



Modified Surface Electrodes with Bentonite Coupling for 2D Electrical Resistivity Tomography (ERT) on Interlocking Paving-Block Surfaces

Riski Kurniawan^{1*}, Muhammad Fachrul Rozi Kurniawan², Yudha Agung Pratama³,
Anugerah Satria Pradana Budiyo⁴

^{1,2,3} Geophysics Engineering, Faculty of Technology Mineral and Energy, Universitas Pembangunan Nasional “Veteran” Yogyakarta, Indonesia

⁴ Geomatics Engineering, Faculty of Technology Mineral and Energy, Universitas Pembangunan Nasional “Veteran” Yogyakarta, Indonesia

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Abstract

Electrical resistivity tomography (ERT) surveys on non-penetrable surfaces are challenging because conventional spike electrodes require direct ground penetration, limiting their use on interlocking paving-block surfaces. This study developed and field-tested a modified surface electrode (MSE) made of stainless steel, using bentonite clay as a coupling medium between the electrode and the paving-block surface. The MSE was compared with conventional spike electrodes using the Wenner- α configuration with an electrode spacing of 2.50 m under comparable acquisition conditions. A total of 84 Wenner- α measurements were acquired using 24 electrodes and subsequently subjected to quality control and two-dimensional resistivity inversion. The MSE produced an RMS error of 7.3% after seven iterations, compared with 5.7% after five iterations for the conventional spike electrodes. Both inversion models reproduced similar principal low- and high-resistivity patterns. The resistivity measurements showed a strong linear relationship, with a correlation coefficient of $R=0.9368$ and a coefficient of determination of $R^2=0.8777$. The results indicate that the MSE measurements followed a similar resistivity trend to the conventional spike-electrode measurements under the tested conditions. The MSE with bentonite coupling therefore shows potential for non-invasive ERT surveys on interlocking paving-block surfaces under the tested conditions, although further evaluation using quantitative agreement measures and different surface conditions is required.

Keywords *Closed Surface, Resistivity, Modified-Surface-Electrode, Conventional-Spike-Electrode, Correlation*

INTRODUCTION

Electrical Resistivity Tomography (ERT) is a widely used near-surface geophysical method for imaging the subsurface based on electrical resistivity variations. By injecting direct current and measuring potential differences, ERT generates apparent-resistivity data that are inverted to reconstruct subsurface resistivity distributions. The resistivity method is sensitive to variations in lithology, water content, porosity, fracturing, and weathering. ERT has applications in groundwater, engineering, environmental, geohazard, mineral, geothermal, and infrastructure investigations (Balasco et al., 2022; Binley, 2015; Ducut et al., 2022; Herring et al., 2023; Rejckær et al., 2021; Diallo et al., 2023). ERT has also been applied to monitor subsurface changes associated with infrastructure excavation (Kim et al., 2022).

Measurement reliability depends on the resistivity meter, cables, connectors, switching system, and, in particular, electrode-surface electrical contact. Conventional spike electrodes provide effective contact through ground penetration but are unsuitable for closed surfaces such as concrete, paving blocks, and building floors, where penetration may increase acquisition

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Corresponding author's email: riski.kurniawan@upnyk.ac.id

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complexity and cause surface damage (Athanasidou et al., 2007; Caselle et al., 2024; Jeong & Nam, 2024; Pavoni et al., 2022).

Non-penetrating electrodes provide an alternative for such environments. Athanasidou et al. (2007) demonstrated their feasibility for non-destructive DC resistivity surveys, while Kurniawan et al. (2017) reported comparable anomaly patterns between conventional and surface-contact electrodes. However, non-penetrating electrodes such as modified surface electrodes (MSE) require an intermediate coupling medium, making measurements sensitive to contact resistance, surface roughness, moisture, coupling-medium properties, contact area, and surface-cover characteristics (Jeong & Nam, 2024; Yang et al., 2024).

Conductive coupling is therefore an important component of non-penetrating ERT. Previous studies have used clay-based materials and saline solutions to improve electrode-surface contact and current transmission (Athanasidou et al., 2007; Jeong & Nam, 2024; Klanica et al., 2024; Pavoni et al., 2022). Automated multi-electrode switching can also reduce manual intervention and improve acquisition efficiency under non-penetrating electrode conditions (Xia et al., 2021). Despite these developments, the quantitative performance of a stainless-steel surface electrode using bentonite as a coupling medium and integrated with a multi-electrode switching system remains insufficiently evaluated under consistent field conditions.

