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Correlation between electrical resistivity tomography and mackintosh probe in unsaturated soil

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ABSTRACT

Subsurface investigation plays an important role in geotechnical engineering by providing information on soil conditions required for design and construction. Electrical Resistivity Tomography (ERT) and Mackintosh Probe (MP) are commonly used methods for evaluating subsurface characteristics. ERT is a non-destructive geophysical technique that measures the electrical properties of soils, whereas the Mackintosh Probe is an in-situ penetration test used to assess soil resistance and stiffness. This study investigates the relationship between ERT resistivity values and Mackintosh Probe blow counts in unsaturated tropical residual soils at Kempas, Johor. Laboratory tests including sieve analysis, Atterberg limits, and natural moisture content tests were conducted to characterize the soil properties. The sieve analysis results classified all samples as poorly graded sand (SP), while the Atterberg limit and moisture content tests indicated moderate to high plasticity and varying moisture conditions throughout the study area. Field investigations were carried out using a 2-D Electrical Resistivity

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Tomography survey and Mackintosh Probe testing were conducted at selected locations along two survey lines. The comparison of ERT and MP results revealed inconsistent trends between electrical resistivity and penetration resistance. While certain locations exhibited similar increasing patterns, most locations demonstrated contrasting responses. The findings indicate that electrical resistivity is strongly influenced by moisture content, degree of saturation, and pore water conductivity, whereas Mackintosh Probe resistance is governed primarily by soil density, stiffness, and particle interlocking. Consequently, a reliable proportional relationship between ERT and MP measurements could not be established. The study concludes that both methods should be considered complementary subsurface investigation techniques rather than interchangeable approaches for evaluating unsaturated tropical soils.

Nomenclature (Greek symbols towards the end)

N_m	Blow Count
Ωm	Ohm-meter
m	meter

Abbreviations

CPT	Cone penetration testing
ERT	Electrical resistivity tomography
LL	Liquid limit
MP	Mackintosh probe
PI	Plasticity index
R1	Survey line 1
R2	Survey line 2
SP	Poorly graded sand
SPT	Standard penetration testing
USCS	Unified soil classification system

1. INTRODUCTION

Subsurface investigations are essential in geotechnical engineering to determine soil characteristics prior to the design and construction of engineering structures. Accurate assessment of subsurface conditions reduces uncertainties associated with foundation design, slope stability, and earthwork construction. Conventional geotechnical investigations such as boreholes and penetration tests provide direct measurements of soil properties but are often time-consuming and costly. Consequently, geophysical techniques have increasingly been adopted as complementary investigation tools due to their efficiency and ability to provide continuous subsurface information [1-3].

Electrical Resistivity Tomography (ERT) is one of the most widely used geophysical methods for subsurface characterization [3]. The technique measures variations in soil resistivity, which are influenced by moisture content, pore-water conductivity, degree of saturation, and soil composition [1] and [4]. In

contrast, the Mackintosh Probe (MP) is a lightweight dynamic penetration test commonly used in tropical regions to evaluate soil resistance and stiffness through blow count measurements [5-6].

Previous studies have attempted to establish correlations between geophysical and geotechnical parameters to improve subsurface characterization and reduce investigation costs [7-8]. However, the relationship between electrical resistivity and penetration resistance remains complex, particularly in unsaturated soils where moisture distribution and matric suction significantly influence soil behaviour [9-11]. Therefore, this study investigates the relationship between ERT resistivity values and Mackintosh Probe blow counts within unsaturated tropical soils at Kempas, Johor.

2. PROBLEM STATEMENT

Although both Electrical Resistivity Tomography and Mackintosh Probe testing are commonly used for site investigations, their relationship within unsaturated tropical soils remains uncertain. Electrical resistivity is primarily affected by moisture content and pore-water conditions, whereas Mackintosh Probe resistance reflects soil stiffness and penetration resistance. Consequently, it is necessary to evaluate whether a meaningful correlation exists between the two methods under unsaturated soil conditions.

3. OBJECTIVES

The main purpose of this research is to investigate the relationship between Electrical Resistivity Tomography (ERT) and Mackintosh Probe (MP) testing in unsaturated tropical soils at Kempas, Johor. The study aims to evaluate the capability of both geophysical and geotechnical methods in characterizing subsurface conditions and to assess the feasibility of establishing a correlation. The objectives of this study are:

(i) To determine the subsurface resistivity distribution using Electrical Resistivity Tomography survey method.

(ii) To conduct Mackintosh probe tests to obtain corresponding blow counts (N_m) at Kempas area.

