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A field evaluation of peat settlement on road infrastructure: integrating 2D electrical resistivity tomography (ERT) and geotechnical instrumentation

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Abstract. Peat soils within Sarawak region pose significant challenges to road embankment construction due to their high compressibility, low shear strength, and spatial variability. This study employs 2D Electrical Resistivity Tomography (ERT) as a rapid, non-invasive technique to evaluate peat settlement behavior along the Sebuyau–Lingga (Package B1) section of the Sarawak Second Trunk Road (SSTR). Multiple ERT profiles were acquired across the alignment to delineate peat thickness, identify subsurface variability, and characterize soft ground conditions. In-Peat geomechanical monitoring data were integrated to correlate and validate resistivity interpretation. Results show a clear relationship between resistivity values and measured settlement magnitude, with low-resistivity zones corresponding to highly compressible peat layers. Field settlement observations further support these correlations. The integrated geophysical–geotechnical approach enhances the rapid detection of critical soft ground sections, improves investigation efficiency, and supports more informed design and construction decisions in peat-dominated terrain. Additionally, the resistivity method effectively differentiates between hard-filled embankment materials, peat, and clay, providing valuable subsurface characterization for construction control.

1 Introduction

Road construction over peat deposits is a recurring geotechnical challenge in Sarawak, particularly along coastal and low-lying corridors. Peat soils are characterized by very high natural water content, organic content, and void ratio, resulting in large primary consolidation and long-term secondary compression under embankment loading [1, 2]. In Sarawak, peat thickness and properties can vary significantly over short distances, leading to differential settlement and serviceability issues for road pavements if not properly managed [3].

Conventional site investigation methods, such as boreholes and cone penetration tests, provide point-based information that may not adequately capture the lateral variability of peat thickness and underlying strata. This limitation is particularly critical in large-scale road projects, where sparse investigation spacing is often adopted for economic reasons. Malaysian guidelines and experience from peatland infrastructure projects emphasize the importance of supplementary investigation and monitoring methods to reduce geotechnical uncertainty [2, 4].

Electrical Resistivity Tomography (ERT) has emerged as a valuable geophysical technique for imaging subsurface conditions in soft ground environments. This technique has been adopted in subsoil profiling works in recent time.

This paper presents a case study from the Sebuyau–Lingga road project (SSTR Package B1), where 2D ERT surveys were integrated with settlement and geotechnical monitoring to evaluate peat behaviour during embankment construction. The objective is to demonstrate how this integrated approach can improve interpretation of peat settlement, support construction-stage decision-making, and align with Malaysian best practice for road construction over peat deposits.

1.1 Fundamentals of resistivity

Equation (1) is the general apparent resistivity equation and Equation (2) showed the geometric factor for Wenner–Schlumberger array [5].

$$\rho a = K \cdot \Delta V / I \quad (1)$$

$$K = \pi a(n+1)(n+2) \quad (2)$$

The relationships defined in Equations (1) and (2) form the basis for field resistivity measurements and directly govern survey design parameters. In practical application, the geometric factor **K** controls the depth of investigation and sensitivity of the measurements, while electrode spacing **a** and spacing factor **n** determine the resolution and penetration of the resistivity imaging. For peatland environments characterized by strong resistivity contrasts and significant lateral variability, careful selection of electrode spacing is critical to balance vertical detection capability and lateral continuity [5]. Accordingly, the survey configuration adopted in this study was optimized to resolve shallow

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peat stratigraphy while maintaining sufficient depth coverage to capture the peat–mineral soil interface relevant to embankment performance assessment.

1.2 Resistivity and equipment

2D Electrical Resistivity Tomography (ERT) is a non-invasive geophysical technique widely used to image subsurface electrical properties in two dimensions. By injecting electrical current into the ground and measuring potential differences, ERT produces apparent resistivity data, which are then inverted to generate 2D resistivity profiles representing spatial variations in soil and rock [7]. The equipment used in this study is ABEM Terramenter LS2.

Table 1. shows the characterization of different type of peat with different decomposition extent. The estimate of resistivity from different studies observed that the range of resistivity value, correspond to different decomposition state of the peat.