Therefore, this study evaluates an integrated system comprising a stainless-steel modified surface electrode (MSE), bentonite coupling medium, and 24-electrode single-channel switching panel. The MSE is compared with conventional spike electrodes using the Wenner- α configuration with an electrode spacing of 2.50 m on an interlocking paving-block surface. Performance is evaluated using the resistivity relationship, RMS inversion error, and spatial similarity of the principal resistivity anomalies. The principal contribution is the field-based evaluation of the integrated MSE-coupling-switching system for non-invasive ERT under the tested conditions.

LITERATURE REVIEW

Electrical Resistivity Tomography and Electrode Contact

Electrical Resistivity Tomography (ERT) measures the electrical response of the subsurface using a four-electrode configuration, in which current is injected through a pair of current electrodes and the potential difference is measured between a pair of potential electrodes. The apparent resistivity is expressed as:

$$\rho_a = K \frac{\Delta V}{I} \quad (1)$$

where ρ_a is the apparent resistivity (Ωm), K is the geometric factor (m), ΔV is the measured potential difference (V), and I is the injected current (A). For the Wenner- α configuration:

$$K = 2\pi a \quad (2)$$

where a is the electrode spacing. Thus,

$$\rho_a = 2\pi a \frac{\Delta V}{I} \quad (3)$$

The apparent-resistivity data are then inverted to estimate the two-dimensional subsurface resistivity distribution (Loke & Barker, 1996b; Xia et al., 2021).

ERT quality strongly depends on electrode–surface coupling. Conventional spike electrodes provide effective electrical contact through ground penetration but are unsuitable for closed or paved surfaces. Non-penetrating electrodes provide an alternative through an interface between the electrode and surveyed surface (Athanasίου et al., 2007; Jeong & Nam, 2024; Yang et al., 2024). Coupling conditions such as contact area, surface roughness, moisture, and coupling-medium properties may influence measurement quality and apparent resistivity (Pavoni et al., 2022; Vásconez-Maza et al., 2020).

Modified Surface-Electrodes and Conductive Coupling Media

Researchers have investigated flat-base and other non-conventional electrodes for resistivity surveys where conventional spike electrodes are impractical (Athanasίου et al., 2007; Jeong & Nam, 2024; Pavoni et al., 2025). In this study, bentonite clay is used as a coupling medium between the stainless-steel plate and the interlocking paving-block surface to improve electrode–surface contact. Using bentonite clay in Electrical Resistivity Tomography (ERT) yields images identical to those from conventional electrodes (Kurniawan et al., 2017). Bentonite clay provides a simple coupling medium that conforms to surface irregularities, while alternative systems involve different material properties and electrode configurations (Vásconez-Maza et al., 2020; Pavoni et al., 2025). This study therefore evaluates bentonite experimentally rather than assuming its universal superiority.

Multi-Electrode Switching and Measurement Stability

Automated switching systems improve ERT acquisition efficiency by systematically selecting current and potential electrodes (Xia et al., 2021). For non-penetrating electrodes, consistent positioning, coupling, channel identification, and quality control are important to maintain measurement quality (Oldenborger et al., 2005; Tso et al., 2017; Khabaz et al., 2024). This study integrates a 24-electrode single-channel switching panel with stainless-steel surface electrodes.

Research Gap and Contribution

Previous studies have demonstrated non-penetrating electrodes for paved and reinforced surfaces, but the integrated performance of a stainless-steel plate electrode, bentonite coupling medium, and 24-electrode switching system remains insufficiently evaluated. This study compares the modified and conventional spike electrodes using the Wenner- α configuration with electrode spacing of 2.50 meters on an interlocking paving-block surface. Performance is evaluated using the resistivity correlation, RMS inversion error, and spatial similarity of the principal resistivity anomalies.

RESEARCH METHOD

Research Design

This study employed an experimental prototype-development and field-testing approach to develop and evaluate a MSE for non-invasive ERT. The workflow comprised electrode fabrication, integration with a 24-electrode single-channel switching panel, system testing, field acquisition, resistivity inversion, and quantitative performance evaluation. The 24 -electrode single-channel switching panel was tested with conventional spike electrodes, and the results showed similar data.

