DIFFERENT THEORIES TO PREDICT THE BEARING OF STONE COLUMN USING COMPUTER PROGRAM

Radhi M Alzubaidi*[1] and Jawad Al-Shreafe[2]

[1]*Professor, Department of Civil Engineering, University of Sharjah, Sharjah, UAE, email: ralzubaidi@sharjah.ac.ae*
[2]*MSc students, University of Technology. Bagdad ,Iraq ,drraddi@yahoo.com*

***Corresponding Author**

ABSTRACT

The bearing capacity of stone column prediction is crucial in geotechnical engineering for various construction and foundation projects. Several theoretical approaches and methods can be used to estimate the stone columns bearing capacity**.** These theories were devoted to investigating the main concepts regarding the bearing capacity and settlement of soft clay reinforced with stone columns. A computer program has been developed using quick basic language, that can perform parametric studies affecting the behavior of stone columns through various theorems for prediction yield load and settlement. Each theoretical approach is thoroughly discussed and compared with one practical case study. Parameters like the undrained shear strength of the surrounding soil, the angle of internal friction of the backfill material, geometry, and dimensions are all investigated through each theoretical approach. The analytical results indicated that the cavity expansion theory provided failure loads and settlement predictions that were close to the results observed in the field case study.

Keyword: *stone column; bearing capacity; settlement; soft soils; shear strength*

1. Introduction

The stone column technique is probably the oldest pattern of improving soil, a small hole filled with non-uniform pieces of rocks was found underneath a number of historical ancient structures. These holes were found in Hatra, old Babylon city and Ur (Al-Recaby, M.K 1999). Das and Dey (2018) predicted the bearing capacity using the Artificial neural network (ANN), in their study, 90 pieces of data were obtained from other published studies to create an Artificial Neural Network (ANN) model. Several coefficients, such as the undrained strength loke clay cohesion, angle of internal friction the stone column material, ratio of spacing to diameter of the stone columns, length of the stone column, and number of the stone columns, were considered as input data to predict the stone column bearing capacity. The explored values of bearing capacity showed good agreement with those from laboratory tests. In 2015, Etezad et al. modified a solution to explore the soft clay-bearing capacity reinforced with stone columns under a rigid raft foundation, considering a general shear failure mechanism. The predicted bearing capacity results were validated for both the case of footings on homogeneous soil and through comparison with laboratory and numerical results available in previously studied cases. Nazariafshar et al. (2019) investigated the bearing capacity of a group of floating stone columns with granular blankets, the results were deduced through laboratory tests. They utilized geotextiles and geogrids for the reinforcement of the stone columns and blankets, respectively. The results of their study explore that the simultaneous application of a group of stone columns and granular blankets distinctively increased the ultimate bearing capacity of soft clays. Ng (2018) explored the load-bearing capacity of a single stone column through three-dimensional numerical analysis. Throughout the study, different failure modes were considered, and the impact of crucial parameters such as the column's friction angle, undrained shear strength of the adjacent soil, and modular ratio were investigated. The resulting findings suggested that the ultimate bearing capacity is predominantly affected by the column's friction angle and the undrained shear strength of the surrounding soil. Fattah et al (2017) developed a common analysis by conducting a statistical solution using the statistical package for the social science software (SPSS) for a case study and some previous studies. The results showed that the most controlling parameter in the proposed equation is the area replacement ratio. The results of bearing capacity increase considerably with the increase of the area replacement ratio. In the research by Kardgar (2018), the PLAXIS finite element software was utilized to simulate the impact of incorporating stone columns on the load-bearing capacity of soft clay. The results underscored the noteworthy importance of both the length of the stone columns and the rigidity of their encasement. These factors emerged as crucial and warrant thorough consideration in the all-encompassing analysis and design of the soil-structure system. The study conducted by Mahawish et al. (2018), urea hydrolysis was employed as a bio-grouting process to enhance the strength of crushed aggregates typically utilized in stone columns. The bio-grouting process involved different phases of reagents, wherein solutions containing bacterial suspension and cementation alternately percolated through the soil column. The findings revealed a notable improvement in the strength of the crushed aggregates. Moayyeri et al. (2018) examined the influence of adding lime and silica fume on their mechanical properties when combined with water. Gypsiferous soil samples were mixed with different percentages of lime and silica fume. They concluded, when adding these additives, distinctive increase in the results of the unconfined compressive strength as compared with untreated samples. Sujatha et al (2018) used coconut coir and lime to improve the soil properties, they concluded that adding lime and coconut to soil showed increase in the compressive strength as compared with soils that not treated. Kim et al (2018) presented the results weathered soil stabilized with ground bottom ash and red mud. The results revealed that there is a distinctive increase in the compressive strength of the stabilized soil after curing for 28 days and that the soil mixture with ground bottom ash and red mud proved environmentally safe.

