Development and Field Testing of Geocomposite Cellular Mats (GCM) to Minimize the Ground Movements of Highway Embankments Founded on Peat Ground

Tuan Noor Hasanah Tuan Ismail[1](✉), Devapriya Chitral Wijeyesekera[2], and Ismail Bakar[3]

[1] Faculty of Technology Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Johor, Malaysia
hasanah@uthm.edu.my
[2] University of East London, Docklands Campus, University Way, London E16 2RD, UK
[3] Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Johor, Malaysia

Abstract. Challenging grounds are often met in planning, design and construction of highway embankments which as a consequence succumb to undesirably excessive ground movements. Such ground conditions can range from unforeseen cavernous grounds to soft compressible organic soils of variable depths. Often alternate route planning is not feasible, and if necessary alternative construction procedures are not adopted, the net result will be unwanted roads user discomforts such as bumpy roads or even fatal road collapse. Highway constructions norms to circumvent such occurrences are to replace with alternative transported foundation soil/ground improvement or use an appropriate form of geo mats. Hence, this paper presents an alternative and innovative lightweight fill material: Geocomposite Cellular Mat (GCM) used to minimize the ground movements of highway embankments over peat ground. The conceptual development of a stiff mat structure but with a weight lighter than the embankment fill soil is described. The material used for the stiff mat is environmentally friendly in utilizing recycled plastic and its structure, enabling the free movement of water to dissipate any excessive pore water pressures. The performance of the GCM was appraised under field trial conditions on a test site in Parit Nipah, Johor, Malaysia. The site comprised of a vast expanse of hemic peat and environmental conditions at the test site were fully monitored. The geotechnical properties of the peat at Parit Nipah were typically high organic matter content (~85%), high moisture content (>600%) and very low undrained shear strength (<15 kPa). Details of the set up and layout of the trial embankments tested are fully described, and the techniques adopted to get a comprehensive narrative of the settlement characteristics using innovative measurement techniques are also described. The performance of the GCM incorporated embankment was compared with that of a similar embankment that was formed of conventional backfill (sand fill). The findings show that the field ground movement observations confirmed that the maximum settlements were reduced by up to 84% with the GCM fills. Moreover, the differential settlements were reduced by up to 70%.

M.-C. Weng et al. (Eds.): GeoChina 2021, SUCI, pp. 84–106, 2021.
https://doi.org/10.1007/978-3-030-79798-0_8

1 Introduction

"The necessity to have well documented full scale field tests of trial embankments" was strongly voiced at an International Symposium on Trial Embankments on Marine clays over three decades ago (Balasubramaniam et al. 1990). A holistic understanding of the geotechnical properties of both the embankment fill and the founding Muar Flats was desired to make a good prediction of the embankment behaviour. This paper describes some field test on embankments at a dominantly peat site in Parit Nipah, (only about 20 km away from Muar, Johor) but in a very different geo environment. It is a prime engineering prerogative to enhance the stiffness of a road subgrade and/or subbase that will have the potential to arrest any indiscriminate road settlement that leads to uneven and bumpy road surfaces. The wide variability of properties and materials encountered in geotechnology demands the applications of Genetic Engineering to bridge between idealist and realism (Ebid 2004). Highway embankments settle when constructed over soft soil subgrades, including silty, clayey and in particular peat. These are very frequently encountered hazardous problems that demand maintenance and repair of such soil-structure scenarios. Figure 1 gives a simple, local example from Malaysia (Kolay et al. 2011). Challenging soft soils have also been described by Zainorabidin and Wijeyesekera (2007), Huat (2004), Edil (2003), Zainorabidin and Bakar (2003), Jarret (1997), Mutalib et al. (1991), Andriesse (1988), Hobbs (1986) and Barden (1968). Such soils are characterised by weak shear strength, low stiffness with long term creep characteristics (a consequence of significant secondary and tertiary consolidation), high moisture content and continuous biodegradation. Consequently, soft peaty soils tend to settle in the short term and then progress to consolidate further with time, much more than firmer soil that have lower natural moisture content.

Fig. 1. Hazardous settlement of approach road with peat ground subsidence in Sibu, Sarawak, Malaysia (Kolay et al. 2011)

Infrastructure constructions on varying compressible soils cause many post construction problems. Hence, some pertinent, sustainable and lasting remedial geo-techniques are urgently desired to ensure embankments and structures constructed on such problematic ground remain stable and strong to mitigate excessive settlement and/or bearing failure. Past literature documents various alternative construction and stabilisation methods; intrusive methods (chemical stabilisation, prefabricated vertical drains) or external methods (surface reinforcement, preloading, sand or stone column, and piles) have been suggested and adopted to support structures over soft yielding ground (Huat et al. 2005; Kadir 2009; Construction Research Institute of Malaysia 2015). However, some of these technologies are constrained by their demands on technical feasibility, space and time limitations and process economics. Even after the adoption of these procedures, differential settlement problems can still remain unaddressed. These methods aim to have the initial peat layer thicknesses reduced by over 50%, with a simultaneous increase in preconsolidation pressure and undrained shear strength. However, such methods are both expensive resource intensive, time-consuming and need safe site access for heavy machinery.

Innovative use of lightweight fill technology has been adopted in construction on the soft yielding ground for over three decades. The increase in stress on the subsoil can be reduced so that the settlement is reduced or even eliminated/compensated via the geotechnical concept of "buoyant/floating foundation" if the road embankment is constructed out of fill material lighter than conventional fill (14–20 kN/m^3). Hence various types of lightweight materials (sawdust, fly ash, slag, cinders, cellular concrete, lightweight aggregates, expanded polystyrene (EPS), shredded tires, and seashells) have been proposed as fills for road embankment construction (Ismail et al. 2019). Table 1 gives properties of some such fills. Most lightweight fills are primarily particulate from that of EPS blocks, which are light (<0.4 kN/m^3) with low water absorption (<2%). However, EPS blocks have inherent technical challenges of uplift, leading to buoyancy failure, flammability of EPS and being susceptible to rodent attack. The research reported in this paper utilized a potential replacement of the conventional or modified fill material to one that is manufactured and has a cellular lightweight mat structure, referred to as Geocomposite Cellular Mat (GCM).

Table 1. Physical properties & performance of some lightweight fills

Lightweight fill	Description	Density (kg/m^3)	Compressive strength (kPa) @ 10% strain	Initial stiffness (kPa)	Approx. cost (RM/m^3)	Performance concerns
EPS	Expanded Polystyrene Ultra lightweight	<40	0.4×10^3	6.5×10^3	200	Hydraulic buoyancy: Flammable: Soluble with oil based products & Chemicals: Prone to rodent attack
Shredded tires	Used above ground water level	<920	80	0.4	90	Geo environment pollution:

(*continued*)

Table 1. (*continued*)

Lightweight fill	Description	Density (kg/m^3)	Compressive strength (kPa) @ 10% strain	Initial stiffness (kPa)	Approx. cost (RM/m^3)	Performance concerns
Wood fibre	Used below ground water	<1020	0.83×10^6	0.83×10^6	65	Combustible; Decomposable
Expanded clay	Non uniform Depends on compaction	<700	1.2	4×10^4	185	Hydraulic buoyancy' Water absorption
Fly ash	Self hardening, non uniform, granular material	<1550	1.2×10^3	11×10^6	65	Wind erosion

2 Road User Safety and Comfort

By virtue of the benefit of the area covered land transport is the most convenient mode of transportation and the main element for a nation's economic development. Sound highway/urban road infrastructure coupled with efficient traffic management gives rise to riding comfort and road safety to their users. Highway design involves the selection of a road's dimensions and its visible features of alignment and controlling highway architecture. Their construction normally involves a vast amount of earthwork; cutting hilly areas, backfilling low lying areas, crossing wetlands and alike. Often in the case of road embankments, the interaction in the behaviour of its essential elements of the pavement, the embankment fill and the foundation provides the user with comfort or otherwise. A significant role is played by the respective construction industries to contribute to the development of a green road/highway, in being environmentally responsible, eco-friendly and sustainable. The condition of the road surface needs to be visually inspected with regular measurements of rut depths, longitudinal evenness to be acceptable to predefined guidelines. The unsustainable common practice of indiscriminate use of transported earth backfill can be replaced with the adoption of an appropriate choice of a lighter backfill given in Table 1. This will have the added benefit of not imposing undesirably higher stresses on soft foundations leading to excessive deformations of the foundation, which will be reflected in giving an uneven road surface.

