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SHALLOW SOIL LAYER CHARACTERIZATION USING THE ELECTRICAL RESISTIVITY TOMOGRAPHY FOR SHALLOW SUBSIDENCE POTENTIAL IN PRINGSEWU

KARAKTERISASI LAPISAN TANAH DANGKAL MENGGUNAKAN TOMOGRAFI RESISTIVITAS LISTRIK UNTUK POTENSI AMBLESAN DANGKAL DI PRINGSEWU

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Abstract. The study area is located in the Lampung Formation (QTl), which consists of pumiceous tuff, tuffaceous sandstone, and tuffite intercalations. These volcanic materials generally exhibit variable degrees of compaction, are porous, and have a relatively high water absorption capacity, thereby having the potential to form weak soil zones that may affect land stability and trigger land subsidence. Accordingly, this study was conducted to characterize shallow soil layers based on Electrical Resistivity Tomography (ERT) data and drilling results, as well as to identify shallow subsurface zones that may be susceptible to land subsidence in the study area. The study employed the Electrical Resistivity Tomography (ERT) method using the Wenner configuration along five survey lines, which were correlated with drilling data and soil sample observations. The inversion results show resistivity values ranging from 21.7 to 274 Ωm. Low-resistivity zones (<80 Ωm) identified within the shallow subsurface (0–3 m) are interpreted as relatively less compact materials based on the correlation with drilling observations and are considered potentially susceptible to shallow land subsidence. The correlation between ERT data and drilling results supports the interpretation of shallow soil layer characteristics. The findings of this study provide preliminary information for infrastructure development planning by identifying shallow subsurface zones that may be be susceptible to land subsidence. However, ground deformation and soil compressibility were not directly measured; therefore, the results should be interpreted as a preliminary assessment of subsidence susceptibility rather than evidence of active land subsidence.

Abstrak. *Lokasi penelitian terletak pada Formasi Lampung (QTl), yang terdiri dari tuf pumis, batupasir tufan, dan sisipan tufit. Material vulkanik ini umumnya memiliki tingkat pemadatan yang bervariasi, bersifat porous, dan memiliki kapasitas penyerapan air yang relatif tinggi, sehingga berpotensi membentuk zona tanah lunak yang dapat memengaruhi stabilitas lahan dan memicu penurunan muka tanah (land subsidence). Oleh karena itu, penelitian ini dilakukan untuk mengarakterisasi lapisan tanah dangkal berdasarkan data Electrical Resistivity Tomography (ERT) dan hasil pemboran, serta untuk mengidentifikasi zona bawah permukaan dangkal yang mungkin rentan terhadap penurunan muka tanah di lokasi penelitian. Penelitian ini menggunakan metode ERT dengan konfigurasi Wenner pada lima lintasan survei, yang dikorelasikan dengan data pemboran dan pengamatan sampel tanah. Hasil inversi menunjukkan nilai resistivitas berkisar antara 21,7 hingga 274 Ωm. Zona resistivitas rendah (<80 Ωm) yang teridentifikasi pada bawah permukaan dangkal (0–3 m) diinterpretasikan sebagai material yang relatif kurang padat berdasarkan korelasi dengan pengamatan pemboran, dan dianggap berpotensi rentan terhadap penurunan muka tanah dangkal. Korelasi antara data ERT dan hasil pemboran mendukung interpretasi karakteristik lapisan tanah dangkal tersebut. Temuan penelitian ini memberikan informasi awal bagi perencanaan pengembangan infrastruktur dengan mengidentifikasi zona bawah permukaan dangkal yang mungkin rentan terhadap penurunan muka tanah. Namun, deformasi tanah dan kompresibilitas tanah tidak diukur secara langsung; oleh karena itu, hasil penelitian ini sebaiknya diinterpretasikan sebagai penilaian awal mengenai kerentanan terhadap penurunan muka tanah, bukan sebagai bukti adanya penurunan muka tanah yang sedang aktif terjadi.*

1. INTRODUCTION

Soil is a structural and functional element formed through geological and climatic processes, and its physical and chemical properties strongly influence environmental and regional stability (Antarissubhi et al., 2019). In geotechnical engineering, soil characteristics are important because weak or unstable zones may have low bearing capacity and contribute to land subsidence and infrastructure instability (SM et al., 2024). Therefore, geotechnical investigations, including resistivity geoelectric surveys, are required to characterize shallow subsurface conditions and identify potential weak zones before construction (Antarissubhi et al., 2019; Minmahddun, 2024). This study was motivated by the need to assess the relationship between shallow soil characteristics and resistivity responses to identify areas potentially susceptible to subsidence.

