, the results showed three layers with the following resistivity range:

![Figure 4. Processed Digital Elevation Model of Citeurep area](image)
Table 1. Interpreted Layer Resistivity from VES Method

| Rock layer type          | Resistivity |
|--------------------------|-------------|
| Alluvial                 | 20-27 Ωm    |
| Pyroclastic tuff deposit | 6-11 Ωm     |
| Koleberes Formation      | 148–390 Ωm  |

Figure 5. Southern side of Three-Dimensional Resistivity Data

From the three-dimensional cross section, it can be seen that there is a thick sedimentary layer (the deepest can reach 50 meters) symbolized by yellow (alluvial) and beige color (weathered pyroclastic) from this model we know that the Breccia Rocks form a structure like a “weir”. Based on previous study by Mr. Sugiyono and PT. Muciondo drilling data, the surface of this area is covered by an alluvial layer, followed by pyroclastic tuff deposit that contains sandy grains. Below tuff deposit, there is a hard breccia layer from Koleberes Formation and it acts as an impermeable layer and as a slip plane (Figure 5). ERT resistivity data was processed using the Res2Dinv program. In this program topographic input are added from the Digital Elevation Model. The following Figure is the two-dimensional resistivity model.

Figure 6. Two-dimensional Resistivity Model
(a) lane 1 (b) lane 2 (c) lane 3
ERT data acquired in this Citeurep area is defective since the fields are always flooded by water for approximately 5cm and making the resistivity value reading less precise due to unexceptional electrodes used for measurements in water. Therefore for ERT itself we interpret the model based on its resistivity and use VES resistivity values in Table 1 as a reference, to clarify this we will create a ERT 2D fence model using VES resistivity value in Figure 7.

It can be seen in the fence model that the ERT pathway has similarities with the three-dimensional VES point modeling where there are thick sediments (yellow and blue) and breccia rocks (red) form a “weir” like structure.
From Figure 8 (a) the main concern in this model is the blue contrast zone with high conductivity-low resistivity which has its underground water flow contained in meter 10-30, 40-50, 60, 85-90, and 110-130. At meter 110-130, it is suspected there is an underground water flow zone area that is more prone to building damages since the water will flow into the weakest geological zone. Moreover, high
resistivity zones are thought to occur due to solidified rock which prevents water from passing through the layer.

From Figure 8 (b) in meters 20-50, 60-100, and 120-148 have high conductivity-low resistivity (allegedly saturated with water due to underground water flow, symbolized in blue). This zone of high conductivity-low resistivity is located along the artificial wall meant to hold the weak zone load (the wall starts at meter 42 and ends at meter 84), there is also a high resistivity at meter 55 due to the measurement path regarding the concrete wall.

From Figure 8 (c) in meter 30-55 have high conductivity-low resistivity (allegedly saturated with water, symbolized in blue) this area is a part of damaged waterway and it is replaced by a more flexible pipe, assuming that the area is indeed a vulnerable geological zone for buildings because underground water flow through the area. Starting from meter 0 to meter 30, it’s a weak geological zone that can be seen from the appearance from the rock barrier (rock holding the ground motion) flushing area that has been damaged due to ground movement.

4. Conclusion
The lithology of the study area is dominated by alluvial sediments and weathered pyroclastic rocks with grains of sand so that they are saturated with water, having an effect on adding mass, and reducing cohesion between rock grains. Koleberes Rock Formation (breccia) is a hard rock which is considered bedrock in the Citeurep area research.

Based on the electrical survey model, it is found that creeping is caused by soil mass overload from the upper part of the hill as well as water abundance which later results in layer cohesion reduction, added load, and the absence of a strong barrier to stop ground movement. At the same time, Koleberes Formation rocks formed a “weir” structure that restrains soil movement due to mass loading. This causes the absence of large landslides even though there is still a slow soil movement (creeping).

According to the VLF measurements, the artificial wall and some parts of the road and northern side of the canyon (next to the waterway) of Citeurep area is at risk of damage because of water-saturated weak zones in that specified area. Therefore, it is not recommended to construct any building in these vulnerable areas.

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