Conventional embankment fill comprises of well compacted earthen material used to fill a void space during the process of raising the natural ground surface to a predesigned grade level. Two types of granular materials (type 1 and type 2) is specified by the Department of Transport (UK) for road works. Type 1 is a well graded aggregate of crushed rock, well burnt colliery shale with a notable absence of plastic fine grained soil. Type 2 includes additionally natural sand and gravel with an upper limit of 6%

of particles finer than 425 μm. When used as a subbase, CBR (California Bearing Ratio) value of such compacted fills must be higher than 20% and needs protection from wet conditions. The durable performance of a pavement depends on the subgrade with particles finer than sand in it gives lower CBR values and yields unfavourable support to the pavement.

Such particulate fills with low stiffness lack rigidity and imposes a non -uniform stress distribution on the foundation. Consequentially, the settlement of the embankment often closely follows the pattern of the stress distribution giving a characteristic bowl shaped deformation. This in turn can cause severe damage on the overlying layers of the pavement-fill system (Fig. 2). Johansson (2010) used a hydrostatic profiler which can determine the relative movements of a flexible hose buried integrally into the foundation along with fill foundation interface, in order to verify this deformation pattern. Allowable/acceptable settlement will depend on the importance of the infrastructure, the pavement type (flexible/semi rigid or rigid) and factors such as any differential settlement risks. The roadway's economic life may be considered tolerable if the settlements are uniform and occurring slowly over time.

The behaviour of the pavement-fill-foundation system is best and realistically studied only through well instrumented and monitored full scale trial embankments. Studies using software programs and small scale models have also been done. Table 2 gives summary details of such studies relevant to the core focus of this paper; Peat ground. Outline of the challenges with peat ground follows this.

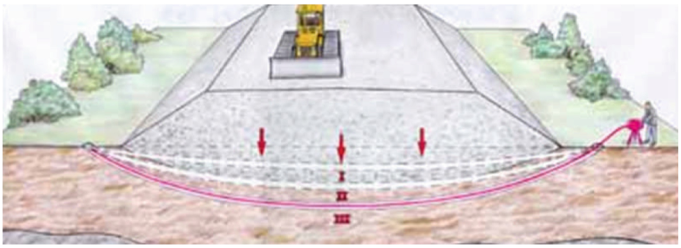


Fig. 2. Settlement pattern at the fill foundation interface made with hydrostatic profilometer observations (Johansson 2010).

Table 2. Outline of some published research studies of trial embankments founded on peat ground.

Site name	Muar clay plain, Malaysia	Booneschans, Netherlands	Parit Nipah, Johor Malaysia	Parit Nipah, Johor Malaysia
Geometry of embankment	55 × 90 × 2.5 m	750 × 100 × 6 m	3,5 × 1 × 1 m	3.6 × 3.6 × 0.15 m concrete raft
Principal foundation soil	17.8 m of Marine Muar soft silty clay	1.8 m clay layer overlying peat	Peat	Peat

(*continued*)

Table 2. (*continued*)

Site name	Muar clay plain, Malaysia	Booneschans, Netherlands	Parit Nipah, Johor Malaysia	Parit Nipah, Johor Malaysia
Thickness of and depth to peat layer	0.6 m thick peat layer at a depth from 17.8 m	2 m thick peat layer at a depth from 1.8 m	4 m thick peat layer from the ground surface	4 m thick peat layer from the ground surface
Field tests and instrumentation	Settlement gauges, piezometer, inclinometer, settlement rings, heave markers, piezocone	CPT, Begemann sampling system (boreholes), inclinometer, pore pressure transducer, trial pit	Boreholes, well points for water table depths, Visual observation of fill deformation Environmental monitoring	Geodetic surveying method. TOPCON AT-B4
Embankment fill composition	Well compacted fill	Sand core with a clay cover on top	Layers of Geocomposite Cellular Mat (GCM) topped with Uniformly compacted sand fill	Sand bags on Concrete raft
Research methodology/ies	Total and effective stress slip circle analysis. CRISP Finite element analysis	Use of sensors to detect movement before failure	Settlement observations and Validating Large strain consolidation predictions	Installation of slab to reduce/minimise settlement
Reference/s	Balasubramaniam et al. (1990), Indraratna et al. (2010) and Brand (1991)	Zwanenburg et al. (2005)	Ismail (2017) Ismail et al. (2014a, b)	Zainorabidin et al. (2019)

3 Geotechnical Challenges Associated with Malaysian Peat Ground

In a strict geotechnical engineering context and as adopted by the extended Malaysian Soil classification System, Peat is defined as soil with more than 75% organic content (ASTM D4427-92 1997; Jarret 1995). Furthermore, contrary to normal soils, the composition and properties of peat deposits are both non homogeneous and is subjected to a dynamic and conflicting process of disintegration cum preservation under very moist anaerobic conditions environments, akin with the formation of bogs, moors, muskeg, mire, tropical swamps and fens (Landva 2007). Peat further defies one of the Terzaghi assumptions in soil mechanics, in that the peat particles themselves are variably compressible. Tropical woody peat found in Malaysia consist of semi-decomposed to decomposing plant remains of tree stumps, roots and leaves and the peat in Johor, Malaysia is dark reddish brown to black and have been formed as varying thicknesses and in an acidic environment. The renowned Von Post peat classification system in use is based on categorization in accordance with botanical composition, degree of humification, moisture content, content of fine and coarse fibers and content of woody remnants. The von Post scale for peat has a spread ranging from H1 (completely unhumified fibrous peat) to H10 (completely amorphous non fibrous peat). Hobbs (1986) extended the classification system to include categories for organic content, tensile strength, odour, plasticity and acidity. Based on the extent and type of fiber content, they are also referred to as Fibric (>66%), Hemic (33–66%) and Sapric (<33%). The unique geotechnical characteristics of peat soil are a high moisture content (>200%), high compressibility ($C_c > 0.5$), high organic content (>75%), low shear strength (5–20 kPa) and low bearing capacity (< 8 kN/m^2). Such attributes of peat are the cause of undesirable geotechnical challenges with peat ground to the engineers in the field of construction. Table 3 gives a summary of published geotechnical information on Malaysian Peat Soils.

Table 3. Published geotechnical properties of some Malaysian Peat soil

Geotechnical characteristic	Peat soil - location		
	West Malaysia	Johore Hemic Peat	East Malaysia
Source reference	Huat (2004)	Zainorabidin and Ismail (2003)	Huat (2004)
Natural moisture content (%)	200–700	230–500	200–2207
Organic content (%)	65–97	80–96	50–95
Liquid limit (%)	190–360	220–250	210–550
Plastic limit (%)	100–200	–	125–297
Specific gravity	1.38–1.70	1.48–1.8	1.07–1.63
Unit weight (kN/m^3)	8.3–11.5	7.5–10.2	8.0–12.0
Undrained shear strength (kPa)	8–17	7–11	8–10
Compression index, C_c	1.0–2.6	0.9–1.5	0.5–2.5

By virtue of its genesis, peat is necessarily heterogeneous; far from uniform and homogeneous, even within a single laboratory sample. The macro/micro structure of deposits of natural peat is in a continuing process of dynamic diagenesis with humic acid interaction. Peat soils are recognized to be dark reddish brown to black with acidic (pH ~ 3) pore fluid. Table 2 shows that some researchers' claim that peat is not actually plastic per se, as a plastic limit cannot be determined. A further dilemma is that whether peat is granular or cohesive in shear. The macrostructure of peat shows a network of fibers that defines any pseudo frictional characteristics of peat (Zainorabidin et al. 2010). Kogure et al. (2003) suggested a multi-phase system for peat comprising of solid organic, mineral soil particles, and water in the inner and outer voids. These nonconformities are prime reasons for the classical secondary/tertiary consolidation behaviour (C_{α}/C_{c} ~ 0.06) of peats that leads to indiscriminate settlements. Ground subsidence is essentially a consequence of volume change except in the cases where lateral ground movements induced by shear movements. Peat is very susceptible to volume change that may arise due to any one or combinations of the fo0llowing three different causes, which are;

(i) Consolidation of peat due to an increase in effective stress,
(ii) Shrinkage resulting from the movement of the free moisture consequent to a change in the thermal or hydrological environment, and
(iii) The cracking of the otherwise peat continuum due to aggressive and hostile thermal environments leading at times to irreversible break down of the cell structure of the decaying tree roots and other biological remains.

