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SETTLEMENT FOR CONSTRUCTION ON SOFT CLAY IMPROVED USING FLOATING RIGID INCLUSIONS CONSIDERING THE INSTALLATION EFFECT

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ABSTRACT

This paper presents a novel approach to predicting induced deformations in clay deposits that have been improved by a system of floating rigid inclusions. The improvement of clay deposits is a complex process that is governed by a wide range of factors, making it challenging to accurately predict the expected settlement. The proposed approach aims to address this issue by developing reliable and user-friendly charts that estimate the settlement improvement factor (N), which is defined as the ratio of settlement values after soil improvement to those before improvement. To achieve this objective, the paper employs the cavity expansion method to model the installation process of the rigid inclusions in soft clay formations. A comprehensive parametric study is conducted using numerical modeling to investigate the variation in the improvement factor for a 15.00m thick clay deposit, where inclusions may be stopped before penetrating the firm stratum below the considered soft deposits. The study considers the variation of the treated soil stiffness and the geometry of the rigid inclusion system. The analyses are performed for a case study of a zone loading test conducted at New Mansoura city in Egypt, using the finite element software (PLAXIS 3D). The comparison of settlement associated with loading both the improved and unimproved soils is conducted for each studied condition in the parametric study to determine the improvement factor (N). The findings of the study demonstrate that the rigid inclusions have a significant impact on reducing the settlement associated with construction on the improved soft clay. The achieved improvement factor varies between 2.31 and 8.23, with an average value of about 4.65. The paper's contributions are twofold. Firstly, it presents a reliable approach for predicting the induced deformations in clay deposits improved by a system of floating rigid inclusions. Secondly, it provides a straightforward tool for predicting the settlement values associated with construction on improved soft clay formations with rigid inclusions under different conditions. This tool can be used to improve the design and construction of infrastructure projects built on soft clay deposits, leading to more cost-effective and sustainable solutions.

Keywords: Rigid Inclusions, Soft Clay, Improvement Factor, Installation Effect; Cavity Expansion.

I. INTRODUCTION

Menard first introduced the technique known commercially as Controlled Modulus Columns (CMC) in the 1990s as the rigid inclusion technique [1]. This technique requires more research to develop a reliable design approach that can estimate the settlements of the soft soil-rigid inclusions matrix and consider the effect of the rigid inclusion installation on the soft soil properties. The following section gives a brief of the former researchers' works that have provided a great contribution to investigate the behaviour of soil-rigid inclusion matrix in order to enhance the accuracy of estimated settlements:

Gigan [2] reported the first use of rigid inclusions in France without considering the mechanism at which the rigid inclusions were driven as cast-in-place piles without bonding them to the structures to improve the characteristics of former embankments.

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Combarieu [3], [4] published two consecutive publications on the analytical design of rigid inclusion groups based on two detailed studies on negative skin friction on piles. The first study provided an approach for the mesh pattern and the resistant inclusion embedment, as well as determining the settlement of compressible soil due to embankment construction. The second study proposed a procedure for calculating the inclusion groups for flexible or rigid foundations.

Van Eekelen [5] studied the behaviour of the load transfer mechanism in the soil–rigid inclusions matrix through experimental work but ignored the installation effect. Huu Hung et al. [6], [7]studied the effect of installation sequences of plain concrete rigid inclusions on the existing CMCs using finite difference software but did not introduce the enhancement in soil parameters due to the installation effect.

Muhannad T. Suleiman [8] studied the interaction between the laterally loaded pile and the surrounding soil and introduced the alteration in horizontal soil stress. Suleiman also [9] reported a full-scale field vertical load test on a CMC to investigate the short-term effect of installation on the surrounding soil but did not consider the impact of a group of rigid inclusions acting together.

This paper's goal is to create new and simple charts that can help predict the settlement values of soft clay formations that are improved with rigid inclusions under various conditions. These charts are novel and useful for this improvement method. The settlement values can be calculated by finding an improvement factor, which is the ratio between the settlement value before and after soil improvement.

Marco et al. [10] have previously presented similar charts, but for rigid inclusions that penetrate a strong stratum and rest on it, so the presented charts in this paper can be complementary charts to those that are introduced previously to extend the study of rigid inclusions technique in the different bearing conditions.

