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Embankments on Peat: Evaluating Rigid Inclusions and Load Transfer Platform with High Stiffness Geotextile Reinforcement

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ABSTRACT: Rigid inclusion is a well-established pile-supported embankment method for a construction on soft soils, designed to transfer embankment loads to competent underlying layers rather than solely enhancing the properties of the soft soil itself. Among rigid inclusions, mortar column inclusion (MCI) is widely utilized in combination with a load transfer platform (LTP) to support embankments. While extensive researches on pile-supported embankment have majorly investigated the application in soft cohesive soils, its application on peat is still underexplored. This article presents the evaluation of a pile-supported embankment system on peat in Padang Pariaman, Indonesia, where a trial embankment of 8-m high was built on MCI piles under a LTP layer with high stiffness geotextile-reinforcement. Field instrumentation—including vibrating wire pressure cells, fiber optic sensors, strain gauges, piezometers, and settlement profilers—was employed to monitor ground movements, MCI displacements, and material stresses. Numerical verification using Finite Element Method (FEM) Plaxis 2D and 3D models, simulating high-moisture and high-void-ratio peat with the Soft Soil Creep (SSC) model under drained conditions, revealed minimum excess pore pressure during loading and no mobilization of skin friction on MCI piles, distinguishing their load transfer mechanisms from those in soft cohesive soils. Comprehensive field monitoring revealed insights into load transfer mechanisms, deformation patterns, and MCI performance, which were further validated through finite element analyses (FEAs). The agreement between field and FEA results highlights the method's effectiveness to build embankment on peat.

KEYWORDS: Embankment, geotextile reinforcement, load transfer mechanism, mortar column inclusion, peat, rigid inclusion.

1 INTRODUCTION

Embankment construction is typically regarded as the most cost-effective method in infrastructure development for roadways, flood control barriers, and runways. If embankments are located adjacent to wetlands, riverbanks, or other challenging terrains, issues frequently occur. In these regions, the soils commonly contain highly organic soil and peat. These soils are highly compressible with inadequate bearing capacity. The major problem in building an embankment on highly organic soil or peat is to offer an alternative to the current regular technique. Long-term settlement may be effectively reduced using deep foundations. Nevertheless, this is expensive, making pre-loading and fast consolidation perhaps the most economical options. This method demands substantial construction duration. Additionally, there are further issues regarding long-term settlement, particularly pertaining to the secondary compression of the organic soil or peat.

Peat enhancement techniques have been evaluated by numerous investigators (e.g., Wissmann et al., 2000; Fox & Edil, 2000; Allgood et al., 2001; Axelsson et al., 2002; Winter et al., 2005); Carchedi et al., 2006; Black et al., 2007; and Deboucha et al., 2008). These evaluations included ground enhancement in particular constructions, including railroad, runway, building structure, and road embankment built on peat. In more recent year, investigations were performed to study the characteristics of fibrous tropical peat where the ground was reinforced using cement column (i.e., Hashim & Islam, 2008; and Kazemian & Huat, 2009) studied compressibility. Peat improvement successfully provided the necessary bearing capacity for the design load (Huat et al., 2014). Nevertheless, the pile-supported method exhibited no significant settlement throughout the years.

The efficacy of pile-supported embankment utilizing LTP with geotextile has been examined by Hewlett & Randolph (1988). Afterward, many investigators have attempted to study this topic (e.g., Low et al., 1994; Yun-min et al., 2008; van Eekelen et al., 2012; Lu & Miao, 2015; Briançon & Simon, 2017; and Al-Naddaf et al., 2019). Their researches mostly concentrated on compressible soft soils, geotextile forces, and arching mechanisms. The authors recognize that the performance of pile-supported embankments on peat or organic soil has been assessed less thoroughly than on soft cohesive soils.

