Mitigating Settlement of Structures founded on Peat

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Abstract. Observations made of two common failures of structures founded on peat/organic soil in Johor, Malaysia is presented. Critical evaluation of current lightweight fill technology to mitigate such settlement is also discussed. Lightweight technology, such as Expanded Polystyrene (EPS), has been used in construction on soft yielding ground for decades. Regrettably, some published information of EPS failures to perform on construction sites are also cited in this paper. This paper outlines some concepts leading to the development of an alternative innovative lightweight fill is that the idealised cellular structure of the GCM permit free flow of water and complemented by the mat structure which evens out any differential settlement. A further highlight of this paper is the monitoring of the field performance of this lightweight fill (GCM) as a feasible alternative to fill weight reduction on yielding ground. Hence, a prime research objective was to compare the fill settlements observed with 1m high fill of surcharge loading on peat ground (comparison of the case of using a partial 0.6m high GCM and that of a total of 1m of conventional sand backfill).

Keywords: Soft soil, cellular mat, Settlement mitigation.

1. Introduction
Stability of civil engineering structures depends on the geotechnical properties of the foundation such as shear strength, permeability, and compressibility of the soil. The low strength of highly organic soil such as peat cause excessive settlement and failure of the civil engineering superstructure. Consequent cracking occur on the main superstructure or pavement when there is excessive settlement leading to super structure failure.

Figure 1 (a) shows an example of such settlement failure observed at Parit Nipah, Johor, Malaysia. Although, the main activity at Parit Nipah is farming and therefore the volume of even moderately heavy trucks are limited but the road surfaces shows signs of distress (longitudinal cracking, potholes and differential settlements giving rise to a bumpy road). This adverse problem is due to non-uniform and excessive consolidation settlement. Bumpy roads result from such differentially settling roads proved to be damaging, uncomfortable and hazardous to the threesome of vehicle, driver and passenger. The second example of failure is that which has occurred repeatedly at the bridge approach in Parit Yaani, Johor, Malaysia (Figure 1 (b)). This is a popular road used by local community to commute from Sri Garding to Parit Yaani and it is therefore heavily used. This road has been repaired several times with the placing of additional asphalt. However, sometime (6 month) after repair this
approach begins to settle again. Such affect can be and have been modeled in the laboratory through physical and software modeling. Both sites are considered unfavourable as the local drift material on both sites is either highly organic clay or decomposed peat.

Such soft organic soils are prone to moisture induced ground movements which pose undesirable challenges to the field construction even during this modern age. These types of soil are simply not capable of bearing the load exerted by a structure due its extraordinarily high field moisture content that can be as much as 800% at times [1]. As a result, the structure sinks into the soft soil, somewhat similar to how a person standing in the mud sinks into soft and wet clay. Figure 2 shows the distribution of peat throughout Peninsular Malaysia and their occurrence seems to be confined to the coastal area. Hence, there is an urgently emerging construction issues for structures founded on such areas of yielding soil. Peat and organic soil have been identified as major group of problematic and challenging soils from a civil engineering perspective. Peat is found in many countries, including peninsular Malaysia, where 3.0 million hectares or 8% of the country land area is covered with tropical peat. Peat covers more than 4 million km$^2$ of the planet’s surface and represents 50 – 70% of the total wetlands on the earth [2]. Peat soil is by nature complex and highly variable and consequently its properties cannot be determined with precision. Peat is an organic soil with more than 75% of organic content and therefore poses many problematic physical and mechanical issues such as: soil surface subsidence, high water table, loose soil structure, and high volumes of subsurface woody debris. It is noteworthy that contrarily, these properties are the most favourably desired properties for agricultural purpose; the very productive palm oil farms are popularly located on peat ground.

Figure 1. Road settlement failure; (a) roller coaster scenarios in different settling road at Parit Nipah, (b) bridge approach settlement in Parit Yaani
Many researchers have attempted to provide a mitigating solution with the addition of stabilizing material such as cement, lime, fly-ash, pozzolanas and blast furnace slags [4]. However, the effect of this type of stabilizations is much localised and temporary because the distribution of this non-uniform peat is widely variable both in area and depth.

With decades of research on Forensic Geotechnical Engineering, many innovative approaches have been used to mitigate settlement of structures on peat. For example, Expanded Polystyrene (EPS) was adopted for retaining structures to provide a reduction in lateral pressure as well as preventing settlement and improving waterproofing. Regrettably there are documented instances where the EPS construction sites have experienced floatation failure situation associated with buoyancy forces arising from water level fluctuations. Two examples of such failures were published in Horvath 1999 [5]. The first case was a failure that occurred at Carousel Mall in Syracuse New York. The fill was under construction when a water main burst, filling the surrounding area of the EPS with water. The second case shown is from a roadway in Norway during an unusually high flood. Hence, this project focuses on the development of another innovative lightweight fill which could reduce settlement of structure on peat and eventually reduce the impact on environment.

