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Evaluation of the Effect of Encased Stone Columns Technique in Liquefaction Mitigation of Sandy Soil Using UBC3D-PLM Model

Ahmed O. K. Mahmoud[a,*], Khaled Abdelsamie[a], Hesham G. Nouby[b], Mohamed M. A. Hussein[a]

[a] *Civil Engineering Department, Faculty of Engineering, Sohag University, Sohag, 82524, Egypt*
[b] *Civil Engineering Department, Faculty of Engineering, Sphinx University, New Assuit, Egypt*

Abstract

Liquefaction of sandy soil during earthquakes poses a significant risk to infrastructure, leading to severe ground deformation and structural failure. The encased stone column (ESC) is a promising ground improvement technique to mitigate this phenomenon. This study utilized two-dimensional Finite Element analyses using PLAXIS 2D software with the UBC3D-PLM model to evaluate the ESC technique's efficacy. The research deals with the role of encased stone columns in mitigating liquefaction at different permeabilities, with a strong focus on their effectiveness in reducing excess pore pressure at various depths. The numerical study used the 1940 El Centro earthquake data to assess liquefaction potential. The results showed a significant reduction in excess pore pressure and soil stability with ESCs.Also, the technique of ESC demonstrates their superior performance over traditional stone columns. ESCs enhanced ground stability by reducing the settlement of the soil, making them a more effective solution for liquefaction mitigation in sandy soils. Furthermore, it was found that the higher permeability in the stone columns helps to dissipate pore pressure more effectively, thereby reducing the risk of liquefaction. These findings provide valuable insights for engineering practice, enhancing the safety and resilience of infrastructure against seismic hazards.

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Keywords: Liquefaction, Encased Stone Column, Stone Column, Pore Pressure, Plaxis 2D, UBC3D-PLM

1. INTRODUCTION

Soil liquefaction, a phenomenon where saturated, granular soils lose their strength and stiffness due to the rapid build-up of pore water pressure under cyclic loading conditions, such as those induced by seismic activities, is a significant threat to infrastructure [1-5]. The potential for catastrophic damage to buildings, bridges, and other critical infrastructure during earthquakes [6] underscores the need for effective mitigation techniques.

Extensive research has been conducted on reducing liquefaction, and several strategies have been developed to tackle this problem [7-8]. Various approaches can be employed to enhance the stability of liquefiable soil in seismic regions, including dynamic compaction, soil reinforcement techniques such as stone columns(SC), encased stone columns (ESC) or rigid inclusions, jet grout, and deep soil mixing. SC and ESC are highly efficient techniques for enhancing the earth's stability and strength.

Stone columns improve the compactness and ability of the soil to drain, thereby diminishing the accumulation of water pressure inside the soil's pores during seismic activities [9-11]. Research has demonstrated that using traditional stone columns can improve the mechanical properties of liquefiable soils, resulting in substantial resistance to deformations caused by liquefaction [12-20]. Moreover, the effectiveness of stone columns can be significantly improved by encasing them in geosynthetic materials, leading to ESC. The encasement provides additional confinement, reducing lateral deformation and increasing the load-bearing capacity of the columns [21,22]. ESC not only improves the shear strength of the soil but also offers better performance under dynamic loading conditions, making it a promising solution for liquefaction mitigation [23-25].

* Corresponding author: Ahmed.mahmoud@eng.sohag.edu.eg

Numerical modeling plays a crucial role in evaluating the performance of ESC under various loading conditions. Advanced numerical methods, such as finite element analysis using PLAXIS 2D software with the UBC3D-PLM model, enable detailed simulation of complex soil-structure interactions. This approach allows for optimizing design parameters and accurate prediction of field performance [26]. Recent studies using PLAXIS 2D have demonstrated ESC's effectiveness in static and dynamic conditions, highlighting their potential in liquefaction-prone areas [27,28].

The ESC method has received little attention compared to other methods in recent studies. Therefore, this study focuses on evaluating the efficacy of the ESC technique in mitigating liquefaction by comparing its effectiveness with scenarios of no-stone and traditional stone columns. The two-dimensional finite-element program (PLAXIS 2D) with the UBC3D-PLM model is employed in the numerical analysis. This study aims to analyze ESC's superior performance over SC in reducing excess pore water pressure (EPP) and illustrate its effects on the soil during seismic events. Specifically, the study examines the impact of different stone column permeabilities on liquefaction resistance. The goal is to identify the optimal conditions and configurations for ESCs to enhance the safety and resilience of infrastructure against seismic hazards. Acceleration data from the 1940 El Centro earthquake was used to verify the effectiveness of ESCs under real-world seismic conditions. This article comprehensively evaluates the ESC technique for mitigating liquefaction in sandy soils using Nevada sandy soil properties. Also, it highlights the importance of permeability in ESCs, showing that higher permeability significantly enhances pore pressure dissipation, thereby improving soil stability and reducing liquefaction risks.

The remainder of the article is as follows: The next section provides an overview of the computational program and constitutive model used in this study. Section 3 presents the numerical model validation and the equivalent strip approach for stone columns for two-dimensional plane strain analysis. Section 4 describes the numerical modeling methodology utilized. Section 5 discusses the results and analysis. The final section concludes the study.