(iii) To analyse the relationship between resistivity and MP using comparative method.

4. SCOPE OF STUDY

The study was conducted at Kempas, Johor, Malaysia. Field investigations included Electrical Resistivity Tomography surveys and Mackintosh Probe testing along selected survey lines. Soil samples were collected for laboratory testing, including sieve analysis, Atterberg limits, and natural moisture content determination. The correlation between resistivity values and Mackintosh Probe blow counts was subsequently evaluated.

5. LITERATURE REVIEW

Unsaturated tropical residual soils are widely distributed throughout Peninsular Malaysia and exhibit complex engineering behaviour due to the presence of both air and water within the soil pores [12]. The degree of saturation and matric suction significantly influence soil strength, stiffness, and hydraulic behaviour, making moisture conditions an important factor in geotechnical investigations [1] and [13-14].

Residual soils derived from weathered granitic rocks are common in Johor and often display heterogeneous subsurface characteristics due to varying weathering processes and moisture distribution [5] and [15].

Electrical Resistivity Tomography (ERT) is a non-destructive geophysical technique used to investigate subsurface conditions through measurements of electrical resistivity [3]. Soil resistivity is influenced by moisture content, pore-water conductivity, porosity, degree of saturation, and soil composition [7], [9] and [11]. Electrical resistivity in unsaturated soils varies non-linearly with moisture variations and soil suction, making ERT an effective tool for identifying moisture anomalies and groundwater conditions [4] and [11]. Consequently, ERT has become a widely accepted tool for groundwater exploration, environmental studies, and geotechnical investigations because it provides continuous subsurface information with minimal site disturbance [2-3].

The Mackintosh Probe (MP) is a dynamic penetration test commonly used for preliminary site investigations in tropical regions [5]. The test evaluates soil penetration resistance by measuring the number of hammer blows required to achieve a specified depth increment [16]. Light dynamic penetration tools like the Mackintosh Probe measure resistance through cumulative impact blows (Nm), which directly reflect soil consistency, density, and relative stiffness [6] and [16]. Compared to conventional borehole investigations, the Mackintosh Probe offers a rapid and economical method for assessing shallow subsurface conditions [5].

Several studies have attempted to establish relationships between geophysical measurements and geotechnical parameters to improve subsurface characterization [2], [13], [15] and [17]. However, the relationship between electrical resistivity and penetration resistance remains inconsistent, particularly in unsaturated soils where moisture distribution and matric suction strongly influence electrical behaviour [4]. Since ERT and MP respond to different controlling soil parameters, a universal empirical correlation may not always be achievable [4] and [15]. Therefore, this study investigates the relationship between Electrical Resistivity Tomography and Mackintosh Probe measurements in unsaturated tropical soils at Kempas, Johor.

6. METHODOLOGY

6.1 Study area

The study was conducted at Kempas, Johor, Malaysia. The area is characterised by tropical residual soils derived from weathered granitic materials. These soils commonly exhibit variable moisture content, heterogeneous structure, and unsaturated conditions. Fig. 1 illustrates the overall research methodology adopted in this study, summarising the key stages from field investigation to data analysis and interpretation.

