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Numerical Analysis of Soft Clay Improvement Using Ordinary and Geogrid-Encased Stone Columns with PLAXIS 3D

Marwah Fadhil Al-Ghaith*[1], Assist. Prof. Dr. Osamah S. Abdulkareem Al-Salih[2], Prof. Dr. Samoel Mahdi Saleh[3]
[1] Civil Engineering Department, Engineering College, Basrah University, Iraq
[2] Civil Engineering Department, Engineering College, Basrah University, Iraq
[3] Civil Engineering Department, Engineering College, Basrah University, Iraq

Correspondence
* Marwah Fadhil Al-Ghaith
Postgraduate Student, Department of Civil Engineering, University of Basrah
Email: marwa.fadhil2025@gmail.com

Abstract

This study investigates the application of Ordinary Stone Columns (OSCs) and Geogrid-Encased Stone Columns (GESCs) in enhancing the properties of soft clay soils through numerical analysis using PLAXIS 3D (version 2024). The study contrasts numerical findings with two well-researched field case studies: one in Korea and one in Iraq. The analyses were calibrated using the Mohr–Coulomb and Hardening Soil models, and settlement responses were assessed for different reinforcement scenarios, including untreated soil, OSCs, and GESCs. The results show a strong match between PLAXIS 3D simulations and field measurements, confirming the method's reliability. In the floating case (in Iraq), OSCs increased load-bearing capacity by about 21%, while GESCs improved it by around 30% compared to untreated soft clay. For the end-bearing case (in Korea), even greater enhancements were recorded, with OSCs increasing the bearing capacity by nearly doubling it and GESCs by almost 2.5 times compared to untreated soil. Geogrid encasement is presented as significantly improving settlement control and bearing capacity, with PLAXIS 3D proving to be an important design aid in geoground improvement systems.

Keywords
Bearing capacity, geogrid encasement, soft clay, stone column, PLAXIS 3D

I. INTRODUCTION

The rapid growth in population and urban development worldwide has increased the demand for large-scale infrastructure projects, including storage tanks, embankments, highways, and railroads. Many of these facilities are constructed on soft to very soft clay deposits, which are characterized by low shear strength, high compressibility, and excessive settlement **[1, 2]**. These unfavorable soil conditions pose serious challenges to geotechnical engineers during both design and construction.

Several improvement methods have been proposed to overcome these challenges, including soil replacement, sand drains with preloading, lime stabilization, dynamic compaction, and stone columns **[3]**. Among them, stone columns are one of the most effective and economical techniques for improving soft soils to reduce the settlement and increase the bearing capacity of soft soil, especially under light structures such as embankments and railways **[4-6]**. The technique dates back to the early 19th century, when French engineers used stone columns to reinforce foundations on soft soils.

The most widely used technique for constructing stone columns is the Vibro-Replacement Method, also known as the Vibro-Displacement Method by some (**Fig. 1**). Stone columns function by transferring loads to deeper and stronger strata. Depending on the thickness of the soft clay, they can be either end-bearing or floating columns (**Fig. 2**). However, lateral bulging often limits their efficiency, especially in very soft soils **[7]**. To address this limitation, Geogrid-Encased Stone Columns (GESCs) were developed. The geogrid provides additional lateral confinement, increasing column stiffness and improving settlement and bearing capacity performance.

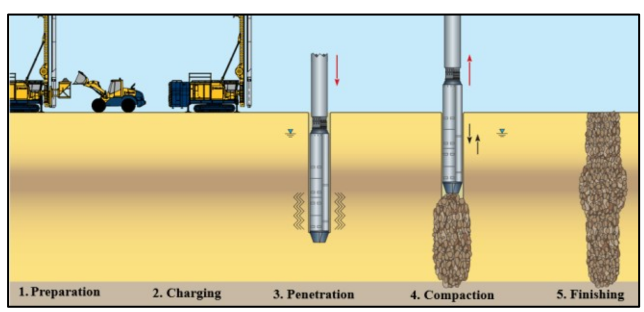

Fig. 1: Installation of vibro-stone columns **[8]**

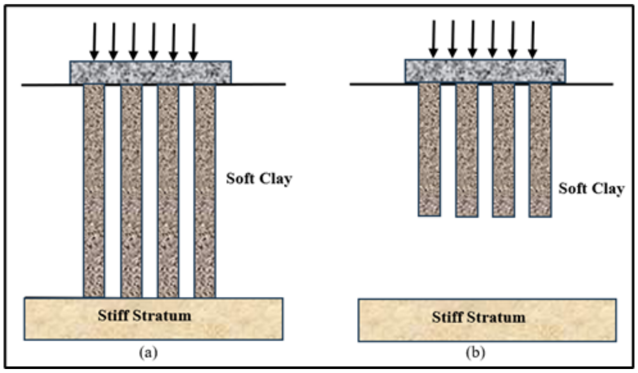

Fig. 2: Types of stone columns (a) End bearing stone columns, (b) Floating stone columns.

Numerous experimental and numerical studies have confirmed the superior performance of GESCs over ordinary stone columns **[9-15]**. These studies show that encasement significantly increases load-bearing capacity and reduces settlement, even in partially encased cases. With the advancement of numerical modelling tools such as PLAXIS 2D and PLAXIS 3D, soil–structure interaction can now be simulated with high accuracy and validated against field data.

In Iraq, where soft clay deposits are common across the central and southern regions **[16]**, Effective ground improvement methods are essential for infrastructure development. Although the benefits of ordinary stone columns (OSCs) and geogrid-encased stone columns (GESCs) are well recognized, most prior research has been confined to laboratory tests or two-dimensional analyses, with limited three-dimensional (3D) studies validated against field data. Investigations conducted within the unique soil conditions of Iraq are notably limited. To address this gap, the current research employs PLAXIS 3D (version 2024), which incorporates both Mohr–Coulomb and Hardening Soil models, validated through two empirical case studies, to assess the impact of geogrid encasement on minimizing settlement and enhancing bearing capacity.

II. Methods

Numerical modelling was adopted in this study to investigate the performance of Ordinary Stone Columns (OSCs) and Geogrid-Encased Stone Columns (GESCs) in soft clay using the finite element software PLAXIS 3D (V2024). The methodology consists of the following steps:

1. Software Description

PLAXIS 3D is an advanced finite element software that has been widely adopted in geotechnical engineering **[17]**. It provides a comprehensive set of constitutive soil models that allow for the simulation of elastic, elastoplastic, and nonlinear soil responses under various loading and boundary conditions, including the Linear Elastic, Mohr-Coulomb, and Hardening Soil models, among others.

