CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 5, ISSUE 2, 2025, 313 - 326
DOI: https://doi.org/10.15282/construction.v5i2.12682

RESEARCH ARTICLE

Improved Settlement Modeling of Leca Column–Raft Systems in Soft Clay: Influence of Friction Angle and Material Properties

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ABSTRACT - Stone columns are widely recognized as an effective ground improvement technique to enhance the bearing capacity of soft clay, reduce compressibility, and accelerate consolidation by providing drainage for excess pore water. Conventional columns are typically filled with coarse aggregates, but increasing attention is now given to sustainable and lightweight alternatives. This study investigates the use of Lightweight Expanded Clay Aggregate (LECA) as filler material in column raft systems. Numerical modelling was performed in PLAXIS 3D (2020), with LECA represented by the Mohr-Coulomb model and soft clay by the Hardening Soil model. Drained analysis was adopted to capture long-term settlement behaviour. A comprehensive parametric study examined the effects of area replacement ratio, raft thickness, and internal friction angle on settlement performance. The novelty of this research lies in the development of two predictive models for estimating settlement in LECA-filled column raft systems. Unlike previous studies, the proposed models extend the existing Settlement Prediction Model (IP_CR-2019_0349) by incorporating a wider range of LECA properties, including internal friction angle and modulus, which vary with production sources. The validated design chart provides practical guidance for engineers in applying LECA columns to improve soft clay foundations. Overall, the study demonstrates that LECA is a lightweight, durable, and environmentally friendly alternative to conventional aggregates, with strong potential for sustainable ground improvement.

ARTICLE HISTORY

Received	:	24 June 2025
Revised	:	11 September 2025
Accepted	:	9 October 2025
Published	:	29 December 2025

KEYWORDS
Soft soil
Stone column
LECA
Replacement
Numerical analysis

1. INTRODUCTION

The construction industry in Malaysia has been growing rapidly, especially in Peninsular Malaysia, due to continuous infrastructure development. Whether in rural or urban areas, selecting a suitable soil site is a critical step in the construction process. Different soils have different strengths: some can support heavy structures like skyscrapers, while others can only bear lighter loads. With the fast pace of development, construction is sometimes forced onto whatever land is available. However, not all soils provide the required engineering properties for safe construction. Certain types of soil, such as clayey soil, are considered weak and unsuitable for supporting large structures. Developing large-scale infrastructure, such as high-speed transportation systems, high-rise buildings, and underground works, is especially problematic in urban areas underlain by soft soils [1]. To enable construction on such problematic soils, a range of ground improvement techniques has been developed to enhance bearing capacity and reduce settlement. These techniques generally involve modifying, stabilizing, or combining both approaches to improve soil properties. Soil stabilization, commonly used in highway and airport projects, is a process that enhances the engineering properties of soil and makes it more stable. It reduces undesirable characteristics such as high permeability and compressibility, while increasing shear strength [2]. Soil modification, on the other hand, involves adding materials to alter specific soil properties, whereas soil stabilization is a more permanent treatment that improves strength and reduces settlement, making weak soils suitable for construction [3].

Lightweight Expanded Clay Aggregate (LECA) has emerged as a promising alternative filler material for stone columns. Classified as a lightweight aggregate, LECA has a unit weight lower than water but exhibits high water absorption. Its application in geotechnical engineering offers potential benefits in reducing the compressibility of soft soils and the overall weight of compacted fills. Replacing conventional stone aggregates in columns with LECA can reduce the total fill weight by up to 50%. Furthermore, Malaysia has abundant raw materials suitable for LECA production, highlighting its potential for local application [4] Previous studies also confirm that LECA's physical properties make it a viable substitute for natural aggregates in stone column construction and other civil engineering works [5]

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2. LIGHTWEIGHT AGGREGATES IN GEOTECHNICAL APPLICATIONS

There are relatively few studies on the use of Lightweight Aggregate (LWA) in soil stabilization works. Lightweight fill is primarily applied to reduce the overall load on embankments, thereby minimizing the permanent stresses transferred to foundations. Various forestry by-products, such as bark, woodchips, and sawdust from the timber industry, have long been used as lightweight fills [6], [7]. Similarly, shredded waste tyres and tyre bales have also been employed as alternative lightweight construction materials on soft soils [8], [9], [10], [11], [12], [13]. Among the most widely adopted lightweight materials are manufactured products such as Expanded Polystyrene (EPS) Geofoam blocks [14], [15], [16] . More recently, Lightweight Expanded Clay Aggregate (LECA) has been introduced as a soil replacement material, often in combination with stone columns, to address settlement and stress distribution problems in soft clay soils. Several studies have highlighted the potential of LECA to improve both structural and geotechnical performance, making it a highly versatile material increasingly applied in civil engineering works. LECA has been successfully used as a geotechnical fill in Europe for more than 40 years. For example, Gollas (2002) compiled numerous case histories where LECA was applied in abutment fills, embankments over soft soils, and fill extensions to existing embankments [17]. More recent guides and studies have summarized its many applications in geotechnical engineering. However, one of the main precautions in such applications is to limit the maximum load applied to the filling to avoid grain breakage. Roces et al. (2021) recommended keeping the applied stress below 150 kPa, while Zukri et al. (2018) suggested a maximum effective stress of 100 kN/m² to prevent particle crushing in LECA [18].

Previous studies have shown that Lightweight Expanded Clay Aggregate (LECA) has been successfully used as a filler material in a wide range of applications, including road embankment construction, retaining wall backfills, airport pavement subgrades, landscaping, and storm water drainage systems [19]. More recent investigations have continued to confirm its versatility in geotechnical works. For instance, Zukri et al. (2023) applied LECA as a replacement fill in soft soils and developed compaction guidelines during a field project at Masjid At-Taqwa in Malaysia, highlighting its effectiveness in controlling settlement [20]. Similarly, Zukri has carried out a series of studies using finite-element modelling to investigate LECA rafts beneath footings on soft clay. These works consistently demonstrate that LECA significantly improves bearing capacity and reduces settlement, with performance strongly influenced by raft thickness and the material's internal friction angle [5], [20]In addition, Aljboori et al. (2025) investigated soil–LECA mixtures and reported that adding 10–30% LECA by volume can reduce soil density by up to 60% and increase unconfined compressive strength by nearly 94%, confirming LECA's suitability as a sustainable lightweight replacement material [21]Collectively, these studies highlight LECA's dual benefits of improving geotechnical performance while promoting sustainability, making it a promising material for future ground improvement and infrastructure development projects on soft soils.

