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Bearing Capacity Assessment of Collapsible Soils Improved by Deep Soil Mixing Using Finite Element Method

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Abstract

Problematic soils usually cause considerable problems to engineering projects. As an example, soil structure collapse caused by moisture increment or rising underground water level results in huge settlements. This type of problematic soil, named collapsible soil, can cause dramatic problems and should be amended where exists. Today, the use of different techniques for soil reinforcement and soil improvement is widely used to treat soil properties. One of these methods is Deep Soil Mixing (DSM) method. This method becomes more important in the cases of studying and examining collapsible soils. In this research, the settlement of amended collapsible soils, applying deep soil mixing method, is examined. The experiments show that soil amendment using this method, well prevents the settlement of collapsible soils giving rise to bearing capacity.

Keywords

Collapsible Soil, Settlement, Deep Soil Mixing, Finite Element Method

1. Introduction

Collapsible soils are sensitive to moisture content and are prone to huge changes in porosity. The moisture change affects the bonds between soil particles. By weakening the linkages between soil particles, the structure of the soil is collapsed leading to volume changes and the reduction of shear strength of the soil. These soils usually exist in arid and semi-arid regions. In these conditions, the moisture of the soil quickly evaporates and there is no time for the consolidation due to the weight [1] resulting in loose honeycomb-type structure at a large void ratio. The cohesion exhibited by these soils is as a result of bonding by dry clay or other chemical materials, therefore, wetting will bring about collapse. The amount of collapse or settlement is a function of permeability, degree of saturation, primary porosity, pre-consolidation ratio and the layer thickness. The major problem with collapsible soils is that the collapse potential soil must be distinguished before construction. Therefore, identification of collapsible soils and estimation of collapse potential are the most important issues to distinguish the behavior of these soils at any site [2].

In 2013, Houston *et al.* defined collapsible soils as soils that are highly sensitive to moisture. They stated that settlement amount is increased by the increase of moisture. They examined the amount of settlement that saturated collapsible soil showed and measured the amount of their strain. **Figure 1** shows the results of the experiment in which three samples have maximum strain, when they reach 100% saturation or have reached failure conditions [3].

Holtz and Hilf in 1791 suggested that dry density at the liquid limit may be used to estimate the collapse potential. They provided an assessment chart of collapse of soil types. There are several methods to control the effect of soil collapse on the foundation such as using piles to transfer the load of structures to deeper reliable layers. Moreover, in some cases, strip foundation may be more economical and more optimal, and also can minimize asymmetric subsidence [4].

Another way to overcome the problem of collapsible soils is deep soil mixing method. DSM is one of the soil improvement methods, which is used in wide range of soils to a depth of about 50 meters. The aim of soil mixing is to achieve modified geotechnical parameters such as compressive strength, shear strength and permeability [5]. This is also used in environmental fields to limit or prove harmful chemical materials in the soil. In addition, valuable results can also be achieved in the construction of ports and marine structures. The *in situ* improvement of soil properties achieved by DSM can be regarded as a great advantage of this method. Furthermore, the work can be controlled and confirmed during the project. The phrase of soil mixing at a depth refers to the method in which stabilizer materials such as cement or lime are mechanically mixed with the soil by using a digger with a hollow shaft. Soil mixing process produces a uniform pile of soil and additive materials. Continuous walls can be constructed at depths by overlapping these piles [6]. The purpose of soil mixing is to achieve modified geotechnical parameters such as compressive strength, shear strength, and permeability [7].

Mixing device may have a single drill with a diameter of 0.6 to 1.5 meters or a set of two to eight drills with a diameter of 1.5 meters. These columns have been implemented in America to a depth of 20 meters and in Japan to a depth of 60 meters. DSM method is one of the amendment methods, which is used in wide range of soil types to depth of about 50 meters [8].

Economical, time-dependent and environmental constraints sometimes cause other soil improvement methods such as pre-load or dynamic methods not to be appropriate. On the other hand, these two methods cannot be used in urban areas because of high vibrations and sound. DSM method has proved its capabilities as an appropriate alternative for these two methods, as well as for deep foundations method (piles execution). Despite the mentioned advantages, this method is not widely used, although almost 40 years have passed since the beginning of applying this method. This is because of the lack of the necessary technology for implementation in some countries. There are many regions in the world that are prone to use this method for amendment and this make the importance of using this method clear more than ever. For example, in seismically active countries, where there is a possibility of liquefaction phenomenon, the use of this method reduces the liquefaction potential and prevents its problems. The aim of this research is to investigate and evaluate the behavior of collapsible soils that are amended using DSM method based on previously published data available in the literature [9].