Lightweight cellular mat structures are presented as a further feasible alternative of weight reducing material in this research study. The idealised cellular structure of the GCM permits free flow of water while the mat structure evens out any differential settlement. The use of cellular solids has been introduced widely to replace or substitute the use of conventional materials like soil and rock. Cellular solid mechanic is different from soil mechanics. Cellular solid is made up of a cell structure that help share the load, and soils are particulate (as illustrated in Figure 3) [6]. Figure 4 shows examples of natural materials with cellular structure as found in wood, cork, sponge, cancellous bone, skull and Plant Stems.
2. Conceptual and Model Study of the Cellular Mat Structure

Physical modelling was carried out through laboratory testing to show the concept of failure by application of lightweight cellular mat structure (illustrated as a rigid foundation) compared to the conventional material (sand used to represent a flexible foundation). This study identified three types of settlement as shown in Figure 5. Figure 5(a) shows the uniform settlement that occurs with a rigid foundation. The tilt of superstructures in Figure 5(b) is a result of variable thickness of the foundation materials leading to differential settlement. The non-uniform settlement in Figure 5(c) is a result of the flexibility of the foundation structures as portrayed by the effect of the particulate material in the conventional field.

Figure 6 shows two different types of failures that occurred at the Palace of Fine Arts, Mexico City and Transcano Elevator, Canada, respectively. The Palace of Fine Arts (The Palacio de Bellas Artes) was built comprising a structural steel frame supported on a raft (or mat) foundation on soft clay. This structure settled in several stages. Based on the pattern of settlement shown in Figure 5 this is referred to as a case of uniform settlement. The second case study shows the non-uniform tilt settlement failure that occurred at Transcano Elevator, Canada. The foundation of the elevator consisted of a large rectangular raft resting on a plastic clay deposit [9]. The foundation settled as a rotational slip and the failure of the structure was due to the instability of the clay to support load placed.
Figure 5. The diagram of settlement failure [8]

Figure 6. Settlement failure; (a) uniform settlement occur on The Palace of Fine Arts (b) non-uniform failure of the Trancano Elevator, Canada

3. Site soil condition
Peat soil is by nature complex and has wide varying engineering properties depending largely on the deposit’s depth below the ground surface and its proximity to the water table. Table 1 shows a summary of the varying properties of peat in Johor by. Based on the vane shear tests conducted, the undrained shear strength of peat at Parit Nipah is around 8-11 kPa (as shown in Table 1). Natural moisture contents observed are commonly in the range of 670 and 808%. Moreover, the liquid limit
and plastic limit are generally in the range of 119 – 410% and 123 - 243, displaying high sensitivity. Compression index as high as 3.76 – 5.30 has been reported by [10]. At this high compressibility, strain rate effects can be significant.

The effectiveness of the cellular mat structure to mitigate settlement was mainly conducted on Parit Nipah peat, which extends to a maximum depth of 6.5m. Underlying this layer is silty clay. The tests were divided into two models – model (1) contained no cellular mat structure and model (2) had cellular mat structure at 0.6m depth, in order to compare the settlement failure of lightweight technology and conventional fill material. These two models were setup in the soil box having a size of 1x1x1.2m on the same site but next to each other. Square cellular mats with size of 0.95m width, 0.95m length and 0.2m depth were fabricated. The first soil box was filled with sand (as a conventional fill material) up to 1m depth. Three layers of cellular mats were placed in the second soil box together with a 0.4m sand cover, amounting to a total height of 1m.

| Parameter                      | Johore Hemic Peat | Parit Nipah Peat |
|--------------------------------|-------------------|------------------|
| Undrained shear strength (kPa) | -                 | 8 - 14           |
| Natural water content, W (%)   | 230 – 500         | 808              |
| Liquid limit, LL (%)           | 220 – 250         | 119              |
| Plastic Limit, PL (%)          | -                 | 123 – 243        |
| Specific gravity (Gs)          | 1.48 – 1.8        | 1.27             |
| Organic content (%)            | 80 – 96           | 95.44            |
| Unit weight (kN/m^3)           | 7.5 – 10.2        | -                |

4. Field Instruments for monitoring the performance
Considering the limitations of the site condition and cost, it was decided to adopt conventional geodetic surveying methods to monitor vertical displacement (or deformation). A special settlement gauge staff was developed to monitor the settlement of the soft ground. The uniqueness of this instrument is that it is lightweight hence not intrusive, easy to use, inexpensive and requires less human resources are required. Moreover, these instruments will be available on site until the completion of the testing period which is approximately about 6 months. Since these instruments will not be moved, more plausible results are expected to be obtained. There will be less soil disturbance compare to other conventional methods. Five settlement gauges were installed in each case and these included an observation at the centre of each soil box test. All settlement gauges were read through the digital auto level (with 0.001m accuracy) to monitor vertical settlement.

