Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (43) No. (1) January 2021

Improvement of soft clay using a group of stone columns- Case Study

Mostafa A. Yousef
A.Prof., Housing and Building Research Center, HBRC, Egypt. E-mail: mostafa.abdelfadil@yahoo.com

ملخص البحث :

تعتبر الأعمدة الحجرية من إحدى الطرق المستخدمة لتحسين خصائص التربة الطينية الضعيفة لتقليل الهبوط وزيادة قدرة تحمل التربة. وتنفذ الأعمدة الحجرية من الزلط أو كسر الأحجار باستخدام الهزاز. وفى هذا البحث تم استخدام أعمدة كسر الحجر لتحسين خصائص التربة في أحد المشروعات السكنية المزمع إنشاؤها فى مدينة بور فؤاد بمحافظة بورسعيد نظرا لتواجد تربة طينية ضعيفة في موقع المشروع والتى من المتوقع عند التأسيس عليها حدوث هبوط كبير. ويتألف المشروع من عدد (80) عمارة يتكون كل منها من عدد (6) أدوار. وكان من المقرر إنشاء العمارات بالأسلوب الهيكلى من الخرسانة المسلحة ، والأساسات عبارة عن لبشة مسلحة. وقد تم رصد الهبوط لعدد (9) عمارات أثناء الإنشاء وحتى الانتهاء من الهيكل الخرسانى ، وتم مقارنة الهبوط المقاس في الموقع مع الهبوط المحسوب بطريقة العناصر المحددة باستخدام برنامج الحاسب الآلى (ديانا) ، كم تمت المقارنة كذلك مع الهبوط المحسوب بطريقة بريب التقريبية (Priebe method). وقد وجد أن طريقة بريب التقريبية أعطت هبوطا قريبا من الهبوط المحسوب بطريقة العناصر المحددة ، بينما كان الهبوط المقاس فى الموقع أقل بنسبة كبيرة من الهبوط المحسوب ، ويرجع السبب فى ذلك إلى قصر مدة الرصد حيث لم يحدث تدعيم كامل (consolidation) للتربة.

Abstract :

Stone columns are one of the methods used to improve the properties of weak clay soils to reduce settlement and increase the bearing capacity of the soil. Stone columns are executed from gravel or crushed stones using vibrators. In this research, stone fracturing columns were used to improve soil properties in one of the residential projects to be established in Port Fouad City, Port Said Governorate, due to the presence of weak clay soil at the site of the project, which upon foundation is expected to cause a major settlement. The project consists of (80) buildings, each of which consists of (6) floors. The buildings were intended to be constructed using reinforced concrete skeleton system, and supported on raft foundations. The settlement of (9) buildings was monitored during construction until the completion of the concrete structure. The measured settlement on the site was compared with the settlement calculated using the finite element method using the general purpose finite element program DIANA® VER. 10.3 (TNO DIANA BV. 2019). Also, comparison was done with the calculated settlement using Priebe method. It is noticed that the reinforcement by stone

columns makes a significant settlement reduction possible. It was found that the approximate Priebe method gave a fall close to the calculated settlement using the finite element method. On the other hand, the measured settlement at the site was significantly less than the calculated. The reason for this is due to the short monitoring period as no complete consolidation of the soil occurred.

Introduction

A stone column is one of the soil stabilizing methods that is used to increase strength, decrease the compressibility of soft and loose fine graded soils, accelerate a consolidation effect and reduce the liquefaction potential of soils. The columns consist of compacted gravel or crushed stone arranged by a vibrator. Stone columns behaved as rigid element to carry higher shear stresses to reduce settlement, and improving the deformability and strength properties of soft soil (Istuti Singh, Anil Kumar Sahu, 2019). On the load application column rapidly drains the excessive pore water pressure originated. Many researchers have developed theoretical solutions for estimating the bearing capacity and settlement of foundations reinforced with stone columns. Priebe (1995) proposed a method for estimating the settlement of foundations resting on an infinite grid of stone columns. The method is based on the unit cell concept and the columns are considered to be in a plastic state, while the surrounding soil behaves elastically. The solution is given as a settlement improvement factor, n, defined as the ratio of the final settlement with and without columns. The basic improvement factor, n_0, is derived from the assumption that the columns possess an infinite modulus of elasticity. A correction to this assumption is made by considering the compressibility of the columns with a more realistic value, and this yields a reduced improvement factor, n_1. The final improvement factor, n_2, takes into account the variations in stress with depth which are ignored during the initial formulation of n_0.