2. Materials and Methods

2.1. Used Information

Parameters and properties of the soil analyzed in this research have been reported in reference number [2] and are presented in Table 1 and Table 2.

2.2. Specifications of Model

The Plaxis software version 8.5 was used in this research. The 6-node triangular element was applied and other characteristics of the model can be listed as: plane strain, Mohr-Coulomb model and elastic soil behavior.

Computational modeling consists of seven phases as follows:

First Phase (initial condition): is done automatically by the software over which the initial stresses in the soil are calculated.

Second Phase: site flattening

Third Phase: DSM columns are implemented at the desired location. The columns

Table 1. Geotechnical parameters of the different layers [2].

ν	E (kg/cm^2)	$(SPT)_{ave}$	c_u (kg/cm^2)	γ (kN/m^3)	Depth (m)	Soil Type	Layer No.
0.4	$500c_u = 400$	12	0.8	20	0 - 6.5	Clay	1
0.4	$1000c_u - 500c_u = 300 - 550$	5 - 17	0.3 - 1.1	20	6.5 - 20	Clay	2
0.3	500	20	0	20	20 - 30	Sand	3
0.4	$500c_u = 800$	25	1.6	20	30 - 35	Clay	4
					35 - 40	Clay	5

Table 2. Characteristics of different blocks foundation [2].

q (kPa)	Max Stories	L (m)	B (m)	Block
88	6	75.3	31.5	A
59	4	68.4	27.9	B
59	4	68.4	44.7	C

with 25 cm in diameter, spaced 2 meters in longitudinal and transversal are used for the soil stability.

Fourth Phase: a thin soil layer with a thickness of 30 cm is embanked at the top of the piles primary surface.

Fifth Phase: geogrid layer is installed.

Sixth Phase: a thin soil layer with a thickness of 20 cm is embanked over the geogrid surface.

Seventh Phase: the desired load (caused by the weight of the structure and/or embankment) is applied.

In the experiments, the amount of settlement on the project results has been examined in both long-term and short-term modes. The amount of soil settlement in each stage has been calculated by using Plaxis 2D software.

2.3. Settlement of Mat Foundation before Soil Amendment

Bearing capacity of mat foundations should be controlled based on two criteria of shear strength and settlement, and at least these two to be offered as allowed bearing capacity. Both settlement consolidation and elastic settlement of clay and sandy layers have been considered in the calculations of settlement. Classical equations have been used to calculate consolidation and elastic settlement as follows [1]:

$$\frac{C_c}{1+e_o} H \ \operatorname{Log} \frac{P_o+\Delta p}{P_o} = \text{If } P_o,\ P_o+\Delta p > P_c : S_c \tag{1}$$

$$\frac{C_s}{1+e_o} H \ \operatorname{Log} \frac{P_o+\Delta p}{P_o} =,\ P_o+\Delta p < P_c : S_c \tag{2}$$

$$\text{If } P_o < P_c,\ P_o+\Delta p < P_c \frac{C_s}{1+e_o} H \ \operatorname{Log} \frac{P_c}{P_o} + \frac{C_c}{1+e_o} H \ \operatorname{Log} \frac{P_o+\Delta P}{P_c} \tag{3}$$

$$S_e = P.B \frac{1-\nu^2}{E} I_p \tag{4}$$

$$S_c + S_e.S_t = \mu_g \tag{5}$$

where:

P_o: effective pressure

Δp: pressure increase caused by overburden

P_c: over-consolidation pressure

H: Thickness of the layer

C_c: Coefficient of compaction indicator (0.120)

C_s: Coefficient of swelling indicator (0.015)

B: foundation width

ν: Poisson coefficient

E: elasticity modulus

I_P: Impact coefficient (dimensionless)

P: pressure (at times)

S_c: Consolidation settlement

S_e: Elastic settlement

S_t: Total settlement

μ_g: Scempton and Birum coefficient (0.7)

In calculations, below the depth of 6.5 m, the soil has been considered over-consolidated, and the soil layer below this depth is divided into several sub-layers to calculate the settlement to avoid errors. The results of calculations are shown in the below (Tables 3-9).

