VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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PHYSICAL AND SOFTWARE MODELLING FOR CHALLENGING SOIL STRUCTURE INTERACTION

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ABSTRACT

Construction of structures on soft soils gives rise to some difficulties in Malaysia and other countries especially in both short and long term deformation. The most critical geo-environment challenges are excessive settlement and in particular differential settlement leading to hazardous and discomfort in road usage (bumpy road) and structural distress (differential crack) in buildings. The settlement studies in soft yielding soil require effort, time and expense through field and/or physical model testing. Thus software modelling is a better and faster alternative to solve many such problems with varying parameters. Concepts in the prediction and observation in physical modelling using cellular mat are presented.

Keywords: soil settlement, physical and software modelling, soft soils, lightweight fill.

INTRODUCTION

In modern Civil Engineering, emerging problems are solved using both physical and software modelling. Modelling is defined as a process of solving physical problems by appropriate simplification of reality. The skill in modelling is to spot the appropriate level of simplification, distinguish important features from those that are less important in a particular application and use engineering judgment. The advancements in computational techniques and material science are incorporated into a software algorithm based on the analysis of physical phenomena and constitutive laws applied in geotechnical engineering and in this case, soil structure interaction.

In soft yield foundation the self-weight of the structure cause excessively undesirable settlement. This constraint intuitionally includes any construction of structures on soft soils that necessarily undergo settlement either in short and/or long term. Such settlement as large as 0.5m - 1.0m maximum have been recorded (Burland *et al,* 2009). Soft soils are characterised by low strength and rapid settlement for some foundations in unavoidable circumstances which lead to ground failure.

An example of soft soils is soft organic clays and peat which have the characteristics of very low shear strength, high compressibility and high permeability. Figure-1 shows the area covered by peat soils in Malaysia. These raise challenges for engineers facing all sorts of problem to design and construct foundations of building, road and highway embankment. They are subjected to large primary and long-term consolidation settlement even when subjected to a moderate load.

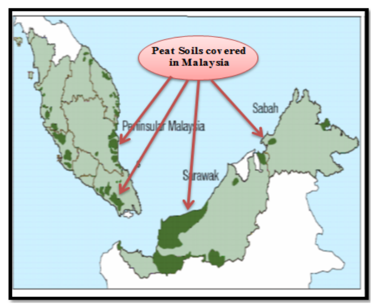

Figure-1. Location of peat swamps in Malaysia (modified from Zainorabidin and Wijeyesekera, 2007).

Recently some of the construction developers have tried solving these extensive problems by using lightweight fill material such as expanded polystyrene EPS, tyre shred etc. An example of such use was lightweight concrete pile which generally has low density and low strength compared with normal concrete pile. (Sulaemen *et al*, 2010) The use of the lightweight concrete for piling is very rare due to high porosity and being poor in strength.

CHALLENGING AND PROBLEMATIC SOILS

Soil structure interaction (Soft soils)

Soils have many different properties, including water holding capacity, pH (whether the soils are acid or alkaline), texture and structural architecture. These properties merge into soils whereby they are applied for a wide range of purposes. The differences in soil structure behaviour usually influence the development of houses and buildings having numerous ways of structure or architecture. The particles of sand and clay in a soil rarely

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occur as separate particles but are more or less loosely combined into aggregates.

Types of structure in soil depend to a large extent on the texture, the amount of organic matter in the soil and the way the land is managed. The aggregates that make up the soil fabric or microstructure may be as small as a few millimetres such as granules and crumbs or as large as several centimetres in superstructures such columns and prisms. Soft soils are loose in nature and does not have strong shear strength in the soil particles. Soft clay and peat are among the examples which belong to this group.

