



Stabilization of Soft Clay Soil by Deep Mixing

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Abstract: East Port Said Port is considered one of the most important industrial regions in Egypt with soft clay soil. This paper focuses on the geotechnical properties of this area. To study the rehabilitation of this important region. Deep mixing method (DMM) with ordinary Portland cement or quicklime is used for soil improvement. In the laboratory, trial mix designs are used to compare soil properties before and after treatment. Effects of binder type, binder content, various water cement ratio and curing duration on soft clay improvement are studied. Three small-scale laboratory models (untreated soil model, model with end bearing deep mixing columns and model with floating deep mixing columns) are instrumented to measure the settlement of soil. Two Dimensional finite element analysis is carried out using PLAXIS program. A comparison between the 2D finite element analysis results and the physical model results is done. Results agree generally with each other. A finite element analysis is carried out to show the comparison between the performance of the soil with and without deep mixing. Effects of pile depth, pile spacing, pile diameter, pile type and soil compression index are illustrated in this study. Finally, according to the previous results, an equation is predicted to calculate the settlement using deep mixing method.

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Keywords: East Port Said Port, Soft clay, Deep mixing method, Stabilization, Finite element analysis.

1. Introduction

East Port Said Port is one of the largest national projects constructed on soft clay soil which opened in October 2004 to serve the world trade. Many projects are executed in this region. Settlement rates in this region were typically high (Hamed, O., 2017). Studying the effect of soft clay improvement using deep mixing method illustrated in many researches (Jiang et al., 2013). Three dimensional finite element methods are used to illustrate the settlement behavior of soft soils improved by deep mixed columns. Columns modulus, soft soil thickness, and area replacement ratio decrease the settlement of treated soft soil (Madhyannapu and Puppala, 2014). The effectiveness of the deep mixing technology and construction are discussed. An analytical model proposed for a deep soil mixing (DSM) to predict the settlement behavior of expansive sub-soils. Finally, the results indicated that the deep mixing method (DMS) technique was effective to improve soft clay soils. (Caraşca, 2016) Stated that soil treatment and stabilization by mixing is considered an economical method to improve soft clay. To understand the

properties of the improved soils, many experimental tests were performed on different artificial soils. Flexure strength, unconfined compressive strength tests and wave velocity measurements were carried out experimentally. In addition, porosity, permeability and density were studied on the hardened improved soil. Results in this paper follow the same trend as the results of the other studies. A laboratory- scale model is used to investigate the effect of improving the clay soil by installed deep mixing piles in a compacted clay soil (Abiodun and Nalbantoglu, 2014). Chemical reactions of soil produces strong inter particle bonds; which increases the unconfined compressive strength. (Yao et al., 2016) Illustrated that the in-situ test is not economic and easy. Physical model were used to study the effect of some properties of deep mixing method such as, column length, the area replacement ratio and surcharge load. Increasing of column length and area replacement ratio decreases the foundation settlement at the same surcharge load. However, increasing in column length is more efficient than higher area replacement ratio (Jamsawang et al., 2017).

2. Soil Properties Of Port-Said Clay

East Port Said Port area is composed of soft to medium stiff clay extending to depth exceeding 50 meters (Hamed, O., 2017). Soil samples were collected from the study region and field investigations carried out through the Suez Canal Authority Research Center. The investigated zone has an approximated area of 42 square kilometers. Six boreholes with depths ranging from 42 to 63m were performed.

The generalized soil properties obtained from the boring logs are shown in Table 1. The soil strata are classified into several layers. Natural water content ranges from 57.50 to 84.21%, total unit weight ranges from 15.8 to 16.7 kN/m³, liquid limit ranges from 57 to 125%, plastic limit oscillates from 25 to 46%, and undrained shear strength varies from 6.5 to 34.5 kPa, which indicates that Port-Said clay layers are classified as very soft to firm clay (Hamed, O., 2017).

Table 1: Properties of Port-Said (Hamed, O., 2017).

Sample	Extraction depth (m)	W _c (%)	Specific gravity	γ (kN/m ³)	LL (%)	PI (%)	I _L	S _u (kPa)
1	6-8	57.50	2.671	16.7	84	53	0.50	22.5
2	12-14	60.7	2.633	16.0	57	32	1.12	15
3	20-22	83.04	2.674	16.1	108	76	0.67	6.5
4	26-28	79.59	2.561	16.1	125	98	0.54	21.5
5	34-36	76.62	2.470	16.2	101	72	0.66	27.5
6	40-42	84.21	2.475	16.1	116	70	0.55	22.5
7	46-48	80.06	2.658	15.8	109	66	0.56	34.5

3. Soil Improvement

Problematic soft clay soil is characterized by its low bearing capacity, low shear strength, high compressibility and volume instability (Hebib and Farrell, 2003). Under such circumstances, any structure would be unstable, or the expected deformation during and/or after construction would exceed the allowable value, so necessary solutions must be undertaken (Larsson, S., 2003).

- Changing the type of structure foundation.
- Replacing the problem soils.
- Improving the properties of soft soil.
- Introducing reinforcing material into soft soil.

Soil improvement covers (b), (c) and (d) above (Kitazume and Terashi, 2013).

4. Laboratory Program

The laboratory Program is divided into two phases.

- Trial mix samples according to.

- Small scale model.
- ### 4.1. Trial Mix Samples

The main objective of this phase is to confirm the feasibility of using deep mixing method to improve strength and compressibility of soft clay soil for the studied region through an experimental program in the laboratory. After reviewing literature and projects on soil improvement, Samples are prepared by changing binder type, binder quantity, water cement ratio, and curing duration. Samples taken from depth 26 to 28m are selected for trial mix tests to test the properties before and after treatment. Five cement ratios, two binder types, three binder contents, and four curing duration are used for comparison of the results as shown in Table 2. The experimental program procedures and the variables were chosen based on past researches (Liu et al., 2017), (li et al., 2016), and (Mullins et al., 2015).

Table 2: Experimental Program for Mixing Tests

Binder	Binder quantity	Water cement ratio	Curing time
Cement	150 kg/m ³	0, 1, 1.2, 1.4, 1.6	7
Cement	150 kg/ m ³	1	3, 7, 14, 28
Cement	200 kg/ m ³	1	3, 7, 14, 28
Cement	250 kg/ m ³	1	3, 7, 14, 28
Quicklime	150 kg/ m ³	1	3, 7, 14, 28
Quicklime	200 kg/m ³	1	3, 7, 14, 28
Quicklime	250 kg/m ³	1	3, 7, 14, 28

In order to determine the optimum water cement ratio of the soil, soft clay samples were intimately mixed with cement at quantity of 150 kg/m^3 of wet soil, and at various water cement ratios. First, wet cement slurry was prepared by mixing cement with water according to a 0, 1, 1.2, 1.4, and 1.6 water cement ratio. Water was added in three separate batches into the cement to allow slurry homogenization. The slurry was mixed with two spatulas and hand for one minute in between each interval of pouring to assure a homogeneous mixture. The final state of the slurry should be liquid.