Mat foundation settlement of each block is as follows (Table 9).

Given that the building is sensitive to settlement, so the allowed settlement in such a structure was limited to 2 inches (approximately 5 cm). According to the results shown in Table 9, total settlement of the two blocks of B and C is nearly in the allowed range but block A will have settlement more than allowed settlement. Therefore, the soil layer below this block should be modified by an appropriate method.

Table 3. The amount of consolidation settlement under the foundation of block A. Consolidation Settlement under mat foundation (block A: B = 31.5 m, L = 75.3 m).

	Pc(Kn/m)Δ	75		Excavation depth(m)		6.5					
	C_c (1 + e_0)	0.120		Ground water depth from natural ground level		1.0					
	C_c (1 + e_0)	0.015									
Layer No.	Z(m)	γ_W(Kn/M^2)	γ_W(Kn/M^3)	P0(Kn/M^2)	q(Kn/M^2)	B(m)	L(m)	Δq(Kn/M^2)	P_0Δq	Pc(Kn/M^2)	S(mm)
1	0	20	10	0.0	88	31.5	75.3	88.00	88.00	75.00	0.00
2	2	20	10	20.0	88	31.5	75.3	80.61	100.61	95.00	26.28
3	4	20	10	40.0	88	31.5	75.3	**75.15**	**114.15**	**115.00**	**13.66**
4	6	20	10	60.0	88	31.5	75.3	**68.46**	**128.46**	**135.00**	**9.92**
5	8	20	10	80.0	88	31.5	75.3	**63.44**	**143.44**	**155.00**	**7.61**
6	10	20	10	100.0	88	31.5	75.3	**58.96**	**158.96**	**175.00**	**6.04**
7	12	20	10	120.0	88	31.5	75.3	**54.96**	**174.96**	**195.00**	**4.91**
8	14	20	10	140.0	88	31.5	75.3	**51.37**	**191.37**	**215.00**	**4.07**
9	16	20	10	160.0	88	31.5	75.3	**48.13**	**208.13**	**235.00**	**3.43**
10	18	20	10	180.0	88	31.5	75.3	**45.20**	**225.20**	**255.00**	**2.92**
11	20	20	10	200.0	88	31.5	75.3	**42.53**	**242.53**	275.00	**2.51**
										S_{oons} (mm)	**81**
										μ9	**0.70**
										S_c (mm)	**57**

Table 4. The amount of elastic settlement under the foundation of block A. Elastic Settlement under mat foundation (block A: B = 31.5 m, L = 75 m).

q(kN/m^2)	88.00	q'(kN/m^2)	52.24	q'(kN/m^2)	52.24	q'(kN/m^2)	38.41
B(m)	31.5	B'(m)	45.0	B'(m)	45.0	B*(m)	55.0
L(m)	75.3	L'(m)	88.8	L'(m)	88.8	L*(m)	98.8
L/B	2.39	L'/B'	1.97	L'/B'	1.97	L*/B*	1.80
I_p	1.62	I''_p	1.51	I''_p	1.51	I''_p	1.41
μ_1	0.4	μ_2	0.4	μ_2	0.3	μ_2	0.3
E_1(kN/m^2)	42,500	E_1(kN/m^2)	42,500	E_2(kN/m^2)	50,000	E_2(kN/m^2)	50,000
S_1(mm)	88.76	S_2(mm)	70.15	S_3(mm)	64.60	S_4(mm)	54.22
			S_I(mm) = $S_1 + S_2 + S_3 + S_4$ =		29		
			S_I(mm) = $S_c + S_i$		86		

Table 5. The amount of consolidation settlement under the foundation of block B. Consolidation Settlement under mat foundation (block B: B = 27.9 m, L = 68.4 m).