2. METHOD OF ANALYSISSTONE COLUMS

There are many available theories and methods to solve and analysis the foundation stone-columns system, details of each approach are stated as below,

2.1 Passive Pressure Theory

Greenwood (1970), used Bell's theory (1915) for passive pressure to estimate the radial stress and reported that for spread footing The load tends to focus on the column as the more robust element within the composite foundation soil. The column undergoes expansion, exerting lateral stress on the adjacent soil, and this lateral stress is countered by passive pressure. So, there is tri-axial stress system within the column and the failure stress could be evaluated using conventional theory of passive pressure.
The ultimate stress carried by the stone column can be expressed as follows:

$$q_{ult} = k_{ps} \,.\, \sigma_3 = [(1+\sin\phi_s)/(1+\sin\phi_s)] \,.\gamma_c \,.z \,.\, k_{ps} + 2c\sqrt{k_{ps}} \quad (1)$$

where
σ_3 = the ultimate undrained lateral stress
γ_c = the unit weight of the surrounding soil
z = depth of failure zone, generally taken at depth of 4 times the diameter of stone column.
k_{ps} = Rankine passive pressure coefficient of soil = $\tan^2(45 + \phi_c/2)$
ϕ_s = angle of internal friction of the stone column.
ϕ_c = angle of internal friction of soil.

2.2 Cavity Expansion Theory

The bulging-type failure of a single stone column is considered to be similar to the cavity developed during a pressuremeter test. Gibson and Anderson (1961) used elastic-plastic theory on a frictionless material and an infinitely long expanding cylindrically cavity.
The ultimate stress carried by the stone column can be expressed as :

$$q_{ult} = k_{ps} .\, \sigma_3 = [(1+\sin\phi_s)/(1+\sin\phi_s)]\, [\sigma_{ro} + c\ \{1 + \ln(E_c)/2c(1+v)\}] \quad (2)$$

where
σ_{ro} = total in situ lateral stress at rest = $K_o\, \bar{\sigma_v}$
K_o = coefficient of lateral earth pressure
$\bar{\sigma_v}$ =effective vertical stress, generally taken at a depth of 4 times the diameter of the stone column
E_c = elastic modulus of the soil.
c = undrained cohesion of the soil.
v = Poisson's ratio.
k_{ps} = Rankine passive pressure coefficient of soil = $\tan^2(45 + \phi_c/2)$
ϕ_s = angle of internal friction of the stone column.
ϕ_c = angle of internal friction of soil.

2.3 Conventional Bearing Capacity Theory

Short column failure may occur either by a general shear failure or may be by punching in a soft underlying soil layer. Madhav et al (1978) envisaging a probable failure scenario involves considering a broad shear failure mechanism, with due consideration given to Coulomb's criterion as the guiding principle for soil yielding, and they showed the plane strain condition for a common bearing capacity failure. They presented a solution for the ultimate bearing capacity of the stone column as follows:

$$q_{ult} = (B/2) \,.\, \gamma_c \,.N_\gamma + c \,.\, N_c + D_f \,.\, \gamma_c \,.N_q \quad (3)$$

Where

B = width of footing
γ_c = unit weight of surrounding soil
c = cohesion of surrounding soil
D_f= depth of footing
N_γ , N_c and N_q= dimensionless factors which depend on the properties of stone and soil material and the ratio D/B.

2.4 The Original and Modified Hughes and Withers Theory

Hughes et al (1975) proposed the limiting values of the shear stresses along the sides of the column is equal to the undrained cohesion of the soil. If the column in the bulged region near the top of the column is a critical state of stress, then, the outcomes of rapid pressuremeter tests conducted in different locations demonstrate a satisfactory approximation to the analytical expression for the total limiting radial stress.:

$$\sigma_{r\,L} = 4C + \sigma_{ro} + u_o \tag{4}$$

Where
$\sigma_{r\,L}$ =radial stress
σ_{ro} = total in situ lateral at rest stress
C= undrained shear strength
u_o= initial excess pore water pressure
As the stone within the column approaches shear failure characterized by an internal friction angle ϕs, the ultimate bearing capacity can be ascertained.:

$$q_{ult} = K_{ps}\ \sigma_{r\,L} = [(1+\sin\phi_s)/(1+\sin\phi_s)](4C+\sigma_{ro}) \tag{5}$$

This analysis is valid only when the ratio of the diameters of the stone column D and the loaded area of the footing B is unity (D/B=1).
Madhav et al (1978) modified the solution of Hughes et al (1974) for D/B less than 1 as follows :

$$q_{ult} = [(1+\sin\phi_s)/(1+\sin\phi_s)](4C+\sigma_{ro}+\alpha.k_o.q_s)(D/B)^2 + [1-(D^2/B^2)]\,q_s \tag{6}$$

q_s= ultimate bearing capacity of the untreated soil expressed as
$q_s = (2/3)\ c.N_c$
k_o= coefficient of earth pressure at rest of the soft soil.
$\alpha = (1- D/B)$
With this modification, Hughes and Withers's solution becomes general and applicable to any ratio of D/B in the range of 0 to 1.

