A Short State-of-the-Art Review on Construction and Settlement of Soft Clay Soil Reinforced with Stone Column

A. Vahedian, S. Mahini, and S. A. Aghdaei

***Abstract*—The primary application of various geotechnical construction techniques is for ground improvement. Many soil improvement methods have been developed due to the ongoing increase in urban and industrial growth and the need for greater access to lands. Stone columns are one of the best available techniques for soft clay soil improvement. In this method, subsurface soils which are weak and unstable are replaced with compacted dense aggregate columns that often entirely penetrate into the weak layers. This paper aims to present a short state-of-the art on the stone column ground improvement technique based on existing literature and standards. Due to high permeability of the material component used in the stone columns, not only the load carrying capacity of the soil is raised, but also the soil settlement is reduced considerably and the post construction settlement is minimized. To achieve this goal, several significant characteristics of stone column in terms of design parameters are considered. One example of the behavior assessment of reinforced soil using stone column is included. A new one-dimensional analysis has been studied in addition to a simplified nonlinear finite element method. The results indicate that the new method is reliable. It is also indicated that the settlement of the soil without stone columns is significantly higher than the similar soil reinforced with stone column.**

***Index Terms*—Ground improvement, one-dimensional analysis, settlement, simplified finite element, stone column, soft clay.**

I. Introduction

Various geotechnical constructions techniques are used to improve soft clay soils. The major reasons for utilization of ground improvement techniques are related to the ongoing increase in urban and industrial growth and the need for building on lands formed with soft clay. Therefore, it is necessary to perform land reclamation to be able to use ecologically problematic lands. To upgrade unproductive land, it is possible to use ground improvement techniques.

The soft soil is extensively located in many areas which usually have a low bearing capacity, low permeability, and high compressibility, and insufficient strength [1], [2]. The cohesive soil has a flocculated structure which is unstable, and under the influence of increasing overburden and pressure, it will be compressed. Cohesive soils can be improved by using methods such as compaction piles, displacement and replacement; vacuum pre-consolidation, pre-consolidation using prefabricated vertical drains, and soil reinforcing [3]. The solutions for ground improvement primarily depends on the type of the soil present on the site ground, ground conditions, design loads, size of the treatment area and site location [1].

In many sites with weak ground conditions, the most economical approach is to improve the bearing capacity rather than attempt to pretermit the weaker soils with piled foundations. Ground improvement techniques are cost effective and can be applied by 50% of the costs of a piling scheme [4], [5]. Stone columns are one of the most cost effective and environmentally friendly techniques that are installed into the soft soils to improve the soil problems. This technique can decrease the excessive and differential settlement and the shear strength and also can accelerate the consolidation progress [6]-[8]. In this method, the partial of unsuitable subsurface soils, are replaced with a compacted stone column that often completely permeates with the weak layers [7], [8]. Reference [9] declares that due to high permeability and the material components used in the stone column, not only the load carrying capacity of the soil raise, but also it reduces the soil settlement considerably and minimizes the post construction settlements. In fact, the stone columns also act as vertical drains thus induce rapid consolidation process. Moreover, compaction of granular materials during the installation processes and replacing the soft soils with stronger materials significantly increase the unit weight of the soil [1].

II. Methods of Construction of Stone Columns

Method of construction of stone column depends on the equipment availability and applicability. To create required strength of compacted column, the granular materials consisting of stone or stone sand should be compacted [9]. The following sections are briefly explained the principal construction methods based on available state of-the art literature.

A. Vibro-Replacement Method

This is one of the applicable methods of stone column installation that is widely used in cohesive soils. A mechanical vibratory unit called vibro-flot is employed to create a hole in the ground and then compact the granular materials in the hole (Fig. 1). Stone columns can be constructed either by wet process, or dry process based on equipment availability and the ground condition. Better depth

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of execution and high speed are the main advantages of this method [5], [10].