$$n_0 = 1 + \frac{A_c}{A}\left[\frac{5 - \frac{A_c}{A}}{4K_{ac}\left(1 - \frac{A_c}{A}\right)} - 1\right]$$

$$K_{aC} = \tan^2(45° - \varphi_C/2)$$

Where:

Kac = coefficient of active earth pressure for column material

Ac = stone column area

A = grid area

ϕ_C = Friction angle of the backfill material

The compressibility of column material is considered as reduced improvement factor n_1

which can be computed based on the following formula:

$$n_1 = 1 + \frac{\overline{A_c}}{A}\left[\frac{5 - \frac{\overline{A_c}}{A}}{4K_{ac}\left(\frac{\overline{A_c}}{A}\right)} - 1\right]$$

Taking account of depth, the improvement factor is increased from n_1 to n_2 as follows:
$n_2 = f_d . n_1$

$$f_d = \frac{1}{1 + \frac{K_{ac} - 1}{K_{ac}} \cdot \frac{\Sigma(\gamma_s \Delta d)}{P_c}}$$

Where:
γ_s = unit weight of initial soil
Δd = depth of subsoil layer from ground surface
P_c = pressure within the column along depth
The relation between the improvement factor n_0, the reciprocal area ratio A/A_C and the friction angle of the backfill material ϕ_C which enters the derivation is illustrated in the well-known diagram of Figure 1. The additional amount on the area ratio $\Delta(A/A_C)$ depending on the ratio of the constrained moduli of the stone column and soil (D_C/D_S) can be readily taken from the diagram in Figure 2. The simplified diagram in Figure 3 considers the same bulk density γ for columns and soil which is not on the safe side. Therefore for safety reasons, the lower value of the soil γ S should be considered in this diagram always.

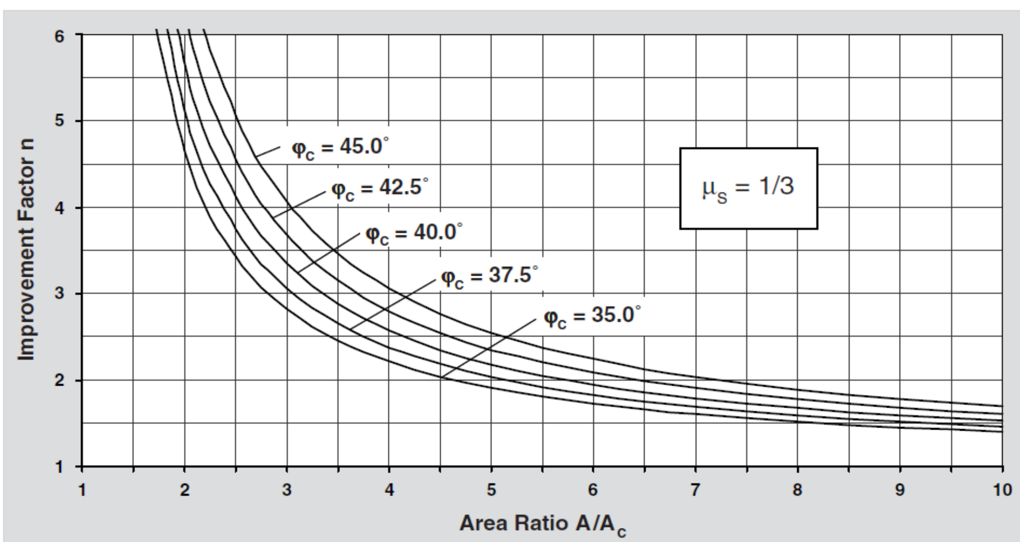

Figure 1: Design chart for vibro replacement (Priebe, 1995)

