Seepage Patterns in an Earth-Rock Fill Dam Evaluation using Electrical Resistivity Tomography (ERT) Method

Y A Fata¹,*, E Suhartanto², Hendrayanto¹, and P Rubiantoro²

¹Forest Management Department, IPB University, Bogor, Indonesia
²Water Resources Engineering Department, Brawijaya University, Malang, Indonesia

*Corresponding author: yulia_7796@apps.ipb.ac.id

Abstract. Seepages in the earth-rock fill dam are usually monitored by pore pressure, seepage water table, and seepage discharge. However, those monitoring are difficult to describe the seepage patterns because they are installed only in certain points. This research evaluated the seepage pattern resulting from Electrical Resistivity Tomography (ERT). The resistivity was measured by installing electrodes upstream of the Dam at every 10 m and downstream at 20 m distances. The seepage pattern was analysed from the resistivity 2Dimension distribution using the RES2DINV program. The results showed that the seepage pattern resulting from the ERT method's resistivity data, which was compared with data of surface dam deformation, pore pressure, and seepage water table, could explain the seepage discharge data. Based on those confirming data, the resistivity data of the ERT method was appropriate to explain the seepage pattern in the earth-rock fill dam and can be further utilized for dam stability analysis.

Keywords. Earth-rock fill Dam, seepage patterns, ERT, seepage monitoring

1. Introduction
Dams have to be inspected and investigated regularly to ensure the safety and sustainability of their functions. Geotechnical inspection and investigation of dams, especially for earth-rock fill dams are essential to assess the dam geological character. One of the geotechnical parameters important to be inspected and investigated in earth-rock fill dams is the seepage flow and its pattern [3].

Seepage in the earth-rock fill dams is usually monitored by pore pressure, seepage water table, and seepage discharge parameters [20]. Results of monitoring those parameters are difficult to use for figuring out the seepage pattern in the dams. Therefore, alternative methods for monitoring seepage flow and patterns need to be introduced.

The existence of seepage is indicated by higher water content. Water content has a relationship with rock and soil material resistivity values [19]. The relationship between the two shows that the lower the resistivity, the higher the water content [13], and it has a non-linear relationship.

Resistivity measurement methods to estimate the water content of a media have been developed, including the ERT method. The ERT method has been widely applied to predict dam deformation [5] [9] [19], the karstic features of the Dam, seepage of the Dam [5] [10] [11] [22], geology and structure
[3], and water leakage [1]. However, the ERT method is rarely applied to measure resistivity in an earth rock-fill dam.

The ERT method application for monitoring seepage in the earth-rock fill dam was potential for identifying the seepage distribution [1] [3] [10]. This research is aimed to evaluate the seepage flow and pattern resulting from the ERT method applied in an earth-rock fill dam. The earth-rock fill dam was chosen to apply the ERT method because it has a higher seepage potential than the concrete Dam.

2. Materials and Method

2.1. Study Site
This research was conducted in Sutami Dam. Sutami Dam is an earth-rock fill dam located in Karangkates Village, Sumber Pucung Sub-district, Malang Regency, East Java Province, Indonesia (Figure 1). Sutami Dam was built as a flood control supplier of irrigation water, hydropower, water supply, etc. The designed flood discharge of Sutami Dam was 2580 m³/s with a catchment area of 2050 km². It also has 100 meters in height and 780 m in length of the cross-section.

2.2. Research Logical Framework
The ERT method using the Wenner Schlumberger arrays with a RES2DINV computer program can measure the 2D resistivity distribution in the Dam's body. Many types of research have shown the relationship between resistivity and water content. Lower resistivity showed higher water content [13] [15] [23], and the relationship was not linear. However, the relationship was not being constructed in the rock-fill Dam.

This research attempted to give more evidence of the relationship between resistivity measured by the ERT method and water content in a rock-fill dam. The resistivity data analyzed using RES2DINV computer program showed the 2D distribution of resistivity. The 2D resistivity data were compared to the pore pressure data measured by vibrating wire piezometer. The surface dam deformation was measured periodically using the water pass and theodolite. An open standpipe piezometer measured the seepage water table. Those data are not water content data, but those data also have a relation to water content. Water content in the dam structure is rarely measured directly.
Pore pressure data saw a strong relationship with the water content of media [2] [15]. The pore water pressure within the Dam is altered by external loading conditions like rapid drawdown of reservoir water, earthquake, and rise of water table caused by rainfall infiltration. Water infiltration in the Dam indicated various pore pressure values. The high pore pressure value developed at the middle level of the core dam is caused by water content distribution.

