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Grounding Optimization Using Soil Resistivity and Parallel Rod Electrodes for a 3 m³/s Flood Pump

Lilin Elvira Ruliawati[1], Lusia Rakhmawati [2],
State University of Surabaya, Indonesia

Lilin.23004@mhs.unesa.ac.id

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Abstract

A critical component of flood pump electrical installations is the grounding system, as it provides a low-impedance path for leakage current, fault current, and transient overvoltage to flow into the earth. The grounding system at the Jagir Kalimir Flood Pump Station in Surabaya was optimized for a pump with a capacity of 3 m³/s by calculating in-situ soil resistivity using the Wenner method and implementing a parallel electrode design. The initial grounding resistance was 13.31 Ω, exceeding the PUIL 2011 limit of ≤5 Ω, indicating that it was insufficient to dissipate fault current effectively. The Wenner four-probe method, with probe spacings of 1.0 m, 1.5 m, and 2.5 m, yielded an average apparent soil resistivity of approximately 6.48 ± 0.19 Ωm. This result indicates that the soil had low apparent resistivity, which is consistent with wet soil conditions during the rainy season. However, a detailed geotechnical classification was not included in this study. Before optimization, field measurements recorded a leakage current of 312 mA and an average of four protection trips per week in the low-voltage main distribution panel (LVMDP) and control panel, indicating the presence of electromagnetic induction and arcing. The optimization was implemented using two vertical electrode rods, each approximately 2.5 m long, installed with a spacing of 2.5 m between them and connected to the main distribution panel through a 20 m grounding conductor. After optimization, the grounding resistance decreased from 13.31 ± 0.06 Ω to 1.11 ± 0.02 Ω, representing a reduction of 91.66 ± 0.15 percentage points. Dwight's analysis predicted an ideal grounding resistance of 1.12 Ω for the proposed configuration, while the measured value obtained using the two parallel rods showed a deviation of approximately 1.04%, demonstrating close agreement with the analytical prediction. However, the limitation of mutual resistance between the electrodes was still recognized. After optimization, the leakage current decreased to 28 mA, and no protection trips, looping, or arcing were recorded during approximately one week of observation. The novelty of this research lies in the combination of Wenner soil resistivity profiling at the specific site, electrode dimension selection based on Dwight's analysis, and field validation for the grounding system of a flood pump electrical installation.

Keywords: Soil resistivity; Parallel rod electrode; Grounding resistance; Wenner method; Dwight equation; Flood pump electrical installation.

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INTRODUCTION

Flooding is one of the most common natural disasters that frequently occurs in urban areas, lowlands, and regions with inadequate drainage systems. During the rainy season, conventional drainage systems are often unable to accommodate the increased water flow, making flood pumps essential for transferring excess water to rivers, drainage channels, or other water bodies [1]. In this context, the operational reliability of high-capacity flood pump stations is critical because any interruption in pump operation reduces drainage capacity and prolongs waterlogging during heavy rainfall [1].

In addition to the mechanical performance of the pump, the reliability of the electrical system is essential to ensure the continuous operation of high-capacity flood pump installations. The pump is driven by an electric motor and supported by distribution panels, protection devices, control systems or variable-speed drives, and other auxiliary equipment [2]. Since the operating environment is humid, located near water, and susceptible to overvoltage and nuisance tripping, a reliable grounding system is required.

The grounding system provides a low-impedance path for fault current, leakage current, and transient overvoltage to flow safely into the earth. It protects personnel from excessive touch and step voltages, provides a stable reference potential for control wiring, and reduces the risk of damage to electrical equipment [3], [4]. According to the Indonesian Electrical Installation Requirements (PUIL 2011), the grounding resistance should not exceed 5 Ω. Meanwhile, IEEE Std 80-2013 recommends that grounding system design should also consider ground potential rise (GPR), touch voltage, step voltage, and soil resistivity.

Grounding performance is primarily determined by soil resistivity and electrode configuration. Soil resistivity is influenced by soil type, moisture content, mineral composition, temperature, salinity, porosity, and density. Meanwhile, electrode configuration includes the number of rods, rod length, diameter, installation depth, spacing, and connection geometry, all of which affect the effectiveness of current dissipation into the surrounding soil [6], [7]. In this study, grounding optimization is defined as selecting an appropriate electrode dimension and configuration based on measured local soil resistivity and validating the resulting grounding resistance through both theoretical prediction and field measurement.

Previous studies have investigated grounding systems in various applications. Reference [3] examined grounding performance using low-resistivity materials and different electrode configurations, with a particular focus on the effect of grounding resistance on substation grounding grids. Reference [6] evaluated the grounding resistance of rod electrodes installed in high-resistivity podzolic soil, while [7] compared grounding performance under different soil characteristics in electrical distribution systems.

Unlike these previous studies, the present research evaluates the grounding system of a flood pump station by combining in-situ soil resistivity measurements using the Wenner method, analytical determination of electrode dimensions using Dwight's equation, installation of two parallel grounding rods, and field evaluation of grounding resistance and operational disturbance indicators before and after optimization.

The initial condition at the Jagir Kalimir Flood Pump Station confirmed the existence of a practical grounding problem. Before optimization, the measured grounding resistance was 13.31 ± 0.06 Ω, exceeding the maximum allowable limit of 5 Ω specified in PUIL 2011. Under earth-fault conditions, the ground potential rise (GPR) can be expressed as GPR = If × Rg. Accordingly, the initial condition can be represented as GPR = 13.31If, whereas after optimization it becomes GPR = 1.11If.