Properties of challenging soft clay and peat soil

Soft clays are defined as cohesive soil whose water content is higher than its liquid limit. Soft clays are well known for their low strength and high compressibility (Ho and Chan 2011). Based on the index properties of the soil, the soil can be categorized as CH (Inorganic Clays of High Plasticity) according to Unified Soil Classification System (Robani and Chan, 2009). The physical properties of Batu Pahat soft clay at RECESS have been experimentally investigated by many researchers as shown in Table-1.

Table-1. Physical properties of soft clay in Batu Pahat.

Typical average of geotechnical parameters	Researchers	
	Robani and Chan (2009)	Ho and Chan (2011)
Bulk Density (Mg/m3)	-	-
Specific Gravity	2.62	2.62
Plastic Limit (%)	32	32
Liquid Limit (%)	68	68
Plasticity Index (%)	36	-
Average Moisture Content (%)	84	85
Cohesion, c	10	13.80
Friction Angle, ϕ	-	13.10

Peat has been described as ''organic soil'' and as a histosol. This is on the basis of mass composition (Murtedza *et al*. 2002), i.e., soils that contain at least 65 % organic matter or, conversely, less than 35 % mineral content. Zainorabidin *et al*, (2007) stated that the high natural moisture contents result from the water that is held in the organic matter and cells of the plant. Accordingly, the water content is higher for fibrous peat than that for other peats.

Organic contents in the range of 65~98 % have been reported. Liquid limit and plastic limit properties also show higher ranges of 190~550% and 100~297%, respectively. The physical properties of peat soil in Malaysia have been experimentally investigated by many researchers as shown in Table-2.

Table-2. The physical properties of peat soil in Malaysia (Zainorabidin *et al*, 2007).

Soil deposit	West Malaysia peat and organic soil	East Malaysia peat and organic soil	Johore hemic peat
Natural water content, W (%)	200-700	200-2207	230-500
Liquid limit, LL (%)	190-360	210-550	220-250
Plastic Limit, PL (%)	100-200	125-297	-
Plasticity Index, PI (%)	90-160	85-297	-
Specific gravity (Gs)	1.38-1.70	1.07-1.63	1.48-1.8
Organic content (%)	65-97	50-95	80-96
Unit weight (kN/m3)	8.3-11.5	8.0-12.0	7.5-10.2
Undrained Shear strength (kPa)	8-17	8-10	7-11
Compression Index,Cc	1.0-2.6	0.5-2.5	0.9-1.5

VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
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CONCEPT OF SETTLEMENT IN SOFT YIELDING SOILS AND METHODS OF MITIGATING SETTLEMENT

Concept of soil settlement

When a load is applied or the pore water pressure is decreased in compressible foundation layer, it increases the vertical effective stress. This increase in stress causes a time dependent vertical strain in the soil causing the ground to settle. Table-3 outlines the soil settlement scenarios that occur due to other causes.

Table-3. Some other causes in soil settlements.

Causes of settlements	Description of the way in settlements occur	References
Moisture content changes	Soft clays expand due to changes in volume (increase or decrease of water content)	Foster et. al, 2013
Moisture extraction through vegetation	Draining effect of the roots from trees.	Atkinson, 2007
Lowering in groundwater table	Water table in the surrounding ground is lowered when water is pumped out from an excavation. This causes a reduction in water table and increases the effective stress in soil beneath (consolidation)	Atkinson, 2007
Changes in temperature	Severe shrinkage (furnaces) in clay soils occur due to drying out.	Wray, 1995
Seepage and scouring	Movement of water flushes out fine particles: Seepage- removal of soil particles by surface water or stream (scouring).	Ouyang et. al, 2015
Loss of lateral support	Bearing capacity of soil directly beneath a footing is dependent on the lateral support provided by the surrounding soil	Khan, 2012
Effects of mining subsidence	Coal mining – Coal is continuously mined across a wide surface as workings advance, the space left is partly filled with waste material and the pit props removed. Then the unsupported roof slowly subside with the overburden, up to the ground surface thus undergo settlement	Foster et. al, 2013