Pc(Kn/m)Δ	75	Excavation depth(m)	6.5
C_c (1 + e_0)	0.120	Ground water depth from natural ground level	1.0
C_c (1 + e_0)	0.015		

Layer No.	Z(m)	γ_W(Kn/M^2)	γ_W(Kn/M^3)	P0(Kn/M^2)	q(Kn/M^2)	B(m)	L(m)	Δq(Kn/M^2)	P_0Δq	Pc(Kn/M^2)	S(mm)
1	0	20	10	0.0	59	27.9	75.3	68.4	59.00	75.00	0.00
2	2	20	10	20.0	59	27.9	75.3	68.4	73.49	95.00	**16.96**
3	4	20	10	40.0	59	27.9	75.3	68.4	**88.75**	**115.00**	**10.38**
4	6	20	10	60.0	59	27.9	75.3	68.4	**104.64**	**135.00**	**7.25**
5	8	20	10	80.0	59	27.9	75.3	68.4	**121.05**	**155.00**	**5.40**
6	10	20	10	100.0	59	27.9	75.3	68.4	**137.89**	**175.00**	**4.19**
7	12	20	10	120.0	59	27.9	75.3	68.4	**155.10**	**195.00**	**3.34**
8	14	20	10	140.0	59	27.9	75.3	68.4	**171.61**	**215.00**	**2.73**
9	16	20	10	160.0	59	27.9	75.3	68.4	**190.39**	**235.00**	**2.27**
10	18	20	10	180.0	59	27.9	75.3	68.4	**208.39**	**255.00**	**1.91**
11	20	20	10	200.0	59	27.9	75.3	68.4	**226.59**	**275.00**	**1.63**
										S_{oons} (mm)	**56**
										μ9	**0.70**
										S_c (mm)	**28**

Table 6. The amount of elastic settlement under the foundation of block B. Elastic Settlement under mat foundation (block B: B = 27.9 m, L = 88.4 m).

q(kN/m^2)	59.00	q'(kN/m^2)	33.21	q'(kN/m^2)	33.21	q'(kN/m^2)	23.84
B(m)	27.9	B'(m)	41.4	B'(m)	41.4	B*(m)	51.4
L(m)	68.4	L'(m)	81.9	L'(m)	81.9	L*(m)	91.9
L/B	2.45	L'/B'	1.98	L'/B'	1.97	L*/B*	1.79
I_p	1.64	I''_p	1.63	I''_p	1.51	I''_p	1.41
μ_l	0.4	μ_2	0.4	μ_2	0.3	μ_2	0.3
E_1(kN/m^2)	42,500	E_1(kN/m^2)	42,500	E_2(kN/m^2)	50,000	E_2(kN/m^2)	50,000
S_1(mm)	53.36	S_2(mm)	41.57	S_3(mm)	38.26	S_4(mm)	31.44
			S_I(mm) = $S_1 + S_2 + S_3 + S_4$ =		29		
			S_I(mm) = $S_c + S_i$		86		

Table 7. The amount of consolidation settlement under the foundation of block C. Consolidation Settlement under mat foundation (block C: B = 44.7 m, L = 67.4 m).

Pc(Kn/m)Δ	75	Excavation depth(m)	6.5
C_c (1 + e_0)	0.120	Ground water depth from natural ground level	1.0
C_c (1 + e_0)	0.015		

Layer No.	Z(m)	γ_W(Kn/M^2)	γ_W(Kn/M^3)	P0(Kn/M^2)	q(Kn/M^2)	B(m)	L(m)	Δq(Kn/M^2)	P_0Δq	Pc(Kn/M^2)	S(mm)
1	0	20	10	0.0	59	44.7	68.4	59.00	59.00	75.00	0.00
2	2	20	10	20.0	59	44.7	68.4	74.87	74.87	95.00	**17.20**
3	4	20	10	40.0	59	44.7	68.4	91.16	91.16	**115.00**	**10.73**
4	6	20	10	60.0	59	44.7	68.4	68.4	107.82	**135.00**	**7.64**
5	8	20	10	80.0	59	44.7	68.4	107.82	124.80	**155.00**	**5.79**
6	10	20	10	100.0	59	44.7	68.4	124.80	142.06	**175.00**	**4.57**
7	12	20	10	120.0	59	44.7	68.4	142.06	159.57	**195.00**	**3.71**
8	14	20	10	140.0	59	44.7	68.4	159.57	177.29	**215.00**	**3.08**
9	16	20	10	160.0	59	44.7	68.4	177.29	195.21	**235.00**	**2.59**
10	18	20	10	180.0	59	44.7	68.4	195.21	213.30	**255.00**	**2.21**
11	20	20	10	200.0	59	44.7	68.4	213.30	231.54	**275.00**	**1.91**
										S_{oons} (mm)	**59**
										μ9	**0.70**
										S_c (mm)	**42**

Table 8. The amount of elastic settlement under the foundation of block C. Elastic Settlement under mat foundation (block C: B = 44.7 m, L = 68.4 m).