3. Settlement Prediction of Soil Improved By Stone Columns

There are many methods for estimating the settlement of structures resting on stone column foundations, these methods are as follows:

3.1 Hughes et al Method

Hughes et al (1975) approaches grounded in the assumption that the column undergoes radial expansion during settlement, while keeping the volume constant, are utilized for settlement estimation. The column is divided into layers, and the total settlement is subsequently assessed by :

$$S_t = S_{t1} + S_{t2} + \ldots + S_{tn} \tag{7}$$

$$S_i = \sum_{i=1}^{n} S_{ti}$$

where

S_{t1} =settlement of first layer, as

S_{t1}= 2 Hi (S_{t1} / r)

where

Hi = thickness of first soil layer

S_{t1} /r = radial strain for the first layer which obtained from pressuremeter test.

3.2 Mattes and Poulos Method

Mattes and Poulos (1969) presented an analytical solution by using linear elastic theory for the prediction of preliminary settlement of a single stone column in a semi -infinite soil. The settlement can be calculated as follows:

$$S_t = (q/E_c\ L)\ I_p \tag{8}$$

where

S_t = settlement of the stone column
q = total applied vertical load
E_c = Young' s modulus of clay soil
L = length of stone column
I_p = displacement influence factor.

3.3 Balaam and Book Method

Balaam et al (1976) developed a solution using the elastic theory to calcuate the settlement for single zone of influence containing a unit pile, by assuming that both soil snd column materials behave elastically. They proposed the following equation to calculate the settlement under uniform stress (q) as follows:

$$S_t = q\ .H\ (\ S^2_{eq}/\ M) \tag{9}$$

S_t = Total settlement
q = uniform stress
H= thickness of the layer
S_{eq} = the equivalent ratio
M= constant

3.4 Priebe Method

Priebe (1995) proposed a method for settlement calculation, assuming the stone column is in plastic equilibrium under a triaxial stress state, while the surrounding soil within the unit cell is treated as an elastic material. Priebe presented a chart to estimate stone column settlement based on a combination of elasticity and Rankine earth pressure theory.

4. Case Study

The case study that been taken in present research, is the case study of Hughes et al (1975) in Canvey Island, England. The soil consists of 9m of soft grey clay rests on 11m silty sand. The project is to construct a tank on the top soil. This case study has simulated to the computer program that perform comparative studies for the theories that predict the bearing capacity and settlement and been compared with actual measurement in the field. Stone columns, each measuring 10 meters in length, were installed by penetrating through soft clay into stiffer sand or silt layers. Predictions were made for a cylindrical column with an assumed diameter of 0.66 meters, based on stone consumption data from previous contract work on tank foundations in similar soil conditions at a nearby site. The surrounding soil is considered frictionless, with a unit weight of 18 kN/m³. The undrained shear strength (C) is estimated to be 22 kPa, derived from site investigation data. The assumed angle of internal friction for the column material is 38˚. The backfill stone comprises round river gravel from Thames gravel, uniformly graded between 20 mm and 40 mm. The properties of the soil and stone column are summarized in Table (1).

Table (1) Characteristics of materials used in the analysis of the case study

Parameter	Soft clay	Stone column
Unit Weight ,γ (KN/m^3)	18	20
Coefficient of earth pressure at rest (K_o)	0.8	0.38
Cohesion intercept, C (KN/m^3)	22	0.0
Angle of internal friction ,ϕ	0.0	38˚
Poisson's ratio, ν	0.49	0.3
Modulus of elasticity E(KN/m^3)	4000	8000

5. Field Tests

The stone column was subjected to testing with a concentric circular plate measuring 660 mm in diameter. Before the field testing, there were predictions made regarding the load-settlement relationship for the plate loading of a stone column in soft clay. The column, constructed using vibro-replacement, was later excavated to verify its dimensions. The basis for these predictions stemmed from the analysis of the behavior of isolated stone columns, as proposed by Hughes et al (1975).

6. Results of Bearing Capacity

AlShreafe (2001) developed a computer program to perform parametric studies affecting the behavior of stone columns through various theorems for predicting yield load and settlement. The results of the bearing capacity using the computer program deduced from different theories are presented and compared with results evaluated from the case study conducted in the field by plate loading test. As can be seen in Fig.1, the values of the bearing capacity for the tone column are deduced from different compared with values obtained from the field test. The passive pressure theory underestimates the bearing capacity by 58% as compared with the field test, this may be attributed to the assumption that the theory is originally based on plain strain condition.