2. Numerical Procedure

The numerical simulation followed three main stages:

1. Initial geostatic equilibrium: The in-situ stresses were generated using the K_0 procedure, recommended for horizontally layered soils and groundwater conditions **[17]**.

2. Insertion of stone columns: OSCs were modeled by replacing soft soil elements with stone material, while GESCs included additional geogrid reinforcement and interface elements.

3. Application of footing load: A rigid footing was simulated as a plate element, and axial loading was applied to evaluate settlement and load-bearing behavior.

3. Mesh Generation and Boundary Conditions

- PLAXIS 3D provides different mesh refinements ranging from very coarse to very fine. A medium mesh was adopted and locally refined around the stone columns to ensure accuracy without excessive computational cost.

- Boundary dimensions were chosen such that boundary effects were minimized, and depth also varied according to the case study.

4. Verification With Field Studies

Two field case studies were selected for validation:

- **Al-Qayssi (2001)[18]**: A conventional OSC installed under a shallow footing in Baghdad.

- **Yoo & Lee (2012)[19]**: A GESC was installed at the Pohang site in Korea.

The material properties for soil, stone, and geogrid were taken from the respective field studies and implemented in PLAXIS 3D to ensure consistency. The comparison between numerical and measured results was then carried out to assess the accuracy of the modelling approach.

III. Numerical Model Verification

To ensure the accuracy of the developed finite element models, the numerical results were validated against two well-documented field case studies**: [18]Al-Qayssi (2001)** in Iraq and **[19]Yoo and Lee (2012)** in Korea [19].

In the first case, **[18]** conducted a field test in Baghdad to evaluate the improvement of shallow foundation bearing capacity using a single ordinary stone column. The foundation was modeled as a square footing (Cap) measuring 2.25 × 2.25 × 0.75 m, supported by a stone column with a diameter of 0.55 m and a length-to-diameter ratio (L/D) of 8.5. The boundary condition of the model implemented by the program is (16x16 m), with a 12 m depth. The characteristics of the crushed stone material are displayed in **Table 1**.

The Hardening Soil Model (HS) and the Mohr–Coulomb Model (MC) were used to simulate the soil profile. The surrounding clay was handled as undrained (Type B), whereas the stone column was modeled under drained conditions in the MC model. The footing was represented as a plate element with appropriate interface conditions to account for soil–structure interaction.

A medium finite element mesh was adopted, consisting of approximately 12,112 soil elements and 19,254 nodes, with mesh refinement near the column to capture stress concentrations.

The simulation results for settlement under applied loads showed a strong agreement with the field measurements, thereby confirming the reliability of PLAXIS 3D in simulating the behavior of ordinary stone columns. **Fig. 3** displays the site's soil profile and the parameters of each layer. The Three-dimensional mesh modeling for the problem is shown in **Fig. 4**. The Stone column and soil system profile are shown in **Figs. 5, 6,** and **7**.

Table 1: Physical properties of the stone material used, **[18]** (As cited by **[20]**).

Property	Value
Specific gravity (Gs)	2.65
Max dry density (KN/m^3)	17.43
Min. Dry density (KN/m^3)	15.3
Angle of internal friction (φ)^O	40
Modulus of elasticity Ei (MPa)	95
Symbol according to U.S.C.S.S	GP

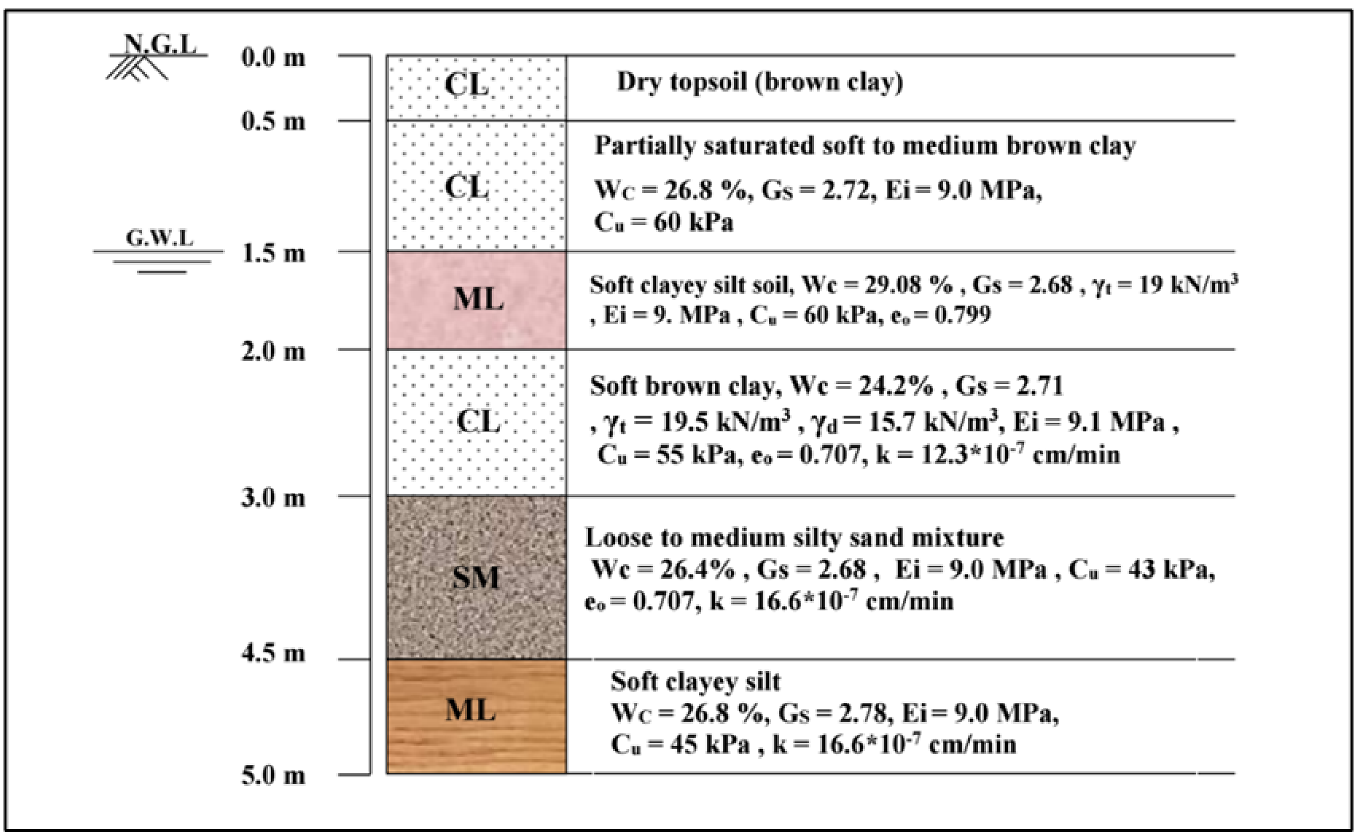

Fig. 3: Soil profile of the site **[18]** (As cited by **[20]**)

