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Systematic monitoring approaches for evaluating peat response to incremental loading

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Abstract. This paper presents the challenges, problems, and key lessons learned from a two-year in-peat geomechanical instrumentation program carried out beneath a road embankment in Sarawak, Malaysia. The monitoring system designed to measure vertical and horizontal stresses, pore water pressure, and settlement within a highly compressible peat layer has provided valuable long-term insights but also revealed significant practical and technical issues during installation and operation. These experiences highlight the complexities of deploying instrumentation in peat and emphasize the importance of robust installation methods, redundancy in sensor layout, and proactive maintenance. The lessons learned from this project provide practical guidance for future full-scale monitoring programs in similar soft-soil environments and contribute to improving the reliability of in-peat geomechanical monitoring techniques.

1 Introduction

Construction of highways over soft ground and peat deposits presents significant geotechnical challenges due to low shear strength, high compressibility, and large long-term settlements [1,2]. Instrumentation and monitoring are therefore essential to verify design assumptions, assess ground response, and ensure construction safety, particularly where time-dependent deformation governs performance [3].

This paper documents the geotechnical instrumentation works carried out for the Proposed Construction and Completion of the Sarawak Second Trunk Road (SSTR), Package B1, from CH26+550 to CH26+650. The project involved construction of a special embankment over peat deposits, requiring extensive soil investigation and real-time monitoring of ground behaviour during construction. The objectives of the instrumentation program were to monitor horizontal and vertical ground movements, pore water pressure changes, earth pressures, and overall embankment performance consistent with the observational method in soft ground engineering [4].

2 Project overview and scope

The project is located in the Samarahan and Sri Aman Divisions, Sarawak, where thick peat and soft clay deposits are prevalent. The selected site consists of approximately 5 m of peat underlain by about 12 m of very soft clay with an SPT N-value of 0.

The scope of work comprised two major components:

1. Site Investigation – including borehole drilling, standard penetration tests (SPT), peat auger investigation, laboratory testing, and in-situ testing.
2. Geotechnical Instrumentation – installation and monitoring of instruments to assess ground response during embankment construction.

Fig. 1 presents the schematic layout of borehole locations and instrumentation installation. A total of two boreholes were drilled, supplemented by peat auger investigations to determine peat thickness and stratigraphy. The instrumentation programme included inclinometers, vibrating wire (VW) piezometers, magnetic extensometers, and a Subsurface Sensor Module (SSM).

3 Site investigation and instrumentation program

The soil investigation program was designed not only to establish stratigraphy but also to characterize the stress–strain behaviour of the peat deposit under staged embankment loading. Emphasis was placed on identifying peat thickness variability, degree of decomposition, and the characteristics of the underlying mineral strata, as these factors directly influence settlement magnitude, consolidation rate, and long-term creep performance.

The instrumentation layout was developed in accordance with the observational method framework, whereby field measurements are continuously compared against predicted performance to guide construction control.