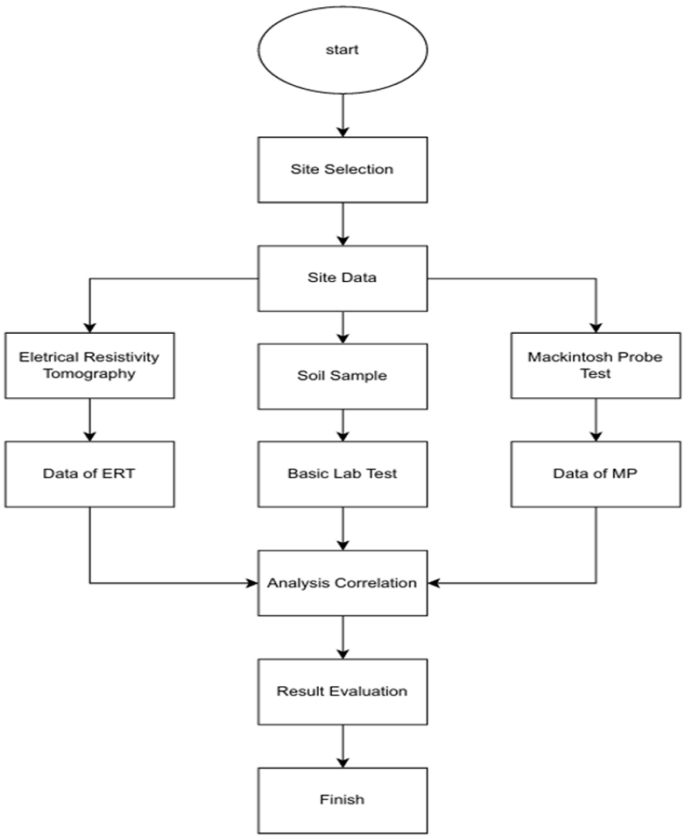


Fig. 1 Flowchart of the study

6.2 Electrical resistivity tomography survey

Electrical Resistivity Tomography (ERT) surveys were conducted along two 20 m survey lines, R1 and R2, using an ABEM Terrameter LS 2 multi-electrode resistivity imaging system. The ABEM system was used as the central data acquisition unit to inject direct current into the ground, measure the resulting potential differences, and record apparent resistivity data through the connected electrode array (Table 1). A Schlumberger array was adopted with a unit electrode spacing of 0.5 m. Stainless-steel electrodes were installed along the survey line and connected to the ABEM Terrameter LS 2 through multi-core resistivity cables, with an external DC battery used as the power supply. The automated electrode switching arrangement allowed successive current and potential electrode combinations to be measured along each line. The acquired apparent resistivity data were subsequently processed and inverted to produce two-dimensional resistivity sections for comparison with the Mackintosh Probe profiles. The apparent resistivity data acquired using the ABEM Terrameter LS 2 were processed and inverted using RES2DINV software to generate two-dimensional subsurface resistivity models. The inversion procedure iteratively adjusted the model resistivity values to minimise the difference between the measured and calculated apparent resistivity data.

Table 1. Field equipment and testing parameters for ERT

Parameter/ Specification	Value/Technical Detail
Equipment Model	Multi-electrode Resistivity System
Array Configuration	Schlumberger Protocol
Unit Electrode Spacing	0.5 m
Survey line Designation	Line R1 and R2
Measurement Type	2D Apparent Resistivity (Ω · m)

6.3 Mackintosh probe testing

Mackintosh Probe (MP) tests were carried out at selected positions adjacent to the ERT lines so that the two datasets could be compared at corresponding locations and depths. Table 2 shows a specification of 4.5 kg hammer, with a 300 mm free fall was used and the number of blows was recorded for each 300 mm penetration increment. Testing continued until the required depth or refusal, taken as 400 blows per 300 mm penetration. The recorded blow count was used as an index of penetration resistance and relative soil stiffness.

Table 2. Specification and parameters of MP testing

Parameter/ Specification	Value/Technical Detail
Hammer Mass	4.5 kg
Free-Fall Drop Height	300 mm
Measurement Interval	Blow count (*Nm*) recorded per 300 mm
Test Refusal Criteria	*Nm* equal or more than 400 blows per 300 mm

6.4 Laboratory testings

Representative soil samples were collected from the study area and subjected to laboratory testing. The laboratory programme consisted of:

(i) Sieve Analysis [18]

(ii) Atterberg Limit Test [19]

(iii) Natural Moisture Content Test [20]

Sieve analysis was conducted to determine particle size distribution and soil classification. Atterberg limit testing was performed to evaluate the plasticity characteristics of the soil. Natural moisture content testing was undertaken to assess in-situ moisture conditions and their influence on resistivity behaviour.

6.5 Data analysis

ERT resistivity values were matched with Mackintosh Probe blow counts at corresponding locations and depths. In addition to profile-by-profile comparison, all matched observations were combined for quantitative assessment. A scatter plot of electrical resistivity against MP blow count was prepared and Pearson's correlation coefficient (r) and the coefficient of determination (R^2) were calculated. Linear

regression was used only to quantify the overall association; it was not assumed to represent a universal predictive relationship.

7. RESULT AND DISCUSSION

7.1 Soil classification and index properties

Laboratory testing was carried out to determine the basic properties of the soil collected from the study area. Particle-size analysis showed that the samples were predominantly sandy, with sand contents of 72.0-92.5% and fines contents of 2.5-5.5%. The samples were generally reported as Poorly Graded Sand (SP). The small proportion of fines indicates that the bulk material is sand-dominated and that its overall behaviour should not be described from the plasticity of the fine fraction alone.