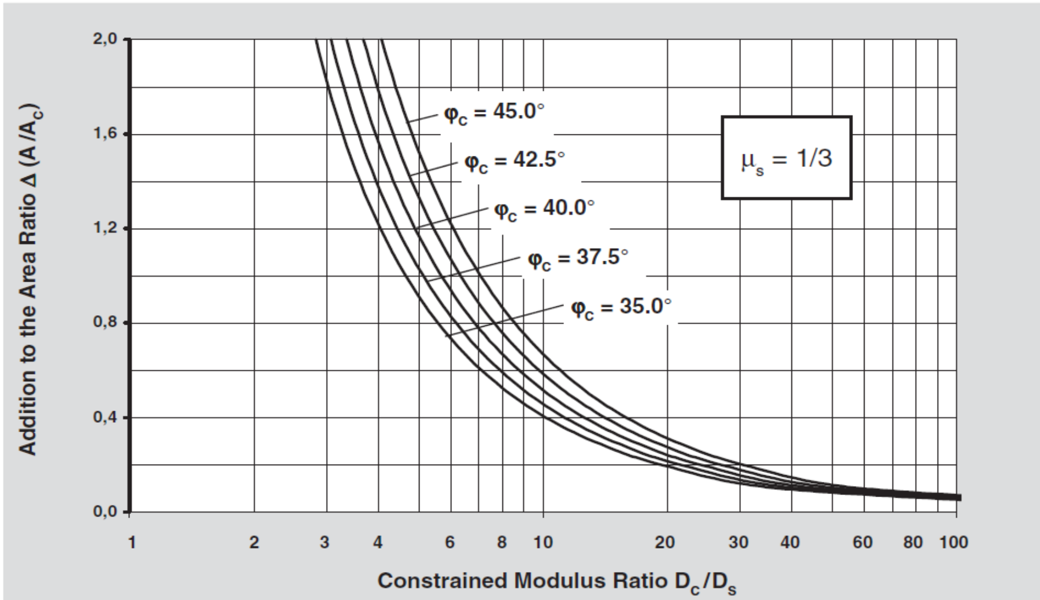

Figure 2: Consideration of column compressibility (Priebe, 1995)

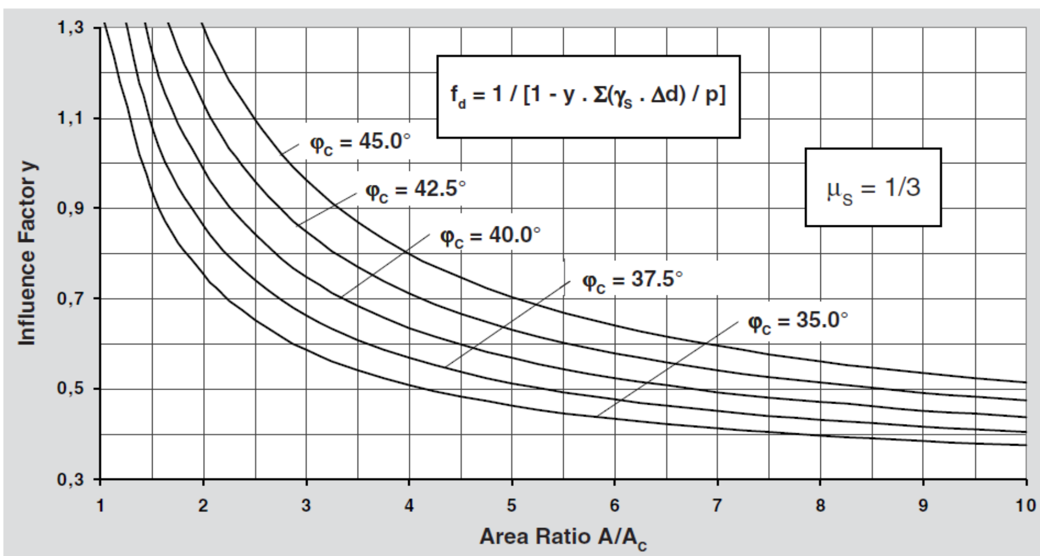

Figure 3: Determination of the depth factor (Priebe, 1995)