The study area is located within the QTl (Lampung Formation), which consists of pumiceous tuff, tuffaceous sandstone, and tuffite intercalations (Amin et al., 1993). These volcanic deposits are relatively porous and unconsolidated, with variable compactness and water absorption capacity, which may contribute to the development of weak subsurface zones (Massinai et al., 2023). The resistivity geoelectric method is effective for identifying variations in shallow subsurface materials (Hosea & Sutanto, 2025) and is therefore suitable for assessing conditions associated with potential subsidence and their implications for infrastructure development (Marwanza et al., 2023). Accordingly, this study aims to characterize shallow soil conditions using Electrical Resistivity Tomography (ERT) and direct soil observations through shallow borehole sampling, and to assess the potential for land subsidence based on the integrated interpretation of resistivity and soil characteristics.

Previous studies have demonstrated the application of ERT for investigating subsurface conditions related to groundwater (Febriarta et al., 2007), lithological variations (Nurdiyanto et al., 2016), foundation conditions (Antarissubhi et al., 2019; Wibowo & Saptorini, 2024), and subsidence-related ground conditions (Sudha et al., 2009; Olabode et al., 2022; Prosperi et al., 2025). Low-resistivity zones may be associated with higher moisture content or fine-grained materials, while resistivity variations can indicate heterogeneous subsurface conditions that may contribute to settlement (Olabode et al., 2022; Prosperi et al., 2025). In contrast to previous studies, this research focuses on shallow soil characterization within the unconsolidated volcanic deposits of the Lampung Formation by integrating two-dimensional ERT inversion with shallow borehole observations and soil sample resistivity measurements. This integrated approach provides complementary information for identifying shallow subsurface variations and potential weak zones associated with land subsidence, supporting preliminary infrastructure planning.

2. LITERATURE REVIEW

2.1. Subsidence

Subsidence is the gradual or sudden lowering of the ground surface caused by natural or anthropogenic processes, including excessive surface loading, groundwater extraction, and earthquakes, which may reduce soil stability and damage infrastructure (Archenita et al., 2015; Asriadi et al., 2023).

Figure 1. Surface subsidence (Sudha, 2009).

2.2. Electrical Resistivity Tomography (ERT)

Electrical Resistivity Tomography (ERT) is a non-destructive geophysical method that characterizes subsurface conditions based on variations in electrical resistivity, enabling the mapping of lateral and vertical resistivity distributions (Naziah & Fahril, 2024; Ade et al., 2022; Febriarta et al., 2007).

The Wenner configuration was employed because it provides adequate sensitivity to lateral and vertical subsurface variations. In this configuration, the electrode spacing is equal, expressed as

$$C_1P_2 = P_1P_2 = P_1C_2 = a \quad (1)$$

where (C_1) and (C_2) are the current electrodes, (P_1) and (P_2) are the potential electrodes, and (a) is the electrode spacing (m). The electrode arrangement is shown in **Figure 2** (Riputra & Malik, 2021; Solehudin et al., 2022).

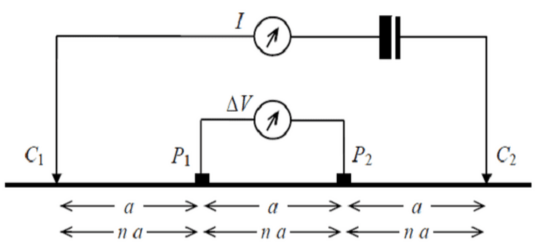

Figure 2. Wenner configuration (Solehudin et al., 2022).

The resistivity obtained from field measurements represents apparent resistivity (ρ_a), which assumes a homogeneous subsurface. It is expressed as

$$\rho_a = K\frac{V}{I} \quad (2)$$

where ρ_a is the apparent resistivity (Ω·m), K is the geometric factor (m), ΔV is the measured potential difference (V), and I is the injected current (A). With the geometric factor of the Wenner configuration expressed as follows:

$$k = 2\pi a \quad (3)$$

The apparent resistivity obtained from field measurements does not directly represent the true subsurface resistivity; therefore, inversion is required to obtain a model that approximates the actual subsurface conditions. In this study, inversion was performed using the smoothness-constrained least-squares method implemented in Res2DInv (Loke & Barker, 1996; Loke, 2004), expressed as:

$$d = G(m) \quad (4)$$

where d is the measured apparent resistivity data vector (Ω·m), G is the forward modelling operator, and m is the subsurface resistivity model (Ω·m). The inversion applied in this study is the smoothness-constrained least-squares inversion, expressed by the following equation:

$$(J^T\mathrm{J} + \mathrm{uF})\mathrm{d} = J^T g \quad (5)$$

where J is the Jacobian matrix, F is the flatness filter matrix, μ is the damping factor, d is the model perturbation vector, and g is the discrepancy vector between observed and calculated data (Loke & Barker, 1996).