Atterberg limit tests were also carried out on the material prepared for the limit tests. Liquid Limit (LL) values ranged from 55.25% to 74.60%, while Plastic Limit (PL) values ranged from 37.24% to 45.81% and Plasticity Index (PI) values ranged from 18.01% to 29.63%. These values describe the tested finer material and should not be taken as evidence that the bulk sand-dominated soil is moderately or highly plastic. Natural moisture content ranged from 24.65% to 57.69%, showing appreciable variation between samples. This moisture variation is particularly relevant to the ERT interpretation because electrical resistivity is sensitive to the amount and continuity of pore water.

The measured moisture contents therefore provide a more direct basis for discussing variations in electrical response than assigning plasticity to the bulk SP soil. The index properties used in the interpretation are summarised in Table 3.

Table 3. Summary of particle-size distribution, Atterberg limits and natural moisture content

Sample	Gravel %	Sand %	Fines %	LL %	PL %	PI %	w %
P1	2.0	92.5	5.5	55.25	37.24	18.01	57.69
P2	2.5	92.0	5.5	60.25	41.03	19.22	37.25
P3	6.5	90.5	3.0	72.70	45.81	26.89	35.85
P4	11.5	86.0	2.5	72.00	45.04	26.96	35.86
P5	24.5	72.0	3.5	74.60	44.97	29.63	24.65
P6	19.5	76.0	4.5	71.90	44.22	27.68	33.32

7.2 Electrical Resistivity Tomography and Mackintosh Probe Results

Electrical Resistivity Tomography surveys were conducted along two survey lines designated as R1 and R2. Mackintosh Probe tests were performed at selected locations along each survey line to facilitate comparison between electrical resistivity values and penetration resistance.

Survey Line R1

The comparison between ERT and MP data along Survey Line R1 revealed varying relationships between resistivity values and blow counts. Fig. 2 shows the diagram of point Mackintosh and Electrical

Resistivity line 1.

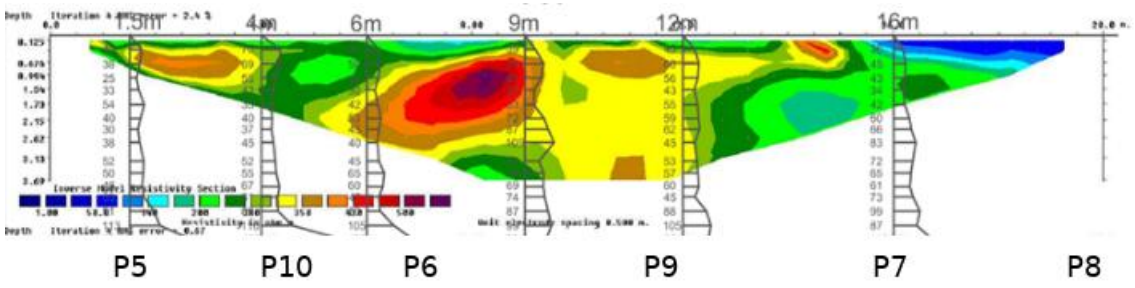
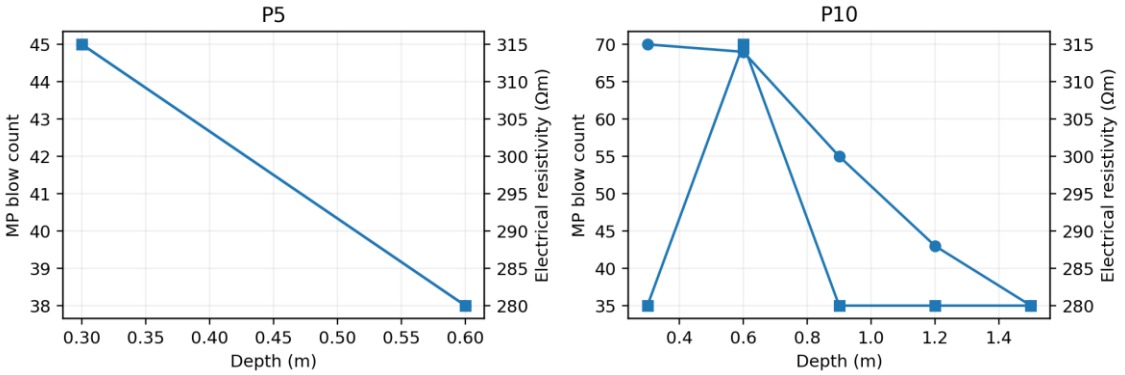


Fig. 2 Resistivity section and matched Mackintosh Probe locations along Survey Line R1