Operational disturbance data were obtained from maintenance logbooks completed by technicians at the Jagir Kalimir Flood Pump Station. Four protection trip events were recorded during the observation period before optimization. These events required additional inspection, system resetting, and maintenance activities during pump operation.

This study addresses this gap by optimizing the grounding system of a flood pump electrical installation using measured soil resistivity, analytical electrode configuration design, and direct field verification. The objectives of this study are to: (1) evaluate the initial grounding condition and its associated operational disturbance indicators; (2) determine an electrode configuration that satisfies the grounding resistance requirement based on the measured soil resistivity; and (3) evaluate the effect of the optimized grounding system on electrical stability and operational reliability. Section 2 presents the theoretical background, Section 3 describes the experimental methods and measurement procedures, Section 4 discusses the results and their theoretical validation, and Section 5 presents the conclusions, limitations, and recommendations for future research.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK A. Grounding system in electrical installations

System grounding is an electrical wiring between a point in the electrical circuit or exposed conductive equipment with the ground. This grounding system was designed to conduct the fault current through a low-impedance path and limit the dangerous voltage rise on metal structure [8],[11]. Grounding can be divided into system grounding, which connects the neutral point of a transformer or generator to earth, and equipment grounding, which protects personnel and equipment when insulation failure energizes exposed metal parts.

The standard Indonesia that applied was PUIL 2011, that require resistance grounding not more than 5 Ω for electrical installation. For high-risk and critical electrical facility, IEEE Std 80-2013 further evaluate the safety through the touch voltage that allowed, step voltage, grid potential rise, fault duration, and human body impedance. Because of that, low resistance grounding was needed but need to be interpreted together with the fault current level and human body current limit.

B. Soil resistivity and its effect on grounding resistance

Soil resistivity (\rho) is the ability of soil to resist the flow of electric current, expressed in \Omega m. It is influenced by soil type, moisture content, mineral content, temperature, groundwater salinity, and density [6],[7]. IEEE Std 81-2012 recommends that soil resistivity be measured directly in the field because tabulated values represent. broad ranges only and cannot replace local measurement. Typical soil-resistivity ranges for several soil conditions are summarized in Table 1. These values serve only as general references and cannot replace direct field measurements.

Table 1. Typical Soil Resistivity Ranges

Soil Type	Typical Resistivity (Ωm)
Swamp/wet peat	5-40

Saturated alluvial clay	5-20
Wet clay	20-100
Agricultural/alluvial soil	50-100
Moist sandy soil	100-300
Rocky/dry gravel soil	500-5.000
Granite/dry sandstone	1.000-10.000

Source:[10],[11],[3]

Low soil resistivity, particularly in saturated alluvial or clayey soils, enables grounding electrodes to disperse fault current more effectively. However, flood pump sites located in riparian alluvial zones may have a non-uniform or two-layer profile, such as surface clay over saturated alluvium. Because of that, the assumption homogeneity need to be checked by comparing the Wenner measurement at some spacing probe. If the variation was high, model soil two layer more suitable than model soil uniform.

C. Grounding resistance of a vertical rod electrode

Rod electrode commonly used because easy to install and can reach deeper soil layer with higher moisture content. For vertical rod on semi-infinite space of homogeneous and isotropic soil, resistance grounding can be estimated using Dwight equation:

$$R = (\rho / 2\pi L) \times [\ln(4L/d) - 1] \quad ...(1)$$

Dwight equation and the common formulation of resistance grounding rod electrode was used as an initial analytical model in design system grounding, especially when the soil condition can be approach as homogeneous and isotropic [9], [11]. This equation show that resistance grounding was directly proportional with resistivity ground and inversely proportional with the length electrode. This equation valid as an initial model when the electrode was installed on relatively uniform soil layer. In this study, the use of it was justified by the small variation on the reading resistivity apparent Wenner at the shallow spacing that chosen, while the modelling two layer was recommended as future research for seasonal validation and deeper depth.

D. Configuration Parallel Electrocode

To achieve a lower grounding resistance value, two or more electrodes can be connected in parallel. The equivalent resistance of two electrodes connected in parallel can be estimated by:

$$1/R_t = 1/R_1 + 1/R_2 \quad ...(2)$$

However, this equation holds ideally only when the current dispersion zones (sphere of influence) of each electrode do not overlap. To avoid interference between electrode, the spacing between electrode must not less than the length electrode itself, according IEEE Std 80-2013. In practice, the total resistance of system parallel often higher than the ideal value because of the effect mutual resistance that depend on the spacing, geometry, and resistivity ground between the electrode [3].

Correction for the effect mutual resistance on two electrode that connected parallel can be expressed as:

$$R_t = (R_1 \times R_2 - R_m^2) / (R_1 + R_2 - 2R_m) \quad ...(3)$$

With Rm was the mutual resistance between the two electrode. For initial design of two identical vertical rod with spacing s on uniform soil, Rm can be approximated with $Rm \approx [\rho/(2\pi L)] \ln[(\sqrt{(s^2 + L^2)} + L)/s]$. This component mutual become smaller when the spacing between rod enlarged and become more significant when the current dispersion zone overlap each other.