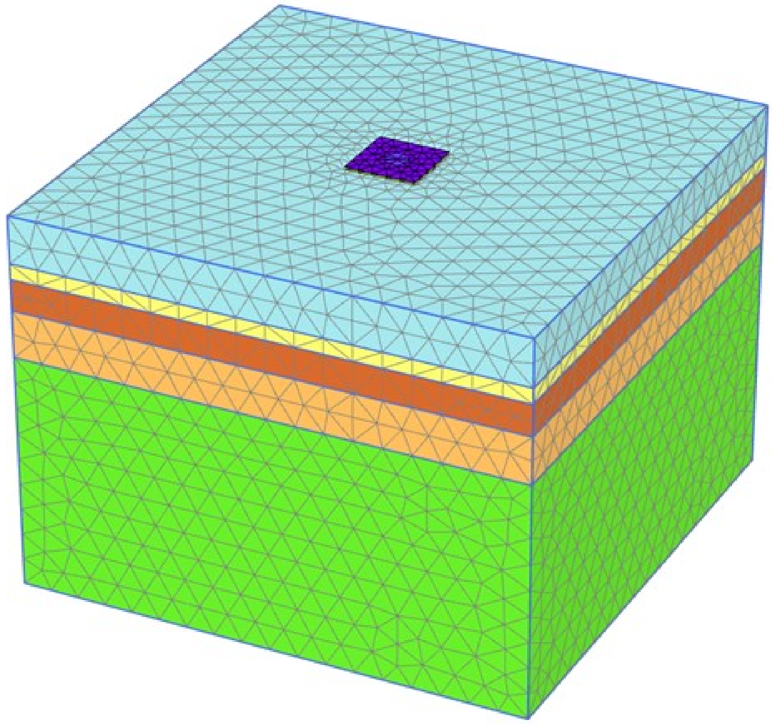

Fig. 4: The mesh of the model for the **[18]** case study in (PLAXIS 3D, 2024)

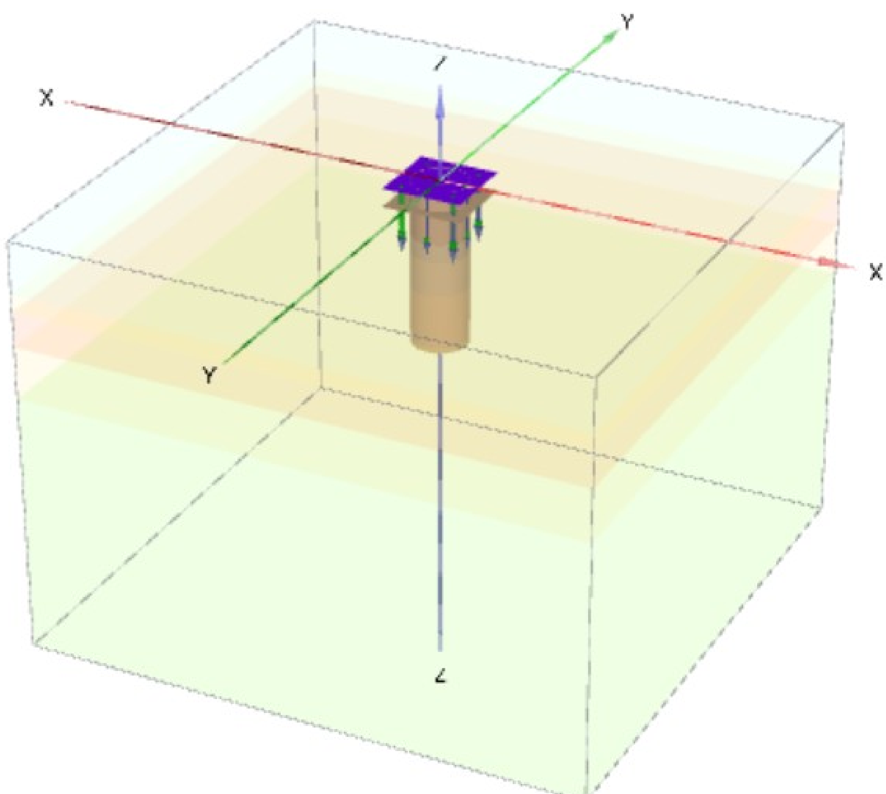

Fig. 5: The stone column model for the **[18]** case study in (PLAXIS 3D, 2024)