Analytical method is proposed by (Boštjan Pulko & Bojan Majes, 2005-2006) to analyze the behavior of rigid foundations resting on soft soil stabilized by a large number of end bearing stone-columns. The results showed that the most important parameters affecting the settlement of the stabilized ground are the column spacing ratio d_e/d_c, the dimensionless load factor $q_A/(H\gamma_s')$, the friction angle of the stone column ϕ_c, the dilatancy angle ψ , the modulus ratio E_c/E_s, the initial lateral earth pressure coefficient K_{ini} and Poisson’s ratio of the soil νs. Shankar and Shroff (1997) conducted experimental studies to study the effect of pattern of installation of stone columns and showed that triangular pattern seems to be optimum and rational (K. S. Beena, 2010). Mitra and Chatopadhyay (1999) showed that in the case of columns failing by bulging the critical length is about three to five times the stone column diameter. (K. S. Beena, 2010) found that the replacement of (30% by weight) of stones by quarry dust can be possible without affecting the strength and performance of the system. (Black, J. A. et al. 2011) stated that settlement can equally be controlled using shorter columns at higher replacement ratios or longer columns at reduced area replacement. In addition, they also showed that an optimum area replacement ratio of between 30% and 40% exists for the control of settlement, and that soil–structure interaction has a significant role in preventing excessive column deformations. Based on past experiences the stone column design is still empirical and always needs field trials before execution. This paper focuses on a comparison between settlement predictions by Priebe's method and finite element program DIANA® VER. 10.3 (TNO DIANA BV. 2019). This comparison is based on a case history of reinforced soft soils by stone columns, for which in situ measurements of settlement are available.

A Study of Case History

A project of construction of 80 investment buildings – 120 m2 model – is located at Port Fouad, Port Said governorate. Each building consists of ground floor and 5 typical floors. It is intended to be constructed using reinforced concrete skeleton system supported on raft foundation. The load imposed by building is approximated quasi-uniform stress of 100 kPa, which largely exceeds the allowable bearing capacity of the initial soil due to the existence of a layer of soft clay. In order to increase the bearing capacity and to reduce the settlement at allowable values, it was decided to use stone columns for soil improvement.

Soil stratification

The soil stratification at the site of the buildings consists of soft silty clay from ground surface down to depth of 5.0 m, followed by sand/silty sand up to depth of 13.0m. Then, there is a lower soft clay layer down to the end of boring at 45.0 m. Figure 4 shows the soil stratification at the site and the characteristics of the soil formations at the site are shown in Table 1.

Arrangement of stone columns

Figure 5 shows the proposed arrangement of stone columns. It was executed along an average depth H = 6 m with a nominal diameter of 1.0 m, and arranged in an equilateral triangular pattern with an approximate substitution factor of 24%. 1.0 m granular cushion is proposed below the raft and stone columns starts directly below the cushion.