Wijeyesekera and Patel (1998) and others have outlined settlement predictions using a numerical analysis approach for the solution of Gibson's large strain consolidation, which is based on the use of Lagrangian coordinates in preference to the Cartesian coordinates. This still leaves the inability to account for the biological cell breakdown as well as to the volumetric deformations arising from drying shrinkage. Notwithstanding these indispensable setbacks to the modelling of peat, notable constructions have been done in Malaysia and elsewhere on Peat ground, viz; Kuala Lumpur International Airport (KLIA) and urban development in Sibu Town (Sarawak), Malaysia. Any soft ground improvement design needs to ensure the stability of the structure as required in the technical specifications (and in the case of a road embankment, to settlement limits after a specified lapse of time from construction, set at the road center and also on a maximum residual differential settlement).

4 Geocomposite Cellular Mat (GCM) Technology

In their quest for an environmentally sustainable solution to the challenges imposed by peat ground on road construction, the authors developed the GCM (Fig. 3) as a further alternative lightweight fill. This research focused on the development and field testing of GCM which is a pronounced improvement on the "Lightweight Blocky" basis adopted in the use of "Expanded Polystyrene" (EPS) blocks but taking on board the following considerations.

- The GCM to be made of recycled waste plastic and having a distinctive honeycomb like cellular structure that makes them marginally heavier, stiffer and stronger than the EPS, and also negates any buoyancy failures in the GCM being more porous and permeable.
- The adoption of recycled waste plastic Polypropylene as a useful material source and also to improve environmental sustainability significantly while supporting the sustainable trend of the circular economy.

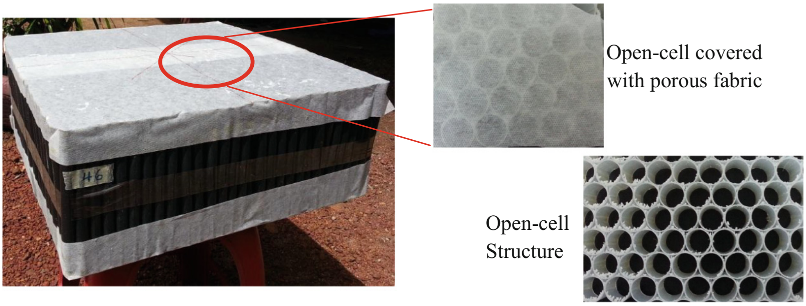


Fig. 3. Structure of Geocomposite Cellular Mat (GCM) block

The GCM technology (Wijeyesekera et al. 2015, 2016; Ismail 2017) is based on the adoption of a relatively firmer foundation structure than a flexible one and thereby anticipates a more even/uniform structural settlement. Particularly in the niche area of Foundation Structure – Soft Soil interaction studies, the vertical displacements and subgrade reactions at the interface of the foundation structure depends on both the soil stiffness and the rigidity of the foundation (Leshchinsky and Marcozzi 1990). A rigid interface enables to negate any non-uniformity (heterogeneity of the subgrade) and redistribute the contact subgrade reactions resulting in a uniform rigid foundation settlement. Intrusive ground improvement techniques, viz. soil stabilization, if not adequately controlled (through uniform admixing and/or specified field compaction) will still produce a particulate and heterogeneous soil, even though it be, at a reduced order of variability.

As outlined by Arellano (2010), Lightweight Fill Technology in highway engineering relies not only on improving engineering properties of the fill but also in reducing the weight of the levee of the embankment and thus the stresses applied on the soft foundation soil. Cellular solids have a macro/micro structure that can have a form ranging from the near perfect order in beehive honeycomb structure of disordered three dimensional networks found in sponges, foams and also in the biological tissues of cork cells or even in mammal/human skins. Open/closed cell polyurethane is found in the EPS blocks adopted as a form of lightweight fill in ground improvement. A closed and ordered connectivity of the individual cell edges and faces is hard to establish in the polyurethane cells, which limits the porosity and more so the intrinsic permeability. Relative density/specific gravity is an important parameter which contributes to the strength of the cellular structure. Thin walled cellular structures have a lower relative density (polymeric foams 0.05–0.2; natural materials, cork ~0.14; two dimensional structures in honeycomb and porous solids >0.3). Thus the physical, mechanical and thermal properties of cellular solids are influenced by a variety of factors including relative density, cell geometry and cell topology. The many advantages in cell structure technology have been harnessed via engineering material science in the manufacture of the body in aircraft technology and honeycomb sandwich technology adopted in building systems in such as lightweight partition walls. An exciting advantage of cellular structures is the auto compensation of any non performing cells by the rest, within reasonable limits. The use of geocells in highway engineering is an example of its application with the collapsible (for packing purposes) but the honeycomb shaped interconnected cells provide the needed all-round confinement to completely encase the heavy granular fill that are placed within the cells.

Development of GCM is principally focused on being green and sustainable with the use of recycled waste plastic having a density ranging from 110 to 125 kg/m^3 and an average specific gravity of 0.915. The specific gravity of the GCM block indicates that the GCM will float but is not much lighter than water (only 10% lighter). Therefore submergence plus additional loading from wearing surface, and road base will significantly decrease the buoyancy of the GCM. Thus, GCM can be classified as a safer fill material when compared with the EPS fill which has a low specific gravity approximately 0.01 to 0.03 (which is 98% lighter than specific gravity of water) as reported by Zornberg et al. (2005). The water absorption of GCM is less than 0.01%, it was achieving equilibrium value at 1day, since polypropylene (PP) does not absorb any significant amounts of water.

GCM block fill possesses far superior mechanical bearing characteristics. GCM fill has a high compressive strength ranging from 3.8 to 4.5 MPa, the initial stiffness at 1% strain was observed to be in the range of 100 to 150 MPa, and secant stiffness was around 190 to 310 MPa. These values are more than 50% higher compared to EPS geofoam. As noted by Zornberg et al. (2005), the maximum compressive strength and initial stiffness of EPS is around 0.04 to 0.49 MPa 4 to 10 MPa, respectively. The idealised cellular structure adopted in this technology allows water to flow freely and vertically (unidirectional), and it also reduces the potential of floating due to open porous structured cells (Fig. 3). Furthermore, the open-porous cellular structure of the GCM facilitates accelerated consolidation settlement within the sub-grade through rapid dissipation of the excess pore water pressure developed. Both top and bottom surface of the open-porous GCM was covered with high strength filter fabric to avoid soil particle from passing through them. GCM follows the masonry brickwork/ blockwork concepts closely, and are made in block form. Placement of the GCM blocks can be empirical or with a rational analysis to form the entire embankment with an appropriate spacing and arrangement patterns for the blocks. Therefore additionally, the concept of a cellular mat structure with interspersed blocks further enables the sharing of the load and minimising the differential settlement. The performance of this technology constructed on peat soil is critically studied in this research.

5 Geo Environmental Observations at the Field Test Site (Parit Nipah, Johor, Malaysia)

Field testing was conducted at Parit Nipah Darat (Johor, Malaysia). Ground investigations at the site consisted of drilling 4, 10 m deep boreholes and field vane shear tests carried out that revealed a peat layer extending to approximately 4 m in depth, which in turn was underlain by a layer of soft clay. This has been further confirmed recently by Basri et al. (2019) with subsurface profiling using Electrical Resistance Tomography results for the 2-D stratigraphy profiles obtained shown in Fig. 4. The image shows a clear contrast between different soil layers confirming the peat thickness. The natural moisture content of the peat obtained from the site ranged from 698% to 721%. The laboratory observations of the unit weight of peat soil were in the range of 920 to 1100 kg/m^3, and the specific gravity of peat particles was about 1.436. Vane shear strength recorded for peat layer ranged from 8 to 14 kPa. These conform to the expected characteristics of peat to have low shear strength and consequently low bearing capacity inducing large strain settlements and even shear failure.

