Integrated Geophysical Method, Standard Penetration Test, and Remote Sensing For Interpreting, Correlating, and Analysing Cause of Landslides from Irrigation Pipe Leakage, Case Study: CBLP Hydro Power Plant

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Abstract. CBLP Hydro Power Plant has experienced landslide that caused damage to waterway structure. Relocation of waterway was done in order to move into a more stable area. However, this solution is ineffective wherein the southern part of waterway still encounters landslide. Integration of 2.5D Electrical Resistivity Tomography (ERT), 3D Vertical Electrical Sounding (VES), Very Low Frequency (VLF), Standard Penetration Test (SPT), and digital elevation model from Remote Sensing are carried out to determine lithology, hydrology, topography, and determine local anomaly of research area. From VES model, the lithology consists of landslide material, breccia altered into sandstone with high water content, and massive breccia. From ERT model, we found a shallow anomaly of low resistivity in line 3 and 7. This anomaly is validated by doing 2 meters deep excavation and found a rapid flow of water caused by a leak from irrigation pipe. VLF model is used to validate water leakage continuity. In conclusion, northern part of waterway is relatively safe due to water leakage continuity absence, with relative density of 34 (SPT) and resistivity number 6.87 Ωm, whereas the southern part of waterway is high risk because affected by continuity of water irrigation pipeline leak.

1. Introduction
Landslides can occur in a short time and with large volumes. Some factors that influence changes in length include steep slopes, high rainfall intensity, permeable subsurface layers, and air layers that exist beneath the surface. CBLP Power plant is located on the slope of a mountain, an area prone to landslides that requires geophysical and geotechnical integration data to make landslide-prone mapping.

1.1. Regional Geology of Research Area
CBLP Power Plant is located in the formation of Kadupandak Clay Layer from Bentang Formation. There is only 1 geological structure of folding with the East-West direction. No fault structure was found. Based on the Geological Map of the Sindang Barang and Bandar Waru Sheet, Java by M. Koesmono, Kusmana & N. Suarno in 1966, the Center for Research and Development of Geological Stratigraphic units found at CBLP Power Plant site, described as the following:
1.1.1 *Aluvium and Beach Deposit (QHA)*. Sand, gravel and mud; sand along the coast, containing titanomagnetite; to form a spur; in some places this unit consists of avalanche material.

1.1.2 *Upper Bentang Formation (Tmbu)*. Crystal tuff, tufa ash (glass tuff), rock tuff, generally marbled and rocky, intertwined with tuffaceous sandstones, tufa napal and marbled limestone, glauconite sites; napal and maritime rocks increase in abundance to the south; contains many fossils that indicate the age of Late Miocene - Pliocene. Neritic environment. Maximum thickness of 350 meters.

1.1.3 *Lower Bentang Formation (Tmbl)*. Sandstone, tuff sandstone, claystone, mudstone, limestone sandstone with glauconite, claystone sandstone, with inserts of rocky claystone, rocky tuff, tuffs, tuffs, limestone, tuffs breccias and conglomerates; locally containing lignite, resin and plant residues; more conglomerates at the bottom, and more tuff breccias in the east; tuffs and tuff breccias are andesite and dacit; local limestone layers containing abundant mollusks; the lower part of this unit in the east gradually flattens out to the Beser Formation (Tmbv); in the western regions this unit gradually flattened into the Cibodas Formation (Tmci); overlap inconsistencies with the Jampang Formation (Tmjv); deposited in terrestrial, brackish, littoral and neritic environments. Late Miocene age, maximum thickness of 500 meters.

1.1.4 *Kadupandak Clay Layer from Bentang (Tmbk*). Clay, green, brownish green and dark gray, with insertions of the tufa-batupa and local tuff breccias, locally containing lignite and rarely of fossils; the claystone layers thicken toward the southeast, and the tuff breccias increase in the northwest; this unit might gradually become a Beser Formation (Tmbv). Sedimentation environment.