Fig. 3 illustrates the graph ERT vs Mackintosh blows at P5 and P10. At P5, a consistent agreement was observed between resistivity and penetration resistance within the shallow subsurface. From a depth of 0.3 m to 0.6 m, both datasets exhibited a slight, concurrent decrease. The resistivity value dropped from 315 Ωm to 280 Ωm, while the MP blow count decreased from 45 blows to 38 blows. This uniform downward trend suggests a highly correlated relationship between the parameters at this specific location. At P10, an inverse relationship between resistivity and penetration resistance developed with the increasing of depth. Between 0.3 m and 0.6 m, resistivity rose from 280 Ωm to 315 Ωm while the MP blow count remained virtually unchanged. Beyond 0.6 m, resistivity stabilised at 280 Ωm whereas the blow count steadily declined from 69 blows down to 35 blows at 1.5 m depth. This divergent behavior implies that factors altering subsurface density had a negligible impact on the material's electrical properties.

At P6 as referred in Fig. 4, the datasets demonstrated a largely decoupled relationship across the surveyed profile. While the MP blow count fluctuated marginally within a tight range of 30 to 53 blows, the resistivity trended upward, rising from 280 Ωm near the surface and plateauing at 350 Ωm beyond a depth of 1.5 m. This behavior indicates that changes in moisture content or soil composition driving the higher resistivity did not significantly affect the material's penetration resistance.



(a) (b)

Fig. 3 Dual-axis depth profiles: (a) P5 and (b) P10 (left axis: MP blow count; right axis: electrical resistivity)

At P9 as illustrated in Fig. 5, a partial agreement was observed between resistivity and blow count, though a notable depth lag occurred. From 0.3 m to 0.6 m, both parameters initially increased. However, beyond 0.6 m, the resistivity steadily decreased from a peak of 420 Ωm to 280 Ωm at depth. In contrast, the MP blow count fluctuated independently, decreasing until 1.5 m before rising to a maximum of 109 blows at 2.4 m. This inconsistency suggests that the primary drivers for electrical resistivity and soil density varied significantly across the layers.

Fig. 5 also shows that at P7, both datasets exhibited minor fluctuations but lacked a consistent, direct correlation. The resistivity values remained elevated, generally maintaining a plateau of 350 Ωm with subtle drops to 315 Ωm. Concurrently, the MP blow count displayed an independent, wavy profile that varied closely between 43 and 62 blows across the entire 3.0 m depth. The absence of a synchronised trend indicates a weak overall agreement between the electrical and mechanical properties at this location.

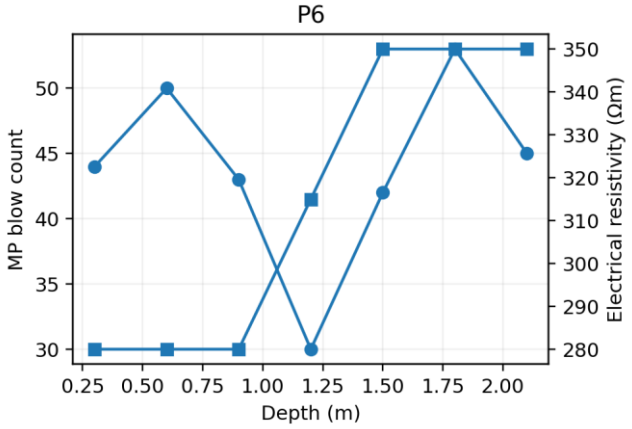
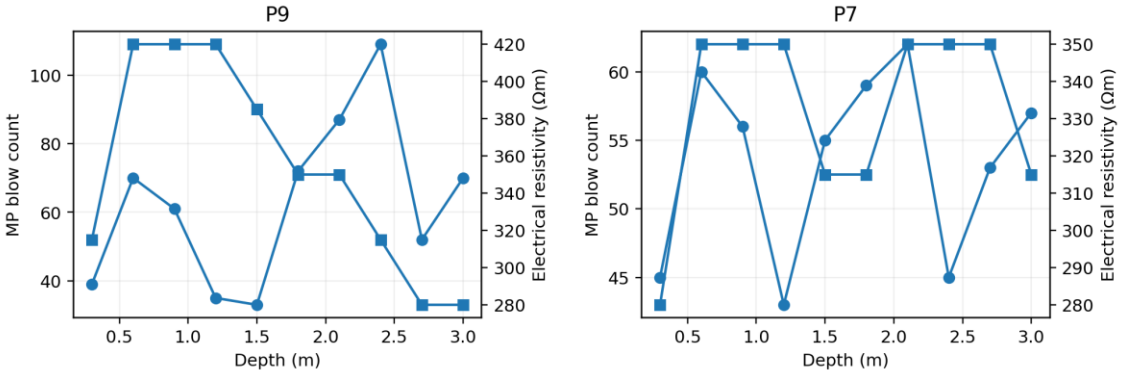


