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SOILwrap: An Innovative Confined Embankment System using Wrap-around Technique for Peat Soils

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ABSTRACT

Peat soils are known for their high-water content, low shear strength, and high compressibility, posing significant challenges for infrastructure construction such as road embankments. With the rapid development across Malaysia and increasing scarcity of suitable land, road construction over peatlands has become more common. Traditional ground improvement methods are often costly and environmentally unsustainable, particularly with the large-scale disposal of excavated peat. This study introduces a novel SOILwrap concept that integrates wraparound geotextile reinforcement filled with reused peat soil, aimed at enhancing the stability and settlement performance of road embankments on soft ground. The geotextile performs multiple functions as reinforcement, filtration, drainage, and separation ensuring a confined, stabilized embankment layer. Three conceptual models were proposed targeting embankment fill, subgrade improvement, and a combined system. The comparative benefits of wraparound over planar reinforcement in terms of bearing capacity, land use efficiency, and settlement reduction are discussed. Preliminary findings suggest that the SOILwrap technique has potential as a sustainable approach for road embankment development on challenging peat ground.

Keywords: Reuse peat soil, Road embankment reinforcement, Wraparound geotextile

1. BACKGROUND OF STUDY

1.1 Peatland in Malaysia

Peat soils are formed in wetland environments when the dead plant materials accumulate and partially decompose over time due to a lack of oxygen from inside [1]. The peat found in Malaysia is classified as tropical peat, it tends to be more heterogeneous and is made up largely of partially decomposed woody debris, such as tree trunks, branches, and coarse roots, embedded in a dark brown organic matrix [2]. Peat and other soft soils are common within the Quaternary deposits that dominate the coastal plains of Malaysia. These tropical peatlands are usually located in poorly drained low-lying areas, including river basins and estuaries. Most of these peatlands are classified as peat swamp forests, although areas with frequent inundation often support sedges, grasses, or shrubs as surface vegetation.

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In Malaysia, approximately 8% amounts to about 2,457,730 ha of the 32,975,800 ha of the total land area covered with peat as shown in Figure 1 [3]. The peatland area is spread over 3 main areas, in Peninsular Malaysia (642,918 ha), Sabah (116,965 ha) and Sarawak (1,697,847 ha). Peat soil is characterised by a high organic content, high water content, large void ratio, high compressibility, and low bearing capacity [4]. Most of the time, this behaviour makes it extremely.

Inaccessible in construction, particularly when there is alternative land available. However, the consequent rapid development has resulted in large-scale infrastructure developments. The lack of suitable land hinders these developments; consequently, the areas with poor ground conditions such as soft peat soil are being considered for the infrastructure works, for example the road construction [2].

Figure 1. Peat Soils areas in Malaysia. [5]

1.2 Road Embankment

In road construction, the pavement system typically consists of multiple layers designed to distribute traffic loads safely into the ground. Figure 2 shows the general road components. The subgrade is the bottom-most layer, usually formed by the existing natural ground or compacted soil as foundational support. Above subgrade lies the subbase and base course which further distribute the load from the pavement.

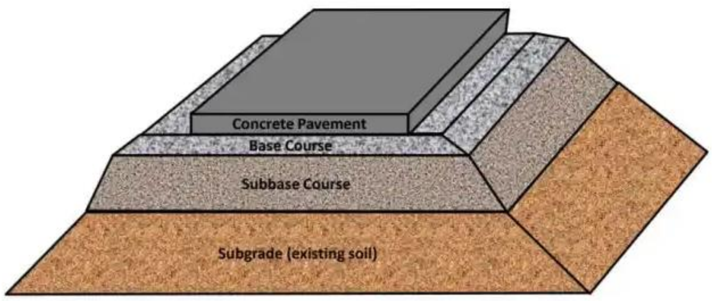


Figure 2. General road components [6]