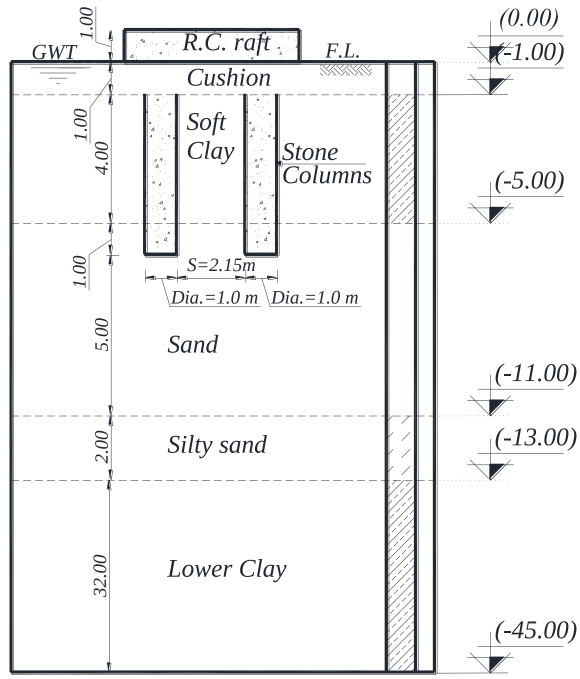

Figure 4: Soil stratification

Table (1): Soil Parameters and Model

Parameter			Soil Layer			
	Cushion	Stone C.	Soft Clay	Sand	S. Sand	L. Clay
Bulk unit weight (kN/m^3)	20	20	17	17.5	17.5	17.5
Cohesion C (kPa)	1	1	1	1	1	1
Friction angle, ϕ (degree)	40	40	20	35	32	20
Diltancy angle, ψ (degree)	8	8	0	5	2	0
E50 (kPa)	100000	100000	2000	50000	20000	5000
Poisson's ratio, ν_{ur}	0.30	0.30	0.30	0.30	0.30	0.30
Initial void ratio, e_0	--	--	1.67	--	--	1.67
Coefficient of earth pressure at rest, K_0	0.5	0.45	0.77	0.48	0.47	0.62
Soil model	Mohr-Coulomb					