Second, untreated soils were homogenized with the Matest Mixer. Samples were transferred to the mixer's metal bowl and placed under the mixer's mechanical mixing hook. A mixing speed setting of Level 1, or 140 RPM, was used for 10 minutes to homogenize the clay soil before cement addition. Next, binder slurry was added to the untreated soil in

four batches. The mixer was turned off first to add the first batch of binder slurry. Then the mixture was allowed to mix for one minute at the speed Level 1. After one minute, the second batch was added with the same mixing procedure until all binders were added. During the mixing intervals, the side of the mixing bowl was scraped with spatula to ensure consistent homogenization of the mixture. The mixing speed was switched to Level 2 or 240 RPM after adding the fourth batch of cement slurry to further homogenize the mixture. Figure 1 shows preparing of the specimen in laboratory.

After the soil was mixed, it was compacted into steel tubes with diameter 5 cm and depth 15 cm, in 3 layers, tamping between each layer. Finally, the samples were extracted from the tubes and saved in paraffin wax and stored in climate-controlled area for 7 days.



Figure 1: Preparing of the specimen in laboratory.

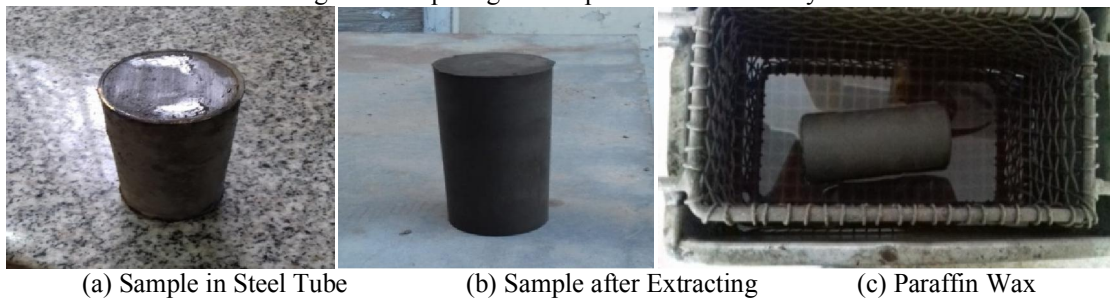


Figure 2: Sample Saving and Curing

The results show that the ideal water cement ratio for the samples is one. The same previous steps were repeated with quicklime at content of 150, 200, and 250 kg/m³ of wet soil, water cement ratio of one, and at curing time of 3, 7, 14, and 28 days. Three specimens were molded for each curing period. The average undrained shear strength of the samples for each curing period was determined by unconfined compression tests (Bergado et al., 1999).

The unconfined compression test was used in this research as the main benchmark test to determine the efficiency of deep mixing method in improving the strength of soft clay soil. After curing the samples were removed from wax and trimmed with a saw to ensure two flat ends surfaces and placed in the unconfined compression instrument to determine the unconfined compression strength. Figure 3 shows the saw used in the trimming and samples before, during and after unconfined compression test.



(a) Trimming Saw (b) Sample before Test (c) Sample during Test (d) Sample after Test
Figure 3: Sample Trimming Saw, Samples before, during, and after Test.

4.1.1. Results

Unconfined compression tests were performed on both virgin samples (soft clay) and cement or quicklime treated samples. This section is divided into three sub-sections to present results of soft clay samples, soft clay treated with cement, and soft clay treated with quicklime samples.

4.1.1.1. Virgin Soil Samples

Unconfined compression tests for virgin samples performed by Suez Canal Authority Research Center as previously mentioned. The typical undrained shear strength varies from 6.5 to 34.5 kPa. Stress strain curves of virgin samples are shown in Figure 4.

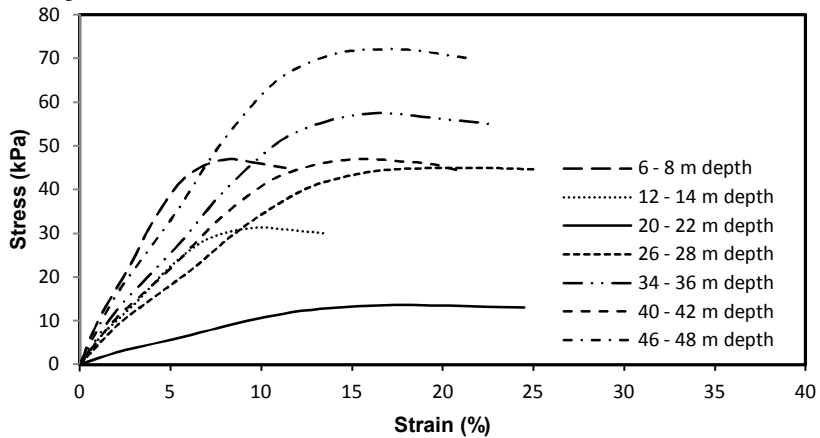


Figure 4: Stress Strain Curves of Virgin Samples

Table 3: Unconfined Compression Test Results for Samples with Various Water Cement Ratios.

Binder	Binder quantity	Water cement ratio	Curing time	S_u (kPa)	Young's Modulus (kPa)
Cement	150 kg/m ³	0	7	62.14	6173
Cement	150 kg/m ³	1	7	146.63	11598
Cement	150 kg/m ³	1.2	7	122.13	10835
Cement	150 kg/m ³	1.4	7	109.63	10124
Cement	150 kg/m ³	1.6	7	72.09	8409

4.1.1.2. Soft Clay Treated with Cement

Before starting of tests, the samples with cement content of 150 kg/m³, water cement ratio of 0, 1, 1.2, 1.4, and 1.6, and at curing time of 7 days were tested to determine the optimum water cement ratio. The optimum water cement ratio for the studied soft clay is one. The unconfined compression tests for samples with various water cement ratios are summarized in **Error! Reference source not found.** Then, the remaining cement samples were prepared and tested with different cement contents, water cement ratio of one, and at various curing days. The unconfined compression tests for soft clay treated with cement are summarized in Soft Clay Treated with Quicklime

Table 4.

4.1.1.3. Soft Clay Treated with Quicklime

The efficiency of quicklime treatment is tested by using samples taken from the test pits. Quicklime stabilization was effective in strengthening organic soils (Liu et al., 2017). High calcium quicklime was used in this study. The quicklime quantities were 150,

The efficiency of quicklime treatment is tested by using samples taken from the test pits. Quicklime stabilization was effective in strengthening organic soils (Liu et al., 2017). High calcium quicklime was used in this study. The quicklime quantities were 150, 200, and 250 kg/m³ and curing durations were 3, 7, 14, and 28 days.