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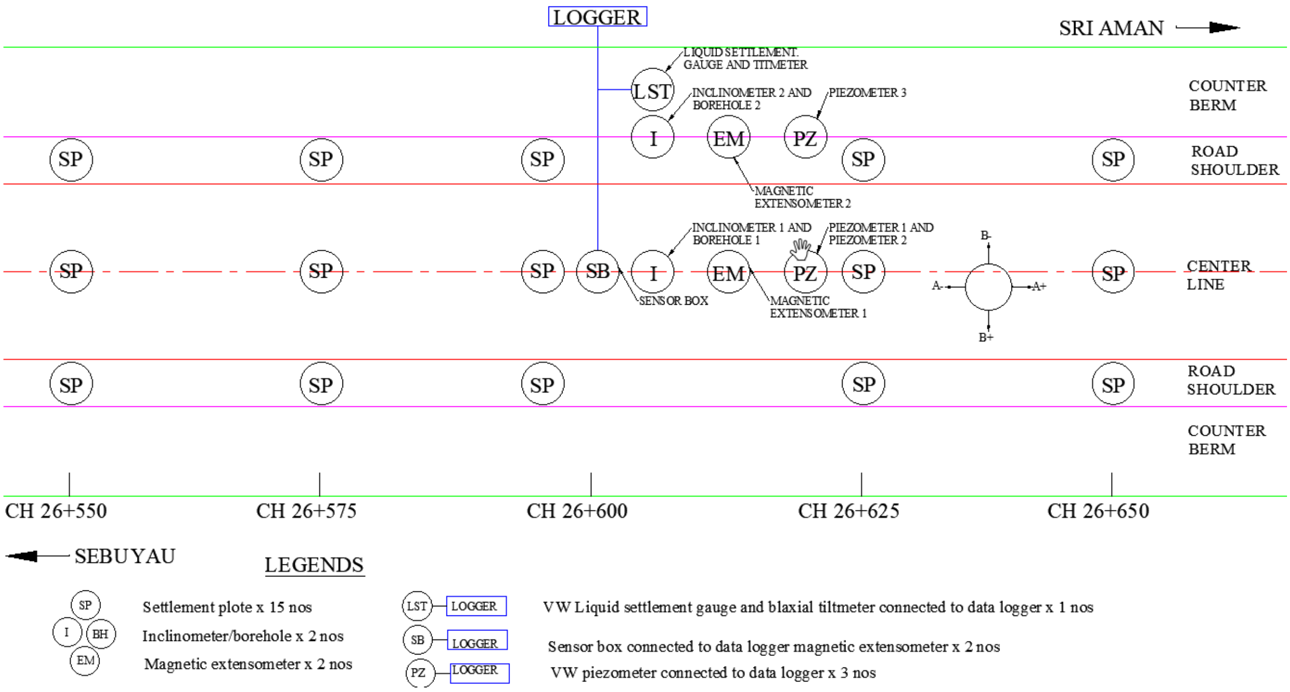

Fig. 1. Layout of instrumentation.

The integration of inclinometers, magnetic extensometers, vibrating wire piezometers, earth pressure cells, and tiltmeters enabled simultaneous monitoring of deformation, pore pressure response, and stress redistribution within the peat layer being monitor on site.

Placement of the Subsurface Sensor Module (SSM) at mid-depth of the peat layer was strategically selected to capture internal stress transfer mechanisms and excess pore pressure evolution within the most compressible stratum. By correlating total stress measurements from earth pressure cells with pore water pressure readings, changes in effective stress could be interpreted, allowing assessment of consolidation progress within the organic soil mass

3.1 Site investigation works

Rotary wash boring shown in Fig. 2a was adopted using drilling rigs capable of reaching depths up to 90 m. Boreholes were advanced using roller cutting bits for soil and diamond bits for rock, with water circulation to remove cuttings and stabilize the borehole. Fig. 2b shows the temporary casings were installed to prevent collapse in soft ground conditions.

Standard Penetration Tests (SPT) were conducted at 1.5 m intervals, and both disturbed and undisturbed soil samples were collected for laboratory testing. Undisturbed samples were sealed with paraffin wax to preserve moisture content. Peat auger investigations were carried out to identify peat thickness and classify peat using Von Post classification system, which is commonly adopted for engineering characterisation of peat deposits [1, 5].

3.2 Inclinometer installation

Inclinometers are widely used to measure lateral displacements in the ground and in subsurface structures such as retaining walls and embankments. A conventional inclinometer casing contains four orthogonal internal grooves that guide the inclinometer probe during readings, ensuring consistent orientation and reliable measurement of horizontal deformation. For this project, inclinometers were proposed to be installed on the counter berm and centre line of the embankment to monitor lateral ground movement induced by staged embankment loading. The proposed inclinometer layout is shown in Fig. 1. Inclinometers are to be terminated at a maximum depth of 35 m or extended at least 10 m into material with Standard Penetration Test (SPT) values greater than 30, whichever occurs first, to ensure anchorage within a competent stratum and meaningful lateral displacement monitoring. Fig. 3 depicts the installation of the inclinometer.