2. COMPUTATIONAL PROGRAM

2.1. PLAXIS 2D

This study utilizes the implicit finite-element program PLAXIS 2D. The model domain is discretized with 15-node triangular elements, selected for their precision in handling complex geotechnical analyses. PLAXIS 2D uses the Gauss integration scheme, ensuring accurate computation of element responses. Similar functions are used for interpolating displacement and pore pressure fields, maintaining consistency throughout the model.

To avoid spurious reflections of waves within the soil domain, the study employs specific boundary conditions. Tied degree of freedom boundary conditions are applied at the sides of the model to simulate free-field conditions, ensuring that lateral boundaries do not reflect seismic waves into the model. A compliant base boundary condition is used at the base of the model, which allows for the appropriate simulation of incoming and outgoing wave energy. These boundary conditions help minimize artificial reflections and provide a more realistic simulation of the soil-structure interaction during seismic events [29].

2.2. UBC3D-PLM Model

UBC3D-PLM is a highly efficient elastoplastic stress model that can accurately simulate the occurrence of liquefaction in sandy soil when subjected to dynamic loads [30-31]. This model is derived from the original UBCSAND (University of British Columbia Sand) model, which was developed by Puebla et al. [32] and Beaty and Byrne [33]. This model is based on classical plasticity theory and uses a hyperbolic strain-hardening rule derived from the modified Duncan-Chang technique. The fundamental difference between the UBCSAND model and the UBC3D-PLM model is that the UBC3D-PLM model includes a generalized 3D formulation, applying the Mohr-Coulomb yield condition within a 3D principal stress space.

3. NUMERICAL MODEL VALIDATION

Validation of the PLAXIS 2D using the UBC3D-PLM constitutive model and the equivalent stone column technique is vital to assure the accuracy and reliability of the numerical simulations done in this study. The validation process involves comparing numerical results with experimental data to verify that the models accurately represent real-world behavior. In this context, the centrifuge test results from Adalier et al. [14] serve as a benchmark for validating these models. This section details the validation efforts and demonstrates the fidelity of the numerical approach in capturing the critical aspects of liquefaction mitigation using stone columns.

3.1. Equivalent strip approach for stone column

In numerical modeling for two-dimensional plane strain problems, converting from a three-dimensional stone column configuration is essential for accurate representation. The column-wall method proposed by Tan et al. [24] facilitates the conversion of the three-dimensional arrangement into a two-dimensional framework. This method involves calculating the width of the equivalent strip or column-wall (d_{cw}) to preserve the same area replacement ratio between the columns and the surrounding soil as in the three-dimensional model. Specifically, the width of the stone column in the plane strain model is determined using Equation (1) from Tan et al. [24], which relates to the spacing (S) between columns. This formulation ensures that the effective cross-sectional area is maintained. It is important to note that this calculation applies only to cases where the columns are arranged in a square pattern. By employing this method, the plane strain model accurately represents the impact of stone columns on soil behavior, enabling a more precise and practical analysis in a two-dimensional context.

$$d_{cw} = \frac{(d_{3d})^2\pi}{4\,S} \tag{1}$$

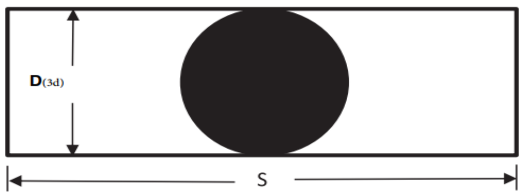


Fig. 1.- Equivalent Plain Strip.by Tan et al. [24]

3.2. Centrifuge test validation

The centrifuge test findings from Adalier et al. [14] validated the UBC3D-PLM model and the comparable plane strip technique. The experiment involved a 23 × 12.5 × 7.8 m tank filled with fully saturated pure silt. Inside the tank were 45 stone columns with a diameter of 1.26 m and a center-to-center spacing of 2.5 m, as shown in Fig. 2. The columns were arranged in a grid with 5 rows and 9 columns. The computer model was created to simulate these conditions accurately, using specific material parameters for the silt at a relative density (RD) of 60% and the stone columns filled with Nevada sand at a relative density (RD) of 65%, as outlined in Table 1. The investigation consisted of twenty repetitions of harmonic motion, where the amplitude gradually increased until reaching a maximum stimulation of 0.3 g at a frequency of 1.8 Hz. Pore pressure measurements were conducted at specific sites, identified as points A and B, to determine any excess pore pressure and point C to determine the settlement. The comparison between the findings obtained from the 2D plane strain finite-element analysis and the centrifuge test results, as shown in Fig.3, demonstrates a strong correlation, confirming the accuracy of the numerical model as Chakraborty did [27]. Nevertheless, certain inconsistencies were noticed in the anticipated EPP at the stone column at point B, indicating the need for additional improvements in the modeling methodology. This validation verifies the model's capacity to appropriately depict the influence of stone columns on soil behavior, establishing a dependable framework for future research.