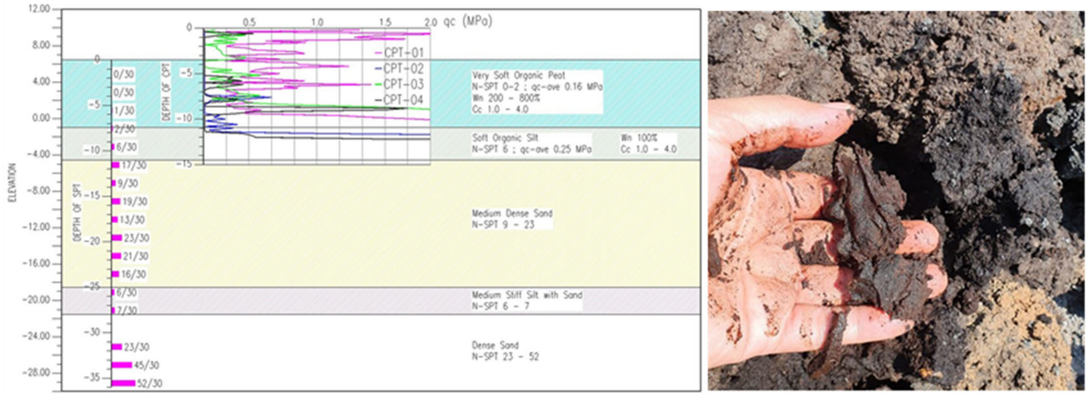
This paper briefly reports the use of mortar column inclusion (MCI) combined with high-stiffness geotextile-reinforced LTP in a full-scale field trial conducted over peatland in West Sumatra, Indonesia. In Indonesia, MCI is also known as Inklusi Kolom Mortar (IKM). In general term, MCI is also known as rigid inclusion. The embankment was comprehensively instrumented and supported by numerical modeling to evaluate deformation and load distribution mechanisms. Interested readers are suggested to read Himawan et al. (2024) for the details of this trial embankment study.

2 TRIAL EMBANKMENT

A trial embankment was built in Padang Pariaman, West Sumatera, Indonesia, as a section of Trans-Sumatera Toll Road. The site lies on a hemic peat deposit, as confirmed by geotechnical investigations (Figure 1).

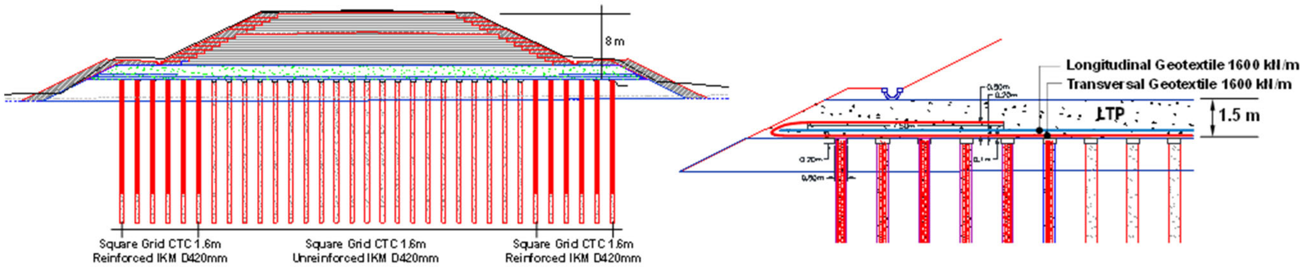
The embankment spans 140-m long and 50-m wide, with a design height of 8 m. The foundation system utilized mortar column inclusions (MCI) installed in a 1.6 m grid. Each IKM had a diameter of 420 mm and penetrated depths ranging from 15 m to 17 m depending on installation resistance (Figure 2A).

A load transfer platform (LTP) made from 1.5-m thick granular was built over the pile heads and reinforced in two perpendicular directions using high stiffness geotextiles of 1,600 kN/m tensile strength. Pile caps and reinforcement cages were added to the outer piles to enhance lateral resistance (Figure 2B). Geotextiles installation and LTP construction are presented in Figure 3.



(A) (B)

Figure 1. (A) Soil profile & (B) hemic peat deposit in trial embankment site (Himawan et al., 2024).



(A) (B)

Figure 2. (A) Trial embankment cross-section & (B) geotextile configuration in the LTP (Himawan et al., 2024).

3 FIELD INSTRUMENTATION

The field instrumentation aimed to capture load distribution, deformation, and pore water response. Earth pressure cells (VWEPCs) were placed on pile caps in the LTP to assess vertical stresses (Figure 4).