2 Project background

The Sebuyau–Lingga road section forms part of Sarawak's strategic Sarawak Second Trunk Road (SSTR) infrastructure, traversing extensive peatland areas requiring carefully staged embankment construction and monitoring to control settlement and stability. Fig.1 shows the proposed network for whole SSTR. It is observed that the proposed road networks involve construction along low lying coastal and riverine area. Most of the proposed construction for SSTR passes peat area. Road embankment is necessary to be constructed until formation level of the road level. Fig. 2 shows the proposed study area.

2.1 Geological and geotechnical setting

The site is underlain by peat measuring up to approximately 5.0m overlying silt with noticeable amount of sand. Groundwater levels are typically shallow, contributing to high peat compressibility and long-term consolidation behaviour.

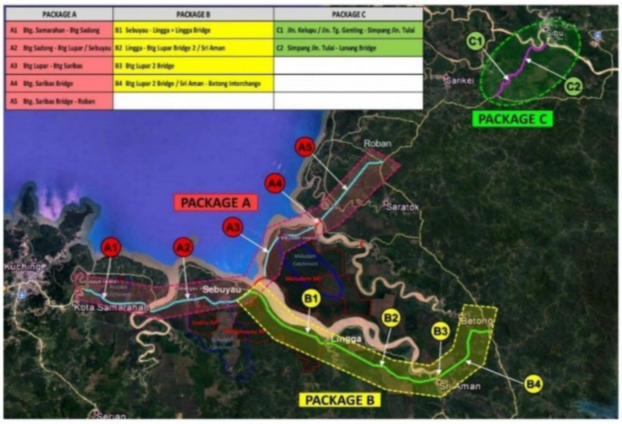

Fig. 1. Sarawak second trunk road (SSTR) road network plan.

Table 1. Soil types related to peat and embankment from related study.

Material Type (Malaysia)	Description / Local Characteristics	Typical Resistivity (Ω·m)	Source / Study
Fibrous / lightly decomposed peat	High fibre content, high water content; early peat layers	100 – 140	[6] observed peat resistivity in this range, validated with peat sampler profile in Johor, Malaysia
Moderately decomposed peat	Intermediate peat with less fibrous structure, mixed hydrophilic behaviour	~80 – 120	[7] demonstrated ERT peat delineation with MASW correlation, matching borehole logs in studied peat profiles
Highly decomposed / amorphous peat	High compressibility, amorphous	30 – 80	Correlation with general peat behaviour [1,8] and reinforced by reduced resistivity in peat zones [3]
Organic clay / peaty clay transition	Mixed peat–clay zones beneath thicker peat, variable water content	40 – 100	General Malaysian peat–clay stratigraphy, supported by baseline geophysical interpretations
Soft marine clay (underlying peat)	High plasticity, saturated clay beneath peat layers	1 – 40	Typical values from Malaysian coastal deposits [2,9]
Sandy / stiff residual soil	Deeper foundational strata with high strength	>80 – >150	Resistivity classifications adapted from [5].

Fig. 2. Study area during road construction.

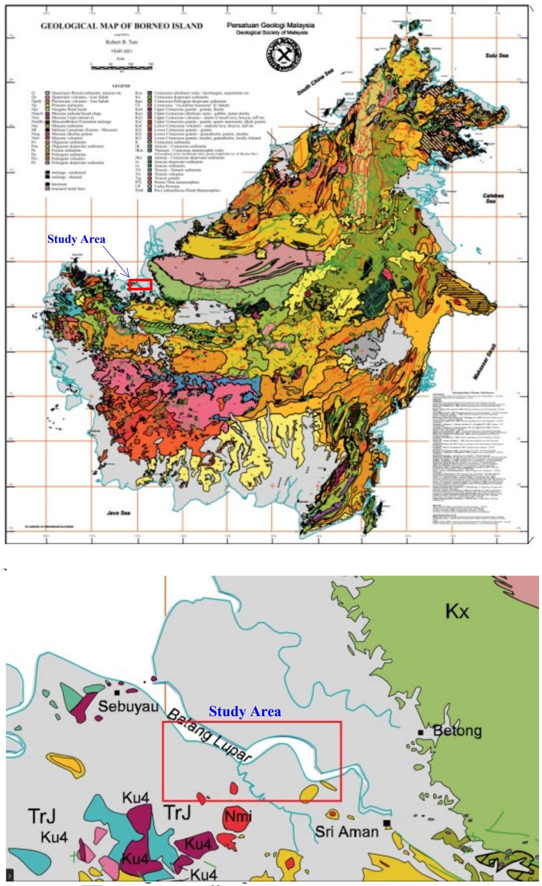

Fig. 3. Geological setting of the proposed study area.

