The Settlement Evaluation of Improved Soft Clay Using LECA Replacement Technique

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ABSTRACT: Soil replacement technique is the easiest and oldest method to improve the soft soils underneath the shallow foundations by reducing the settlement by replacing weak soil (e.g. medium or soft clay and organic soils) with more competent materials such as sand, gravel or other suitable granular materials. This paper presents the research on soft soil improvement underlain a large embankment using Lightweight Expanded Clay Aggregate (LECA) as a replacement material which is substitute of normal aggregate. LECA has been used successfully in geotechnical application where weight is an issue because the materials can help reduce dead loads by more than half. The analysis of performance of LECA as a replacement material was conducted through finite elements methods by using Plaxis 3D software and the recorded settlement magnitude then were compared to Tarzaghi's equations for evaluating the average settlement of uniform loading. The obtained results demonstrated that the settlement decreases with increasing of LECA replacement thickness.
Keywords: Soft clay, settlement, numerical modelling, soil improvement, replacement technique.

1. INTRODUCTION

Soil replacement is one of the improvement methods which can upgrade the soft soil performance. According to the review made by M. Gaafer et al. (2015), there is an urgent need to study the technique of 'remove and replace' for improving a weak soil in term of geotechnical requirements, (which is settlement and bearing capacity) and the price to get the optimum thickness of replacement layers as well as the most suitable material to minimize total cost of foundation works (Gaafer, Bassioni, & Mostafa, 2015). However, the impact on environment and sustainability matters also need to be concerned in term of suitable material selection for replacement.

Light weight expanded clay aggregate (LECA) are among the common lightweight materials that have been applied successfully in geotechnical application. It can reduce the weight of compacted geotechnical fills by up to one-half. This material is currently being used in many civil engineering works due to its low weight, high strength and favourable drainage characteristics. In terms of their dimensions, the LECA particles can be classified as gravels. Previous study shows that the LECA has been used as fill material for road embankment construction and filling behind retaining wall, airport pavement subgrades, planting and storm water drainage system (Holm & Valsangkar, 1993).

2. SOIL REPLACEMENT

2.1 General

Poor soil conditions make the form of traditional construction expensive, it may be economically viable to improve soil engineering properties before construction begins. This can be done by reducing pore pressure, by reducing the volume of voids in the soil, or by adding stronger materials to soft soils.

2.1.1 Soil replacement

Replacement method has been commonly used to improve geomaterials under continuous (strip) and isolated footings and also in highway and railways construction when problematic soil are encountered within limited areas and depths (Han, 2015). The condition of foundation can be strengthened by replacing poor soil with more competent materials such as sand, gravel or crushed stone. The soil replacement under shallow foundation will reduce consolidation settlement and increase soil bearing capacity, eliminate expansion/shrinkage of expansive soil and the freeze–thaw of frozen soil. The advantages of this simple technique over other improvement methods and deep foundation is it more economical, reliable, well established and requires less time, therefore can speed up the construction process. It does not require specialty contractors and special machineries except excavators and rollers.

This replacement method can be equated with the concept of reinforced gravel rafts. The method involve the construction of a 1.2 meter thick compacted 'raft' of engineered aggregate. Once constructed the shallow gravel raft provides a stable platform which creates a more uniform pressure distribution and reduces the differential settlement.

2.2 Thickness of replacement

Generally, the determination of the thickness of soil is based on experience which in many cases is questionable. However, the thickness of the replaced zone should be greater than 0.5 meter, where dimensions of a replaced zone is depend on the problem to be diminished (Gabr, 2012). For example, to increase the bearing capacity and reduce the settlement of a footing on a soft soil, Lawton (2001) proposed the replaced zone length and/or width of 1 to 3 footing width and a thickness of 0.5 to 1.5 footing width. This problematic soil behaviour can be improved either by fully or partially replacing the inadequate soils with compacted granular fill layers.

The full replacement is done to increase the bearing capacity and reduce settlement, while the partial replacement done is mainly to increase the stability of the side slope(Das, 2010; Han, 2015). For an embankment over a soft soil, Broms (1979) suggested full and partial replacement of soft soil under the embankment as shown in Figure 1.