B. Vibro-Composer Method

This method is applicable to stabilize soft clay soils, especially in locations that the level of groundwater is high. The prevalent of pile diameter that can be conveniently constructed using this method is 600–800 mm. The granular compactions are constructed by penetrating the casing pipe to the desired depth using a heavy, vertical vibratory hammer located at the top of the pipe. The casting pipe is repeatedly extracted and partially redriven to the soil using the vibratory hammer starting from the bottom (Fig. 2). The process is frequently repeated until a fully penetrating compacted granular pile is constructed [9], [11].

C. Cased Borehole Method or Rammed Columns

In this method, the stone columns are implemented in several stages by compacting granular materials in the pre-bored holes via heavy falling weight which are usually between 15 to 20 KN from a height of 1.0–1.5 m (Fig. 3). This method becomes uneconomical and very slow when the depth increases more than 12-15 m [9], [11].

III. Performance Mechanism

The design load for stone column is approximately between 20 and 50 tons. Usually 15 to 35 per cent of the weak soil is replaced by stone. There is a remarkable difference between shear strength of the native soil and the stone column replacement. This presence gives a complex of a material with lower overall compressibility and higher share strength. The vertical stress at the ground surface applies to the stone and the weak soil move downward. It causes stress concentration within the stone column which is primarily due to higher stiffness of the column than the soil. A large bulge with a depth of 2-3 meters beneath the surface will take place resulting from axial load. This bulge raises the stress within the clay which provides extra confinement for the stone. A single stone column will experience more bulging than a group of stone column loaded over the entire area. The confinement of stone column reduces when an embankment is constructed over a soft ground since the lateral spreading of the ground occurs beneath the embankment. The relative displacement (slip) may also occur between the stone column and surrounding soil at higher stress levels. The incidence of either lateral spreading or slip eventuates in greater settlement of stone column and improves ground than when otherwise occur [11], [12].

IV. Stone Column Uses

Basically, stone column method has proven successful in (1) enhancing slope stability of natural slopes and embankments (2) improving the bearing capacity (3) decreasing total and differential settlements (4) proving less possibility of sand liquefaction and (5) increasing the time rate of settlement. Stone columns are constructed to improve the soil characteristics, support the structure overlying both in very soft to firm cohesive soils and also loose silty sands having greater than about 15 percent fine aggregates [11]. Stone columns have been used successfully in many projects worldwide including embankment fill support, highway facilities, bridge abutments, structures, railroads and wharf structures. In Europe, however, stone columns have been used more extensively to support structures such as warehouses, tanks and buildings rather than embankments. In Japan, stone columns have been used widely for the support of fills, embankments, tanks, and structures. Stone columns can also be used to stabilize existing slopes and also to reduce the liquefaction potential of cohesion less soils surrounding existing or proposed pile foundations as well as supporting embankments, abutments and beneath shallow foundations in earthquake prone areas [11].

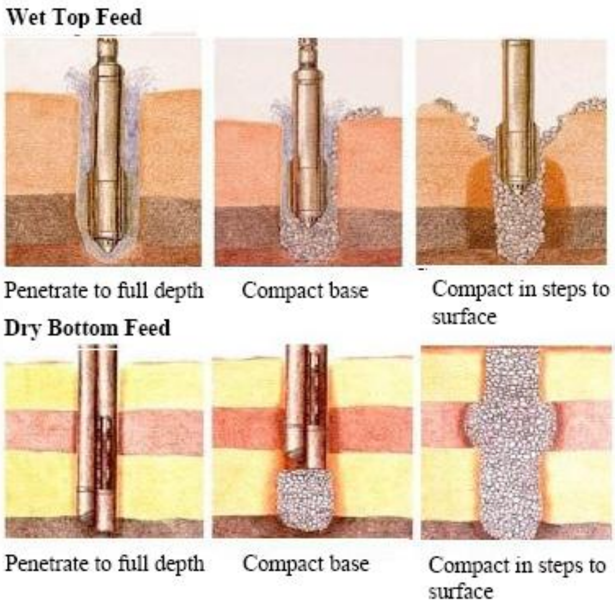


Fig. 1. Vibro-replacement method -wet and dry process.