The quality of the inversion results is evaluated using the Root Mean Square Error (RMSE) value, which indicates the degree of discrepancy between the measured data and the model-calculated data. A smaller RMSE value indicates a better fit of the model to the observed data. The RMSE value can be expressed as follows:

$$RMSE(\%) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{d_{obs,i}-d_{cal,i}}{d_{obs,i}}\right)^2} \times 100\% \quad (6)$$

where (n) is the number of observations, ($d_{obs,i}$) is the observed apparent resistivity (Ω·m), and ($d_{cal,i}$) is the calculated apparent resistivity (Ω·m).

Interpretation of resistivity values was performed based on lithological resistivity ranges. Low resistivity generally indicates conductive materials with higher moisture content, whereas high resistivity is associated with relatively dry or compact materials. In this study, low-resistivity zones are interpreted as weak zones characterized by relatively high porosity and low soil density (Winarsih et al., 2024; Triani et al., 2026).

2.3. Drilling (Hand Boring)

Hand boring is a manual drilling method used to obtain shallow soil samples and describe subsurface soil characteristics, including soil type, texture, and visual condition, to support geological interpretation (Rtumbanua, 2023).

Figure 3. Drilling results.

Figure 3 presents the soil samples obtained from Borehole 1, which were used to support the interpretation of the ERT results. The integration of ERT data with borehole observations and soil sample measurements provides complementary information for interpreting shallow subsurface conditions, thereby facilitating the identification of weak zones susceptible to land subsidence and supporting the assessment of their potential impact on buildings and infrastructure.

3. RESEARCH METHODS

This research comprised ERT data acquisition, soil sampling, data processing, and correlation of resistivity data with soil characteristics. The study focused on shallow soil layers in the Pringsewu region based on ERT resistivity values and supporting soil samples. The research location and ERT acquisition design are presented in **Figure 4**.

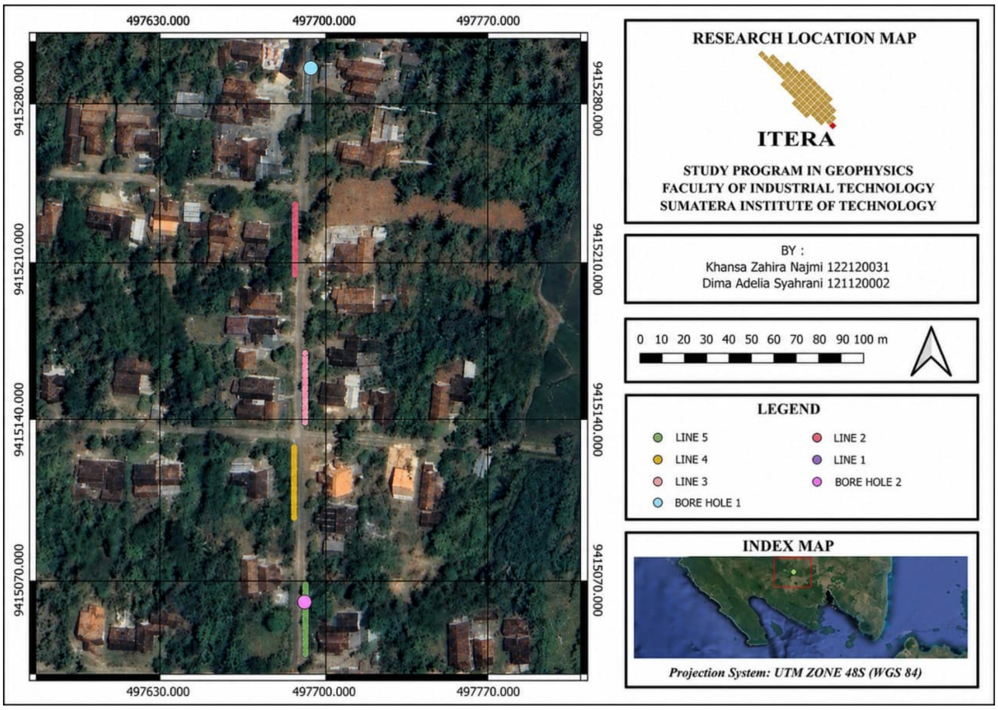

Figure 4. Acquisition Design Map.

The ERT survey was conducted in February 2026 using a Multichannel Resistivitymeter Series CSX 003 with the Wenner configuration. Five survey lines were acquired, each consisting of 32 electrodes with 1 m spacing, giving a survey length of approximately 31 m and an investigation depth of approximately 5 m. Electrode contact was checked before acquisition to ensure stable current injection, while surface topography was incorporated into the Res2DInv inversion. The instruments used for ERT acquisition and soil sample resistivity measurements are presented in **Figure 5**.