Vibrating wire strain gauges (VWSGs) were embedded within selected IKMs and geotextile layers (Figure 5). In addition, Brillouin optical time-domain analysis (BOTDA) fibers were placed on the geotextile for distributed strain sensing (Figure 6).

Figure 3. Geotextile installation and LTP construction as part of trial embankment (Himawan et al., 2024).

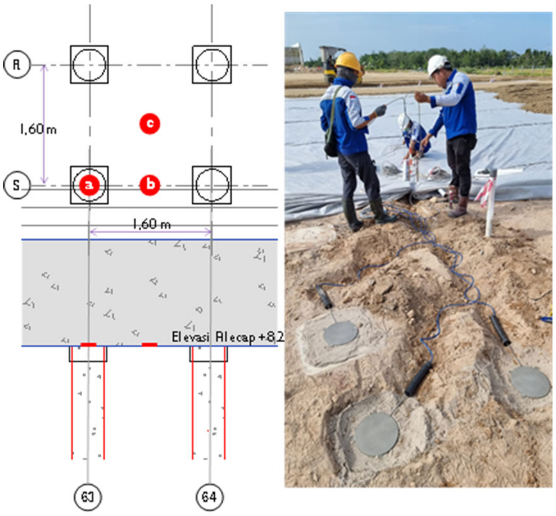


Figure 4. VWEPCs in the IKM columns (Himawan et al., 2024).

Figure 5. VWSG sensors in the reinforced IKM columns (Himawan et al., 2024).

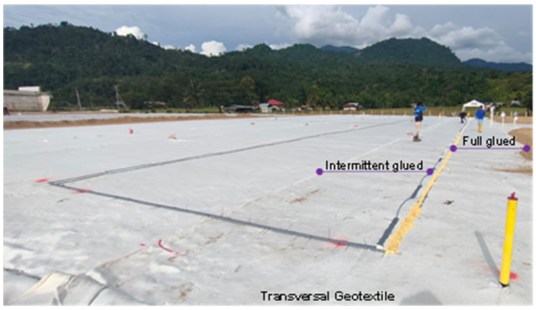


Figure 6. BOTDA module on the geotextile (Himawan et al., 2024).

Inclinometers were positioned both around the embankment and inside IKMs to assess lateral movement (Figure 7). The ground settlement was monitored using settlement profilers, magnetic extensometers, and settlement plates placed beneath the embankment (Figure 8).

Figure 7. Inclinometer installation (Himawan et al., 2024).

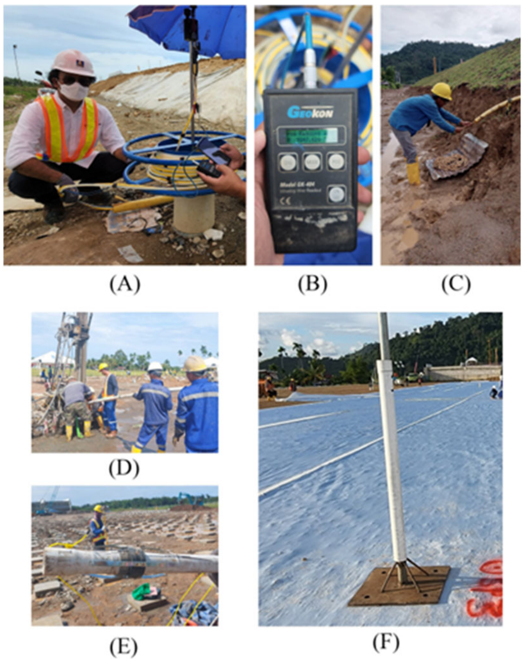


Figure 8. (A–C) Settlement profiler system, (D–E) magnetic extensometer, and (F) settlement plate (Himawan et al., 2024).