1.1.5 *Beser Formation (Tmbv*). Consists of two units, a volcano especially a volcano, and a lava. The main parts of this formation are volcanic breccias, lava breccias, tuff breccias, tu-fa, tufa limes, with inserts of tuffaceous sandstones, tuffaceous clays and conglomerates; these volcanic rocks are generally andesitic; they contain the remnants of plant and eroded wood; the local claystone contains layers of coal several inches thick; the local sandstones contain mollusks and balanuses. Sedimentation environment from land to beach; likely to gradually become Tmbl and overlap incompatible with the Cimandiri Formation (Tmcn and Tmcb) and Jampang Formation (Tmjv and Tmjc).

1.1.6 *Jampang Formation (Tmjv*). It consists of three units, the main part being mostly volcanic breccias, Cikarang members which mainly consist of tuffs, and Ciseureuh Members consisting of lava.
The main part is volcanic breccia, fine-grained to very coarse; pieces generally range from a few centimeters to 100 centimeters; some are 350 cm long, angled - angled responsibility, pieces consisting of porphyry peroxene andesite, some amphibian andesite, dacit and basal coarse porphyry, gray, brown and black; with inserts of lava, tuff breccias, lapilli tuffs and tuffs; locally containing peaks and cracked and illicit wood and limestone lenses; to the east of Cigaru there are corkolite gabro, pyroxenite, hornblendite and other igneous rocks; contains many clay cracks, cracks, stems and veins which profilise the surrounding rocks; mostly mostly amygdaloid, marine and partially sedimentary environments, Early Miocene Age.

Method

2.1 Resistivity Method

Resistivity is the ability of rocks to resist electricity. The greater the resistivity, the smaller the rock's ability to conduct electricity. In contrast to resistance, resistivity is invariant which means it does not depend on the shape of the rock (Asquith and Gibson, 2004). The resistivity method is an active geophysical method by measuring the potential difference generated somewhere due to the injection of an electric current.

$$\rho = \frac{V.A}{I.L}$$

(1)

For a single current electrode embedded into the surface of a homogeneous medium with a resistance type \(\rho\), the current flow moves radially. The potential difference between the two points on the surface can be explained by the potential gradient decreasing in the direction of current flow. Lines of "equipotential" voltage cut across current lines to form an angle. The density of the current (\(J\)) is the current (\(I\)) divided by the area where the current is distributed (half ball, \(2\pi r^2\)), so that the current density decreases with increasing distance from the current source. voltage \(V\), at point \(r\) of the current.

$$V_r = \int \delta V = -\int \rho \frac{1}{2\pi r^2} \cdot \delta r = \frac{\rho I}{2\pi} \cdot \frac{1}{r}$$

(2)

2.1.1 Electrical Resistivity Tomography. The ERT acquisition was carried out with 3 tracks (CBL 6, CBL 8, CBL 10) where each track have a length of 50 m and 4 m spaces between the electrodes. The maximum depth expected is 15 m. Electrode configuration used in ERT measurements is Schlumberger. The raw data are then entered into the Res2Dinv program, where in this program the inversion process is carried out to create a 2 dimensional resistivity cross section model. All the data are then correlated using Rockwork to create 2.5 dimensional Model.
2.1.2 Vertical Electrical Sounding. VES acquisition were carried out as many as 12 points of VES measurement. The location of the VES point can be seen in Figure 3. The acquisition of the VES method uses the Wenner-Schlumberger configuration with the aim of obtaining sufficient penetration depth as well as reasonably good vertical resolution. The length of the VES measurement range is 50 m - 120 m, so that the maximum depth expectations reach 25 m - 75 m. Resistivity data of the measurement results was processed using Progress program for inversion and to make 2 dimensional resistivity modelling as a comparison with ERT model.

![Figure 3. Vertical Electrical Sounding Measurement](image)

2.2 Very Low Frequency Method (VLF-EM)

Very Low Electromagnetic Frequency (VLF-EM) method is a geophysical method based on electromagnetic principles with passive measurement techniques. The primary magnetic field caused by radio frequency can induce conductors that are below the surface, so that the secondary magnetic field arises. The propagation of electromagnetic waves at VLF can be explained through Maxwell's equations. Two of Maxwell's four equations explain the relationship between the electric field vector and the magnetic field. The two equations are known as Faraday's Law and Ampere-Maxwell's Law whose formulations can be seen in (3) and (4).