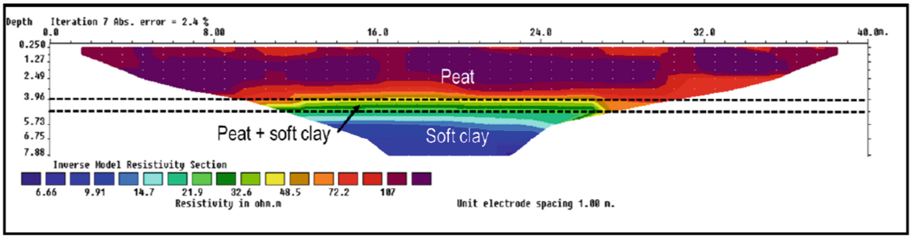


Fig. 4. 2-D ERT stratigraphy profiles for Parit Nipah Darat (adopted from Basri et al. 2019)

Environmental (rainfall, air temperature, humidity, groundwater table fluctuation and ground surface subsidence) conditions at the site were regularly monitored during the testing program. These enabled to compensate for errors arising from the environmental effect in order to obtain the net settlement data arising solely from respective fill loadings only. Temperature and humidity data as in Fig. 5 were measured using digital temperature and humidity meter to the nearest 0.1 °C and 1%, respectively. It was monitored throughout a research testing period. The temperature observations during the test period ranged between 22 °C and 30 °C. High ambient temperatures and low humidity reduce soil moisture and vice versa. Figure 6(b) shows the variation in humidity observed at Parit Nipah test site to be in the range of 78 to 89%.

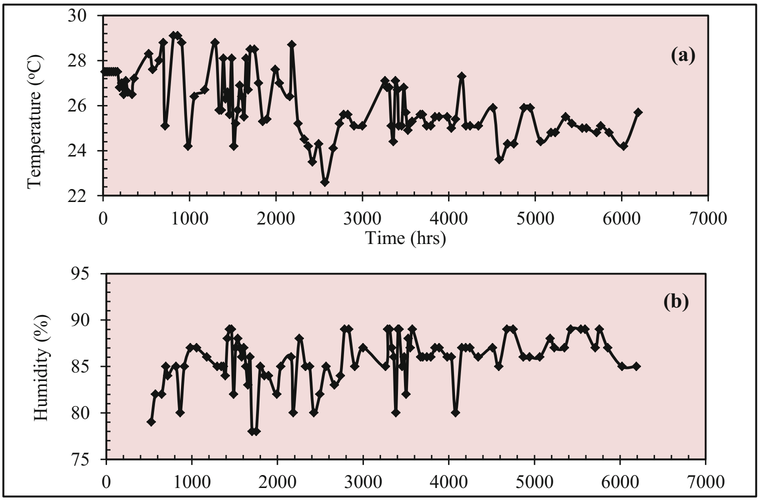


Fig. 5. Temperature and humidity variations observed at the test site

Groundwater level observations were made at three different but permanently installed standpipe locations on the test site. A stiff flat measuring tape with a readable accuracy of 0.001 m was used to ascertain the depth to local groundwater table. The measuring probe incorporated an insulated gap between electrodes to give an audible signal when it made contact with the water. The groundwater level variations depended on various factors such as water extraction demand by vegetation, local dewatering, but primarily the rainfall. Figure 6 is a comparison of the groundwater level changes in the peat layer on a backdrop of the observed rainfall. An extreme fluctuation of 27.7 cm in groundwater level was observed with intermittent rise and fall in its level, responding to the rainfall intensity and occurrence.

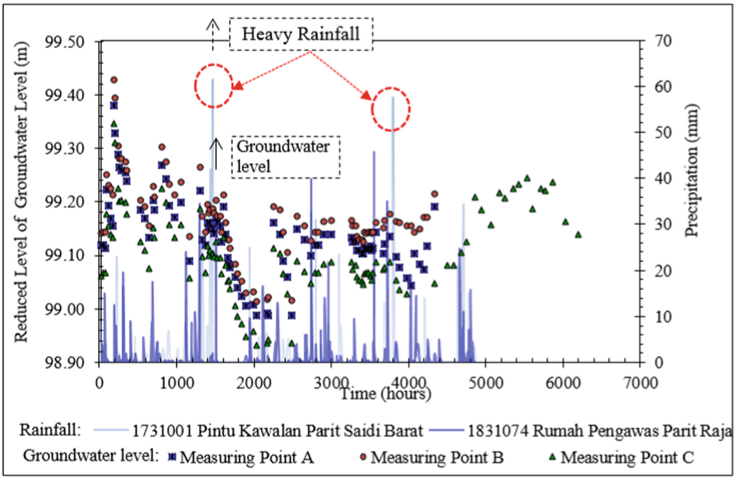


Fig. 6. Variation of local groundwater level in response to rainfall with time at the test site

6 GCM Technology – Field Performance

The performance of the GCM was closely observed in a real field environment at the site and analyzed. The superstructures were kept under canvas cover so that the test fills only were protected from wind and rain. The need to obtain holistic settlement observations at points on the loaded bases and beyond was a prime objective accommodated to fit the limits of time and available research funding. Environment tests mentioned above and innovative improvised instrumentation were adapted to measure surface settlements. Therefore, the adoption and installation of a large number of electronic settlement gauges needed and hydrostatic profilers proved to be both expensive and challenging as it would disturb the soft peat soil. The number of measurement points needed was not thus compromised, and a geodetic surveying technique; Topcon AT-B4 auto level with fixed individual staff at each measurement point was installed. Each levelling staff was fastened to a rigid base plate (100 × 100 mm) for stability and to provide a representative observation. The visible portion of each levelling staff displayed a securely attached barcode portion of a leveling staff. Hence remote observations were possible, avoiding the hassle of handling heavy levelling staff and also eliminating any disturbance of the many measuring points. Net ground movement (settlement or heave) was thus measured to an accuracy of 1 mm.

The GCMs were made in the laboratory as blocks which measured either 500 × 500 × 200 mm or 500 × 250 × 200 mm. In practice, the GCM could be custom made to a required size and shape. The blocks can be arranged in a staggered pattern to distribute the load evenly between the layers. Figure 7(a) shows a typical arrangement of the GCM blocks within an embankment. The blocks are surrounded by conventional fill at the top and on the sides. 400 mm thick fill on the top of the blocks, and beneath the road pavement was proved to be sufficient in a parallel research study. This paper presents results from two distinctly different series of research testing. First was series U of uniform loading, which conceptually represents the loading arising from the central portion of the embankment as illustrated in Fig. 7(b). The second was series E of embankment loading which comprised of the central part and the two levees (see Fig. 7) that impose a triangular loading on the base.

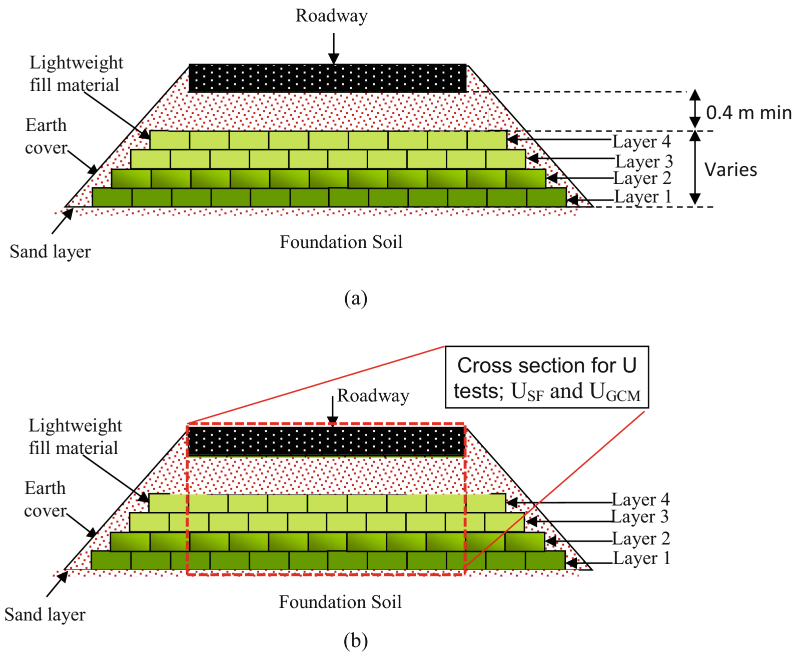


Fig. 7. Conceptual logic for the basis of U_{SF}, U_{GCM} tests & the embankment loading tests