$q(kN/m^2)$	59.00	$q'(kN/m^2)$	37.85	$q'(kN/m^2)$	37.58	$q'(kN/m^2)$	28.78
B(m)	27.9	B'(m)	58.2	B'(m)	81.9	B*(m)	91.9
L(m)	68.4	L'(m)	81.9	L'(m)	81.9	L*(m)	91.9
L/B	2.45	L'/B'	1.41	L'/B'	1.41	L*/B*	1.35
I_p	1.64	I''_p	1.34	I''_p	1.34	I''_p	1.32
μ_l	0.4	μ_2	0.4	μ_2	0.3	μ_2	0.3
$E_1(kN/m^2)$	42,500	$E_1(kN/m^2)$	42,500	$E_2(kN/m^2)$	50,000	$E_2(kN/m^2)$	50,000
$S_1(mm)$	53.36	$S_2(mm)$	58.33	$S_3(mm)$	53.72	$S_4(mm)$	47.16
		$S_l(mm) = S_1 + S_2 + S_3 + S_4 =$			19		
		$S_l(mm) = S_c + S_i$			61		

Table 9. Foundation settlement of different blocks.

S_t (mm)	S_e (mm)	S_c (mm)	Block
86	29	57	A
58	19	39	B
61	19	42	C

2.4. Calculation and Examination of Allowed Bearing Capacity and Mat Foundation Settlement

The calculations are done to achieve followings by implementation of soil amendment using DSM method for a six-floor building:

- the bearing capacity of at least 1 kg/cm^2
- limiting the settlement under the building foundations to the maximum 5 cm

These calculations are based on the results of geotechnical investigations related to the amount of settlement, in the block of DSM (S1) columns, and clay layer consolidation settlement under (S2) DSM column with elastic meeting clay layer (S3), and on sand under (S4) DSM columns. Changes in foundation total settlement located on DSM columns in the center of foundation compared to the columns length in Figure 1 and the related settlement values have been presented in Table 10. The corresponding values for the aforementioned foundation corner (caused by northern mat foundation interaction) have been presented in Figure 1, Figure 2 and Table 10 & Table 11, respectively.

Skempton pore pressure coefficient at failure is obtained 0.31 based on the line slope of the diagram illustrated in Figure 3.

2.5. Soil Amendment Assessment

Plaxis 3D Foundation ver. 2.12 and Plaxis 3D 2012 software were used in order to

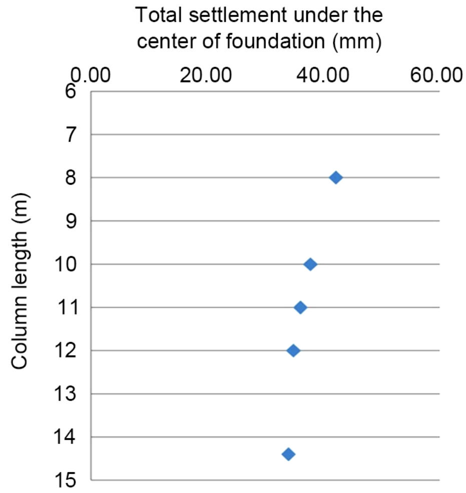

Figure 1. Foundation total settlement (center) with DSM columns length.

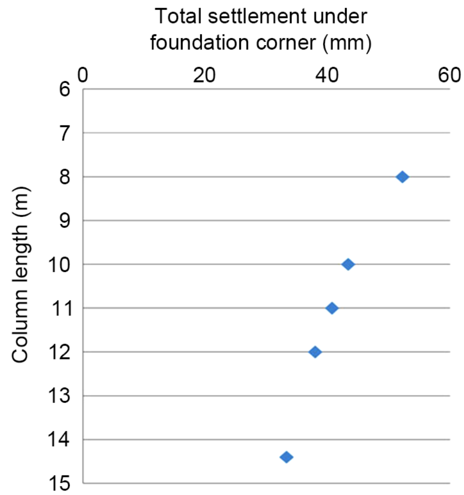

Figure 2. Foundation total settlement (corner) with DSM columns length.