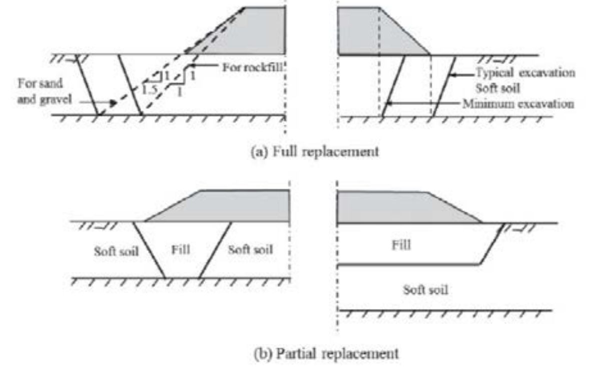

Figure 1 (a) Full and (b) Partial replacement under an embankment (Modified from Broms, 1979)

2.3 Previous researches on soil replacement

Many studies have been conducted on soil replacement works. Most of the studies were focused on settlement of soft soil under square or circular footings. However, a number of researchers are also interested to evaluate the settlement behaviour of soil with column raft installation (soil replacement and stone column).

A. K. Gabr (2012) conducted a study on the effect of replacement soil depth in controlling the settlement of square footing through centrifuge test and numerical modelling. The three dimensional numerical analysis was carried out using the software Plaxis (2005) adopting the Mohr-Coulomb soil behaviour mode (Gabr, 2012). The study found that, the use of replacement soil can reduce the settlement magnitude. It was observed that during the experiment, when a uniform load exceeding 100kN/m^2, the soil suffered complete failure if the soil replacement was less than 0.2B (B is footing width). However, the numerical model results indicated no signs of failure for the whole range of loads and soil replacement thicknesses, where the settlement values recorded increase almost linearly and do not trend towards a constant value which is does not seem logical, as there is a minimum limit to the void ratio of any soil. This may be due to the fact that no lower limit condition is assigned for the void ratio in the Mohr-Coulomb failure surface.

The performance of partial replacement for soft clay under square footing has been analysed using finite elements methods (PLAXIS 3D program), where clay soil and sand material were simulated by the standards of linear elastic-perfectly plastic Mohr-Coulomb theory (Abbas, 2016). Sand was used as a replacement materials. The settlement values recorded were compared to Janbu equations which is adopted to calculate the average settlement of flexible foundations on saturated clay soils. The obtained results demonstrated that the stress-settlement behaviour increases with increasing the thickness of sand layer. Similar findings were found by Abdel Salam through the study on the effect of using different types and thickness of replacement layer on increasing bearing capacity and reducing consolidation settlement of soft clayey soil experimentally, where the study concluded that the vertical settlement decreased with increasing of the replacement layer thickness (S. Abdel Salam, 2007).

The artificial neural networks (ANNs), and the multi-linear regression model (MLR) have been utilised to predict the bearing capacity of circular shallow footings supported by layers of granular replacement over natural clay soil (Ornek, Laman, Demir, & Yildiz, 2012). The data used in running the network models have been obtained from an extensive series of field tests, including large-scale footing diameters. The results indicate that the use of granular fill layers over natural clay soil has a considerable effect on the bearing capacity characteristics and that the ANN model serves as a simple and reliable tool for predicting the bearing capacity of circular footings in stabilized natural clay soil. In addition, the field test results indicate that the use of partially replaced granular-fill layers over natural clay soil has considerable effects on the bearing capacity and the settlement characteristics. For a given value of replacement thickness to footing diameter ratio, H/D, the ultimate bearing capacity increases in a nonlinear manner with the footing diameter. On the other hand, for a given value of D, the magnitude of q_u increased with the increase in the compacted granular-fill layer thickness, H (Ornek, Laman, Yildiz, & Demir, 2012).