Based on the unconfined compression test results, the efficiency of quicklime in treating the site clay is very low. Normally quicklime is not efficient in treating soft clay soils though it may be excellent for other problematic soils (Liu et al., 2017). The unconfined compression tests for clay treated with quicklime are summarized in Table 5.

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Table 4: Unconfined Compression Test Results for Soft Clay Treated with Cement Samples

Binder	Binder quantity	Water cement ratio	Curing time	S_u (kPa)	Young's Modulus (kPa)
Cement	150 kg/m ³	1	3	98.4	7872
Cement	150 kg/m ³	1	7	147.6	11648
Cement	150 kg/m ³	1	14	168.3	13464
Cement	150 kg/m ³	1	28	196.8	16588
Cement	200 kg/m ³	1	3	111.4	8912
Cement	200 kg/m ³	1	7	195.0	16608
Cement	200 kg/m ³	1	14	222.7	18448
Cement	200 kg/m ³	1	28	247.4	22032
Cement	250 kg/m ³	1	3	142.0	11360
Cement	250 kg/m ³	1	7	213.0	17936
Cement	250 kg/m ³	1	14	232.9	19616
Cement	250 kg/m ³	1	28	284.0	25120

Table 5: Unconfined Compression Test Results for Clay Treated with Quicklime Samples.

Binder	Binder quantity	Water lime ratio	Curing time	S_u (kPa)	Young's Modulus (kPa)
Quicklime	150 kg/m ³	1	3	22.5	2007
Quicklime	150 kg/m ³	1	7	33.8	2970
Quicklime	150 kg/m ³	1	14	39.6	3433
Quicklime	150 kg/m ³	1	28	45.0	4230
Quicklime	200 kg/m ³	1	3	34.2	2273
Quicklime	200 kg/m ³	1	7	40.8	4235
Quicklime	200 kg/m ³	1	14	48.8	4704
Quicklime	200 kg/m ³	1	28	51.0	5618
Quicklime	250 kg/m ³	1	3	43.0	2897
Quicklime	250 kg/m ³	1	7	58.9	4574
Quicklime	250 kg/m ³	1	14	61.0	5002
Quicklime	250 kg/m ³	1	28	71.7	6406

4.2. Small Scale Models For Deep Mixing Method

In order to confirm the findings in (4.1) Trial Mix Samples 1/100 scale testing was performed using simulated field conditions where both end bearing and floating deep mixing columns were employed. These two methods were compared with untreated soft clay soil (origin model). After treatment, all three portions were individually loaded by adding loads placed on each test model. Loads were added in increments over time. Both load and displacement were monitored throughout the testing. End bearing, floating deep mixing columns, and untreated soft clay soil (origin model) were designed to simulate a roadway subjected to 5m of fill. The equivalent load of the roadway is approximately one kPa.

To show the differences between end bearing and floating deep mixing columns, the same cement content of 250 kg/m³ was used in both methods. This phase presents all the steps of small scale laboratory testing which includes the scale factor. The set-up of the untreated soil model, model with end bearing deep mixing columns, model with floating deep mixing columns and test results (Mullins et al., 2015).

4.2.1. Model Scale Factor

In a small-scale modeling, there are some scaling factors for stress, force, dimension, time, and strain. Those are used to obtain the similarity behavior between the model and the full-scale prototype. Different scaling factors are used in scaled modeling depending on the case problem.

Table 6 shows the scaling factors normally implemented in models (Sulaeman et al., 2015), where n is the scale factor.

Table 6: Relations of Small-Scale Laboratory Modeling and Full-Scale Prototype.

Item	Full scale prototype	Small scale model
Linear dimension	1	n
Stress	1	n
Area	1	n ²
Strain	1	1
Force	1	n ³
Time	1	n ²
Settlement	1	n

4.2.2. Models Set-up

The model consists of three steel boxes for untreated soil, treated soil with end bearing deep mixing columns, and treated soil with floating deep mixing columns with dimensions of 60 × 17 × 12cm.

4.2.2.1. Untreated Soft Clay Model

The steel box was filled with soft clay soil; where the soil was placed through four layers of 2cm thick each. Each layer was compacted by jolting table. A sand layer of 3cm thick was placed above the final clay layer to guarantee uniform test loading.

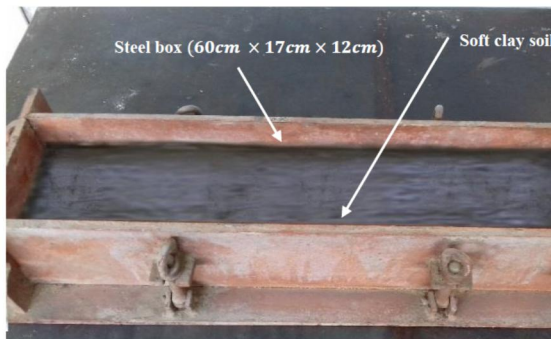


Figure 5 shows the untreated soil model.

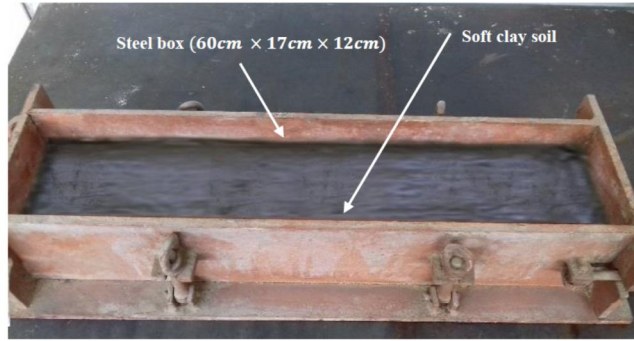


Figure 5: Untreated Soil Model.

4.2.2.2. Model with End Bearing Deep Mixing Columns

The same procedure described in (4.2.2.1) was repeated. After placing the clay layers, end bearing columns were represented as holes of 0.6 cm diameter

spaced every 1.5 cm in two orthogonal directions. The holes were filled with soft clay treated with 250 kg/m^3 cement along the full depth of the clay layer. A sand layer of 3 cm thick was placed above the clay layer to guarantee uniform test loading.

