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Prediction of the Effect of Using Stone Column in Clayey Soil on the Behavior of Circular Footing by ANN Model

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ABSTRACT

Shallow foundations are usually used for structures with light to moderate loads where the soil underneath can carry them. In some cases, soil strength and/or other properties are not adequate and require improvement using one of the ground improvement techniques. Stone column is one of the common improvement techniques in which a column of stone is installed vertically in clayey soils. Stone columns are usually used to increase soil strength and to accelerate soil consolidation by acting as vertical drains. Many researches have been done to estimate the behavior of the improved soil. However, none of them considered the effect of stone column geometry on the behavior of the circular footing. In this research, finite element models have been conducted to evaluate the behavior of a circular footing with different stone column configurations. Moreover, an Artificial Neural Network (ANN) model has been generated for predicting these effects. The results showed a reduction in the bending moment, the settlement, and the vertical stresses with the increment of the stone column length, while both the horizontal stress and the shear force were increased. ANN model showed a good relationship between the predicted and the calculated results.
Key Words: stone column, circular footing, ground improvement, artificial neural network, bending moment, and shear forces.

التنبؤ بتأثير استخدام الاعمدة الحجرية في الترب الطينية على سلوك الاساس الدائري باستخدام نموذج العقد العصبيه الصناعية

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الخلاصة

تستخدم الاسس الضحلة عادة لاسناد المنشآت ذات الاحمال الخفيفة او المتوسطة حيث ان التربة اسفل المنشأ تحمل هذة الاحمال. في بعض الحالات، قوة تحمل التربة و خواص اخرى ممكن ان تكون غير كافية وتحتاج الى تحسين باستخدام احد تقنيات تحسين التربة. تعتبر الاعمدة الحجرية واحدة من طرق تحسين التربة الشائعة حيث يتم تثبيت عمود من الحجر بشكل عمودي في التربة الطينية.

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تستخدم الاعمدة الحجرية لزيادة قابلية تحمل التربة الطينية ولزيادة الانضمام فيها حيث تعمل الاعمدة الحجرية كانابيب تصريف عمودية. هنالك الكثير من الدراسات لاحتساب سلوك التربة بعد التحسين ولكن لا توجد بحوث تاخذ بنظر الاعتبار تاثير وجود الاعمدة الحجرية على تصرف الاساس. في هذا البحث، تم بناء موديلات باستخدام طريقة العناصر المحددة لدراسة سلوك الاسس الدائرية المسندة على الترب الطينية المحسنة بمجاميع مختلفة من الاعمدة الحجرية. أضاقة لذلك تم عمل نموذج من الشبكات العصبية الصناعية لتوقع تأثير الاعمدة الحجرية على تصرف الاسس الدائرية. اظهرت النتائج نقصان في عزم الانحناء والهطول للاساس والاجهادات العمودية في التربة عند زيادة عمق الاعمدة الحجرية بينما كانت هنالك زيادة في الاجهادات الافقية للتربة وقوى القص في الاساس. كما اظهرت نماذج الشبكات العصبية تقارب جيد بين النتائج المتوقعه والنتائج المستحصلة.

الكلمات الرئيسية: الاعمدة الحجرية، الاساس الدائري، تحسين التربة، الشبكات العصبيه الصناعية، عزم الانحناء و قوى القص.

1. INTRODUCTION

Stone column method can be considered as a common and economical ground improvement technique that usually used to improve the strength and the consolidation of clayey soil. Also, this technique can be applied to the construction of various types of structure like oil tanks, embankments, and mat foundations, **Beena, 2010**. **Fattah, et al., 2016**, have conducted experiments to study the behavior of an embankment rests on ordinary stone columns. Furthermore, they have studied the effect of the stone column encasement and compared it to the ordinary stone columns. The results showed that the ratio of improvement increased when the stone column spacing reached a value of two and a half times the diameter of the stone column. The effect of the spacing between the stone columns on the height of the embankment rests on has been studied recently, **Fattah, et al., 2015**. The results showed that as the spacing of the stone column increased, the probability of stone column arching increased.