E. Touch voltage and safety

One of the primary objectives of a grounding system is to reduce touch voltage to a safe level. The potential touch voltage can be estimated as:

$$Vt = If \times Rg \quad ...(4)$$

Model touch voltage that safe need to include the human body impedance and resistance foot/contact, expressed as Vt:

$$Vt\_safe = Ik(Zbody + Rfoot) \quad ...(5)$$

With Ik was the threshold current body that allowed. Based on IEC 60479-1, the risk fibrillation ventricular depend on the magnitude current, path current, and duration, so the evaluation touch voltage should not only depend on Rg but also on the setting protection and impedance human body.

F. Reliability of the flood pump electrical system

Reliability of an electrical system refers to its ability to perform its intended function over a specified period of time without failure. In flood pump installations, the reliability of the electrical system is influenced by the stability of the supply voltage, the integrity of the protection system, the condition of cable and motor insulation, and the effectiveness of the grounding system [2] [2].

System grounding that not optimal can cause high leakage current, noise on signal control, tripping repeated on MCCB/MCB, and interference with SCADA or system control automatic. Because of that, optimization of system grounding directly contribute to the improvement of reliability operational flood pump, especially during condition control flood emergency.

METHOD

A. Research Design

This study uses an experimental design paired with a quantitative approach. An experimental design was appropriate here since the work involves physically installing, testing, and evaluating a grounding system within the electrical installation at the Jagir Kalimir Flood Pump House. The quantitative side comes in through how system performance is assessed by measuring numerical values such as grounding resistance, voltage, current, and how stable the pump system's operation remains [4].

B. Flowchart

The overall research procedure, from the literature review and preliminary measurement to data analysis and conclusion, is illustrated in Figure 1.

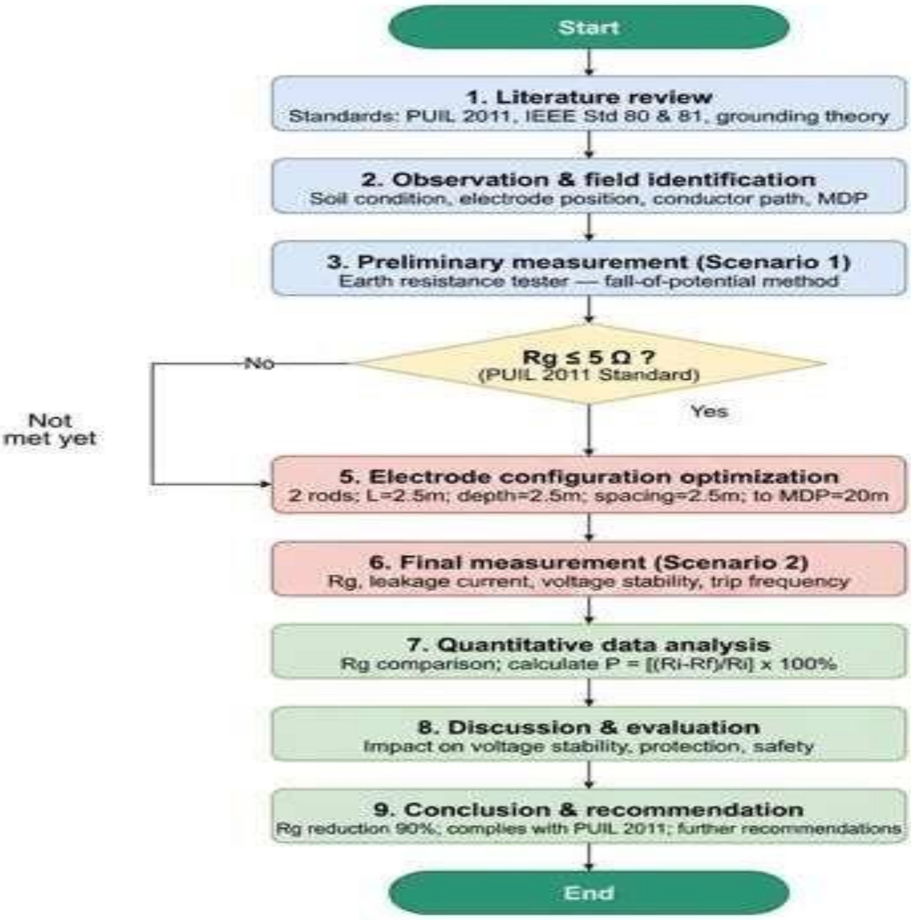

Figure 1. Research flowchart

C. **Research object and location**

The research location at the Jagir Kalimir Flood Pump Station in Surabaya is shown in Figure 2.

Figure 2. Research location

This study was conducted on the grounding system connected to the Main Distribution Panel (MDP) of a 3 m^3/s flood pump installation at the Jagir Kalimir Pump House, Surabaya. Testing was carried out directly in the field to obtain actual data on the condition of the grounding system before and after optimization. The Wenner soilresistivity measurement was conducted in March 2026 during the rainy season, when the ground surface was wet.

D. Measuring Instruments

The three-point fall-of-potential measurement arrangement used to determine the grounding resistance is illustrated in Figure 3.