When the natural ground is uneven or lies below the design elevation, a road embankment is constructed using selected fill materials to raise the road's elevation relative to the surrounding area. The construction involves two essential construction components namely fill and foundation [7]. Embankment fill is defined as selected fill placed and compacted with the required engineering performance to comply with respective standards. The characteristics of fill material, the degree of compaction and the factors affecting the workability are considered for best results in the construction of embankment fill. Common fill materials are soil, natural aggregates, and lightweight filling material. These fill materials must possess the required characteristics such as proper drainage to prevent saturation, good performance in compaction properties, compressibility, and shear strength. While the foundation serves as a placement for embankment structure. [8]

1.3 Wraparound Geotextile Reinforcement

Geosynthetic materials used is one of the ways for soil improvement at the base of the embankment to strengthen the soil before the construction work [9]. Among the various types of geosynthetic materials available for soil improvement, geotextiles are one of the most widely used. The efficiency of geotextile reinforcement in increasing shear strength and decreasing compressibility has gained significant attention in enhancing shear strength and reducing compressibility, improving the soil's capacity to withstand vertical loads without excessive deformation [10]. With geotextile, the road performance will significantly improve by reducing the vertical settlement and increasing the resistance to horizontal displacement, extended pavement service life, and reduced foundation thickness to withstand repetitive load [11].

The conventional soil reinforcement method consisted of single or multiple horizontal layer(s) placed in horizontally planar form [12]. Wraparound reinforcement is a technique where the ends of the reinforcement layer are folded along the longitudinal axis [13]. These folded ends also called wraparound ends, which form an enclosed system, completely surround the soil and prevent particle movement through the reinforcement layers [14]. In contrast to the planar geosynthetic reinforced model, the failure pattern of the wraparound geosynthetic reinforced foundation soil is shown in Figure 3. The wraparound geotextile reinforcement approach can have an increased ultimate bearing capacity in four zones of change. In Zone I, the soil moves down and pushes the adjacent soil to the sides, which is similar to normal unreinforced soil. Zone II, the soil tends to move horizontally to the sides, the wraparound geosynthetic helps stop it by giving more shear resistance compared to the planar reinforcement. Zone III provides the passive resistance by confining the soil and keeps it from moving. Zone IV is normal unreinforced soil below the geosynthetic layer. In context of these mechanisms, the wraparound ends of the geosynthetic offer passive resistance from soil confinement as shown in the zoomed view and Figure 3 (a), as well as shear resistance at the soil-geosynthetic interface. This increases the ultimate bearing capacity of wraparound reinforced model foundations when compared to planar reinforced foundations [15].

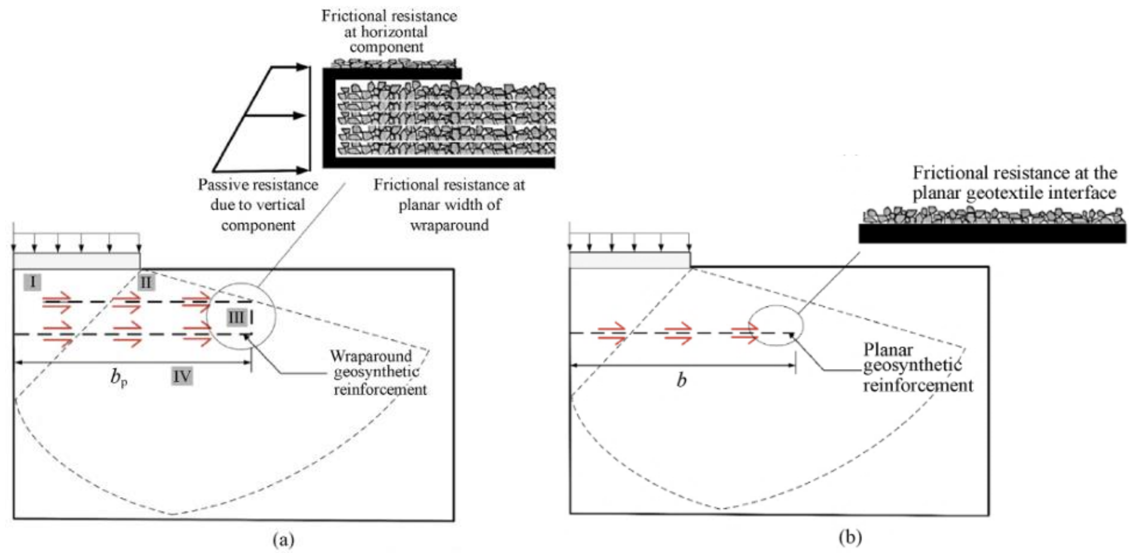


Figure 3. A schematic mechanism of failure pattern of reinforced model for (a) wraparound ends and (b) planar reinforcement. [13]