According to **Som and Das, 2003**, using a poker vibrator with a diameter of (300-500) mm can provide a stone column diameter of (600-900) mm. However, **Nayak, 1982**, showed that the diameter of the stone column is greater than the poker diameter by (20-25) %. A relationship between the diameter of the vibrator and the diameter of the stone column depending on the shear strength of the soil has been developed by him as shown in **Fig. 1**. **Greenwood, 1970,** showed that the spacing between stone columns affects the settlement improvement ratio of the treated soil to the untreated soil. He suggested the use of stone column spacing to diameter ratio of 2.5 up to 4. In addition, **Varghese, 2012,** suggested that the stone column arrangement should be extended for at least 2 m beyond the loaded area. He also recommended that the depth of a stone column should be equal or greater than six times the stone column diameter in order to prevent the direct penetration of the stone column through the soil.

Artificial Neural Network can be defined as a computerized system that had been built to simulate the neural network in the human. Throughout the last years, Artificial Neural Networks (ANNs) have been solved with a good degree of success many geotechnical problems such as prediction of pile capacity, modeling the behavior of soil, and stability of slopes, **Shahin, et al., 2001**.

In this research, a circular water tank with a diameter of $20\,m$ and a height of $10\,m$ has been considered as the superstructure that rests on a clayey soil which will be improved by different stone column configurations. The effect of using stone column on the bending moment, the shear forces, and the settlement of the circular footing has been studied in this research. Furthermore, an ANN model has been generated using IBM SPSS software to predict the effect of the stone column configurations on the behavior of the circular footing.

2. FINITE ELEMENT MODELING

Finite Element method has been adopted to simulate the circular footing and the soil underneath using the Plaxis2D software as shown in the **Fig. 2.**

2.1 Geometry and Elements

An axisymmetric model has been conducted for each case study to simulate the circular footing and the soil underneath. A linear elastic behavior has been adopted to simulate the circular footing, while Mohr-Coulomb model has been used to simulate the behavior of the soil and the stone column. The simulation of the soil mass has been bounded to a width of two times the diameter of the circular footing and a depth of four times the diameter of the circular footing where more than 90% of the vertical stresses is dissipated, **Lambe and Whitman, 1969**. Boundary conditions have been selected to be roller along the soil mass sides and hinged along the soil mass base to simulate the behavior of the surrounding soil**, Al-Hity, 2007**. Stone column diameter, depth, and spacing have been changed for each case study.

2.2 Material Properties

The concrete has been modeled as a linear isotropic material. The compressive strength of the concrete has been assumed to be 28 MPa and a value of 0.2 has been used for Poisson ratio as recommended by **Nilson, et al., 2010**. According to **ACI 318, 2008**, the modulus of elasticity of the concrete has been calculated based on the concrete compressive strength using Eq. (1). While the shear modulus has been calculated based on Eq. (2), **Popov, 1968.**

$$E = 4700 \times \sqrt{f_c'} \tag{1}$$

$$G = \frac{E}{2 \times (1 + \nu)} \tag{2}$$

The material properties of the clayey soil and the stone column have been adopted from **Al-Shammarie, 2013** and **Karim, et al., 2009**. The adopted properties are presented in **Table 1** and represent the properties of the local materials.

2.3 Applied Loads

Loads have been distributed uniformly on the circular tank base to simulate the water pressure on the footing. The weight of tank walls has not been simulated in the model because it is negligible when compared to the water pressure.

3. CASE STUDIES AND RESULTS

As mentioned in the introduction, the geometry of stone column can be related to its diameter. Based on this the adopted stone column diameters were 600 mm up to 1000 mm with an increment of 200 mm. The depth of the stone column has been changed from 6 to 8 times the diameter of the stone column with an increment of 2 times the stone column diameter. Moreover, the spacing between the stone columns has been ranged from 2.5 up to 3.5 times the diameter of the stone column with an increment of 0.5 times the diameter of the stone column. The properties of the stone column, the clayey soil, and the footing have been maintained the same for all case studies.