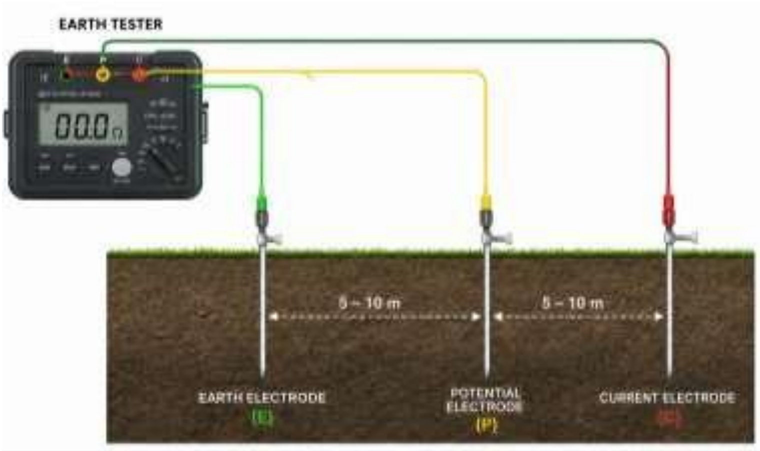

Figure 3. Grounding Resistance Measurement Scheme Using the three-Point Method

Grounding resistance was measured with a DUOYI DY4100 earth resistance tester using the three-point fall-of-potential method, following IEEE Std 81-2012. Phase-to-phase voltage was recorded with a ZOYI ZT-102A digital multimeter; on the 600.0 V AC range, the instrument has a resolution of 0.1 V and a manufacturer-stated accuracy of ±(1.0% of reading + 3 digits). Leakage current, meanwhile, was assessed using a HIOKI CM3289 AC clamp meter, which has an AC current range of 42.00–1000 A and a manufacturer-stated basic accuracy of ±1.5% of reading ±5 digits. Since this clamp meter is primarily built for ampere-level measurements, the milliampere-range leakage-current readings obtained here should be treated as indicative field values rather than precise data, and further verification with a dedicated milliampere-range leakage clamp meter is recommended. All instruments were visually inspected and functionally checked before use, and operated according to their respective manufacturer guidelines.

E. Soil Resistivity Measurement Using the Wenner Method

Soil resistivity was measured before electrode installation using the Wenner four-probe method. Four probes are positioned along a straight line at equal intervals *a*, with probe depth *b* kept small relative to this spacing. The two outer probes carry the injected current, while the two inner probes register the resulting potential difference. From these readings, apparent resistivity is calculated as $\rho a = 2\pi aRw$, where Rw denotes the measured Wenner resistance. Each spacing was tested three times and averaged to improve repeatability. The Wenner resistivity results appear in Table 2, and Table 3 lists the repeated grounding-resistance readings together with the manufacturer-stated accuracy of each instrument.

Table 2. Wenner Soil Resistivity Measurement Results

Probe spacing a (m)	Mean Wenner resistance Rw (Ω)	Apparent resistivity ρa (Ωm)	Repetition
1.0	1.06	6.66	3 times

1.5	0.69	6.50	3 times
2.5	0.40	6.28	3 times
Mean ± SD	-	6.48 ± 0.19	-

ɜurement Repe

Table 3.
Accuracy

Condition	Repeated readings (Ω)	Mean ± SD (Ω)	Manufacturer-stated accuracy
Before optimization	13.25; 13.31; 13.37	13.31 ± 0.06	±1%
After optimization	1.09; 1.11; 1.13	1.11 ± 0.02	±1%

The grounding resistance value reported here is the mean of three repeated measurements, with the accompanying ± figure representing the standard deviation of those readings. The manufacturer's stated instrument accuracy of ±1% is reported separately and was not combined with this repeatability figure. Consequently, the uncertainty presented in this study does not represent a full GUM-based uncertainty evaluation, but should instead be interpreted simply as a measure of repeatability.

F. Research parameters

The parameters observed included:

- Grounding resistance (Rg), measured in Ω
- Soil apparent resistivity (ρa), measured in Ωm using the Wenner method
- Number, length, depth, and inter-electrode spacing of electrodes
- Distance from the grounding point to the Main Distribution Panel (MDP)
- Leakage current at the Low Voltage Main Distribution Panel (LVMDP) and control panels
- Operating voltage stability and trip frequency of protective devices

G. Research Variables

The treatment variable in this study was the grounding-electrode configuration, covering the number of rods, electrode length, diameter, burial depth, spacing between electrodes, and connection arrangement. Dependent variables included grounding resistance, leakage current, voltage range, protection-trip frequency, and indications of electromagnetic induction and arcing. Since soil resistivity was measured rather than deliberately varied, it was treated as a contextual site parameter rather than a controlled variable. Factors held constant throughout the study included the measurement location, instruments used, measurement method, probe orientation, panel connection point, and observation duration.

H. Optimization Procedure

The configuration of the two parallel rod electrodes and their connection to the Main Distribution Panel is illustrated in Figure 4.