Fig. 4 Dual-axis depth profile at P6 (left axis: MP blow count; right axis: electrical resistivity)



(a) (b)

Fig. 5 Dual-axis depth profiles: (a) P9 and (b) P7 (left axis: MP blow count; right axis: electrical resistivity)

At P8 as referred to in Fig. 6, a clear agreement was limited strictly to the initial layer, turning inconsistent with depth. Between 0.3 m and 0.6 m, both profiles increased concurrently, with resistivity rising from 140 Ωm to 200 Ωm and blow counts moving from 36 to 45 blows. Past 0.6 m, however, the resistivity perfectly plateaued at 200 Ωm, while the MP blow count varied between 34 and 43 blows independently. This indicates that the subsurface properties stabilising the electrical resistivity did not uniformly dictate the mechanical penetration resistance.

Overall, the results obtained from Survey Line R1 indicate that ERT and MP measurements responded differently to subsurface conditions. Electrical resistivity was strongly affected by moisture distribution, whereas Mackintosh Probe resistance reflected changes in soil density and stiffness.

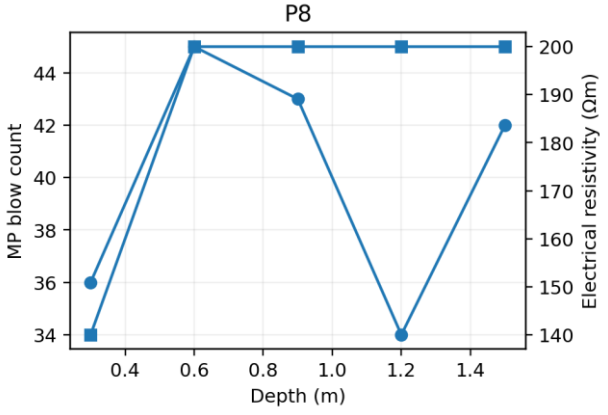


Fig. 6 Dual-axis depth profile at P8 (left axis: MP blow count; right axis: electrical resistivity)

Survey Line R2

Survey Line R2 exhibited similar behaviour to that observed along R1. Fig. 7 illustrates the diagram of point Mackintosh and electrical resistivity line 2.

At P13 as shown in Fig. 8, a positive correlation was limited strictly to the shallow subsurface before turning into an inverse relationship with depth. From 0.3 m to 0.6 m, both parameters increased significantly, with resistivity rising from 170 Ωm to 240 Ωm and blow counts climbing sharply from 12 to 106 blows. Past 0.6 m, however, resistivity continued to rise up to 420 Ωm while the MP blow count dropped steadily to 28 blows. This divergence indicates that the factors driving the higher electrical resistivity at depth did not correspond to an increase in mechanical penetration resistance.

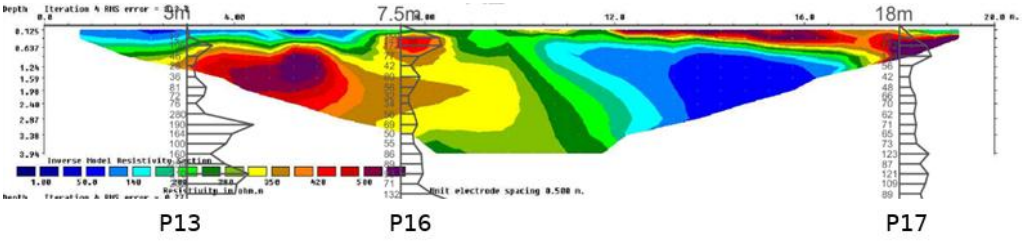


Fig. 7 Resistivity section and matched Mackintosh Probe locations along Survey Line R2

At P16 as illustrated in Fig. 9, the datasets displayed a strong apparent agreement within the upper layers, followed by a decoupled relationship at greater depths. Between 0.3 m and 1.2 m, both profiles decreased concurrently; resistivity dropped from 420 Ωm to 350 Ωm, while blow counts fell from 172 to 42 blows. Beyond 1.2 m, the resistivity perfectly plateaued at 350 Ωm, whereas the MP blow count fluctuated independently between 32 and 80 blows. This behaviour implies that the deeper subsurface variations affecting mechanical strength had no impact on the material's electrical properties.