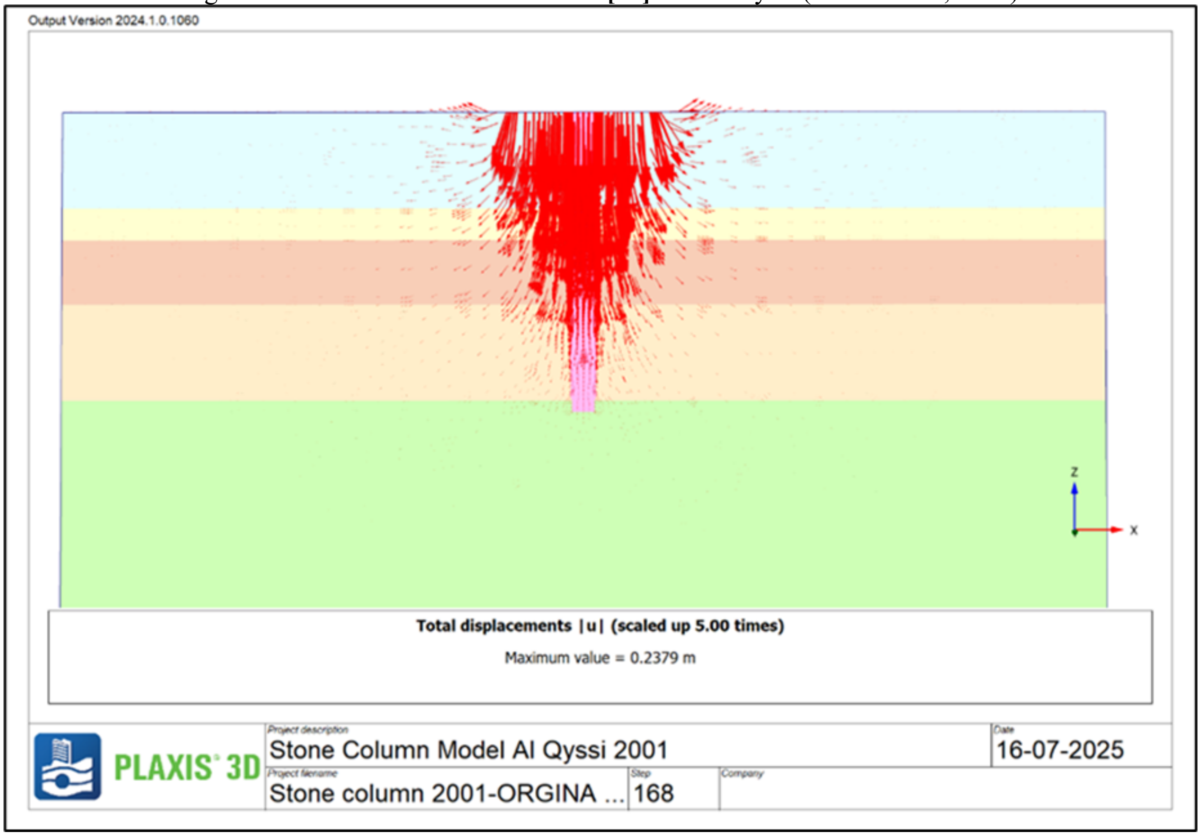

Fig. 6: Stone column and soil system profile for the **[18]** case study in (PLAXIS 3D, 2024)

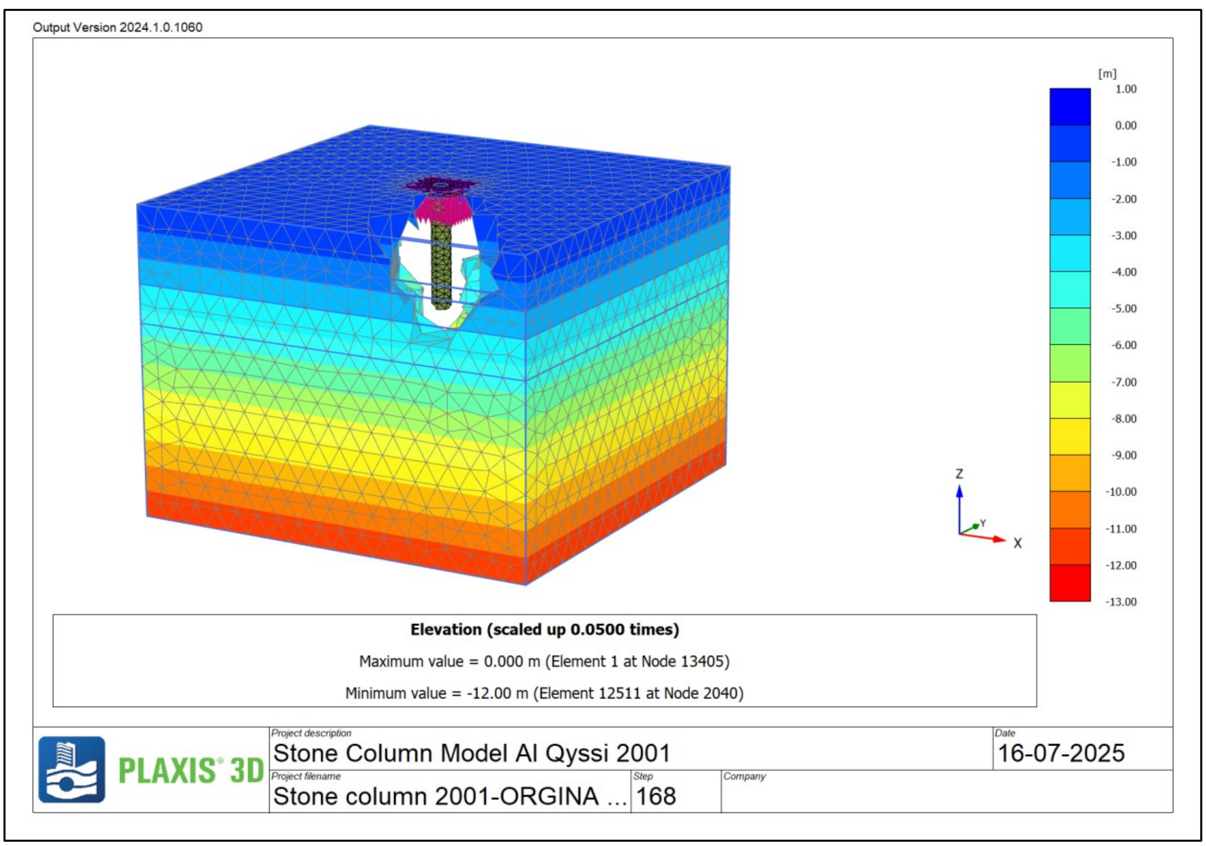

Fig. 7: The finite element analysis for **[18]** case study in (PLAXIS 3D, 2024)

The second verification study was conducted by **[19]** through a full-scale field test at the Pohang site in Korea, where geogrid-encased stone columns were installed in a multilayered soft ground. A layout of the load test setup is shown in **Fig. 8**. The ground profile consisted of 1.7 m of fill material underlain by a 5.4 m thick silty clay layer, which rested on Weathered soil in (BH 2), as shown in **Fig. 9**. The encased stone column had a diameter of 0.76 m and a length of 8 m and was reinforced with geogrid. The mechanical properties of the geogrid material used are displayed in **Table 2**, and the engineering properties of the soil layers used in the finite element analysis (PLAXIS,3D 2024) are summarized in **Table 3**. Two different constitutive modeling approaches were employed in the finite element analyses. The first applied the Mohr–Coulomb model (MC) at drained condition to the fill material and stone column, while the clay layer was treated as undrained (type B). The second approach used the Hardening Soil (HS) model for the clay layer at undrained (type B), with the Mohr–Coulomb model assigned to the other layers at drained conditions. The boundary condition of the model implemented by the program is (3.6x3.6 m), and 12 m depth. A medium mesh consisting of approximately 5,334 soil elements and 9,729 nodes was adopted for the simulation. The soil layers and the three-dimensional Model for the **[19]** case study, as shown in **Fig. 10**. The simulation of the soil layers and location of the stone column are shown in **Fig. 11**. The plastic point failure is illustrated in **Fig. 12**. The total displacement result is presented in **Fig. 13**.

Table 2: Properties of geogrid **[19]**.