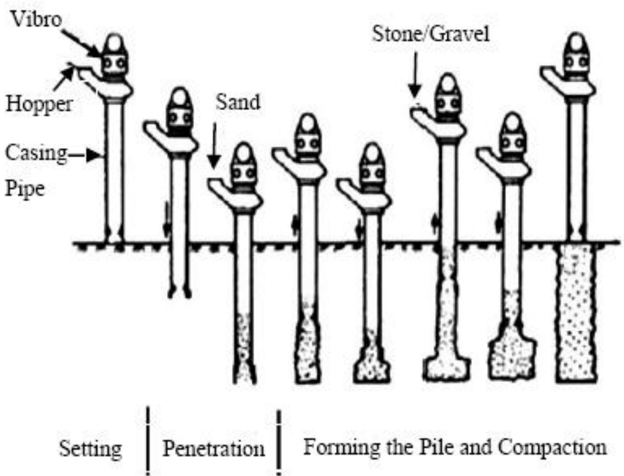


Fig. 2. Vibro-composer method [9].

V. Basic Design Parameters

A. Stone Column Diameter, D

The vibration or ramming causes lateral displacement, therefore, the created diameter of the hole is always bigger than the diameter of the casing. In vibro-flot method, the stone column diameter varies between 0.6 m in case of stiff clays to 1.1 m in very soft cohesive soils. The stone column diameter constructed by wet technique is bigger than that of a dry technique [13]. The stone column diameter by using rammed process is between 400 to 750 mm. The length of stone column, maximum and minimum densities of the stone effectively impact on the diameter of the stone column in the field [9].

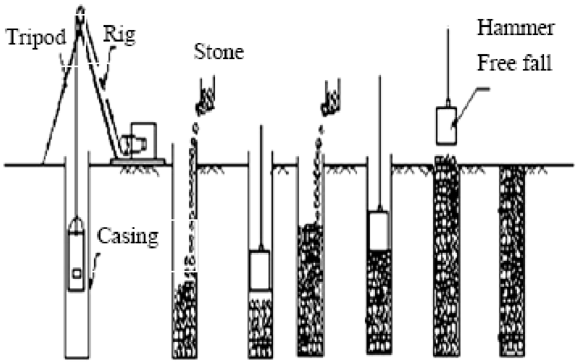
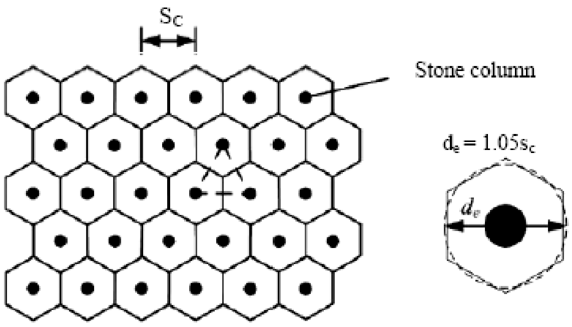
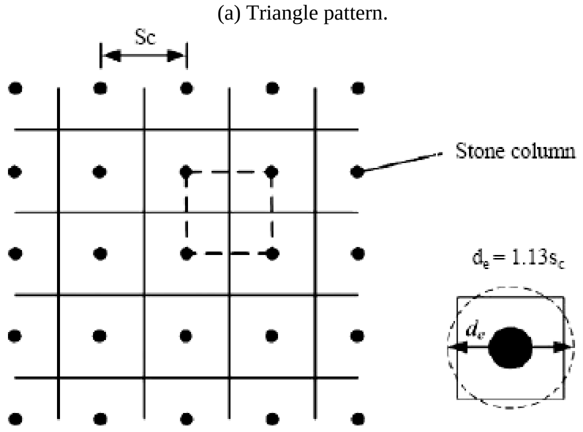


Fig. 3. Cased borehole method [9].



(a) Triangle pattern.



(b) Square pattern.

Fig. 4. Typical stone-column installation patterns and the equivalent diameters: (a) triangular pattern; (b) square pattern [9].

B. Pattern and Spacing

The square pattern is a possible installation of stone column, but the most optimum and desirable installed shape is the triangular pattern since it gives the most dense and compacted packing of stone columns in a given area. The layouts of these two patterns are shown in Fig. 4.