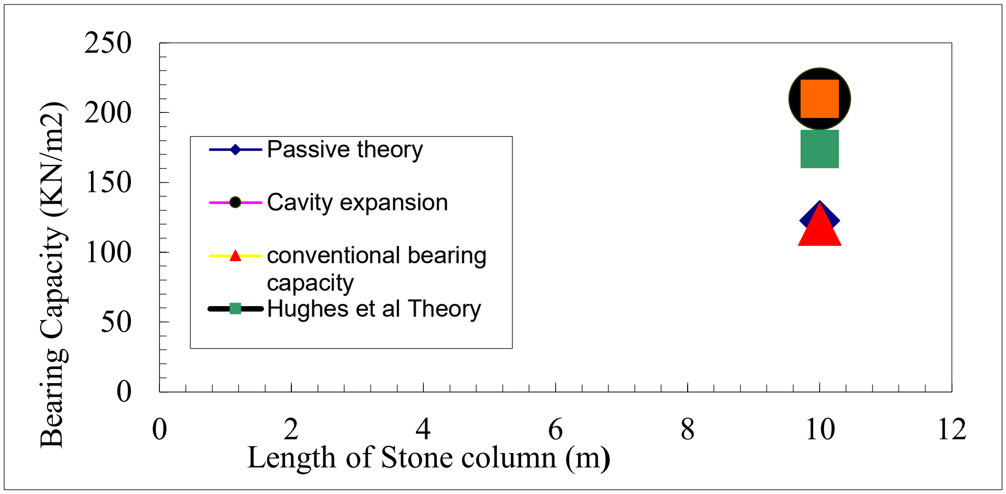

Figure 1 Values of bearing capacity from different theories

The cavity expansion theory predicted the value of bearing capacity as the same value deduced from the field test. The cavity expansion theory is an invaluable tool for grasping the factors affecting the yield values of vertical stress in stone columns. Its utility extends to the interpretation of load test data, facilitating the extraction of insights that can be applied to assess and fine-tune design parameters. The conventional bearing capacity theory underestimated the value of the bearing by 58% less than the field value, this value is like that predicated by passive pressure theory because both theories assumed plain strain condition. The original and modified Hughes et al theory showed better agreement between the values of the bearing capacity predicted from this theory as compared with the field value, the calculated bearing capacity was less than the field value by 17%. The case study data was taken as a common base for the comparison purposes of many parameters between the different theories. As can be seen in Fig. 2, the load-carrying capacity versus the diameter of the column. The passive pressure and conventional bearing capacity theories showed lower values and were more conservative compared with cavity expansion and Hughes et al theories. The field results are in good agreement with the expansion theory. Fig. 3 shows the relationship between the angle of internal friction of the stone column ϕ, and the load capacity for different theories. The passive pressure and conventional bearing capacity theories are close to each other and more conservative and exhibit a small rate of change through the range of ϕ values. The cavity expansion theory provides a sharp increase in the load-carrying capacity by increasing the angle of internal friction. Fig.4 demonstrates the effect of the cohesion of soil with increasing load capacity. The cohesion seems to be more effective than the angle of internal friction of the backfill material. The increase in load-carrying capacity varies linearly with cohesion for all theories, the values corresponding to the field test showed very close to the cavity expansion theory