(a) (b)

Fig. 2. Boreholes drilling: (a) setting up of SI drilling machine, and (b) drilling works.

Fig. 3. Installation of inclinometer.

Installation Procedure:

1. Drill a 100 mm diameter hole to the required depth and, where possible, into a stable rock layer. Install temporary steel casing to the bottom of the borehole to prevent collapse and ensure vertical alignment. Clear drilling mud and debris from the borehole prior to instrument installation.
2. Attach the bottom cap securely to the lowest section of the inclinometer casing to prevent grout intrusion.
3. Pump the grout mix into the borehole. The grout mix comprised cement : bentonite : water in a ratio of 1 : 3 : 10, providing adequate backfill consistency and strength.
4. Lower the inclinometer casing into the borehole, adding casing sections as necessary until the specified depth is reached. The inclinometer casing is filled with water during installation to counteract buoyancy forces when grouting begins.
5. The maximum inclinometer length shall be 35 m or at least 10 m into material with SPT > 30, whichever criterion is met.
6. Withdraw the temporary steel casing upon completion of inclinometer casing installation.
7. Top off the borehole with grout and install a protective cover at ground level to prevent damage during construction activities.

3.3 Vibrating wire piezometers

VW piezometers were installed to monitor pore water pressure changes during embankment construction. The instruments were installed at depths of 3.0 m, 5.0 m, and 7.5 m below ground level. Prior to installation, the vibrating wire piezometers were calibrated in the laboratory using a 200 mm diameter PVC column filled with water. Fig. 4 shows that the calibration column marked at 1 m intervals up to a maximum height of 5 m to simulate incremental hydrostatic pressure conditions. At each 1 m water head increment, corresponding piezometer readings were recorded and compared with the theoretical water pressure values to verify sensor accuracy and linearity.

The installation procedure:

1. The vibrating wire piezometer shall be immersed in clean, de-aired water for at least 24 hours prior to installation to ensure full saturation of the porous filter element. Fig. 5 shows each piezometer was fully saturated prior to installation. Proper saturation is essential to obtain reliable pore water pressure measurements. The piezometer is to be installed with the filter tip oriented upwards to minimize air entrapment within the intake zone.
2. Drill a 75 mm diameter borehole to the specified installation depth below ground level. Upon reaching the target depth, flush the borehole thoroughly with clean water to remove drilling debris and ensure that the borehole is free of obstructions.
3. Slowly introduce bentonite pellets into the borehole to form a sealing plug of a minimum 1 m thickness at the base. This plug serves to prevent vertical seepage and isolate the monitoring zone.
4. After completion of the bentonite plug, carefully place approximately 400 mm thickness of clean, washed sand into the borehole to form the lower intake zone. Once the first 400 mm of sand is in place, lower the piezometer into the borehole with the filter tip pointing upwards. Subsequently, place an additional 400 mm thickness of clean sand around the piezometer to complete the sand intake zone, ensuring proper hydraulic contact between the surrounding soil and the sensor.
5. Following installation of the sand intake zone, slowly introduce bentonite pellets above the clean sand to form a minimum 1 m thick sealing layer. The remaining borehole shall then be backfilled with grout or suitable material to ground level. This layered installation ensures hydraulic isolation of the piezometer tip and prevents crossflow between soil strata.

Fig. 4. Piezometer calibrated in the PVC column.

Fig. 5. Piezometer was saturated before installation.