Parameters	Value
Polymer type	Polyester
Thickness (mm)	1.2
Tensile strength (kN/m)	120
Mesh aperture spacing (mm)	30x30

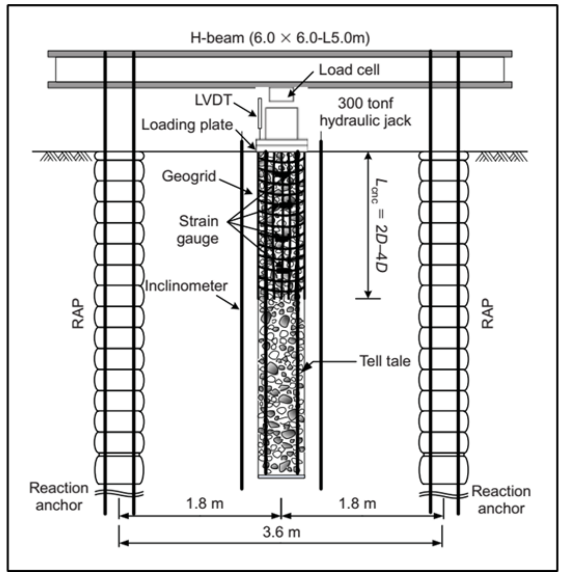

Fig. 8. Load test setup, **[19]** case study.

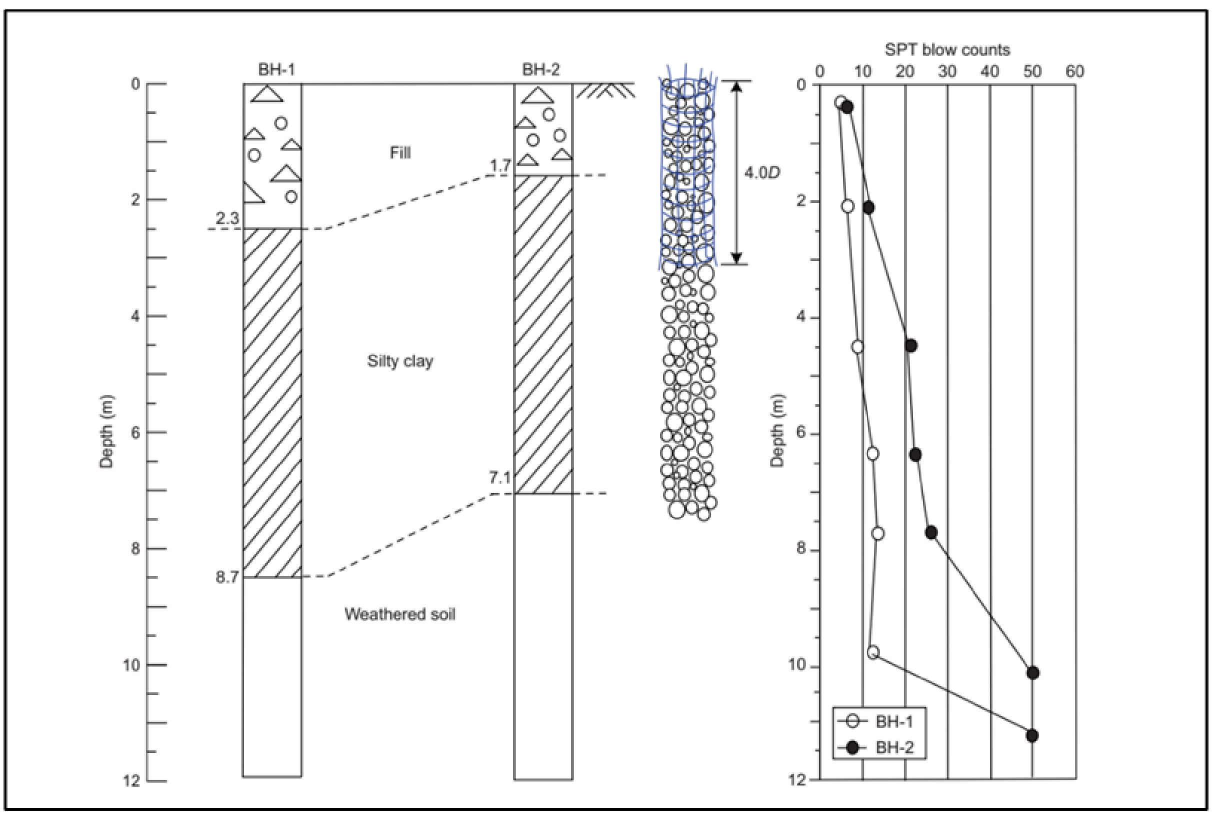

Fig. 9: Ground condition (Pohang site) **[19]**

Table 3: Summary of material parameters used for full-scale load test in PLAXIS 3D (**Pohang site**) **[19].**

Material	**Saturated unit weight, γ_{sat} (kN/m^3)**	**Effective cohesion, c' (kPa)**	**Effective internal friction angle, φ (degrees)**	**dilation angle, ψ (degrees)**	**Young's modulus, E (kPa)**	**Undrained shear strength, S_u (kPa)**
Fill	20	4	28	5	12000	-
Silt clay	17	2	-	0.1	-	35
Stone column	23	5	45	10	45000	-

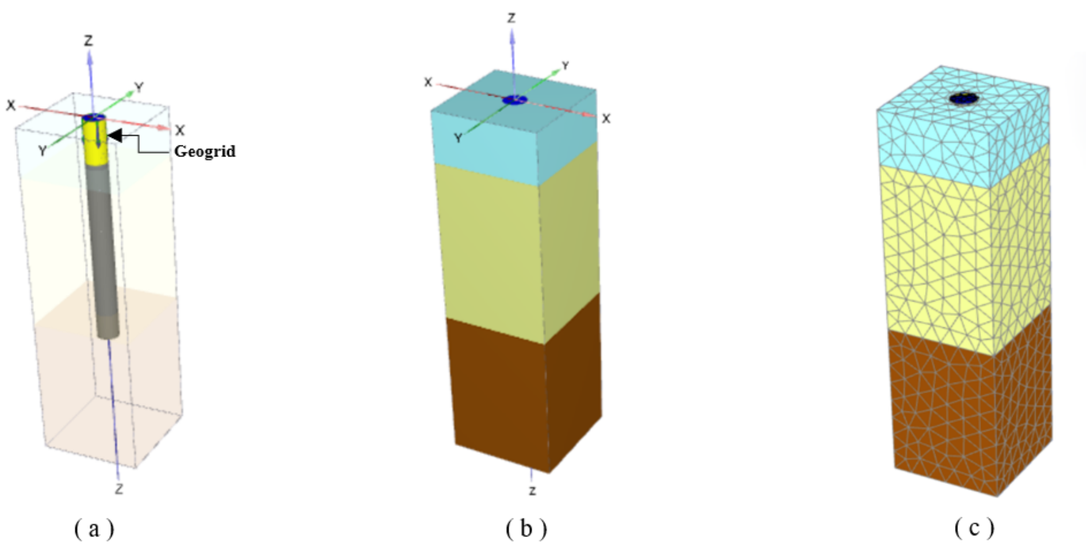

Fig. 10: The stone column model for the **[19],** (**PLAXIS 3D, 2024**), (a) illustrate the geogrid encased, (b) 3D simulation, (c) The mesh of the model