The soil structure interaction also plays a significant role in the distribution of settlement. Figure-2 compares schematically the settlement profile for flexible and rigid foundations. The interaction from the rigid foundation is to redistribute the stresses in such a way to provide a uniform rigid foundation settlement. Leshchinsky and Marcozzi (1990) mentioned that the effect of stiffness of a shallow foundation on its ultimate load bearing capacity has been observed from the behavior of small-scale flexible and rigid foundation models resting on dense sand. The results indicate that reducing the foundation's stiffness at soil interface may significantly increase its load-bearing capacity but also is associated with increased settlement. It is suggested that the apparent increase in bearing capacity is due to differences in the contact pressure distributions combined with the phenomenon of progressive failure.

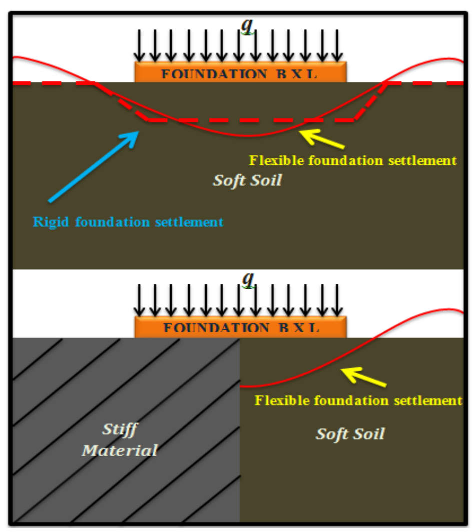

Figure-2. Settlement in shallow flexible and rigid foundation.

Types of settlements

Settlements occur in four different ways viz:

(i) Uniform settlement - Settlement is uniform, if all paths of the structure undergo equal settlement. Uniform settlement occurs under a structure supported by a very rigid raft foundation. If the settlement is

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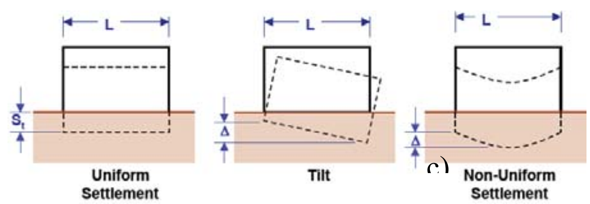
uniform, structural failure will not take place. However, if the uniform settlement is very excessive its function is impaired. (Das, 1999) (See Figure-3a)

(ii) Tilt settlement - The structure experiences differential settlement. (Lambe and Whitman, 2008 and Naser, 2013) (See Figure-3b)

(iii) Angular Distortion/Non-uniform settlement - When two foundations supporting columns/walls settle unequally, the structure will be subjected to angular distortion. If angular distortion or tilt exceeds certain limits, the structure could fail in several ways. (Das, 1999) (See Figure-3c)

(iv) Permissible Settlement - Different type of structures have their limit to tolerate a certain amount of maximum or differential settlement. It is difficult to measure differential settlement and hence permissible settlement is expressed in terms of maximum total settlement.



a) b)

Figure-3. Types of Settlement (Lambe and Whitman 2008).

Field settlement monitoring equipment

The hydrostatic profile gauge (shown in Figure 4) consist of a control and readout unit and a length of triple tubing connected to a settlement probe which can be pushed (with aluminium rods) or pulled (with a draw-cord) through the access tube. Two of three small tubes are filled with water and are constantly back-pressurized in order to overcome surface tension effects, and to prevent the formation of bubbles. Measurements of elevation are taken at regular intervals in the access tube which is laid in a sand-filled trench. The hydrostatic head at the probe 'H' is measured with the aid of a differential pressure transducer. These readings are related to a reference point outside the tube and in this manner a complete profile of the tube can be established. By comparing profiles taken at different times, the vertical displacement of the tube can be determined to an accuracy of ± 1.0 cm, which is excellent for this application. (Zvanut, 2003). This settlement defines that which occurs in a yielding soil layer. The deformation of soil layer then affects the embankment on top of it. The top surface of embankment will cease to be horizontal and produce the bumpy road effect.