A circular footing with a diameter of $20m$ and a thickness of 400 mmm has been adopted in all cases. Also, a uniform load of 100 kN/m^2 has been applied for all the cases.
Referring to **Fig. 2**, the different parameters of case studies and the results obtained from the finite element models have been listed **Table 2**.

4. ANN MODEL

4.1 Data Standardization

In order to generate an accurate ANN model, the stone column parameters stated in **Table 2** have been normalized to be related to the stone column diameter of 600 mm. Furthermore, the maximum bending moment and shear force in the footing, the settlement of the footing, and the maximum vertical and horizontal stress generated in the soil listed in **Table 2** have been normalized to those obtained from the first case study where no stone column has been used. The normalized data are shown in **Table 3**.
In addition to the normalization of the data, standardization has been done for them using Eq. (3) shown below:

$$\boldsymbol{x}^* = \frac{\boldsymbol{x}' - \overline{\boldsymbol{x}}}{\boldsymbol{\sigma}} \quad (\mathbf{3})$$

4.2 Model Generation

Based on the standardized data, an ANN model has been generated using (IBM SPSS) software. A single hidden layer has been adopted in the generation of this mode (shown in **Fig. 3**). The hyperbolic tangent function has been used within the hidden layer, while identity function has been used for the output layer. The modeling process can be made using Eq. (4). 65% of the data has been selected randomly the training of the model while 25% of the remaining data has been selected randomly for testing the generated model. The remaining 10% of the data has been held out for verification of the final ANN model.

$$\begin{Bmatrix} h_{1,in} \\ h_{2,in} \\ h_{3,in} \end{Bmatrix} = \begin{bmatrix} V_{1,1} & V_{1,2} & V_{1,3} \\ V_{2,1} & V_{2,2} & V_{2,3} \\ V_{3,1} & V_{3,2} & V_{3,3} \end{bmatrix} \times \begin{Bmatrix} D^* \\ S^* \\ L^* \end{Bmatrix} + \begin{Bmatrix} B_{in1} \\ B_{in2} \\ B_{in3} \end{Bmatrix} \quad \text{Eq (4, a)}$$

$$\begin{Bmatrix} h_{1,act} \\ h_{2,act} \\ h_{3,act} \end{Bmatrix} = \begin{Bmatrix} \dfrac{2}{1 + e^{(-2\times h_{1,in})}} - 1 \\ \dfrac{2}{1 + e^{(-2\times h_{2,in})}} - 1 \\ \dfrac{2}{1 + e^{(-2\times h_{3,in})}} - 1 \end{Bmatrix} \quad \text{Eq (4, b)}$$

$$\{Y_{in}\} = [W_{1,1} \quad W_{1,2} \quad W_{1,3}] \times \begin{Bmatrix} h_{1,act} \\ h_{2,act} \\ h_{3,act} \end{Bmatrix} + \{B_{out}\} \quad \text{Eq (4, c)}$$

$$(Predicted\ value)^* = \{Y_{act}\} = \{Y_{in}\} \qquad \text{Eq}(4,\text{d})$$

The predicted normalized values using this model have been drawn against the calculated normalized values for the bending moment, the shear force, and the settlement of the circular footing as shown in **Figs. 4, 5, and 6**. The important factor and the normalized importance of each independent variable namely (stone column diameter, length, and spacing) have been listed in **Table 4**.