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3.4 Magnetic extensometers

The Soil Instruments Magnetic Extensometer is used to measure vertical compression within embankments, foundations, and engineered fills, as well as to monitor settlement movement in soft ground resulting from staged embankment construction. The extensometer system enables measurement of both total settlement and layer-specific compression by identifying the depths at which vertical displacement occurs. Fig. 6 and 7 depict the fixing spider magnet and installation of the spider magnetic extensometer

For each monitoring location, a total of six (6) magnetic spider magnets and two (2) plate magnets will be installed. The magnetic spider magnets will be positioned at depths of 2.5 m, 5.0 m, 7.0 m, 9.0 m, 14.0 m, and 15.0 m below existing ground level (EGL). A datum magnet will be installed at 16.0 m below ground level to serve as a stable reference point anchored in relatively incompressible material. In addition, a plate magnet will be installed at existing ground level to measure surface settlement.

This configuration allows differentiation between surface settlement and compression occurring within specific soil strata, thereby providing valuable insight into the consolidation behaviour of the peat layer and underlying deposits under embankment loading. It also facilitates a more detailed evaluation of how each layer contributes to the overall settlement profile.

Fig. 6. Fixing spider Magnet at its respective depth.

Fig. 7. Installation of spider magnet extensometer.

3.5 Subsurface sensor module (SSM)

The instruments attached to the SSM are shown in Fig. 8. The SSM was installed within the peat layer at approximately mid-depth of the peat stratum. The sensor box incorporated a bi-axial tiltmeter, vibrating wire settlement gauge, vibrating wire piezometer, and earth pressure cells. The details of the SSM sensor models are shown in the Table 1. Fig. 9 shows all the sensors were pre-installed on the SSM and calibrate at laboratory with water prior to installation on site.

Fig. 10 presents a structured field procedure developed for installing subsurface instrumentation in peat soil. The installation location was carefully set out relative to the borehole alignment, after which a large-diameter steel casing was vertically pushed into the peat layer (Fig. 10(a)) to provide temporary lateral support and control ground disturbance during excavation and sensor placement.

Excavation within the casing was carried out to the target depth using mechanical and manual methods as appropriate (Fig. 10(b)), ensuring minimal disturbance to the surrounding peat. Fig. 10(c) depicts the SSM carefully lowered to the base of the excavation using secured support ropes. Instrument cables were bundled and supplemented with additional support lines, while excess cable length was deliberately introduced to accommodate ongoing ground settlement and prevent tensile damage to the instrumentation.

Table 1. Instrument in SSM.

Instrument	Sensor model
Bi-axial tiltmeter	RST In-Place MEMS Tilt Meter Model IC 6656
Vibrating wire liquid settlement gauge	RST SSVW105-300
Vibrating wire earth pressure cell	RST 9" Total Pressure Cell LTPTC09-V and LTPC09-V-M
Vibrating wire piezometer	RST VW2100-0.35

Following sensor placement, the excavation was backfilled using the original peat material (Fig. 10(d)), and the steel casing was gradually extracted to avoid imposing additional stresses on the installed instruments and cables (Fig. 10(e)). The cables were subsequently laid loosely to further reduce settlement-induced tension. The successful implementation of this procedure resulted in stable sensor installation and reliable long-term monitoring capability, demonstrating its applicability for subsurface instrumentation works in peat and other soft ground environments. Fig. 10(f) shows all the cables were connected to the data logger and liquid settlement gauge.

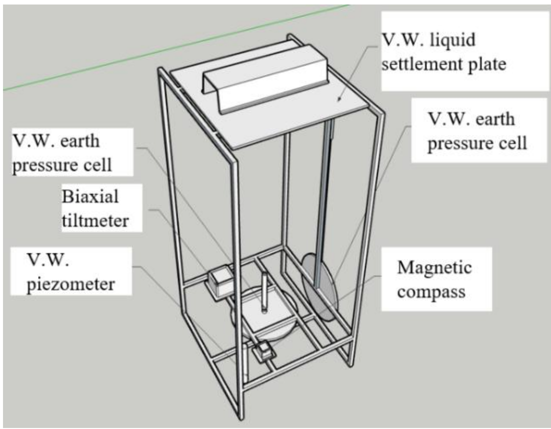

Fig. 8. Orientation of Instruments in SSM.