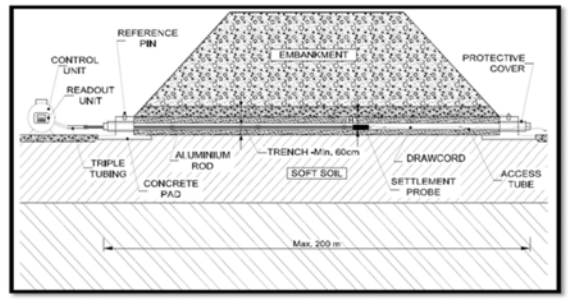


Figure-4. Schematic arrangement of the hydrostatic profiler (Zvanut, 2003).

PHYSICAL MODELLING OF PROBLEMATIC SOIL STRUCTURE INTERACTION

Settlement observation with full sponge model

The initial testing was made on the full length of sponge fill in a physical modelling soil box having dimensions of 100cm (length) x 50cm (width) x 40cm (height) as shown in Figure-5 below.

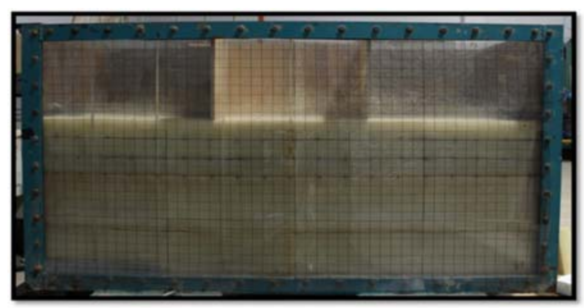


Figure-5. The placement of three equal size sponges in the physical modelling box with the full dimension of 100cm (length) x 50cm (width) x 40cm (height).

The test was conducted to determine the differences in settlement between flexible, rigid and mat foundations. From here, an observation of the alignment or deformation curve that occured shown in Figure-6 and Figure-7 observed using three coloured of sticks inserted at equal distances and layers of the sponges. The first layers of blue sticks exhibit that the top layer which indeed a quick and large settlement, green sticks as the medium layer exhibit partial settlement whereas the final red sticks exhibit the final layer which did not show any deformation. The following observation was made from Figure-6 and Figure-7 where a rigid foundation (mat design) and flexible foundation were tested respectively.

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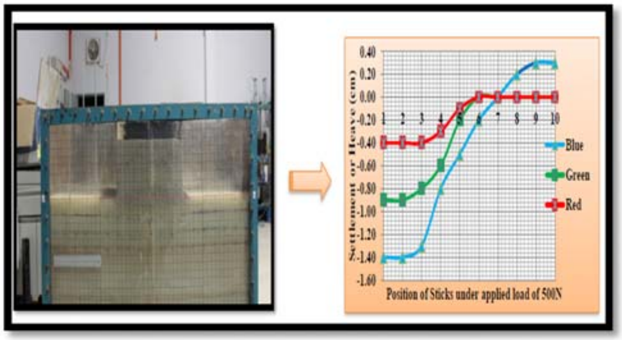

Figure-6. The graphical results obtained from flexible full sponge.

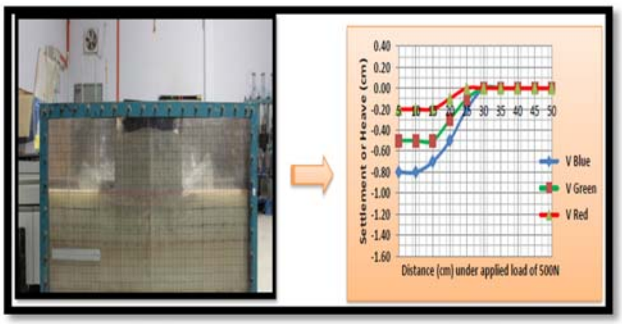

Figure-7. The graphical results obtained from mats 4-layers full sponge.

