Jordan Journal of Civil Engineering, Volume **15**, No. **2**, **2021**

Numerical Analysis of the Performance of Stone Columns Used for Ground Improvement

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ABSTRACT

This paper describes a case history of soft ground that has high compressibility, located in Skikda, Algeria, treated by stone column technique. The case history was studied using a two-dimensional finite element model to simulate the behavior of stone columns under loads. The numerical study was carried out using the unit cell approach. The elastic-perfectly plastic behavior of Mohr-Coulomb was adopted for the soil and the column. The numerical results of settlements were compared with the field measurements collected from the case history, which showed good agreement. The equivalent area method was used and verified in this study. The equivalent area method yields similar values to field measurements. This study also investigated the effect of various parameters, including the stiffness of column material, stone column diameter, spacing between the columns and height of embankment fill. The results of the parametric study with the unit cell approach showed good agreement compared to the equivalent area method for predicting settlement.

KEYWORDS: Stone columns, Soil improvement, Numerical analysis, Loading test, Unit cell, Settlement.

INTRODUCTION

The installation of stone columns is one of the ground improvement methods in the world used to treat soft soils problems. The construction of stone columns consists in installing and compaction piles of stones into the ground, by a wet or dry method, following a grid pattern previously determined by a trial test. Stone columns are columns of crushed rock or gravel with high stiffness, constructed in clayey soils. The stone column technique is typically used in soft cohesive soils with undrained shear strength of 7-50 kN/m² (Juran and Guermazi, 1988) and granular soil with high fines content, which creates a composite soil structure capable of supporting substantial loads (embankments, large raft foundations, storage tanks). Several methods of soil improvement have been used by many researchers (Bouassida et al., 1995; Shahu et al., 2000; Hajimollaali et al., 2015; Hasanzadeh and Shooshpasha, 2017; Maher, 2017; Sridhar and Prathapkumar, 2018; Alfach, 2019; Djabri and Benmebarek, 2020). Stone columns represent an effective method extensively applied to improve the ground. This technique of ground improvement increases the load carrying capacity, reduces the settlement for foundations of structures, improves the slope stability, reduces liquefaction risk in seismic zones, acts as vertical drains and accelerates the rate of consolidation of weak soil (Han and Ye, 1992). Stone columns deform and fail under the applied load by bulging (Hughes and Withers, 1974; Hughes et al., 1976).

Several researchers evaluated the behavior of stone columns (Priebe, 1976; Poorooshasb and Meyerhof, 1997; Ambily and Gandhi, 2007; Basack et al., 2016; Debnath and Dey, 2017; Mehrannia et al., 2018; Zhao et al., 2019). Many experimental studies of soil reinforced with stone columns have been adopted (Anderou et al.,

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Received on 29/11/2020.
Accepted for Publication on 4/3/2021.

2008; Shivashankar et al., 2011; Afshar and Ghazavi, 2014; Nazariafshar et al., 2019; Farah and Nalbantoglu, 2020). Analytical methods to estimate the settlement of soil treated by stone columns have been proposed (Greenwood, 1970; Hughes et al., 1976). Various numerical modeling techniques have been carried out for studying the behavior of stone columns (Balaam and Booker, 1981; Shahu and Reddy, 2011; Ehsaniyamchi and Ghazavi, 2019). Foundations on soil reinforced by stone columns have been studied (Bouassida et al., 1995; Dhouib and Blondeau, 2005; Afshar and Ghazavi, 2014).

Many numerical methods exist for estimating bearing capacity and settlement of soils reinforced by stone columns and are found to be more flexible compared to experimental investigations. The unit cell model is the most popular model used for modeling stone columns, in which a single stone column and its surrounding soil are modeled (Priebe, 1976; Goughnour, 1983; Van Impe and Madhav, 1992; Shahu et al., 2000; Han and Ye, 2001; Ambily and Gandhi, 2007; Ng and Tan, 2014). Homogenization method treats the improved soil (stone columns and the surrounding soil) as an equivalent homogeneous material with equivalent properties (DiMaggio, 1978; Schweiger and Pande, 1986; Wang et al., 2002; Han et al., 2005; Abdelkrim and de Buhan, 2007; Abusharar and Han, 2011; Zhang et al., 2014; Ng and Tan, 2015).

This paper presents a numerical simulation of soil reinforcement by stone columns. The first part presents and discusses a numerical study of the behavior of soils reinforced by stone columns under the main structures of effluent treatment plant (ETP) in the area of Skikda Refinery, Algeria. A field loading test on column N°338 located in zone D (D338) of the ETP area was considered in the numerical analysis. A numerical study was carried out by using the unit cell method and the homogenization method. Finite element analysis was performed to study the behavior of soil reinforced with stone columns in terms of settlement. The obtained results from this study are presented to allow for a comparison between the numerical analysis and the field data results obtained from the case history carried out by loading test on column D338. In the second part, the effect of various parameters was investigated, including Young's modulus of stone columns, the diameter of stone columns, the spacing between columns and the height of embankment fill, using the unit cell method and the homogenization method. The numerical results obtained by the two models are compared in order to study the performance of each numerical model.