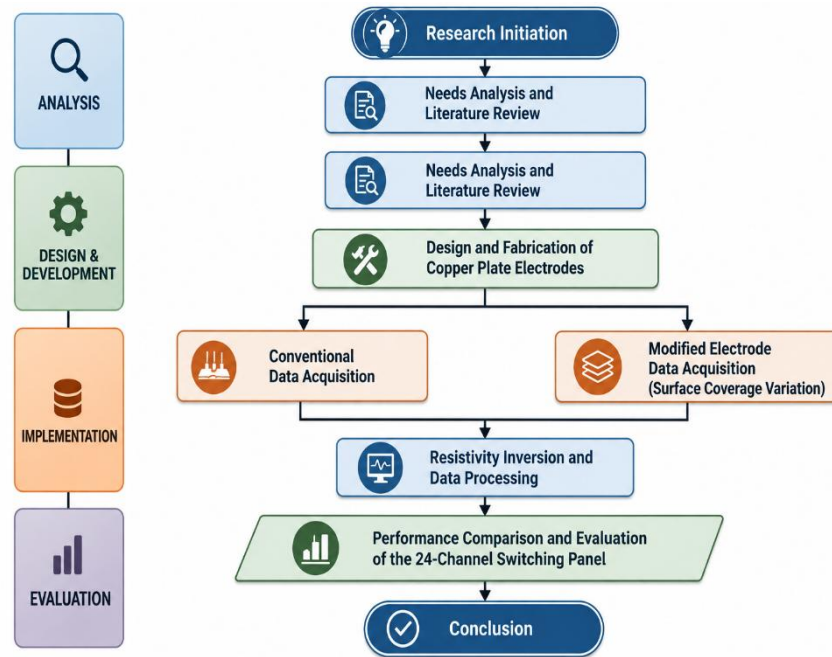


Figure 1. Workflow for the development and evaluation of the modified surface electrodes integrated with the 24-Electrode Single-Channel Switching Panel

The modified surface electrodes were fabricated from a stainless-steel circular plate for electrical conductivity and mechanical durability. Each electrode had a 12 cm-diameter flat circular base for direct placement on closed surfaces without penetration. The modified surface and conventional spike electrodes were compared under an identical Wenner-alpha configuration and 2.50 meters of electrode spacing based on resistivity response, inversion quality, and spatial consistency of subsurface anomalies.



a



b

Figure 2. Components of the acquisition: (a) 24-Electrode Single-Channel Switching Panel and (b) circular stainless-steel modified surface-electrode design

Data Acquisition

Data were acquired using a two-dimensional electrical resistivity survey at the test site in Yogyakarta. The electrodes were arranged along the survey line with an electrode spacing of $a = 2.50$ m. The 24-electrode single-channel switching panel was used to select the current and potential electrode combinations during acquisition. The switch panel serves as the primary control unit, managing integrated switching of current and potential electrodes and eliminating the need for manual electrode repositioning. The modified surface-electrode array was deployed along a survey line covered with paving blocks, whereas the conventional electrode array was placed along an open line allowing direct electrode insertion. The two test lines were separated by approximately 70 cm (See Figure 3) to ensure both remained within a single survey transect representative of the same subsurface conditions. Data acquisition was carried out sequentially, beginning with measurements using conventional electrodes, followed by measurements with the modified surface electrodes upon completion



Figure 3. Test site conditions and electrode arrangement along the ERT survey line. The left side shows the application of MSE on the closed surface, and the right shows the application of conventional spike electrodes on the open surface

The electrode configuration (Wenner – Alpha with 2.50 meters electrode spacing) and parameter acquisition (3 stacking) were kept identical for conventional and modified surface electrodes to ensure comparable measurement conditions. The Wenner Alpha array configuration was selected for this study due to its high signal-to-noise ratio and superior sensitivity to vertical variations in subsurface resistivity, making it particularly effective for resolving horizontal stratification. Bentonite gel was prepared by mixing bentonite clay with water at a ratio of 40% by clay mass. The primary function of the bentonite gel is to enhance surface contact between the modified surface electrode and the paving block surface. Two measurement conditions were evaluated: (1) conventional spike electrodes as the benchmark and (2) modified surface electrodes coupled with bentonite gel.