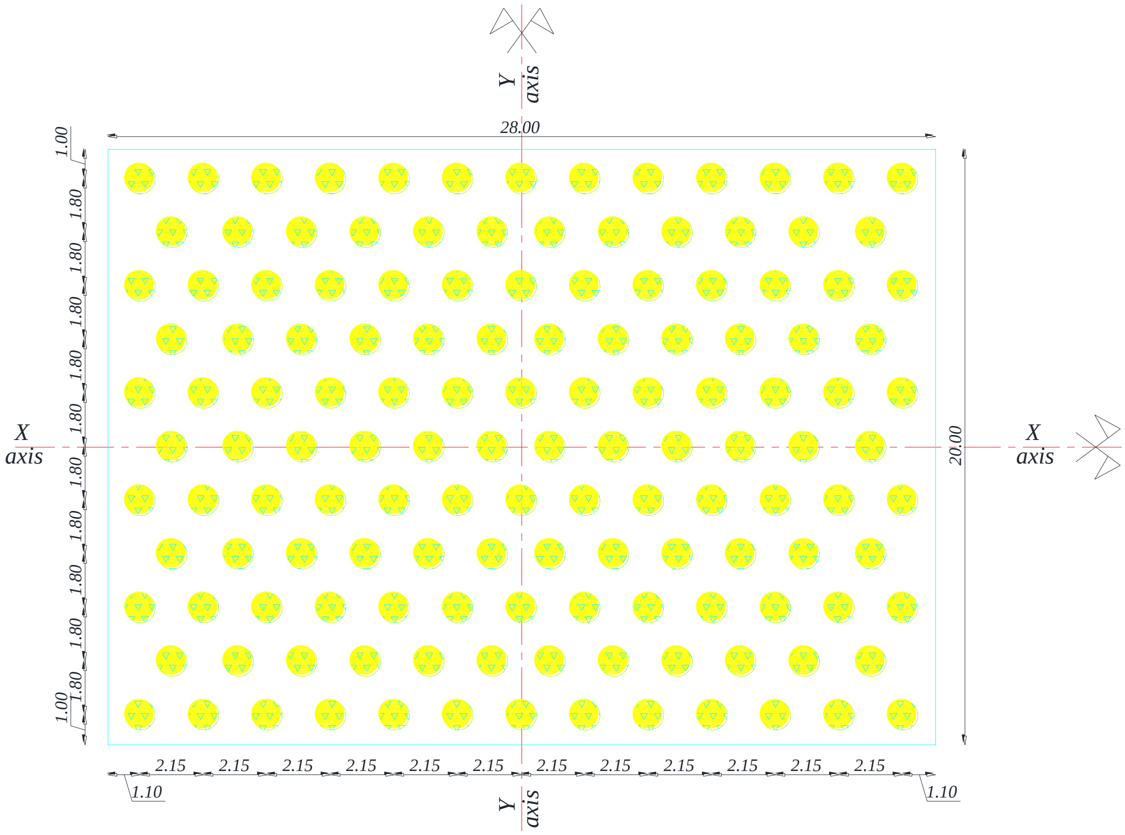

Figure 5: Stone column arrangement

Detailed 3D Nonlinear FE Model

In the model, the existing soil-structure is appropriately modeled making use of the available data. In order to determine the effects of construction history and show the critical construction stages, different construction phases were simulated via phased-analysis option. Soil strata are modeled using Mohr–Coulomb elasto-plastic model. Raft is modeled as linear elastic. The soil layers and the raft are modeled using solid elements. The yield condition of the Mohr-Coulomb is shown in Figures 6. The finite element analyses were carried out using the general purpose finite element program DIANA® VER. 10.3 (TNO DIANA BV. 2019). The soil parameters used in the FEM analyses are listed in Table (1). The full 3D finite-element model of the problem is shown in Figure 7. Contours of vertical settlement under uniform load of 80 kPa are shown in Figure 8.

