The study of buoyancy behaviour of polyurethane foam as a ground improvement by constant rate strain test

D C Lat1,2*, N Ali1, B Mohamed Jais3, N Z Mohd Yunus1 and A N Zainuddin2, and D A Mat Yusof2

1 Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia
2 Faculty of Civil Engineering, Universiti Teknologi MARA Pasir Gudang, Johor
3 Faculty of Civil Engineering, Universiti Teknologi MARA Shah Alam, Selangor

* dianacl@uitm.edu.my

Abstract. The buoyancy of lightweight polyurethane (PU) foam as a ground improvement is of important aspect to be investigated to ensure the stability of the founded structure. Constant Rate Strain test (CRS) was carried out to evaluate the buoyancy behavior of PU foam in water and to determine the effect of different water content of the marine clay to the settlement and uplift in short term undrained condition. The percentage thickness of PU foam to soft clay layer and water varies from 10% to 80%. The buoyant force of PU foam to immerse at the water surface depends on the thickness of PU foam that displace the water. On top of that, water content in the soil has a crucial effect on the buoyancy of PU foam. For PU foam partial replacement on water, the downward displacement is very less compared to the settlement for PU foam partial replacement on marine clay soil due to higher buoyant force produced in the earlier condition. However, the settlement for improved condition of marine clay reduce significantly compared to the condition of existing condition. In addition, the reduction in soil weight as part of the soil is replaced with lightweight PU foam assist to reduce the overburden load imposed on the soil. Therefore, settlement reduces significantly with the increase in PU foam thickness. The verification of the buoyancy test results was done using finite element model PLAXIS 2D.

1. Introduction
The weight of a fill imposes new stress on soft ground and buried structures thus may overload them and cause damage to the underground infrastructure. Normal fills are heavy, for example 2 m thick fill has about the same weight as a six-storey building. If the natural soils below the fill are soft, its weight will cause them to consolidate thus producing large settlement at the ground surface. Other than that, the weight of fill behind retaining wall imposes stresses on the wall and decreases the stability of slope when the fill is placed on the slope possibly leading to a landslide. Therefore, in this study, alternative to geofoam namely polyurethane foam is used as a fill material for the purpose of ground improvement. The ground improvement work is executed by partially excavate the soft soil at shallow depth and replace the soft soil with PU foam. To produce the PU foam, two chemicals namely polyol and isocyanate are mixed in a rectangular-shaped foam work. Reaction occurs between both chemicals, then expands and hardens in few minutes to produce PU foam slab. Major concern for lightweight material as a ground improvement application is the buoyancy of the materials [1]. Study by Stephen [1] revealed that geofoam was potentially vulnerable to uplift movement during periods of flooding due to inadequate
weight of the earth fill above the geofoam. There were a few failure cases of embankment founded on lightweight geofoam reported by Frydelund [2,3] due to buoyancy. The thickness of the foam is an important consideration whereby it effects the reduction in weight and buoyant force [4]. Buoyancy turned out to be the primary controlling factor in determining the most cost-effective redesign alternative and corresponding factor of safety against uplift [5]. The challenge to cast lightweight treated soil below water table is the unit weight control to avoid buoyancy and the effect of mechanical behaviour due to considerable water pressures [6]. Study by Timothy et al. [7] found that the EPS geofoam buoy up due to its closed-cell structure and light weight. Mohamed Jais [8,9] has successfully undertaken the rapid remediation works using polyurethane (PU) foam injection system in road construction and maintenance works on soft soil. On top of that, PU foam inclusion has successfully improved compressibility of peat soil [10].

2. Research Methodology

2.1 Preparation of PU foam sample
Polyol and isocyanate were mixed in an aluminium mould of 150 mm diameter using spatula. The mixtures reacted to each others, expanded and hardened in few minutes as shown in Figure 1. The prepared polyurethane foam was removed from the mould after 24 hours and have been cut into average size of 76 mm in diameter that fixed into the CRS body. There are four (4) numbers of sample with various thickness and at least three (3) different sample specimens were prepared for each thickness to achieve reliability in the data obtained. Average of the three data represented the results of one sample.