Table 1 shows the comparison between planar and wraparound ends reinforcement with unreinforced method from the experimental results by various researchers. The studies show the wraparound end of geotextile technique was introduced to increase the load-bearing capacity of soils, less settlement, and less occupied land used.

Table 1 Comparison between planar and wraparound ends reinforcement

Criteria	Conventional Planar Reinforcement	Wraparound Reinforcement	References
Bearing Capacity Improvement	increase was about 45%	increase was up to 120%	Aria *et al.* [14]
	12% - 30%	65% - 80%	Kazi *et al.* [16]
Settlement Reduction	41% less settlement	45% less settlement	Raja & Shukla [13]
Land Use Efficiency	fully wrapped reinforcement requires approximately 50% less occupied land width than planar single-layer for same amount of geotextile		

The wraparound geotextile reinforcement technique has demonstrated superior performance in multiple aspects. While planar reinforcement improved bearing capacity by approximately 12-30%, but recorded improvement up to 45% in some cases, the wraparound method achieved more significant bearing capacity improvement of average 65-80% up to 120%, nearly doubling the load-bearing strength. Similarly, wraparound reinforcement also showed comparable or slightly better settlement reduction, with up to 45% less settlement compared to 41% in planar systems. More significantly, the wraparound system offers a clear advantage in land use efficiency. Because it confines soil in a fully enclosed loop, the same volume of geotextile can provide structural stability in a much narrower and reducing required land width by up to 50% compared to planar arrangements. This makes the wraparound technique particularly attractive for applications in roadside embankment projects, where lateral expansion is limited.

2. TYPES OF PEAT SOIL

The term peat often referred to as "organic soil", is a naturally occurring material composed of plant remains consist of undecomposed, partially decomposed, and highly decomposed [3]. Peat is formed when organic matter accumulates more quickly than it humifies. It is distinct from other organic soils by its high organic content (> 75%) under MSCS standards. Peat soils are generally classified based on fiber content, degree of humification, organic content, and other physical properties. The classification helps in identifying peat types such as fibric, hemic, and sapric peat, which differ in fiber content and decomposition level. Degree of humification represents the state of decomposition or decay of the organic plant remains from which the peat or organic soil was originally formed [17]. The von Post scale is a recommended field classification system to specify the decomposition or humification (H1 to H10) of peat soil sample on site, it refers to the appearance of soil water and the peat that escaped between fingers upon squeeing in the hand [18]. Peat classified as H1–H3 is fibric, showing minimal decomposition, light coloration, and identifiable plant fragments. As decomposition increases, peat progresses through hemic stages (H4 H6) to sapric (H7–H10), where it becomes highly decomposed, pasty, and structureless, with very dark water discharge and nearly complete breakdown of organic matter. Fiber content is the primary indicator of degree of decomposition. Fibric peat (with > 67% fibers under ASTM standards) is the least decomposed and typically retains identifiable plant structures. As decomposition increases, fiber content decreases, leading to hemic (with 33% < fibers < 67%) or sapric peat (with < 33% fibers). High fibre content contributes to high water absorption capacity [19] where lower fibre content results in higher specific gravity values [20]. Fibric peat retains more water due to its open structure and high void ratio while as decomposition increases and the structure collapses, water retention reduces as sapric peat exhibits lower water absorbency.