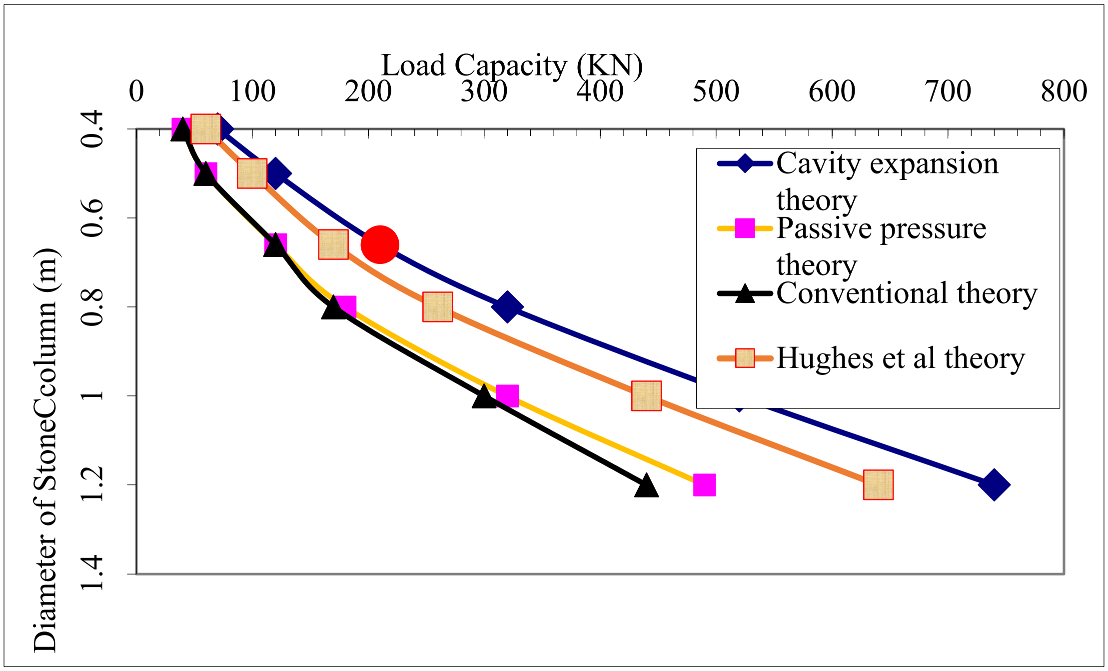

Figure.2 Relation between diameter and load capacity of stone column for different theories

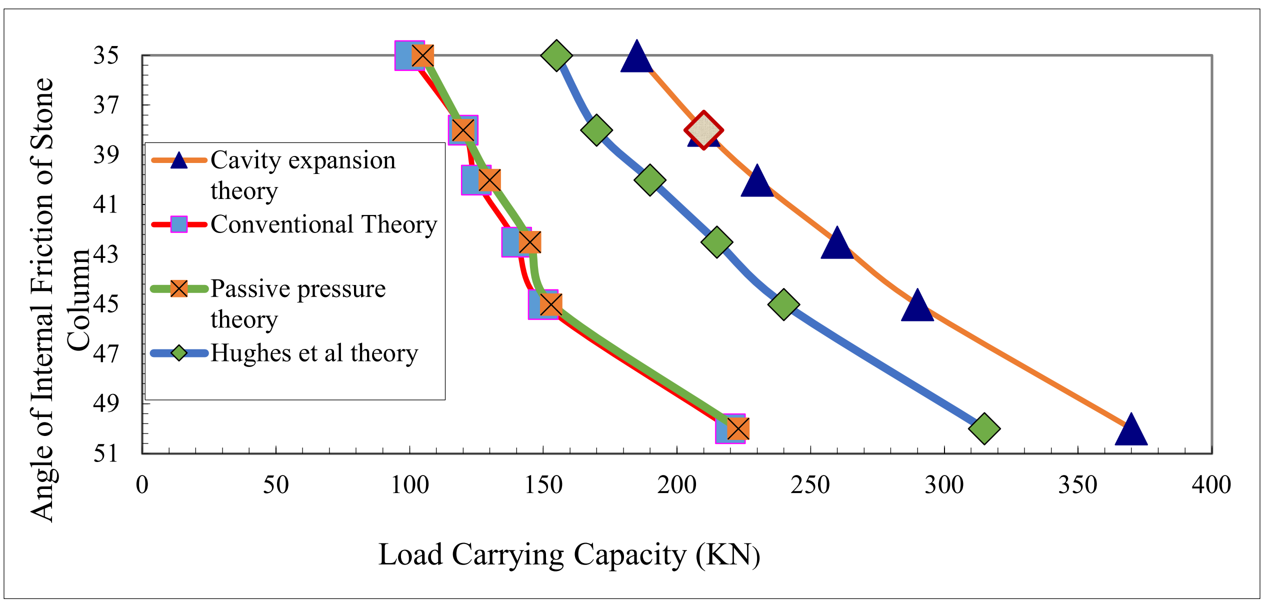

Figure.3 Relation between angle of internal friction and load capacity of stone column for different theories