3 Methodology

2D ERT surveys were conducted along selected chainages of the road alignment, including longitudinal profiles parallel to the centre line and transverse profiles across the embankment. A multi-electrode resistivity system (Terrameter,ABEM LS2), Fig. 4, with uniform electrode spacing of 1.0m was used to achieve investigation depths sufficient to image the full peat sequence and the underlying mineral soils.

Fig. 4. ABEM Terrameter LS2 system.

A total of 50 numbers of electrodes were laid out in a straight line. Survey design and data acquisition followed established near-surface geophysical practices for soft, saturated ground conditions [5, 10]. Fig. 5 show typical setting up of the geophones and data acquisition unit.

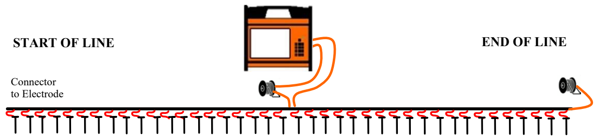

Fig. 5. Schematic of cable arrangement for the resistivity survey.

The Wenner–Schlumberger array was adopted to provide a balance between vertical resolution, lateral coverage, and signal strength, and has been shown to be effective for delineating peat and soft clay layers beneath embankments [5]. Apparent resistivity values were calculated from measured current and potential differences and inverted using commercially available software to produce true resistivity sections.

Interpretation of the resistivity sections was guided by a Malaysia-specific resistivity classification for peat and associated soils (Table 1), developed from ERT studies calibrated against peat sampling and integrated geophysical–geotechnical investigations [6, 7]. Low to moderate resistivity zones were interpreted as peat of varying decomposition grades, while higher resistivity layers were associated with organic clay, marine clay, or sandy strata.

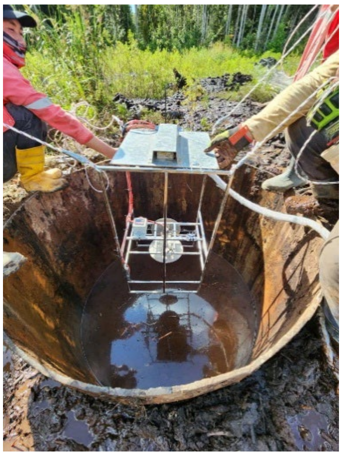

Fig. 6. Installation of subsurface sensor module into the peat layer.

This study involves installation of a subsurface sensor module (SSM) show in Fig. 6, where a vibrating wire liquid settlement gauge (SSVW 105) is attached. The dimension of subsurface sensor module is 500mm x 450mm x 950mm constructed using stainless steel hollow member. Apart from the liquid settlement gauge, other instruments such as one number of vibrating wire piezometers, 2 numbers of vibrating were earth pressure cells (EPC1 and EPC2) were also attached to the SSM by mechanical fasteners and high-tensile cable ties. The location of the SSM were position at the centre line of the proposed road chainage CH26+600. This paper shall focus on the settlement performance of the peat under embankment surcharge. As such, the vibration wire liquid settlement gauge data shall be adopted for the analysis to assess settlement of the peat during construction of the road embankment.

Due the very soft and extremely high-water content of peat soil, the installation of the SSM was facilitated by using a temporary steel casing of 1.0m diameter and 20mm thickness. The temporary steel casing was lowered down into the soil prevent the peat from collapse into the excavation during lowering down of the SSM. Upon installation and securing the SSM to designated level of 3.0m below ground level, the excavated peat was manually backfilled back into the ground prior to extraction of the casing. Subsequently the cables were extended to ground level. To protect the cable from damages due to vehicle, machineries of construction activities, a cable trench were dug, and cables were laid across the embankment to far end where data loggers were position. Fig. 7 shows a typical installation cross section and Fig. 8 illustrates the cable trench routing and sand bag protection to ensure the cables are secured.