II. PREDICTING THE MODIFIED SOIL PARAMETERS AFTER APPLYING THE CYLINDRICAL CAVITY EXPANSION APPROACH

Rigid inclusions are usually installed by driving a precast concrete section or a closed-end pipe to the desired depth. This installation process reduces the void ratio of the surrounding soil for two main reasons. The first reason is the lateral and vertical displacements that happen when the rigid inclusion is created in the soil (i.e., from a zero radius to the final radius of the rigid inclusion). The second reason is the compaction of the surrounding soils by the energy transmitted while driving the inclusion near the soil mass around it. Yu [11] showed the expected deformation directions that occur during the rigid inclusion installation, which can cause surface heave for the top soil layer.

The void ratio of the surrounding soil decreases when the rigid inclusions are installed, which improves the deformation parameters of the surrounding soil. The improvement in the surrounding soil parameters is higher for larger rigid inclusions and deeper depths because of the effect of the stress level on the displacements. Installing a rigid body in a soil matrix by driving force can change the initial in-situ stress state of fine-grained soils a lot.

Based on this approach, many techniques were developed to simulate the installation effects in the numerical modelling. Elshazly et al. [12] used a simple method that increased the coefficient of lateral earth pressure (K_o) of the soil around the rigid inclusion. This method analytically predicted the new lateral earth pressure coefficient instead of using numerical modelling. Another more accurate method was used by some researchers, such as Guetif et al. [13] and Debats et al. [14], which used axisymmetric finite element analysis to simulate the installation effects. In the cylindrical cavity expansion technique, they applied a cylindrical enlargement using a "dummy material", which they then changed into the actual material properties of the rigid inclusion.

Although both methods have proved to predict the actual conditions of soil after improvement in several applications, the cylindrical cavity expansion technique is more commonly applied with the software utilized in the presented paper as adopted previously by other researchers [15], [16].

III. PREDICTING IMPROVED SOIL PARAMETERS

The study deals with the inclusion of a diameter of 0.50 while also focusing on soft to medium stiff clay behaviour with undrained shear strengths of values of 10 kPa, 17.50 kPa, and 25 kPa. Furthermore, the studied thickness of soft clay layers is 15.00m, representing a thick, soft deposit where inclusions may be stopped before penetrating the firm stratum below the considered soft deposits. Consequently, the applied displacement to the dummy material is 0.20m to reach a final radius of 0.25m. The soil deformation modulus of clay was estimated according to the Duncan and Buchignan chart [17], which depends on the over consolidation ratio considered in our study to have a value of about 1.00 (i.e., normally loaded soil). It also depends on the plasticity index value, which is mostly above 50%. Consequently, the ratio between the initial deformation modulus and the undrained shear strength is considered to have a value of 200 (i.e., for c_u = 10 kPa, an initial deformation modulus of 2000 kPa is used).

Figure 1 shows the axisymmetric model developed to study the enhancement in the soft soil at which the rigid inclusion lengths are chosen to represent a commonly utilized percentage of the clay layer thickness. The axisymmetric models generally start with a load transfer platform with a thickness of 1.00 m, followed by a layer of silty clay of a thickness of 15.00 m, underlain by an extended layer of dense sand, while the rigid inclusion lengths are chosen to be 7.50 m, 10.00 m, and 12.00 m below the LTP where the ratios between the inclusion lengths and the clay layer thickness are 0.50, 0.67, and 0.80.

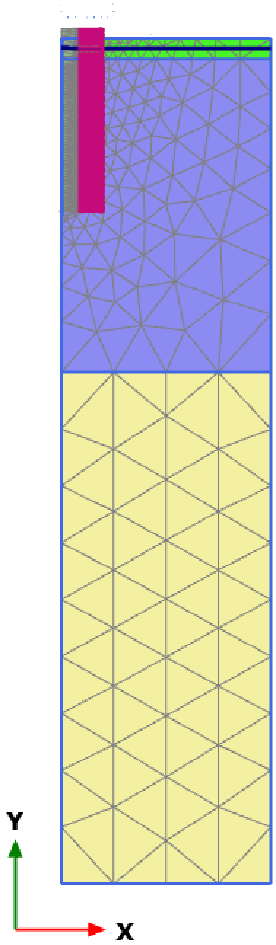

Figure 1.a: Generated mesh of the axisymmetric model developed to study the radial displacement effect in the case of floating rigid inclusion length to the clay layer thickness is 0.50.