3. METHODOLOGY

The objective of the study is to evaluate the effects of a LECA aggregates thickness, H as soil replacement substitute the normal aggregate in reducing compressibility, S of soft clay soil through numerical modelling. Three dimensional numerical analysis will be performed using commercial software Plaxis 3D (2017). To permit timely analysis in this research and to simulate long term soil behaviour, drained analysis is adopted to allow for a greater number of sensitivity and parametric analysis to be done. Sensitivity analysis needs to be conducted before numerical modelling is carried out.

3.1 Constitutive model

It is very important to choose the right constitutive model to represents the soft soil behaviour during conducting the numerical analysis. Numerous models have been introduced and used by researchers to analyse the behaviour of soft soil stabilized by various methods. In order to select the right constitutive model, several famous models have been selected for analysis in this study. The selection of model made based on availability of soft soil and LECA properties. While the non-existent parameters will be calculated based on correlation or indirectly calculated using others suitable parameters, and this particular matters readily available in Plaxis 3D. The results obtained from the analysis will be compared to analytical calculation.

3.1.1 Comparison of soil constitutive models

Consolidation settlement magnitude can be predicted using analytical method One-dimensional Terzahgy's Equation. Immediate Settlements and settlements due to primary consolidation occur during construction, while settlements due to secondary consolidation and creep occur after the end of construction. However, only primary consolidation settlement will be calculated since, the immediate settlement is insignificant in clay and can be ignored, while secondary consolidation settlement is more important in highly compressibility clay and organic soils such as peat. In over consolidated inorganic clay, the secondary compression index is very small, of less practical significance (Das, 2015).

The models selected for analysis are; Mohr Columb Model (MC), Linear Elastic Model (LE), Soft Soil Model (SSM), Soil Hardening Model (SHM) and Soft Soil Creep Model (SSC). From the sensitivity analysis conducted, Soil Hardening Model and Soft Soil Creep Model (SSC) gave a closed result to analytical calculation. However, since creep behaviour is only significant in organic soft soil and peat, therefor, Soil Hardening Model will be adopted to analysis the behaviour of soft soil in this study.

For untreated soil, the settlement magnitude calculated is 0.3153m (for 50kN/m^2 uniform load) Plaxis 3D provided a result slightly higher, as predicted by SS model, while MC model predicted lower value up to 40%. Compare to other models, SSC and SHM estimated closed value, however SHM model provided almost equal to analytical value (0.3209m) where the percentage was less than 2%. However, since the sensitivity analysis is based on analytical calculations, the physical model should be carried out to see the accuracy of the settlement values estimated by each model.

3.2 Methodology of numerical analysis for LECA replacement

The numerical analysis of LECA replacement has been performed based on following conclusions and limitations;

- Mesh refined used in the analysis: Fine Mesh.
- Since the replacement of soft soil by LECA will be constructed on very large area with uniform distributed load, the boundary distance is not critical, the replacement was modelled using three dimensional.
- Type of analysis: Drained analysis was selected in this study to reduce the time consumed and to simulate the soft soil behaviour in long-term, and also to allow for a greater number of sensitivity and parametric analyse to be done.
- Type of constitutive model used in the study; MC (drained) model for LECA and SHM to represent the soft clay behaviour.
- Construction effect was neglected in the analysis.
- The total load applied on the structural system is assumed to be uniformly distributed over the entire surface area of the LECA replacement surface and plate will be assigned as a medium for load transfer to the above ground. The uniform load imposed used in this study are 50, 100 and 150 kN/m^2.

- The analysis of settlement was focused to the centre of load, therefor settlement behaviour at the edge of surface loading was not include in the study.
- Unit weight of LECA: from the review of the previous study and numerous LECA manufacturer through the world, the unit weight of LECA was found to be various between 3 to 10 kN/m^3, which is lower than water density. Therefore, the settlement of soft clay will be evaluated based on the different value of LECA density (3kN/m^3, 5kN/m^3, 7kN/m^3 and 9kN/m^3).
- The analysis of normal aggregate used as a replacement material was also performed as comparison.
- Depth of soft soil is 10 meter.
- Settlement analysis was analysed based on different depth of replacement; which are 1.5m, 2.5m and 3.5m.
- Two stage of calculation involved; initial and loading phase as shows in Table 1;