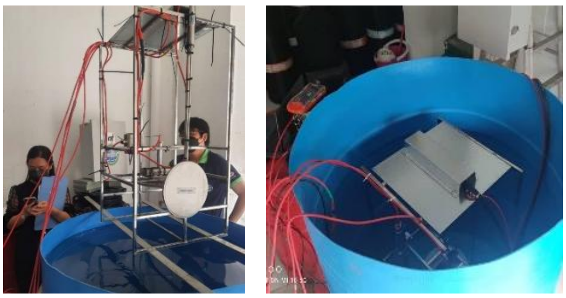

Fig. 9. The SSM was calibrated in laboratory.

4 Installation challenges in peat ground

Installation of geotechnical instruments in peat ground posed several challenges due to the extremely low shear strength, high compressibility, and fibrous structure of peat, which are known to complicate borehole stability and instrument survivability [1,2]. Borehole collapse, excessive deformation during installation, and risk of cable damage are commonly reported issues in peat environments [3].

Installation of geotechnical instruments in peat ground posed several challenges:

- Limited site access and sections that were initially inaccessible during the early stage of the project.
- Requires construction of proper access and working platform to allow machinery and manpower to carry out installation works.
- Space and access constraints: Soft peat limited the working platform and restricted the use of heavy machinery.
- Borehole and excavation stability: Peat exhibited a high tendency to collapse, necessitating the use of steel casings.
- Manual excavation requirements: Limited reach of excavation equipment required manual excavation within casings.
- Instrument alignment and orientation: Ensuring correct orientation of sensor boxes and inclinometers required additional guides and alignment tools.
- Risk of instrument and cable damage: Construction machinery and backfilling activities posed significant risks to exposed instruments and cables.

Mitigation measures included the use of steel casings, manual excavation and backfilling, cable trenching with secondary protection, and provision of excess cable length to accommodate post-installation settlement, in line with recommended practices for instrumentation in soft ground [6].


(a)


(b)


(c)


(d)


(e)

(f)

Fig. 10. SSM installation procedure: (a) pushing of steel casing into peat soil, (b) excavation of peat from casing, (c) lowering of sensor box, (d) back filling of peat, (e) extraction of casing, and (f) connection of sensor to data Logger.

5 Observed in-peat response under staged embankment loading

Fig. 11 presents the data collected long-term instrumentation monitoring results for a highway embankment constructed over peat along the centre line of the alignment. The monitoring period spans 25^{th} July 2023 to 20^{th} October 2025 and includes data from vibrating wire (VW) settlement sensors installed at various depths within the peat and underlying strata, together with records of embankment fill thickness.

The settlement records exhibit a progressive and staged response that closely follows the sequence of embankment construction. Each increment of fill placement triggered an immediate increase in vertical displacement, reflecting rapid compression of the highly porous peat structure and generation of excess pore water pressure. This initial response was followed by a gradual reduction in settlement rate during periods without additional loading, indicating dissipation of excess pore pressure and progressive transfer of effective stress to the peat skeleton.

Depth-dependent measurements demonstrate that compression occurred throughout the full thickness of the peat layer rather than being confined to the upper zone. Larger cumulative settlements recorded at deeper sensors confirm that the entire peat column participated in load transfer and deformation. This behaviour reflects the high compressibility and low permeability of fibrous peat, where drainage is fabric-controlled and consolidation proceeds slowly.

Importantly, measurable settlement continued even during extended periods of constant embankment height, demonstrating that secondary compression (creep) governs the long-term deformation behaviour of the peat deposit. The sustained settlement rate under nearly constant effective stress conditions highlights the rheological nature of organic soils, where particle rearrangement, fibre realignment, and progressive structural breakdown contribute to time-dependent strain accumulation.