- The mat design with 4-layers clearly reduced the uneven settlement compared to other foundations (flexible, rigid and 1-layer mats).
- The Mat's effect is demonstrated (Figure-7) a 50% reduction in settlement that will occurs with the normal flexible full design shown in Figure-6.

Settlement of fill loading on hemic peat soil

The analysis of flexible and innovative cellular mat foundation using the physical modelling box is described. In order to evaluate the settlement occuring in peat soil, the observation of analysis was made on surface of the physical modelling box shown in Table-4, to predict the total number of mats (layers) needed to reduce the settlement in peat soil. Particularly the test was conducted for half hemic peat soil with half solid to simulate the settlement in a bridge approach embankment.

Table-4. The differences in settlement design in foundations (half peat soil).

<table>
<tr><th>Foundations</th><th>Control Load</th><th>Applied Load 500N</th></tr>
<tr><td>Flexible</td><td></td><td></td></tr>
<tr><td colspan="3">Remarks: In the flexible form there is large amount of differential settlement occur as seen in the tilt of the structure.</td></tr>
<tr><td>Rigid</td><td></td><td></td></tr>
<tr><td colspan="3">Remarks: Differential settlement occur when using uncut piece of innovative cellular mat.</td></tr>
<tr><td>Mats 3-layers</td><td></td><td></td></tr>
<tr><td colspan="3">Remarks: The settlement is being reduced compared to the others (flexible, rigid and 2-layers) thus as predicted if more layers are used then the level between innovative cellular mats and the solids will vary.</td></tr>
</table>

CONSTRUCTION MATERIAL

Super-structure loading from the construction materials are often interpreted from diffent kind of loading with suitable weight and the size of area built on. Heavy superstructures such as Petronas Twin Towers (Figure-8) required loading to be developed from the heavy materials with approximate weight over 300, 000 metric tons per tower. Compared this to the embankment fill at Muar which required preloaded vertical drains as shown in Figure-9, the maximum loading being transferred from the road surface aprroximately 51,000 kg from the articulate vehicle with 7 axles (1+2+4)/trailers.

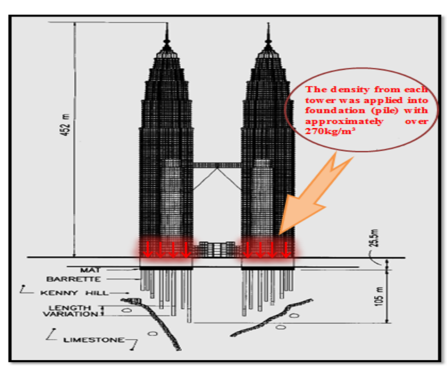

Figure-8. Tower profile with foundations (modified from Thornton *et al*., 1997).

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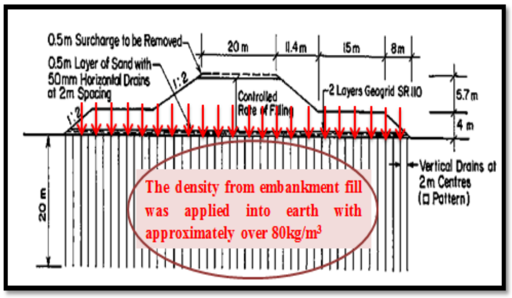

Figure-9. Embankment constructed on preloaded foundation stabilized with geogrids and vertical drains (modified from Indraratna *et al*., 1997).

LIGHTWEIGHT STRUCTURAL MATERIAL

Cellular solid structure

Human cells are connected with each other as a solid and flexible structure. The pressure and other kind of physical contact distribute uniformly to the epidermis area. If any part of the cells is damaged due to minor injuries or etc./dead cell, other parts of cells will help in sharing the shear resistance from physical form of forces without any massive failure to the structure.