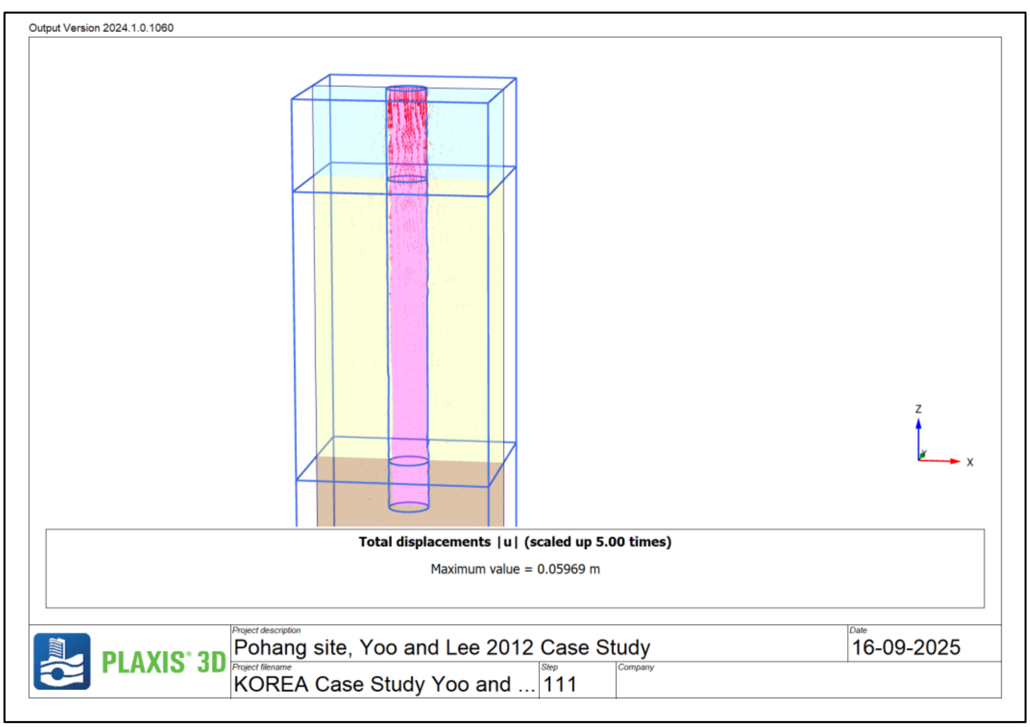

Fig. 11: Stone column and soil system profile analysis (GESC) for **[19]** in (**PLASIX 3D, 2024**)

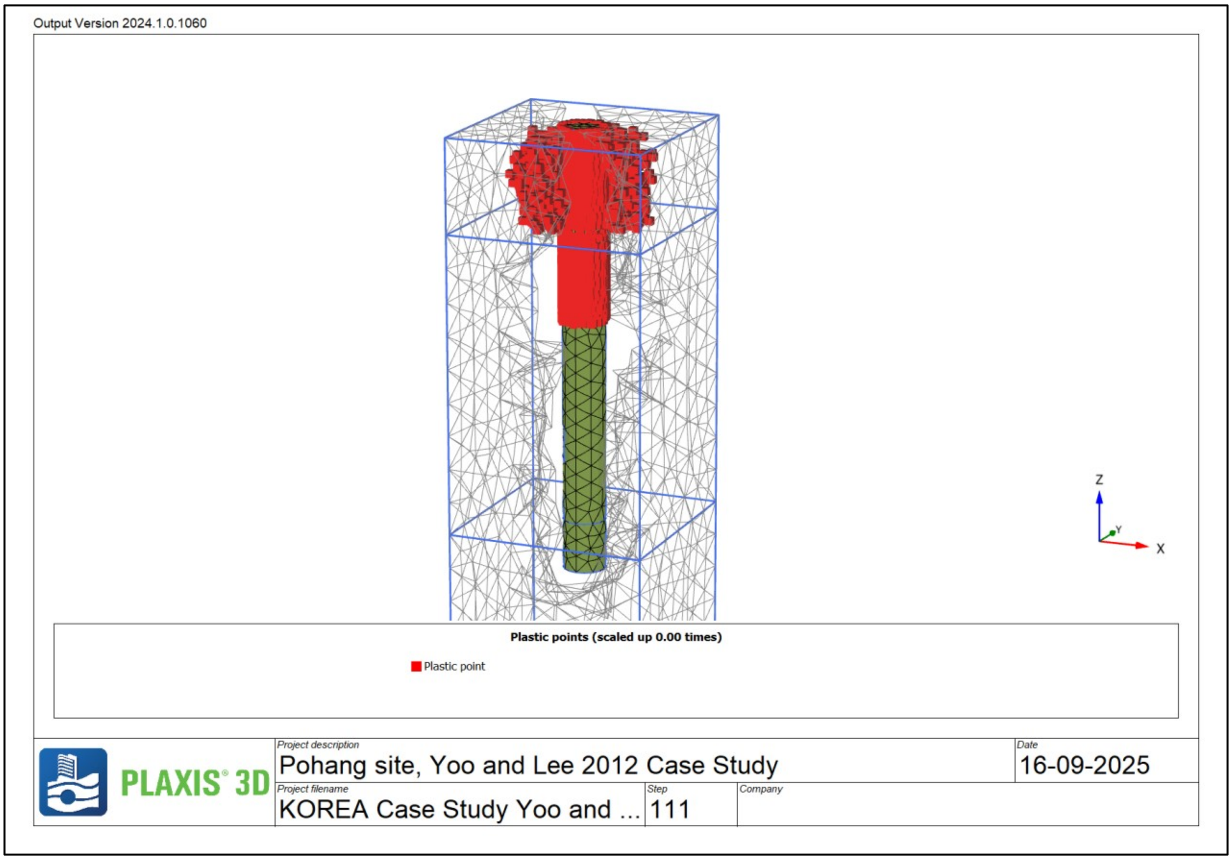

Fig. 12: The plastic point failure of the finite element analysis(GESC) for **[19]** in (**PLASIX 3D, 2024**)