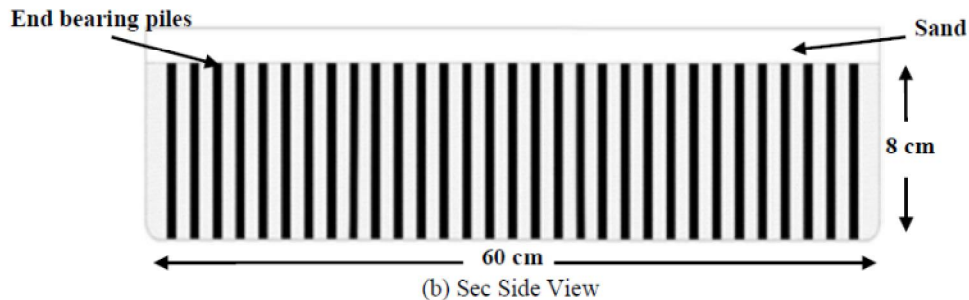
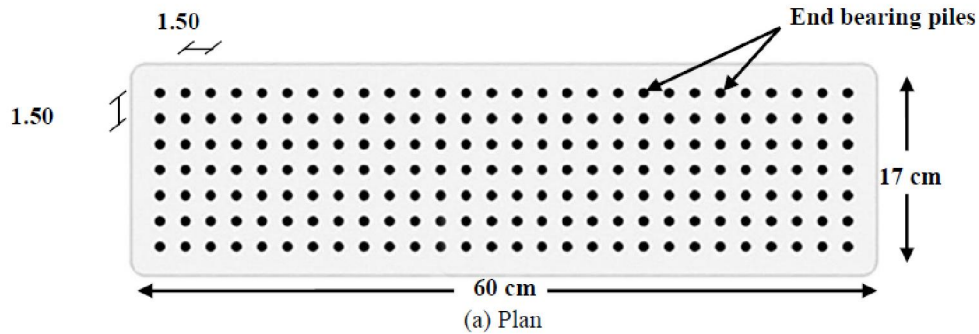
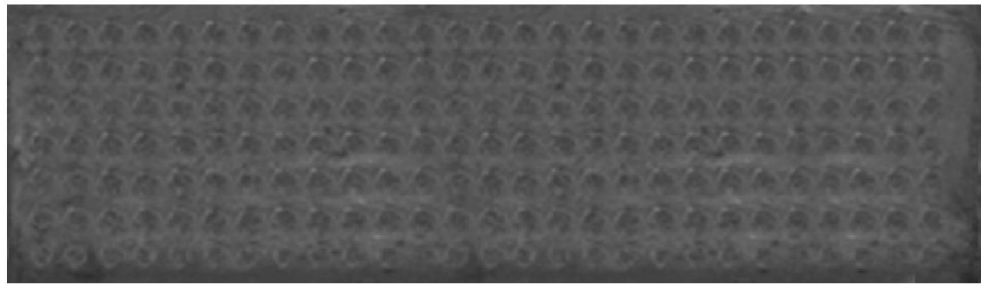


Figure 6: Model with End Bearing Deep Mixing Columns.

4.2.2.3. Model with Floating Deep Mixing Columns

The model with floating deep mixing columns is the same of the model with end bearing deep mixing columns (0), but the holes were filled with soft clay

treated with 250 kg/m³ cement along depth of 5 cm of

the clay layer.

Figure 7 shows the model with floating deep mixing column.

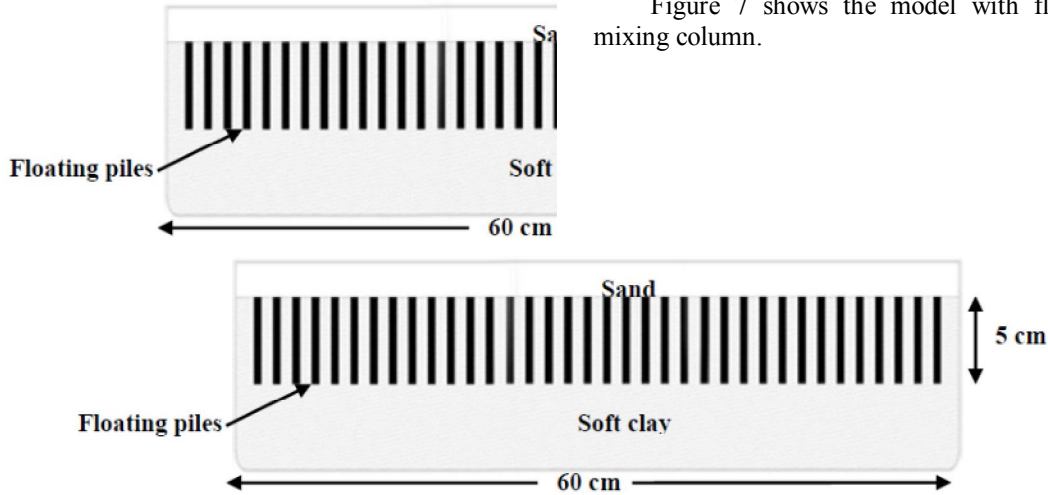


Figure 7: Model with Floating Deep Mixing Columns.

4.2.3. Test Procedure

The test load was applied in four stages. Load increased by 0.25 kPa in each stage of loading over an area of (15×15 cm) until it reach 1.0 kPa at the end of the test. Each load increment applied until the settlement stopped. During the initial load increment, the settlement readings recorded at 0, 1, 15, 30, 60,

120, 240, 480, 960,1440, 2880, 4320, 5760, 7200 min until the settlement stopped using mounted dial gauge on the model. The same steps repeated in each load increment.

4.2.4. Test Results

Loading versus settlement is summarized in higher consolidation time where the model with end bearing deep mixing columns has the lower settlement and lower consolidation time.

Table 7 and shown in Figure 8. The figure shows that the untreated soil model has higher settlement and

Table 7: Loading Versus Settlement.

Load (kPa)	Untreated model		End bearing model		Floating model	
	Settlement (mm)	Time (day)	Settlement (mm)	Time (day)	Settlement (mm)	Time (day)
0.25	4.4	5	2	5	0.99	5
0.50	7.38	10	3.36	10	1.66	10
0.75	10.4	15	4.73	15	2.34	15
1.00	13.28	20	6.04	20	3	20

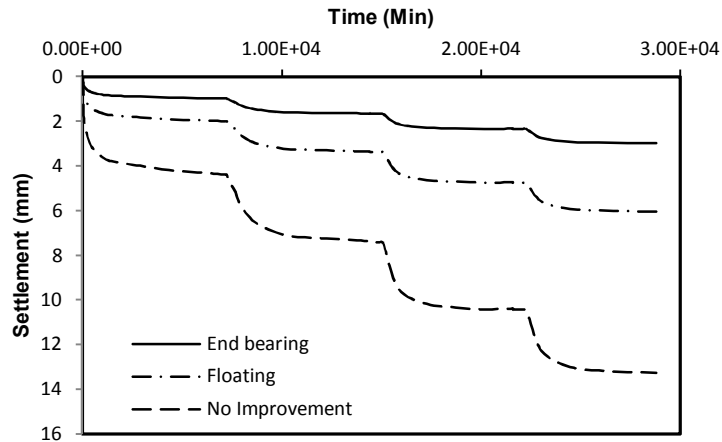


Figure 8: Loading Versus Settlement Curve

5. Verification Of Results Using Finite Element Method

To verify using the finite element method in deep mixing method, untreated soft clay soil, improved soil by 5 cm long cement piles at 1.5 cm spacing (square pattern), and improved soil by 8 cm long cement piles at 1.5 cm spacing (square pattern) were modeled by (2D) finite element method in the plane strain case. In order to use (2D) finite element method; cement piles must be converted into a continuous wall having the same area replacement ratio (Bergado et al., 1999). For cement piles of 0.6 cm diameter at a spacing of 1.5 cm, the continuous-wall thickness in the plane strain case was 0.19 cm due to the following equation.

$$b = a_{pile}/s$$

Where:

b: The continuous wall thickness.

a_{pile} : Pile area.