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{3}
\]

\[
\partial \vec{E} = \vec{J} + \frac{\partial}{\partial t} \vec{D} \tag{4}
\]

Equation (3) is Faraday's Law which physically means that the circulation of an electric field can result from changes in the magnetic field with respect to time. In equation (3), \( \vec{E} \) is the value of the intensity of the electric field, while \( \vec{B} \) is the value of magnetic induction. Whereas equation (4) is the Ampere-Maxwell Law which physically explains that the circulation of a magnetic field can be generated from an electric current and changes in the electric field with respect to time. In equation (4), \( \vec{H} \) is the value of magnetization intensity, \( \vec{J} \) is the current density, and \( \vec{D} \) is the current transfer. From equations (3) and (4), by applying an identity vector we will produce equations (5) and (6).

\[
\nabla^2 \vec{E} = \mu \sigma \omega \vec{E} - \mu \epsilon \omega^2 \vec{E} \tag{5}
\]

\[
\nabla^2 \vec{H} = \mu \sigma \omega \vec{H} - \mu \epsilon \omega^2 \vec{H} \tag{6}
\]
Electromagnetic waves in the form of plane waves, consisting of electric field vectors and magnetic fields whose directions are perpendicular to each other. The ratio of the intensity of the electric field to the magnetic field is called the impedance \( Z \). In heterogeneous media below the earth's surface, polarization \( E \) can be used to determine apparent resistivity \( \rho_a \). With the \( Z \) impedance as follows:

\[
Z = \frac{E_x}{E_y} \quad (7)
\]

\[
\rho_a = (0.2 \, T) \, Z^2 \quad (8)
\]

where \( \rho_a \) is apparent resistivity with unit \( \Omega \text{m} \), whereas \( T \) is period with unit \( s \), \( E_x \) is horizontal electric field with unit \( \text{mV} / \text{km} \), and \( H_y \) is orthogonal magnetic field with unit \( \text{nT} \). The apparent resistivity \( \rho_a \) changes to the actual resistivity \( \rho \) if the medium under the earth's surface is homogeneous. If the resistivity value below the earth's surface varies, then the apparent resistivity value will also change. Therefore, the distribution of apparent resistivity values can be used to map subsurface structures.

2.2 Skin depth. An electromagnetic wave will experience a skin effect, where the attenuation of the waves towards the depth exponentially occurs. Skin depth \( \delta \) can be defined as the depth at which the amplitude of electromagnetic waves is attenuated to be \( 1/e \) or one third of the original amplitude when on the surface of the earth. The value of skin depth is formulated by equation (7), where \( \delta \) is the depth of penetration (skin depth) with m units, \( \rho \) is the resistivity in units of \( \Omega \), and \( f \) is the frequency of electromagnetic waves with units of Hz.

\[
\delta = 503 \sqrt{\frac{\rho}{f}} \quad (9)
\]

Based on equation (9), it is known that depth can be affected by subsurface frequency and resistivity. In the case of using the same transmitter frequency, the depth of penetration will be even greater when electromagnetic waves hit a medium with a large resistivity value. Conversely, the depth of electromagnetic wave penetration will be smaller if it is on a conductive medium. Very low frequency acquisition is done as a validation data on the resistivity measurements made. In addition, it wants to find the direction of movement of irrigation pipe leaks that want to know its continuity. Data quality control is carried out at every measurement point by looking at the amount of noise and signal to noise ratio to get stable data and less noise. The acquisition design is depicted in red lines as illustrated in Figure 4 with total of 4 tracks perpendicular with electrical resistivity tomography measurement.

Figure 4. Very Low Frequency Measurement
2.2.2 Karous Hjelt Filter. Karous-Hjelt Filters produce subsurface anomaly spreads based on current density parameters. The results obtained from this filter are in the form of 2-dimensional contour maps with pseudo-deep ones (Yadi et al., 2017). Data processing uses the Karous-Hjelt filter according to the equation (8)

\[ KH_n = 0.102H_n - 3 - 0.059H_n - 2 + 0.561H_n - 1 - 0.561 H_n + 1 + 0.059 H_n + 2 - 0.102 H_n + 3 \]  

(10)

2.2.3 Noise Assisted- Multivariate Empirical Mode Decomposition Filter. The NA-MEMD filter is a filter developed by Rehman and Mandic to describe the general class of multivariate data (containing more than 2 signals) simultaneously (Wijayanto et al., 2015). The NA-MEMD algorithm tries to eliminate noise interference that occurs in the EEMD and reduces the mixing mode at the EMD and MEMD outputs. This method operates by forming a multivariate signal consisting of input data and noise on separate channels (Purwanto and Minarto, 2015).