Figures 8 and 9 present information for/from the uniform loading tests U_{SF} and U_{GCM} and helps to compare the performance of the GCM fill with that of the conventional sand fill. Test U_{SF} consisted of 1000 mm of compacted sand fill only ($\rho_d = 1400$ kg/m^3 $\pm$ 2%) whereas U_{GCM} was with 3 layers of GCM ($\rho_d = 125 \pm 10$ kg/m^3) and 400 mm thick sand fill at the top. Nomenclature for the embankment loading test followed the same logic. The site preparation for both series was similar in first excavating and removing approximately 200 mm of top soil and spreading 50 mm depth of sand on the prepared surface. The base plate of each settlement gauge was placed level and positioned with a level zero assigned at specified observation points as shown in the layout diagrams. The vertical framed structure was used to contain the fills laterally. These were suspended carefully on to the prepared surface, ensuring that there was no additional loading imposed on the ground. Sand fill was placed within the frame/s in 5 uniformly placed layers of 200 mm each making up a 100 mm thick fill. Contrarily, the GCM fills consisted of placing three layers of GCM blocks (3 × 200 mm = 600 mm thick), and the balance 400 mm consisted of two layers of 200 mm thick sand layers that was placed on top of the GCM blocks. Therefore the total initial height of fill for each test was 1000 mm. The construction loading settlements occurring were monitored after the placement of each 200 mm fill. The settlement observations from all the gauges were monitored at regular intervals for the duration of the construction loading. The settlements were determined from the ground surface. Figures 8, 9 and 10 show the loading base dimensions for the U and E test series to be 1000 × 1000 mm and 3500 × 3000 mm, respectively. The locations for the settlement observation points were as indicated.

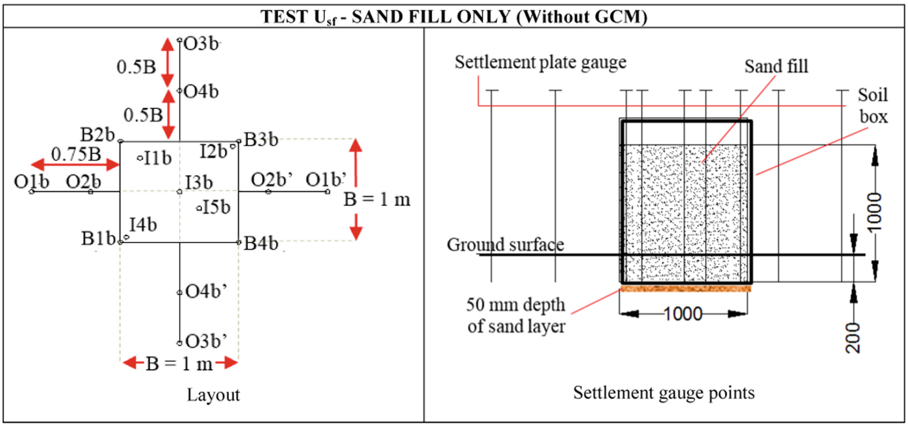


Fig. 8. Layout of uniform loading (sand fill only)

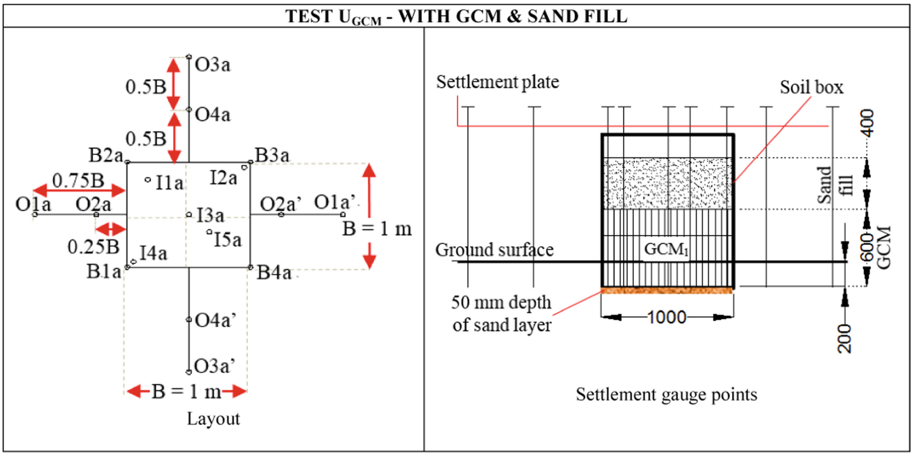
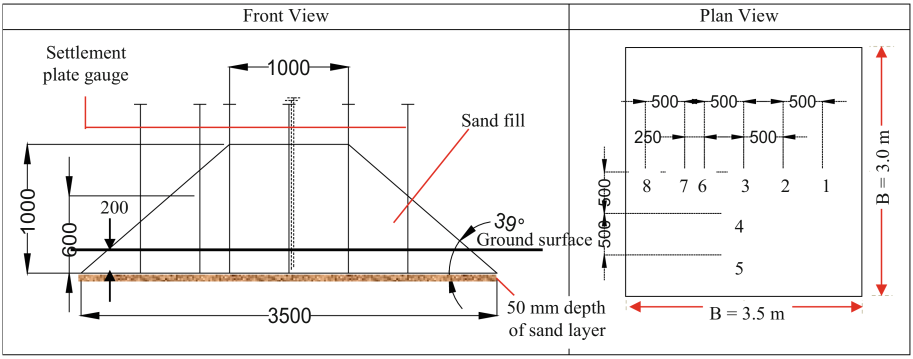
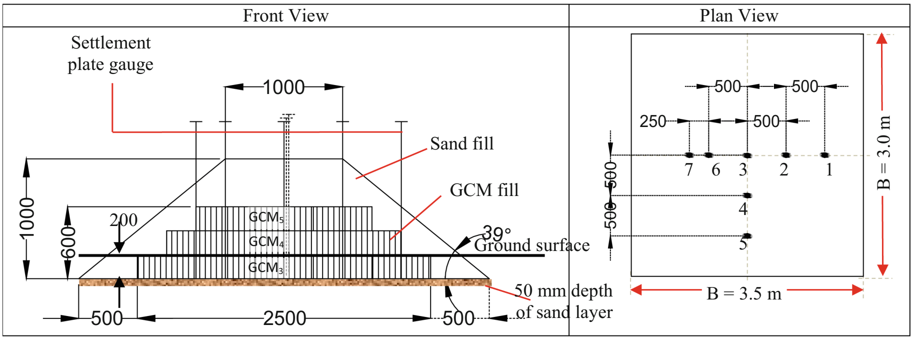


Fig. 9. Layout of uniform loading (GCM & sand fill)



(a) Test E_{sf} Sand Fill Only (Without GCM)



(b) Test E_{GCM} with GCM & Sand Fill

Fig. 10. Layout of embankment loading

Figure 11 shows the differential settlement with respect to the center point ($\Delta H_x = \delta_x - \delta_{I3a/b}$), the point I3a and I3b being considered the base reference for both conditions. It compares the progressive differential settlement with time under both sand fill loading (U_{SF}) and GCM fill loading (U_{GCM}) gave maximum values of >10 mm and <3 mm for U_{SF} and U_{GCM}, respectively. Figure 10 also shows that with the U_{SF} test in particular there was a rapid initial settlement followed by secondary and tertiary consolidation effects. This phenomenon was not prominent in the U_{GCM} test.

Figures 8 and 12 gives details of the layout for the sand fill Uniform loading test U_{SF} and the absolute local differential settlement profile in the transverse and longitudinal directions. These profiles are nearly identical. The maximum absolute settlements recorded were 86 mm and 71 mm observed at the center (ΔH_3) and edge (ΔH_2). This gave $\Delta H_3/\Delta H_2$ ratio to be 1.211. Furthermore, these observations portray a non-uniform settlement with a sagging profile under sand fill (flexible foundation behaviour). The constant settlement resulting at any time with U_{GCM} is further endorsed in Fig. 13 and in both transverse and longitudinal settlement profiles. The maximum settlements recorded were 56 mm and 55 mm at the center (ΔH_3) and edge (ΔH_2). The settlement ratio ($\Delta H_3/\Delta H_2$) for U_{GCM} was 1.018 in this case. Hence, the observed differential settlement was both uniform and 70% less than that observed with the sand fill loading U_{SF}. This observation shows that the GCM fills have addressed the methodology can overcome the non-homogeneity on the peat ground (rigid foundation behaviour).