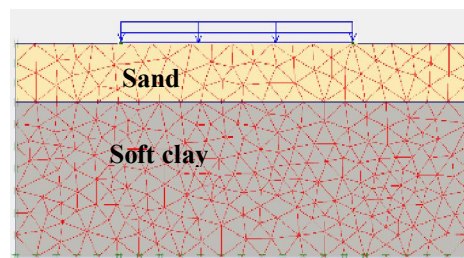
s : Pile spacing.

The Soft Soil Creep Model (SSCM) was used to simulate the soft clay soil. The Mohr-Coulomb Model (MC) was used to simulate the sand. The Linear Elastic Model (LE) was used to simulate the cement piles (Bergado et al., 1999). Table 8 lists the soil parameters used in the model, with dimensions of 60 cm width and 11 cm depth. Stresses of 0.25, 0.5, 0.75 and 1.0 kPa are used; respectively with loaded width of 15 cm. Figure 9 shows the finite element mesh for each model.

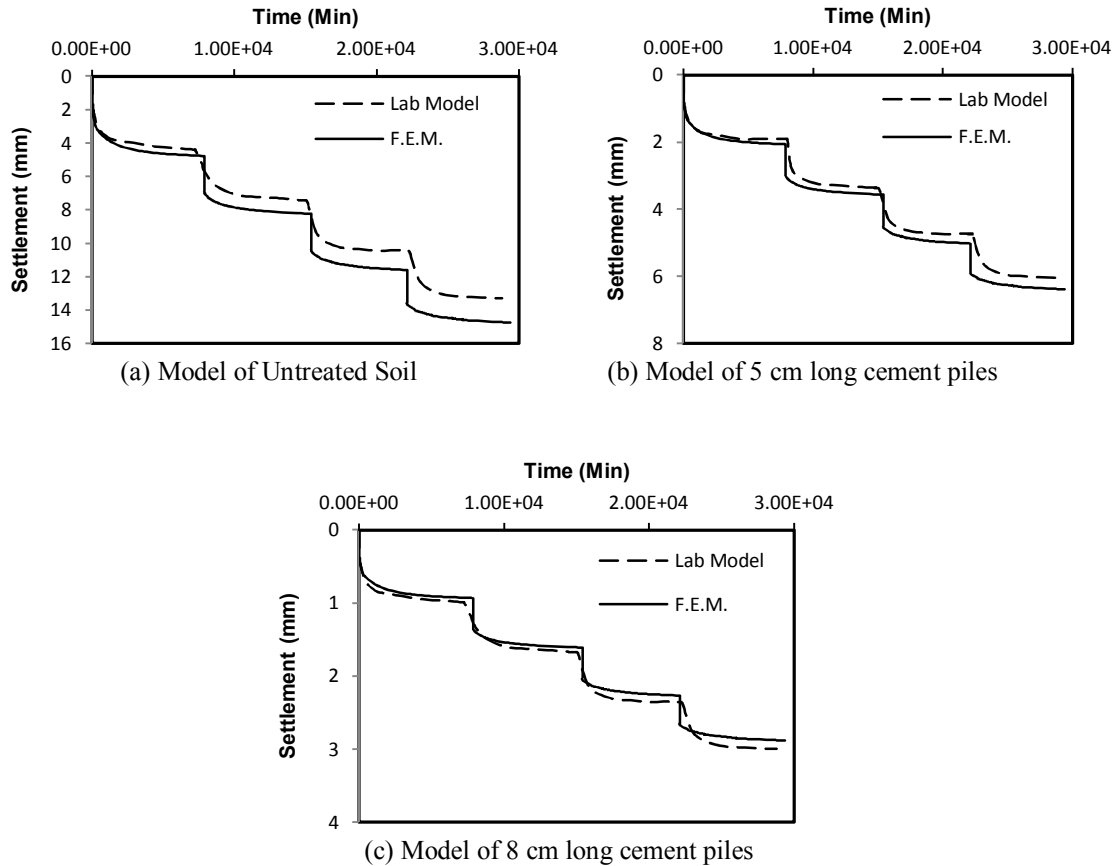
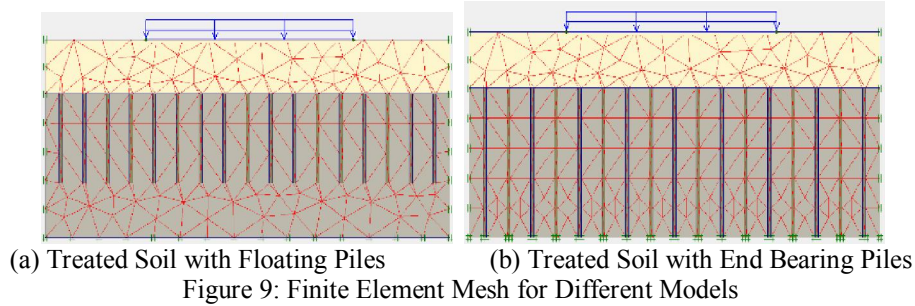
Results of settlement with time calculated from the numerical modeling compared with the corresponding measured data from the physical models (case of untreated soil, 5cm long cement piles, and 8cm long cement piles); respectively, as illustrated in Figure 10. The figure shows that the results are in good agreement.

Table 8: Parameters of Soil Used in Finite Element.

Parameter	Sand	Clay	Cement pile
Depth (m)	0-3	3-11	3-11
Material Model	MC	SSCM	LE
γ (kN/m ³)	17	16.4	17.8
e_o	0.5	1.917	-
E_{50}^{ref} (MPa)	20	-	25
ν (nu)	-	-	0.33
λ^*	-	0.103	-
k^*	-	0.029	-
μ^*	-	1.94 E-03	-
c' (kN/m ²)	0.0	1.0	-
ϕ' (°)	29.0	22.0	-
k_x (m/day)	2.35	2.23E-05	1.24E-05
k_y (m/day)	2.35	1.12E-05	6.2E-06



(a) Untreated Soil



6. Numerical Parametric Study Of Using Dmm In Port Said Clay

Finite element analysis was carried out to show the comparison between the performance of the soil with and without deep and shallow mixing, the effect of binder type, binder content, pile depth, spacing, diameter, pile type, embankment width, and soil

compression index as shown in Table 9. Embankment of 4m high on soft ground improved by cement piles (square pattern) was modeled by finite-element method (FEM) in the plane strain case. Soil depth of 55m is used in this study. Ground water table is 3m depth. The parameters of the soil and the parameters of the piles are shown in Table 10 and Table 11