Note that the value of spacing, S_c and diameter, d_c significantly impact on the settlement; large value for diameter and a small amount of spacing reduce the settlement [14].

The spacing of stone columns is generally determined by the design load, the degree of improvement required for providing a satisfactory foundation, specific stone column factors, soil tolerance, construction site circumstances and the process of installing. Reference [9] stated the practical experience shows that closer spacing is preferred under isolated footings than beneath large rafts. However, the column spacing may broadly range from 2 to 3 times the diameter of the column.

C. Replacement Ratio

To quantify the volume of soil substituted by the stone column, the area replacement ratio is defined a_s (Eq. 1). It introduces the ratio of the area of the stone column after compaction (A_s) to the total area within the unit cell (A) where D and D_e are diameter of stone column and triangular pattern respectively [15] (Fig. 4 and Fig. 5). It is strongly recommended that to improve bearing capacity of treated ground significantly by stone column, it requires an area replacement ratio of 0.25 or greater [16].

$$a_s = As / A \tag{1}$$

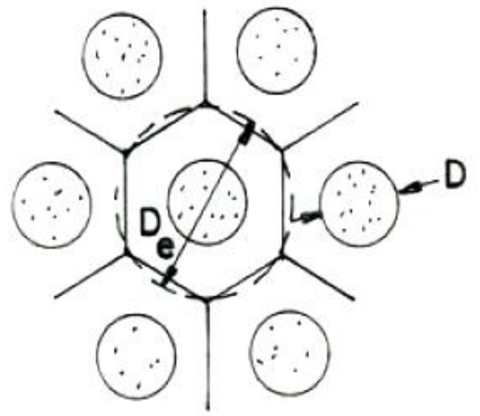


Fig. 5. The stone column is concentric to the exterior boundary of the unit cell [9].

D. Stress Concentration Factor

After loading the stone column reinforced ground, concentration of stress occurs in the stone column, and an accompanying decline in stress occurs in the surrounding softer soil. Concentration Factor (n) is the ratio of stress in the stone column (σ_c) to the stress in the surrounding cohesive soil (σ_s). The amount of stress concentration depends on the stiffness of stone column and the surrounding soil of the stone column. Generally, the value of "n" is between 2 to 6. The stress in the clay and stone using the stress concentration factor n are calculated using the following equations:

$$n = (\sigma_s) / (\sigma_c) \tag{2}$$

$$\sigma = \sigma_s a_s + \sigma_c (1 - a_s) \tag{3}$$

$$\sigma_c = \sigma / [1+(n-1)\, a_s] = \mu_c \sigma \tag{4}$$

$$\sigma_s = n\sigma / [1+(n-1)\, a_s] = \mu_s \sigma \tag{5}$$

where μ_c and μ_s are related to the replacement ratio and stress concentration factor. The above equations are significantly useful in both settlement and stability analysis.

Stress concentration factor increases with the time of consolidation as well as increasing in the area replacement ratio. Stress concentration factor reduces along the length of the column and also when the applied load is increased [9].

E. Backfill for Stone Columns

Crushed stone or gravel for the column backfill shall be clean, hard, unweathered stone free from organics, trash or other deleterious materials. To select the efficient backfill type, three criteria of availability, suitability and economy should be considered. A mixture of crushed stone and sand may also be used in proportion of 1:0.2–0.5 by volume.

VI. Critical Column Length

The results of past researches state that the stone column bulging was more distinguished in the upper portion of the column. It was found also that the depth of the bulging can be considered to be approximately four times the diameter of the column [17]. Reference [18] states that the diameter of stone column has more impact on the depth of bulging zone rather than depth ratio and strength of soil. Moreover, the critical column length is the shortest column which can carry the ultimate load regardless of settlement. The outcomes of experimental investigation indicated that the critical column length is roughly 6 times the diameter [19]. Although, the stone columns that are longer than the critical length did not indicate an increase in load-carrying capacity, longer columns may be needed to control the settlements [9].