Research also saw that the water content was higher in places where the surface dam deformation occurred [15]. The infiltration of the water reservoir can cause the deformation of the Dam. The water reservoir finds its way downstream through the Dam. The force behind the water can create new or enlarge existing water pathways. This process can cause stability problems when high water pressure and saturation in embankment and foundation soils cause the earth materials to lose strength [2] called piping. The piping developed the deformation of the soil in the body of the Dam.

The data corresponding to resistivity, pore pressure, and dam surface deformation data, saw that resistivity data were strongly related to water content. Strong relation of resistivity data in the points of pore pressure and dam surface deformation measurement were used to analyze the two-dimension water content distribution through the resistivity distribution data as the indicator of seepage distribution flows. Furthermore, the distribution of seepage flows data was compared to the seepage water table and discharge measured by vibrating wire piezometer and open standpipe piezometer, respectively. The corresponding resistivity data and their distribution to all data of pore pressure, dam surface deformation, seepage water table, and discharge were used to assess the validity of resistivity data measured by the ERT method using the Wenner Schlumberger arrays with a RES2DINV computer program to analyze the presence of seepage and their distribution in two-dimension of the rock-fill Dam.

2.3. Data Collection
The location of data measurements is presented in Figure 2.

As electrical resistivity tomography (ERT) measurement, Line I and Line II were located upstream and downstream of the crest dam, respectively. The two types of piezometer, the open standpipe piezometer (W1, W2, W3, W4, and W5) as seepage water table instrument and the vibrating wire piezometer (HP1–HP16) (Figure 5) as a pore pressure meter instrument, were installed. The cross-section lines refer to Figure 4 and Figure 5. The surface deformation point (P1–P6 and ST1–ST5) was installed as a surface deformation instrument. The v-notch channel (Gallery, Dried, DR, DP1, DP2, D4) as a seepage discharge instrument was installed in the toe of the Dam of the downstream site (Figure 2).
2.3.1. **Resistivity Measurement**

The resistivity was measured using the ERT method with the Wenner Schlumberger configuration by injecting current into the ground through two current electrodes (C1 and C2) and injecting voltage difference at two potential electrodes (P1 and P2). The electrodes were installed in the order C1-P1-C2-P2 with the rules of the distance between the electrodes of C1-P1 20 m, P1-P2 10 m, and C2-P2 20 m (Figure 3).

![Figure 3. The Wenner Schlumberger Arrays](image)

This distance is then multiplied by the "n" factor, the distance ratio between the electrodes C1-P1 and P2-C2 when used to find the depth of "na." In Figure 3, the distance between the electrodes to get a depth of n = 1 is shown at station 1. Furthermore, each electrode moves along with the required depth value "na" under the Wenner Schlumberger configuration equation with a distance of 2na + a. This measurement was done repeatedly along the 780 m length of the dam body. The electrodes that were injected on the ground read an "apparent resistivity" of the geo-electrical instrument. The "apparent" resistivity value changes to the "true" resistivity using a computer program. This research used the RES2DINV program to interpret the true resistivity in 2D (two-dimension) images.

2.3.2. **Surface Dam Deformation Measurement**

The deformation was measured using theodolite and water pass. The measurement was conducted every three months periodically in a year. The locations of deformation measurements are presented in Figure 2.

2.3.3. **Seepage Water Table Measurement**

Three open standpipe piezometers measured the seepage water table. The measurement was conducted every two weeks periodically in a month. The location of the seepage water table is presented in cross-section C-C' as presented in Figure 2 and Figure 4.

![Figure 4. The Location of Open Stand Pipe Piezometer in Sutami Dam](image)
2.3.4. Pore Pressure Data
Pore pressure was measured by a vibrating wire piezometer (pore pressure meter). The measurement is conducted every two weeks periodically in a month. There were 14 vibrating wire piezometers in Sutami Dam. The sensors' locations were in the dams' body and are presented in every cross-section of A-A', AB-AB', and B-B' of Figure 2 and Figure 5.

2.3.5. Seepage/Leakage/Spring Discharge Measurement
The measured seepage, leakage, and spring water channel, downstream of the Dam (Figure 2). The measurement was conducted every two weeks periodically in a month. The water discharge came from seepage from the reservoir or groundwater from the dam rock cliff left and right. Two v-notch channels were dried in the D2 and Dried outlets from 1999 (Figure 2).