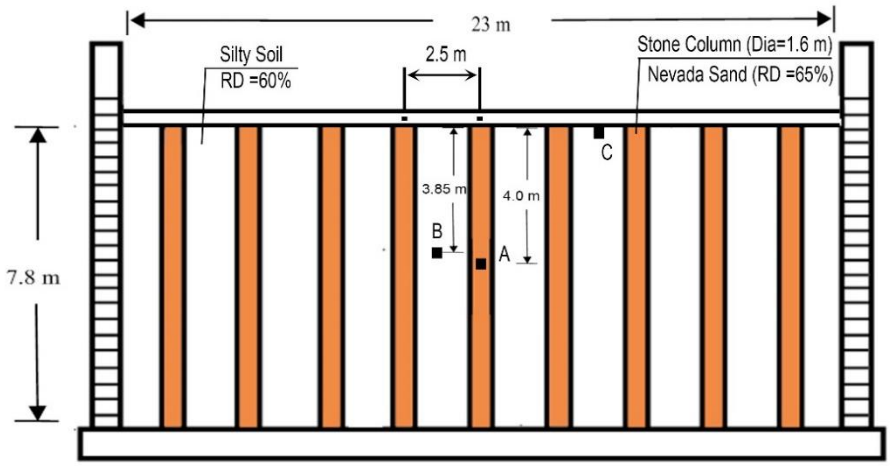


Fig. 2.- Model of centrifuge testing by Adalier et al. [14]

TABLE 1 .UBC3D-PLM MODEL FOR NUMERICAL VALIDATION

Parameters	Nevada Sand [a]	Silt[a]
Relative density (%)	65	60
γ_{dry}(kN/m^3)	15.76	13.4
$e_{initial}$	0.661	0.7
k (m/s)	1.37×10^{-5}	4.3×10^{-6}
ϕ_p	37°	25°
ϕ_{cv}	33°	21.7°
K^e_B	789.9	773.63
K^e_G	1,128.4	1,105.2
K^p_G	1,378.7	1,050
m_e	0.5	0.5
n_e	0.5	0.5
n_p	0.4	0.4
R_f	0.705	0.722
Fac_{hard}	0.45	0.45
fac_{post}	0.1	0.1
Corrected SPT blow count [$(N1)_{60}$]	19.435	16.56

[a] UBC3D-PLM parameters by Chakraborty [27].

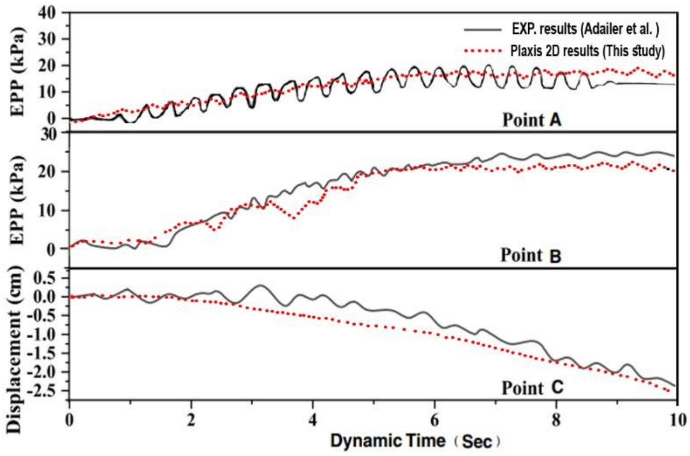


Fig. 3. Comparison the results from Plaxis 2D with the results obtained from centrifuge study by Adalier et al. [14].

4. NUMERICAL MODELING

This study presents an in-depth numerical investigation using Plaxis 2D to assess the effectiveness of encased stone columns in mitigating liquefaction. The analysis was conducted within a domain of 20 meters in width and 12 meters in depth. Three distinct models have been employed to investigate variations in excess pore pressure and displacement under seismic loading conditions without surcharge, as illustrated in Fig 5, indicating the locations of Points A, B, C, and D selected for analyzing the EPP behaviour and soil stability. The first model, consisting of Nevada sand soil without mitigation measures, served as a baseline for understanding the soil's natural response. The second model featured stone columns, 1 meter in diameter and 8 meters in length, to evaluate their impact on reducing excess pore pressure and mitigating liquefaction. The third model incorporated encased stone columns, reinforced with a geogrid of 2000 kN/m stiffness, to further enhance the mitigation performance.

In addition to the primary models, permeability variations within the stone columns were investigated in both the second and third models to examine how changes in permeability affect liquefaction mitigation. Each model was subjected to dynamic loading based on the El Centro earthquake acceleration records as Fig. 4 to replicate realistic seismic conditions. At PLAXIS 2D, Boundary conditions included tied degrees of freedom on the lateral sides and a compliant base at the bottom to accurately simulate the foundation's interaction with the soil. Fine meshing has been utilized in the current numerical model to achieve greater accuracy in the predicted results. Also, a Rigid interface is assumed between the stone column aggregate and the surrounding soils. The UBC3D-PLM model was utilized for the simulations, with calibrated parameters provided in Table 2 taken from Kumari [28]. This methodology enabled a comprehensive evaluation of how different mitigation strategies and permeability levels influence excess pore pressure and displacement, offering valuable insights into the effectiveness of stone and encased stone columns in reducing the impacts of liquefaction.