5. CONCLUSIONS

Based on the results obtained from the PLAXIS software **Table 2,** the ANN model **Figs. 4, 5, and 6**, and the important factors for the independent variables **Table 4,** the following conclusions can be made:

- The use of stone column can reduce the bending moment and the settlement of the footing and the vertical stresses of the soil. However, it causes an increment in the shear forces in the footing and the horizontal stresses in the soil.
- From a structural engineering perspective, the use of stone column will cause some problem with the footing thickness because it is mainly governed by the shear forces developed in the footing.
- For the same stone column spacing and length, an increase of the stone column diameter will result in a reduction in the bending moment and settlement of the footing and vertical stresses in the soil. While this increment will increase shear forces of the footing and the horizontal stresses in the soil.
- For the same stone column diameter and length, an increase of the stone column spacing will result in a reduction in the vertical and horizontal stresses in the soil. While, this increment will increase the bending moment, shear forces, and settlement of the footing.
- For the same stone column diameter and spacing, an increase of the stone column length will result in a reduction in the bending moment, shear force, and settlement of the footing. Also, it will decrease the horizontal and vertical stresses in the soil.
- ANN model gave a good prediction of the bending moment, shear force, and settlement of the footing with a value of (R^2) equals to 0.721, 0.904, and 0.960 respectively.
- The ANN model showed that the most important factor that had an effect on the results was the length of the stone column. While the stone column spacing had the least effect with a normalized importance around 75%.

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7. NOMENCLATURE

f_c'= the cylindrical compressive strength of concrete, MPa
E= modulus of elasticity, MPa
ν= poisson's ratio
G= shear modulus, MPa
D= the diameter of a stone column, m
S= the spacing of stone column, m
L= the depth of stone column, m
M_{max}= maximum bending moment in the footing, $kN.m$
V_{max}= maximum shear force in the footing, kN
δ_{max}= maximum settlement of the footing, mm
$\sigma_{v_{max}}$= maximum vertical stress in the soil, kN/m^2
$\sigma_{h_{max}}$= maximum horizontal stress in the soil, kN/m^2
D'= normalized value of stone column diameter
S'= normalized value of stone column spacing
L'= normalized value of stone column depth
M'_{max}= normalized value of maximum bending moment in the footing
V'_{max}= normalized value of maximum shear force in the footing
δ'_{max}= normalized value of maximum settlement of the footing
$\sigma'_{v_{max}}$= normalized value of maximum vertical stress in the soil
$\sigma'_{h_{max}}$= normalized value of maximum horizontal stress in the soil
x^*= standardized value
σ= the standard deviation of the value that will be standardized
$\bar{x}$= mean of the value that will be standardized
$\{h_{in}\}$= the vector of hidden layer units
$[V_{matrix}]$= synaptic weights for input layer
$[B_{in}]$= bias vector for input layer
$\{h_{act}\}$= the vector of hidden layer activated units
$[W_{matrix}]$= synaptic weights for the hidden layer
$[B_{out}]$= bias vector for the hidden layer
$\{Y_{in}\}$= the vector of output layer units
$\{Y_{act}\}$= the vector of output layer activated units

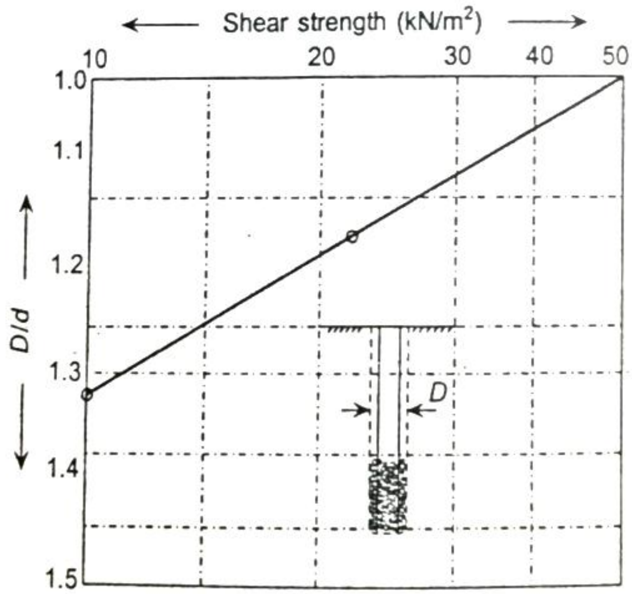

Figure 1. Soil shear strength vs. stone column diameter, **Nayak, 1982**.