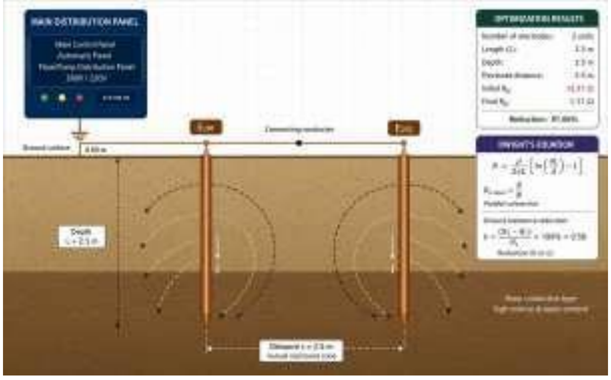

Figure 4. Configuration of two parallel rod electrodes at the Jagir Kalimir Flood Pump Station, Surabaya

The initial grounding condition was assessed using the fall-of-potential method, yielding a value of 13.31 Ω, well above the PUIL 2011 safety limit of ≤5 Ω. Field logs collected prior to optimization showed electromagnetic induction affecting the distribution panel, signs of arcing, and recurrent tripping across both the LVMDP and control panels. With a measured apparent soil resistivity of 6.48 ± 0.19 Ωm, a two-rod vertical electrode configuration was selected as the optimization approach.

The optimization involved driving two copper rod electrodes, each 16 mm in diameter and 2.5 m long, vertically into the ground to a depth of 2.5 m. Electrode spacing was set equal to the rod length at 2.5 m, so as to minimize overlap between the current dispersion zones. A grounding conductor roughly 20 m long connected the grounding point to the MDP. Applying the Dwight equation with ρa = 6.48 Ωm, L = 2.5 m, and d = 0.016 m gave an estimated single-rod resistance of approximately 2.24 Ω. Under an ideal parallel configuration, the two rods were therefore expected to produce a combined resistance near 1.12 Ω, before accounting for the mutual-resistance correction.

I. Test Scenarios

The two test scenarios used to evaluate the grounding system before and after optimization are summarized in Table 4. Table 4. Grounding System Test Scenarios

Scenario	Test Condition	Key Parameter
Scenario 1	Initial grounding system condition before optimization (existing electrode)	Initial Rg = 13.31 Ω
Scenario 2	After optimization: 2 rod electrodes; length 2.5 m; depth 2.5 m; inter-electrode spacing 2.5 m; distance to MDP 20 m	Final Rg = 1.11 Ω

J. Data analysis

Data analysis was carried out using three approaches: descriptive quantitative comparison, theoretical calculation, and standard compliance evaluation. Grounding resistance values before and after optimization were compared, while measurement consistency was obtained from the mean and standard deviation of repeated measurements. In addition, the theoretical value from the Dwight equation was compared with the measured final Rg value as a form of verification of their agreement. The magnitude of resistance reduction was expressed as a percentage, obtained from the following equation:

$$P = [(Ri - Rf) / Ri] \times 100\% \quad ...(6)$$

Evaluation of the percentage results was carried out based on PUIL 2011 and IEEE Std 80-2013. In this study, the maximum prospective short-circuit current was not measured directly; instead, safety analysis based on Ground Potential Rise (GPR) was presented parametrically and validated using leakage-current data obtained from measurement.

RESULTS AND DISCUSSION

A. Initial Conditions and Grounding System Optimization Configuration

The initial grounding-resistance measurement is shown in Figure 5a, while the condition of the distribution panel before the grounding improvement is presented in Figure 5b.

Figure 5. a. Initial grounding-resistance measurement result. b. Distribution-panel condition before grounding optimization

The fall-of-potential method was used in the initial measurement to record an existing grounding resistance value of 13.31 Ω, where this value exceeds the standard set by PUIL 2011 of approximately ≤5 Ω, indicating that the existing grounding path was inadequate to conduct fault and leakage currents. This condition demonstrates the high ground potential rise (GPR) during a fault, which was recorded as approximately GPR = 13.31If. After optimization, GPR became 1.11If, showing a significant reduction of 91.66% for the same earth-fault current magnitude.

To examine the impact of this reduction on operational conditions, operational disturbance data before and after optimization were obtained from the same manual maintenance logbook and evaluated over equal observation periods of approximately 1 week. The pre-optimization observation was conducted on February 14–21, 2026, while the post-optimization observation was conducted on March 8–14, 2026. In the pre-optimization data, electromagnetic induction and arcing indications were recorded in the distribution panel, with a leakage current of 312 mA and 4 occurrences of protection trips. These events resulted in an operational stop (downtime) of approximately 6 hours, with an estimated 1.5 hours for inspection and resetting per trip. In contrast, during the post-optimization period, the leakage current was recorded to have decreased to 28 mA, and no protection trips or arcing indications occurred. Because the leakage-current value was measured using an ampere-range clamp meter, this value was recorded as an indicative field reading.

The main design and measurement parameters of the optimized grounding system are summarized in Table 5.

Table 5. Grounding System Optimization Parameters

Parameter	Value
Test location	Jagir Kalimir Flood Pump Station, Surabaya
Flood pump capacity	3 m^3/s
Measured apparent soil resistivity	6.48 ± 0.19 Ωm
Initial grounding resistance	13.31 Ω
Reference safety limit standard	≤ 5 Ω (PUIL 2011)
Number of electrodes	2 rods
Electrode material and diameter	Copper rod, 16 mm
Electrode length	2.5 m
Electrode burial depth	2.5 m
Inter-electrode spacing	2.5 m
Distance from grounding point to MDP	20 m
Final grounding resistance	1.11

B. Grounding Resistance Measurement Results

The grounding-resistance result after optimization is shown in Figure 6a, while the field measurement process is documented in Figure 6b. The distribution-panel condition after the grounding improvement is presented in Figure 6c. A comparison of the measured grounding resistance before and after optimization is shown in Figure 7.

a. b. c.