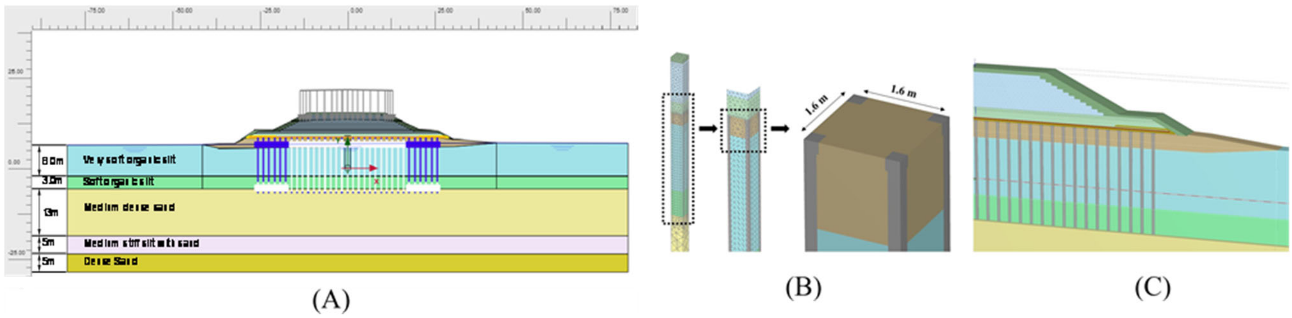


Figure 9. (A) 2D plane strain model, (B) a tributary load area in a 3D IKM column, & (C) trial embankment 3D model (Himawan et al., 2024).

Figure 10. The maximum height of trial embankment (Himawan et al., 2024).

4 FINITE ELEMENT NUMERICAL MODELING

Finite element (FE) numerical modeling was conducted using Plaxis 2D and 3D to analyze the load transfer mechanisms and verify field results. The models considered the sequential construction stages and detailed soil stratigraphy (Figure 9).

The peat and organic silt layers were modeled using the Soft Soil Creep (SSC), accounting for both primary and secondary compressibility. The medium dense sand layer employed using Mohr-Coulomb model, while the deeper silt layer was modeled using the Hardening Soil (HS). Table 1 shows soil parameters for this study.

IKMs were represented using embedded beam row (EBR) elements, providing realistic soil-structure interaction. The high-strength geotextile was simulated by using an anisotropic geogrid element with direction-dependent stiffness and strength. Calibration of stiffness and strength was based on maintaining strain below 5% under operational loads.

5 FIELD MONITORING RESULTS

Monitoring commenced from the initial filling phase and continued beyond the full embankment height achieved in April 2022 (Figure 10). Pore pressure responses in the peat were minimal, rising only 2–10 kPa despite the substantial fill. Vertical settlement profiles indicated rigid body displacement patterns shortly after completion, with peak settlements reaching 31.9 cm at the center and 19.6 cm near the edge (Figure 11). Extensometers in the peat layer recorded up to 21.2 cm of movement (Figure 12). Tensile strains in the geotextile remained well within allowable limits. BOTDA detected strains up to 1,269 με (Figure 13), while VWSGs recorded values up to 2,017 με. Differences in sensor placement and surrounding soil conditions accounted for discrepancies between readings.

6 LOAD TRANSFER MECHANISM

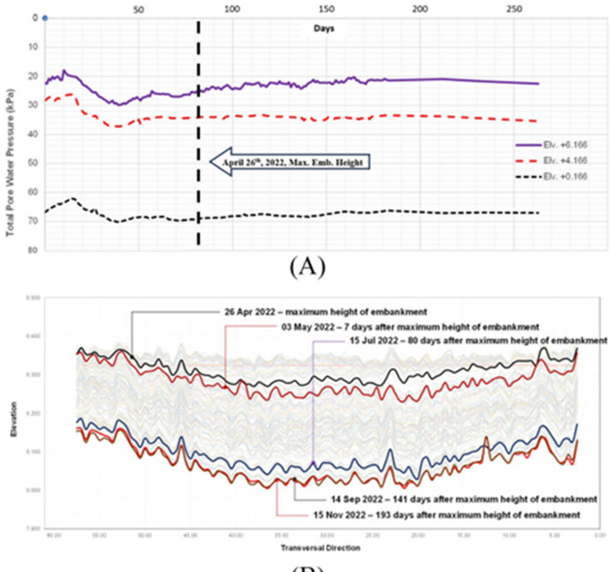
Piezometer and pressure cell data confirmed that the IKM columns largely sustained the embankment load. Minimum embankment load was transferred to the underlying peat. Earth pressure cells recorded maximum vertical stresses at the IKM heads (up to 532 kPa), significantly higher than between the piles (Figure 14).