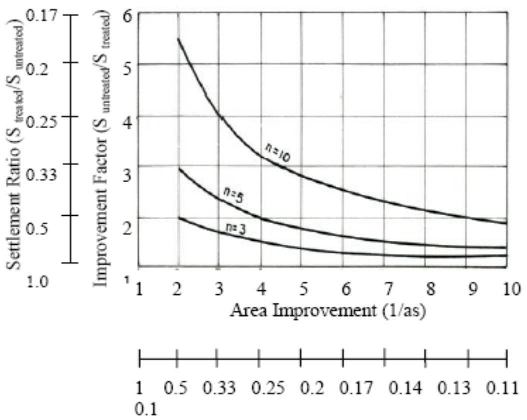


Fig. 6. Maximum reductions in settlement that can be obtained using stone columns equilibrium method of analysis [11].

VII. One-Dimensional Analysis of the Composite Ground Settlement

Based on the dataset, the settlement reduction of reinforced ground with stone columns significantly depends on the group effect, the replacement factor, and the consolidation of the soft soil. Most of the approaches in estimating settlement of loaded area reinforced with stone columns have a constant diameter and spacing. To estimate the reduction in settlement of ground improved with stone columns, a very simple equilibrium method offers realistic engineering approach. Settlement reduction ratio (R), which is the ratio of settlement of the stone column improved ground to the unimproved ground, is given by:

$$R = S_t / S = \log_{10}\left((\sigma_0 + \mu_c \sigma) / \sigma_0\right) / \log_{10}\left((\sigma_0 + \sigma) / \sigma_0\right) \quad (6)$$

For very large σ_0 (long length of stone column) and very small applied stress σ, the settlement ratio relatively rapidly approaches

$$S_t / S = 1 / [1 + (n\text{-}1)\, a_s] = \mu_c \quad (7)$$

where, S_t is settlements of the stone column improved ground and S is the settlements of unimproved ground. R is the ratio of S_t to S. σ_0 is the average of initial effective stress in the clay layer, σ_c is change in stress in the clay layer due to the externally applied loading, and σ is the average of externally applied stress. The equation (6) shows that the improvement depends on the stress concentration factor (as reflected in μ_c), initial effective stress in the clay, and the magnitude of applied stress. It illustrates that, if other factors are constant, a greater reduction in settlement is gained for longer columns and smaller applied stress increments [9]. The equation 7) is shown graphically in Fig. 6.

A. Illustrative Example

1) One-dimensional analysis

This example illustrates calculating settlements of soft clay reinforced with stone columns and loaded by a wide fill. The site consists of 6m of grey, soft silty clay overlying a firm to dense sand. The groundwater table is at the surface. An equilateral triangular pattern of stone columns is used having a spacing of 2m. The diameter of the stone column is estimated to be 1m and a 0.75m sand blanket is to be placed over the soft silty clay for a working platform and drainage blanket (Fig. 7).

$$\sigma = 3.8\text{m} \times 1920\text{kg/m}^3 + 0.75\text{m} \times 1730\text{kg/m}^3 = 8593.5\text{kg/m}^2 \quad (8)$$

$$a_s = C_1 (D/s)^2 = 0.227 \quad (9)$$

where D is the diameter of the compacted stone columns, S is the space of the stone columns and C_1 is a constant dependent upon the pattern of stone columns used in which for a square pattern $C_1=\pi/4$ and for an equilateral triangular pattern $C_1=\pi/(2\sqrt{3})$.

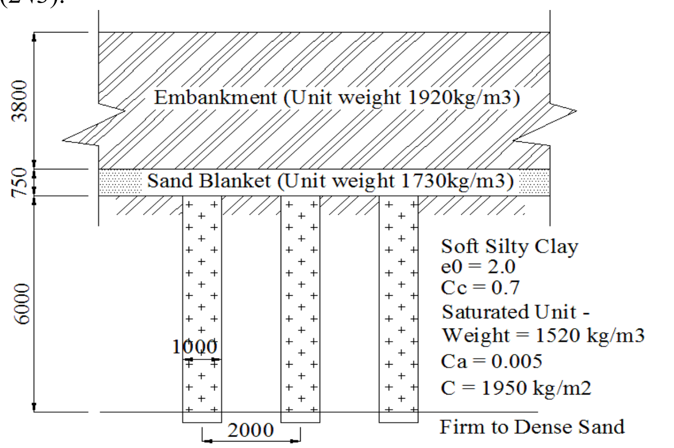


Fig. 7. Wide fill over stone column improved silty clay.