3. STONE COLUMN SETTLEMENT DESIGN APPROACHES

For the case of settlement reduction, most design approaches adopt the unit cell concept, in which an infinitely large area improved by a uniform grid of stone columns of equal diameter is idealized under an even load. The earliest contributions include the empirical method of Greenwood (1975), the finite element approach of Balaam (1977), and the equilibrium method proposed by Aboshi et al. (1979) and Barksdale & Bachus (1983) for sand compaction piles [22], [23], [24], [25]. Further refinements were made with the incremental method (Goughnour & Bayuk, 1979), the elastic method (Balaam & Booker, 1985), and the unit cell approach of Poorooshasb & Meyerhof (1997) [26], [27], [28]. Among these, the semi-empirical method of Priebe (1995), which explicitly incorporates the internal friction angle of the column material, remains the most widely applied in practice [29]. Despite its empirical basis and restriction to an infinite column grid, it has been extensively validated against measured settlements in different soil conditions [30], [31]. Later developments introduced elasto-plastic formulations (Pulko & Majes, 2005; Castro & Sagaseta, 2009) and hybrid approaches combining settlement ratio (β) concepts with stress concentration models [32]. These methods differ in assumptions regarding soil–column interaction and deformation, but all derive from the same unit cell idealization, where the stone column is modelled as a concentric body in a composite soil mass under rigid boundary conditions. Taken together, the evolution of stone column settlement design methods spans from empirical and semi-empirical formulations to advanced numerical, probabilistic, and material-specific approaches. While Priebe's (1995) method continues to be the most applied in engineering practice, modern studies confirm that incorporating material properties, stress concentration effects, and numerical validation provides more reliable settlement predictions for diverse soil conditions and innovative column materials.

4. OBJECTIVE OF THE STUDY

The performance of stone columns installed in soft clay is often expressed in terms of the settlement ratio, S/S_{uc} where S is the settlement of a floating column (either in large or small groups), and S_{uc} is the settlement of an end-bearing column in a unit cell model. This relationship was first proposed by Ng (2017). Interestingly, the performance of LECA columns (without raft) was also successfully predicted using this equation, despite it being originally developed for stone columns with conventional granular materials [4]. However, the design chart established by Zukri (2019) does not incorporate the effects of a replacement layer or granular raft on top of the columns. To address this, Zukri (2019) introduced a dimensionless relationship between settlement ratio (S/S_{uc}) and depth ratio (β), considering various parameters such as raft thickness, column length, and column spacing. The resulting charts were validated using PLAXIS 3D simulations and served as a reference for predicting the settlement of LECA column–raft systems. Nevertheless, the proposed model was developed solely based on a LECA friction angle of 35°, without accounting for the variability of friction angles that may arise due to differences in LECA production processes. Therefore, this study aims to develop extended design charts for predicting the settlement of LECA column–raft systems, with particular emphasis on the influence of varying friction angle values.

5. RELATED WORKS

Recent numerical and experimental studies confirm that the frictional properties and stiffness of column backfill (not just column geometry) substantially control settlement and load sharing in column–raft systems. PLAXIS-based parametric studies on encased and un-encased stone columns have shown marked reductions in settlement as backfill internal friction angle and confinement increase, and analytical or 3D finite element work similarly identifies φ as a key sensitivity parameter for both floating and end-bearing behaviour. These findings imply that Zukri’s (2019) LECA–column–raft charts (developed assuming a single LECA $\varphi = 35°$) may under- or over-estimate settlement when other LECA types or alternative column materials (sand, crushed slag, crushed glass, etc.) with different effective φ and stiffness are used. Therefore, extending the design charts to incorporate a φ-sweep (or to provide separate charts for representative φ ranges) would address a critical gap between the current LECA-based model and numerical evidence, which shows that material friction and raft thickness significantly influence *S/Suc* and column–raft interaction.

Yasser et al. (2022) investigated floating stone column groups reinforced with a granular mattress (GM) in soft clay using three-dimensional finite element analysis. The study showed that a GM significantly reduced settlement, with the most effective thickness being about 1.5 times the column diameter (d). Beyond this value, further thickness increase had little benefit, making GM inclusion a more economical option than extending column length. Settlement improvement from longer columns was also noted, but it became negligible when the column length exceeded about 1.8 times the footing width ($L = 1.8B$). The results further highlighted the importance of the column material’s friction angle (φ). Settlement reduction decreased by about 35% for every 5° drop in φ, and the stress improvement factor (SIF) reduced by roughly 50%. Compared to the reference case, settlement decreased by 60% at $\varphi = 40°$ but increased by 133% at $\varphi = 35°$, showing that proper compaction and adequate friction angle are critical for the effectiveness of the stone column–GM system [33].

Gyawali (2021) investigated the effect of area replacement ratio, friction angle of the stone column, and column stiffness using finite element analysis. The study revealed that the settlement improvement factor increases with an increase in the area replacement ratio, although the selection of a suitable ratio ultimately depends on the specific project requirements. It was also found that the settlement improvement factor rises as the friction angle of the stone column material increases, since higher friction angles lead to reduced settlement. Furthermore, the performance of stone columns is not solely governed by their own stiffness properties but is also strongly influenced by the stiffness of the surrounding soil, which provides the necessary lateral support (Gyawali et al. (2021). Meanwhile, Omar et al. (2025) examined the effect of area replacement ratio on the settlement behavior of floating stone columns through laboratory model tests. The study tested different area replacement ratios (10%, 15%, 23%, and 33%) for both floating and end-bearing stone columns. The results showed that increasing the area replacement ratio reduced settlement in floating stone columns. Interestingly, the settlement behavior of floating columns was not significantly different from that of end-bearing columns. These findings improve the understanding of settlement behavior and highlight the potential use of floating stone columns in ground improvement works [35].

Furthermore, 28 simulation runs were conducted in ANSYS to model both improved and unimproved soil conditions. In the axisymmetric model, the interface between the stone column and surrounding clay was defined as bonded. The analysis revealed a clear relationship between normalized settlement and the stone column area ratio. In addition, a simple equation was developed to relate the deformation ratio to the footing diameter. The findings showed that footings with larger area ratios experienced lower settlements under the same applied pressure, while a reduction in footing diameter also led to lower normalized settlement for identical normalized loading conditions [36].

6. METHODS AND MATERIALS

A three-dimensional numerical model was developed using PLAXIS 3D (2021) to evaluate the final settlement of ground reinforced with a group of LECA column–raft systems. The columns were arranged in a square configuration, and a fine mesh generation was adopted by setting the global coarseness parameter of the model. The Mohr–Coulomb constitutive model was applied to represent the behavior of the LECA granular material, whereas the Soft Soil Hardening (SSH) model was used to capture the stress–strain response of the underlying soft clay. The Mohr–Coulomb constitutive model was assigned to the LECA columns. This model was selected because LECA behaves predominantly as a frictional, granular material where strength is mainly governed by cohesionless parameters (φ and γ), making the simple linear elastic perfectly plastic Mohr Coulomb model an appropriate and computationally efficient choice [37]. In addition, the SSH advanced model was chosen because it can adequately capture the time-dependent stress–strain behavior of soft soils, including compression hardening and shear hardening mechanisms. Compared to the basic Mohr Coulomb model, SSH provides a more realistic description of soil yielding and plasticity under long-term loading conditions, which is essential for settlement analysis in soft clays. A drained analysis was performed to account for the long-term consolidation behavior of soft soil under sustained loading. Drained conditions were adopted because the primary interest of this study was to simulate the final settlement after dissipation of excess pore water pressures, rather than short-term undrained responses. This approach also permits timely computation and allows for a greater number of sensitivity and parametric analyses. Loading conditions consisted of a uniformly distributed vertical pressure of 50 kN/m² and 100 kN/m², applied over the entire raft area. A rigid plate was incorporated in the model to simulate the structural load transfer to the reinforced ground. Since the analysis focused on settlement behavior under a large loaded area, the results were not significantly affected by boundary conditions. The stone columns were modeled using the "wish-in-place" assumption, where installation effects such as soil disturbance and smear were neglected. Accordingly, the interface reduction factor (R_{inter}) was set to 1.0, ensuring full interaction between the column and surrounding soil.