Figure 6. a. Grounding-resistance measurement result after optimization, b Groundingresistance measurement process after optimization, c. Distribution-panel condition after
grounding optimization

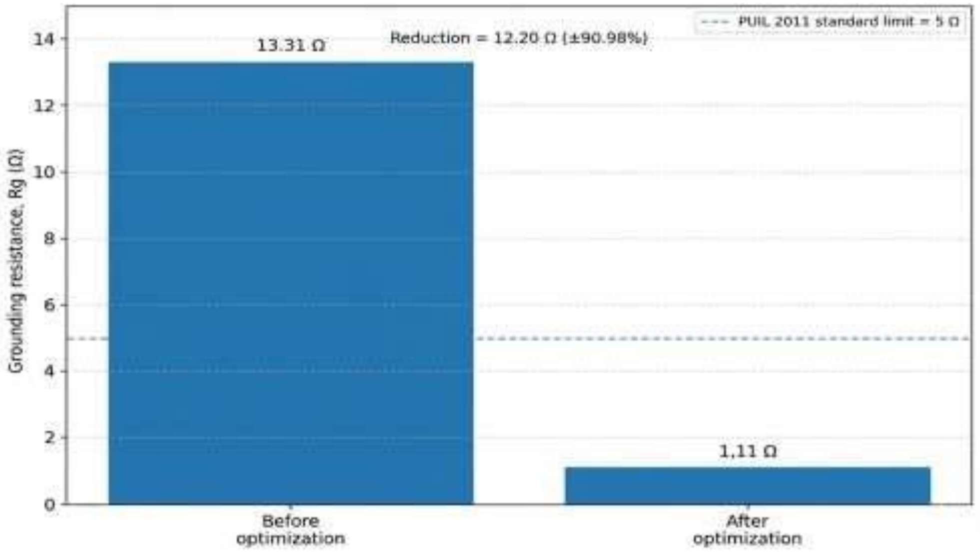

Figure 7. Comparison of grounding resistance before and after optimization

After electrode configuration optimization, grounding resistance decreased from 13.31 Ω to 1.11 Ω. The absolute reduction was 12.20 Ω, and the percentage reduction was 91.66%. A detailed comparison of the grounding resistance before and after optimization is presented in Table 6.

Table 6. Comparison of Grounding Resistance Before and After Optimization

Test condition	**Grounding resistance**	**Reduction percentage**	**Reduction standard**	**Compliance**
Before optimization	13.31 Ω	-	-	Noncompliance
After optimization	1.11 Ω	12.20 Ω	91.66%	Compliant (< 5 Ω)

Percentage reduction calculation:

$$P = (13.31 - 1.11) / 13.31 \times 100\% = 12.20 / 13.31 \times 100\% \approx 91.66\%$$

The final value of 1.11 Ω meets the PUIL 2011 requirement (≤ 5 Ω) with an excellent margin (the actual value is only approximately 22.2% of the permitted maximum limit). This result also demonstrates that the optimized grounding system has a far greater capability to provide a low-impedance path for fault currents

C. Theoretical Analysis of Grounding Resistance Reduction

1. Local Soil Characteristics

Based on Wenner measurements, the average apparent soil resistivity was approximately 6.48 ± 0.19 Ωm, indicating that the soil condition has low resistivity. Measurements were carried out during the rainy season, when the ground surface was wet. This relatively low apparent resistivity value was consistent with the high-moisture conditions at the site. However, soil resistivity alone is insufficient to conclusively classify the soil as saturated alluvial clay, since several soil types have overlapping resistivity ranges. Detailed information on groundwater depth, grain-size distribution, mineral composition, and subsurface moisture was not available. Because the variation among the three probe spacings was relatively small, the uniform-soil assumption was considered acceptable for preliminary analysis using the Dwight equation. Further measurements during the dry season and at greater spacings need to be carried out to evaluate seasonal variation and possible soil layering.

2. Effect of electrode depth

Installing each electrode at a depth of 2.5 m increased the contact area between the copper rod and the soil with low resistivity. Using the Dwight equation with ρ = 6.48 Ωm, L = 2.5 m, and d = 0.016 m, the single-rod resistance was approximately 2.24 Ω. Under an ideal parallel assumption, two identical rods would produce a resistance of approximately 1.12 Ω.

3. Parallel Configuration and Mutual Resistance Effect

Using two electrodes connected in parallel reduced the equivalent grounding resistance compared with the calculated resistance of a single rod. With an inter-electrode spacing of 2.5 m, the current-dispersion zones of the two rods may interact. therefore, a mutual-resistance approximation was also considered. The calculation produced a mutual resistance of approximately 0.36 Ω and a corrected two-rod resistance of approximately 1.30 Ω. This value was higher than the measured grounding resistance of 1.11 Ω.

The difference indicates that the simplified mutual-resistance model did not fully represent the actual field grounding arrangement. The newly installed rods were bonded to the existing MDP grounding conductor, and the resistance contributions of the existing grounding path and other buried conductive components were not measured separately. Therefore, the source of the difference cannot be quantified using the available data. The close agreement between the measured value of 1.11 Ω and the ideal Dwight estimate of 1.12 Ω should consequently be interpreted as empirical agreement rather than complete validation of the ideal two-rod model. This difference is acknowledged as a limitation of the analytical approximation used in this study. The analytical parameters, calculated resistance values, and field-measurement result used for theoretical validation are summarized in Table 7.