Soil sampling was carried out to a depth of approximately 3 m using a hand auger. Borehole 1 was located along Survey Line 1 and represented Survey Lines 1–3, while Borehole 2 was located along Survey Line 5 and represented Survey Lines 4–5 because of the close spacing of the survey lines within the same geological setting. Soil resistivity measurements were performed using a Naniura Resistivity Meter (Model NRD-300) on cylindrical samples collected using a PVC sampling pipe approximately 3.8 cm in diameter and 10 cm in length. Samples were measured immediately after retrieval under natural moisture conditions using two electrodes placed at both ends of the sample. The measured values were correlated with the ERT inversion results to support interpretation of shallow subsurface conditions.

(a) (b)

Figure 5. Equipment used in this study: (a) Multichannel Switching Unit for ERT data acquisition and (b) Naniura resistivity meter for soil sample resistivity measurement.

Measurements were conducted at increasing electrode spacings and progressively shifted along each survey line to obtain the required investigation depth and coverage.

The data analysis was carried out by correlating ERT data with soil sample measurements. ERT data processing was performed using Res2DInv software. Before inversion, the apparent resistivity data were checked for completeness, consistency, and electrode contact quality. No manual data rejection or bad datum point removal was applied. Least-squares inversion was then performed to obtain a two-dimensional resistivity model. The resulting resistivity cross-sections were correlated with the nearest borehole observations and soil sample measurements to support interpretation of shallow subsurface conditions (Nurdiyanto et al., 2016). The Wenner electrode arrangement used during acquisition is shown in **Figure 6**.

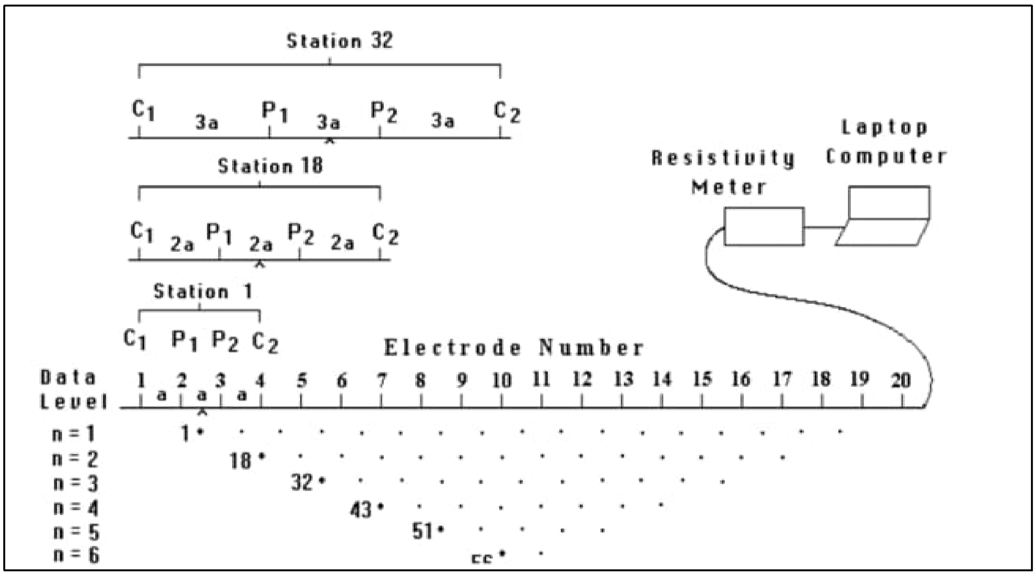

Figure 6. Wenner configuration electrode arrangement for 2D resistivity survey (Loke, 2021).

4. RESULTS AND DISCUSSION

4.1. Geoelectric Data Processing Results

The 2D resistivity geoelectric measurement results in this study were obtained from 5 survey lines using the Wenner configuration, with each electrode having a spacing of 1 meter. Data acquired during the acquisition process were subsequently processed using Res2Dinv software to obtain a 2D cross-section model of the subsurface resistivity distribution. Variations in resistivity value distribution were observed across the survey lines, indicating differences in subsurface material characteristics throughout the study area to an investigation depth of approximately 5 meters. The color differences in the cross-sections further reflect variations in resistivity values associated with changes in the type and condition of subsurface soil layers.