A systematic review conducted by Pakir *et al.* [21] highlighted that the basic properties of peat soils in Malaysia exhibit highly variable engineering properties, primarily due to their organic and fibrous nature. The degree of decomposition ranges between H3 and H7, indicating moderately to highly decomposed peat. The moisture content of Malaysian peat is extremely high, varying from 230.89% to 2683%, which is directly influenced by its organic content (56.1% to 99.42%) and fibre content (5.67% to 80%). Higher fibre and organic contents generally lead to greater water retention. In terms of inorganic content, the ash content of Malaysian peat ranges from 3.65% to 7.23%, while its specific gravity is relatively low, between 0.69 and 1.39, demonstrating the prevalence of small organic materials. The liquid limit of peat is also notably high, between 136.11% and 309%, indicating its very high plasticity, although the plastic limit is typically non-plastic or difficult to determine due to the interference of fibrous material. Besides, Malaysian peat soils are highly acidic, with pH values ranging from 3.00 to 4.15, and it possess relatively high permeability, measured around 0.89 m/day, which facilitates drainage but can also lead to instability under loading.

3. ROAD CONSTRUCTION OVER PEAT SOILS

In geotechnical engineering, peat is classified as an extremely soft and problematic soil [22]. The high-water content in peat soils is attributed to the very loose and hollow nature of the soil fibres, low bulk density, high buoyancy, and high pore volume [23]. A large void ratio is observed, making the peat soil very soft, compressible, and sensitive from a construction perspective [24], affecting the low shear strength and high compressibility [25]. The low shear strength and high compressibility limits the soil's ability to resist imposed stresses, potentially leading to bearing capacity failure and large deformation under the structure's load [26]. It also poses challenges for the stability of cuts and slopes, especially during deep excavation when groundwater is high [27], [28]. Moreover, the low bearing capacity of peat soil is influenced by factors such as the water table and the presence of subsurface woody debris [28]. Due to its low bearing capacity, peat cannot support the weight of structures, even small ones [29]. Most of the time, long-term consolidation settlement happens when subjected to a moderate load [30]. This settlement can continue for many years [31]. The excessive settlement is a primary cause of structural failure on peat. Figures 4 and 5 show the example of road pavement failure over peat soils.

Figure 4. Damage to the road pavement due to surrounding peat area with ground water lowering. [3]

Figure 5. Long-term non-uniform settlement of road on peat ground. [31]

When loaded by an embankment or soil fill, the soft and waterlogged peat soil takes a long time to settle. In this scenario, even if the soils do not fail by displacement, the embankment will continue to settle into the ground below. Figure 6 illustrated the depression of additional fill into the embankment which leads to further settlement and make the condition even worse. The road failure issue typically arises from two main structural components which are the embankment fill and the subgrade. Embankment often related to issues from poor drainage, which causes water to accumulate within the fill material. This trapped water increases the overall self-weight of the embankment, leading to additional loading on the subgrade. Overload of the embankment fill also leads to the issue. Meanwhile, subgrade problems occur when the natural ground is soft, highly compressible, and with low shear strength which are common in peat soils. Peat soils are unable to adequately support imposed loads, resulting in excessive deformation and differential settlement. A key consideration is that achieving zero settlement is generally unrealistic, especially over soft ground. Instead, the aim is to minimize and control settlement during the design stage, ensuring it stays within the allowable settlement in terms of serviceability limits both as a function of time. In Malaysia, a maximum of 250 mm over the first 5 years post construction years and maximum differential settlement of 200 mm within 100 m remote from structures were specified in the guidelines for construction on peat and organic soils in Malaysia [3].