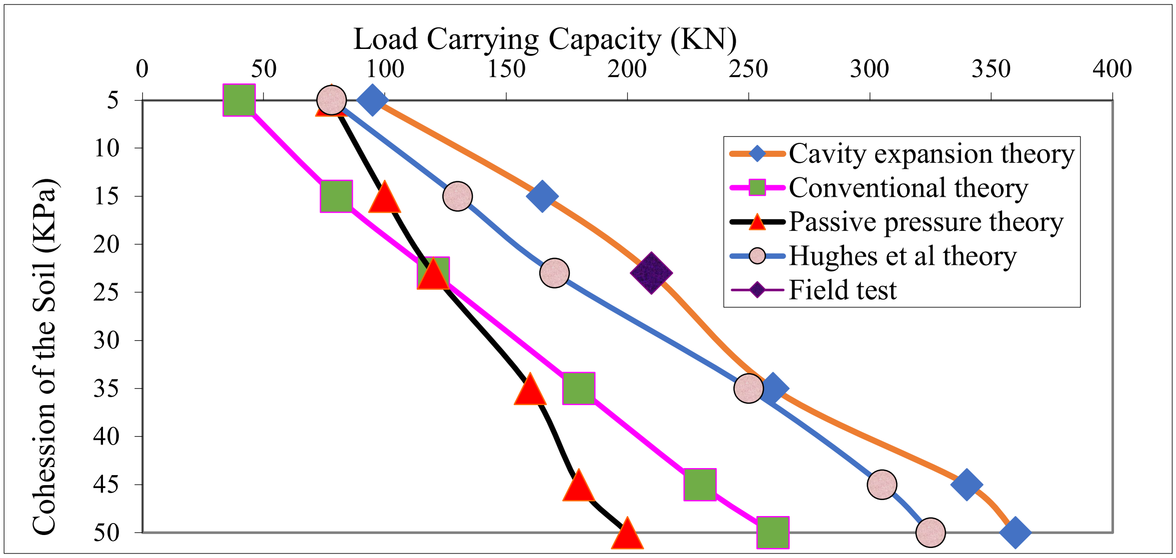

Figure.4 Relationship between cohesion of the soil and load carrying capacity for different theories

7. RESULTS OF SETTLEMENT

The results of settlement deduced from different theories for structures rest on stone column are presented and compared with case study

7.1 Hughes et al theory

The settlement calculated from this theory using the computer program when the stone column is loaded was found to be 0.21m. The observed settlement from the case study scores a maximum of 0.17m which represents a good agreement. To verify the computing program, Fig. 5 shows the applied load-settlement relationship for the typical case study calculated by the program as visually shows the good agreement.

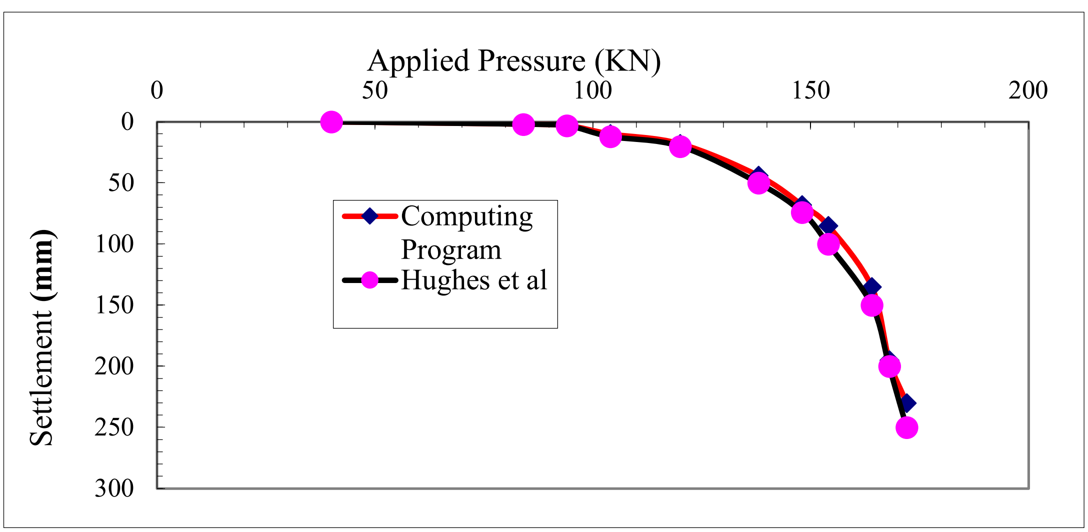

Figure.5 Load - settlement for Hughes et al theory and case study

7.2 Mattes and Poulos Theory

The load-settlement curve is shown in Fig. 6 for stone columns with different lengths. The settlement is decreased with increasing the stone column length. The maximum settlement computed by the computing program is 0.2 m compared to the observed value, of 0.17 m. The convergence is increased between the observed and the predicted values in this theory.

7.3 Balaam and Booker Theory

This method, introduced by Balaam and Booker (1976), addresses the settlement of a rigid foundation supported by soft clays stabilized with numerous stone columns. The solutions within this method assume the elastic behavior of both the stone column and the clay throughout the applied load range. These solutions are derived from the analysis of a "unit cell," consisting of a stone column and the surrounding soil within the column's zone of influence. The behavior of this "unit cell" is deemed representative of the stabilized clay's overall response. The results obtained through this method indicate that the key factors influencing the settlement of a stabilized clay deposit primarily revolve around the column diameter, Poisson's ratio of soil and stone column, ratio of modulus of elasticity of stone to modulus of soil, and the arrangement of stone column. The maximum settlement predicted by this method was 0.11 m, this showed lower values than Mattes and Poulos method and even lower than the observed value. This may have been attributed to the variance of the load application pattern, where the load is applied to the soil-stone column assembly (unit cell).