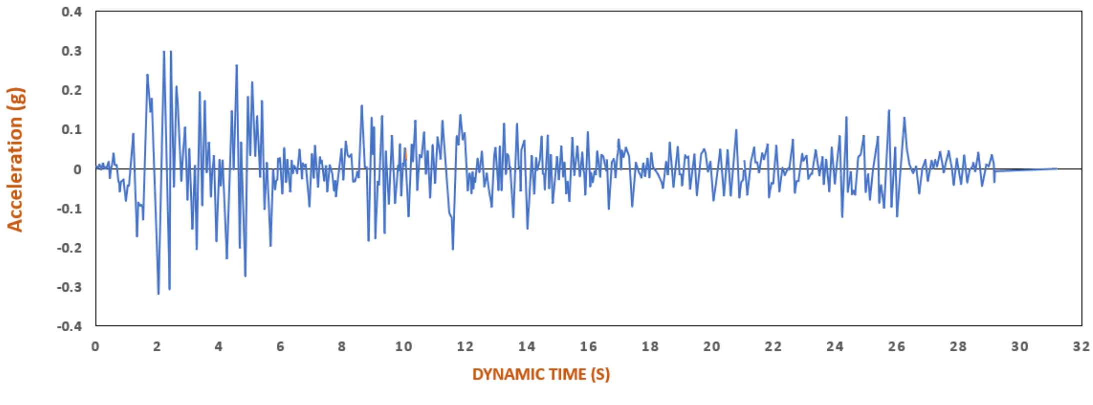


Fig. 4.- El-Centro earthquake time history

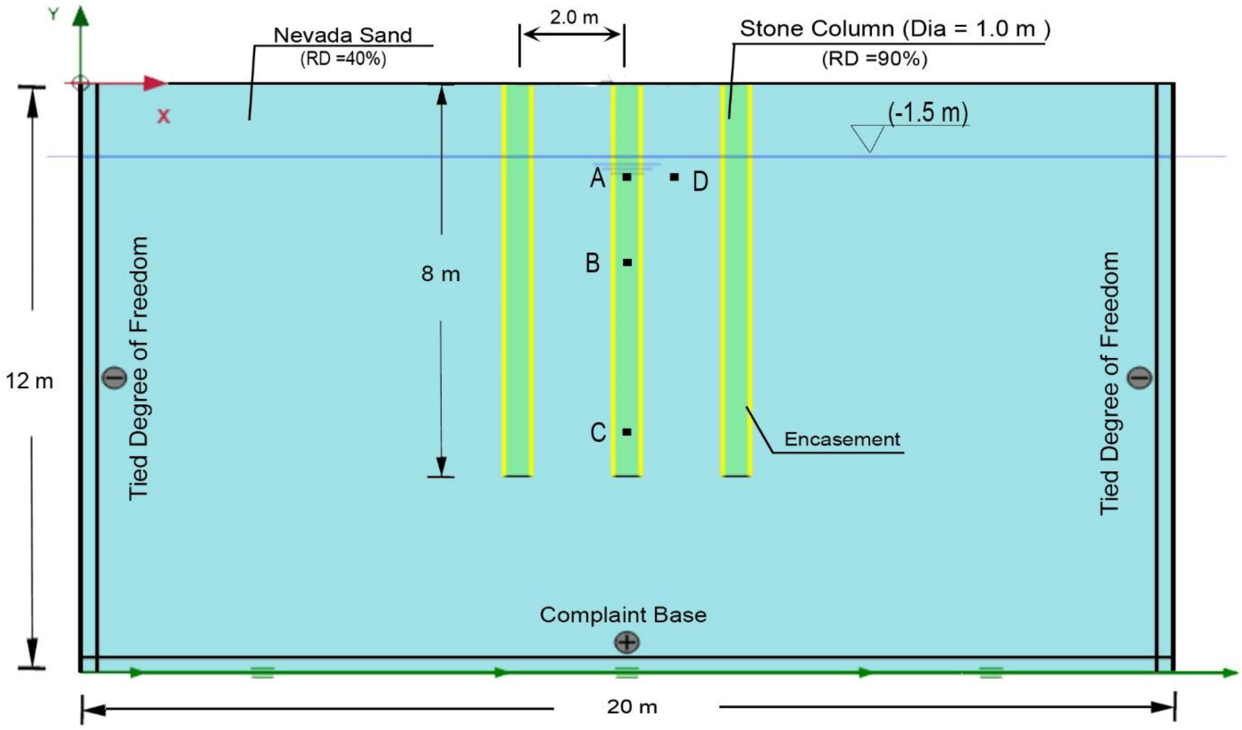


Fig. 5. Determination of instruments' position in the model

TABLE 2 .UBC3D-PLM MODEL FOR THIS STUDY

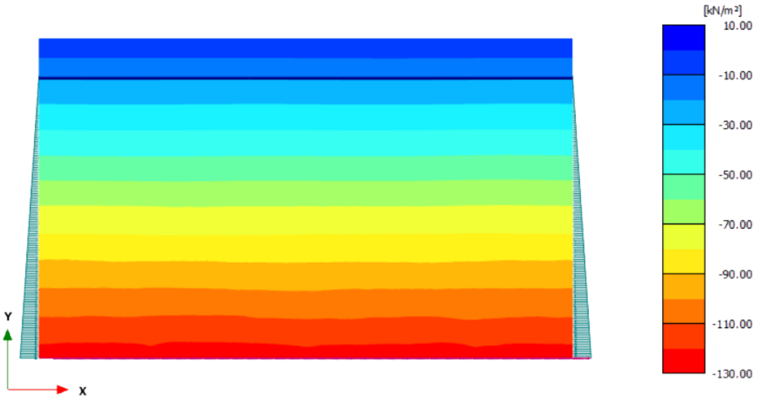
Abbreviation	Description of parameters	Nevada Sand [a] (UBC3D MODEL)	Stone Column [a] (UBC3D MODEL)
γ_{unsat} (kN/m^3)	Unit weight	15.08	18.6
γ_{sat} (kN/m^3)	Saturated unit weight	19.60	20.4
e_{int}	Void Ratio	0.7360	0.546
RD (%)	Relative Density (%)	40	90
$N1_{60}$	Corrected SPT blow counts	6.5	37
ϕ_{cv} (°)	Constant volume friction angle (°)	33	33
ϕ_P (°)	Peak friction angle (°)	34.47	33.65
K^e_G	Elastic shear modulus number	809.4	890
K^e_B	Elastic bulk modulus number	566.6	623
K^P_G	Plastic shear modulus number	202.6	3755
m_e	Elastic bulk modulus index	0.5	0.5
n_e	Elastic shear modulus index	0.5	0.5
n_p	Plastic shear modulus index	0.4	0.4
R_f	Failure ratio	0.83	0.64
P_a	Atmospheric pressure	100	100
σ_t	Tension cut-off	0	0
fac_{hard}	Densification factor	0.45	0.45
fac_{post}	Post liquefaction factor	0.1	0.1