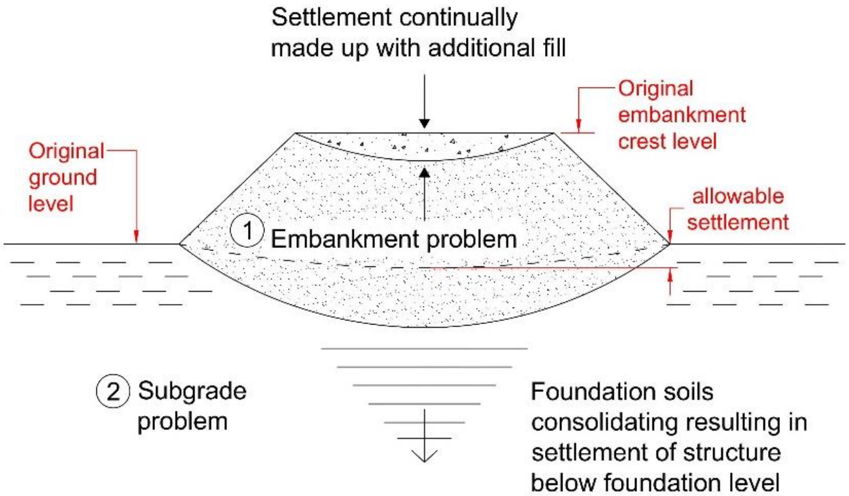


Figure 6. Long term settlement problem in soft ground conditions, adopted from [32]

In recent years, road construction on soft soil has become increasingly common in Malaysia due to rapid development and the lack of suitable land for development. As a result, soft soils have been considered for infrastructure projects. Conventionally, the construction on peat involves two main approaches: peat removal and peat left in place [4]. Peat removal includes avoidance, excavation, replacement, and displacement of peat before construction. In contrast, leaving peat in place avoids bulk earthworks and uses methods like consolidation acceleration by PVDs, ground improvement, load modification, stabilization, and piling. In certain cases, the effectiveness of conventional ground improvement method severely limits due to heavy machinery required. The heavy construction machinery frequently sinks into the ground especially with the presence of deep peat deposits. Moreover, the replacement method will make it challenging for the disposal of peat soils on an extensive level in the future [30]. Disposal of poor-quality surplus material can be regarded as one of the most significant environmental problems in construction. As in this study, an alternative is to reusing peat soil through geotextile stabilization or incorporation into embankment fill and try to minimize the large disposal issues.

Conventional approaches to peat treatment, while widely adopted but remain resource-intensive and environmentally unsustainable due to high disposal volumes, imported material demand, and long-term settlement risks. A summary comparison is presented in Table 2, contrasting existing peat treatment methods with the proposed *SOILwrap* system.

Table 2 Comparison between conventional peat treatment methods and *SOILwrap*

Aspect	**Conventional Peat Treatment Methods**	***SOILwrap* System**
Soil Usage	Requires removal of peat and replacement with imported fill, lead to large-scale disposal of peat soil.	Reuses on-site excavated peat, minimizing disposal and external material demand.
Ground Improvement	Methods such as PVD, preloading, cement/lime stabilization cause high machinery requirement, soil chemistry alteration.	Lightweight geotextile system with minimal machinery and no chemical additives.
Environmental & Sustainability	Needs truck hauling for disposal and imported fill hence more time, cost, fuel, emissions.	Reuses peat on site hence less hauling, faster work, lower cost and emissions.

4. CONCEPT OF *SOILwrap*

The wraparound geotextile reinforcement technique has found wide application in retaining walls [33-34] and embankments [35-38]. It has demonstrated improved stability, resilience under seismic loading, and efficiency compared to conventional designs, with successful applications in railway networks and flood protection projects in Bangladesh [39]. However, most of these applications rely on imported engineered fill materials, while the potential to reuse on-site excavated soils such as peat within wraparound systems remains underexplored.

The concept of *SOILwrap* is to explore an alternative to embankment fill construction by using layered wraparound geotextile reinforcement filled in with reused excavated peat soil on site. As illustrated in Figure 7, the *SOILwrap* system integrates multiple geotextile functions as separation, filtration, drainage, and reinforcement which to enhance stability, control settlement. The separation function is fundamental, preventing the intermixing of the peat foundation and the peat-sand fill above. Filtration is another key function. The non-woven geotextile allows vertical water flow through the embankment layers while retaining fine soil particles, as shown by the downward arrows in the figure. This prevents soil migration that could clog drainage paths or lead to internal erosion (piping). The presence of transmissivity within the geotextile also contributes to drainage. Water captured within the soil mass can move horizontally along the geotextile plane, reducing pore water pressure buildup and mitigating waterlogging or instability during consolidation. The *SOILwrap* system utilises the most important reinforcement function of geotextiles. As seen in the figure, the wraparound layers resist tensile forces generated by embankment loading. The geotextile interacts with the adjacent soil to form a composite material that can better resist shear and reduce lateral spreading. This increased load-bearing capacity results in reduced surface settlement and enhanced structural stability. In essence, the *SOILwrap* technique transforms a soft ground foundation into a more stable composite system, using geotextiles that not only hold the structure together but also improve drainage, prevent material contamination, and reinforce the embankment against deformation.