6.1 Parametric Study

LECA rafts with variable thickness (1.5 m, 2.5 m, and 3.5 m) and five (5) different LECA friction angles, namely φ'=35º, φ'=40º, φ'=42º, φ'=43º and φ'=45º, were selected in this study. According to the various properties of LECA available worldwide, the friction angle value of LECA was found to vary from 35˚ to 53˚. The unit weight of LECA varied between 3 kN/m^3 to 9 kN/m^3, which is lower than the density of water [38]. Since this study focuses on five (5) different values of the internal friction angle, an empirical correlation is required to estimate the corresponding unit weight and Young's modulus (E) of LECA for each selected value. Figure 1 presents the correlation between the friction angle and the density of LECA, which is valid for unit weights ranging from 2 kN/m³ to 10 kN/m³, consistent with the density range reported for LECA [39]. The Young's modulus of LECA aggregates is then evaluated using Eq. (1) proposed by [40], which relates stiffness to density and material characteristics.

Furthermore, the dilatancy angle (ψ) of LECA is obtained from Eq. (2) suggested by [41], where ψ is expressed as a function of the internal friction angle (φ). As summarized in Table 1, two calculation stages are considered in the analysis: the initial phase and the loading phase. A finite element analysis (FEA) was performed on the LECA column–raft system to evaluate the final settlement magnitude (S). The input material properties employed in the numerical simulation are listed in Table 2, while Figure 2 illustrates the schematic configuration of the LECA column–raft model. In this study, the LECA column diameter was set at 700 mm, embedded within a soft clay layer of 10 m thickness. The column spacing was defined through the area replacement ratio (α), representing the proportion of column area to the tributary area of soil.

$$E_{Gpa} = 8.96\, \rho_{ton/m^3} - 3.78 \tag{1}$$

$$\psi = \phi - 30° \tag{2}$$

Table 1. Stage of calculation in numerical modelling

Type of analysis	Stage	Calculation type	Type of loading input
Settlement analysis	Initial stage	K_0 procedure	Stage construction
	Loading stage	Plastic Analysis	Stage construction

Table 2. Materials parameters utilized in numerical modelling

Parameters	Kaolin Clay	LECA				
Constitutive model	Hardening Soil	Mohr Coulomb				
Analysis type	Drained	Drained				
Unit weight, γ (kN/m³)	16	3.5	4.5	5.5	6.0	8.0
Young's Modulus, E (kN/m²)	3807	2430	5353	6543	7050	8497
Cohesion, c' (kN/m^3)	7	0	0	0	0	0
Friction angle, ϕ' (º)	0	35	40	42	43	45
Dilatation angle, φ (º)	0	5	10	12	13	15
Permeability, k (m/day)	2.229 x10^{-5}	2.253 x10^{-2}				
Poisson's ratio, v	0.30					
Undrained shear strength (kN/m2)	7.5	n.a				
Cc	0.256	n.a				
Cr	0.058	n.a				
e_0	2.39	n.a				

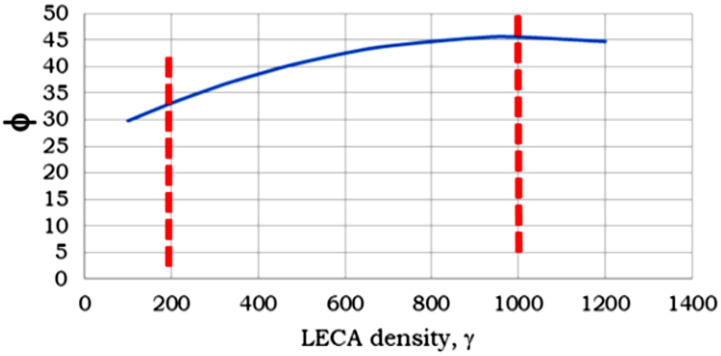


Figure 1. Internal Friction Angle for various LECA Density [39]

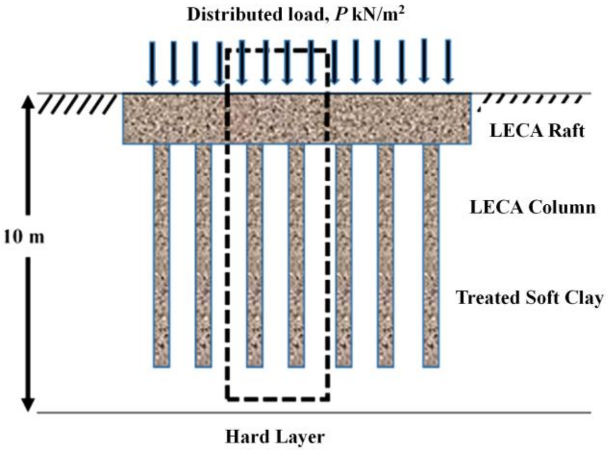
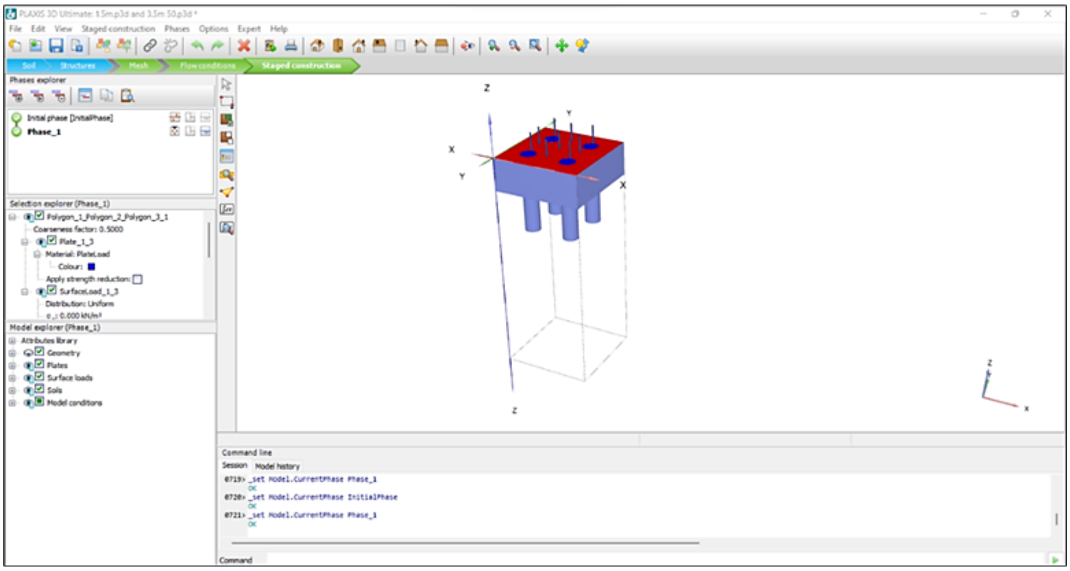