Another notable observation seen in both Figs. 12 and 13 is somewhat similar and circa 3 mm maximum heave of the ground outside the loaded base area. This is a consequence of the softness and the weak peat shear strength inducing a complete local shear slip surface beneath the loaded base.

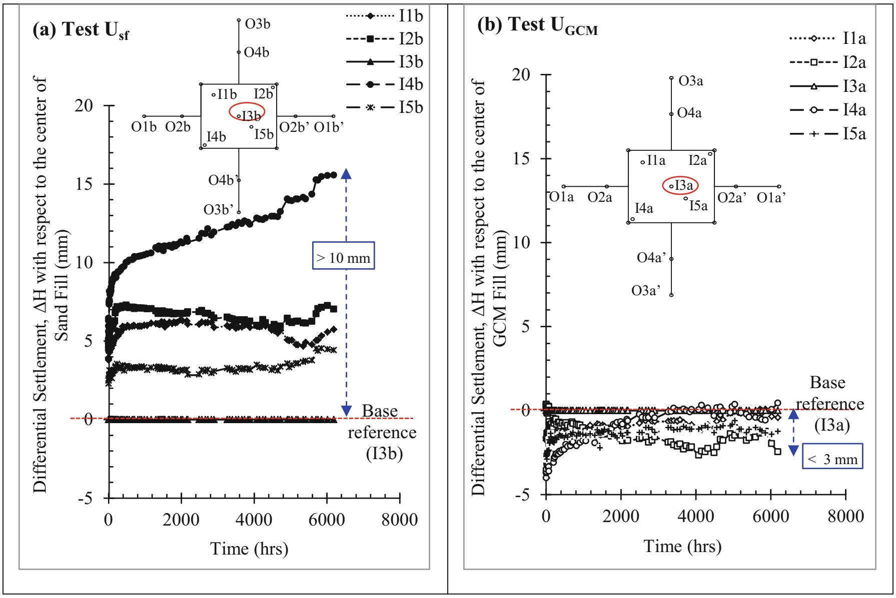


Fig. 11. Comparison of differential settlement at strategic points on the base in U_{SF} and U_{GCM} tests

Figure 14 and 15 refers to the observations obtained with the embankment loading tests E_{sf} and E_{GCM}, respectively. The differential settlement with respect to the center of fill embankment ($\Delta H_x = \delta_x - \delta_3$) in E_{sf} were significantly greater (>90%) than that from the E_{GCM} test as shown in Fig. 14(a). The results show settlement ranged from 5 to 125 mm. Non-uniform settlements experience under E_{sf} that increased with time and can be seen clearly through both transverse (see Fig. 14(b)) and longitudinal profiles (see Fig. 14(c)). The non-uniform thickness of peat deposit also contributes to the occurrence of bumpy roads, mainly when the road rests on the peat ground. Many researchers (e.g. Sas and Malinowska (2006); Oh et al. (2007a, b) and Ganasan (2016)) reported that a similar settlement pattern occurs when flexible foundation rests on the soft compressible soil.

However, results from E_{GCM} did not show any significant variation (<6 mm) as illustrated in Fig. 15(a). This is due to the stiff and contiguous mat structure and the consequent load sharing mechanism of the mosaic layer of the mats. The uniform settlement seen in the case of E_{GCM} is further endorsed in Figs. 15(b) and 15(c) through the transverse and longitudinal settlement profiles observed at any time, respectively.

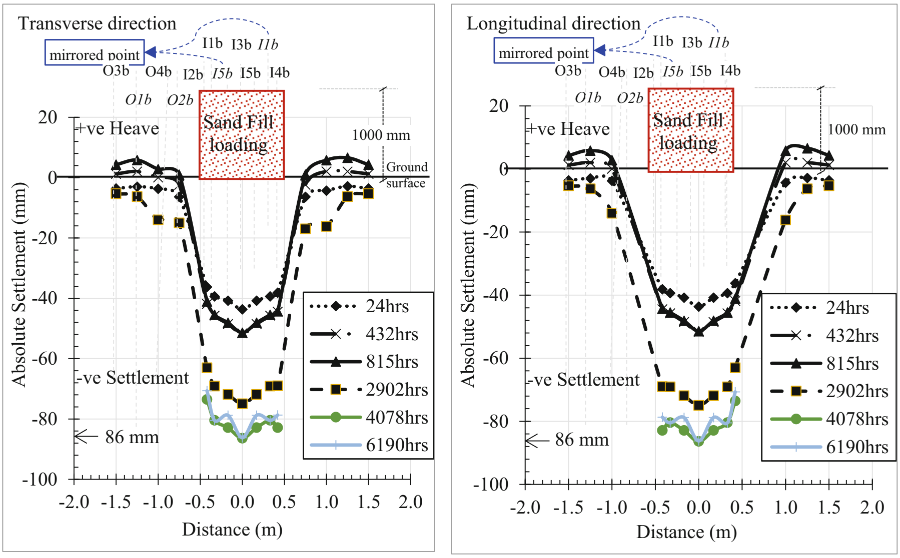


Fig. 12. Settlement profiles in transverse and longitudinal directions -test U_{sf}

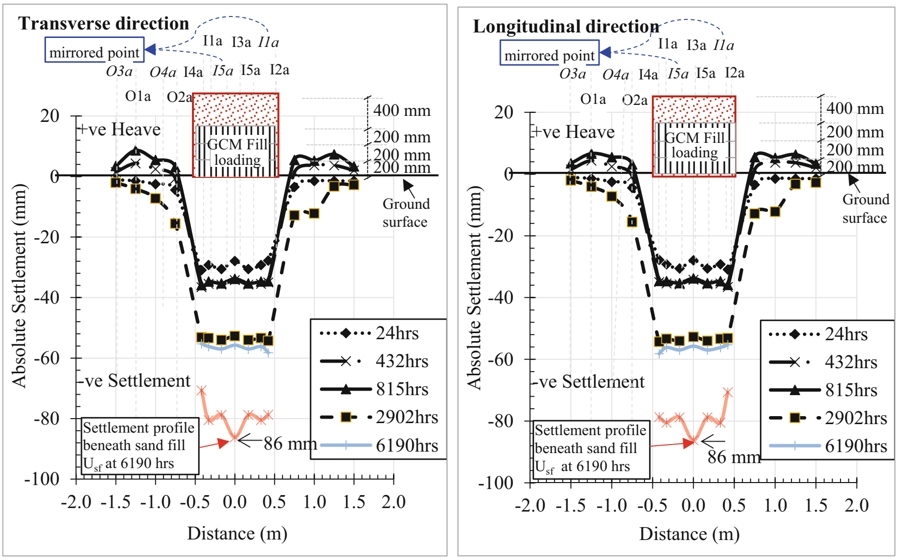
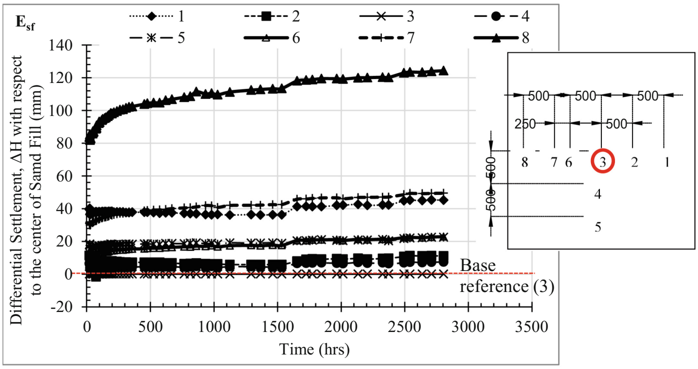


Fig. 13. Settlement profiles in transverse and longitudinal directions -test U_{GCM}

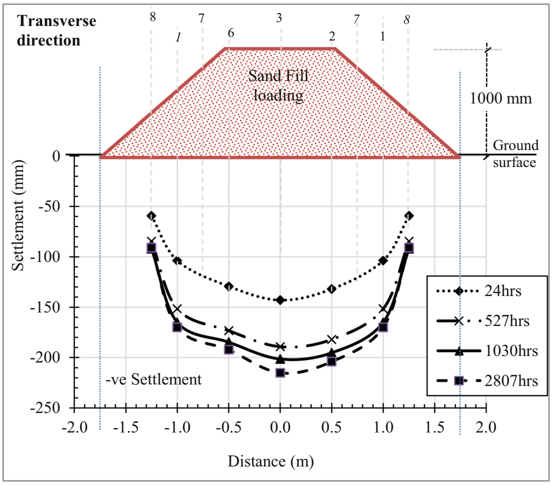
A long time after construction, the ground surface beneath sand fill embankment settled about 215 mm and 192 mm at the center and edge respectively (a ratio of 1.120) while similar observations with the GCM fills embankment were only 35 mm and 36 mm at the center and shoulder respectively (a 0.06 ratio). This can be further reduced with increasing the number of GCM fills (>3 layers). The results showed that the use of GCM reduced the total settlements by about 84%. Higher settlements at the base lead to excessive deformation of pavement and stress enhancement. The presence of lightweight GCM fills (with a density range of 110 to 120 kg/m^3) to replace sand fill (with a density of 1400 kg/m^3) provided desired results, GCM being remarkably negating any differential settlement.