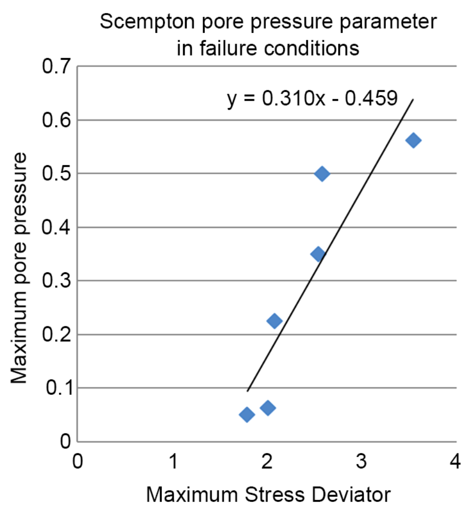

Figure 3. Skempton pore pressure coefficient.

Table 10. The amount of foundation total settlement located on DSM columns in the center of foundation compared to the columns length.

Settlement in the center of foundation		
Length of the entire pillar	(S1 + S2 + S3 + S4) Total settlement	(S1 + S2 + S3) Settlement
M	Mm	Mm
8	42	35
10	38	32
11	36	31
12	35	31
14.4	34	32

S1: Settlement of columns Block (mm); S2: Consolidation settlement (mm); S3: Elastic clay Settlement (mm); S4: Elastic sand Settlement (mm).

Table 11. The amount of foundation total settlement located on DSM columns in the corner of foundation compared to the columns length.

Length of the entire pillar	(S1 + S2 + S3 + S4) Total settlement	(S1 + S2 + S3) Settlement
M	Mm	Mm
8	52	45
10	43	40
11	41	38
12	38	35
14.4	52	32

S1: Settlement of columns Block (mm); S2: Consolidation settlement (mm); S3: Elastic clay Settlement (mm); S4: Elastic sand Settlement (mm).

examine the amandation calculation. Analyzes have been carried out for soil amandation canter.

2.5.1. Analysis applying Plaxis 3D Foundation 2012

Geotechnical parameters have been used to analyze this model. Upper clay with undrained strength of 50 kpa in contact with the foundation is increased to 72 Kpa at the level under DSM columns, and Su of DSM columns equal to 850 Kpa have been considered. The data and results obtained from the analysis have been shown in Figure 4.

2.5.2. Analysis by Plaxis 3D 2012

This software is the latest three-dimensional model by Plaxis for static and dynamic analysis of geotechnical problems. This has removed the constraints of previous software that all depths have fixed elementation. For the soil model, the geotechnical parameters were used according to a report from a real project. Upper clay with undrained strength of 50 Kpa in contact with the foundation is increased to 72 Kpa at the level