Figure 2. Schematic diagram of LECA columns raft

7. RESULTS AND DISCUSSION

A comprehensive series of finite element simulations was conducted to evaluate the settlement behavior of soft clay reinforced with LECA columns. In total, several hundred models were developed, considering variations in applied loading intensity, column length (thickness of reinforcement), and internal friction angle of LECA. Specifically, three levels of vertical loading, three column lengths, and five different friction angles (φ′) were analyzed to capture a wide range of soil–structure interaction responses.



Coarseness factor: 0.5000
Material: PlateLoad
Colour: ■
Apply strength reduction: ☐
Distribution: Uniform
σ_z: 0.000 kN/m²

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0719> _set Model.CurrentPhase Phase_1
      OK
0720> _set Model.CurrentPhase InitialPhase
      OK
0721> _set Model.CurrentPhase Phase_1
      OK
```

Figure 3. Three-dimensional modelling utilized in PLAXIS 3D

The three-dimensional finite element model employed for the settlement analysis under large-loaded areas is illustrated in Figure 3. The effectiveness of the LECA column–raft system was quantified in terms of the settlement improvement factor (η), which is expressed as:

$$\eta = S/S_{uc} \tag{3}$$

The settlement improvement factor is defined as the ratio of the settlement of an untreated soil to the settlement of a treated soil. A higher value of η indicates greater improvement in ground performance due to column installation.

7.1 Variation of Settlement Improvement Factor with Area Replacement Ratio and Friction Angle

The area replacement ratio **(**α**)** plays a critical role in controlling the load transfer mechanism between LECA columns and surrounding soft clay. It is defined as the proportion of the column area to the tributary area of soil, and thus directly reflects the degree of reinforcement provided within the ground system. Simulation results indicate that an increase in α leads to a noticeable enhancement in the settlement improvement factor, confirming that closer column spacing or larger column diameters significantly reduce ground settlement. Moreover, the magnitude of improvement was strongly influenced by the internal friction angle of the LECA material. Columns with higher friction angles mobilized greater shaft resistance, thereby contributing to higher settlement reduction efficiency.

Figures 4, Figure 5 and Figure 6 present the plots of settlement improvement factor (η) against the area replacement ratio (α) for different LECA friction angles. The plots show that η increases with higher α values, and this trend is consistently observed across all friction angles of LECA aggregates. LECA with the highest friction angle contributes to the greatest settlement improvement factor for α = 0.1, 0.2, 0.3, and 0.4, respectively. The rise in settlement improvement factors suggests that closely spaced columns transfer the applied load more efficiently to their base. The analysis further indicates that the optimum replacement ratio lies between α = 0.2 and α = 0.4, as the settlement improvement factor remains nearly constant within this range. Hence, area replacement ratios of 0.2 to 0.4 are sufficient to achieve effective settlement reduction. The plot for φ = 35° is included as a reference line, based on findings reported by Zukri (2019).

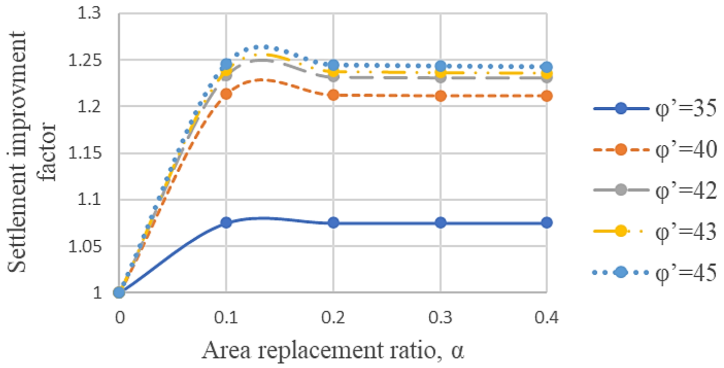

Figure 4. Settlement improvement factor versus area replacement ratio (Hr=1.5m, L/D=5)

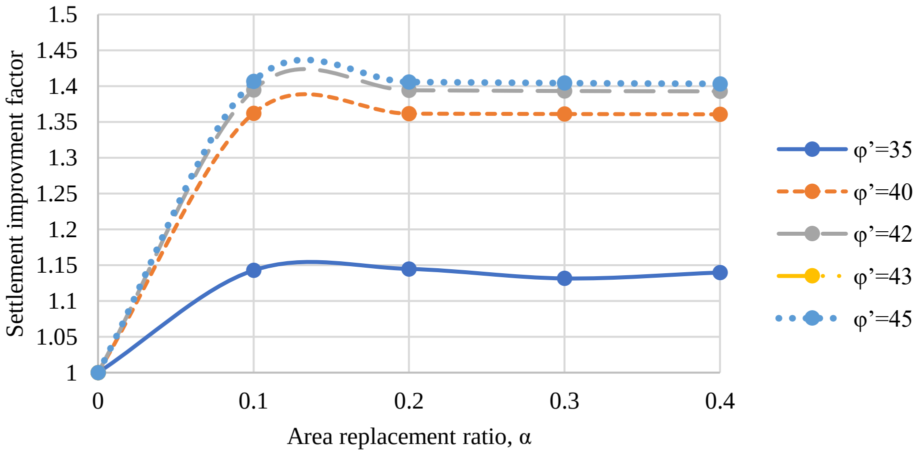

Figure 5. Settlement improvement factor versus area replacement ratio (Hr=2.5m, L/D=6)