CASE HISTORY DETAILS

The site of the ETP area is located in the western part of the south zone of the Refinery in Skikda, Algeria, presenting weak mechanical characteristics, high compressibility and low bearing capacity. The ETP area was reserved for ground improvement by stone columns; dry bottom feed method (vibro-displacement) was used to install stone columns, where the stone is installed directly from the bottom of the vibro-lance. With this method, water is not used and there is no flushing of material. Figure 1 displays the installation of stone columns.

The site of the ETP area is in a sedimentary area of this region and the land in question is marshy, heterogeneous and presents alternative sedimentation. The whole site of the ETP area is covered by a layer of fill of an average thickness which varies between 5.00 m and 8.30 m posed without compaction, presenting weak mechanical characteristics. The geotechnical investigations in the ETP area were carried out in November 2011; these geotechnical investigations include 14 boreholes' data (ABH01-ABH18) with a depth of 25 m, 4 pressure meter tests (PMT) with a depth of 25 m (Figure 2) and 6 vertical electrical soundings (Figure 3). From the results, the geological formation found in the ETP area consists of:

- Fill, composed of heterogeneous, non-compact soil, down to 7.2 m.
- Silty marly caly with medium density, down to 18 m.
- Dense silty sand with medium to very high density, down to 25m.

The typical ground cross-section of the ETP area is illustrated in Figure 4.

The site of the ETP area was divided into several zones (A, B, C, D, E, F, G, H, I, J and K), as shown in Figure 5. In the present study, we are interested in zone D, in which the ground should accommodate a storage tank in an area of approximately 2000 m². According to the geotechnical investigations of the site of the ETP area, this zone has a low bearing capacity and significant settlements. In order to remedy these problems, it was decided to improve the ground with stone columns, where 832 stone columns were installed. The stone columns had an average depth from the ground surface of 9 m and a diameter of 0.6 m and were installed in a square pattern at a spacing of 1.5 m. The level of groundwater was observed at 4 m depth below the ground level. For verification of the design and in order to confirm the achievement of the required bearing capacity of the improved soil of zone D, in December 2011, a static load test has been performed on a single stone column surrounded by other columns. Static-load testing has been conducted on the column D338, consisting of an incrementally applied load with measurement of settlement; the loading test has taken a time of about 5h55. Figures 6 and 7 show the loading test on the stone column and the static load testing procedure on column D338, respectively. The maximum load applied during the test was 127kN.