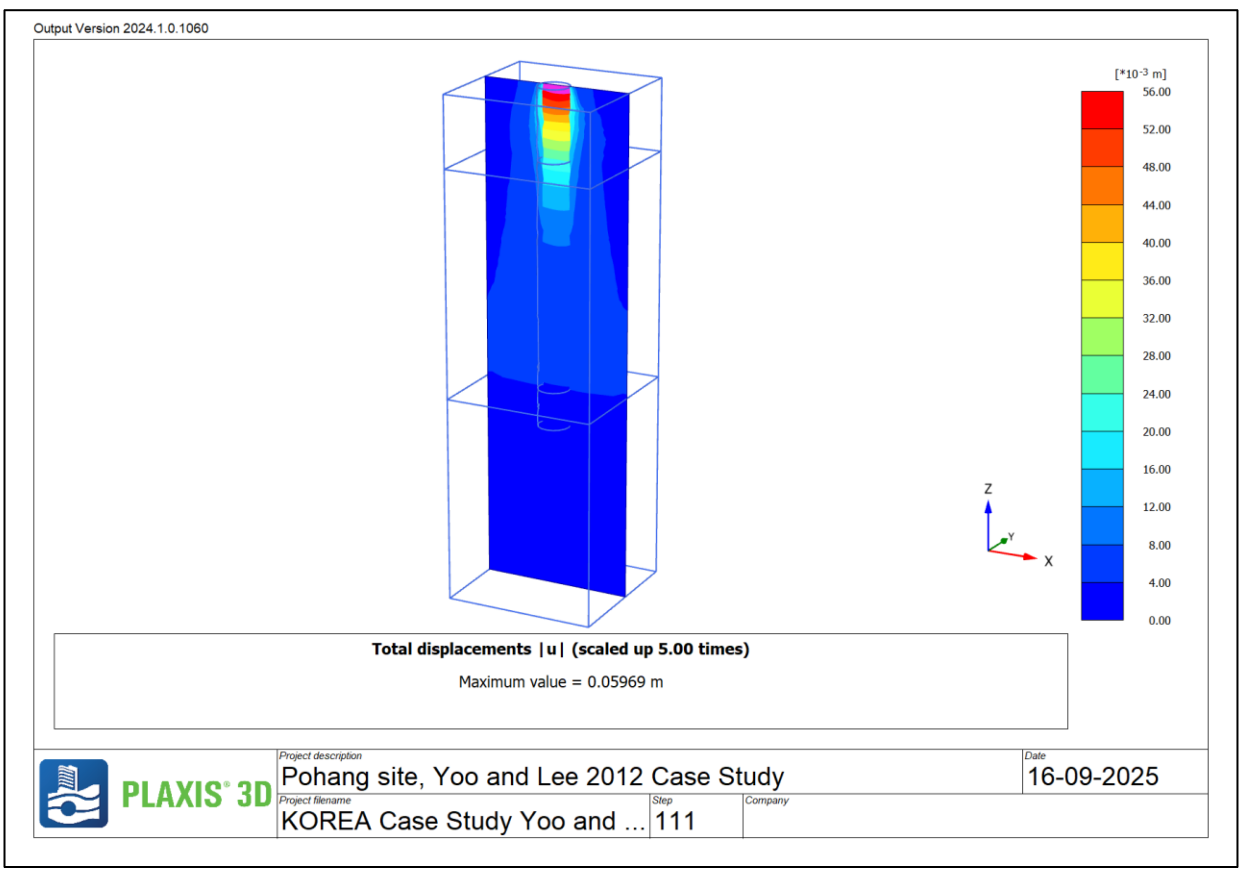

Fig. 13: The finite element analysis for the **[19]** case study in (**PLAXIS 3D, 2024**)

IV. RESULTS AND DISCUSSION

A clear correspondence was observed between the field load–settlement measurements reported by **[18]** and the numerical analyses conducted using PLAXIS 3D (2024), as illustrated in **Figs. 14** and **15**. Both the Mohr–Coulomb (MC) and Hardening Soil (HS) models reproduced the general shape of the field curves, but the HS model provided more accurate predictions of settlement and bearing capacity, especially under higher stress ratios, whereas the MC model slightly underestimated the deformations. This consistency between field and numerical results confirms the reliability of the adopted numerical approach. It should be noted that in this case, the stone column was of the floating type, embedded in soft clay without reaching a firm bearing stratum. At the reference settlement ratio of S/B =10%, the quantitative comparison in **Table 4** highlights the progressive improvement between the three cases. For the untreated footing (cap-only), the settlement was about 0.225m, and this value was taken as the baseline. With the inclusion of a single ordinary stone column (OSC), the load-bearing capacity increased by approximately 21% relative to the cap-only. When the stone column was encased with a geogrid (GESC) with a length of 2D, where D is the diameter of the stone column, and with the same properties in **Table 2**, the improvement was more evident, with the capacity increasing by about 30% compared with cap-only, representing an additional about 9% increase relative to the OSC case.

Table (4): Comparison of footing response at S/B=10%

Case	Settlement (m)	q/Cu at S/B=10%	Capacity Gain vs. Cap-only (%)
Cap-only	0.225	7.3	0.0
OSC	0.225	8.8	21.0
GESC (HS Model, PLAXIS 3D, 2024)	0.225	9.5	30.0

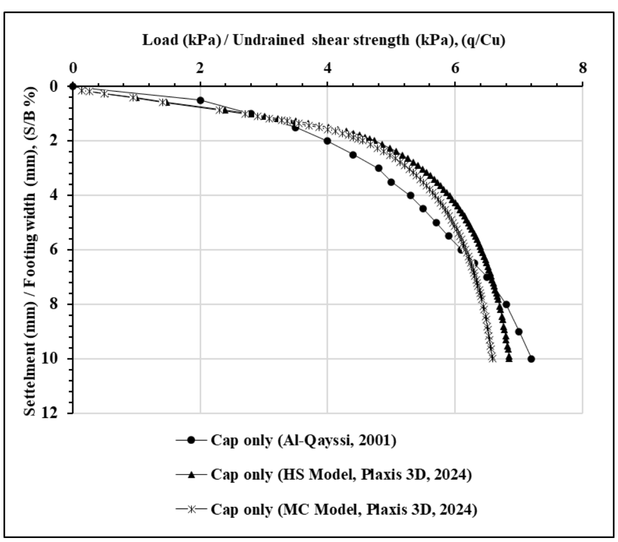

Fig. 14: Load settlement curve of an isolated footing for **[18]** case study

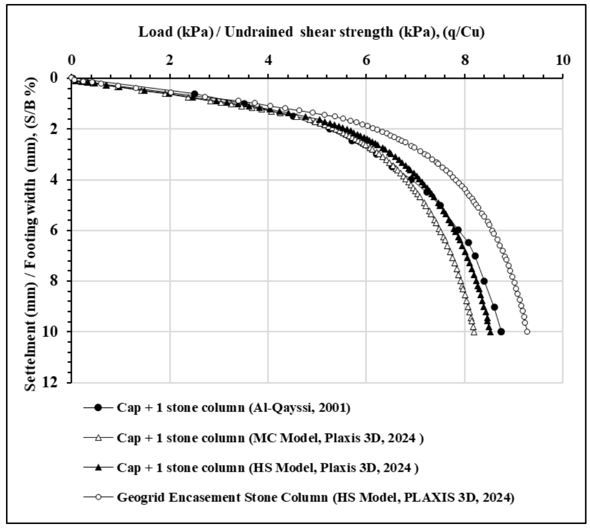

Fig. 15: Load settlement curve for a single stone column supported by an isolated footing for **[18]**case study