At P17 as referred to Fig. 10, a consistent parallel agreement was observed between the datasets across the entire profile. From a depth of 0.3 m to 0.9 m, both resistivity and penetration resistance increased concurrently. Resistivity rose from 460 Ωm to a plateau of 500 Ωm, while the MP blow count steadily increased from 56 blows to 134 blows. This synchronised upward trend suggests a highly correlated relationship, potentially indicating a transition to a denser, drier subsurface stratum.

The observations obtained from Survey Line R2 reinforce the conclusion that different controlling factors within unsaturated tropical soils govern electrical resistivity and penetration resistance.

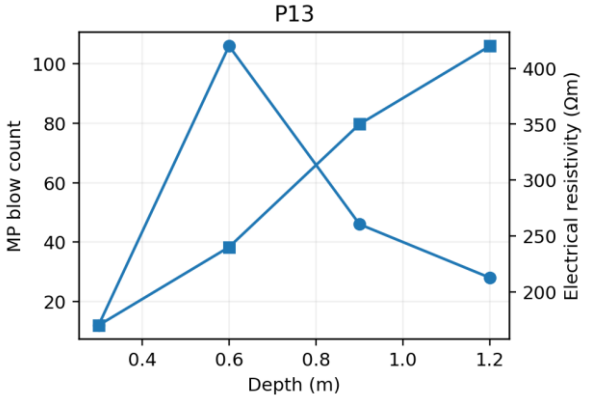


Fig. 8 Dual-axis depth profile at P13 (left axis: MP blow count; right axis: electrical resistivity)

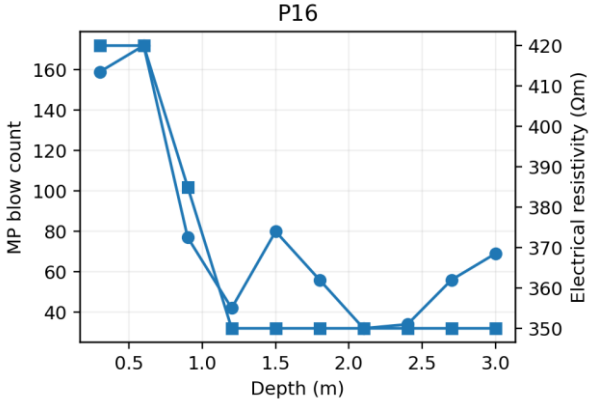


Fig. 9 Dual-axis depth profile at P16 (left axis: MP blow count; right axis: electrical resistivity)

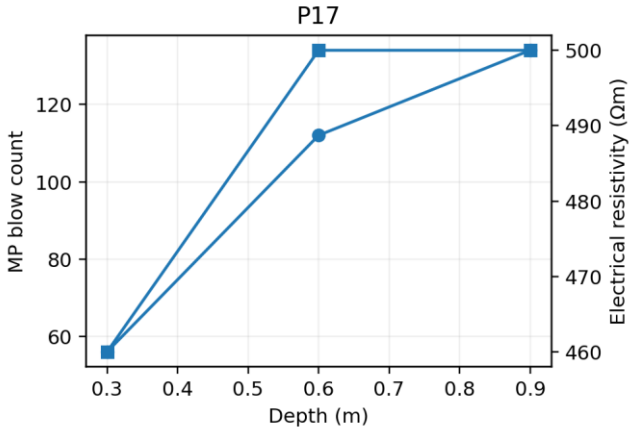


Fig. 10 Dual-axis depth profile at P17 (left axis: MP blow count; right axis: electrical resistivity)

Correlation Analysis Between ERT and Mackintosh Probe

A quantitative analysis was carried out using all 56 matched resistivity-blow count pairs available from P5, P10, P6, P9, P7, P8, P13, P16 and P17. Fig. 11 shows the combined dataset produced a Pearson correlation coefficient of r = 0.458 and a linear coefficient of determination of R^2 = 0.210. The positive r value indicates an overall tendency for higher blow counts to occur with higher resistivity; however, the low R^2 shows that resistivity alone accounts for only about 21% of the observed variation in MP resistance. The scatter is therefore too large for the fitted line to be used as a reliable site-wide predictive relationship.

The location profiles also showed that the direction and strength of association are not uniform. Some profiles show local agreement, particularly P16 and P17, whereas P6, P9 and P13 showed little or inconsistent association. The very high apparent correlation at P5 is based on only two matched observations and is therefore not considered statistically informative. These results support interpretation of ERT and MP as complementary measurements rather than interchangeable indicators of the same soil property.