Data Quality Control

Quality control (QC) for the ERT survey was performed by monitoring the continuity of the apparent resistivity curves to eliminate extreme spikes between adjacent measurement points. Additionally, data stacking (3 cycles per measurement point) was conducted to ensure consistency of the apparent resistivity while maintaining low electrode contact resistance for optimal current injection and noise reduction.

Data Processing

After quality control, the apparent-resistivity data from both electrode types were inverted using Res2Dinv to obtain two-dimensional subsurface resistivity models. The statistical and qualitative analyses in this study were conducted using a dataset comprising 84 observation points distributed along the survey lines to ensure adequate spatial coverage. Identical inversion procedures and parameters were applied to both datasets to ensure a consistent comparison. Apparent resistivities were subjected to identical QC procedures before inversion, including checks for missing data, electrode position and channel assignment, extreme resistivity values, and consistency of repeated measurements.

After QC, both datasets were inverted using Res2Dinv with identical inversion settings based on the smoothness-constrained least-squares approach (Loke & Barker, 1996a, 1996b). Inversion was terminated when the convergence criterion was reached, or the maximum iterations were completed. Model performance was evaluated using RMS data misfit, iteration, resistivity distribution, anomaly continuity and geometry, and estimated depth. RMS was interpreted together with spatial characteristics because a lower misfit does not necessarily indicate more accurate subsurface recovery. Although a physical electrode spacing of 2.5 m was deployed during field acquisition, the 2D inversion scheme in Res2Dinv incorporated a half-unit electrode spacing mesh of 1.25 m. This refinement was applied to enhance the forward modeling resolution and block density within the shallow subsurface zone.

Performance Evaluation

The performance of the modified surface-electrode and switching system was evaluated using three criteria.

Resistivity Relationship

Modified surface- and conventional-electrode measurements were compared using cross-plots and linear regression:

$$\rho_{mod} = \alpha \rho_{conv} + \beta \quad (4)$$

Where ρ_{mod} and ρ_{conv} are the resistivities obtained using the modified and conventional electrodes, and α and β are the slope and intercept. The correlation coefficient (R) was used to assess consistency between the two datasets.

Inversion Quality

Model performance was assessed using RMS misfit, number of iterations, resistivity distribution, anomaly continuity, geometry, depth, and spatial similarity. RMS was interpreted together with spatial characteristics because lower misfit does not necessarily indicate more accurate anomaly recovery.

Anomaly Pattern

Where a known anomaly was available, we compared its inverted position, depth, shape, and boundaries with the actual target. Overall, the modified surface electrodes were considered a potential non-invasive alternative when they provided stable measurements, strong agreement with conventional electrodes, comparable resistivity patterns and inversion quality, and reliable anomaly representation without penetrating or damaging the surveyed surface.

FINDINGS AND DISCUSSION

Relationship between Modified and Conventional Electrode Resistivity

The modified surface- and conventional electrode measurements showed a strong linear correlation ($R = 0.9368$), indicating that the modified surface-electrode measurements explained 93.68% of the variation in conventional electrode resistivity (Figure 4). Supported by a slope of 1.0545, close to 1, this shows that the modified electrode delivers identical and reliable measurement performance, making it a viable alternative to the conventional electrode. A high correlation coefficient indicates strong resistivity correlation and supports the potential use of the modified surface electrode for surveys on closed surfaces, provided coupling conditions (bentonite clay as conductive gel) are controlled, and appropriate calibration is applied (Athanasidou et al., 2007; Jeong & Nam, 2024). The modified surface electrodes showed no significant under-scaling or over-scaling across both low- and high-resistivity measurements. Each $1 \Omega m$ increase in the modified surface-electrode reading corresponded to an approximate $1.05 \Omega m$ increase in the conventional electrode measurement. The negative intercept indicates a systematic offset, with the modified surface-electrodes yielding slightly higher resistivity values than the conventional ones, particularly at lower resistivity ranges. This behavior likely reflects differences in contact resistance or the physical characteristics of the modified surface-electrode material.