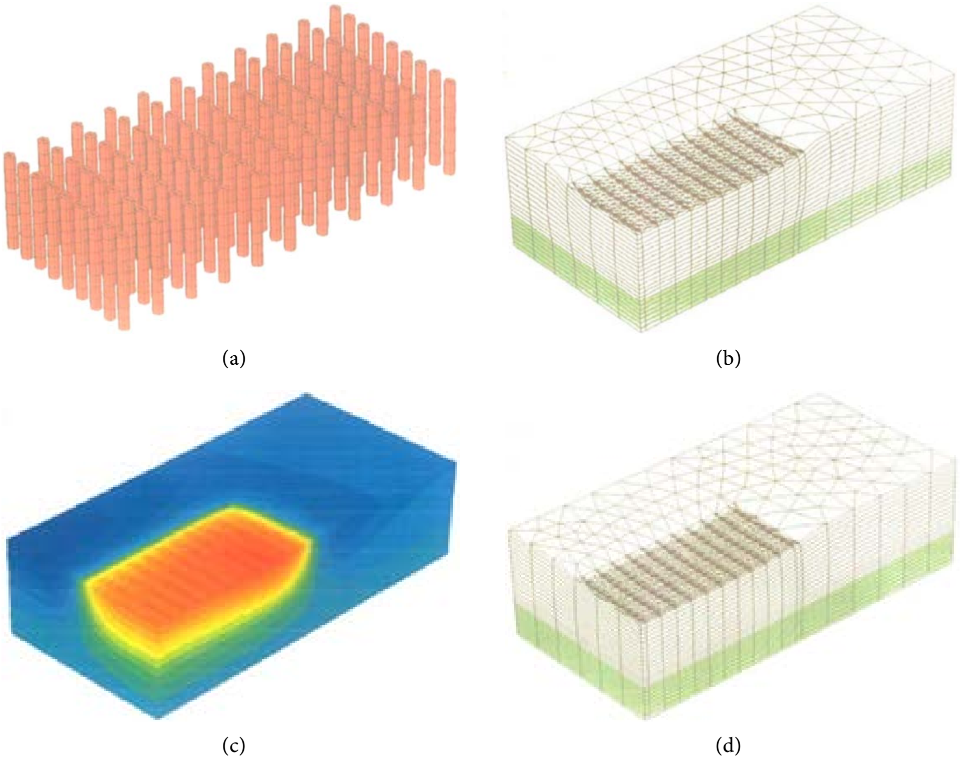

Figure 4. Columns equivalent to bean-shaped 0.81 square meters; (b) undrained settlement of amended soil equivalent to 24.54 mm; (c) undrained settlement of amended soil equivalent to 49.75 mm; (d) erect settlement soil of amended soil equivalent to 24.54 mm.

under DSM columns, and S_u strength of DSM columns equal to 850 Kpa have been considered. The data and results obtained from the analysis have been shown in Figure 5.

2.5.3. Analysis by Plaxis 3D 2012 with Simplified Section of Soil Block Equivalent for Amended Soil

In this case soil around the desired foundation with DSM columns as an equivalent blocks, and dimension of 75.5 mm in 31.5 mm and a thickness of 8 meters has been modeled with following characteristics:

$$(S_u)_{ave} = 162 \text{ kPa at top of DSM}$$

$$(S_u)_{ave} = 182.3 \text{ kPa at bottom of DSM}$$

Some data and results obtained from the analysis have been shown in Figure 6.

Considering the above contents, results table for settlement of foundation center is as follows (Table 12, Table 13).

3. Conclusion

Physical and mechanical properties of soil layers have been numerically investigated before and after amendment using DSM method with cement as stabilizer material. The results of experiments imply the efficiency and effectiveness of this method. With the

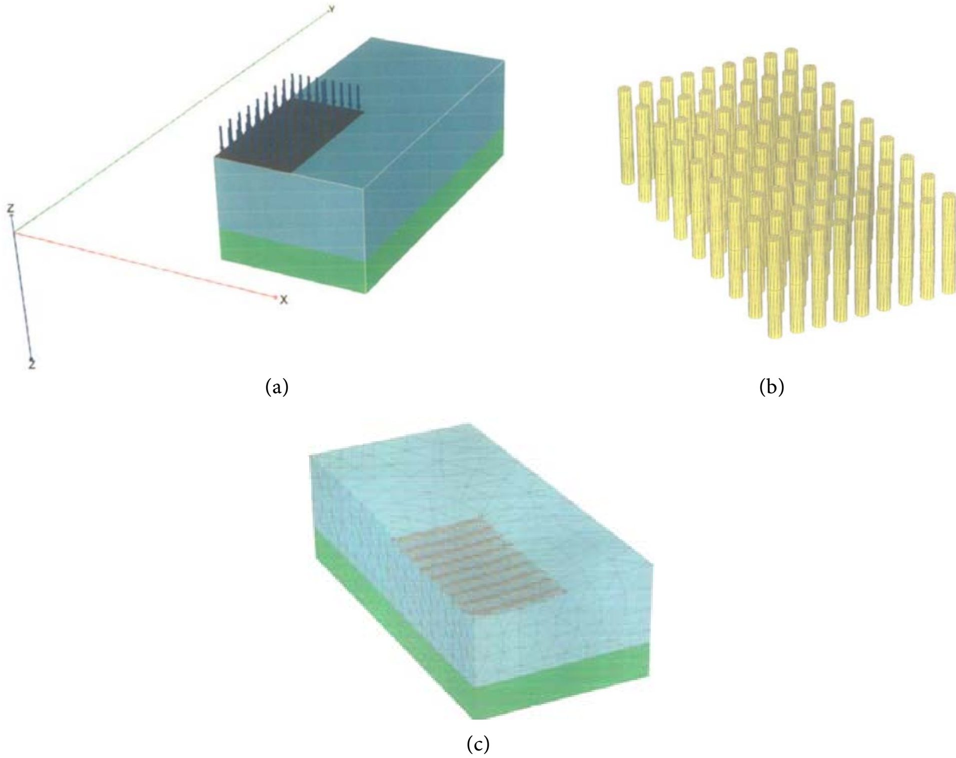

Figure 5. (a) Elements of DSM columns; (b) Amended foundation model 1.4, (c) Drained settlement (long-term after soil consolidating) amended soil equivalent to 44.88 mm.