This theoretical concept can be applied to the cellular mat whereby the cells being combined into a solid cellular structure thus help to reduce the pressure exerted from load applied to any part of structure. Even if there is any one of the cells shattered or damaged, the other parts of cells will compensate the frictional and shear resistance force without any failure.

Cellular solid structure is made up of an interconnected network of solid struts which form the edges and faces of cells. The typical types of structures are shown in Figure-10.

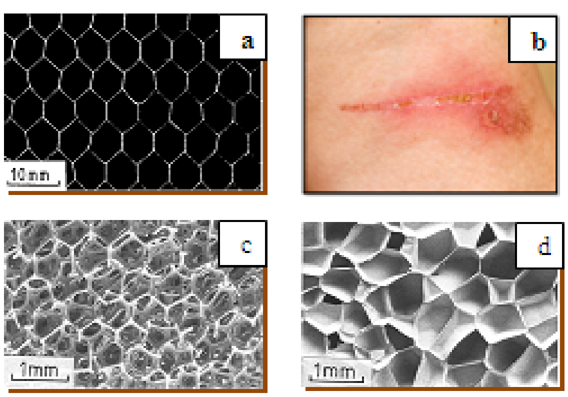

Figure-10. [a] Two-dimensional honeycomb (Gibson, 2004), [b] Self-healing structure, [c] Self-compensating open cell polyurethane foam (Gibson, 2004), [d] Expanded polystyrene (EPS) structure, (Gibson, 2004).

Cellular solids have physical, mechanical and thermal properties which are measured using the same method as those used for fully dense solids. Four main properties that define cellular solid are density, thermal conductivity, Young's modulus and the compressive strength. These properties create foams which cannot easily be filled by fully dense solids and offer potential for engineering ingenuity.

The low densities permit the design of light and stiff components such as large portable structures. The low thermal conductivity allows reliable thermal insulation that can be done using vacuum-based methods. The low stiffness makes foams ideal for a wide range of cushioning applications such as elastomeric foams. The low strengths and large compressive strains make foams attractive for energy-absorbing application.

Engineering application of cellular structures

The honeycomb of the bee portrayed as prismatic hexagonal cells usually used in metal and ceramic for panels in advancing the aerospace components. This metal (aluminium) having energy absorbing applications (can be seen in Apollo II and aircrafts using crushable aluminium honeycombs as shock absorbers). The advantages of this type of cellular studies in aircraft are in reducing the wind turbulence, obtaining standard wind tunnel profile (temperature and flow speed) and allow the minimization of the amount of used material to reach minimal weight and minimal material cost. Figure-11 shows the honeycomb cellular structure found in aviation.

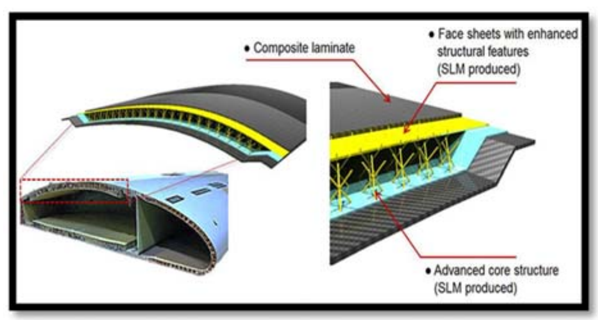

Figure-11. Left: Standard honeycomb sandwich design. Right: Advanced features of the composite core structure manufactured with selective laser melting (SLM) (http://www.rmit.edu.au/seh/staff/intheloop/october2013).

Expanded Polystyrene (EPS) geofoam is a lightweight, closed cell, rigid and plastic foam invented in 1950s (BASF, 1997). Geofoam has been utilized in a number of countries (Norway, Netherlands, United States as shown in Figure 12, Japan, Germany and Malaysia). A 139m section of a road in Solbotmoan, Norway experienced significant settlement.