7.4 Priebe Method

Priebe (1995) provided a settlement prediction chart based on a combination of elasticity and Rankine earth pressure theory. Within this chart, an improvement factor "n" is defined as the ratio of settlement in the untreated ground to settlement in the treated ground, or its tropical (Sr) is plotted versus area ratio as in Fig.7 for a series of ϕ_s values ranging from 35˚ to 50˚. The present method uses a similar technique as in the Balaam and Broker method in the pattern of load application. The program computed the settlement as 0.17 m which is close to the observed value of 0.2 m.

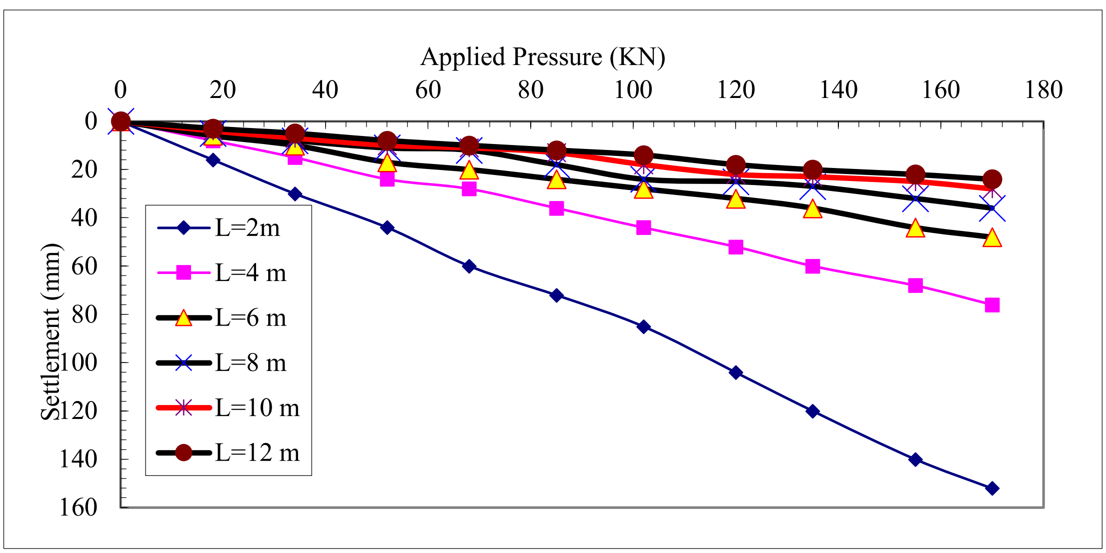

Figure.6 Effect of Length of Stone column on Load - Settlement Relationship

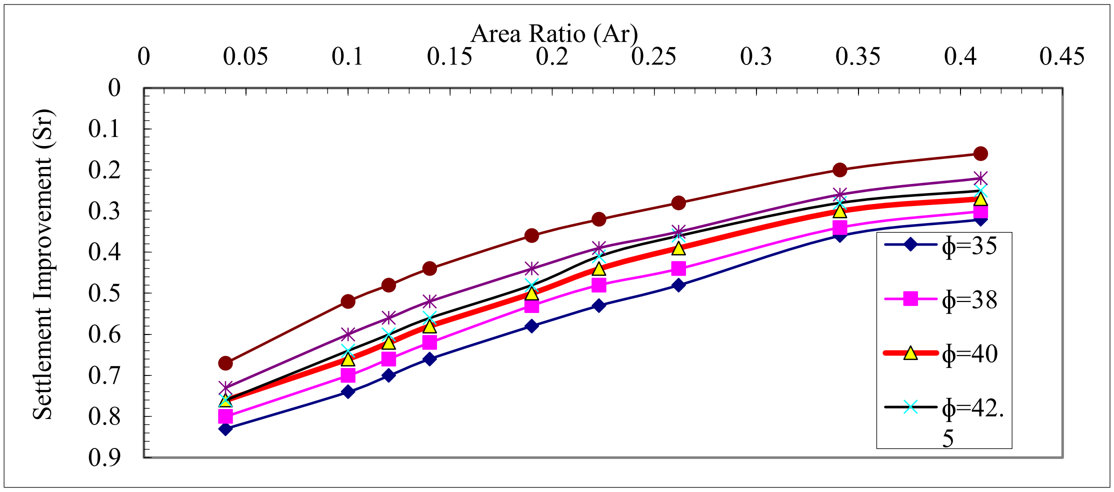

Figure.7 Relation between settlement improvement and area ratio for different angle of friction of stone column

8. CONCLUSIONS

Based on the analysis of all the theories, regarding the load-carrying capacity and settlement of soft clay reinforced with stone columns. The following points can be drawn:

1- A computer program has been developed that can perform parametric studies affecting the behavior of stone columns through various theorems for prediction yield load and settlement.