The current settlement readings obtained after 60 days of monitoring are shown in Table 2. These readings show evidence that cellular mat structure can be effectively used to reduce settlement and accelerate consolidation settlement. Model 1 with no ground improvement had 41% more subsurface settlement than model 2. The field monitoring of settlement is still ongoing to date.

| Model     | Description                                      | Maximum vertical settlement for 60 days (mm) |
|-----------|--------------------------------------------------|---------------------------------------------|
| Model 1   | Conventional material only without cellular mats | 63.12                                       |
| Model 2   | 0.6m depth of cellular mats + 0.4m depth of sand | 44.53                                       |
The in-situ settlement time plots observed at the centre point of each field soil box test are shown in Figure 6. These plots present the ground level settlement observations at the base of the fill loading, with Figure 7(a) plotted using Casagrande’s log time method, and Figure 7(b) plotted using Taylor’s square root of time method. The settlement data is more demonstrable with Casagrande’s method than the Taylor’s square root of time method. Both figures illustrate the primary settlement of the lightweight fill material to cease somewhere around 25mm (for the conventional fill loading around 33mm for Casagrande’s method and 37mm using Taylor’s method). This confirms that the lightweight fill material reduces and accelerates settlement that occurs on peat ground.

**Figure 7(a).** Measured settlement at the centre of the model (Casagrande’s method)

**Figure 7(b).** Measured settlement at the centre of the models (Taylor’s method)
Both observations presented in Figure 7(a), show two sharp rises (indicating a temporary ground heave) in both setups occurring at a time of around 191 and 815 hours after the commencement of the construction phase. This might be due to the heavy rain that occurred at the test site on the night previous to the day of the said observation. The water table at the site recorded the highest level, corresponding to a depth of 0.358m and 0.470m from the surface respectively. The heavy rain fall caused the ground in the vicinity of the test site to be flooded. It was observed that at the covered test site the water entered the sand fill box from the bottom and caused the ground to rise and heave (also made the sand moist and heavier). Even though so, the lightweight fill experienced lesser heave compared to the conventional fill. This confirms that the cellular structure of the innovative lightweight material functioned well in reducing the floatation by allowing the flow of water through it.

5. Applicability of Terzaghi Theory for Peat
The commonly adopted Terzaghi’s one dimensional consolidation theory assumes that the soils are fully saturated, homogeneous, the soil compression and water flow occurs vertically, and to obey a generalized Darcy’s law which takes into accounts the movement of solid particles. Moreover, the classical Terzaghi theory only considers small strain consolidation which is definitely contrary to the settlements experienced with the peat ground settlement.

Hence, for the field study on fibrous peat at Parit Nipah, it can be considered that some of the assumptions of Terzaghi theory is invalid and therefore the Terzaghi theory is not appropriate to predict settlement on peat soil. This is because fibrous peat is not homogeneous and the consolidation process takes a long time due to the high fibrous and high moisture content. However, hemic peat which is very highly decomposed maybe considered as a homogenous soil. Besides that, peat is a type of soft soil that is expected to behave as anisotropic. It is to be expected that if there is a dominant direction along which the fibres (old tree roots etc) are aligned, the peat will show anisotropic behaviour. The reaction of peat when loaded perpendicular to the main fibre direction will be different than it is loaded in the main fibre direction.

Furthermore, since peat is a soft soil, settlement predictions need to consider instead the large strain consolidation theory such as the Gibson theory. A further restriction to the use of small strain theory to peat settlement is that it also invalidates the assumption that the soil particles are incompressible and defining strain in an element of a fixed volume and ignoring the boundary movement as consolidation occurs.

6. Conclusions
This study has helped to obtain the field evidence for performance of the innovative lightweight material as a feasible and effective alternative lightweight fill. It is concluded that the lightweight fill mat can help mitigate settlement in both reducing and accelerating settlement that occur on soft yielding ground like peat. Field performance observations showed that the GCM has reduced the total settlement by 41% compared with that observed using conventional fill material. Furthermore, by using GCM the primary consolidation only needs 25 hours to complete compared to the conventional fill material which required 44 hours. The promising performance as seen from the preliminary data obtained creates an opportunity for the material to be tested in the scale of a real trial embankment.

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