Figure (1): Installation of stone columns

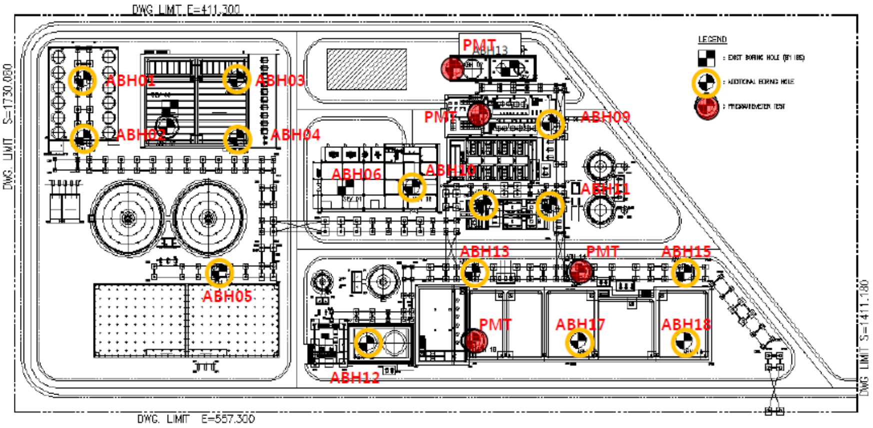


Figure (2): Test location

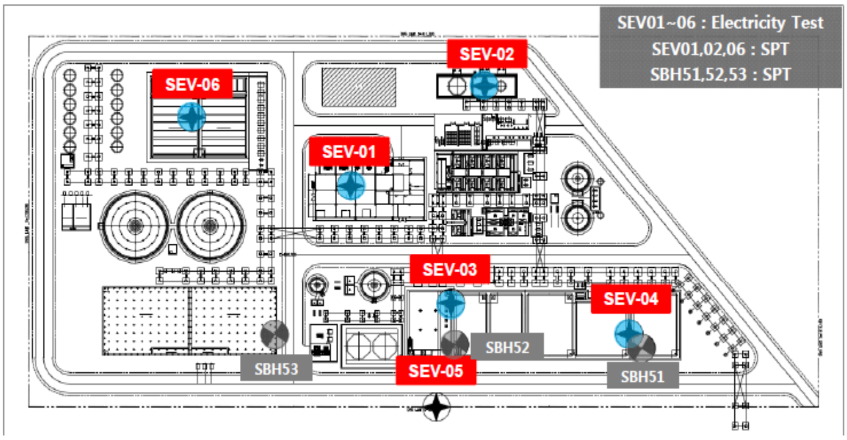


Figure (3): Borehole locations for the ETP area

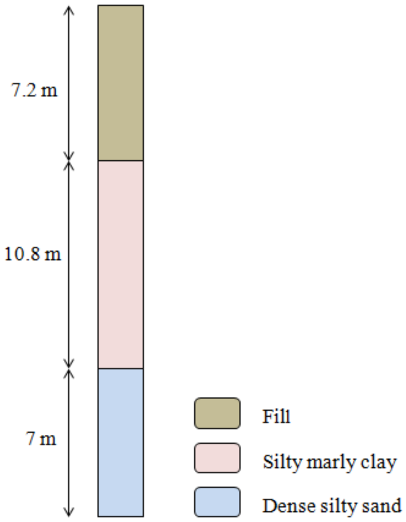


Figure (4): Typical ground cross-section of the ETP area

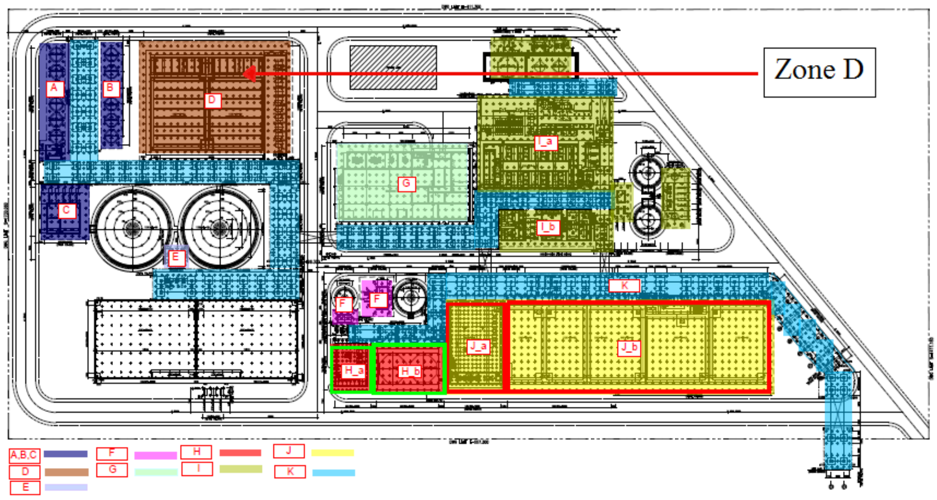


Figure (5): Stone column zoning map

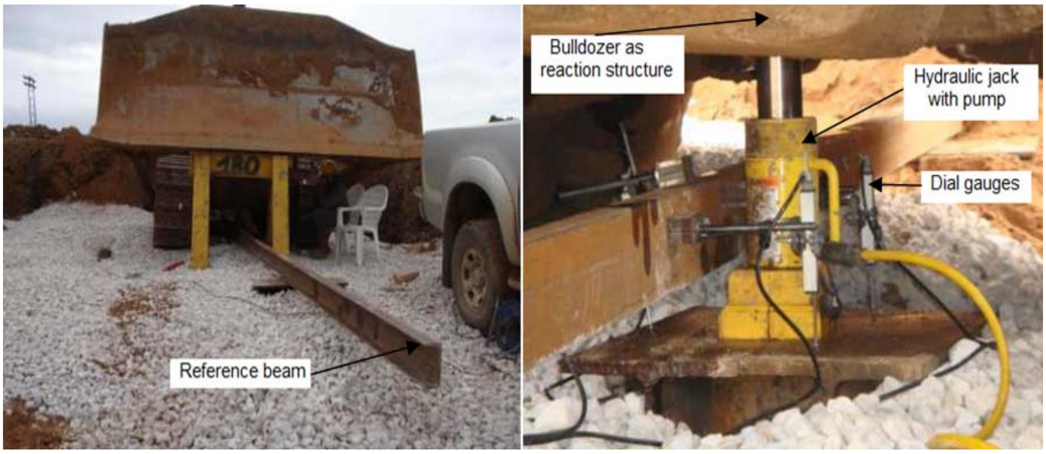


Figure (6): Load test on stone column

The load was applied using a 50T hydraulic jack carefully centered over the test plate. A steel frame was used to reduce the distance between the hydraulic jack and the bottom of the bulldozer used as a reaction frame. The steel plate has been centered on the axis of the column without any blanket and directly on the surface of the stone column after excavation to the final elevation. Three dial gauges (Capt01, Capt02 and Capt03) were installed on the top of the stone column to measure the settlement at each load step. The settlement was measured with respect to the reference beams placed along the test column. The maximum allowable settlement at the design load was 50.8 mm. The measured settlement at the design load was about 7 mm, which is less than the allowable settlement.