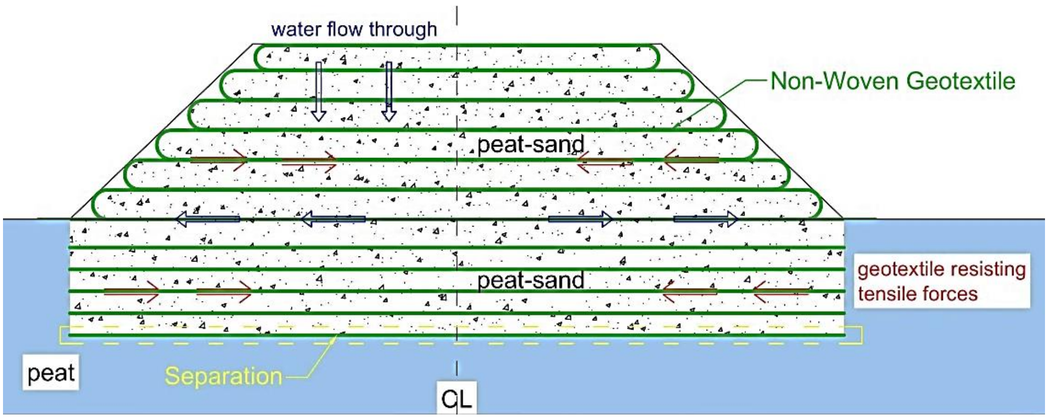
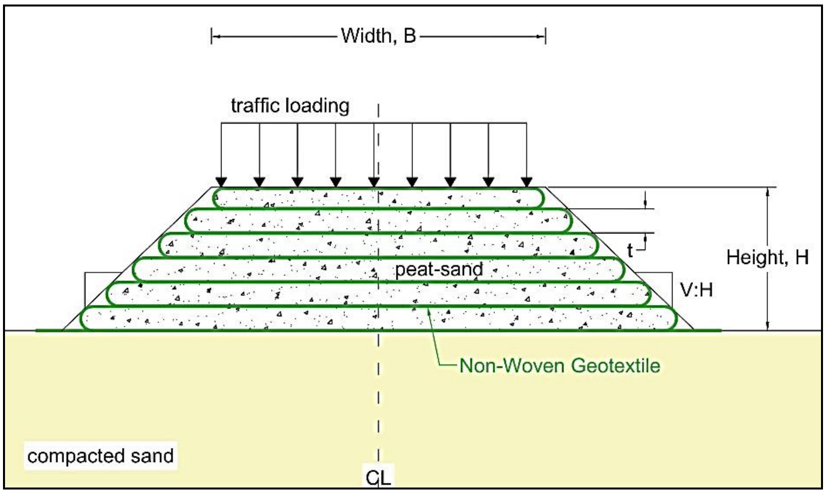
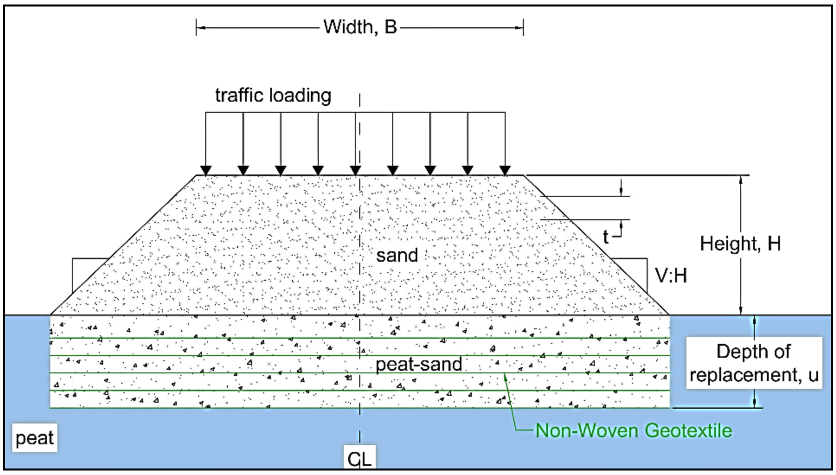