The geotextile effectively contributed to load distribution, bearing tension between piles and aiding arching action. Numerical models supported these findings, predicting consistent stress patterns and settlement magnitudes with field data (Figure 15).

Table 1. Soil parameter for FE analysis

Layer	1. Very soft organic silt	2. Soft organic silt	3. Med. dense sand	4. Med. stiff silt with sand	Unit
Model of Material	SSC	SSC	MC	HS	—
Type of Drainage	Undr. A	Undr. A	Dr.	Undr. A	—
Unsat. Unit weight	11.5	13	18	16	kN/m^3
Sat. Unit weight	12	13	18	16	kN/m^3
Porosity	0.88	0.71	0.33	0.61	—
Void ratio	7.32	2.50	0.50	1.56	—
λ^*	0.22	0.12	—	—	—
κ^*	0.019	0.024	—	—	—
E'	—	—	20,000	—	kN/m^2
C_c	4.0	1	—	0.3	—
C_s	0.70	0.1		0.03	
C_α	0.16	0.045	—	—	—
Poisson's ratio ν ur	0.15	0.15	—	—	—
Poisson's ratio ν	—	—	0.3	0.2	—
c'	4	4	2	12	kN/m^2
ϕ'	13	19	32	29	°
Perm. k_x	0.06	0.06	0.1206	0.0475	m/day
Perm. k_y	0.06	0.03	0.1206	0.0475	m/day
Change in perm., Ck	3.75	1.25	—	1.25	—

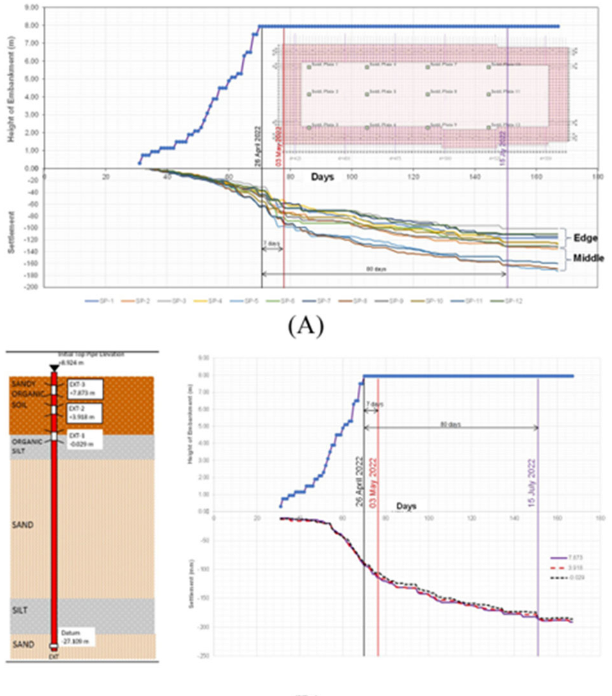
Long-term settlement beneath the embankment was attributed to consolidation in deeper, stiffer layers beneath the peat. FE analysis identified compressive behavior as well as excess pore water pressure dissipation in these zones (Figure 16).



(A)

(B)

Figure 11. (A) Pore water pressure & (B) settlement profiler results (Himawan et al., 2024).



(A)

(B)

Figure 12. (A) Settlement plate & (B) extensometer results (Himawan et al., 2024).