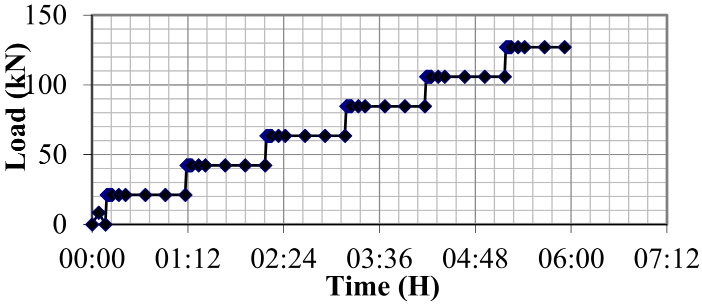


Figure (7): Static load testing procedure on stone column D338

NUMERICAL MODELING

The finite element code Plaxis was used for numerical modeling. The unit cell concept was adopted for two-dimensional numerical modeling using an axisymmetric model, in order to model the load settlement behavior of the stone column, as shown in Figure 8. The bottom boundary was fixed in both horizontal and vertical directions and the side boundaries were fixed in the horizontal direction and free in the vertical direction. Medium mesh was used for the numerical analysis. The equivalent diameter (D_e=1.7 m) of the unit cell for a square arrangement of stone columns was calculated by the relation D_e=1.13s, where (s) is the spacing of the columns (Balaam and Booker, 1981). The numerical model used in the current study was validated using the data from the loading test on the stone column D338.

The soils and stone column were modeled by Mohr-Coulomb failure criterion. The properties of various materials used in the numerical analysis are summarized in Table 1. Figure 9 shows the numerical results of settlement by unit cell model compared to field measurements provided by the instrumentation with three dial gauges (Capt01, Capt02 and Capt03) on the stone column D338. Both the numerical and field measurements values show that the settlement increases with load application stages. The results of the numerical analysis were compared and validated with the field measurements in terms of settlement.

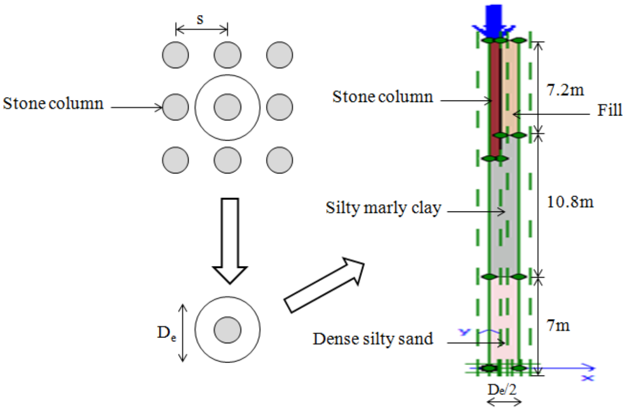


Figure (8): Unit cell model in axisymmetric condition

Table 1. Properties of materials used for modeling

	Stone column	**Fill**	**Silty marly clay**	**Dense silty sand**
Unit weight, γ (kN/m^3)	20	18	18	17
Saturated unit weight, γ_{sat} (kN/m^3)	21	20	19	18
Cohesion, *c* (kPa)	0	3	10	1
Friction angle, φ (°)	38	33	25	30
Young's modulus, *E* (kPa)	45,000	N/A	14,000	45,000
Poisson's ratio, ν (-)	0.33	0.33	0.3	0.3