K (m/s)	Permeability	6.6 x 10^{-5}	0.1 - 0.015

[a] UBC3D-PLM parameters by Kumari [28]

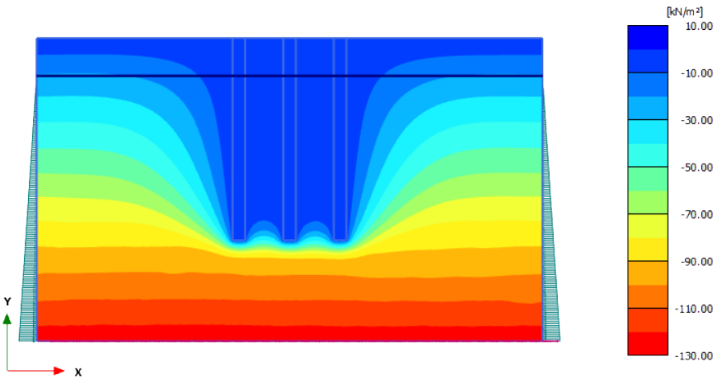
5. RESULTS AND DISCUSSION

5.1. The effect of SC and ESC on EPP distribution

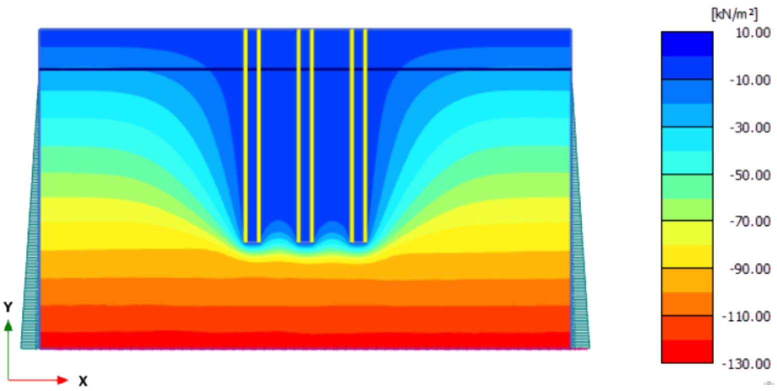
The study analyzed EPP distribution in Nevada sand soil with SC and ESC compared to the case without SC. The results demonstrated that without SC, there were no mitigating effects, showing a constant rise in excess pore pressure across the soil profile. The absence of mitigation leads to high negative pore pressures, indicating a significant risk of liquefaction as the soil loses shear strength. On the other hand, Using SC and ESC reduces excess pore pressure, with noticeable decreases around the columns, as shown in Fig. 6-b and Fig. 6-c. The columns act as drainage pathways, facilitating excess pore water pressure dissipation and stabilizing the soil. Additionally, The results indicated that the ESC is an effective mitigation approach for liquefaction, as it reduces excess pore pressure and enhances soil stability.