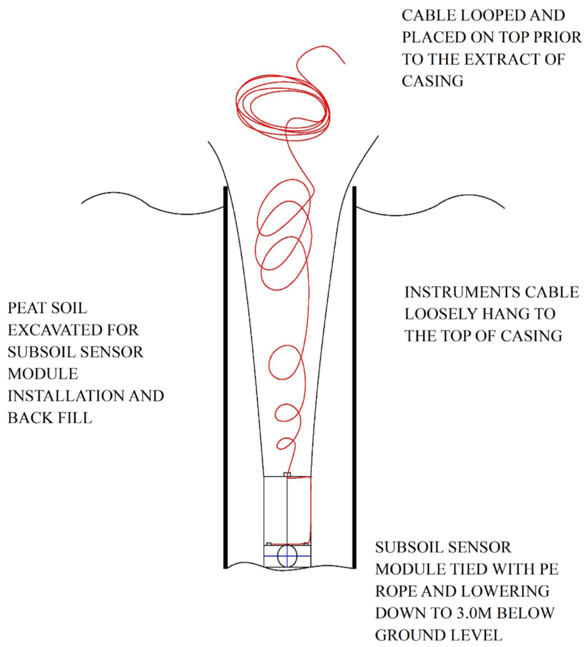

Fig. 7. Schematic of the subsurface sensor module (SSM) where liquid settlement is attached.

Fig. 8. A cable trench was dug to lay cables below embankment construction and covered with sandbags as protection.

A ERT survey was carried out on the 4th September 2024, where the backfilled embankment thickness is approximately 2.63m. While the interpretation of resistivity contrasts in peat environments may be subject to uncertainty, particularly due to overlapping resistivity ranges between peat, organic clay, and saturated soft soils, the primary objective of this study is not to establish definitive lithological boundaries. Instead, the emphasis is placed on evaluating the practical correlation between resistivity variations and observed settlement behaviour. Resistivity values are influenced by multiple factors, including moisture content, pore water conductivity, and soil fabric, which may complicate direct material classification [5]. However, from an engineering perspective, these same factors are intrinsically linked to compressibility and deformation characteristics. Therefore, even where resistivity contrasts may be debatable in strict geological terms, the measured spatial variations remain highly informative for identifying zones of differential settlement response. This pragmatic approach aligns with performance-based assessment principles commonly adopted in soft soil engineering, where relative behaviour and deformation trends are often more critical than precise stratigraphic delineation.

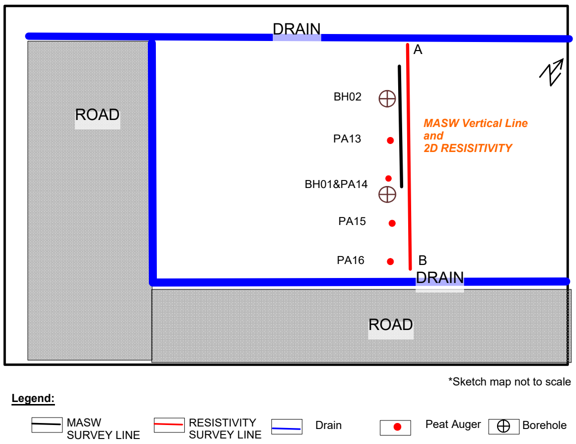

Fig. 9. Layout of the 2D Resistivity Lines.

A resistivity survey line (Fig. 9) was conducted during both the pre-embankment and post-embankment stages to evaluate changes in subsurface resistivity and to correlate these variations with geotechnical instrumentation data and embankment response.