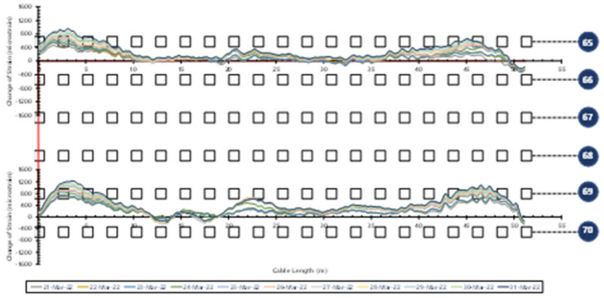
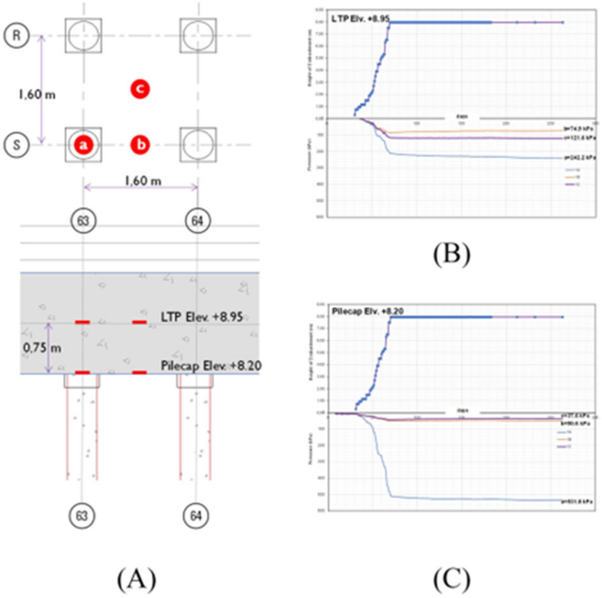


Figure 13. BOTDA geotextile strain (Himawan et al., 2024).



(A)

(B)

(C)

Figure 14. VWEPC: (A) configuration & (B, C) readings from 2 measurement points (Himawan et al., 2024).

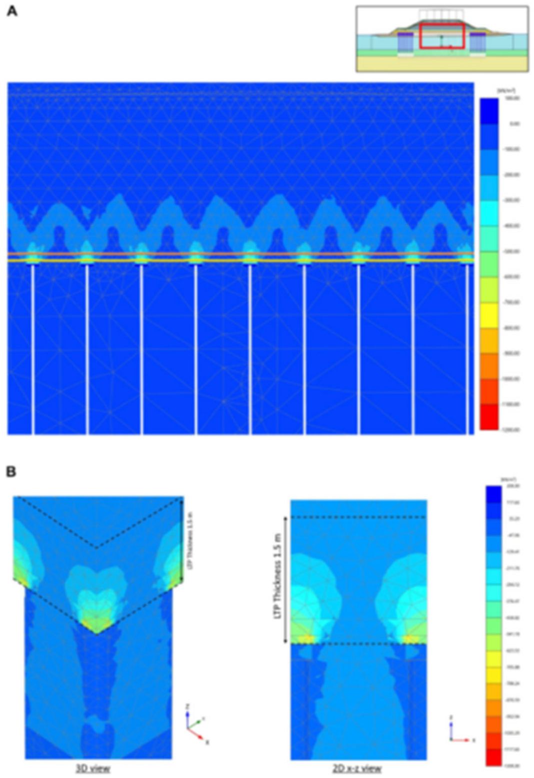


Figure 15. Principal effective stress directions post-consolidation: (A) 2D & (B) 3D views (Himawan et al., 2024).

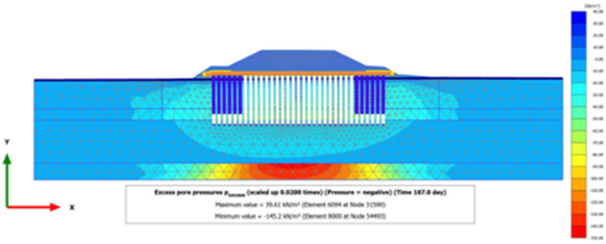


Figure 16. Excess pore water pressure in the sand and silt layers attributed to the embankment load (Himawan et al., 2024).

7 CONCLUSIONS

This study confirms the effectiveness of combining mortar column inclusions and geotextile-reinforced LTP for supporting embankments over peat. The system enabled efficient load transfer, minimized settlement, and maintained structural stability.

Field instrumentation captured key aspects of embankment behavior, which were further verified through robust numerical simulations. The arching mechanism and tensile contribution of the geotextile were central to the success of the system.

The proposed method offers a viable and efficient alternative for embankment construction on peat, with potential applications in other regions facing similar geotechnical challenges. Interested readers are referred to Himawan et al. (2024) for further details of this trial embankment study.

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