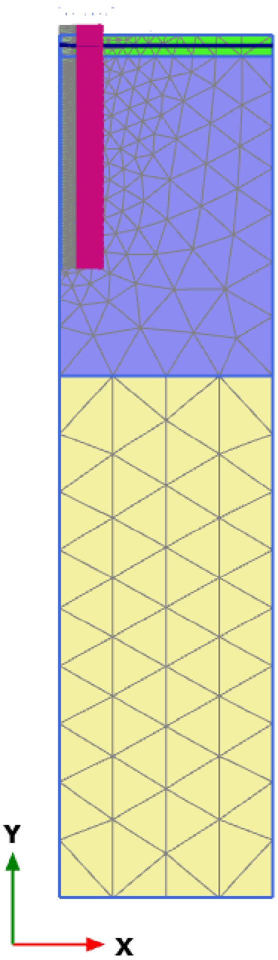

Figure 1.b: Generated mesh of the axisymmetric model developed to study the radial displacement effect in the case of floating rigid inclusion length to the clay layer thickness is 0.67.

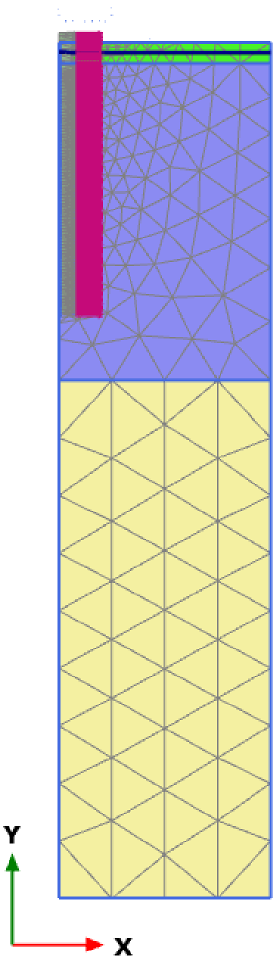

Figure 1.c: Generated mesh of the axisymmetric model developed to study the radial displacement effect in the case of floating rigid inclusion length to the clay layer thickness is 0.80.

Figure 1: Generated Mesh of the axisymmetric model developed to study the radial displacement effect

Tables 1 and 2 show the soil and rigid inclusion parameters utilized in the axisymmetric models. Figure 2 presents the deformation contours where the installation effect extends to a distance of about four times the

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rigid inclusion diameter. Figure 3 shows the improvement in the deformation modulus of the clay layer responsible for most of the anticipated settlement.

Table 1: Parameters of different soil layers used in the FEM

Soil layer	Thickness (m)	γ (kN/m³)	OCR	C_U (kPa)	□' (deg.)	E_{50}^{ref} (kPa)	E_{ur}^{ref} (kPa)	Power m	R
LTP	1.00m	20.00	--	--	40	100000	300000	0.50	0.7
Silty Clay	15.00 m	17.00	1.00	Varies from 10 to 25	--	Varies from 2000 to 5000	Varies from 6000 to 15000	1.00	0.7
Sand	Extended	18.00	--	--	35	50000	150000	0.50	0.7

Table 2: The Material model parameters used to simulate Rigid inclusions

layer	Diameter (m)	Length (m)	γ (kN/m³)	E (kPa)	□
Rigid Inclusion	0.50	Varies from 7.50 to 12.00 m	25.00	22000000	0.15