(a)



(b)



(c)

Fig. 6.- EPP Distribution, a) Without SC, b) With SC, c) With ESC

5.2. The effect of permeability of SC and ESC on EPP

. Permeability is a critical parameter that significantly influences liquefaction behavior. Two values were used to study the effect of the permeability of the stone material used in both SC and ESC: 0.1 m/s and 0.015 m/s.The results indicated that with a permeability of 1 m/s without using SC or ESC, the Epp values at the locations of A, B, C, and D are 30 kPa, 45 kPa, 90 kPa, and 35 kPa, respectively. However, when using both SC and ESC, the values were significantly reduced to approximately 1.15 kPa, 1.15 kPa, 2 kPa, and 1.5 kPa, representing decreases of about 96%, 97%, 98%, and 95% at the corresponding points as shown as Fig 7. Where the results showed that when using the permeability of 0.015 without using SC or ESC, The EPP values at the locations of Points A, B, C, and D were 30 kPa, 45 kPa, 90 kPa, and 35 kPa, respectively. However, in both SC and ESC, the values were significantly reduced to approximately 5 kPa, 8 kPa, 10 kPa, and 7 kPa, representing decreases of about 83%, 82%, 89%, and 80% at the corresponding points, as shown in Fig 8. Notably, the results indicate that SC and ESC exhibit only a minor difference in performance when applied to Nevada sand (RD = 40%) during the El Centro earthquake, confirming the reliability of both techniques in reducing liquefaction risk under dynamic conditions.