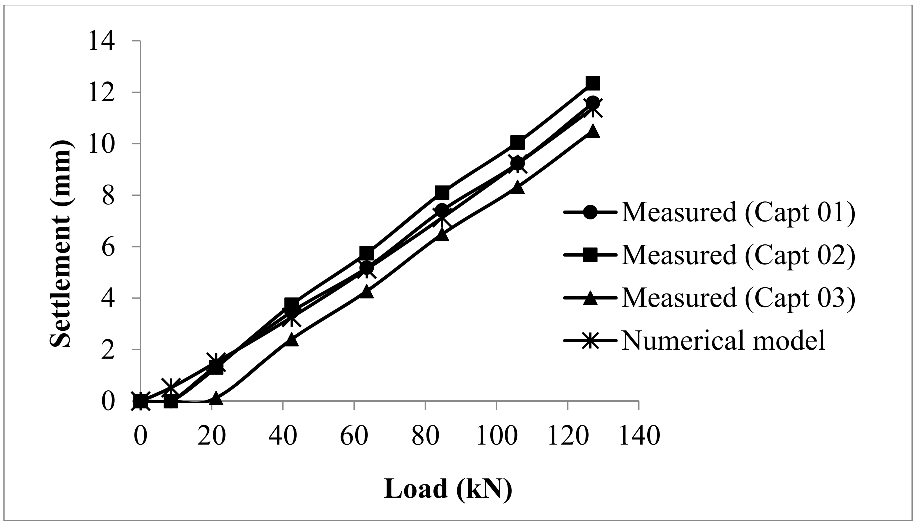


Figure (9): Results of single stone column load test

Two-dimensional numerical modeling is generally used for its simplicity compared to three-dimensional numerical modeling. Several two-dimensional equivalence methods exist. Among these methods is the homogenization method (also called the equivalent area method). The homogenization method is more commonly used in practice. Several studies of soil reinforcement by stone columns have used the homogenization method (Han et al., 2005; Abusharar and Han, 2011; Zhang et al., 2014; Ng and Tan, 2015).

The homogenization method replaces the soil and the column by an equivalent area with equivalent properties. In this study, the homogenization method is called the equivalent area method. Figure 10 presents the numerical models of the present study of soil reinforced by stone column with a) unit cell and b) equivalent area.

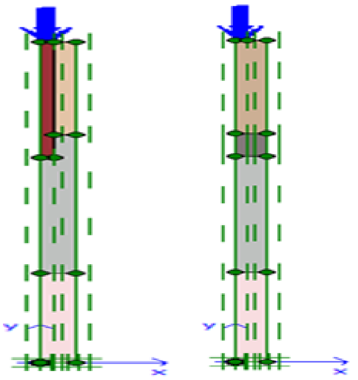
The equivalent parameters of the equivalent area method can be calculated as follows (Han et al., 2005; Abusharar and Han, 2011; Zhang et al., 2014):

$$\gamma_{eq} = \gamma_c a_s + \gamma_s (1-a_s) \quad (1)$$

$$\varphi_{eq} = \tan^{-1}(\tan\varphi_c a_s + \tan\varphi_s (1-a_s)) \quad (2)$$

$$c_{eq} = c_c a_s + c_s (1-a_s) \quad (3)$$

$$E_{eq} = E_c a_s + E_s (1-a_s) \quad (4)$$



a) Unit cell **b) Equivalent area**

Figure (10): Numerical models of the present study

In the equations above, the indices eq, c and s represent the equivalent parameters, column and soil, respectively. a_s is the area replacement ratio (a_s=A_c/A; A_c: area of the column, A: total influence area).

The equivalent area method was used in this study to investigate the stone column behavior. To validate the accuracy of this method, the results of the settlement obtained by the equivalent area model are compared with the results of the unit cell model and with the field measurements, as shown in Figure 11. Field measurements are the average of Capt01, Capt02 and Capt03. Figure 11 shows that the unit cell method provides a better prediction for the measured settlements at load levels higher than 40 kN, whereas both methods deviate from the measured settlements at lower load levels. The maximum difference of settlement results between the two numerical models is 10%. The homogenization method can reasonably simulate the behavior of stone column-reinforced soil.

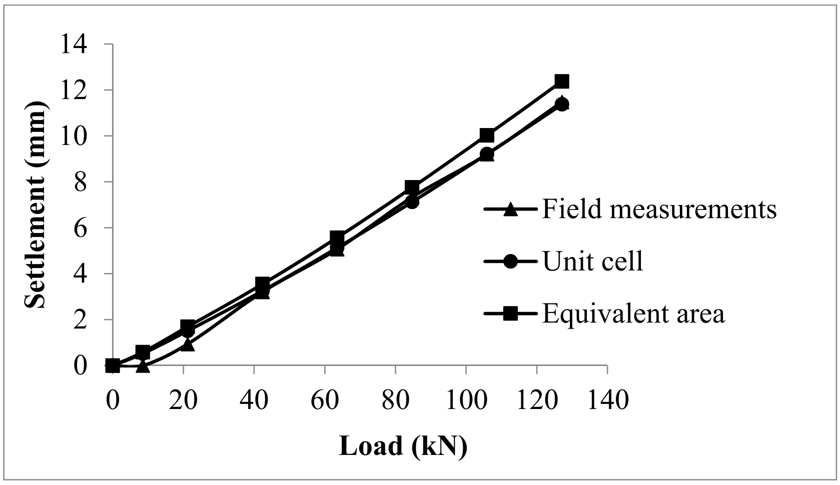


Figure (11): Results of settlement with different modeling methods

PARAMETRIC STUDY

For the parametric analysis, an embankment constructed on reinforced soil by stone columns was adopted in order to examine the accuracy of the equivalent area method. The description of the numerical model used for the parametric study was given by Ng and Tan (2015). The stone columns have a diameter of 1m and a spacing distance between columns of 2m and are arranged in a square grid. The numerical simulation of the present study of the embankment construction on reinforced soil was made by the unit cell concept using an axisymmetric model. The equivalent diameter of the unit cell model was D_e=2.26 m. Figure 12 presents the embankment with the stone column-reinforced soil using the unit cell model. The properties of soil and column materials for the reference case are presented in Table 2.