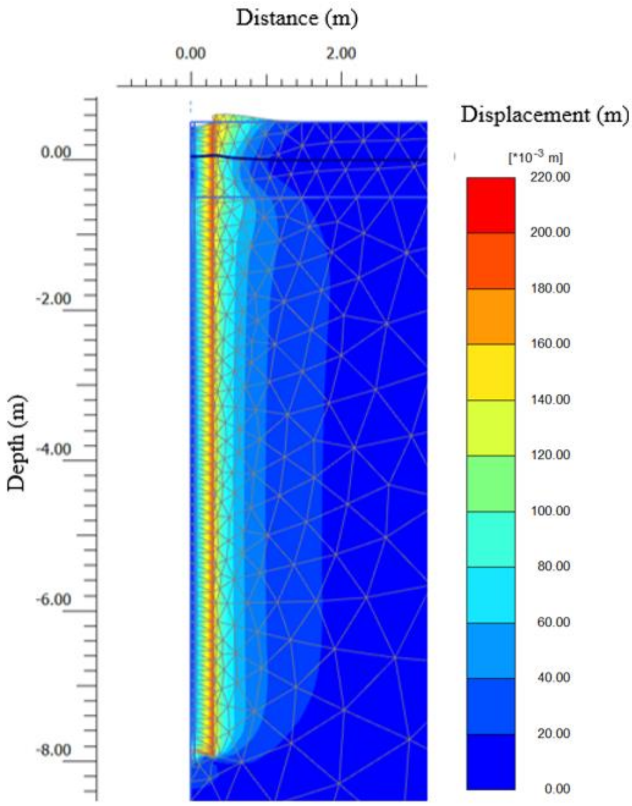

Figure 2: Deformation contours after applying the radial displacement of 0.20m

Through the axisymmetric analyses, the improvement that occurs in the deformation modulus of all soil layers is estimated due to the installation effects of the rigid inclusions. The deformation modulus value of the clay layer is the most important factor in predicting the total settlement, as it is responsible for most of the anticipated settlement. For the clay deposits, the ratio between the improved deformation modulus and the initial deformation modulus ranges from 1.91 to 3.10, as presented in Figure 5.

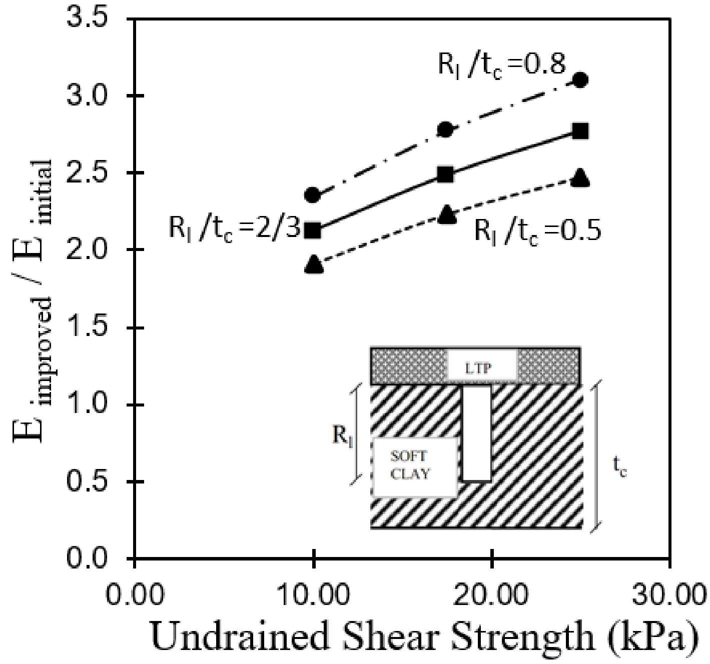

Figure 3: Correlation between the ratio of the improved deformation modulus to initial deformation modulus, varying the ratio between the rigid inclusion length (R_l) to the thickness of the clay layer (t_c) and the undrained shear strength (C_U).

IV. NUMERICAL MODELLING

Improved soil parameters resulting from applying the cavity expansion approach to simulate the installation process of rigid inclusions in the soil are utilized in three-dimensional analyses to predict the induced deformations under the applied loads. The increase in soil modulus and over consolidation pressure is used in the 3D model prepared to study various conditions. The 3D model dimensions are chosen based on sensitivity analyses to exclude the boundary effect on the estimated results where a uniform surcharge is applied on a load transfer platform with a thickness of 1.00m. The applied surcharge will affect the soil layers with an equal value as the model simulates an oedometer test setup, which accurately mimics a raft foundation with large dimensions resting on a thick layer of soft clay. For each studied case, three models are prepared considering the different spacings between rigid inclusions most commonly used (i.e., two, three, and four times the inclusion's diameter). The rigid inclusions are simulated in the 3D FEM as volume elements [18], [19], [20]. The linear elastic material model is utilized for simulating the behaviour of rigid inclusions where the elastic modulus is assumed to be 22000 MPa (i.e., compatible with a characteristic cube strength of the concrete value of 25 MPa).