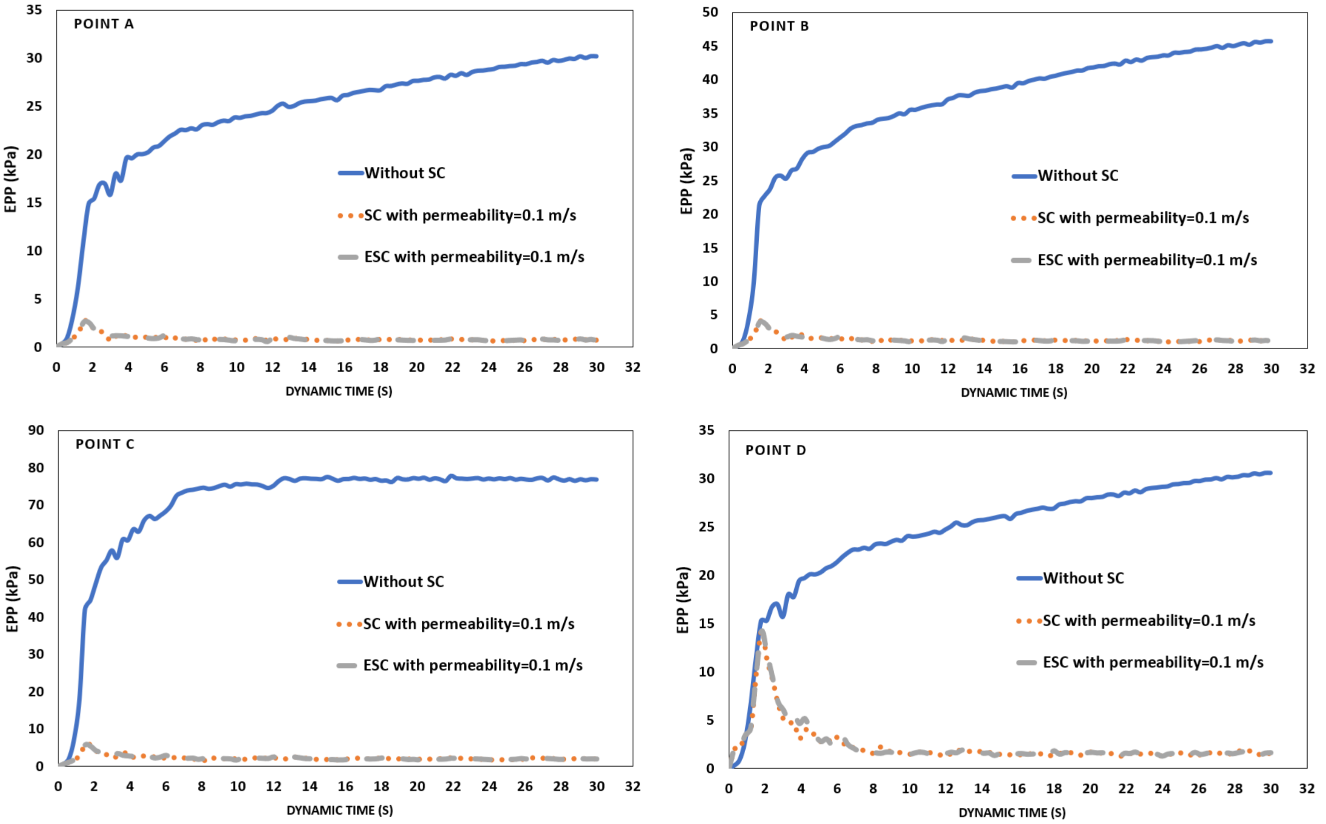


Fig. 7.- EPP curves at different locations with permeability 0.1 m/s

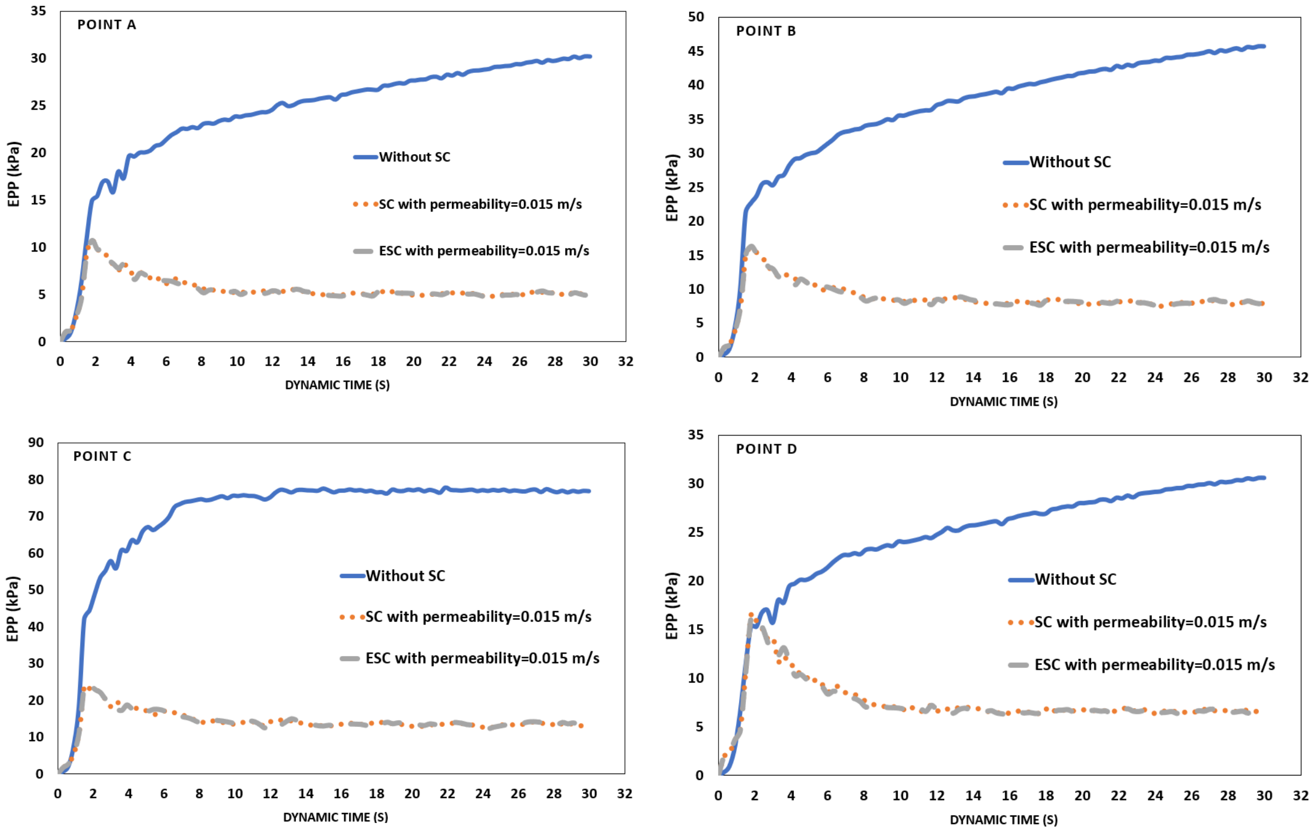


Fig. 8. EPP curves at different locations with permeability 0.015 m/s

The results indicate that EPP is more effectively reduced in high-permeability ESC compared to low-permeability ESC, as shown in Fig. 9. The results reveal that ESC with a permeability of 0.1 m/s consistently achieves lower EPP levels than those with a permeability of 0.015 m/s. The EPP for the high-permeability ESC is around 1 kPa at Point A, whereas it reaches approximately 5.5 kPa for the low-permeability ESC. Similarly, at Point D, the high-permeability ESC results in an EPP of about 1.5 kPa, compared to 6.5 kPa with the low-permeability ESC. These findings highlight the enhanced effectiveness of higher permeability ESC in dissipating excess pore pressures, thereby providing superior liquefaction mitigation and improved soil stability. This demonstrates that permeability significantly influences liquefaction potential, with higher permeability enhancing the soil's ability to manage pore water pressure during seismic events.