![Figure 1.](image)

*(a) Polyol and isocyanate raw materials (b)Mixing process of chemicals (c) Chemicals reaction to produce PU foam, expand and harden*

2.2 Soil Properties
The physical and engineering properties of marine clay soil were obtained from laboratory tests those were carried out on a few samples of marine clay soil taken from Selangor area as tabulated in Table 1. The tests were conducted with reference to BS 1377:1990. The properties of soft clay were obtained from laboratory test on soft marine clay soil such as Consolidated Undrained (CU) test and 1-D Oedometer test. Total and effective stress parameters were obtained from CU test whilst consolidation parameters were obtained from Oedometer test conducted on soft marine clay soil. The properties of PU foam were obtained from Unconfined Compression Test (UCT) those were carried out on PU foam.

2.3 Finite Element Analysis PLAXIS 2D
Finite element analyses using PLAXIS 2D were carried out on different thickness of PU foam those are 1 m, 1.5 m, 2 m and 3 m, respectively as well as existing condition. The soil excavation depth is based on the PU foam thickness as the replacement with PU foam will be done afterwards. The limitation of PU foam thickness is up to 3 m considering the difficulties, stability and safety of excavation works on the soft soil. The model of analysis for existing and improved conditions are shown in Figures 2 and 3.
Figure 2. Condition of the site before ground improvement with PU foam partial replacement.

Figure 3. Condition of the site after ground improvement with PU foam partial replacement.

Table 1. Properties of soil and PU.

|       | Soft clay | Hard layer | PU                |
|-------|-----------|------------|-------------------|
| Type  | Undrained | Drained    | Non-porous        |
| Model | Soft Soil Creep | Mohr Coulomb | Linear Elastic |
| $\gamma_{\text{unsat}}$ [kN/m³] | 14 | 18 | 3.7 |
| $\gamma_{\text{sat}}$ [kN/m³] | 15 | 20 | - |
| $k_x$ [m/day] | $1.45 \times 10^{-5}$ | 0.010 | - |
| $k_y$ [m/day] | $1.45 \times 10^{-5}$ | 0.010 | - |
| $E_{\text{ref}}$ [kN/m²] | - | 50000 | 30000 |
| $\square$ [-] | 0.495 | 0.3 | 0.3 |
| $c_{\text{ref}}$ [kN/m²] | 3 | 5 | - |
| $\phi$ [°] | 22 | 30 | - |
| $\lambda^*$ | 0.093 | | |
| $\kappa^*$ | 0.041 | | |
| $\mu^*$ | 0.0046 | | |

2.4 Constant Rate Strain (CRS) Test
CRS test was conducted on the sample of marine clay soil and water with PU foam partial replacement. Buoyant force was measured by applying strain rate of 1 mm/min whilst the force and displacement
were recorded. The thickness of samples including PU foam was 45 mm and the diameter was 76 mm for water for buoyant force determination.

![Figure 4](image1.png)

**Figure 4.** (a) Empty mould, CRS mould filled with (b) water (c) soil with 75% water content (d) optimum water content.

![Figure 5](image2.png)

**Figure 5.** PU foam was placed on the soil or water followed by platen load (for soil only).

![Figure 6](image3.png)

**Figure 6.** Setup of CRS equipment

Whilst for soil condition, the thickness of soil including PU foam was 35 mm as the length to diameter (L/D) ratio for CRS equipment should not less than 2. PU foam thickness varies from 5 mm, 10 mm, 15 mm and 20 mm. The test was terminated when the recorded pressure achieved 600 kPa. For soil condition, the samples were prepared in two water content conditions those were with optimum soil water content of 32% and higher water content of 75% respectively. Blank sample of soil without PU foam was also being tested. The purpose of CRS test carried out for PU foam on water sample was to determine the buoyant force of the PU foam on water whilst this test was carried out on the soil sample to evaluate the effect of different water content of soil to the settlement and uplift of the ground improved with PU foam partial replacement. Figures 4 to 6 show the preparation and setup of CRS test.
3. Results and Discussions

3.1 Relationship between buoyant force and PU foam thickness
CRS test was carried out for PU foam partial replacement in water to determine buoyant force for different thickness of PU foam. Initially the PU foam was floated off on the water due to the weight of PU foam is lighter compared to water.