The observation under embankment fill loading shows that the total relative settlements in GCM fill embankment E_{GCM} was 84% less than that from the sand fill embankment (E_{sf}). This is demonstrably seen in Fig. 16. Horizontal black lines in the figure represent the initial 0.2 m levels. Therefore, initial layer levels are datum lines and the red lines represent the observed settlement profiles of each layer traced by observing the movement of powdered tracer coal dust that was placed on the surface of each layer and near to the transparent wall to enable visibility.

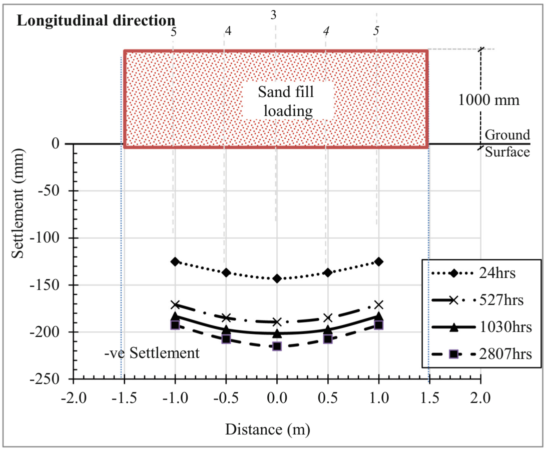
Based on the findings from the field study, it can be seen that the GCM fills not only reduces the excessive settlement but also the differential settlement. GCM also helped to accelerate the consolidation settlement within the sub-grade through the dissipation of any excess pore water pressure through the open-porous cellular structure of the GCM blocks.



(a) E_{sf} - Differential settlement plot

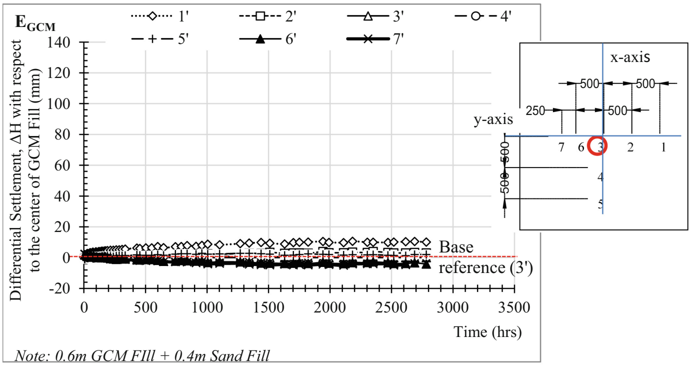


(b) E_{sf} - Transverse Settlement Profile

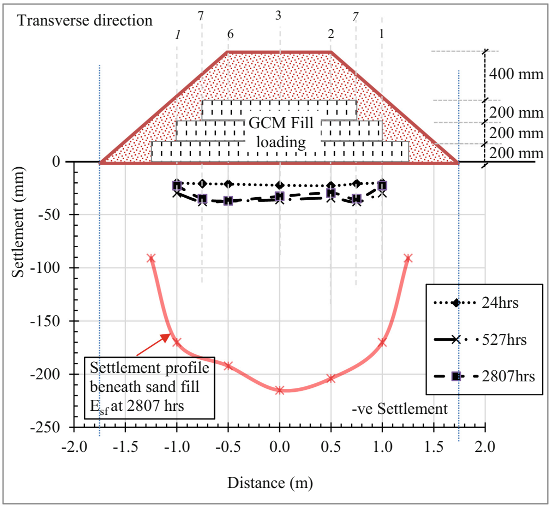


(c) E_{sf} - Longitudinal Settlement Profile

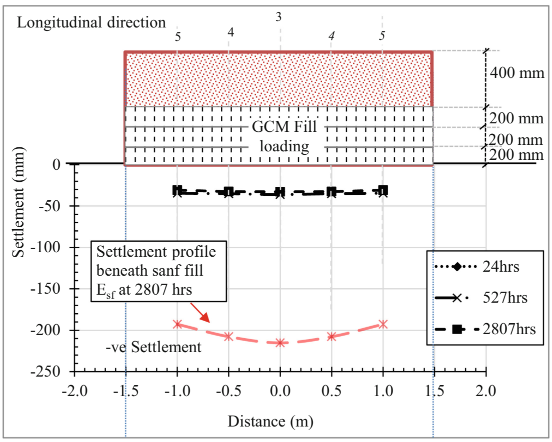
Fig. 14. Embankment loading test analysis– differential settlement and settlement profiles of test E_{sf} sand fill only (without GCM)



(a) E_{GCM} - Differential settlement plot



(b) E_{GCM} -Transverse Settlement Profile



(c) E_{GCM} -Longitudinal Settlement Profile

Fig. 15. Embankment loading test analysis– differential settlement and settlement profiles of test E_{GCM} (with GCM)

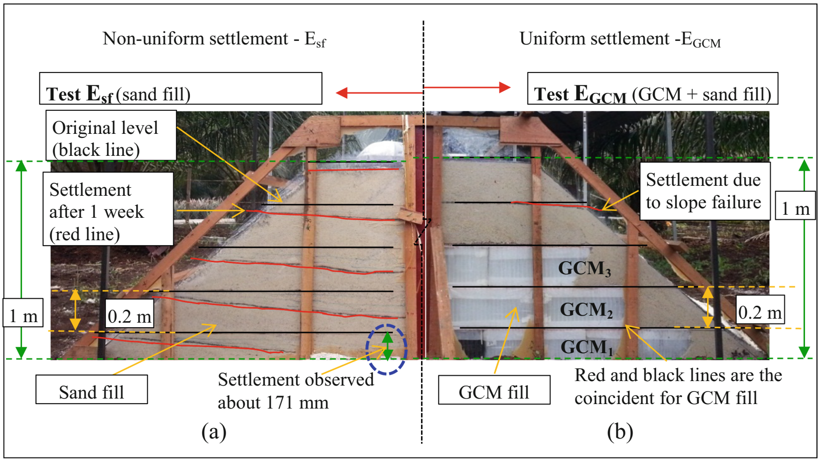


Fig. 16. Visual observation of settlement profile for field test group; (a) non-uniform settlements observed in flexible foundation test E_{sf}, and (b) uniform and minute settlements observed in rigid foundation E_{GCM}

7 Conclusions

Engineers need to circumspectly consider "Peat" either as a "misnomer" of being called a "soil" or accept this unique soil as an "outlier" within the realms of traditional soil mechanics and provide stiff porous lightweight fills such as the Geocomposite Cellular Mat (GCM) to negate or minimize any untoward excessive non uniform settlements. The findings show that the soil settlement significantly improvement with the GCM fills, which the maximum settlements and differential settlement were reduced by up to 84% and 70%, respectively.

Acknowledgement. The authors would like to express gratitude to Universiti Tun Hussein Onn Malaysia (UTHM) for the financial support to carry out this research and publish this paper.