Table 9: Parametric Study Program

Binder Type	Binder (kg/m ³)	Content	Pile Depth (m)	Pile Spacing (m)	Pile Diameter	Stabilization Method
Cement, Quicklime	250	40	1.5	0.6		Deep Mixing
Cement	150, 200, 250	40	1.5	0.6		Deep Mixing

Cement	250	20, 30, 40	1.5	0.6	Deep Mixing
Cement	250	40	1.5, 2.0, 2.5	0.6	Deep Mixing
Cement	250	40	2.5	0.6, 0.8, 1.0	Deep Mixing
Cement	250	40	1.5	0.6	Deep Mixing

Table 10: Port Said Soil Parameters Used in PLAXIS 2D

Parameter	Fill & Sand	Clay 1	Clay 2	Clay 3	Clay 4	Sand
Depth (m)	0-3	3-15	15-25	25-35	35-51	51-55
Material Model	MC	SSCM	SSCM	SSCM	SSCM	MC
γ (kN/m ³)	17	16.7	15.9	15.8	15.7	18
e_o	0.5	1.64	1.90	2.01	2.03	0.5
E_{50} (MPa)	20	-	-	-	-	30
λ^*	-	0.084	0.118	0.114	0.111	-
k^*	-	0.031	0.026	0.028	0.032	-
μ^*	-	0.0009	0.0015	0.0019	0.0021	-
c' (kN/m ²)	0.0	1.0	1.0	1.0	1.0	0.0
ϕ' (°)	29.0	22.0	22.0	22.0	22.0	35.0
k_x (m/day)	4.70	4.62E-5	3.63E-5	3.23E-5	2.69E-5	4.70
k_y (m/day)	2.35	2.31E-5	1.81E-5	1.63E-5	1.34E-5	2.35
K_o	0.52	0.557	0.691	0.752	0.779	0.43

Table 11: Deep Mixing Piles Parameters Used in PLAXIS 2D

Parameter	Pile (150 kg cement)	Pile (200 kg cement)	Pile (250 kg cement)	Pile (250 kg Quicklime)
Depth (m)	0-40	0-40	0-40	0-40
Material Model	LE	LE	LE	LE
Υ (kN/m ³)	17.5	17.6	17.8	17.65
E_{50} (MPa)	16.5	22	25	6.5
ν (nu)	0.33	0.33	0.33	0.2
k_x	1.47E-5	1.35E-5	1.24E-5	1.42E-5
k_y	7.3E-6	6.7E-6	6.2E-6	6.9E-6

6.1. Effect of Binder type

Effect of binder type has been studied using a binder content of 250 kg/m³, 40 m pile depth, 1.5m pile spacing, 0.6m pile diameter, and two different binder types (quicklime and cement). The embankment width is 24m. The equivalent continuous wall width in the plain strain case was 0.19m. The FEM mesh of soil treated with deep mixing is shown in Figure 11. Final settlements measured by this model

at the crest center of embankment are 1.43, 0.73, and 0.34 m for untreated soil, treated soil with quicklime and treated soil with cement, respectively as presented in Figure 12. Settlement reduction factors are 0.48, and 0.76 for treated soil with quicklime and treated soil with cement, respectively. Figure 13 shows the deformed meshes for 4m high embankment on untreated soil and on treated soil with various binder types.

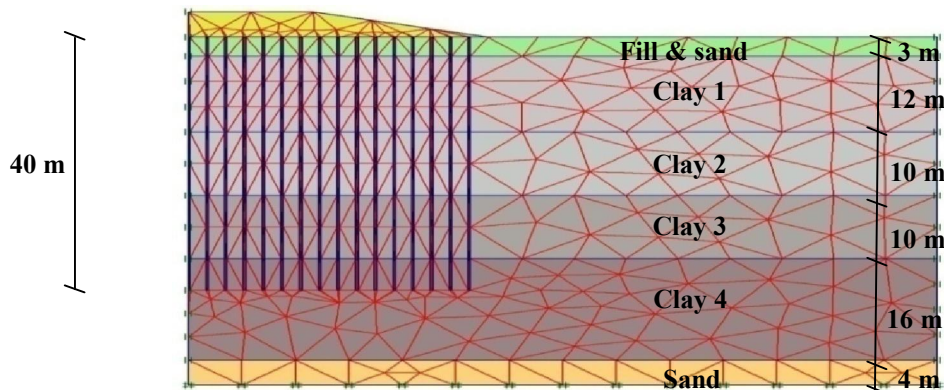


Figure 11: The FEM Mesh of Deep Mixing Method.

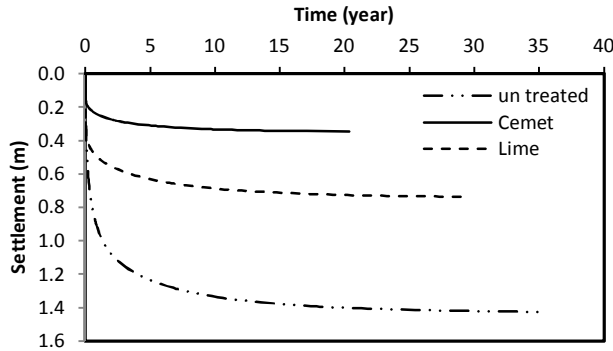
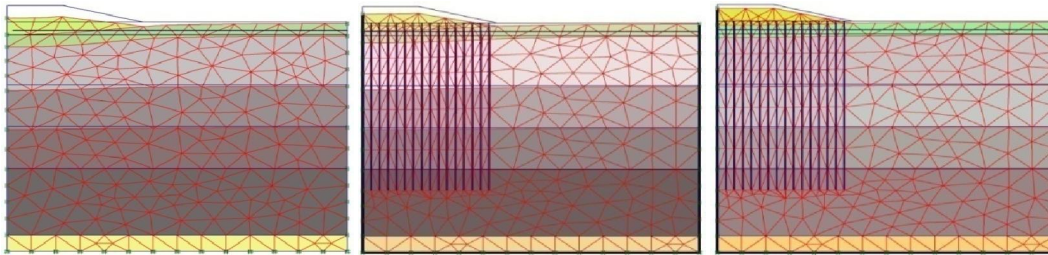


Figure 12: Settlement-Time Relationship for Deep Mixing at Various Binder Types.



(a) Untreated Soil (Max Settlement = 1.43m) (b) Treated Soil with Quicklime (Max Settlement = 0.73m) (c) Treated Soil with Cement (Max Settlement = 0.34m)

Figure 13: The Deformed Meshes of 4m High Embankment for at Various Binder Types.