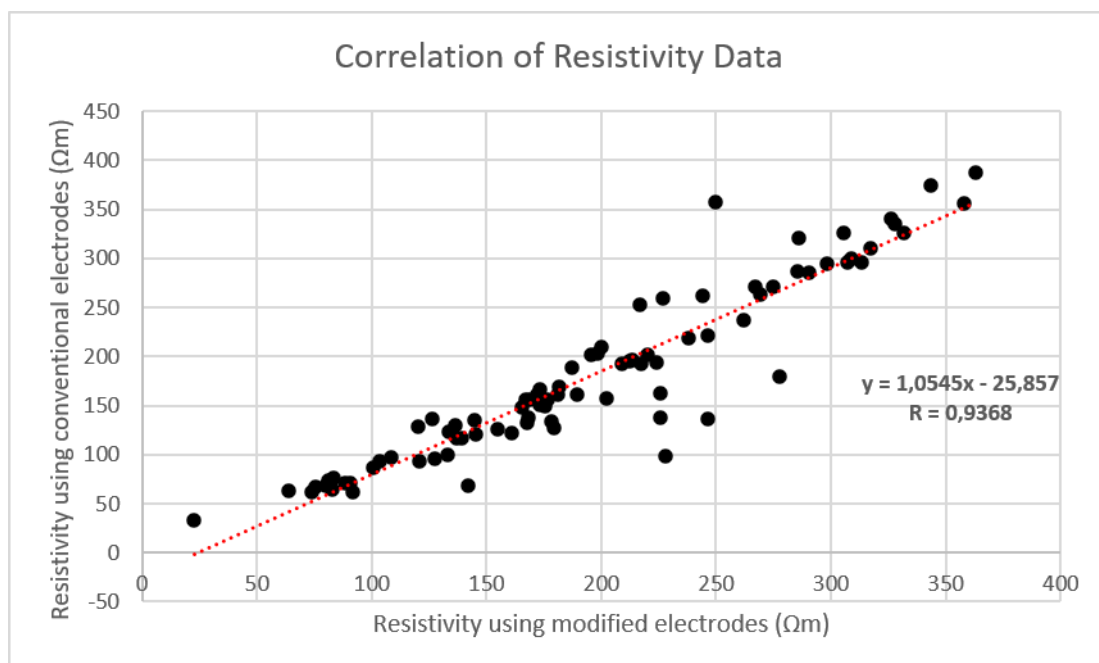


Figure 4. Correlation of resistivity data between conventional and modified surface electrodes. The red dashed line represents the linear regression trendline with a coefficient of correlation of 0.9368 (strong correlation)

The agreement between the modified surface electrode and conventional electrode

measurements ($N = 84$) was evaluated using a Bland–Altman plot (see Figure 5), which revealed a mean bias of +15, indicating that the modified electrode yields slightly higher resistivity values on average. The 95% limits of agreement (LoA) ranged from -47 to $+77$, encompassing 94.05% (79 out of 84) of the data points, with only five points falling outside the boundary lines as outliers. Although dispersion is higher within the mid-range median values (150–250), the overall distribution shows strong agreement without significant proportional bias, confirming that the modified surface-electrode configuration provides reliable, comparable measurements to the conventional method.