For **[19]** A case study was reported at the Pohang site in Korea, where stone columns with a diameter of 0.76 m and a length of 8 m were installed within a 5.4 m thick silty clay layer and encased with geogrid. A good agreement was observed between the field measurements from this case and the PLAXIS 3D (2024) simulations (**Fig. 16**). Both the MC and HS models reproduced the initial response of the encased columns; however, the HS model provided more accurate predictions of settlement and bearing capacity at higher stress levels, while the MC model tended to slightly underestimate the deformations. Unlike the Al-Qayssi case, here the stone columns were of the end-bearing type, penetrating through the clay layer and transferring load directly to the underlying firm stratum. At a fixed settlement of 60 mm, the quantitative comparison presented in **Table 5** indicates a consistent ranking in performance, with GESC showing the highest capacity, followed by OSC, and then the cap-only case. Quantitatively, the cap-only footing required 420 kPa; the OSC required 800 kPa, which is 1.90 times the cap-only; the GESC (MC) required 900 kPa, which is 2.14 times the cap-only, amounting to a further 12% improvement relative to OSC; and the GESC (HS) required 1000 kPa, which is 2.38 times the cap-only, corresponding to an improvement of about 25% over the OSC. The field response is around 1050 kPa, which is 2.50 times the cap-only response.

Table (5). Comparison of bearing pressures at S=60 mm

Case	Pressure (kPa)	Capacity ratio vs. Cap-only	Increase (%)
Cap-only (HS Model, PLAXIS 3D, 2024)	420	1.0	0
OSC (HS Model, PLAXIS 3D, 2024)	800	1.9	90
GESC (MC Model, PLAXIS 3D, 2024)	900	2.2	114
GESC (HS Model, PLAXIS 3D, 2024)	1000	2.4	138
Field (Yoo & Lee, 2012)	1050	2.5	150

The miner enhancement noted in the **[18]** case is mainly due to the floating column configuration, where the geogrid encasement primarily limits lateral bulging but does not mobilize base resistance. In contrast, end-bearing columns were used in the **[19]** case, where geogrid confinement improved base and shaft resistance, leading to significantly larger bearing capacity gains. Overall, the findings confirm the ability of PLAXIS 3D to realistically emulate field behavior such that although the MC model is useful for initial estimations, the HS model is more accurate in portraying nonlinearity for higher stress conditions. Additionally, the analysis identifies the important role played by geogrid encasement for stone columns, such that when assessed at equivalent levels of settlement, it significantly contributes to bearing capacity alongside improving settlement restraint.

These findings are consistent with previous research. According to **[15]**, load-settlement performance is enhanced by both horizontally and vertically reinforced stone columns, and FEM simulations show good agreement with laboratory data. In a similar vein, **[10]** verified that the field behavior of stone column-reinforced soil under embankment loading can be accurately replicated using finite element modeling. **[11]** have reported that, in comparison to untreated clay beds, geosynthetic encasement can increase the ultimate load capacity of stone columns by four to eight times. This conclusion is supported by the current study, which demonstrates that even partial geogrid encasement significantly improves stiffness, reduces settlement, and enhances load-bearing resistance.

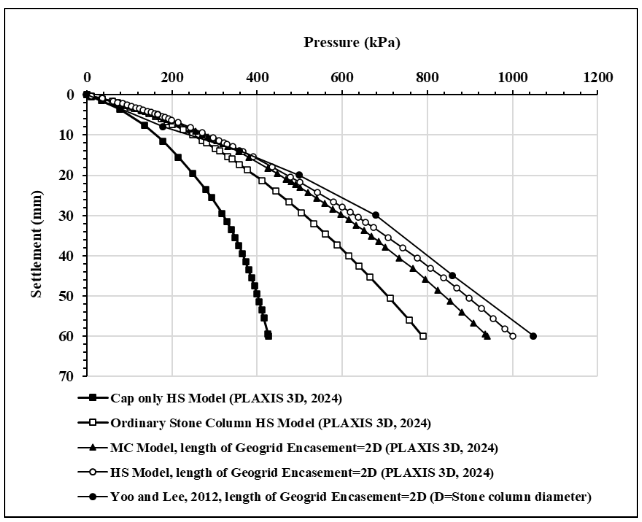

Fig. 16: The load settlement curve, when the cover's length doubles the column's diameter) for **[19]**, in (**Plaxis-3D, 2024**) by using MC and HS Models.

Mechanistically, the geogrid's ability to confine the stone column and prevent excessive lateral bulging at shallow depths is primarily responsible for the improvement. This confinement provides column stiffness and enables more effective stress transfer within the surrounding soil. Therefore, geogrid-reinforced stone columns are observed to settle less and carry higher loads, which are essential for infrastructures seated on soft clays. Significant agreement between the predictions of the numerical model (PLAXIS 3D) and the field measurements of both **[18]** and **[19]** not only confirms the framework describing the model but also fortifies the overall conceptualization of soil–foundation interaction within stone column–strengthened ground.

V. CONCLUSIONS

Based on validation against field research and numerical simulations, the following conclusions can be drawn:

1. The PLAXIS 3D finite element model showed reasonable agreement with field measurements, confirming its reliability for simulating stone column–reinforced soft clay.

2. The HS model provided more accurate predictions than the MC model, especially at higher stress levels.

3. In the floating case **[18]**, the load-bearing capacity increased by around 21% with OSC and by about 30% with GESC compared with the untreated footing.

4. In the end-bearing case **[19]**, the OSC and GESC cases reached about 1.9 and 2.5 times the cap-only value, respectively.

5. Geogrid encasement achieves the highest effectiveness for end-bearing columns, where both shaft and base resistance are mobilized, leading to a much greater improvement than in floating columns.

1. More research is needed on stone columns to study how they perform over time under dynamic loading, as well as their spacing, arrangement, and group effects.

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