Fig. 10 shows the outcome of ERT survey. The resistivity variations observed between pre-embankment and post-embankment surveys are interpreted as responses to stress-induced modifications within the peat deposit. Embankment loading increases effective stress, leading to volumetric compression, reduction in void ratio, and expulsion or redistribution of pore water. These processes alter the electrical conduction pathways, as resistivity is strongly governed by moisture content, pore fluid continuity, and soil structure [5, 9]. In highly compressible peat, stress increase commonly produces localized resistivity changes associated with density increase and evolving saturation conditions. The spatial coincidence of resistivity anomalies with zones of elevated settlement supports the interpretation that ERT captures construction-stage stress effects. This behaviour highlights the sensitivity of resistivity imaging to deformation processes relevant to soft soil performance, particularly in organic soils where compressibility is strongly coupled with pore fluid behaviour. It is highlighted that, the clay underneath the peat do also experience settlement. However, as the vibration wire liquid settlement was installed within the peat layer, as such, the settlement in clay were not fully capture. It is recommended that, for future instrumentation works to assess settlement, another liquid settlement can be installed within the clay layer.

4 Results

4.1 ERT imaging of peat response for pre and post embankment

The 2D ERT sections clearly delineated peat layers as zones of relatively moderate to higher resistivity, with significant lateral variability in thickness and decomposition grade. Localized depressions in the peat–mineral soil interface were identified, which were not always evident from borehole data alone. Application of the Malaysian peat resistivity classification allowed differentiation between fibrous, moderately decomposed, and highly decomposed peat units.

4.2 Settlement monitoring

The vibrating wire liquid settlement gauge was attached on SSM and was installed prior to commencement of the earth filling works for the embankment. Continuous monitoring was carried out throughout the progress of embankment construction with the data recorded and stored in datalogger DT2055B.

Based on the real time settlement monitoring data, it shows substantial vertical deformation during embankment construction, with total settlement magnitudes generally consistent with areas underlain by thicker or more highly decomposed peat. The vibrating wire liquid Settlement Gauge (LSG) data showed that most of the settlement occurred within the peat layer. To compare the result from the 2D ERT and geotechnical instrumentation, the data extracted from the liquid settlement gauge coincide with the date where 2ERT were carried out between 25th July 2023 and 4th September 2024. Prior to construction of the road embankment, the initial reading was 3323.4mm and the reading on 4th September is 4817.4mm. During this period a total peat settlement of 1494.3mm ~ 1.49m were recorded.

5 Discussion

The case study demonstrates the value of integrating 2D ERT with geotechnical instrumentation for peatland road projects in Sarawak. While instrumentation provides accurate point-based measurements (Fig. 12) of settlement and pore pressure response, ERT offers continuous subsurface imaging that captures lateral variability in peat thickness and decomposition [4,5].

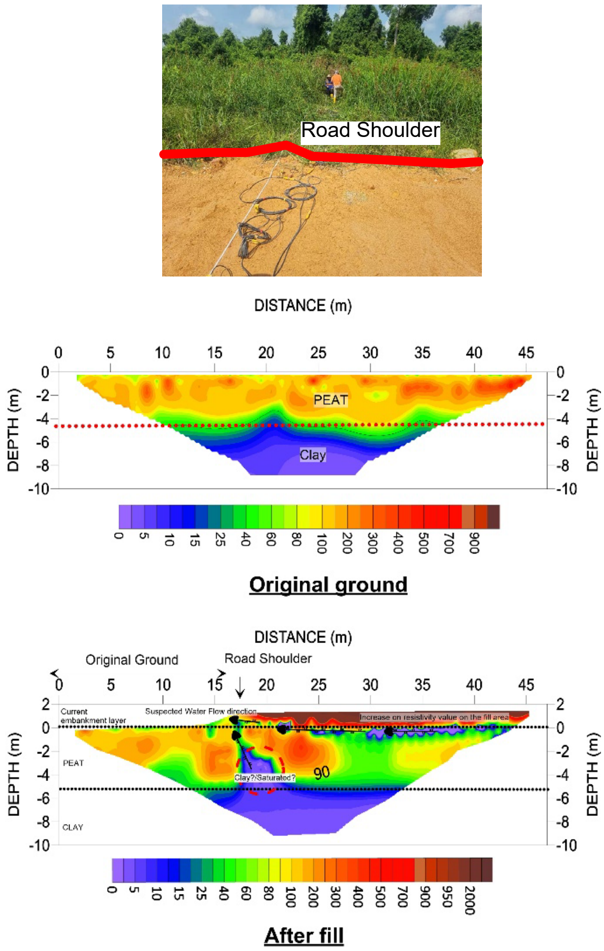

Fig. 10. Resistivity results of pre and post embankment.