2.4. Resistivity Data Processing and Analysis
The resistivity data were processed using the RES2DINV program, which produced a 2D distribution of resistivity. These 2D distributions of resistivity were then analyzed by comparing with the data of surface settlements, seepage water table, pore pressure, and seepage/leakage/spring water to find out the data conformity of resistivity to a moisture level of materials and seepage pattern in the Dam.

Figure 5. The Locations of Vibrating Wire Piezometer Sensors in Sutami Dam [21]
3. Results and Discussion

3.1. Resistivity Distribution
The 2D resistivity distributions in the Sutami earth rock-fill dam resulted from ERT measurement, and a RES2DINV computer program is presented in Figure 6.

The range of resistivity measured and interpolated in two-dimension was 0.31 to 1479.24 ohm.m which were represented by a very dark blue color for lowest resistivity and very dark red for the highest resistivity. The resistivity values were related to the moisture of media, where the media with lower resistivity show more than those with higher resistivity [7] [16]. With the assumption of homogeneous media, the gradation of colors shows the gradation of moistures of media. Based on Figure 6, it can be shown that the lowest resistivity values in Line 2 (downstream) was higher than the lowest resistivity values of Line 1 (upstream), where the colors of dark-blue were very small in Line 1. However, in Line 1, the relatively low resistivity was still found, which was shown by the light-blue colors. These dark and light blue zones are considered as low resistivity and are numbered as 1 to 18 (BUi) for Line 1 (upstream) and 1 to 10 (BDi) for Line 2 (downstream). The relatively low resistivity values occurred in the Dam's surface, such as BU1, BU2, BU3, etc. were suggested due to the infiltrated rainfall, and or the surface drainage outlets, while those inside the Dam, such as BD3, BU5 were due to seepage occurrences.

The material's resistivity depended on the degree of fracturing and the percentage of the fractures filled with groundwater [13] [14]. The resistivity also indicates the presence of groundwater based on high coefficient of permeability and porosity as shown by 2D resistivity through RES2DINV program [17].

3.2. Resistivity and Surface Deformation
The surface deformation is the changes in a surface-level position as compared to a reference surface-level position. The changes could be negative if the surface changes to be higher or positive when the surface changes to be lower than the reference level of the surface. The positive deformation was measured based on maximum positive deformation. In contrast, the negative deformation was measured based on maximum negative deformation from May 1996 till December 2017 [21]. The deformation measured in March, April, and May and their resistivity are shown in Figure 7.
The maximum deformation data are calculated using the surface deformation data in twenty years, from May 1996 to December 2017. The data had positive and negative values representing the body changing of the Dam. The positive value showed that the dam body ran into a lower elevation. In contrast, the negative value showed that the dam body ran into higher elevations from the first measurement in May 1996.

The deformation measurement in March till May 2017 showed the negative value related to the maximum negative deformation. In three months, the highest maximum negative deformation was located in P3 and ST2 (Figures 6 and 9). There were five blue zones in total, in both of surface deformation points and next to the cracked zone in Sutami Dam and the location of drying v-notch (Figure 2 and 6).

In 2014, a new problem was found in the crest of the Sutami Dam. There was a crack zone along a 70 meters path that might be causing the loading and unloading process in the reservoir operation [20]. The latest study in 2017 showed that the crack zone was growing longer than before and could endanger the Dam's stability [8].

Based on this interpretation, the result of resistivity 2D was in agreement with the observed embankment deformation in Sutami Dam, and the seepage pattern was confirmed with the deformation phenomenon in Sutami Dam (Figure 9). [19] showed that deformation increases with decreasing soil density and water content. The prediction with the historical deformation is important to show the Dam's current condition [4].

3.3. Resistivity and Pore Pressure
Comparisons of resistivity data to pore pressure data are presented in Figure 8.

Figure 7. The Deformation and Resistivity in Sutami Dam

Figure 8. Pore Pressure Meter and Resistivity
The pore pressure did not exceed the reservoir water level elevation (WLE) 271.5 m and also have the same location with ERT measurement in Line 1 and 2 (Figure 8). There were a total of 14 vibrating wire piezometers from three cross-sections to represent the pore pressure value. The higher elevation pore pressure data have lower resistivity. In contrast, the lower elevation pore pressure data have higher resistivity (Figure 8). The range of blue zones which had low resistivity was also in agreement with the pore pressure elevation. Furthermore, the result of 2D resistivity was confirmed with the pore pressure data in Sutami Dam. The low resistivity in the blue area is confirmed with the high elevation of pore pressure related to high water content.