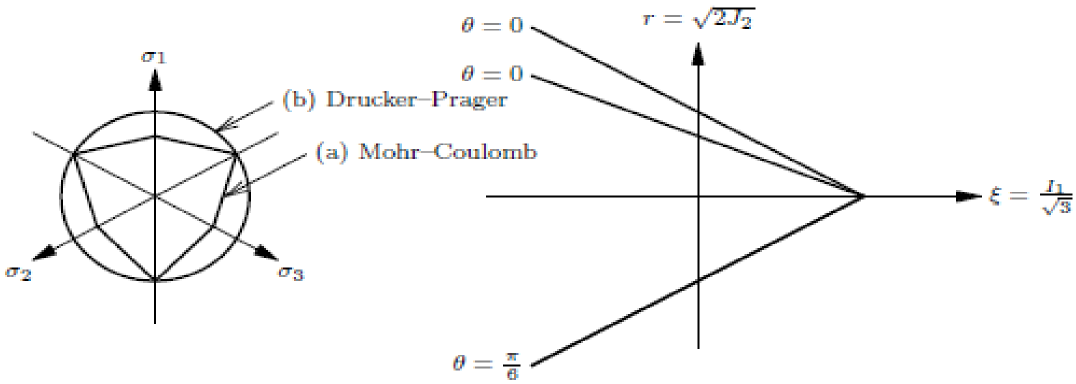

Figure 6: Mohr-Coulomb yield condition

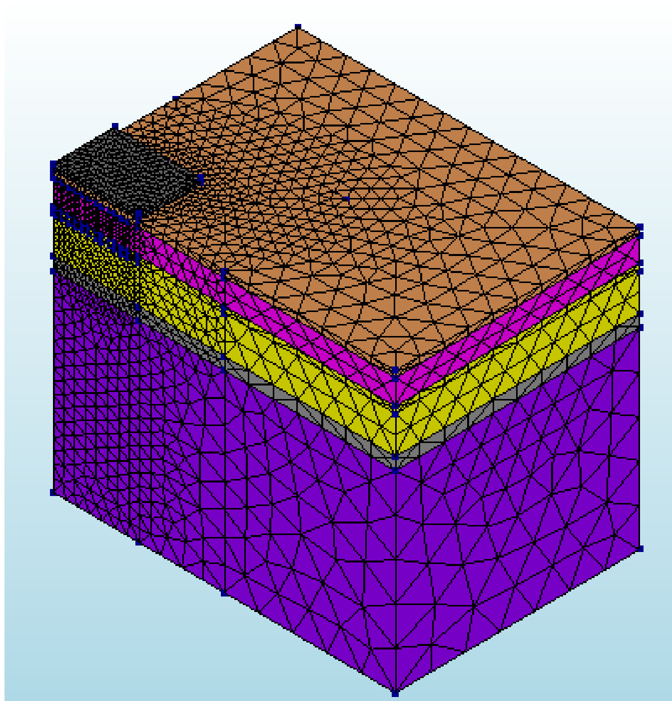

Figure 7: Finite element model

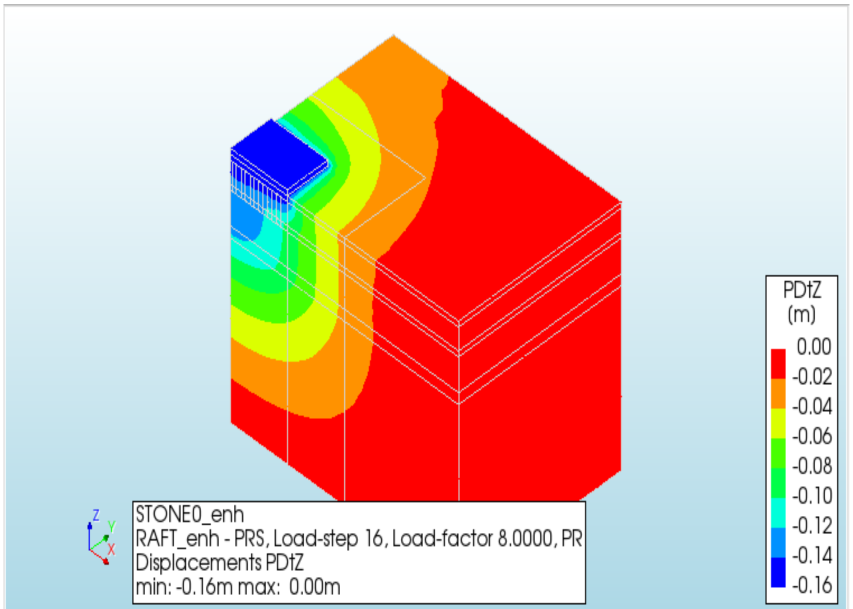

Figure 8: Contours of vertical settlement under uniform load of 80 kPa

Settlement reduction factor using Priebe method (1995)

Settlement reduction factor was calculated using Priebe charts shown in Figures 1, 2, 3 as follows:

$A/A_C = 4.19 \rightarrow$ Fig. 1 $\rightarrow n_0 \approx 2.50$

$D_C/D_S = 50 \rightarrow$ Fig. 2 $\rightarrow \Delta\ A/A_C \approx 0.13 \rightarrow A/A_C = 4.32$

$A/A_C = 4.32 \rightarrow$ Fig. 1 $\rightarrow n_1 \approx 2.4$

$A/A_C = 4.\ 32$, $\Sigma\ (\gamma\cdot d) = 7\cdot 6.0 = 42.0$ kN/m², $p = 100$ kN/m² $\rightarrow$ Fig. 3 $\rightarrow$ fd $\approx 1.34 \rightarrow n_2 = f_d\cdot n_1 = 3.22$

Settlement Monitoring

Settlement monitoring was started firstly after the construction of raft and continued up to the finishing of the skeleton construction. 9 buildings were monitored through measurement points fixed on the building at different locations of its plane, Figure 9. The measurements were compared to fixed points as a bench marks which is totally fixed and not affected by any load or movements. Average measured settlements after completion of the concrete skeleton of the monitored buildings are shown in Table 2. This settlement corresponds to a stress on soil of 80 kPa.