Table 1 Numerical analysis stages

Phase	Calculation type	Loading input
Initial phase	K_0 procedure	Stage construction
Loading phase	Plastic Analysis	Stage construction

3.3 Material properties

Manufactured Kaolin Clay was chosen to represent soft clay soil because it was easily obtained and could be reconstitute homogeneously through consolidation method. Beside, many other researchers also used kaolin in their research and therefore results could be compared. The properties of materials used in this study were tested based on British Standard and/or the American Society of Testing Material (ASTM), based on the suitability and availability of the equipment in the laboratory for the respective tests. Table 2 represents the properties of Kaolin Clay and LECA used in numerical analysis.

Table 2 Materials properties

Parameter	Kaolin Clay	LECA
Constitutive Model	SHM	MC
Type of analysis	Drained	Drained
Unit weight, ɣ (kN/m^3)	16	3,5,7,9
Young's Modulus, E (kN/m^2)	2420	2520
Cohesion, c' (kN/m^2)	7	0
Friction angle, φ' (°)	25°	35°
Dilatation angle, Ψ' (°)	0	5
Poisson's ratio, ν	0.30	0.30
Permeability, k (m/s)	2.58 x 10^{-10}	2.53 x 10^{-2}
LL (%)	54	-
PL (%)	29	-
PI (%)	25	-
Undrained shear strength (kN/m^2)	7.5	-
C_c	0.256	-
Specific gravity	2.60	0.77
C_r	0.058	-
e_0	2.39	-

4. RESULT AND ANALYSIS

Sixty models in total have been developed to simulate the soft soil displacement with LECA used as a replacement material.

4.1 SETTLEMENT

Figure 2 shows the plot of Settlement versus LECA replacement depth for loading 50kN/m^2. From the analysis, the settlement of clay layer was found to be improved when LECA material used as replacement technique. The results show that the increasing of depth of replacement will contribute to decreasing of settlement magnitude for all unit weight of LECA as well as normal aggregates. LECA 3, LECA 5, LECA 7 and LECA 9 represent the LECA with unit weight of 3kN/m^3, 5kN/m^3, 7kN/m^3 and 9kN/m^3, respectively, while NA is normal aggregate. This finding is in good agreement with previous study conducted utilizing other granular materials such as sand and gravel as a replacement material.

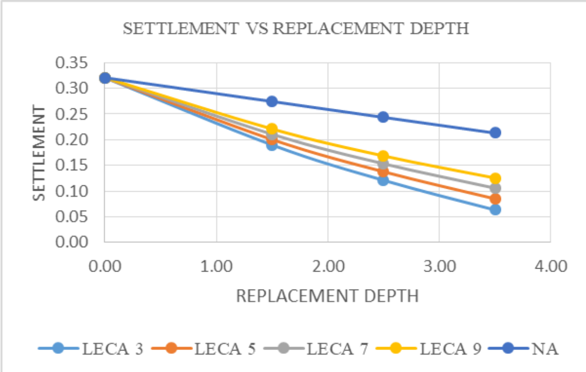

Figure 2 Settlement versus Replacement Depth for Various LECA Density

LECA is known as common lightweight materials with various unit weight between 3kN/m3 to 10kN/m3, which is lower than water density and soft clay itself. According to the previous study this materials can help reduce dead loads and lateral forces by more than half in installations with soft soils. From the analysis, LECA with lowest unit weight which is 3kN/m3 contributed to highest rate of settlement compare to other LECA. This proved that the lightweight materials like LECA can be utilised as replacement material in order to improve the soft soil with limited depth. It also can be seen that the LECA perform well compare to normal aggregate in term of settlement reduction.

Table 3 shows the percentage of settlement improvement when LECA used as replacement material compared to normal aggregate (NA), while Table 4 represents the percentage of settlement when LECA used as replacement material compared to untreated settlement. When the unit weight of the replacement material is low, the percentage of settlement improvement becomes higher up to 41%, 62% and 80% for 1.5m, 2.5m and 3.5m depth of replacement, respectively. The percentage also seen to be increased with increasing of replacement depth for all materials.