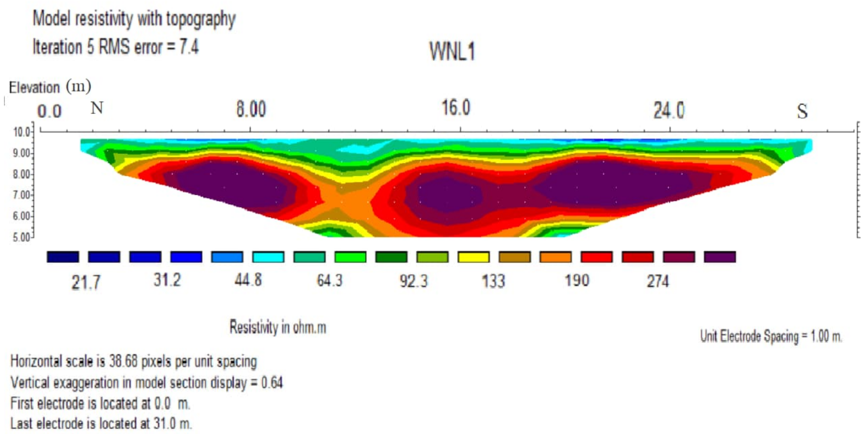

Figure 7. Resistivity Cross-Section of Survey Line 1.

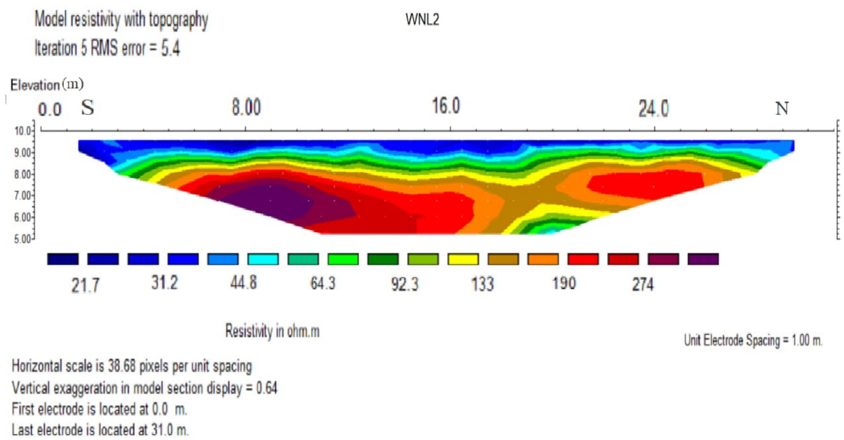

Figure 8. Resistivity Cross-Section of Survey Line 2.

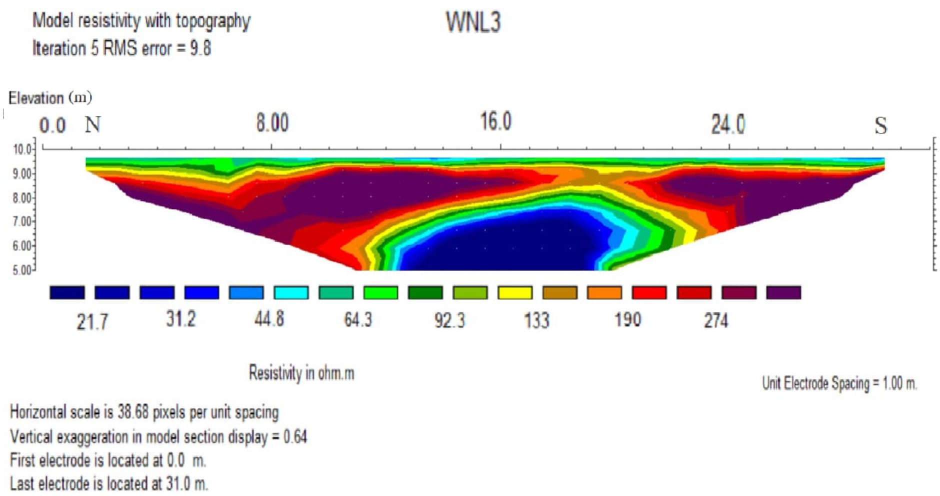

Figure 9. Resistivity Cross-Section of Survey Line 3.