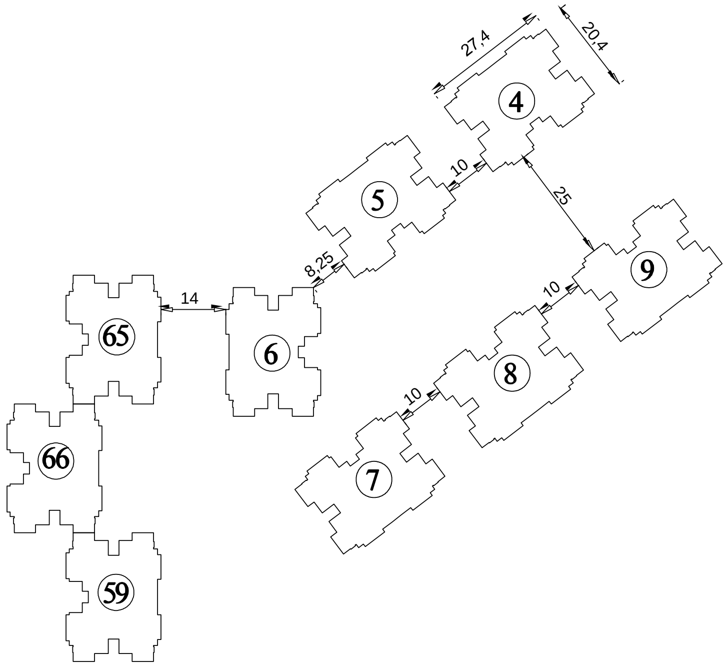

Figure 9: Monitored Buildings

Table (2): Measured Settlements

Building No.	Measured settlement (mm)
4	62
5	87
6	99
7	78
8	89
9	93
59	107
65	70
66	90
Average	**86**

Comparison of Settlement results

The settlement underneath the raft of the unreinforced soil under stresses 80 kPa is estimated to be about 420 mm. Priebe reduction factor caused by stone columns on the settlement of the upper soft clay layer is about 3.22 (Priebe's method). After reduction, settlement will be about 180 mm. The settlement predicted using the software "DIANA" under stresses 80 kPa was 160 mm. Comparison between predicted and recorded settlements is summarized in Table 3. It is noticed that the reinforcement by stone columns makes a significant settlement reduction possible. For this project, the measured settlement was smaller than the predicted settlements. The reason for this is that measured settlement is not the final because of the non-completion of the soil consolidation process.

Table 3. Comparison between settlement predictions

Method	**Settlement (mm)**
Unreinforced soil	420
DIANA	160
Priebe (with *n2*)	183
Measured	86

Conclusions

It is noticed that the reinforcement by stone columns makes a significant settlement reduction possible. The settlement of the unreinforced soil is estimated to be about 420 mm. Settlement predictions using the software "DIANA" and the Priebe's method were 160 mm and 183 mm respectively. The average measured settlement was 86 mm. The measured settlement was smaller than the predicted settlements because of the non-completion of the soil consolidation process.

References

1. Heinz J. Priebe, The Design of vibro replacement, 1995.
2. Boštjan Pulko & Bojan Majes, Simple and accurate prediction of settlements of stone column reinforced soil, Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, 2005–2006, Millpress Science Publishers/IOS Press.
3. M. Bouassida, S. Ellouze & L. Hazzar, Investigating Priebe's method for settlement estimation of foundation resting on soil reinforced by stone columns, Geotechnics of Soft Soils – Focus on Ground Improvement – Karstunen & Leoni (eds) © 2009 Taylor & Francis Group, London, ISBN 978-0-415-47591-4
4. K. S. Beena, Ground Improvement Using Stone Column, International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 2010.
5. J. A. Black, V. Sivakumar and A. Bell, The settlement performance of stone column foundations, Geotechnique 61, No. 11, 909–922, 2011.
6. K.S. Ngn & S.A.Tan, Design and Analyses of Floating Stone Columns, The Japanese Geotechnical Society, Soils and Foundations, 2014; 54(3):478-487.
7. Istuti Singh & Anil Kumar Sahu, A Review on Stone Columns used for Ground Improvement of Soft Soil, International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-8, Issue-7C2, May 2019.