This finding is in good agreement with the parametric numerical research by Gyawali (2021), which confirmed that settlement decreases with increasing area replacement ratio (α), while the friction angle (φ) significantly enhances performance—higher φ values contribute more to the settlement improvement factor (η) than stiffness alone stiffness (Gyawali et al., 2021). Similarly, Nik Omar et al. (2025) reported that increasing the area replacement ratio consistently reduced the settlement of floating stone columns, underscoring the governing role of α in settlement improvement across different column types [35]. These results align with other recent numerical studies, which highlighted that optimizing α together with a higher internal friction angle of column material leads to more efficient load transfer and reduced settlement in soft clay foundations [42].

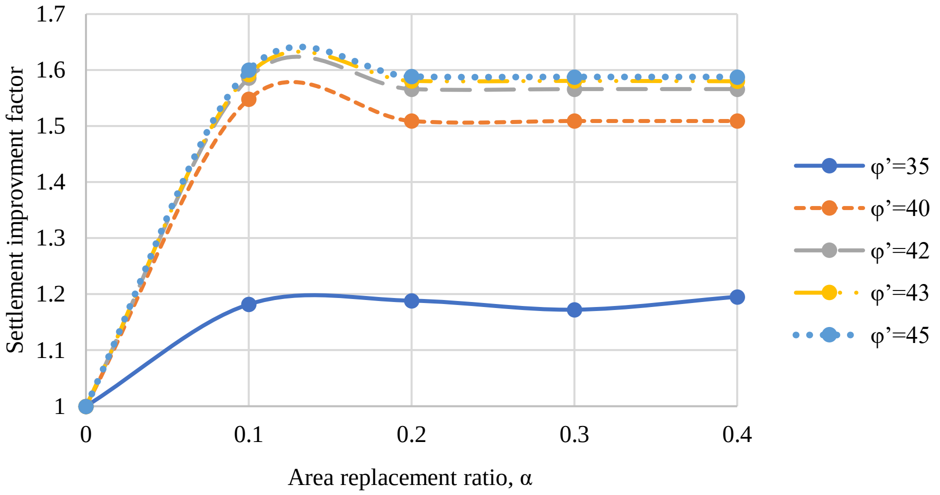

Figure 6. Settlement improvement factor versus area replacement ratio (Hr=3.5m, L/D=7)

7.2 Influence of Depth Ratio to Settlement Improvement Factor

The effects of LECA raft thickness, *Hr*, along with LECA columns, in reducing the compressibility of soft clay soil was also investigated. The settlement of untreated ground (without replacement and LECA column) with similar loading conditions as in the reference case recorded is 203.6 mm and 306.2 mm under loads of 50 kN/m^2 and 100 kN/m^2, respectively. Depth ratio, β, can be calculated using Eq. (4).

$$\beta = L_c/(H_s - H_r) \tag{4}$$

where, L_c is length of LECA column, H_s and H_r are depth of soft soil and raft thickness, respectively. When the depth ratio *(β)* of the LECA columns increases (approaching 1, indicating full penetration or end-bearing), the settlement of the soft soil decreases. This is because deeper columns provide higher composite stiffness to the improved layer, thereby reducing compressibility. In addition, increasing α improves the performance of the columns in reducing settlement. This is because higher α values result in closer spacing of the columns, leading to more concentrated stress on the columns compared to the surrounding soil. Figure 7 and Figure 8 show the plots on the settlement improvement factor for different depth ratios under 50 kN/m^2 and 100 kN/m^2 loading intensity for α = 0.1. Figures 9, Figure 10, Figure 11, Figure 12, Figure 13, and Figure 14 present the plots on the settlement improvement factor for different depth ratios under the same loading intensity for α = 0.2, 0.3 and 0.4. According to the study, the settlement performance improvement does not show significant changes beyond an area replacement ratio (α) of 0.2. This suggests that for economic reasons, closer column spacing (which requires higher α values) might not be necessary beyond α = 0.2.

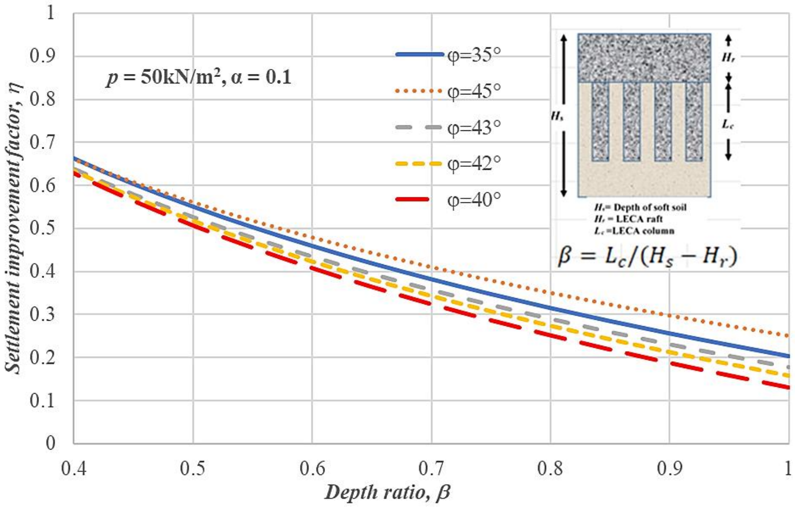

Figure 7. Settlement improvement factor against depth ratio, β (p =50kN/m^2, α = 0.1)

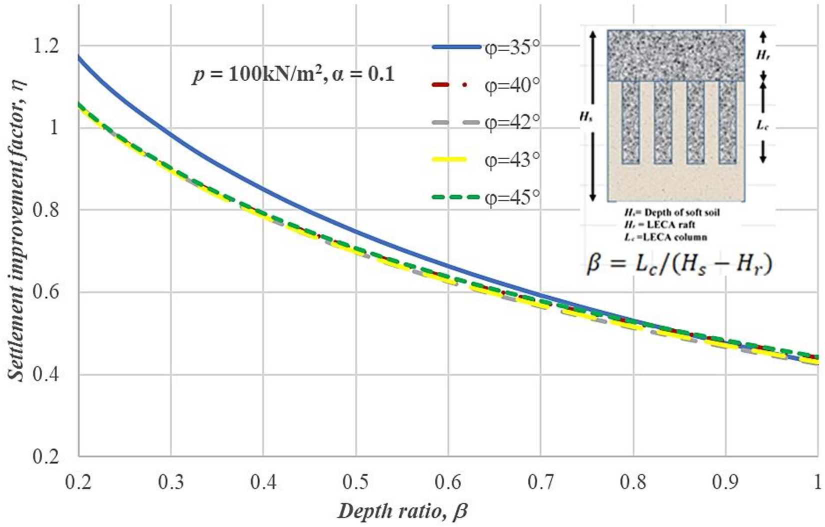

Figure 8. Settlement improvement factor against depth ratio, β (p =100kN/m^2, α = 0.1)

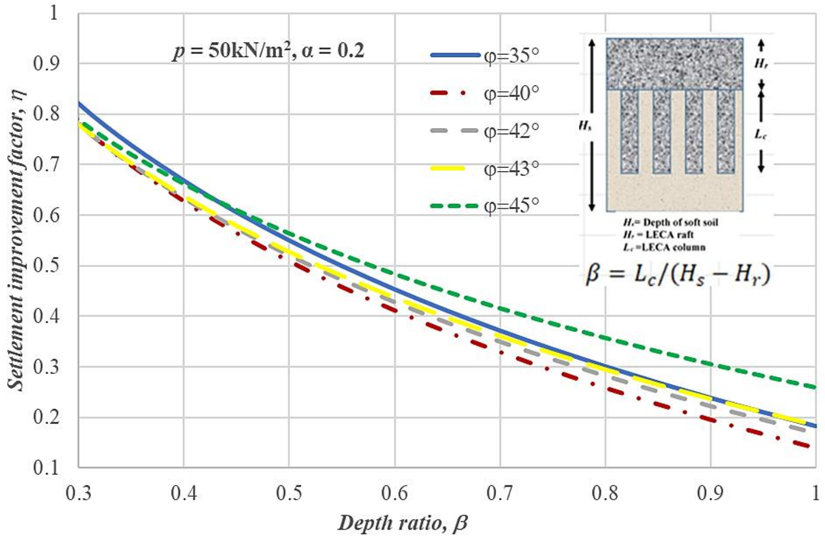

Figure 9. Settlement improvement factor against depth ratio, β (p =50kN/m^2, α = 0.2)

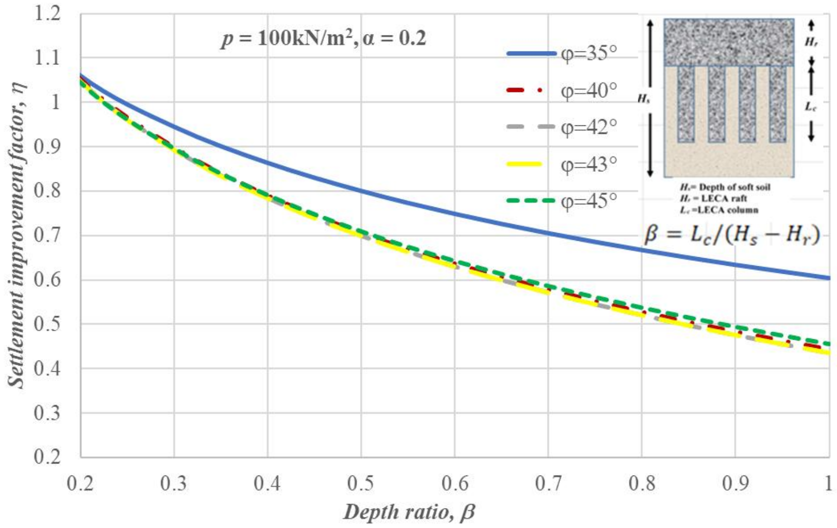

Figure 10. Settlement improvement factor against depth ratio, β (p =100kN/m^2, α = 0.2)

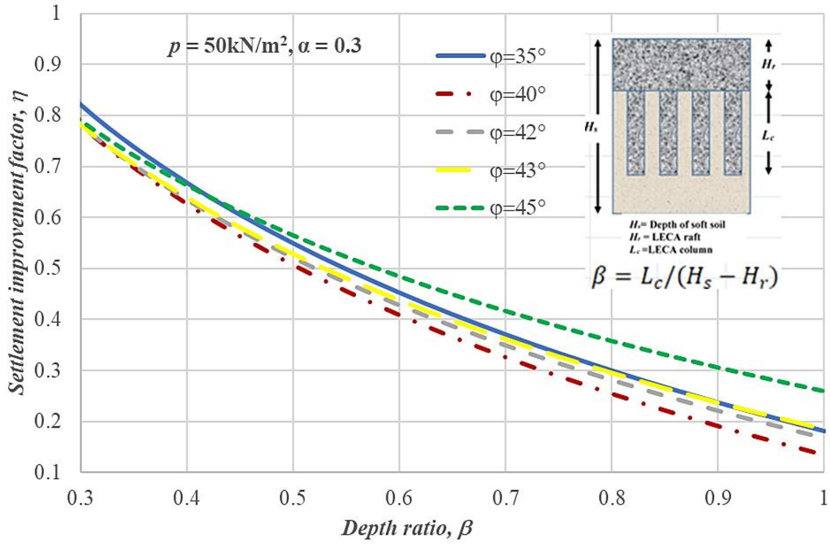

Figure 11. Settlement improvement factor against depth ratio, β (p =50kN/m^2, α = 0.3)

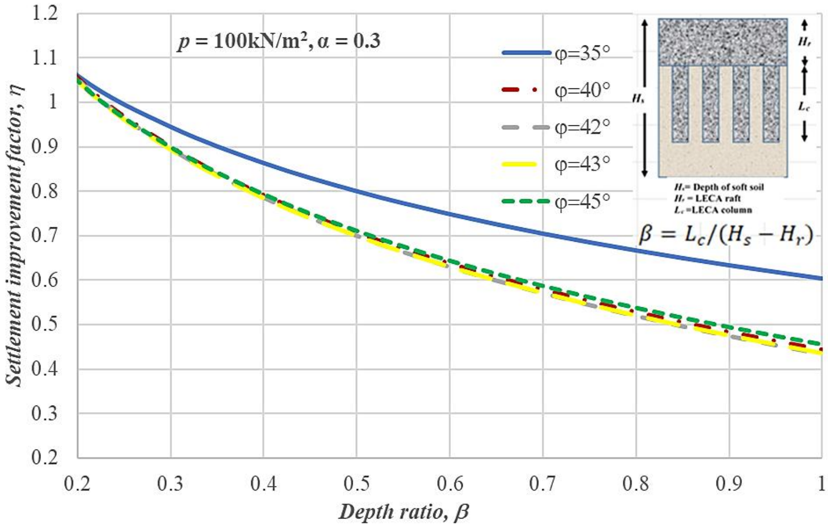

Figure 12. Settlement improvement factor against depth ratio, β (p =100kN/m^2, α = 0.3)

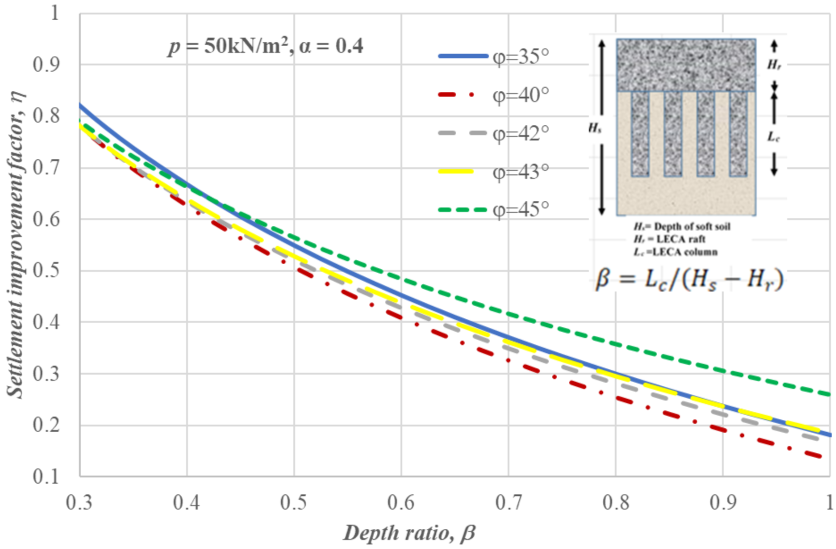