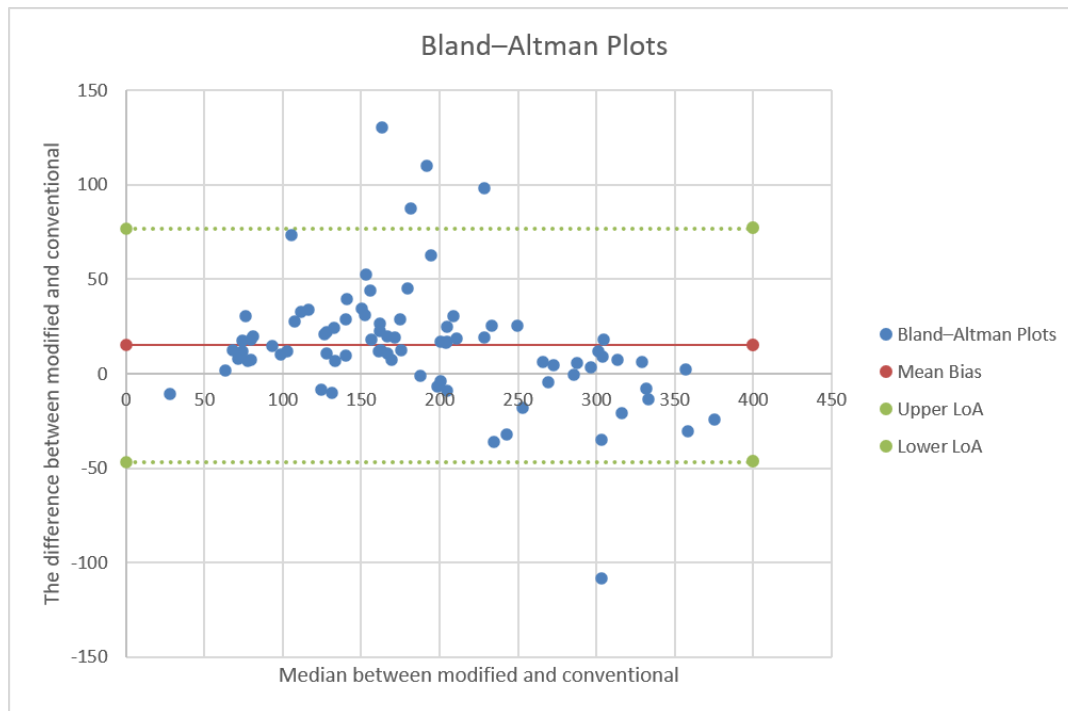


Figure 5. Bland–Altman plot comparing measurements from the modified and conventional electrodes. The solid red line represents the mean bias (+15), and the dashed green lines indicate the 95% limits of agreement (upper and lower; -47 to $+77$.)

Comparison of Two-Dimensional Resistivity Inversion Results

The modified surface-electrode with bentonite clay produced an inversion RMS error of 7.3% after seven iterations, compared with 5.7% after five iterations for the conventional electrode (Table 1). The higher RMS indicates a larger data–model misfit for the modified surface electrodes; however, RMS alone does not determine inversion quality because resistivity distribution and anomaly geometry are also influenced by data quality, electrode configuration, regularization, and inversion parameters (Loke & Barker, 1996a, 1996b; Tso et al., 2017).

Despite the higher RMS error, both models reproduce broadly consistent subsurface resistivity patterns. The low-resistivity anomaly captured in the 6–11 m interval on the left section of the profile aligns with ground-truth field observations, confirming the location of a subterranean water storage tank (in-ground concrete tank with a surface length of 3 meters). A relatively high-resistivity anomaly extends from the center toward the right side of the section (27 to 50 m). The high resistivity corresponds to a subsurface sand layer. This elevated resistivity is attributed to the presence of dry to partially saturated, coarse-grained quartz sand, where air-filled pore spaces significantly restrict electrical conductivity.

Table 1. Comparison of measurement and inversion results

Parameter	Modified Surface-Electrode	Conventional Spike-Electrode
Electrode spacing	2.50 m	2.50 m
Inversion RMS error	7.3%	5.7%
Number of iterations	7	5
Resistivity relationship	$R = 0.0.9368$	Reference
Main anomaly pattern	Relatively consistent	Reference

The spatial correlation of these principal anomalies indicates that the modified surface-electrode preserves the main spatial characteristics of the resistivity model. Such spatial consistency is important for subsurface anomaly mapping and target identification (White et al., 2023). This matters because ERT interpretation depends not only on resistivity values but also on anomaly distribution and geometry (Loke & Barker, 1996a, 1996b; Loke & Dahlin, 2002). Thus, although the MSE yields a higher RMS error, its comparable anomaly patterns demonstrate its potential for non-invasive ERT under the tested conditions.