The pore pressure data have a relationship with the reservoir fluctuation. High water levels caused the high pore water pressure [15]. The high pore water pressure showed low resistivity. The low resistivity showed the water content of the media that can be changed by the rainfall and drying events. Water content in the dam structure is rarely measured directly. However, it is commonly estimated using pore pressure that was measured by a vibrating wire piezometer.

3.4. Resistivity and Seepage Water Table
Comparisons of resistivity data to seepage water table data are presented in Figure 9.

There are three open standpipe piezometer instruments to measure the seepage water table. The seepage water table data did not exceed the reservoir water level and have the same location as ERT measurement in Line 1 and 2. The low resistivity shows the high elevation of the seepage water table, and decreasing of seepage water table elevation has a higher range of resistivity than the high seepage water table elevation (Figure 7). The seepage water table elevation was in agreement with the blue zone interpretation which had the value included in the range elevation. Furthermore, the result of 2D resistivity was confirmed with the seepage water table data in Sutami Dam.

The factors of seepage characteristics depended on pore water pressure load, groundwater level, path and quantity of flow, rainfall, rapid drawdown [2], reservoir water level, temperature, timeliness [22], fractures, and faults [3] [5]. The seepage was routinely monitored by the seepage water table data measured by an open standpipe piezometer [20].

3.5. Resistivity and Seepage Discharge
The seepage discharge data are presented in Figure 10. The data show the discharge value from seepage flow in the body of the Dam.
Figure 10 shows seepage, leakage, and spring water data. The data are normal because they do not exceed the boundary (192 liters/minutes). The DR instrument was located downstream next to the drying v-notch in the toe of the Dam (Figure 6). This report indicated that the seepage flow from drying v-notch was going out in this way after not flowing in the dried v-notch because there was no anomaly in the data.

The dried v-notch located in the BD3 downstream (Figure 7) showed seepage water table elevation downstream, which was also related to BD3. The lower resistivity in this area indicated that the seepage in the dried v-notch might have another way to flow out in the Rock v-notch or other v-notch channels near the dried v-notch (Figure 2 and Figure 6).

Based on the interpretation, the 2D resistivity can be used to detect the water content value. The confirmation of lower resistivity data with the water content showed the seepage existence in the Dam. The higher water content confirmed by the pore pressure data indicated the existence of seepage [15] [18]. The seepage water table data had been proved to have a strong relationship with the pore pressure data. Both data were measured by two types of piezometric pressure meters used to show the seepage elevation in the subsurface of the Dam to identify the dynamic seepage in the Dam [15]. Moreover, the 2D resistivity has been widely applied to predict dam deformation [5] [8] [19].

This identification confirmed the ERT method, which had no damaging impacts on soil structure [6] to show the seepage pattern in the body of the Dam. Seepage patterns can be used for analyzing seepage flow by checking data from the dam instrument. The existence of seepage can be identified by seepage distribution and its pathways [12].

4. Conclusion
This study showed that Wenner Schlumberger arrays of electrical resistivity tomography (ERT) method produced the 2D seepage patterns by measuring resistivity. The results of the 2D seepage pattern in the Dam were confirmed with the data of surface dam deformation, pore pressure, and seepage water table measured by water pass and theodolite, pore pressure meter, and open standpipe piezometer, respectively. The seepage patterns can predict the seepage flow by checking the seepage discharge measured by the v-notch channel downstream of the Dam. The results showed that the seepage pattern resulting from the ERT method, which was compared with data of surface dam deformation, pore pressure, and seepage water table, could explain the seepage discharge data. Based on those confirming data, the ERT method was appropriate to explain the seepage pattern in the earth-rock fill dam. Further, the seepage pattern can be utilized for dam stability analysis.

Seepage pattern analysis required complete and accurate dam instrumentation data/information as validation of ERT measurement results. The instrumentation data being used should have the same location as the ERT line measurement. This study had limitations in measuring ERT in the dam body because the Dam is an earth-rock fill type. Future research should provide ERT measurements at the toe of the Dam to confirm the seepage pattern properly in the earth-rock fill dam.

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