Figure 13. Settlement improvement factor against depth ratio, β (p =50kN/m^2, α = 0.4)

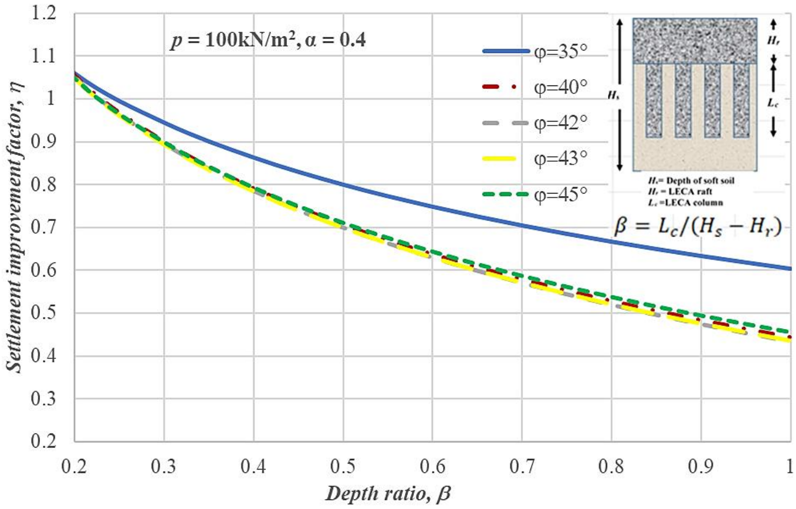

Figure 14. Settlement improvement factor against depth ratio, β (p =100kN/m^2, α = 0.4)

7.3 Settlement Prediction Procedures and Design Charts Establishment

The dimensionless relationship between settlement ratio (S/S_{uc}) and depth ratio (β) was developed in this study, as shown in Figure 15 and Figure 16. These are graphical representations that depict the relationship between settlement ratio (S/S_{uc}), depth ratio (β), and other parameters like area replacement ratios (α) and LECA friction angles. These graphs are expected to be referable to predict settlement under various conditions and design suitable ground improvement strategies.

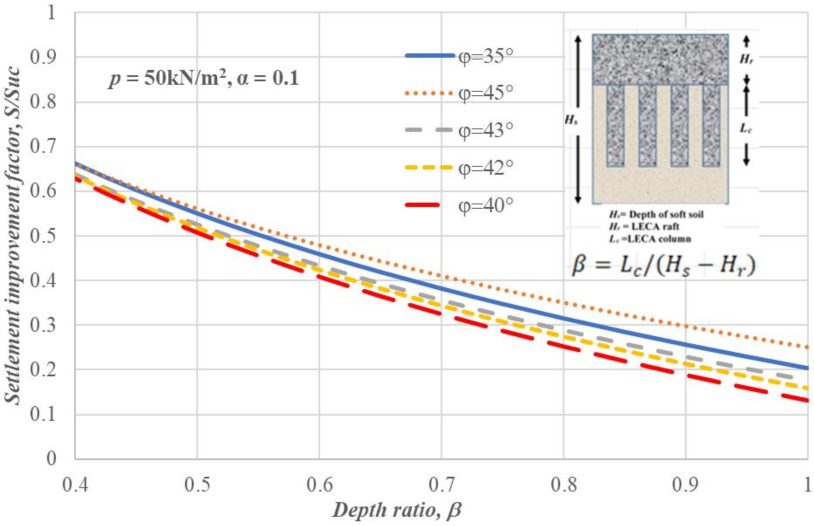

Figure 15. Settlement improvement factor against depth ratio, β (α = 0.1)

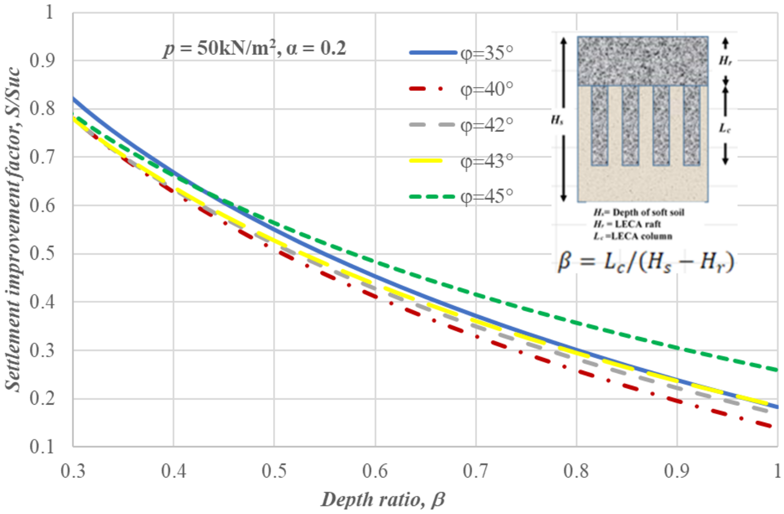

Figure 16. Settlement improvement factor against depth ratio, β (α = 0.2)

The Area Replacement Ratio (α) refers to the ratio of the cross-sectional area occupied by the LECA column to the total land area. It is mentioned that α ranges from 0.1 to 0.2 in the study, which means that the LECA column occupies 10% to 20% of the total area. Study shows the performance of LECA column raft for α more than 0.2 seems to remain at the same level. Therefore, for α exceeding 0.2, the prediction can be referred to the Figure 16. The procedure outlined by Zukri (2019) was used to calculate the settlement under large loads on improved soil using the design graph developed in this study. It provides a systematic approach to applying the empirical data from the graphs to real-world engineering problems. Table 3 tabulates the calculation procedure for predicting the magnitude of settlement under large loads when LECA is used as a column raft in soft soil improvement. Each step involves specific calculations and possibly referencing empirical data or design charts to obtain settlement values under various conditions.

Table 3. Calculation procedures to predict the settlement of LECA columns-raft

Step	Descriptions	Equation
1	Settlement of Untreated Ground under Oedometric Condition ($S_{s,oed}$). This settlement is typically calculated using oedometer tests or empirical correlations based on soil properties.	5
2	Settlement Improvement Factors (n) for End Bearing Columns in Unit Cell Condition. The factor account for the improvement in settlement due to end bearing columns in a unit cell based on column spacing.	6
3	Settlement of End Bearing Columns in Unit Cell Condition (*Suc)*: By referring to the calculated settlement improvement factors, the settlement of end bearing columns in the unit cell condition can be predicted, where the *Suc* will be influenced by the column characteristics and the soil response to loading.	7
4	Using Design Charts established, the settlement ratios like *S/Suc* can be quickly determined based on loading intensity, column length *(Lc)*, raft thickness *(Hr)*, and other parameters such as LECA friction angle.	Figure 15 Figure 16
5	Compute the settlement, *S* of floating column groups	

Considering the end-bearing condition, the settlement of improved layer was calculated using one dimensional settlement approach. The settlement of untreated ground under oedometric condition (*Ss,oed)* typically computed using soil mechanics principles and oedometric testing data. The settlement can be estimated using the relationship between of loading intensity *(p)*, depth of soft soil (*Hs)* and constraint modulus *(E_{oed})* recorded from laboratory test as shows in Eq. (5).

$$Ss,_{oed} = pH_s/E_{oed} \tag{5}$$