Table 3 Settlement improvement percentage compared to normal aggregate

LECA unit weight	Settlement Improvement Percentage		
	1.5 meter	2.5 meter	3.5 meter
LECA 3	30.82%	50.29%	70.24%
LECA 5	26.96%	43.43%	60.05%
LECA 7	23.21%	37.03%	50.28%
LECA 9	19.45%	30.79%	41.03%

Table 4 Settlement improvement percentage compared to settlement of untreated soil

LECA unit weight	Settlement Improvement Percentage		
	1.5 meter	2.5 meter	3.5 meter
LECA 3	40.82%	62.26%	80.25%
LECA 5	37.52%	57.06%	73.48%
LECA 7	34.31%	52.20%	67.00%
LECA 9	31.10%	47.46%	60.86%
NA	14.46%	24.09%	33.62%

Settlement improvement factor (SIF) for LECA and NA also calculated and tabulated in Table 5 below. The factor of settlement improvement is defined as the ratio of the settlement of an untreated soil to the settlement of a treated soil. The factor is used to evaluate the reduction in settlement after improvement. It is stated that the settlement improvement factor was increased with increasing the replacement depth. In addition, the settlement improvement factor for normal aggregate replacement found to be lower compare to LECA replacement.

Table 5 Settlement improvement factor for LECA and normal aggregates

Replacement Depth	**Settlement Improvement Factor = SIF =Su/Sc**		
	1.5 m	2.5 m	3.5 m
LECA 3	1.69	2.65	5.06
LECA 5	1.60	2.33	3.77
LECA 7	1.52	2.09	3.03
LECA 9	1.45	1.90	2.55
NA	1.17	1.32	1.51

The study also find out the effect of compacted shallow LECA layers on the settlement under uniform distributed load. Maximum settlement for each condition was measured. Figure 3, Figure 4 and Figure 5 illustrate pressure-settlement behaviour of improved soft clay by replacing 1.5m, 2.5m and 3.5m of the soft clay with compacted LECA layers, respectively. The simulations results show the vertical settlement at centre of the load imposed equals to 0.5748m or 574.8mm in resistance pressure of 150 kN/m^2. The maximum vertical settlement for improved soil with 1.5m thickness replacement was between 0.44m to 0.45m for various unit weight of LECA. While, settlement magnitude recorded for improved soil with 2.5m and 3.5m were laid between 0.36m to 0.39m and 0.30m to 0.32m, respectively. In addition, the replacement using normal aggregate materials contributed to higher settlement value due to the heavier aggregate weight compared to LECA.