6.2. Effect of Binder (Cement) Content

Effect of binder content was studied using cement piles with 40m pile depth, 1.5m pile spacing, 0.6m pile diameter, and three different cement contents of 150, 200, and 250 kg/m³. The embankment width is 24m. Final settlements measured by this model at the crest center of embankment are 1.43, 0.43, 0.38, and 0.34 m for untreated soil, treated soil with cement content of 150, 200, and 250 kg/m³, respectively as shown in

Figure 14:	Figure 15:
Settlement-Time Relationship at Various Cement Contents	Settlement-Time Relationship at Various Pile Depths

. Settlement reduction factors are 0.70, 0.73, and 0.76 for treated soil with 150, 200, and 250 kg/m³ cement content, respectively.

6.3. Effect of Pile Depth

Effect of pile depth was studied using cement piles with 250 kg/m³ cement content, 1.5m pile spacing, 0.6m pile diameter, and three different pile depths 20, 30, and 40 m. The embankment width is 24m. The equivalent continuous wall width in the plain strain case was 0.19m. Final settlements

measured by this model at the crest center of embankment are 1.43, 0.74, 0.52 and 0.34m for untreated soil, treated soil with 20, 30, and 40 m pile depth, respectively as presented in. Settlement reduction factors are 0.48, 0.64, and 0.76 for treated soil with 20, 30, and 40m pile depth, respectively.

6.4. Effect of Pile Spacing

Effect of pile spacing was studied using cement piles with 250 kg/m³ cement content, 40m pile depth, 0.6m pile diameter, and three different pile spacing 1.5, 2, and 2.5m. Embankment width is 24m. Final settlements measured by this model at the crest center of embankment are 1.43, 0.34, 0.46, and 0.59m for untreated soil, treated soil with 1.5, 2, and 2.5m pile spacing, respectively as presented in

Figure 15:	Figure 16:
Settlement-Time Relationship at Various Pile Spacing	Settlement-Time Relationship at Various Pile Diameters

. Settlement reduction factors are 0.76, 0.67, and 0.58 for treated soil with 1.5, 2, and 2.5m pile spacing, respectively.

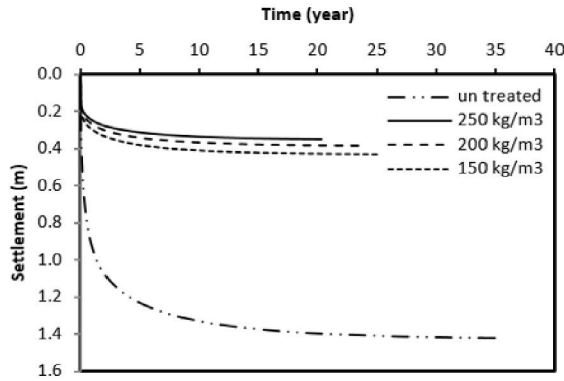


Figure 14: Settlement-Time Relationship at Various Cement Contents

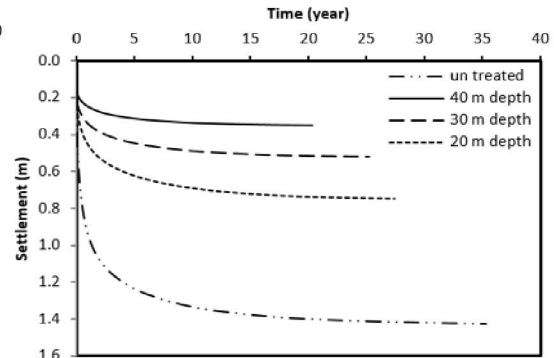


Figure 15: Settlement-Time Relationship at Various Pile Depths

6.5. Effect of Pile Diameter

Effect of pile diameter was studied using cement piles with 250 kg/m^3 cement content, 40m pile depth, 2.5m pile spacing, and three different pile diameters 0.6, 0.8, and 1m. The embankment width is 24m. Final settlements measured by this model at the crest center

of embankment are 1.43, 0.59, 0.44, and 0.36 m for untreated soil, treated soil with 0.6, 0.8, and 1 m pile diameter, respectively as presented in Figure 16. Settlement reduction factors are 0.58, 0.69, and 0.74 for treated soil with 0.6, 0.8, and 1m pile diameter, respectively.

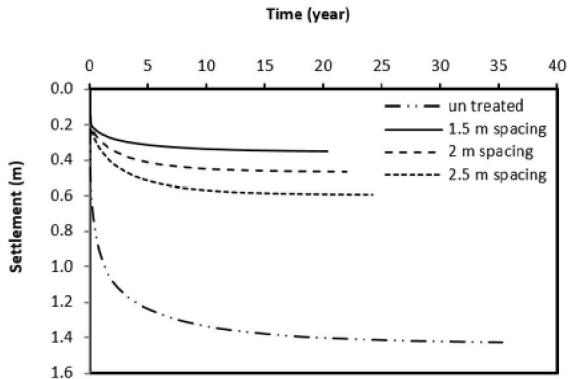


Figure 15: Settlement-Time Relationship at Various Pile Spacing

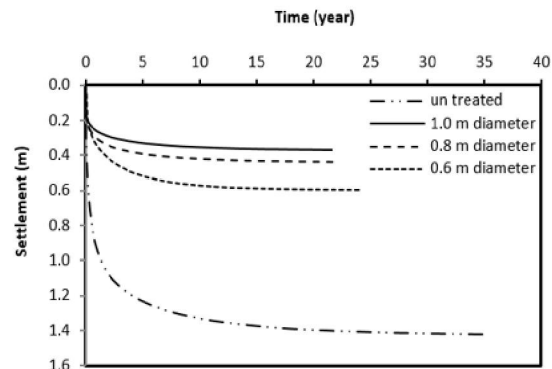


Figure 16: Settlement-Time Relationship at Various Pile Diameters

6.6. Effect of Pile Type

Effect of pile type (floating and end bearing) was studied using cement piles with 250 kg/m^3 cement content, 1.5m pile spacing, 0.6m pile diameter, and two different pile types (floating and end bearing). The embankment width is 24m. Final settlements measured by this model at the crest center of embankment are 1.43, 0.74, and 0.23m for untreated soil, treated soil with floating piles, and end bearing piles, respectively as presented in Figure 17. Settlement reduction factors are 0.48 and 0.84 for treated soil with floating piles and end bearing piles, respectively.

6.7. Effect of Soil Compression Index

Effect of soil compression index was studied using cement piles with 250 kg/m^3 cement content, 40 m pile depth, 2.5m pile spacing, 0.6m pile diameter, and three soil compression indexes (0.69, 0.49, and

0.3). Embankment width is 24m. The equivalent continuous wall width in the plain strain case was 0.19m. Final settlements measured by this model at the crest center of embankment are 1.77, 1.40, 1.09, 0.31, 0.24, and 0.17m for untreated soil of 0.69 compression index, untreated soil of 0.3 compression index, treated soil of 0.69 compression index, treated soil of 0.49 compression index, and treated soil of 0.3 compression index, respectively as presented in Figure 19. Settlement reduction factors are 0.82, 0.83, and 0.84 for treated soil of 0.69 compression index, treated soil of 0.49 compression index, and treated soil of 0.3 compression index, respectively.