The approach proposed by [43] for calculating the settlement improvement factor (n) is applicable under conditions where the column grid spacing (parameterized by α falls within the range of 0.1 to 0.45 as shown in Eq. (6). The equation established by Ng & Tan (2014b) is recognized for its simplicity and practicality in predicting settlements. Despite its straightforward approach, it yields results that closely align with those obtained from more intricate numerical analyses. This characteristic renders it particularly valuable in preliminary design stages or scenarios requiring rapid estimations. Thus, Ng & Tan's method serves as a reliable tool for engineers and planners seeking efficient settlement predictions without the need for extensive computational resources or time-consuming procedures [4][44].

$$n = 9.43\alpha^2 + 1.49\alpha + 1.06 \tag{6}$$

where α is area replacement ratio. From the results calculated in Eq.s (5) and (6), the settlement of end-bearing columns in unit cell condition, S_{uc}, can be predicted using Eq. (7) below.

$$S_{uc} = Ss,_{oed}/n \tag{7}$$

The value of S/S_{uc} was obtained from the design chart in Figure 15 or Figure 16 with a specified depth of soft soil (*Hs*), length of LECA column (*Lc*), raft thickness (*Hr*) area replacement ratio, α and LECA friction angle. The settlement of LECA columns-raft (*S*) was then estimated using the value obtained from the design chart. Depth ratio, *β*, was calculated using Eq. (4). Note that the depth ratio, *β*, should not exceed 1.0.

7.4 Validation of Design Chart

Validation of the established design charts were performed through numerical analysis (PLAXIS 3D) due to lack of existing methods or field data specific to LECA columns-raft settlement prediction. The utilization of the design chart that has been set for the initial design to illustrate the verification process is given below.

Design example: A group of LECA columns with area replacement ratio, α of 0.2, loading intensity, p of 50 kN/m^2, length of floating LECA column, Lc of 5 m and 2.5 m raft thickness, *Hr* is to be installed in a 15 m thick, soft ground with constraint modulus of *Es* of 2420 kN/m^2. The settlement of this floating LECA columns-raft is calculated as follows. The settlement of LECA columns-raft predicted using the developed design chart is 0.12145 m or 121.45 mm. The same design conditions and parameters were analysed using numerical software for error checking. The settlement calculated using PLAXIS 3D software is 0.1315 m or 131.50 mm given the error of 8.28%, which is considered acceptable.

Step 1: Calculate $Ss_{,oed}$ using Eq. (5); $Ss_{,oed} = pHs/E$ = 50 x 15 / 2420 = 0.30992m

Step 2: Calculate n using Eq. (6); n=9.43(0.2)2+1.49(0.2) +1.06 = 1.7352

Step 3: Calculate the Suc using Eq. (7); S_{uc} = 0.30992/1.7352 = 0.1786m

Step 4: Obtain S/S_{uc} from developed design chart in Figure 16 (for α = 0.2);
β = 5/(15-2.5) =0.4, α =0.2, φ = 35°, S/Suc = 0.68

Step 5: Compute the settlement, S of LECA columns-raft;
S= 0.68 x 0.1786 = 0.12145 m =121.45 mm

Based on Table 4, the comparison between the proposed method and FEM (Finite Element Method) analysis reveals that the percentage of error is consistently less than 30%. This level of error is generally considered acceptable in engineering and scientific analyses, suggesting that the proposed method aligns well with the FEM results. This similarity indicates that the proposed method can be relied upon for further design and analysis purposes, as its outcomes are within an acceptable margin of error when compared to a well-established analytical technique like FEM.