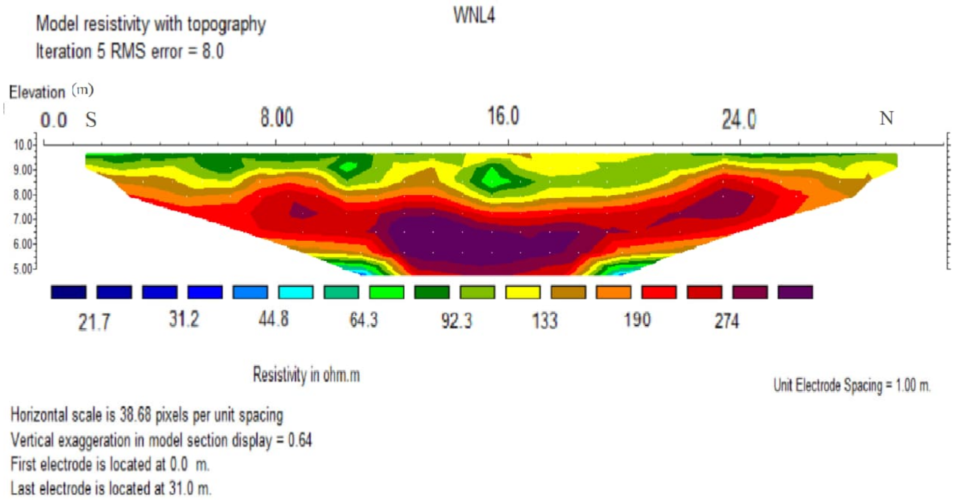

Figure 10. Resistivity Cross-Section of Survey Line 4.

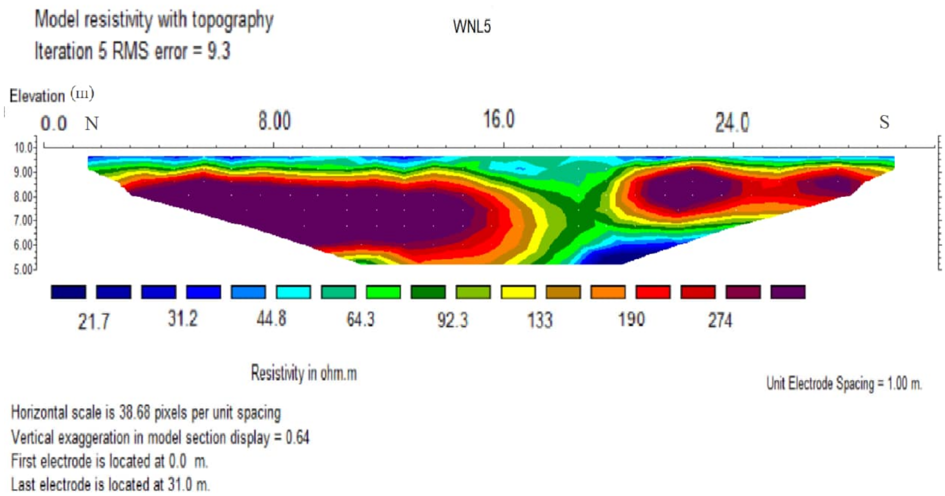

Figure 11. Resistivity Cross-Section of Survey Line 5.

Based on the inversion process, five 2D resistivity cross-sections were obtained from ERT data processing using the Wenner configuration, representing shallow subsurface conditions to a depth of approximately 5 meters. All five survey lines exhibit resistivity value variations ranging from 21.7 Ωm to 274 Ωm. These variations indicate differences in subsurface material conditions, which may be related to variations in lithology, water saturation, and soil properties. The resistivity classification used in this study is presented in **Table 1**, which provides the resistivity ranges and their corresponding lithological interpretations. The classification was determined based on previous studies and supported by resistivity measurements of soil samples obtained using a Naniura soil resistivity meter.

Table 1. Resistivity range and lithology interpretation.

Resistivity (Ωm)	Dominant Color	Characteristics	Shallow Subsidence Potential
< 20	Dark Blue	Highly conductive	Potential weak zone
20 – 80	Blue – Green	Relatively loose	Compaction
80 – 150	Green – Yellow – Orange	More compact	More stable
> 150	Red – Purple	Compact, relatively dry	Hard Layer

Table 2 summarizes the resistivity characteristics and subsidence indications for each survey line. Line 1 is characterized by a low-resistivity shallow layer (<80 Ωm), underlain by intermediate (80–150 Ωm) and higher resistivity (>150 Ωm) zones, indicating a potential shallow weak zone. Line 2 shows a relatively uniform intermediate-resistivity middle layer and is interpreted as relatively stable. Line 3 exhibits a low-resistivity anomaly in the central section, indicating a zone that may have higher moisture content and potentially weaker conditions. Line 4 shows variable resistivity distributions both vertically and laterally, suggesting heterogeneous subsurface conditions and potential local settlement. Line 5 is dominated by higher resistivity at depth but contains a low-resistivity central anomaly, indicating a localized zone requiring attention.

Table 2. Resistivity cross-section interpretation results per survey line.