Additionally, the hardening-soil constitutive model is used to simulate the behaviour of the different soil layers as it can emulate the soil behaviour under both loading and unloading conditions. The drainage type for various soils in the 3D FEM is chosen to consider the actual soil conditions where drained type is selected for the load transfer platform (LTP) and sand layers existing above and below the clay layer, respectively. On the other hand, the undrained (b) type is chosen for the clay layer, where stiffness is defined in terms of effective properties, while strength is expressed in its undrained condition. Figure 4 shows the generated 3D mesh for one of the models prepared for this study.

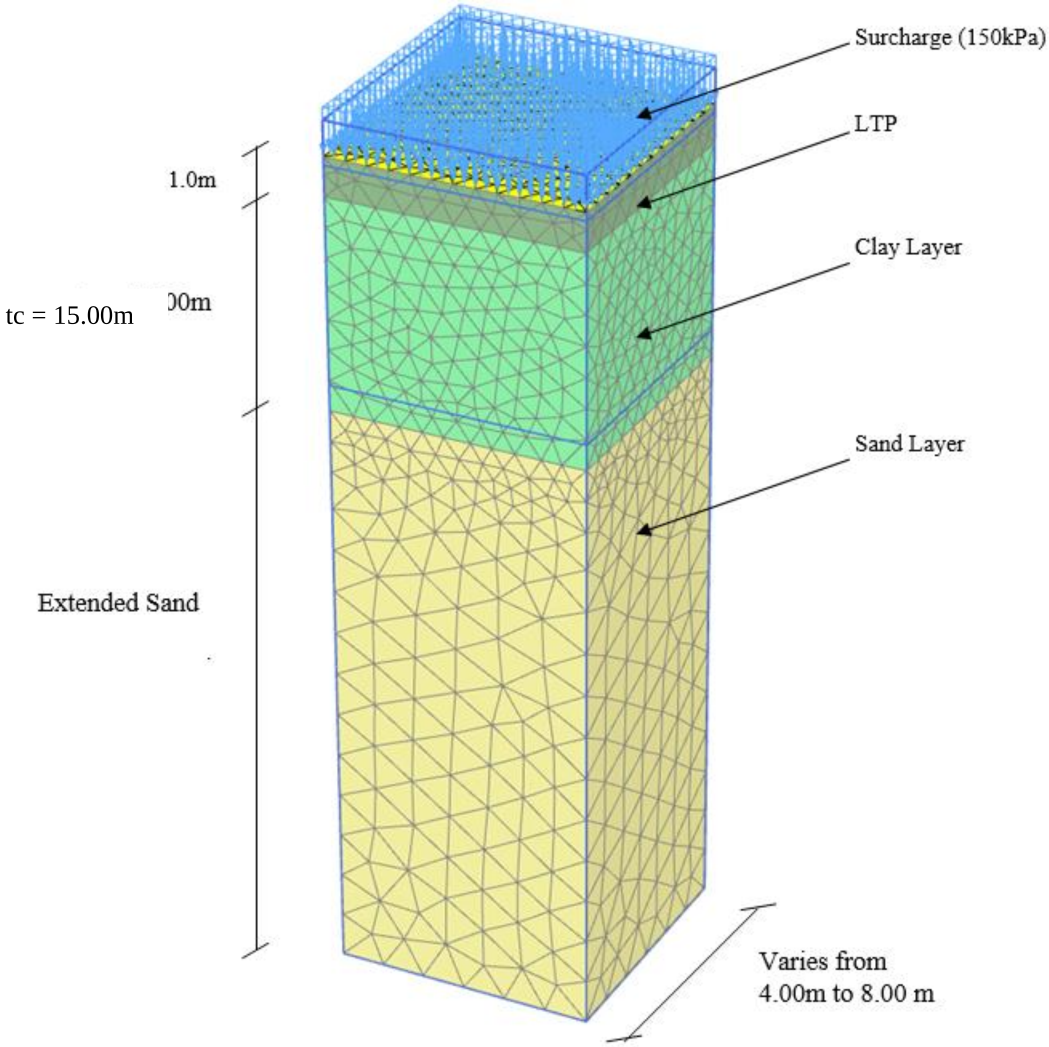

Figure 4: Generated 3D FEM for the soil-rigid inclusions system

V. DESIGN CHARTS FOR PREDICTING THE IMPROVEMENT FACTOR OF FINAL SETTLEMENT FOR NORMALLY LOADED CLAY SOIL IMPROVED BY RIGID INCLUSIONS