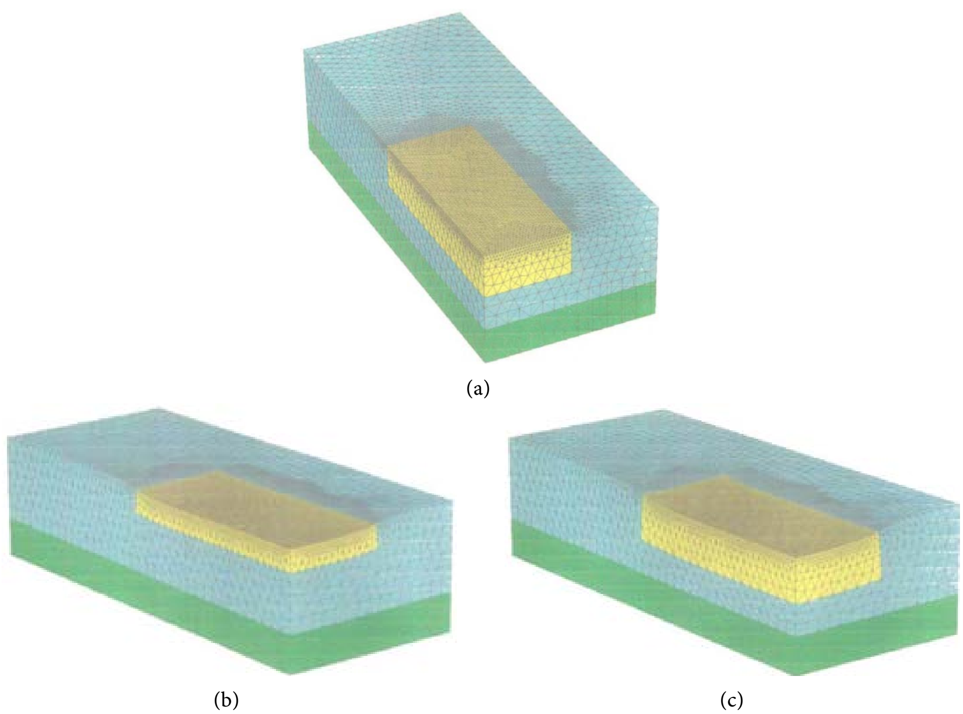

Figure 6. (a) Simplified section of soil block equivalent for amended soil; (b) Drained settlement (long-term after soil consolidating) amended soil equivalent to 46.29 mm; (c) Drained settlement of amended soil equivalent to 28.6 mm.

Table 12. Results for settlement of foundation center.

SES Method mm	Plaxis 3D 2012 equivalent method mm	Plaxis 3D 2012 mm	Plaxis 3D Foundation mm	
29.1	28.61		24.54	Undrained with DSM Short-term amendment before consolidation
42.11	46.29	44.83	49.75	Drained with DSM long-term amendment after consolidation
	29.98		28.82	Undrained Without DSM Short-term amendment before consolidation
	54.98	55.03	60.74	Drained with DSM long-term amendment after consolidation

Table 13. The amount of foundation total settlement located on DSM columns in the center of foundation compared to the columns length.

	Settlement in the center of foundation	
Length of the entire pillar	(S1 + S2 + S3 + S4) Total settlement	(S1 + S2 + S3) Settlement
M	Mm	Mm
8	52	45
10	43	40
11	41	38
12	38	35
14.4	52	32

S1: Settlement of columns Block (mm); S2: Consolidation settlement (mm); S3: Elastic clay Settlement (mm); S4: Elastic sand Settlement (mm).

soil amendment, short-term settlement before and after consolidation is calculated 24.54 and 49.75, respectively, and long-term settlement before and after consolidation reaches 28.82 and 60.74. This shows that consolidation along with soil improvement, when acting together, increases the soil strength against settlement in foundation center. Also, the amount of settlement at the foundation corner is reduced when the length of DSM columns is increased.

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