Line	RMS E	Shallow Layer (0–1 m)	Middle Layer (1–3 m)	Deep Layer (3–5 m)	Subsidence Indication
1	7,4 %	Dominant <80Ωm	80–150 Ωm	>150 Ωm	Shallow layer
2	5,4 %	Dominant <80 Ωm	80–150 Ωm Uniform	>150 Ωm Side of line	Relatively stable
3	9,8 %	Dominant <80 Ωm	80–150 Ωm Non-homogeneous	>150 Ωm Left-right	Low resistivity in center
4	8,0 %	<80 Ωm Variable	80–150 Ωm Variable	>150 Ωm Non-Uniform	Potential local settlement
5	9,3 %	Dominant <80 Ωm	80–150 Ωm Variable	>150 Ωm Dominant	Low resistivity in center

The distribution of low-resistivity zones across several survey lines indicates variations in moisture content and/or material composition. This interpretation is consistent with Olabode et al. (2022), who reported that low resistivity can be associated with materials having higher water content and weaker mechanical characteristics. However, low resistivity is not uniquely indicative of loose soil because clay content and water saturation can produce similar electrical responses; therefore, the interpretation was further evaluated using borehole and soil sample data.

The line-by-line interpretation shows that Line 1 contains a shallow low-resistivity zone, Line 2 is comparatively uniform, Line 3 has a central low-resistivity anomaly, Line 4 exhibits lateral heterogeneity, and Line 5 contains a central low-resistivity anomaly. The occurrence of low-resistivity zones on Lines 3 and 5 may indicate localized areas with higher moisture content, while the heterogeneous distribution on Line 4 may reflect variations in subsurface material conditions. These interpretations are consistent with Prosperi et al. (2025), who reported that subsurface heterogeneity can contribute to variations in soil properties and differential settlement.

4.2. Drilling and Soil Sample Testing Results

To support the interpretation of the 2D resistivity measurement results, soil testing was conducted at two borehole points, each located at a different site. The data were used to determine the vertical sequence of soil layers and to serve as comparative data for the subsurface resistivity model results.

At Borehole 1, the 0–20 cm brown layer has resistivity <80 Ωm and is interpreted as relatively moist, loose topsoil. At 20–60 cm, the light-gray layer has resistivity of 80–150 Ωm and consists of coarse-to-medium volcanic material. The 60–220 cm dark-gray layer has resistivity >150 Ωm and is interpreted as relatively dense material with a silt-to-clay texture. At 220–300 cm, the yellow layer has resistivity of 40–80 Ωm and contains sandy material with relatively higher moisture content. The interpretation of low-resistivity, water-rich material is consistent with Sudha et al. (2009), while resistivity variations in silt and clay may be influenced by soil density and moisture content (Wang et al., 2025). The association between low-to-moderate resistivity and water-bearing porous material is also consistent with Winarsih et al. (2024).

At Borehole 2, the 0–30 cm brown topsoil has resistivity <80 Ωm and relatively high water content. The 30–100 cm light-gray layer has resistivity of 80–150 Ωm and consists of medium-to-coarse volcanic material. The dark-gray layers at 100–160 cm and 180–300 cm have resistivity >150 Ωm and are interpreted as relatively dense silt-to-clay material, while the 160–180 cm yellow layer has resistivity of 50–80 Ωm and is associated with sandy material containing relatively higher moisture content. These interpretations are consistent with Wang et al. (2025) and Winarsih et al. (2024), which indicate that resistivity variations in fine- and coarse-grained materials are influenced by moisture and material properties.

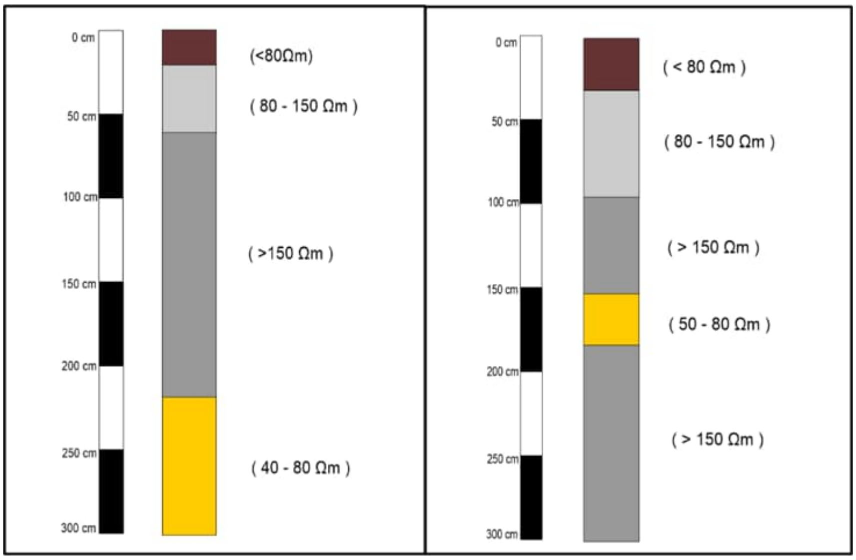

Figure 12. One-dimensional borehole profiles showing lithological layers and resistivity values measured from soil samples using a Naniura soil resistivity meter at Boreholes 1 and 2.