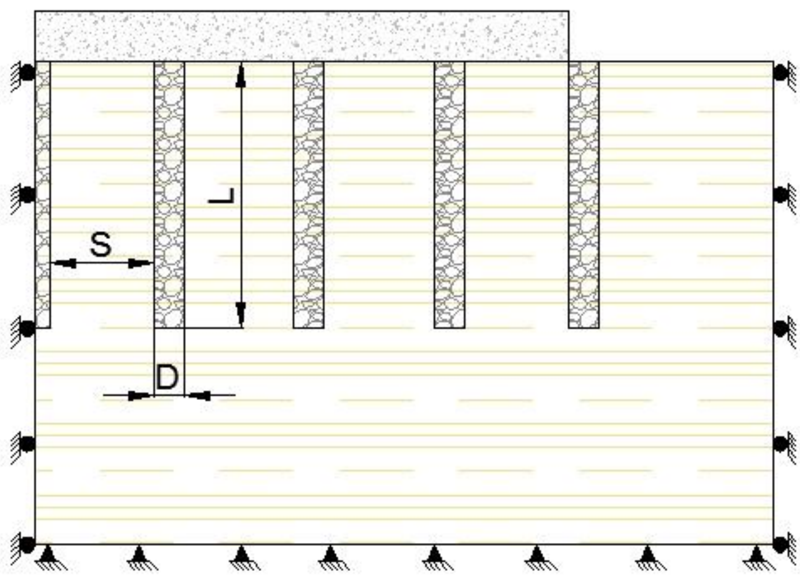

Figure 2. Problem simulation using PLAXIS software.

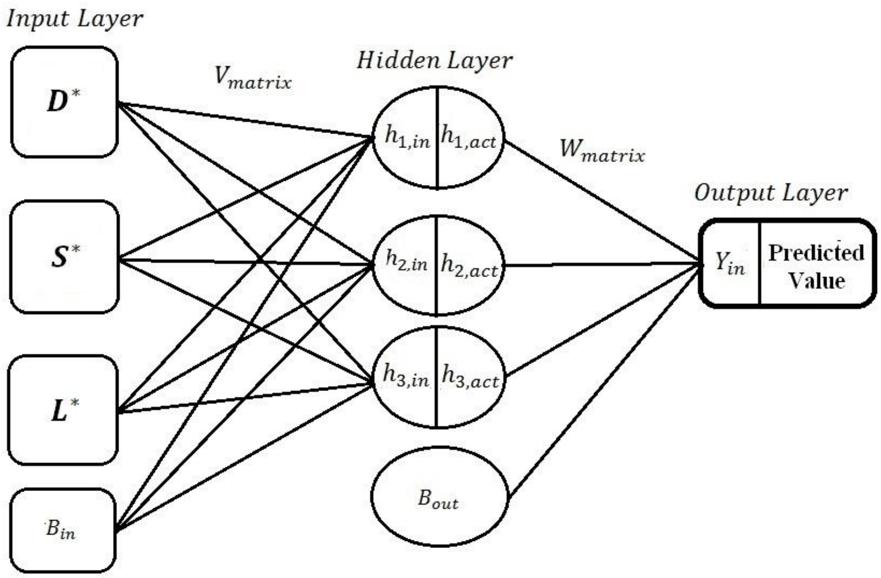

Figure 3. ANN model.