The rate of settlement is large and increasing. The subgrade condition was 5m of peat. Below the peat there was 13m of soft silty clay. In 1975, a road embankment

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was excavated and bark was added up to the ground water level. Foam of height 1.2m to 2.0m (Figure-13) was placed on the top of the bark. For the following five years the road was subjected to traffic. The total settlement varied between 0 and 80mm with a reduced rate of settlement (Elragi, 2006).

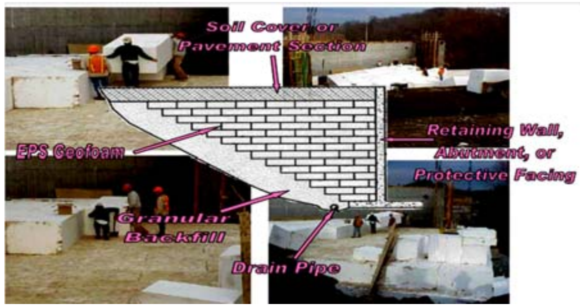

Figure-12. Design and construction of expanded polystyrene fill as a lightweight soil replacement (State of New York Department of Transportation Geotechnical Engineering Bureau, 2008).

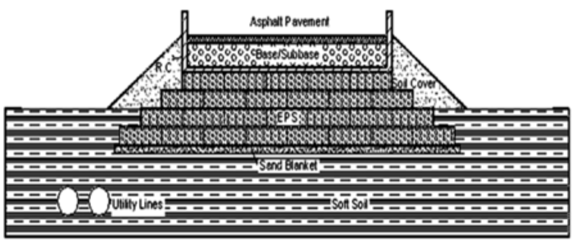

Figure-13. Settlement reduction on utility pipes utilizing EPS Geofoam (NRRL, 1992).

SOFTWARE MODELLING

Geotechnical software

Software is widely developed in every sector of industry thus to minimize and facilitate various kinds of complex problems. For example it can be clearly seen in the application of geotechnical engineering where the solution or prediction of long term soft soil settlement can be modelled into an acceptable scale dimension (centrifuge) thus providing sufficient results in short period. Abusharar *et al*. (2008) stated that the finite element analysis using PLAXIS software was calibrated to investigate and compare the consolidation behavior of a road embankment constructed on both CFG-lime columns and SC-lime columns. Significantly the CFG-lime columns improved the long term stability of the embankment due to having a higher compression modulus factor compared to SC columns.

According to Zdravkovic *et al*. (2002), most of the studies involving the trial embankments are usually simplified into two-dimensional (2D) plane strain finite element software. Back analysis of three full-scale tests fills at St. Alban test embankment, Malaysia trial embankment and the Vernon test embankment were investigated using finite element software ABAQUS have highlighted some important considerations in the design (shape factor) and interpretation of test embankment (Qu *et al*., 2009). Wu *et al*. (2011) mentioned that a system of measurements provided the necessary data for construction control to assure adequate consolidation thus providing an opportunity to evaluate the reliability of predictions of settlement and consolidation using revised finite element analysis model.

Huang *et al.* (2006) focused in providing a complete case study of consolidation behavior of a trial embankment on soft clay located in the coastal region of Eastern Australia by comparing conventional settlement analysis and finite element analysis with field monitoring data from instrumented embankment to achieve reliable correlation between laboratory and field data including the improvement of field instrumentation. Model calibration using inverse analysis technique was applied to minimize the difference between experimental data (lab and field scale) and numerically computed results thus to avoid the finite element simulation for reproduce the soil behavior which clearly leave major significant challenges where real soil is highly nonlinear material with both strength and stiffness depends on stress and strain level (Calvello and Finno, 2004).