4.3. Correlation of Resistivity and Soil Sample Testing

The ERT resistivity values were compared with borehole observations at equivalent depths. Borehole 1 was used to represent Survey Lines 1–3, whereas Borehole 2 represented Survey Lines 4–5. Resistivity values were extracted from the ERT sections at locations nearest to the boreholes and compared with the corresponding soil layers.

At Borehole 1, the ERT data show relatively low resistivity at shallow depths corresponding to the moist upper soil layer. Resistivity increases at approximately 100–220 cm, corresponding to the denser dark-gray layer, and decreases again toward 220–300 cm, where the sandy layer has relatively higher moisture content. This correspondence indicates that variations in ERT resistivity are generally consistent with the observed changes in soil characteristics.

At Borehole 2, low resistivity at shallow depths corresponds to the moist topsoil layer, followed by higher resistivity at 30–100 cm and within the deeper dense layers. The lower resistivity observed at approximately 160–180 cm corresponds to the sandy layer with relatively higher moisture content.

Overall, the ERT and borehole observations show a general correspondence in the identification of vertical variations in shallow soil characteristics. However, no quantitative validation metric was applied; therefore, the correlation is interpreted qualitatively rather than as a statistical validation. The occurrence of relatively moist and potentially weak layers at specific depths indicates conditions that may be susceptible to settlement under additional loading. This interpretation is consistent with Marwanza et al. (2023), who emphasized the importance of identifying soft soil layers in subsidence hazard assessment and infrastructure planning.

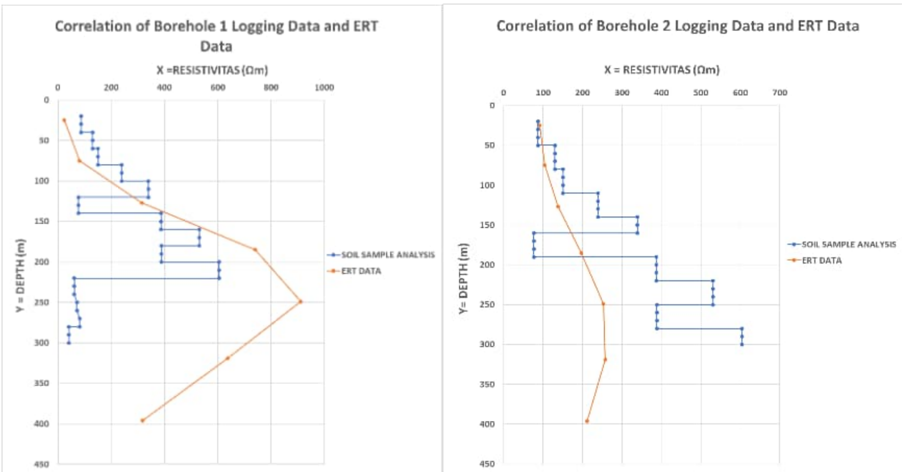

Figure 13. Correlation of ERT measurement resistivity values against soil testing depth at borehole 1 and 2.

5. CONCLUSION

Based on the results of Electrical Resistivity Tomography (ERT) measurements using the Wenner configuration on five survey lines, two-dimensional resistivity cross-sections were successfully obtained to an investigation depth of approximately 5 m, with resistivity values ranging from 21.7 to 274 Ω m. The resistivity distribution reflects variations in shallow subsurface conditions across the study area. Relatively low resistivity values (<80 Ωm) are generally associated with loose, moisture-rich materials, whereas higher resistivity values (>150 Ω m) indicate denser and relatively more compact subsurface layers.

The correlation between the ERT results and borehole observations to a depth of approximately 3 m indicates a general correspondence in representing variations in shallow soil characteristics. Potential land subsidence was interpreted based on the integrated analysis of ERT data and borehole observations rather than solely on low-resistivity values. Survey lines 3 and 5 exhibit prominent low-resistivity zones, while survey line 4 shows laterally heterogeneous resistivity distributions. These conditions indicate relatively loose subsurface materials with higher moisture content and variable compaction, making them more susceptible to settlement under infrastructure loading. Therefore, these zones are interpreted as having a higher potential for land subsidence, providing important preliminary information for infrastructure planning in the study area.

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