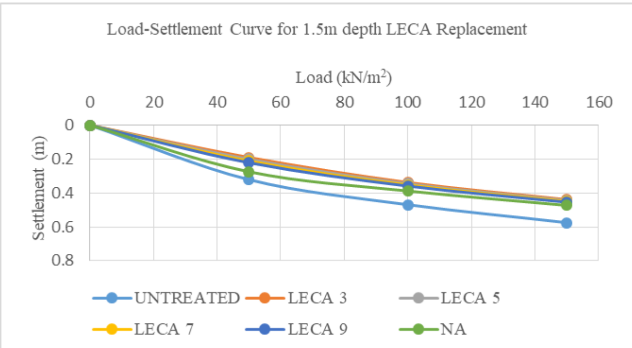

Figure 3 Pressure-settlement behaviour of improved soft clay by replacing 1.5m

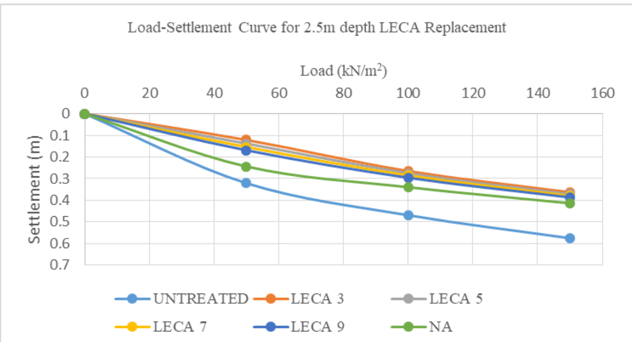

Figure 4 Pressure-settlement behaviour of improved soft clay by replacing 2.5m

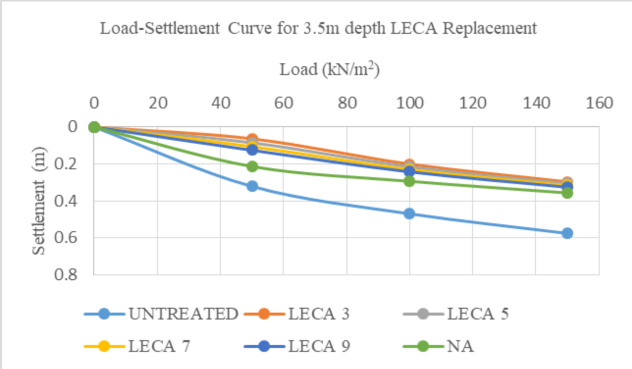

Figure 5 Pressure-settlement behaviour of improved soft clay by replacing 3.5m

The plot of settlement improvement factor (SIF) versus pressure for each replacement depth also established as shows in Figure 6. From the plot, it can be concluded that, the SIF of LECA reached constant value at the point pressure of 120kN/m^2, while constant value of SIF were recorded for NA replacement for all loading imposed.

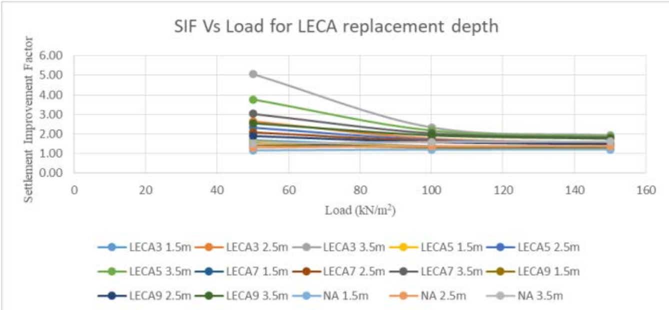

Figure 6 Settlement improvement factor (SIF) versus loading imposed

Figure 7, Figure 8 and Figure 9 present the curve of estimated settlement based on various unit weight of LECA including NA as a comparison under 50, 100 and 150kN/m^2 uniform loading, respectively. The plot shows that, the settlement increases linearly by increasing the unit weight of the substitute substance. This condition proves that the weight of the replacement layer gives advantage to the settlement behaviour.