Figure 7. Conceptual Design of *SOILwrap* System.

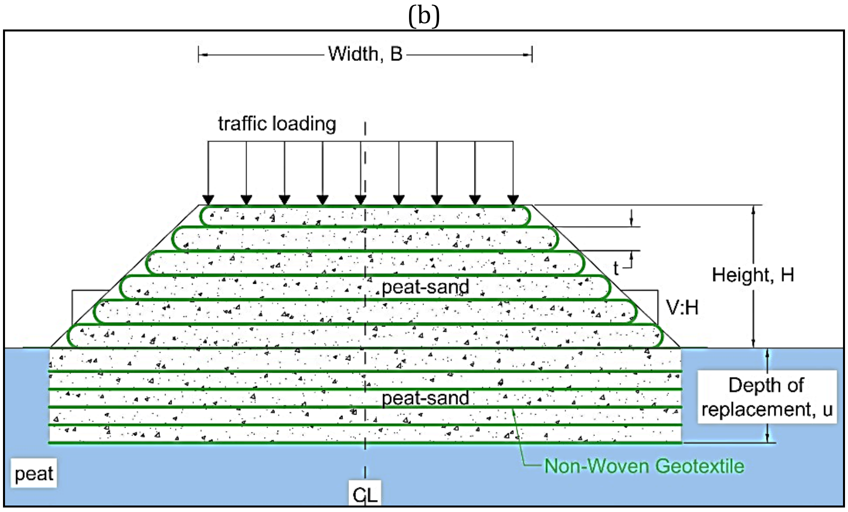
To evaluate the effectiveness of the *SOILwrap* system in different settlement performance, three trial models are proposed, each targeting a different aspect of the problem. The first model shown in Figure 8 (a) focuses on improving the embankment fill itself, where the settlement is typically caused by internal deformation due to poor compaction or weak material. The aim is to optimize the embankment's structural behaviour under loading by enhancing its internal stability. The second model shown in Figure 8 (b) concentrates on the subgrade or foundation soil, which is the underlying peat layer known for its high compressibility and low shear strength. This model introduces geotextile as a separation and drainage-enhancing layer at the embankment-subgrade interface. The goal is to reduce long-term settlement and improve load transfer by maintaining the groundwater level and accelerating consolidation. Finally, the third model shown in Figure 8 (c) combines both approaches by integrating geotextile reinforcement within the embankment fill and at the subgrade interface.



(a)



(b)



(c)

Figure 8. Cross section of the embankment design

5. CONCLUSIONS

This conceptual study explored the potential of the *SOILwrap* system, combining wraparound geotextile reinforcement with reused peat soil, as a sustainable alternative to conventional embankment methods on peatland. The methodology was framed around understanding peat characteristics, evaluating geotextile functions, and proposing optimized reinforcement models. The wraparound configuration was highlighted for its enhanced load-bearing capacity, reduced settlement, and minimized land usage compared to planar reinforcements. Through integration of geosynthetic functions which are reinforcement, separation, drainage, and filtration, the *SOILwrap* system addresses both geotechnical performance and environmental sustainability. Future numerical simulations using PLAXIS 2D will validate the proposed models and guide the optimized design parameters. The study supports the viability of reusing peat soil in embankment design, potentially reducing construction waste and preserving usable land, aligning with sustainable development goals in civil infrastructure.

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