The results of the 3D analyses based on about 27 models are presented in the form of design charts to facilitate a preliminary estimation of the expected improvement factor for final settlement, which will occur after executing rigid inclusions of different diameters and lengths within clay soil deposits of variable shear strength values. The predicted improvement factor considers the enhancement of soil parameters after applying the cavity expansion approach to simulate the installation effects of rigid inclusions. Moreover, the rigid inclusions act as rigid elements with greater stiffness compared to that of the soil, which leads to a significant reduction in the settlement while simultaneously increasing the improvement factor. The predicted improvement factor considers the double effect of the rigid inclusions that play a significant role in enhancing soil parameters due to the lateral deformations that lead to soft soil compaction. Moreover, the presence of the inclusions as stiff vertical elements within the weak soil formation increases the soil-rigid inclusion matrix's equivalent stiffness.

The lateral deformation of the soil associated with the installation effect of the rigid inclusions is modelled by the cavity expansion method in the developed finite element models. After considering the installation effect, the settlement of soils improved by rigid inclusions has been significantly reduced, and thus, the improvement factor has increased.

The following figures illustrate the developed charts for estimating the improvement factors in all the studied cases, considering alternating the undrained shear strengths of 10 kPa, 17.50 kPa, and 25 kPa. The results in all

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cases show similar behaviour for different (S/D) ratios as the improvement factor ranges between 2.31 and 8.23. The ratio of the spacing of rigid inclusion to its diameter (i.e., S/D) plays a great role in enhancing the soil parameters, leading to a significant variation in the improvement factor value where the most enhanced parameters are achieved in the case of the smallest (S/D) ratio. Similarly, the undrained shear strength of the clay deposits dramatically contributes to the concluded improvement factor as the inclusion will be rested on the clay deposits so that the inclusion capacity will be significantly increased with the increase in the undrained shear strength of the soil.

Additionally, the analyses show that applying the radial displacement at deep layers with higher effective stresses results in better improvement than at shallow depths with less effective stresses. Thus, the ratio (L/D) is of great importance in predicting the improvement factor (N). such factor increases significantly with the increase of the thickness of the soft clay layer.

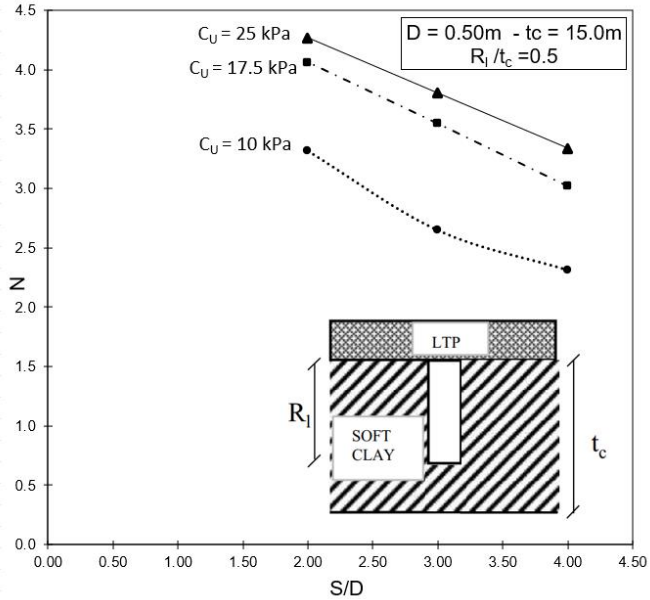

Figure 5: Design chart to estimate the improvement factor for rigid inclusion of diameter 0.50m rested on clay formations with a ratio between the rigid inclusion length (R_l) to the thickness of clay layer (t_c) of 0.50.