This behaviour is consistent with the different physical controls on the two measurements. Electrical resistivity in unsaturated soil is sensitive to moisture distribution, degree of saturation and pore-water conductivity, whereas MP blow count primarily reflects penetration resistance, density, stiffness and particle interlocking. The laboratory results further show a sand-dominated soil with low fines content and variable natural moisture content. Accordingly, changes in moisture condition can alter the electrical response without producing an equivalent change in mechanical resistance.

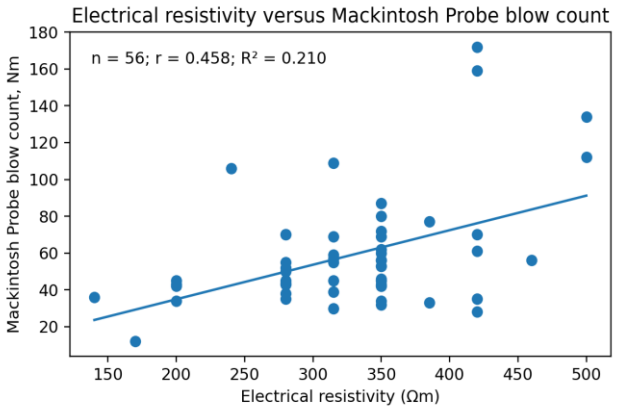


Fig. 11 Scatter plot of electrical resistivity and Mackintosh Probe blow count for all matched observations.

Engineering Implication

The results demonstrate that Electrical Resistivity Tomography and Mackintosh Probe testing provide valuable but different information regarding subsurface conditions. ERT is particularly effective for identifying variations in moisture content, degree of saturation, and subsurface stratification [4], [22]. The method offers rapid, non-destructive investigation and provides continuous subsurface coverage.

Therefore, the Mackintosh Probe provides direct information regarding penetration resistance, soil density, and relative stiffness [6], [16]. The test is useful for assessing the mechanical behaviour of shallow subsurface materials. Because both techniques respond to different soil properties, they should be considered complementary rather than interchangeable investigation methods [3], [15]. The combined use of ERT and MP testing can improve confidence in subsurface interpretation and provide a more comprehensive understanding of soil conditions for engineering applications.

8. CONCLUSION

This study investigated the relationship between Electrical Resistivity Tomography (ERT) and Mackintosh Probe (MP) measurements in unsaturated tropical soil at Kempas, Johor. The laboratory results showed that the tested materials are predominantly sand-dominated, with low fines content (2.5-5.5%) and variable natural moisture content (24.65-57.69%). The reported Atterberg limits characterise the finer material used for the limit tests and are not interpreted as the plasticity of the bulk sandy soil.

The ERT surveys identified variations in subsurface electrical conditions, while the Mackintosh Probe profiles showed corresponding changes in penetration resistance with depth. Quantitative analysis of 56 matched observations gave $r = 0.458$ and $R^2 = 0.210$. Although this represents an overall positive association, the low coefficient of determination and the marked scatter between locations show that a single resistivity-MP relationship is not sufficiently reliable for prediction across the site. Local agreement at several depths should therefore be interpreted as site- and condition-specific rather than as a universal correlation.

Therefore, Electrical Resistivity Tomography and Mackintosh Probe testing should be regarded as complementary site investigation techniques rather than interchangeable methods for evaluating unsaturated tropical soils. The integration of both approaches can provide more reliable subsurface characterization and support improved geotechnical decision-making. Future studies should investigate a wider range of soil types and environmental conditions to further evaluate the relationship between geophysical and geotechnical parameters. Additional investigation methods such as Standard Penetration Testing (SPT), Cone Penetration Testing (CPT), and soil suction measurements may also be incorporated to improve understanding of subsurface behaviour.

9. ACKNOWLEDGEMENTS/FUNDING

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10. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

11. AUTHORS' CONTRIBUTIONS

Muhammad Afiq Naqiuddin Mat Hasni: Conceptualisation, Methodology, Formal analysis, Investigation, Data curation, and Writing-original draft;

Bakhtiar Affandy Othman: Conceptualisation, Formal analysis, Visualisation, Supervision, Writing-review and editing, and Validation.

Dayang Zulaika Abang Hasbollah: Data curation

Assrul Reedza bin Zulkifli: Writing- review and editing

Nur Syahirah Syuhadah Zakaria: Writing- review and editing

12. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) did not use any AI-assisted technologies.

13. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

Available upon request:

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

14. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi Malaysia.

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