(a)

(b)

Fig. 11. (a). Vibrating wire liquid settlement gauges (SSVW 105) for settlement monitoring (b) Data logger DT2055B to record the data throughout monitoring period.

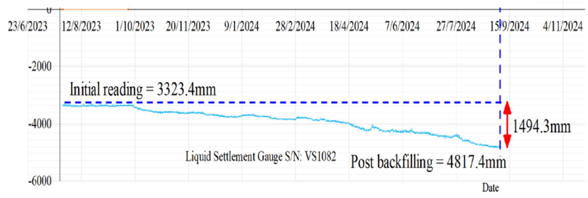

Fig. 12. Liquid Settlement Gauge (LSG) data over the embankment construction period.

The comparison between geotechnical instrumentation and geophysical interpretation indicates a correlation between measured and ERT-estimated embankment fill levels (Table 2). Prior to construction, both methods indicated zero fill thickness. Following embankment construction, the Liquid Settlement Gauge recorded a settlement of approximately 1.49 m, while ERT interpretation estimated a corresponding fill thickness ranging from 1.30 m to 1.50 m. The minor discrepancy reflects lateral variability in fill geometry and resistivity transition zones, demonstrating the capability of ERT to capture construction-stage changes in embankment thickness within acceptable engineering tolerance.

Table 2. Measurement obtained from Liquid Settlement Gauge (LSG) monitoring and ERT survey measurement of earthfill.

Construction stage	Resistivity data acquisition date	Liquid Settlement Gauge data	Measured thickness of earthfill from resistivity data
Before embankment construction	25 July 2023	0.00m	0.00m
After embankment construction	4 September 2024	1.49m	1.30m to 1.50m

Areas interpreted from ERT as being underlain by thicker or more highly decomposed peat generally corresponded to higher total settlement and longer consolidation periods, consistent with established peat behaviour [1, 2]. The Malaysian-specific resistivity classification adopted in this study, derived from [6, 7], improved confidence in distinguishing peat units and transitional organic clays, thereby enhancing interpretation of settlement trends.

Previous studies have shown that resistivity variations can be qualitatively correlated with embankment consolidation in soft ground environments [5]. Similar trends were observed in this study, supporting the use of ERT as a complementary tool for construction-stage assessment. The findings are consistent with Malaysian best practice, which emphasizes staged construction and close monitoring for embankments on peat and soft soils [3, 8].

Despite its advantages, ERT interpretation remains non-unique and influenced by groundwater chemistry and saturation. Consequently, ERT should be applied in conjunction with borehole data, laboratory testing, and geotechnical instrumentation rather than as a standalone investigation method.

Table 3. Soil types related to current peat and embankment study.

Material Type (B1 Lingga)	Description / Local Characteristics	Typical Resistivity (Ω·m)
Peat	High fibre content, high water content; early peat layers	100 – 140
Organic clay / peaty clay transition	Mixed peat–clay zones beneath thicker peat, variable water content	40 – 100
Soft marine clay (underlying peat)	High plasticity, saturated clay beneath peat layers	1 – 40
Compacted soil	Generally hard after surcharge	>150
Sandy / stiff residual soil	Deeper foundational strata with high strength	>80 – >150

6 Findings and recommendations

This study demonstrates that an integrated approach combining 2D Electrical Resistivity Tomography and geotechnical instrumental monitoring provides an effective framework for evaluating peat settlement beneath road embankments in Sarawak. A drastically increase over the resistivity value on the top layer indicates the embankment layer. Adoption of a locally calibrated resistivity classification improved interpretation of peat thickness and decomposition, and enhanced correlation with observed settlement behaviour. Therefore, it is a good technique for rapid mapping in peat area and QA/QC support for the embankment layer. The methodology is applicable to other peatland infrastructure projects in Malaysia and similar tropical environments, offering a practical means of reducing geotechnical uncertainty during construction.

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