The following correlations are estimated from the best-fit interpretation of the previous chart to facilitate the determination of the improvement factor for various S/D ratios:

1- For Undrained Shear Strength of 10 kPa, thickness of clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_l/t_c) ratio of 0.5:

$$N = -0.5008 \cdot \left(\frac{S}{D}\right) + 4.262 \quad (1)$$

2- For Undrained Shear Strength of 17.5 kPa, the thickness of the clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_l/t_c) ratio of 0.5:

$$N = -0.5219 \cdot \left(\frac{S}{D}\right) + 5.108 \quad (2)$$

3- For Undrained Shear Strength of 25 kPa, thickness of clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_l/t_c) ratio of 0.5:

$$N = -0.4644 \cdot \left(\frac{S}{D}\right) + 5.196 \quad (3)$$

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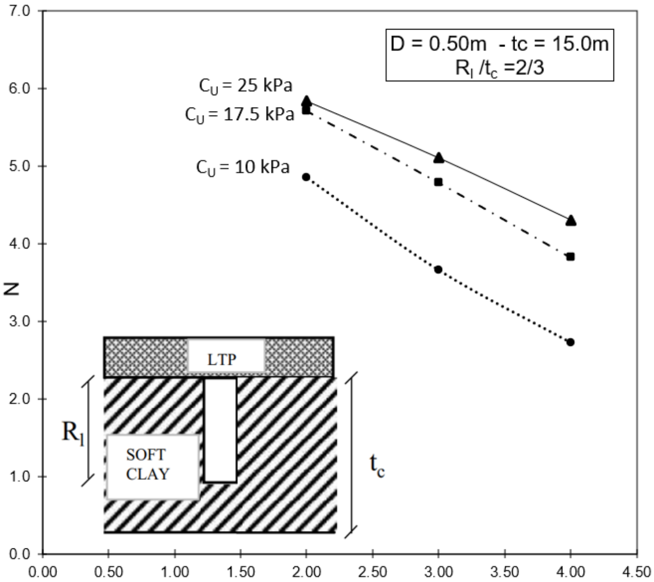

Figure 6: Design chart to estimate the improvement factor for rigid inclusion of diameter 0.50m rested on clay formations with a ratio between the rigid inclusion length (R_l) to the thickness of clay layer (t_c) of 0.67.

The following correlations are estimated from the best-fit interpretation of the previous chart to facilitate the determination of the improvement factor for various S/D ratios:

1- For Undrained Shear Strength of 10 kPa, thickness of clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_l/t_c) ratio of 0.67:

$$N = -1.0676 \cdot \left(\frac{S}{D}\right) + 6.945 \quad (4)$$

2- For Undrained Shear Strength of 17.5 kPa, the thickness of the clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_l/t_c) ratio of 0.67:

$$N = -0.9428 \cdot \left(\frac{S}{D}\right) + 7.601 \quad (5)$$

3- For Undrained Shear Strength of 25 kPa, thickness of clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_l/t_c) ratio of 0.67:

$$N = -0.7668 \cdot \left(\frac{S}{D}\right) + 7.380 \quad (6)$$

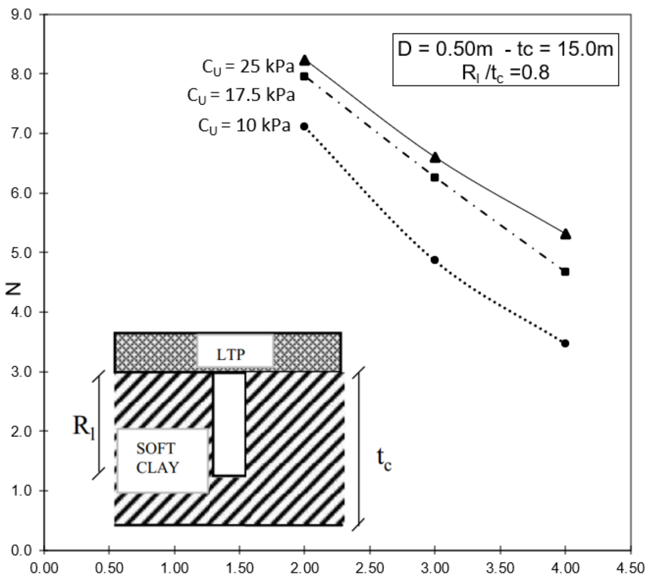

Figure 7: Design chart to estimate the improvement factor for rigid inclusion of diameter 0.50m rested on clay formations with a ratio between the rigid inclusion length (R_l) to the thickness of clay layer (t_c) of 0.80.