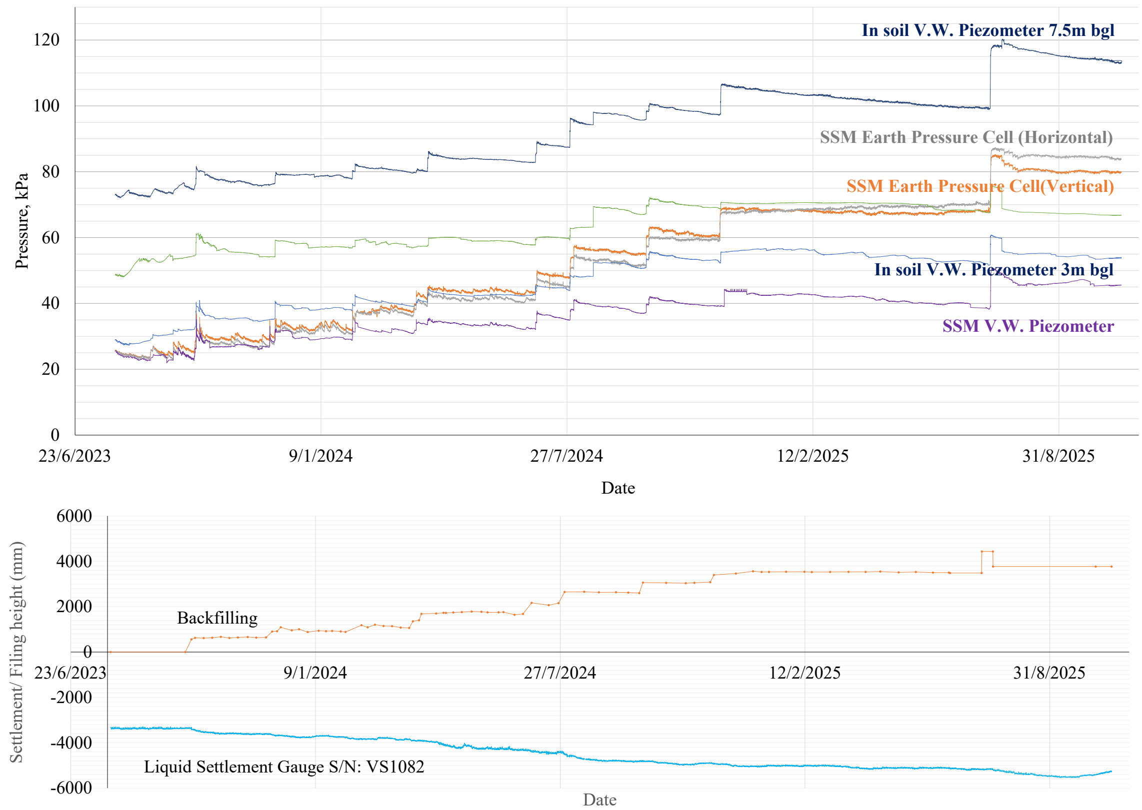

Fig. 11. Data recorded from SSM and in soil piezometer.

The close correlation between embankment fill thickness and incremental settlement confirms that applied loading is the primary driver of deformation. However, the delayed and prolonged settlement response indicates that primary consolidation and secondary compression act simultaneously under staged loading conditions. This combined mechanism underscores the necessity of incorporating creep effects into serviceability design and validating performance through long-term field monitoring.

The embankment fill thickness data show controlled, staged construction throughout the monitoring period. The close correlation between increases in fill thickness and corresponding settlement increments demonstrates that embankment loading is the primary driver of peat compression. The delayed settlement response relative to fill placement suggests low permeability and slow dissipation of excess pore water pressure within the peat, consistent with its organic microstructure and fabric-controlled drainage behaviour [5, 8].

Overall, the instrumentation data confirm that embankment construction over peat is governed by large immediate compression followed by prolonged creep deformation. Even as primary consolidation approaches completion, settlement continues at a reduced but persistent rate.

Depth-dependent settlement measurements confirm that compression occurred throughout the full thickness of the peat layer rather than being confined to near-surface zones, indicating effective stress increase across the entire peat column. This time-dependent response is consistent with the rheological characteristics of fibrous peat, where particle rearrangement and structural breakdown contribute to sustained deformation [7, 8, 9].