2- All the theories provided a certain amount of increase in carrying load capacity due to the presence of stone columns.

3- A comparison between the load-carrying capacity of stone columns deduced from different theories and the case study reported by Hughes et al 1975, demonstrates that the cavity expansion theory is the best theory that provides close results of the field case study.

4- Hughes et al. (1975) theory showed that the calculated carrying capacity is 20% less than the field case study results.

5-The passive pressure theory and the conventional bearing capacity theory deduced the most conservative results. They are 70% less than the actual field case study results.

6- Hughes et al theory provides the nearest results for settlement prediction as compared with the field case study results.

8. REFERENCES

Al-Recaby, M.K (1999) Stabilized stone columns in soft clay with new reinforcement patterns. *MSc, thesis, University of Technology*, Baghdad, Iraq.

AlShreafe, J (2001) "Theoretical Concepts of Stone Columns in Soft Clays, *MSc thesis*, University of Technology Baghdad, Iraq

Balaam, N ,Bookr ,J and Poulos , H (1976) . Analysis of Granular Pile Behaviour Using Finite Element" *Proceeding of International Conference on Finite Element Methods in Engineering*. Adelaide, Australia

Das, M and Dey, A (2018) "Prediction of Bearing Capacity of Stone Columns Placed in Soft Clay Using ANN Model, *Geotechnical and Geological Engineering*, Vol. 36, pp1845–1861

Etezad1, M, Hanna,A and Ayadat,T (2015) " Bearing Capacity of a Group of Stone Columns in Soft Soil" *International Journal of Geomechanics* ,Vol.15,Issue 2

Fattah, M, Al-Neami,M and Al-Suhaily ,A (2017) " Estimation of bearing capacity of floating group of stone columns". *Engineering Science and Technology, an International Journal*, Vol. 20 ,pp1166–1172

Gibson, R and Anderson, W (1961) " In situ measurements of soil properties using pressuremeter . *Civil Engineering and Publication works Rev*. vol.56, pp615-618

Greenwood, D.A (1970), Mechanical improvement of soil below ground surface, *Proceeding ground engineering conference*, Institute of civil engineering

Hughes, J, Withers, N and Greenwood, D (1975). " A field Trial of the Reinforced Effect of a Stone Column in Soil", *Geotechnique*, Vol. 25, No.1, pp 31-44.

Kardgar, H (2018) " Investigation of the Bearing Capacity of Foundations on Encased Stone Columns Using Finite Element Method " *International Journal of Integrated Engineering*, Vol. ,10 No.1, p p. 103-108

Kim, Y, Dang, M, Do, T and Lee, J (2018) " Soil stabilization by ground bottom ash and red mud " *Geomechanics and Engineering* Vol.16, No. 1, pp 105-112

Madhav, M, Iyengar, T, Vitkar ,P and Nadia ,A (1978) . " Increased Bearing Capacity and Reduced Settlements Due Inclusions in Soil" . *Proceeding International Conference on Soil Reinforcement, Reinforced Earth and Other Techniques*, Vol.1, Paris. pp 329-333

Mahawish ,A, Bouazza ,A and Gates, W (2018) "Strengthening crushed coarse aggregates using bio-grouting " , *Geomechanics and Geoengineering* ,Vol.14,Issue 1

Mattes, N and Poulos, H (1969) " Settlement of Single Compressible Pile" . *ASCE Soil Mechanics and Foundation Division Journal*, Vol.95, No.1, pp 189- 207.

Moayyeri , N , Oulapour , M and Haghighi ,A (2018) " Study of geotechnical properties of a gypsiferous soil treated with lime and silica fume" *Geomechanics and Engineering* , Vol. 17, No. 2 pp195-206

Nazariafshar, J, Mehrannia,N , Kalantary,F and Ganjian ,N (2019) " Bearing Capacity of Group of Stone Columns with Granular Blankets ". *International Journal of Civil Engineering*,Vol.17 ,Issue 2,pp 253-263

Ng, K. S, (2018) " Numerical study on bearing capacity of single stone column" , *International Journal of Geo- Engineering* , Vol.9,Issue 9.

Priebe , H (1995) . "The Design of Vibro- Replacement ", *Ground Engineering*, Vol.28, No. 10, pp 31-37.

Sujatha, E, Geetha,A, Jananee,R and Karunya, S (2018) " Strength and mechanical behaviour of coir reinforced lime stabilized soil" . *Geomechanics and Engineerin* ,Vol.16,No.2,pp 627-634