![Figure 7](image)

Figure 7. Linear relationship between PU foam thickness and buoyant force.

Once it is loaded, the non-porous PU foam is pushed under water and the increase in force to push the PU foam to displace the water and immerse under water surface is recorded as buoyant force that is pushing upwards to counter the downward force. Archimeedes’ principle [11] is valid in this test as the buoyant force recorded is equivalent to the weight of water that is displaced by object namely PU foam. Therefore, buoyant force increases with the increase in PU foam thickness as more water is displaced by the PU foam as shown in Figure 7. Thus, the buoyant force of PU foam in water equals to the unit weight of water (9.81 kN/m$^3$) multiplied by the thickness of PU foam per square meter area.

\[ F_b = 0.01T_{pu} \]
\[ R^2 = 0.9946 \]

3.2 Verification with Finite Element Model (FEM) PLAXIS 2D
The soil in FEM analysis is in saturated condition and the water table is at the ground surface. The uplift occurs when the upward force bigger than downward force (overburden load). Upward force is calculated based on the buoyant force by Archimedes’ principle [11] whereby in this study, the water content in the saturated soil is replaced by PU foam, thus, the upward force which is equal to buoyant force is the unit weight of water (9.81 kN/m$^3$) multiplied by thickness of PU foam per square meter area. Figure 8 shows uplift occurs for improved conditions when the overburden load (downward force) per square meter area is lesser than upward force per square meter area as shown by columns 1 and 2. When the overburden load per square meter area equals or greater than upward force as shown in the third column of Figure 8, no uplift occurs. Therefore, the buoyant force determination from CRS test is equivalent with the results obtained in FEM analysis.
### Figure 8. Uplift and settlement of ground improved with different thickness of PU foam.

#### 3.3 Performance for different thickness of PU foam with respect to different water content of soil

CRS test is carried out to determine the uplift and buoyancy of different thickness of PU foam for ground improvement works. The water content of the tested soil are based on optimum moisture content (omc 32%) and the moisture content exceeded the optimum water content (mc 75%) whereby the soil is in soft condition. For optimum moisture content of the clay, the strain is high which is 0.6% for 300 kPa stress for blank soil sample. The strain decreases with the increase in PU foam thickness as shown in Figure 9. The strain is in downward displacement indicating the occurrence of settlement. For each thickness of PU foam, the increase in stress causes the increase in strain. The strain is limited to 600 kPa and still there is no sign showing the reduction in strain as the PU foam is very stiff and not showing much defect after compression. On the other hand, for the blank sample of clay soil with 75% moisture content, the strain is 1.2% for the stress of 300 kPa which is higher compared to the optimum moisture content condition as shown in Figure 8.

The same trend occurs for 5 mm PU foam as a ground improvement. However, the soft soil with 75% moisture content when improved with 10 mm PU foam and higher tends to displace in upward direction. This is because the PU foam is floating on the soft soil and when loaded in undrained condition, the PU foam displaces in upward direction as the buoyant force pushes the PU foam upwards, thus the strain is acting in upward direction. The upward displacement increases with the increase in PU foam thickness. For each thickness of PU foam, the upward displacement increases with the increase in stress. This is due to the uplift of PU foam which produces upward force, increase the stress in short term condition. This stress probably will reduce when the water is drained out in long term condition. The buoyancy of

| Thickness of PU foam (m) | Overburden load per square meter area (kN) |
|-------------------------|------------------------------------------|
| Existing condition      | 0kN                                      |
|                         | 5kN                                      |
|                         | 10kN                                     |
| 1                       | 0kN                                      |
|                         | 5kN                                      |
|                         | 10kN                                     |
| 1.5                     | 5kN                                      |
|                         | 10kN                                     |
|                         | 15kN                                     |
| 2                       | 10kN                                     |
|                         | 15kN                                     |
|                         | 20kN                                     |
| 3                       | 10kN                                     |
|                         | 25kN                                     |
|                         | 30kN                                     |
the soft soil plays important role in this case. With higher moisture content, higher amount of water is displaced by PU foam. Once the PU foam being pushed in upward direction by the buoyant force, the stress increases and the soil becomes stiffer as the soil particles being compacted to fill the void in between the soil particles without the expulsion of water. Figures 10 and 11 show the condition of PU foam before and after CRS test. The PU foam shows not much defect or deterioration even after the tests.