Fig. 12 illustrates the evolution of cumulative lateral displacement profiles obtained from Inclinometer INC 01 along the embankment centre line. The displacement–depth curves reveal a progressive outward movement concentrated primarily within the upper 8–10 m of the subsurface profile, corresponding to the identified peat layer. The maximum lateral displacement consistently occurred between approximately 3 m and 7 m depth, indicating that shear deformation was most pronounced within the highly compressible organic stratum, which is typical of embankments constructed over peat deposits [2, 11].

Below approximately 10 m depth, lateral displacement reduces markedly and approaches near-zero values, confirming that the underlying stiffer mineral soil acts as a competent restraining layer. The negligible movement at depth also demonstrates that the inclinometer casing was adequately anchored, ensuring that measured displacements represent true ground response rather than instrument instability.

The temporal progression of displacement profiles indicates incremental lateral spreading associated with each stage of embankment loading. Rather than exhibiting abrupt curvature or a distinct inflection point indicative of deep-seated rotational failure, the profiles display smooth and continuous deformation. This pattern suggests distributed shear strain within the peat layer, which is characteristic of soft organic foundations subjected to gradual loading and time-dependent creep deformation [2, 12]. The absence of a well-defined shear plane confirms that deformation was governed by ductile compression and lateral squeezing rather than global instability.