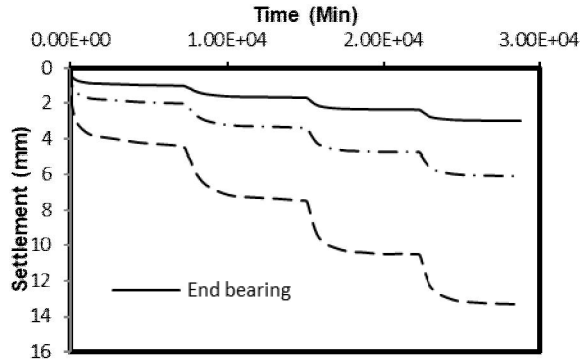


Figure 17: Settlement-Time Relationship at Various Piles Types

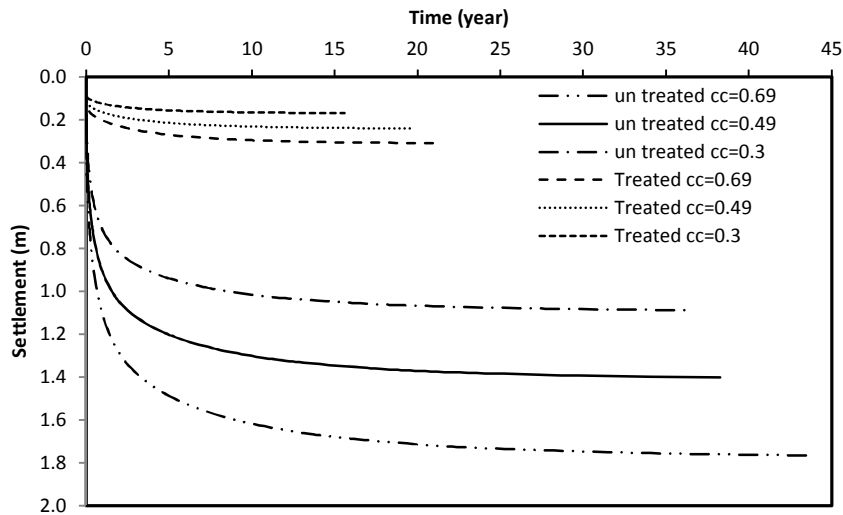


Figure 19: Settlement-Time Relationship for Deep Mixing at Various Soil Compression Indexes.

7. Results

Based on previous results, an equation is predicted for calculating settlement using deep mixing method.

$$\Delta h = \Delta h_1 + \Delta h_2$$

Where:

Δh : Total settlement (m).

Δh_1 : Settlement from the ground surface to the improved depth (m).

Δh_2 : Settlement from the improved depth to bottom of soft soil layer (m).

The settlement Δh_1 is derived as follows;

$$\Delta h_1 = 0.2 \frac{q_1 \times Cc_1 \times L_{col}}{E_{col} \times a_s}$$

Where:

q_1 : Total stress at ground surface = total load / improved area (t/m^2).

Cc_1 : Average soil compression index for improved soil (Bergado et al., 1999).

L_{col} : Column length (m).

E_{col} : Modulus of elasticity of the column (t/m^2).

a_s : Replacement ratio.

The settlement Δh_2 is derived as follows;

$$\Delta h_2 = \frac{Cc_2}{1+e_o} \times H_2 \times \log_{10} \frac{\sigma_{vo}' + q_2}{\sigma_{vo}'} \quad (\text{Miki and Nozu, 2004})$$

Where:

Cc_1 : Average soil compression index for unimproved soil.

e_o : Initial void ratio.

H_2 : Thickness of unimproved layer (m).

σ_{vo}' : The effective overburden pressure (t/m^2).

q_2 : Total stress at the center depth of unimproved depth (t/m^2).

Figure shows the relationship between the calculated values of total settlement from equations and PLAXIS program.

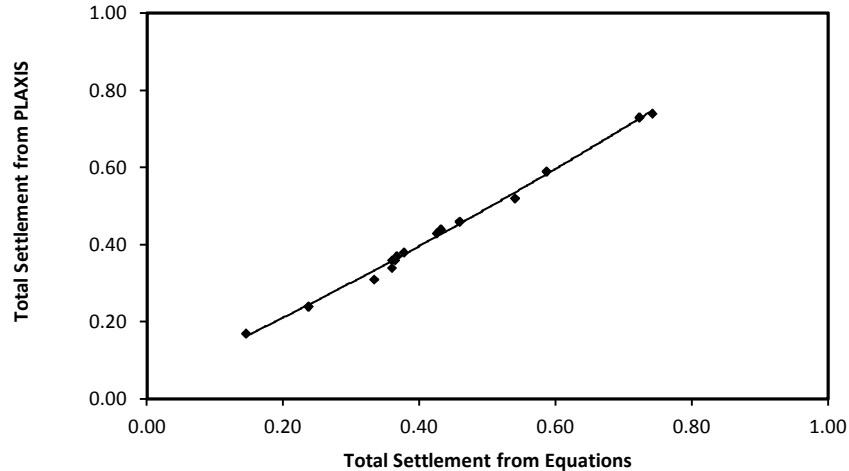


Figure 20: Relationship between Calculated Settlement from Equations and PLAXIS program

8. Conclusion

From the results of laboratory program and numerical modeling, the following conclusions can be drawn.

- Increasing the cement content from 150 to 250kg/m³ improves the unconfined compression strength by 35.5% and decreases settlement of the embankment by 21% after curing time 28 days. One the other hand, increasing the lime content is not efficient to increase the values of the unconfined compression strength.
- Curing time has a significant effect on the unconfined compression strength. Increasing the time from 7 to 28 days increases the strength by 25% at cement content 150 kg/m³.
- The optimum water cement ratio in laboratory mixed samples equals one.
- Settlement of the embankment decreases by 54% when, the pile depth increases from 20 to 40m at cement content 250kg/m³, 1.5m pile spacing and 0.6m pile diameter.
- Pile spacing 1.5m considers a suitable spacing to reduce the value of the embankment settlement. Settlement reduction factor for 1.5m pile spacing equals 0.76 at 250kg/m³ cement content, 40m pile depth.
- Settlement reduction factor increases from 0.58 to 0.74 for pile diameter 0.6m and 1m, respectively at 250kg/m³, 40m pile depth and 2.5m pile spacing.
- End bearing piles are more effective than floating piles in improvement of soft clay.
- Decreasing the compression index from 0.69 to 0.3 decreases the settlement by 45% for treated soil by deep mixing pile.

9. Acknowledgments

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