The validation of the unit cell model adopted in this study was made by comparing the results of the settlement under the embankment, after construction of the embankment from the current numerical analysis, with the results from the plane strain model reported by Ng and Tan (2015). Figure 13 presents the comparison results of maximum settlement after construction of the embankment from the present study by the unit cell model and the plane strain model reported by Ng and Tan (2015). The difference of settlement results between the unit cell model and the plane strain model reported by Ng and Tan (2015) was 4%. The current numerical model was validated and then the parametric study was performed.

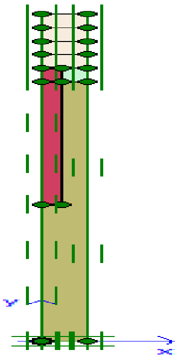


Figure (12): Unit cell model

Table 2. Properties of materials used for numerical modeling (Ng and Tan, 2015)

	Stone column	**Embankment fill**	**Crust**	**Soft clay**
γ (kN/m^3)	19	20	19	18
γ_{sat} (kN/m^3)	20	20	20	18
c (kPa)	1	1	1	1
φ (°)	50	35	30	25
E (kPa)	50,000	15,000	15,000	5,000
ν (-)	0.3	0.3	0.3	0.3
k (m/day)	1	0.001	0.001	0.001

Note: k = permeability.

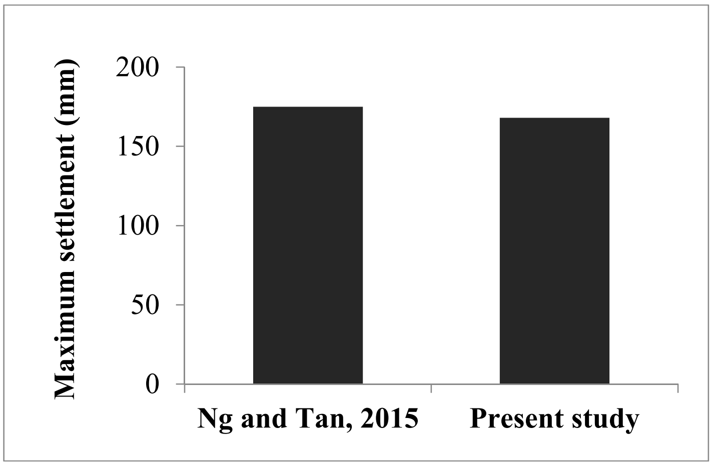
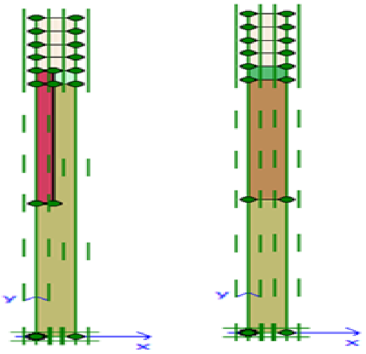


Figure (13): Comparison of results

The parametric study was done using two numerical methods: unit cell and equivalent area. Figure 14 presents the numerical models with a) unit cell and b) equivalent area. The new equivalent parameters of the equivalent area method are calculated by Equations (1), (2), (3) and (4). The parametric study focused on the variation of settlement under the embankment and evaluated the effects of some parameters, such as Young's modulus of stone column (E_c), diameter of the column (D), spacing between columns (s) and the height of the embankment (H), on the performance of stone columns. Table 3 presents a range of different parameters used for the parametric study. The results from both equivalent area and unit cell models are compared and discussed.

Table 3. Range of parameters used for the parametric study

Parameter	**Unit**	**Value Range**
Young's modulus (E_c)	kPa	25,000-50,000
Diameter (D)	m	0.6-1.2
Spacing (s)	m	2-3.5
Height of embankment (H)	m	1-4



a) Unit cell **b) Equivalent area**

Figure (14): Numerical models

Effect of Stone Column Young's Modulus

Young's modulus of the stone columns is higher than that of the surrounding soil. The effect of Young's modulus of the column material on the settlement is depicted in Figure 15. Young's modulus of the column material was varied from E_c= 25,000 kPa to E_c= 50,000 kPa with the same Young's modulus of the surrounding soil E_s= 5000 kPa (i.e., from modular ratio, E_c/E_s of 5 to 10), in order to examine the influence of Young's modulus on the settlement. As indicated in Figure 15, when Young's modulus varies from 25,000 to 50,000 kPa, the settlement decreases from 186 to 166 mm by the unit cell model, representing a reduction of 11% and decreases from 181 to 159 mm by the equivalent area model, representing a reduction of 12%. It is evident that the settlement decreases as Young's modulus increases. Furthermore, the maximum difference of settlement results between the unit cell model and the equivalent area model amounted to 4%. The stone column behavior improved significantly with an increase in the stone column Young's modulus. The stiffness of the column material plays an important role in soil improvement. Consequently, stone column properties directly affect the stone column behavior.