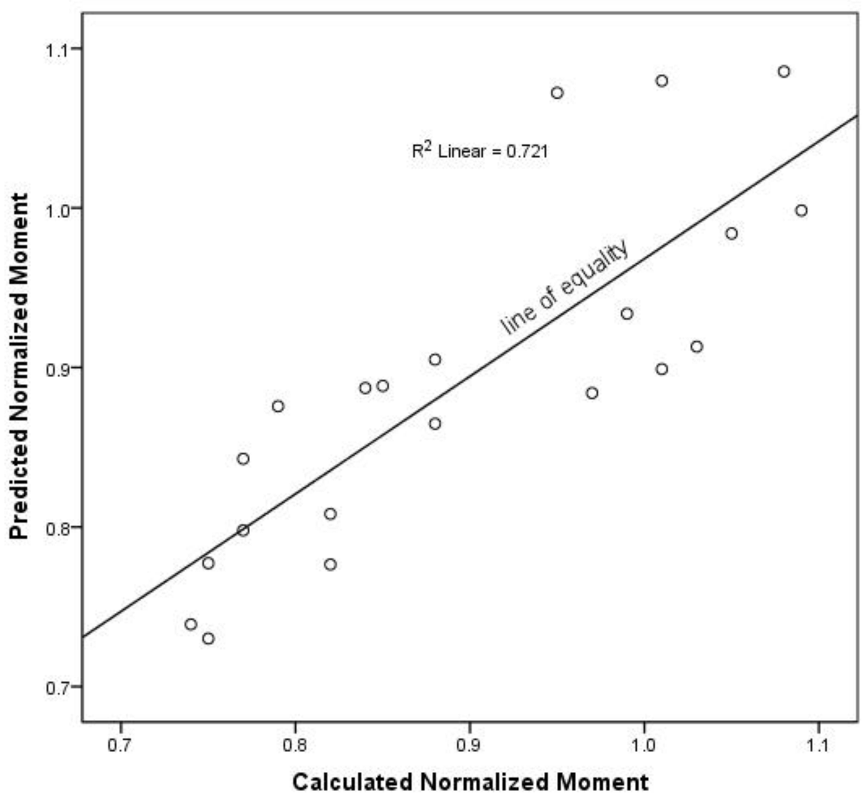

Figure 4. Predicted vs calculated normalized values for bending moment.

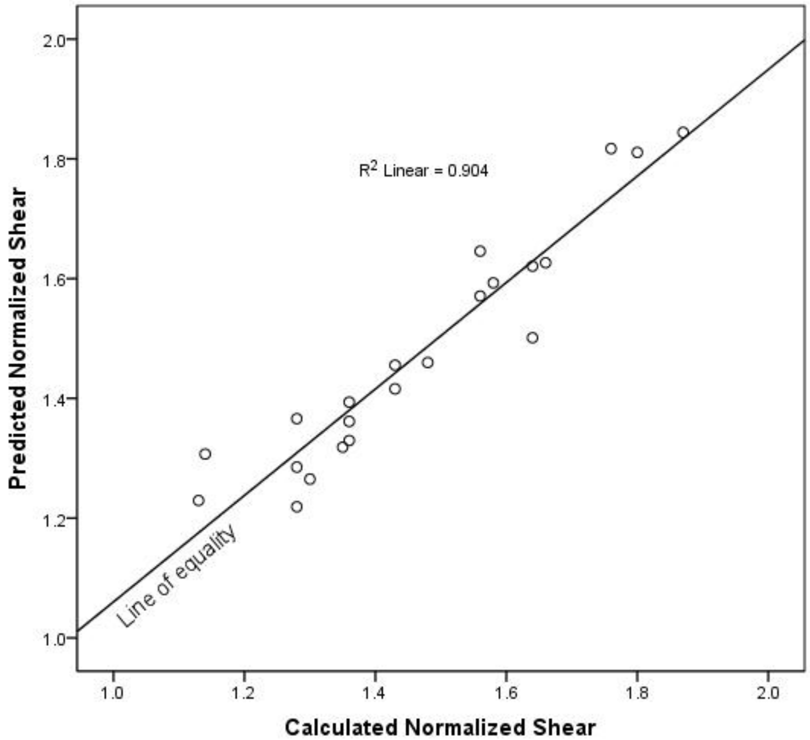

Figure 5. Predicted vs calculated normalized values for shear forces.