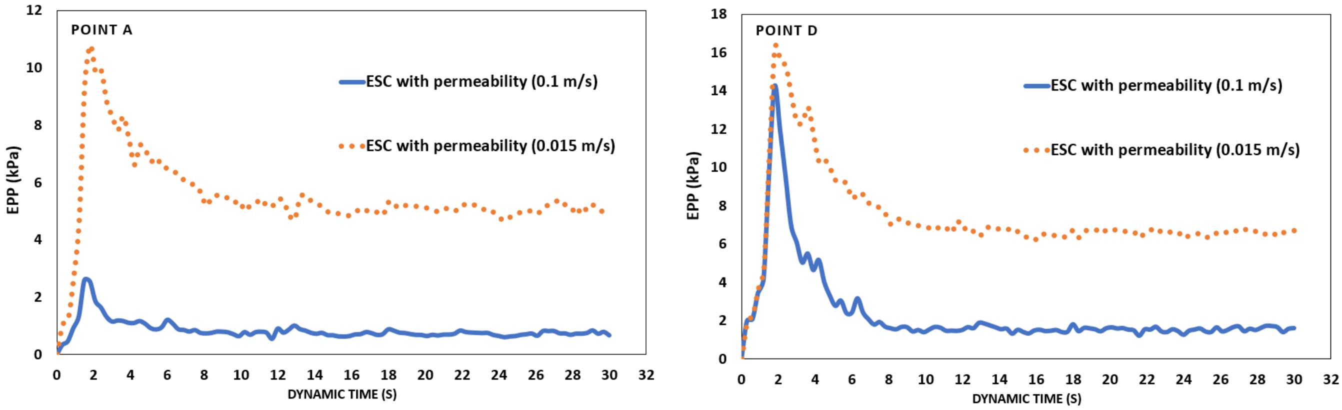


Fig. 9.- Comparison of EPP for different permeabilities at different locations (Points A , D)

5.3. The effect of SC and ESC on the vertical settlement

A load of 25 kN/m was applied at the model's center to study the settlement behavior under earthquake-induced liquefaction for SC and ESC. The results illustrate that integrating mitigation techniques, especially ESC, leads to a marked decrease in settlement relative to another as shown in Fig 10. The maximum settlement without SC or ESC reaches approximately at point A 50 cm, whereas the SC and ESC reduce this to 40 cm and 35 cm, representing an improvement of 20% and 30%, respectively. Also, at Point D, the settlement without SC or ESC approaches 55 cm. , but using SC and ESC reduces settlement to approximately 45 cm and 40 cm, resulting in improvements of around 18% and 27%, respectively. ESC is the most effective method, providing excellent resistance to liquefaction-induced deformation due to the added lateral confinement provided by the encasement. This enhancement leads to improved stability and reduced settlement.

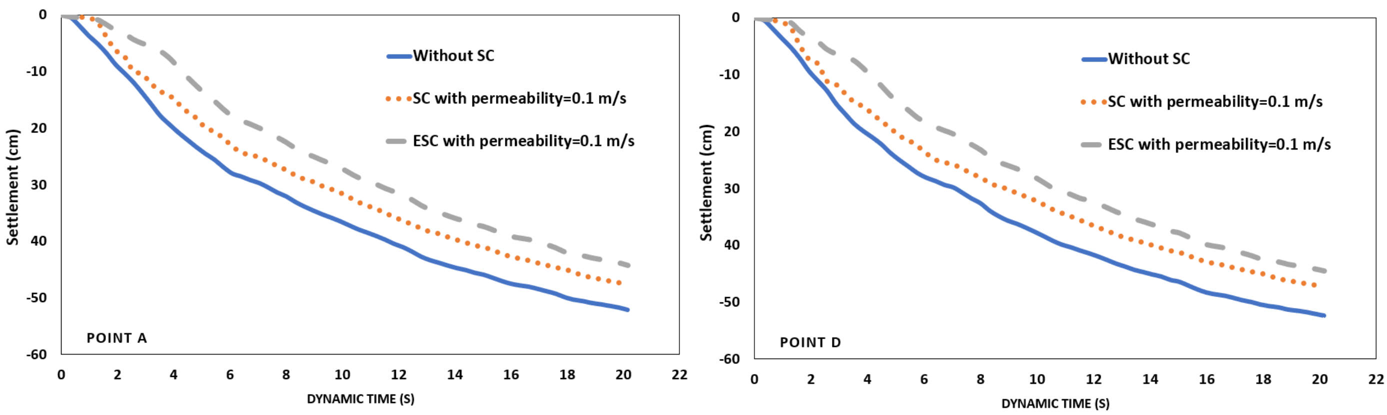


Fig. 10.- Vertical settlement curves at different locations (Points A,D)

6. CONCLUSION

This paper investigates the effectiveness of ESC in mitigating the liquefaction of Nevada sand soil during the El-Centro earthquake and affecting soil stability using the UBC3D-PLM model of PLAXIS 2D. The study also assesses the impact of varying permeabilities of SC and ESC filling material on build-up pore pressure, providing valuable insights for engineering practice. The following conclusions can be drawn :

1. Using the UBC3D-PLM model with PLAXIS 2D proved that it is an effective tool for analyzing the performance of liquefaction mitigation techniques under dynamic loading conditions. It offers detailed insights into soil behavior with different column treatments.
2. The risk of liquefaction can be mitigated using SC and ESC, where excess pore water pressure significantly decreases.
3. The settlement with applied load can be significantly reduced by using both SC and ESC, but ESC decreases more than SC. This leads to enhanced soil stability and reduced deformation, ultimately improving the stress distribution within the soil.
4. The permeability of stone columns is crucial in liquefaction mitigation. Higher permeability improves excess pore water pressure dissipation and provides better soil stabilization.

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