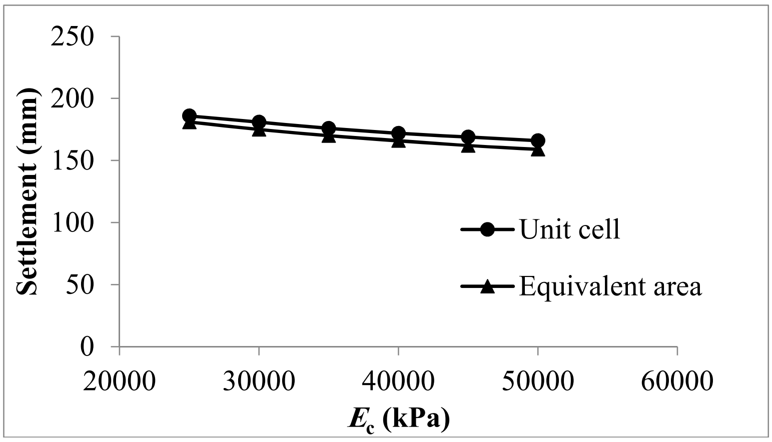


Figure (15): Effect of Young's modulus

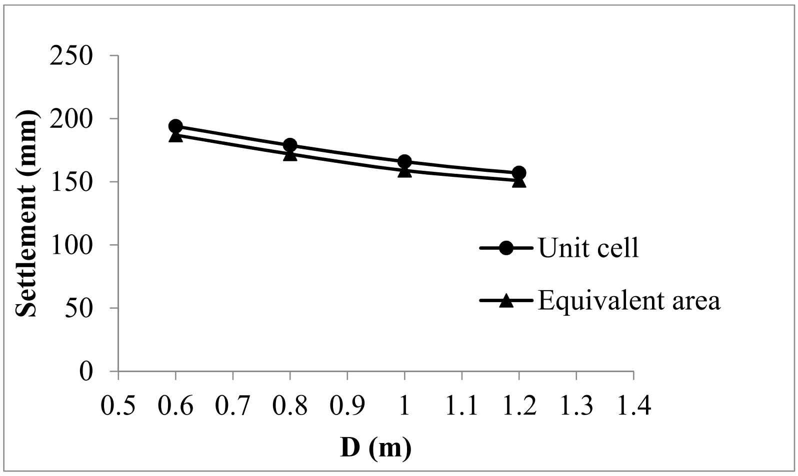


Figure (16): Effect of the stone column diameter

Effect of Stone Column Diameter

Figure 16 shows the variation of the settlement with the variation of column diameter from D = 0.6 m to D = 1.2 m, with a constant spacing, which corresponds to an area replacement ratio of a_s = 7% to 28%, which is used in design practice. For diameters of 0.6, 0.8, 1 and 1.2 m, the values of the settlement are 194, 179, 166 and 157 mm by the unit cell model and 187, 172, 159 and 151 mm by the equivalent area model, respectively. The results show the effect of increasing the diameter of the column on the settlement. By increasing the stone column diameter from 0.6m to 1.2m, the settlement decreases by around 19%. It is evident that the stone column performance was improved by increasing the stone column diameter. The calculated settlement using the unit cell model is about (4%) higher than that calculated using the equivalent area model.

Effect of Stone Column Spacing

The spacing of stone columns is one of the important design parameters in soil improvement with stone columns; it is related to the area replacement ratio of the columns. A series of four values of spacing (2, 2.5, 3 and 3.5 m) was performed, while all other parameters were kept constant. The spacing was increased to see the effect of this parameter on the settlement. Figure 17 shows the variation of the settlement with variation of the spacing from s=2 m to s=3.5 m with a constant diameter, which corresponds to an area replacement ratio of 20% to 6.4%. For spacing values of 2, 2.5, 3 and 3.5 m, the values of the settlement are 166, 179, 188 and 192 mm by the unit cell model and 159, 173, 185 and 192 mm by the equivalent area model, respectively. The two numerical models (unit cell and equivalent area) show that as the spacing increases, the settlement increases. The settlement is increased by a maximum of 21%. Additionally, it is observed that for s=3.5 m, the settlement remains the same for the two numerical models. Stone columns with a lower spacing indicated a better behavior against settlement. To obtain the maximum reduction in the settlement, it is recommended to better choose the spacing of the stone columns.