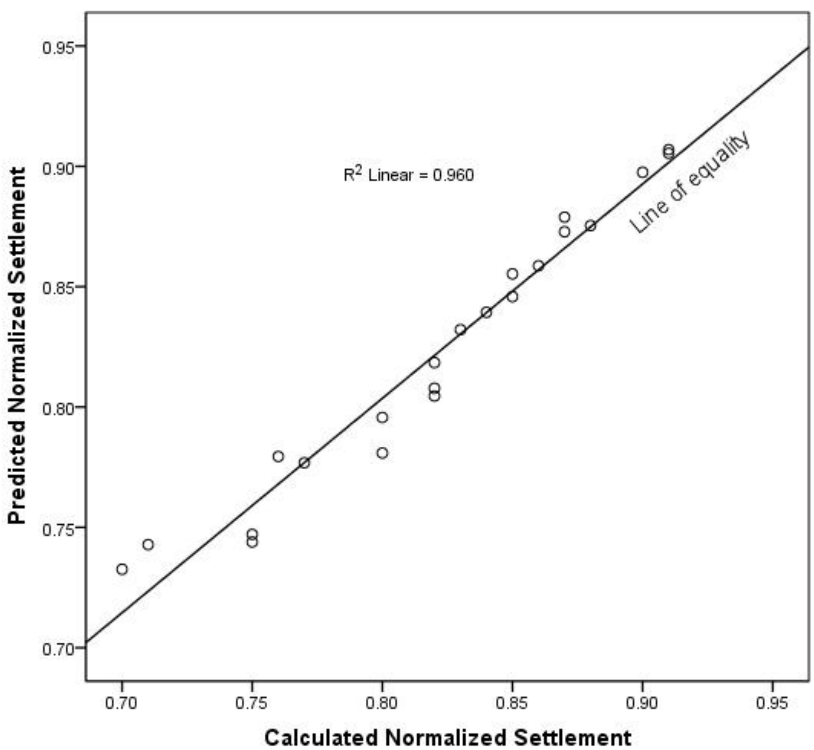

Figure 6. Predicted vs calculated normalized values for settlement.

Table 1. Physical properties of clayey soil and stone column, **Al-Shammarie, 2013**, and **Kariem, et al., 2009**.

Property	**Clayey Soil**	**Stone Column**
Maximum dry unit weight, (kN/m^3)	18.24	15.7
Specific gravity	2.7	2.64
Liquid limit, (%)	47	---
Plastic limit, (%)	23	---
Plasticity Index, (%)	24	---
Coefficient of uniformity	---	1.02
Coefficient of curvature	---	1.05
Modulus of elasticity, (kN/m^2)	3100	45000
Poisson's ratio	0.35	0.2
Undrained shear strength, (kN/m^2)	16	0
Friction angle, $(\emptyset)$	24	45

Table 2. Case Studies and Results.

Case No.	D	S	L	M_{max}	V_{max}	δ_{max}	$\sigma_{v_{max}}$	$\sigma_{h_{max}}$
1	0.0	0.0	0.0	271.3	65.4	359.6	149.7	63.7
2	0.6	1.5	3.6	230.6	83.7	322	120.9	68.1
3	0.6	1.5	4.8	209.3	74.3	308.9	111.9	71.2
4	0.6	1.5	6.0	202.8	74.1	293.2	104	69.3
5	0.6	1.8	3.6	280.4	89	325.5	123.2	98.6
6	0.6	1.8	4.8	273.2	88.5	311.6	109	79.2
7	0.6	1.8	6.0	263.2	83.8	297.3	73.4	82.5
8	0.6	2.1	3.6	239.7	89	328.7	115.5	74
9	0.6	2.1	4.8	226.8	85.3	316.8	118.4	97
10	0.6	2.1	6.0	215.3	83.6	303.7	115.3	102.1
11	0.8	2.0	4.8	239.9	102	306.6	128.1	68.5
12	0.8	2.0	6.4	221.5	93.8	286.9	118.9	64.3
13	0.8	2.0	8.0	204.1	88.8	268.1	117.9	62.5
14	0.8	2.4	4.8	294.7	108.6	313.5	92.9	66.8
15	0.8	2.4	6.4	285.9	107.5	294.1	91.5	66.1
16	0.8	2.4	8.0	267.4	103.6	277.1	92.6	65.3
17	0.8	2.8	4.8	221.2	103.3	317.1	113.6	63.5
18	0.8	2.8	6.4	206.3	98.3	300.8	113.9	62.9
19	0.8	2.8	8.0	191.4	93.6	285	118.4	60.7
20	1.0	2.5	6.0	223	102	293.3	111.6	75.2
21	1.0	2.5	8.0	199.8	96.9	270.7	104.9	70.1
22	1.0	2.5	10.0	182.3	93.3	250.1	125.7	75.6
23	1.0	3.0	6.0	244.4	117.1	297.4	124.3	60
24	1.0	3.0	8.0	225.7	111.3	276.1	120.6	57.3