2.3 Digital Elevation Model
Digital Elevation Model or DEM is a digital representation of land surface topography. DEM is widely used in geographic information systems and 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. DEM data can be divided into two, namely DSM (Digital Surface Model) and DTM (Digital Terrain Model). DSM is a digital model of the surface of the earth recorded by remote sensing devices, including the surface of non-earth objects. Whereas DTM is a digital model of land surface without objects on the surface. These three types of DEM have different geometric structures. Digital contours are based on horizontal lines, while raster or regular grids are based on regular points and TIN are based on irregular points. These structural differences distinguish the geometric shapes of the smallest units that make up each model. In the DEM representation of digital contour types, the geometric shapes are polygons, in rasters are rectangles, and TIN is triangles (Riyanto, 2009). Digital Elevation Model was processed using APS Menci from drone aerial photos. The DEM was georeferenced using GlobalMapper by comparing the landmark coordinates from DEM and the established map. From this Model, elevation of the resistivity measurement points and lines can be known its elevation, to be used in correlation.

2.4 Standard Penetration Test
The Standard Penetration Test (SPT) is one of the tests in the field of civil engineering that serves to determine the position of the depth of hard soil, which can later be estimated how strong the land is in holding the weight established on it. This test does not have the accuracy of how hard the soil is at the measurement location. Standard Penetration Test or SPT testing is carried out during the drilling activities with an interval of testing every 2 meters. SPT testing is done by counting the number of hammer blows to press the split spoon sampler sample tube with a diameter of 2 inches as deep as 30 cm into the ground. The value of N value obtained by the standard Penetration Test can be impelled with a number of other properties than the land concerned (Warnana, 2018). However, the results of this SPT should always be considered as rough estimates, not as careful values. The resulting value is N-SPT, where the value shows how hard the land of the measurement location. The SPT data is used as a validation of each methodology measurement.
Table 2. Table Classification of N-SPT values and Correlation to Soil Density (Skemton, 1986)

| Relative Density    | Dr     | N   |
|---------------------|--------|-----|
| Very loose          | <0.15  | <4  |
| Free                | 0.15-0.35 | 4-10 |
| Is                  | 0.35-0.65 | 10-30 |
| Solid               | 0.65-0.85 | 30-50 |
| Very Solid          | 0.85-1.00 | >50 |

3. Results and Discussion

3.1 Remote Sensing Method

In remote sensing method, elevation model is made to obtain accurate elevation height to get a 3 dimensional model that will be accurate based on the elevation from remote sensing method.

Figure 5. Digital Surface Model Processing Results

Figure 6. Digital Terrain Model Processing Results
3.2 Electrical Resistivity Tomopgraphy

3.2.1 Electrical Resistivity Tomography 2 dimensional model
A 2-dimensional model was performed on the CBL 6 trajectory with inversion parameters of 0.1 for convergence limit. Besides that, the produced inversion models were more detailed and sensitive to variations in resistivity because using 4 nodes on mesh model. The Jacobian matrix was recalculated in the 2 initial iterations and the flatness filter ratio was 1.0.

Figure 8. CBL 6 2D ERT Inversion
A low resistivity anomaly was found at CBL 6 on 18 meter that enlarges with increasing depth. This is the focus of the problem because the blue colour indicates the area of landslide boundaries. The green-purple colour with higher resistivity values is estimated to be a mixture of alluvium, sand, and breccia.

Figure 9. CBL 8 2D ERT Inversion
A low resistivity anomaly was also obtained at CBL 8 from 0 to 48 m. This low resistivity anomaly is predicted as an altered breccia rock that is fully saturated. From the CBL 6 and CBL 8 models, it was predicted that there was a water saturated layer under the a mixture of alluvium, sand, and breccia layer.