References

ASTM D4427-92: Standard Classification of Peat Samples by Laboratory Testing. Annual Book of ASTM Standards, Philadelphia (1997)

Andriesse, J.P.: Permanent constraints in Peat Reclamation. Nat. Manag. Trop. Peat Soils. FAQ Soil Bull. **59**, 81–91 (1988)

Arellano, D.: Preliminary design procedure for EPS block geofoam lightweight fill in levees overlying soft soils. In: 27th Annual Association of State Dam Safety Officials Conference. University of Memphis, Tenessee (2010)

Balasubramaniam, A.S., Phien-Wej, B., Indraratna, B., Bergado, D.T.: Predicted behaviour of a test embankment on a Malaysian marine clay. In: Proceedings of International Symposium on Trial Embankments on Malaysian Marine Clays, Kuala Lumpur, vol. 2, pp. 1-1–1-7 (1990)

Barden, L.: Primary and secondary consolidation of clay and peat. Géotechnique **18**(1), 1–24 (1968)

Basri, K., Wahab, N., Talib, M.K.A., Zainorabidin, A.: Sub-surface profiling using electrical resistivity tomography (ERT) with complement from peat sampler. Civ. Eng. Archit. **7**(6A), 7–18 (2019). https://doi.org/10.13189/cea.2019.071402. http://www.hrpub.org

Brand, E.W.: Predicted and observed performance of an embankment built to failure on soft clay. Geotech. Eng. **22**, 23–41 (1991)

Huat, B.H.: Organic and Peat Soils Engineering. Universiti Putra Malaysia Press, Serdang (2004).ISBN: 983-2871-08-5

Construction Research Institute of Malaysia: Guidelines for Construction on Peat and Organic Soils in Malaysia. Perpustakaan Negara Malaysia (2015). ISBN: 978-967-0242-15-6

Ebid, A.M.: Applications of genetic programming in geotechnical engineering. Doctoral thesis, Ain Shamis University, Cairo (2004)

Edil, T.B.: Recent advances in geotechnical characterization and construction over peats and organic soils. In: Huat, et al. (eds.) Proceedings of the 2nd International Conference on Advances in Soft Soil Engineering and Technology, Putrajaya, Malaysia, pp. 85–108 (2003)

Ganasan, R.: Evaluation of innovation lightweight fill in problematic soil. MSc thesis, Universiti Tun Hussein Onn Malaysia, Malaysia (2016)

Hobbs, N. B.: Mire morphology and the properties and behaviour of some British and foreign peats. Quarterly Journal of Eng. Geology and Hydrogeology, London. **19**(1), 7–80 (1986).

Huat, B.B.K., Maail, S., Mohamed, T.A.: Effect of chemical admixtures on the engineering properties of tropical peat soils. Am. J. Appl. Sci. **2**(7), 1113–1120 (2005)

Jarret, P.M.: Geoguide 6: site investigation for organic soil and peat. JKR Document 20709-0341-95 (1995)

Indraratna, B., Rujikiatkamjorn, C., Wijeyakulasuriya, V., McIntosh, G., Kelly, R.: Soft soils improved by prefabricated vertical drains: performance and prediction (2010). http://ro.uow.edu.au/cgi/viewcontent.cgi?article=1907&context=engpapers

Ismail, T.N.H.T., Wijeyesekera, D.C., Bakar, I., Wahab, S.: New lightweight construction material: cellular mat using recycled plastic. In: Engineering Materials, vol. 594, pp. 503–510 (2014a)

Ismail, T.N.H.T., Hassanur, R., Ganasan, R., Wijeyesekera, D.C., Bakar, I., Sulaeman, A.: Physical and software modelling of performance of mat foundations on soft soil. In: Proceedings of Soft Soils Conference (2014b)

Ismail, T.N.H.T.: A critical performance study of innovative lightweight fill to mitigate settlement of embankment constructed on peat. Doctoral thesis, Universiti Tun Hussein Onn Malaysia, Malaysia (2017)

Ismail, T.N.H.T., Wijeyesekera, D.C., Lim, A.J.M.S., Yusoff, S.A.N.M.: Alternative construction technology over soft yielding ground using lightweight fill materials: an overview. J. Eng. Appl. Sci. **14**(16), 5602–5609 (2019)

Jarret, P.M.: Recent development in design and construction on peat and organic soils. In: Huat, B.K., Bahia, H.M. (eds.) Proceedings of Recent Advances in Soft Soil Engineering, Sarawak, pp. 1–30 (1997)

Johansson, F.: Sättningar i sulfidjord – uppföljning och utvärdering av sättningarnas storlek och tidsförlopp, väg 760 i Norrbotten. Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering (2010)

Kadir, M.I.A.: Long term consolidation study on the tropical peat at Pekan, Pahang, Malaysia. Doctoral thesis, Universiti Malaysia Pahang, Malaysia (2009)

Kogure, K., Yamaguchi, H., Shogari, T.: Physical and pore properties of fibrous peat deposit. In: Proceeding of the 11th Southeast Asian, Geotechnical Conference, Singapore (2003)

Kolay, P.K., Sii, H.Y., Taib, S.N.L.: Tropical peat soil stabilization using class F pond ash from coal fired power plant. Int. J. Civ. Environ. Eng. **3**(2), 79–83 (2011)

Landva, A.O.: Characterization of Escuminac peat and construction on peatland. In: Characterization and Engineering Properties of Natural Soils, Singapore (2007)

Leshchinsky, D., Marcozzi, G.F.: Bearing capacity of shallow foundations: rigid versus flexible models. J. Geotech. Eng. **116**(11), 1750–1756 (1990)
Mutalib, A.A., Lim, J.S., Wang, M.H., Koonvai, L.: Characterization, distribution and utilization of peat in Malaysia. In: Proceedings of International Symposium on Tropical Peatland, pp. 7–16 (1991)
Oh, E.Y.N., Balasubramaniam, A.S., Surarak, C., Chai, G.W.K., Bolton, M.W.: Interpreting field behaviors of embankment on estuarine clay. In: The 17th International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers, Lisbon (2007a)
Oh, E.Y.N., Surarak, C., Balasubramaniam, A.S., Huang, M.: Observed behaviour of soft clay due to embankment loading: a case study in Queensland, Australia. In: Proceedings of the 16th Southeast Asian Geotechnical Conference, pp. 1–6 (2007b)
Sas, W., Malinowska, E.: Surcharging as a method of road embankment construction on organic soil. In: IAEG International Ongress, United Kingdom, Paper Number: 403 (2006)
Von Post, L.: Swedish geological peat survey with the results obtained so far. Sven. Mosskult. Tidskr. **36**, 1–27 (1922)
Wijeyesekera, D.C., Bakar, I., Ismail, T.N.H.T.: Sustainable construction material for challenging highway technology. ARPN J. Eng. Appl. Sci. (2015). ISSN: 1819-6608
Wijeyesekera, D.C., Numbikannu, L., Ismail, T.N.H.T., Bakar, I.: Mitigating settlement of structures founded on peat. In: IOP Conference Series: Materials Sciences & Engineering, vol. 136 (2016)
Wijeyesekera, D.C., Patel, J.C.: A three level finite difference analysis of the large strain one dimensional consolidation equation. Geotech. J. **2**(1), 1–13 (1998)
Zainorabidin, A., Bakar, I.: Engineering properties of in-situ and modified hemic peat soil in Western Johor. In: Proceedings of 2nd International Conference on Advances in Soft Soil Engineering and Technology, Putrajaya, Malaysia, pp. 173–182 (2003)
Zainorabidin, A., Wijeyesekera, D.C.: Geotehnial challenges with malaysian peat. In: Proceedings of the 2nd Annual Conference on School of Computing and Technology. Advances in Computing and Technology, pp. 252–261 (2007)
Zainorabidin, A., Wijeyesekera D., Jayaratne, R.: Fabric of peat soils using image analysis. In: Proceedings of the 5th Annual Conference on School of Computing and Technology. Advances in Computing and Technology, pp. 38–44 (2010)
Zainorabidin, A., Abdurahman, M.N., Kassim, A., Razali, S.N.M.: Settlement behaviour of Parit Nipah peat under static embankment. Int. J. Geomate **17**(60), 1–4 (2019)
Zornberg, J.G., Christopher, B.R., Oosterbaan, M.D.: Tire bales in highway applications feasibility and properties evaluation. Colorado Department of Transportation Research Branch, Report no. CDOT-DTC-R-2005–2 (2005)
Zwanenburg, C.: The Influence of Anisotropy on the Consolidation Behaviour of Peat. DUP Science (2005). ISBN: 90-407-2615-9