25	1.0	3.0	10.0	209.3	107.3	256.7	110.1	54.2
26	1.0	3.5	6.0	293.6	122.6	305.9	93.9	74.4
27	1.0	3.5	8.0	273.9	117.7	288.3	71.4	63.9
28	1.0	3.5	10.0	258	114.9	272.2	69.5	60.2

Table 3. Normalized Parameters and Results.

Case No.	D'	S'	L'	M'_{max}	V'_{max}	δ'_{max}	$\sigma'_{v_{max}}$	$\sigma'_{h_{max}}$
1	0	0.0	0.0	1.00	1.00	1.00	1.00	1.00
2	1	2.5	6.0	0.85	1.28	0.90	0.81	1.07
3	1	2.5	8.0	0.77	1.14	0.86	0.75	1.12
4	1	2.5	10.0	0.75	1.13	0.82	0.69	1.09
5	1	3.0	6.0	1.03	1.36	0.91	0.82	1.55
6	1	3.0	8.0	1.01	1.35	0.87	0.73	1.24
7	1	3.0	10.0	0.97	1.28	0.83	0.49	1.30
8	1	3.5	6.0	0.88	1.36	0.91	0.77	1.16
9	1	3.5	8.0	0.84	1.30	0.88	0.79	1.52
10	1	3.5	10.0	0.79	1.28	0.84	0.77	1.60
11	1.33	3.33	8.0	0.88	1.56	0.85	0.86	1.08
12	1.33	3.33	10.67	0.82	1.43	0.80	0.79	1.01
13	1.33	3.33	13.33	0.75	1.36	0.75	0.79	0.98
14	1.33	4.0	8.0	1.09	1.66	0.87	0.62	1.05
15	1.33	4.0	10.67	1.05	1.64	0.82	0.61	1.04
16	1.33	4.0	13.33	0.99	1.58	0.77	0.62	1.03
17	1.33	4.67	8.0	0.82	1.58	0.88	0.76	1.00
18	1.33	4.67	10.67	0.76	1.50	0.84	0.76	0.99
19	1.33	4.67	13.33	0.71	1.43	0.79	0.79	0.95
20	1.67	4.17	10.0	0.82	1.56	0.82	0.75	1.18
21	1.67	4.17	13.33	0.74	1.48	0.75	0.70	1.10
22	1.67	4.17	16.67	0.67	1.43	0.70	0.84	1.19
23	1.67	5.0	10.0	0.90	1.79	0.83	0.83	0.94
24	1.67	5.0	13.33	0.83	1.70	0.77	0.81	0.90
25	1.67	5.0	16.67	0.77	1.64	0.71	0.74	0.85
26	1.67	5.83	10.0	1.08	1.87	0.85	0.63	1.17
27	1.67	5.83	13.33	1.01	1.80	0.80	0.48	1.00
28	1.67	5.83	16.67	0.95	1.76	0.76	0.46	0.95

Table 4. Importance of independent variables.

Independent Variable	Importance	Normalized Importance (%)
D	0.353	95.6
S	0.277	75.1
L	0.369	100