Table 4. Results comparison and validation

Hr	α	β	p (kN/m2)	Settlement, m	
				Proposed method	FEM
2.5	0.1	0.39	50	0.105	0.147
3.5	0.1	0.43	50	0.095	0.078
2.5	0.2	0.45	70	0.117	0.208
1.5	0.1	0.16	50	0.159	0.249
1.5	0.1	0.16	100	0.317	0.445

8. CONCLUSION

In summary, the study underscores the importance of optimizing the design parameters of LECA columns-raft systems to achieve efficient ground improvement in soft soil conditions, highlighting the balance between depth factor (β) and area replacement ratio (α) as critical factors. The study suggests that for practical and economic considerations, constructing a LECA columns-raft system with an area replacement ratio *(α)* not exceeding 0.2 is more efficient. This approach optimizes the stiffness of the improved ground while balancing construction costs, making it a practical solution for geotechnical engineering applications. By systematically varying *Hr, β* and *α* in the PLAXIS 3D model and observing their effect on settlement performance, optimal design parameters to minimize settlement over time while using LECA aggregates to improve the overall stability and performance of the base system can be obtained. The design charts were created based on numerical analysis (PLAXIS 3D). These charts aim to predict the long-term settlement magnitude under large-loaded areas in soft soil based on various friction angle of LECA aggregates. The design charts are straightforward, easy to use, and reliable for estimating long-term settlement. This makes them practical tools for engineers involved in soft soil improvement work.

The charts were validated using Finite Element Method (FEM) analysis. The validation showed reasonable agreement between the predictions from the design charts and the results obtained from FEM analysis. The established design charts are recommended as reliable tools for practical engineers to estimate settlement in soft soil conditions. Specifically, they are applicable when using techniques like the replacement method, stone columns, and columns-raft with LECA as granular material. Despite the reasonable agreement found in the validation process, it is suggested that more real case studies should validate the proposed design charts. This step is crucial to ensure the reliability and accuracy of the charts across different real-world scenarios. To further validate the design charts, it is advisable to build and test a full-scale model. This approach would involve constructing a physical model that replicates the conditions under which the design charts are intended to be used. By comparing the settlement predictions of the charts with the actual settlements observed in the model, engineers can gain more confidence in the charts' accuracy and applicability. In summary, while design charts show promise in predicting settlements in soft soils under various techniques and conditions, additional real case studies and full-scale model tests are recommended to verify their reliability before widespread adoption in practical engineering applications.

ACKNOWLEDGEMENTS

The authors would like to thank UMPSA for providing facilities during the research work.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS' CONTRIBUTION

A.H. Dayang Zulaika (Conceptualization; Data collection; Funding acquisition; Supervision)
A. Zukri (Methodology; Data analysis; Writing - original draft, review & editing; Resources)
Reza Pahlevi Munirwan (Writing - review & editing, Validation; Formal analysis)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author

ETHICS STATEMENT

Not applicable

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