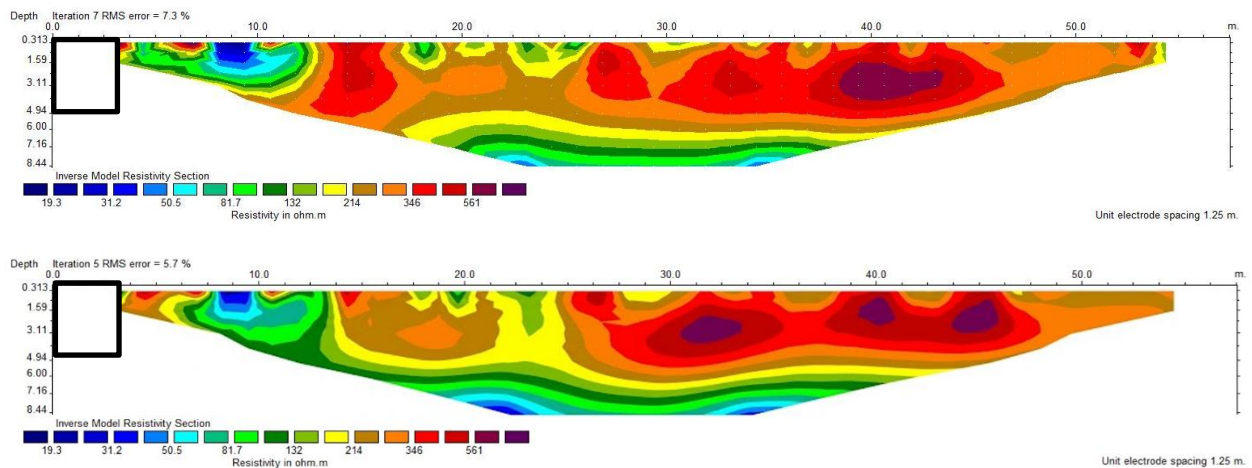


Figure 6. Comparison of two-dimensional resistivity inversion results: (a) modified surface-electrode with bentonite coupling and (b) conventional spike electrode. The main object presented is 7–10 meters, corresponding to an in-ground concrete tank with a surface length of 3 meters

Differences in the Responses of the Two Electrode Systems

The two electrode types showed consistent principal resistivity patterns but differed in resistivity value and anomaly sharpness. The negative intercept in Figure 4 and the mean bias in Figure 5 show that measurements using conventional electrodes yielded consistently lower resistivity values than the modified surface electrodes (MSE). These differences may reflect variations in MSE coupling, contact resistance, effective contact area, and surface-cover properties (Athanasidou et al., 2007; Pavoni et al., 2022; Váscónez-Maza et al., 2020).

Performance Implications of the Modified Surface-Electrode

The modified surface-electrode demonstrated strong correlation with the conventional electrodes and preserved the principal spatial characteristics of the resistivity model. Although its RMS error was higher (7.3% vs. 5.7%), the results indicate that its main advantage is non-invasive,

spatially interpretable ERT imaging rather than exact numerical equivalence (Athanasidou et al., 2007; Jeong & Nam, 2024; Yang et al., 2024). MSE stainless steel is potentially applicable to any closed surface, including paving blocks, infrastructure areas, courtyards, and cultural-heritage sites where conventional electrodes cannot be inserted into the ground surface, including engineering investigations of subsurface defects and deformation (Sheishah et al., 2023). However, performance depends on bentonite moisture, coupling-layer thickness, contact area, applied pressure, stabilization time, and surface-cover conditions (Pavoni et al., 2022; Váscónez-Maza et al., 2020).

CONCLUSIONS

This study successfully developed and field-tested a novel modified surface-electrode (MSE) array utilizing bentonite gel coupling for non-invasive Electrical Resistivity Tomography (ERT) on non-penetrable paved surfaces. The proposed configuration enables reliable data acquisition without damaging the ground surface. A strong linear correlation ($R = 0.9368$) and a tight Bland–Altman agreement were achieved between the MSE and conventional spike electrodes. Furthermore, the negative intercept and positive mean bias indicate that MSE produced higher apparent resistivity values than the conventional electrodes. Although the inverted model for the MSE exhibited a slightly higher inversion RMS error compared to the conventional electrodes, both types of electrodes accurately yielded the high- and low-resistivity subsurface anomalies at consistent spatial locations. Overall, these results confirm that bentonite-coupled surface electrodes serve as a viable non-destructive alternative to conventional electrodes in paved environments.

LIMITATIONS & FURTHER RESEARCH

The primary limitations of this dataset stem from its restricted scope, which comprises a single 57.5 m survey profile conducted at a single field site on one specific surface type (permeable interlocking concrete pavers). Furthermore, the data acquisition was limited to the Wenner-alpha array, yielding a maximum depth of investigation of approximately 8-9 meters. The findings are also constrained by the absence of repeat or reciprocal measurements to evaluate noise levels and data repeatability, as well as the lack of direct contact resistance quantification between the modified surface electrode and the pavement surface. To improve data quality and robustness, future studies should incorporate standardized bentonite moisture content and coupling-layer thickness, measure contact resistance, execute reciprocal and repeated acquisition, and evaluate performance using metrics such as MAE, RMSE, and bias across diverse surface types and array geometries (Tso et al., 2017; Oldenborger et al., 2005; Pavoni et al., 2022).

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