Table 7. Theoretical Validation of Grounding Resistance Using the Dwight Equation

Parameter	Value
Measured apparent soil resistivity, ρa	6.48 Ωm
Rod length, L	2.5 m
Rod diameter, d	0.016 m
Calculated single-rod resistance	2.24 Ω
Calculated ideal two-rod resistance	1.12 Ω
Measured two-rod grounding resistance	1.11

D. Impact on the Stability and Reliability of the Electrical System 1. Reduction in Potential Touch Voltage

Based on Equation (4), the ground potential rise is proportional to the grounding resistance for the same earth-fault current. Because the maximum prospective shortcircuit current of the LVMDP was not measured directly, the safety improvement was evaluated parametrically. The ground potential rise decreased from 13.31If before optimization to 1.11If after optimization.

Using the measured leakage-current readings only as an illustrative example, the calculated ground potential rise was:

$$GPRbefore = 0.312 \times 13.31 = 4.15\ V$$

GPRafter = 0.028 × 1.11 = 0.031 V

As a preliminary illustration, the total body-plus-contact impedance was assumed to be 2,000 Ω (1,000 Ω body impedance and 1,000 Ω foot/contact resistance), where the calculated current when a person is exposed to the full ground potential rise is approximately:

Ibefore = 4.15 / 2,000 = 2.08 mA and Iafter = 0.031 / 2,000 = 0.016 mA

These values just an illustrative and should not be used as an actual touch-current assessment. The actual touch current depends on several factors, namely the ground-surface potential distribution, body condition, contact resistance, current path, fault duration, and protection-clearing time. IEC 60479-1 states that the physiological effect of electric current depends on its magnitude, duration, and path through the body. Therefore, a complete safety evaluation requires the measured prospective fault current, surface-potential distribution, and protection operating time

2. Improvement in protection system reability

Protection devices such as MCCB, MCB, and Earth Leakage Circuit Breaker (ELCB) require a stable reference and a predictable leakage-current path (leakage current). High ground resistance can cause reference potential instability, nuisance tripping, and delayed fault-current dissipation. With the optimization carried out that significantly reduced RG down to 1.11 Ω, leakage current decreased drastically from 312 mA to 28 mA and there were no more repeated trip events.

3. Voltage reference stability

Poor grounding system directly impacts voltage reference fluctuations at the MDP panel and disturbs the pump motor to the control circuits. Before optimization, the phase-to-phase voltage was around 374 V to 404 V during disturbance. And after optimization, the voltage became 387 V to 392 V, which shows that the voltage reference is more stable with a lower disturbance level in the control panel

4. Reduction in leakage current and trip frequency

A visual comparison of the electrical disturbance indicators before and after grounding optimization is presented in Figure 8.

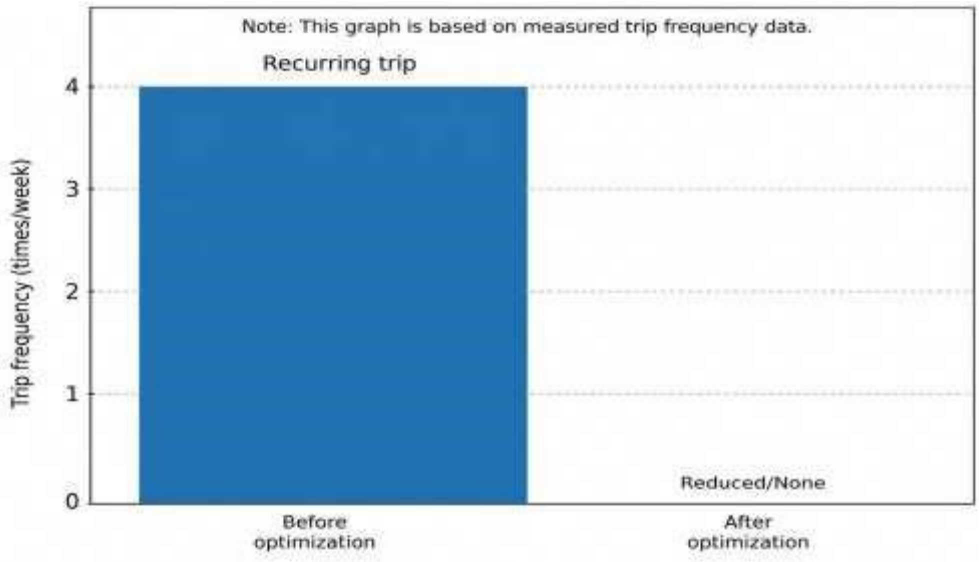

Figure 8. Comparison of electrical disturbance indicators before and after grounding optimization

The quantitative changes in grounding resistance, indicative leakage-current readings, trip frequency, voltage range, electromagnetic induction, and arcing indications are summarized in Table 8.