![Figure 9](image.png)

**Figure 9.** Effect of water content of soil to the stress-strain relationship of PU foam as a ground improvement.

![Figure 10](image.png)

**Figure 10.** Condition of PU foam before and after CRS test on soil.

![Figure 11](image.png)

5mm thick PU foam  10mm thick PU foam  15mm thick PU foam  20mm thick PU foam

**Figure 11.** Condition of different thickness of PU foam after CRS test on soil

4. Conclusions
Based on the results obtained and the observation made in this study, some conclusions are drawn as follows: 1) Buoyant force measurement can be done using CRS apparatus and the test results show that the buoyant force is equal to the weight of water displaced by the object namely PU foam which is
equivalent to PU foam thickness per meter area multiplied by unit weight of water (9.81 kN/m³). 2) Finite element model (FEM) PLAXIS 2D is executed to verify the buoyant force determination from laboratory test and the results show good agreement between laboratory test and FEM. 3) The effects of water content in the soil were determined by carried out constant rate strain test on different water content of soil with variation of PU foam thickness. Optimum water content and higher water content is used in this study and the results show higher water content tend to displace in upward direction whilst optimum water content tend to displace in downward direction. This shows that the soft soil which consists of high water content, when improved with PU foam tend to displace upward (uplift) which is helpful in reducing settlement of the soil compared to other conventional methods of ground improvement which imposed additional load to the underlying soft soil.

Acknowledgements
Special thanks to technical supports at Geotechnical Laboratory Universiti Teknologi Malaysia (UTM) for the valuable assistance to complete this research work.

References
[1] Stephen S 2002 Pressure reduction on wide culverts with EPS geofoam backfill. Retrieved from http://surface.syr.edu, Accessed on 10 Feb 2019.
[2] Frydelund T E and Aaboer R 2002 Lightweight filling materials for road construction, EPS Geofoam 3rd Inter. Conf. Salt Lake City
[3] Frydelund T E and Aaboer R 2002 Use of waste materials as for lightweight fills, Inter. Workshop on Lightweight Geomat..
[4] Daigavane P B and Jain K 2015 Improved foundation system on marine clay using geofoam Int. J. Mod. Trends Eng. Res. (IJMTER), 02, 02.
[5] Riad H L Ricci A L Osborn P W D’Angelo D A and Horvath J S 2004 Design of light-weight fills for road embankments on Boston's Central Artery/Tunnel Project. Inter. Conf. on Case Histories in Geotech. Eng.
[6] Tsuchida T and Tang Y X 2007 Mechanical properties of lightweight treated soil cured in water pressure Soils and Foundation 47, p.4.
[7] Timothy D S Steven F B and David A 2012 Expanded polystyrene (EPS) geofoam applications & technical data, The EPS Industry Alliance 1298 Cronson Boulevard Suite 201 Crofton, MD 21114 800.607.3772 info@epscentral.org www.epsmolders.org.
[8] Mohamed Jais I B 2017 Rapid remediation using polyurethane foam / resin grout in Malaysia. Geotech. Reseach, 4, p. 107–117.
[9] Mohamed Jais I B, Md Ali M A and Muhamad H 2015 Alternative ground improvement solution with polyurethane foam/resin. Proc. of the Inter. Civil and Infra. Eng. g Conf., 425–440, https://doi.org/10.1007/978-981-10-0155-0_38
[10] IBM Jais, DC Lat, TNDT Endut 2019. Compressibility of Peat Soil Improved with Polyurethane – Malaysian Jl of Civil Eng., 31, No 1.
[11] Netz R 2010 The works of Archimedes, 1.