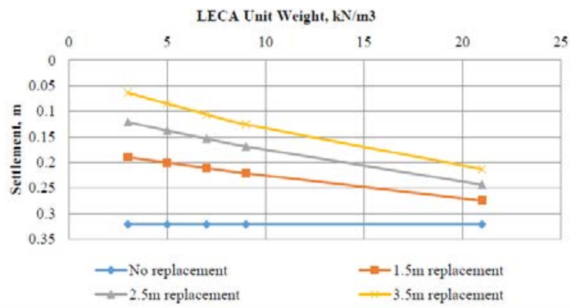

Figure 7 Settlement versus material unit weight for 50kN/m^2 load

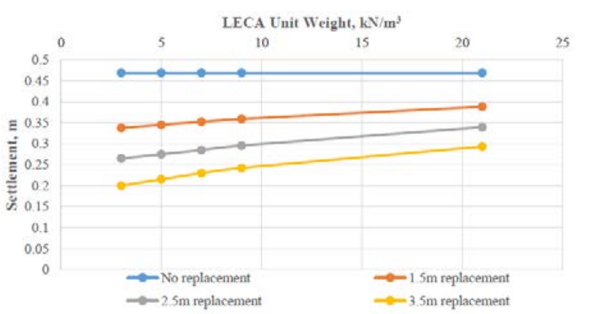

Figure 8 Settlement versus material unit weight for 100kN/m^2 load

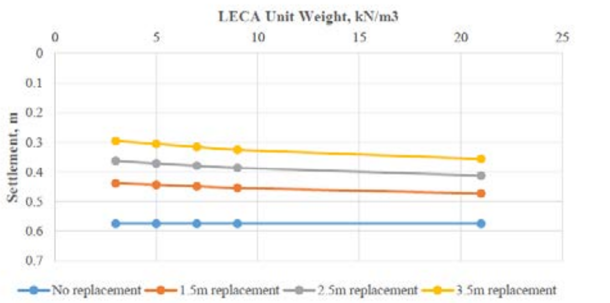

Figure 9 Settlement versus material unit weight for 150kN/m^2 load

4.2 SOIL STRESS

A soil subjected to shearing stress offers shearing resistance which comprises cohesion (*c*), dilatation angle, (φ) and friction angle (ϕ). The maximum resistance of a soil to shearing stresses is Shear Strength. The maximum effective shear strength of the treated ground is also recorded from the numerical analysis. Figure 10 presents the soil stress-settlement behaviour of untreated and treated soft clay by replacement works under 50kN/m^2 loading. The results show the value of soil stress is decreased when the replacing layer increases, while the settlement magnitude decreases.

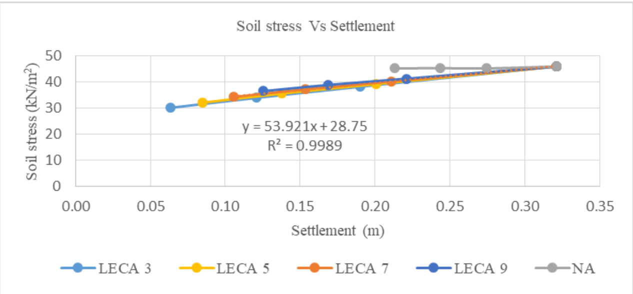

Figure 10 Stress-settlement behaviour of improved soft clay

In addition, stress ratio was found to be increases with increasing of replacement depth as presented in Figure 11. Stress ratio is defined as the ratio of the maximum shear stress of an untreated soil to the shear stress of a treated soil. This finding were contrast with normal aggregate replacement, where the stress resistance will increased up to 12% with increasing of replacement layer under 50kN/m^2 uniform load. However, NA replacement indicates a slight increase (less than 5%) of shear stress when 100 and 150kN/m^2 load are applied.

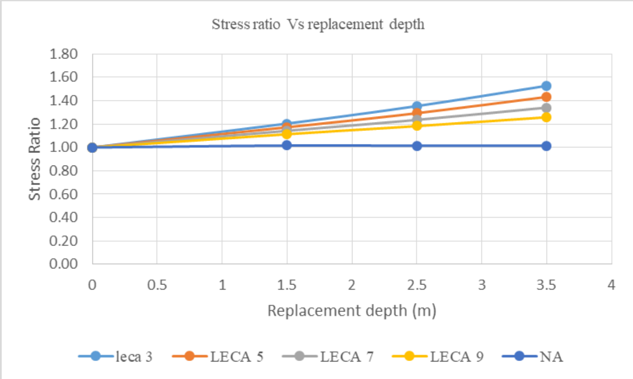

Figure 11 Stress ratio-replacement depth

5. CONCLUSIONS AND RECOMENDATIONS

Numerical analysis was performed to investigate the settlement behaviour of treated soft clay soil in 3D models under drained condition. A few conclusions can be drawn from this study;

- The study concluded that the increasing of depth of LECA replacement will contribute to decreasing of settlement magnitude for all unit weight of LECA as well as normal aggregates. However, it can be seen that the LECA perform well compare to normal aggregate in term of settlement reduction. This proves that the lightweight materials like LECA can be utilized as a replacement material in order to improve the soft soil with limited depth.
- The obtained results concluded that increasing the thickness of replaced soft clay with compacted LECA layer evidently decreases the settlement and also decreases the resistance stress. It can be concluded that use the replacement technique under the loaded area is effective in increasing the settlement factor.
- The resistance stress found to be decreased with increasing of LECA replacement layer. This condition shows that, LECA replacement is effective to improve settlement of soft soil, however, it is proposed to utilise this method along with stone column to solve both settlement and stress behaviour of soft soil.

6. ACKNOWLEDGEMENT

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