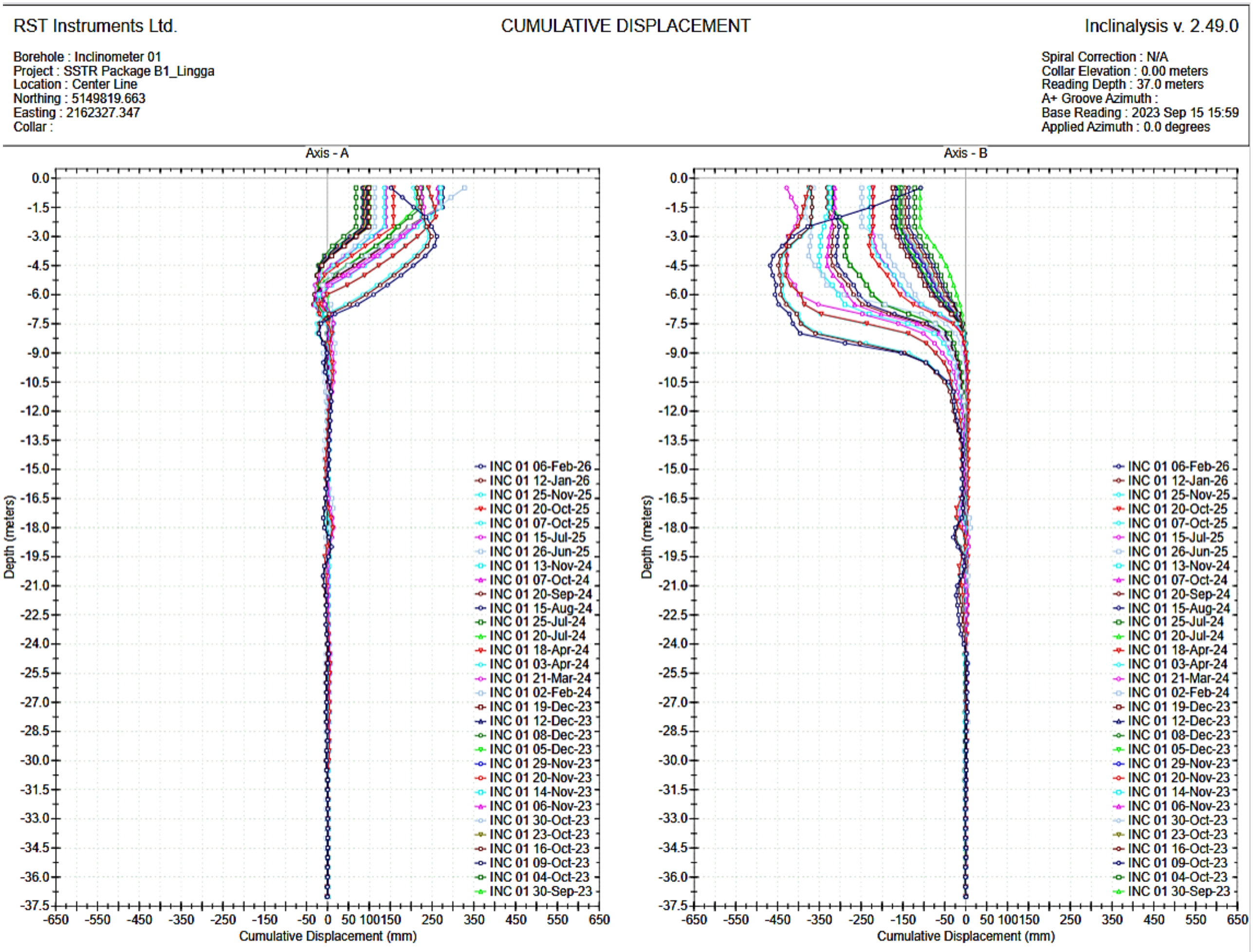

Fig. 12. Inclinometer data at centre line.

The comparable trends observed in both Axis A and Axis B directions further indicate that lateral movement was predominantly controlled by embankment loading rather than localized construction disturbance. The progressive yet controlled nature of displacement throughout the monitoring period demonstrates that staged construction effectively limited rapid shear mobilisation within the peat deposit, consistent with established performance-based monitoring approaches for embankments on soft ground [6,11].

From a stability perspective, the inclinometer data confirm that lateral deformation remained confined to the peat layer and did not propagate into the underlying competent strata. This behaviour aligns with reported field observations of embankments constructed over highly compressible organic soils, where vertical compression and excess pore pressure generation induce outward lateral strain without triggering deep foundation failure [2,11]. The monitoring results therefore validate the effectiveness of staged loading as a risk mitigation measure for embankment construction on peat.

6 Monitoring challenges

Several challenges were encountered during the monitoring phase:

- Correlation of instrumentation data with site-based monitoring systems such as rod settlement gauges.
- Need for close coordination between construction activities and monitoring schedules.
- Limited data storage capacity and high power consumption of data loggers due to frequent data acquisition and high ambient temperatures.
- Several instruments were damaged due to ongoing construction activities, including heavy machinery movement and uncontrolled backfilling operations.
- Occasional data gaps occurred due to power supply interruptions and sensor malfunction, highlighting the need for redundant instrumentation and regular data validation.
- Effective communication among the teams was critical to ensure continuity and reliability of data.

7 Conclusions

This study demonstrates that in-peat geomechanical monitoring under staged road embankment construction provides critical insight into time-dependent soil behaviour that cannot be reliably captured through design assumptions alone. The monitoring results confirmed that peat exhibits rapid initial settlement and excess pore water pressure generation under embankment loading, followed by prolonged time-dependent deformation dominated by secondary compression, consistent with established peat behaviour reported in the literature [2,7].

From an instrumentation perspective, the project highlights the necessity for robust installation techniques, redundancy in sensor systems, and adequate protection of instruments and cables in highly compressible peat ground. These requirements are in line with recommended practices for geotechnical instrumentation and long-term monitoring in soft soil environments [3,6].

The findings support the use of staged embankment construction combined with comprehensive geomechanical monitoring as an effective risk mitigation strategy for infrastructure development on peat and other soft soils [4,6]. The integration of multi-sensor subsurface monitoring demonstrated that reliable interpretation of peat behaviour requires simultaneous measurement of stress, pore pressure, and deformation. Future works should focus on coupling field data with numerical modelling to improve predictive capability for peat embankment performance.

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