Table 8. Quantitative Comparison of Electrical Disturbance Indicators

Parameter	**Before optimization**	**After optimization**	**Improvement**
Grounding resistance	13.31 Ω	1.11 Ω	91.66% lower
Leakage current	312 mA	28 mA	91.03% lower
Trip frequency	4 events/week	0 events/week	Eliminated during observation
Voltage range	374-404 V	387-392 V	More stable
Electromagnetic induction indication	Observed	Not observed	Eliminated
Arcing / panel explosion indication	Observed	Not observed	Eliminated

With a lower-impedance path, leakage current caused by insulation aging and the humid environment of the pump station can be conducted to the ground more effectively. The quantitative comparison in Table 8 shows that the improvement is not only reflected in the reduction of Rg42, but also in lower leakage current, reduced trip frequency, improved voltage stability, and fewer indications of arcing. This supports the operational continuity of the flood pump system, particularly during emergency conditions such as heavy rainfall. These findings are consistent with previous grounding studies, which have shown that soil resistivity measurements and electrode configuration significantly affect grounding performance. Compared with studies based on the LRM method, this study successfully achieved compliance without chemical soil treatment because the study site has a very low measured soil resistivity and the spacing between grounding rods was selected based on local site conditions. Compared with studies conducted on high-resistivity podzolic soils, the flood pump station in this study required fewer grounding electrodes to achieve a low Rg value. A comparison between this study and previous grounding studies is presented in Table 9.

Table 9. Comparison with Previous Grounding Studies

Study	**Soil type / resistivity**	**Configuration**	**Initial Rg**	**Final Rg**	**Reduction**
SinchiSinchi et al. (2022)	1-302 Ωm test soils	Vertical rods / grid with LRM	Varied	Varied	21-81% depending on soil and design
Putra et al. (2022)	Podzolic soil, 214.4-250.8 Ωm	Single Fe rod, 1.0-2.0 m depth	201.7 Ω at 1 m	123.7 Ω at 2 m	38.7% by increasing depth

Fitriani et al. (2024)	Substation soil resistance variation	Substation grid grounding	Sitespecific	Sitespecific	Soil resistance strongly affects grid Rg
This study	Wet, lowresistivity site soil, 6.48 ± 0.19 Ωm	Two 2.5 m copper rods in parallel	13.31 Ω	1.11 Ω	91.66%

Compared with grounding improvement methods using low-resistivity materials (LRM), this study achieved a grounding resistance below 5 Ω without chemical soil treatment because the measured soil resistivity at the site was already low. The installation only required two copper grounding rods, approximately 20 m of grounding conductor, electrode installation, conductor bonding, and a final grounding resistance measurement. In contrast, LRM-based methods require the procurement and placement of enhancement material, soil preparation, and possible long-term monitoring or replacement of the treatment material.

This study did not include detailed data on material costs, labor, equipment, or long-term maintenance. For this reason, the proposed configuration cannot be considered more economical than an LRM-based method. A detailed cost-benefit analysis is still needed by comparing the costs of electrodes and grounding conductors, installation labor, maintenance requirements, replacement of treatment materials, and the operational downtime that can be avoided.

CONCLUSION

This study aimed to optimize the grounding system of a flood pumping station to improve electrical stability and protection reliability. The optimized configuration consisted of two copper rod electrodes, each 2.5 m long and 16 mm in diameter, installed vertically to a depth of 2.5 m with a spacing of 2.5 m between the electrodes, and connected to the Main Distribution Panel (MDP) through an approximately 20 m grounding conductor.

The results showed that the grounding resistance decreased significantly from 13.31 Ω to 1.11 Ω, corresponding to a relative reduction of approximately 91.7%, and satisfied the maximum limit of 5 Ω specified in PUIL 2011. This value was also in close agreement with the ideal value calculated using Dwight’s equation (1.04% difference), indicating good empirical agreement between the analytical estimation and the field measurement. Nevertheless, this agreement should not be interpreted as a complete validation of the analytical model because the contribution of the existing grounding system was not measured separately.

The grounding improvement also resulted in better operational performance, including a reduction in leakage current from 312 mA to 28 mA, the elimination of repeated trip events (from four occurrences per week to none), a narrower phase-to-phase voltage range, and the absence of indications of electromagnetic induction and electrical arcing during the observation period. The improvement also has the potential to eliminate an estimated six hours of weekly downtime caused by repeated trips, thereby supporting the continuous operation of the flood pumping station, particularly during periods of heavy rainfall.

Overall, this study demonstrates that optimizing a grounding system based on local soil conditions can provide a practical and effective approach to improving the reliability of critical electrical infrastructure such as flood pumping stations. The findings may also serve as a reference for operators of similar facilities in planning more reliable grounding and protection systems.

This study, however, has several limitations. The measurements were conducted at a single site during the rainy season, and the measured soil resistivity (6.48 Ωm) therefore represents only seasonal conditions and may differ during the dry season. Soil classification, long-term evaluation of electrode corrosion, and direct measurements of prospective short-circuit current, actual touch voltage, and installation cost were not carried out. As a result, the safety and economic evaluations presented in this study remain preliminary.

Future studies are recommended to refine the two-layer soil model through additional Wenner measurements at wider probe spacings, compare soil conditions between the rainy and dry seasons, and validate the proposed configuration at other flood pumping stations. Long-term operational monitoring, corrosion assessment, direct evaluation of fault current and touch voltage, as well as a cost-benefit analysis comparing installation costs with the potential losses associated with equipment damage and operational downtime, are also needed to strengthen the practical validity of these findings.

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