The following correlations are estimated from the best-fit interpretation of the previous chart to facilitate the determination of the improvement factor for various S/D ratios:

1- For Undrained Shear Strength of 10 kPa, thickness of clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_I/t_c) ratio of 0.80:

$$N = -1.8202 \cdot \left(\frac{S}{D}\right) + 10.608 \quad (7)$$

2- For Undrained Shear Strength of 17.5 kPa, the thickness of the clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_I/t_c) ratio of 0.80:

$$N = -1.6429 \cdot \left(\frac{S}{D}\right) + 11.225 \quad (8)$$

3- For Undrained Shear Strength of 25 kPa, thickness of clay layer of 15.00m & rigid inclusion of diameter of 0.50 m and (R_I/t_c) ratio of 0.80:

$$N = -1.4591 \cdot \left(\frac{S}{D}\right) + 11.092 \quad (9)$$

VI. THE EFFECT OF THE UNDRAINED SHEAR STRENGTH OF SOFT SOILS ON THE IMPROVEMENT FACTOR

The performed study has shown the great effect of the undrained shear strength of the soft soils on the behaviour of the soil-rigid inclusion matrix, especially for predicting the improvement factor for soft soils that are partially improved with rigid inclusions rested on clay deposits. In the case of the rigid inclusions bearing in the clay deposits, the value of the undrained shear strength of the soft soil has significantly affected the value of the improvement factor, at which the highest improvement factor corresponds to the highest undrained shear strength value. However, the improvement factor value is inversely proportional to the undrained shear strength of soft soils in the case of rigid inclusions bearing in the sand layer. This different behaviour may be attributed to the following reasons:

- In the case of rigid inclusions bearing in the sand layer, the bearing in the sand deposits significantly reduces the settlement of the rigid inclusion, resulting in an increase in the improvement factor regardless of the value of the undrained shear strength of soft soils. Simultaneously, bearing in the sand deposits increases the rigid inclusion capacity, where most of this capacity is acquired by the bearing in sand deposits rather than the friction with the surrounding soft soil that depends on the undrained shear strength of soft soil.
- In the case of rigid inclusions that are bearing in the clay layer, the estimated settlement after improvement is much bigger than the settlement estimated in the case of rigid inclusions that are bearing in the sand layer as a result of the reduction in the capacity of the rigid inclusions bearing in the clay soil and the decrease in their efficiency. The capacity of the rigid inclusions is divided into bearing and friction, where the undrained shear strength governs both of them, unlike the inclusions resting in the sand layer where most of the capacity is acquired by the bearing in sand deposits that do not depend on the undrained shear strength of soft soil.
- So, in the case of the rigid inclusions rested on the sand deposits, the improvement factor is inversely proportional to the undrained shear strength, as the capacity of rigid inclusion is approximately independent of the undrained shear strength, while the settlement before improvement is significantly affected directly by the undrained shear strength.
- On the other hand, in the case of the rigid inclusions resting on the clay deposits, the improvement factor is directly proportional to the undrained shear strength, as the capacity of rigid inclusion depends on the undrained shear strength. Furthermore, the undrained shear strength significantly affects the settlement before improvement.

VII. CONCLUSION

Throughout the study, various parameters controlling the overall behaviour of the improvement process, such as the inclusion diameter (S/D) ratio, the ratio between inclusion length to its diameter (L/D), and soil shear strength, were investigated. The following can be concluded from the analysis:

1. The ratio of the improved deformation modulus to the initial deformation modulus in the case of the rigid inclusions bearing in the clay deposits ranges between 1.91 and 3.10, with an average value of 2.47.

2. The ratio between the improved deformation modulus and the initial undrained shear strength in the case of the rigid inclusions bearing in the clay ranges between 382 and 620, with an average value of 493.

3. The improvement factor decreases as the undrained shear strength decreases. The improvement factor considering the different values of the undrained shear strengths in the current study (i.e., c_u = 10, 17.5, 25 kPa) ranges between 2.31 and 8.23, with an average value of about 4.65.

4. The ratio (S/D) is inversely proportional to the improvement factor, where the improvement factor for (S/D = 2) ranges between 3.32 and 8.23, with an average value of 5.70. In contrast, for (S/D = 3), the improvement factor ranges between 2.65 to 6.59 with an average value of 4.58, and for (S/D = 4), the improvement factor ranges between 2.31 to 5.31 with an average value of 3.66.

Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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