Effect of Embankment Height

In order to investigate the effect of the embankment height on the performance of the stone columns, the height of the embankment in this analysis was varied from H=1 m to H=4 m. Figure 18 shows the variation of the settlement with variation in the height of the embankment represented by the two numerical methods used. From Figure 18, it can be observed that as the height of the embankment increases from 1 m to 4 m, the loading to the foundation soil increases and thus, the settlement under the embankment increases. For embankment heights of 1, 2, 3 and 4 m, the values of the settlement are 39, 82, 123 and 166 mm by the unit cell model and 38, 80, 118 and 159 mm by the equivalent area model, respectively. The difference of settlement results between the unit cell model and the equivalent area model ranges between 2% and 4%. It is observed from the parametric study that the embankment height has a significant effect on the settlement of the improved ground.

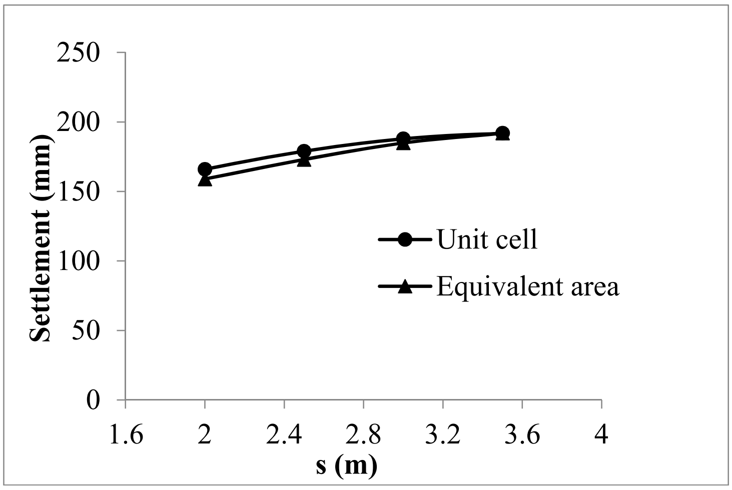


Figure (17): Effect of stone column spacing

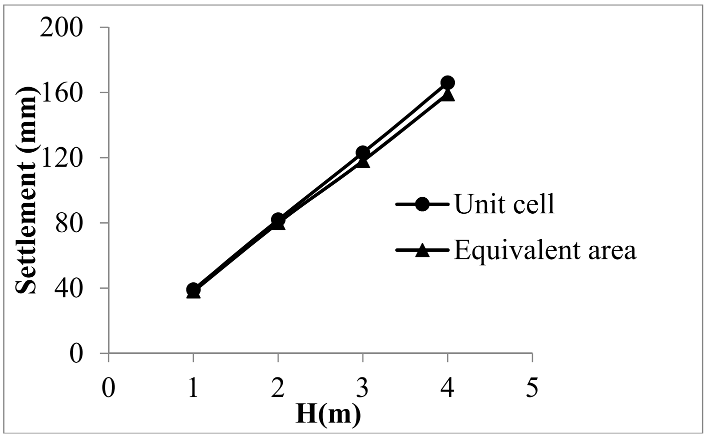


Figure (18): Effect of embankment height

CONCLUSIONS

Ground improvement by stone column method was used in Algeria for heavy industrial structures. In this study, a numerical analysis of the behavior of soils reinforced by stone columns of the ETP area located in Skikda Refinery, Algeria was conducted. A field loading test on stone column D338 was used for the numerical analysis using the unit cell model. The results of the numerical analysis were compared and validated with the field measurements in terms of settlement.

Also, soil behavior in terms of settlement has been predicted by the equivalent area method, to evaluate the performance and the validity of this method in predicting the settlement by comparing the results of the unit cell model and the equivalent area model. Based on the numerical results, the maximum difference of settlement between the equivalent area model and the unit cell model is 10%. The equivalent area method is able to model the behavior of soils reinforced by stone columns in terms of settlement.

A parametric study was carried out to study the influence of some parameters, such as Young's modulus of column material, diameter of column, spacing of columns and height of the embankment fill on the settlement of foundation soils using the unit cell model and the equivalent area model. From the parametric analysis, concluding remarks are summarized as follows:

1. The comparative study shows that the calculated settlement using the unit cell model is higher by about (4%) than that calculated using the equivalent area model.
2. When the stone column Young's modulus increases, the settlement decreases; therefore, the increase in Young's modulus has a significant effect on the improvement of the soil. Consequently, stone column properties directly affect the stone column behavior.
3. The settlement decreases when the column diameter increases from 0.6 to 1.2m (a reduction of 19%), while the settlement increases when the column spacing increases. Stone columns with lower spacing and bigger diameter indicated better behavior against settlement.
4. The increase in the height of the embankment from 1 to 4m affects the increase of the loading on the foundation soils and thus, the settlement under the embankment increases.
5. The results of the parametric study can be used in engineering practice.

Finally, the effect of other parameters can also be incorporated in future works to study the validity of the homogenization method for ground improvement by stone columns.

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