Modelling in PLAXIS

The modeling of full embankment was done for both flexible and rigid foundations. The underlying soil of the fill embankment was placed with (mat foundation) and without (flexible foundation) using new lightweight fill structure (innovative cellular mats) as shown in Figure-14 and 15 respectively. Table-5 depicts the values of full plane strain embankment occuring in both horizontal and vertical directions.

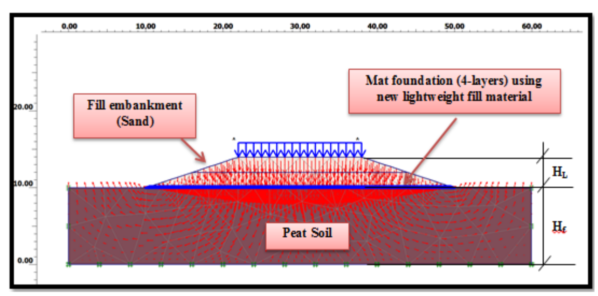

Figure-14. The embankment model with new lightweight fill material in mats form settle as rigid base foundation.

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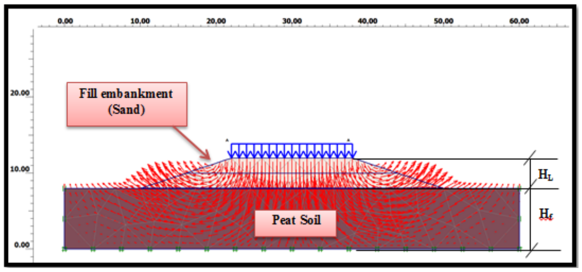

Figure-15. The embankment model acted as flexible base foundation.

Both Figures-15 (rigid) and 16 (flexible) show simulated and visualized settlement behavior as defined earlier from Figure-2.

Table-5. The displacement of the embankment model in both flexible and rigid foundation.

H_f/H_L	l_c/l_e (Flexible)	l_c/l_e (Rigid)
0.5	0.227	0.114
1.0	0.321	0.228
1.5	0.379	0.360
2.0	0.398	0.692
2.5	0.454	0.760

Table-5 and Figure-16 are plotted for both flexible and rigid for different dimension embankment height to soft soil ratios. The software modeling plotted in Figure-16 shows some intriguing and significant result between flexible and mat 4-layers foundation which closely relates to the earlier result of physical modeling from Figure-7. The PLAXIS 2D modeling is indeed has a great advantage compare to the physical modeling done in laboratory where the parameters, size and boundary can be always variable.

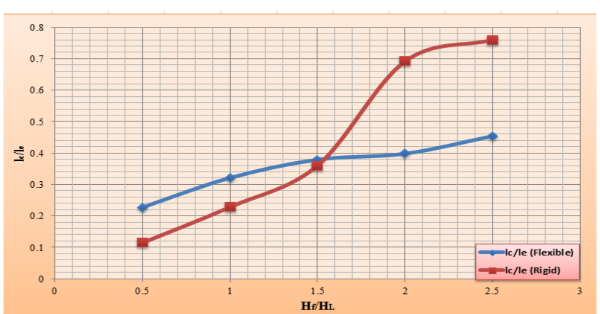

Figure-16. The displacement take place in both flexible and rigid base foundation.

Therefore software using the finite element method reduce unnecessary wastage in time, expenditure and effort spent in physical modelling.

CONCLUSIONS

This paper identified that the soft soils become the major cause of problem that need to be solved in term of engineering. An investigation was made to find the efficacy of the application of a porous lightweight product that will minimize the differential and non-uniform settlement on soft yielding soils. Series of objectives have developed from this application of new lightweight product via both physical and software modelling.

The outcomes show a comparison between these physical and software models testing to be:

a) Develop calibration between physical (laboratory/case studies scale) and software modelling applications in studying differential settlement problem.
b) Critical evaluation of current design guidelines for the use of lightweight cellular mats in highway construction.
c) Comparison of the concepts in predicted and actual settlement scenarios with the use of cellular mats.

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