![Figure 10. CBL 10 2D ERT Inversion](image)

A low resistivity anomaly was also obtained on meters 12 and 22 which were predicted as altered breccia rock that is fully saturated. But the distinguish between CBL 6, CBL 8, and CBL 10 is the absence of seepage in the CBL 8 zone which indicates differences conditions between the 3 measurement locations that need to be integrated using vertical electrical sounding and very low frequency method.

3.2.2 Electrical Resistivity Tomograph 2.5 dimensional model
After 2.5 dimensions modelling was done. There was a continuity between low resistivity data which previously experienced anomaly in the form of low resistivity on VES and ERT results.

![Figure 11. CBL 8 2D ERT Inversion](image)

3.3 Vertical Electrical Sounding
From this model, there are 3 layers. The first layer is a mixture of sand, breccia and clay. The second layer is saturated gravel sand. The third layer is breccia rocks. Saturated gravel sandstone is the boundary area of the landslide layer. It was found in Figure 12 there was a tendency of a low resistivity value sticking up at the 20th meter which has the same tendency as the local anomaly found in Electrical Resistivity Tomography data.

![Figure 12. 3D Model of Vertical Electrical Sounding](image)

3.4 Very Low Frequency
NAMD filter is performed and validated by comparing the qualitative results of the Khffilt filter model with the 2-dimensional inversion model, the same treatment was also carried out at the initial resistivity which is set at 100, lagrange 0.03, and the number of iterations by 50 times.

![Figure 13. The results of processing the Karous Hjelt filter (a) and inversion (b) on VLF 3](image)

On VLF 3, there is an areas with low resistivity values that is indicated by blue colour (figure 13b) and high current density in red colour (figure 13a) which indicate that the area is a water saturated
area. Measurement of this line is located parallel to the irrigation pipe that has indicated leakage, therefore it can be validated that the leakage of the irrigation pipe penetrates into the deep layer to reach a depth of 20 m using SPT data which is a layer of sandstone.

![Image](image_url)

**Figure 14.** The results of processing the Karous Hjelt filter (left) and inversion (right) on VLF 2

On VLF 2, there is an indication that the area is affected by the leakage of the irrigation pipe which has continued towards the waterway and the road. Measurement of this line is located parallel to the irrigation pipe which has been previously indicated leakage, therefore it can be validated that the leakage of the irrigation pipe penetrates into the bottom layer until it reaches a depth of 20 m which is a layer of sandstone, but the effect of the leak is not as large as the effect on line 3 that is directly affected.

![Image](image_url)

**Figure 15.** The results of processing the Karous Hjelt filter (left) and inversion (right) on VLF 1

Measurement of this VLF 1 line is located parallel to the irrigation pipe which has previously did not indicate leakage, therefore it can be validated that the leakage of the irrigation pipe does not penetrate...
into the VLF line 1 because the amount of the conductive layer is only at swallow depth. In addition there are also breccia rocks with high resistivity values that indicate hard rocks that have been found at a depth of 10 m.

3.5 Integration and Validation with Standard Penetration Test

Based on the results of the Standard Penetration Test, it was found that the depth of 0-6 m is very loose with SPT value of 4 until 7 and resistivity value of 6.98 ohm meters. This is due to soil lithology which is a combination of alluvium, sand and clay rock. There is an altered breccia rock that is converted to clay and silt with SPT value of 29 which is characterized by a resistivity value of 5 ohms. Besides that, it is found that the saturated zone is having 29 SPT value with resistivity value of 1-3 ohm meters.

![Figure 16. Results of Integrating Electrical Resistivity Tomography with the Standard Penetration Test](image)

3.6 Validation of Shallow Low Resistivity Zone

After doing 3 meters excavation in the low resistivity area which was previously predicted as water saturated zone. An irrigation pipeline leak was found at the CBL 6 and 10 measurement points that answers a zone that was full of water on the results.

![Figure 17. Irrigation Pipe Leaks on CBL 6 and 10 was Found after Excavation](image)
4. Conclusion
Based on the results of studies that have been carried out, it has been found that that the movement of land and landslides caused by over saturated area from irrigation pipe leakage which caused a reduction in cohesion, increased load, and the absence of a strong ground movement barrier. The north side of the waterway is relatively safe because it is not over saturated due to the absence of irrigation pipe leaks and loading by the paddy field. Where the southern part of the waterway (along 2 meters of the waterway) is affected by irrigation pipe leaks.

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