$$n = \sigma_c / \sigma_s \quad (10)$$

The stress concentration factor assumes to be 5.0. The stress concentration factor μ_c in the clay is given in (11).

$$\mu_c = 1 / [1+ (n\text{-}1)\, a_s] = 1/[1+ (4) \times 0.227] = 0.524 \quad (11)$$

$$\sigma_0 = 3\text{m} \times (1520\text{kg/m}^3 - 1000\text{kg/m}^3) = 1560\text{kg/m}^2 \quad (12)$$

$$\sigma_c = \mu_c\, \sigma = 0.524\ (8593.5\text{kg/m2}) = 4503\text{kg/m}^2 \quad (13)$$

The primary consolidation settlement in the clay layer from one-dimensional consolidation theory is from (14) as

$$S_t = (Cc / (1+e_0)) \times \log ((\sigma_0 + \sigma_c) / \sigma_0)\, H \quad (14)$$

$$S_t = (0.7 / (1 + 2)) \log ((1560\text{kg/m}^2 + 4503\text{kg/m}^2) / 1560\text{kg/m}^2) \times (6\text{m}) = 825\text{mm}$$

The settlement of unimproved ground is from following equation.

$$S = (0.7/ (1+2)) \log ((8593.5\text{kg/m}^2 + 1560\text{kg/m}^2) / 1560\text{kg/m}^2) \times (6\text{m}) = 1139\text{mm} \quad (15)$$

According to (6), the settlement reduction ratio R is

$$S_t / S = 825\text{mm} / 1139\text{mm} = 0.724 \quad (16)$$

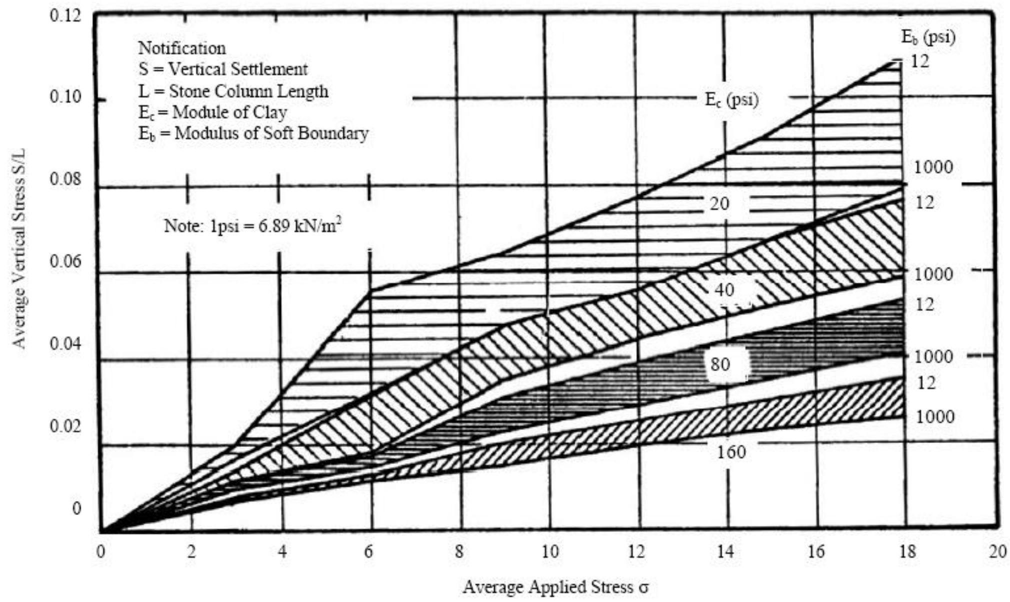


Fig. 8. Nonlinear finite element unit cell settlement curves: as = 0.25, L/D= 5 [11].

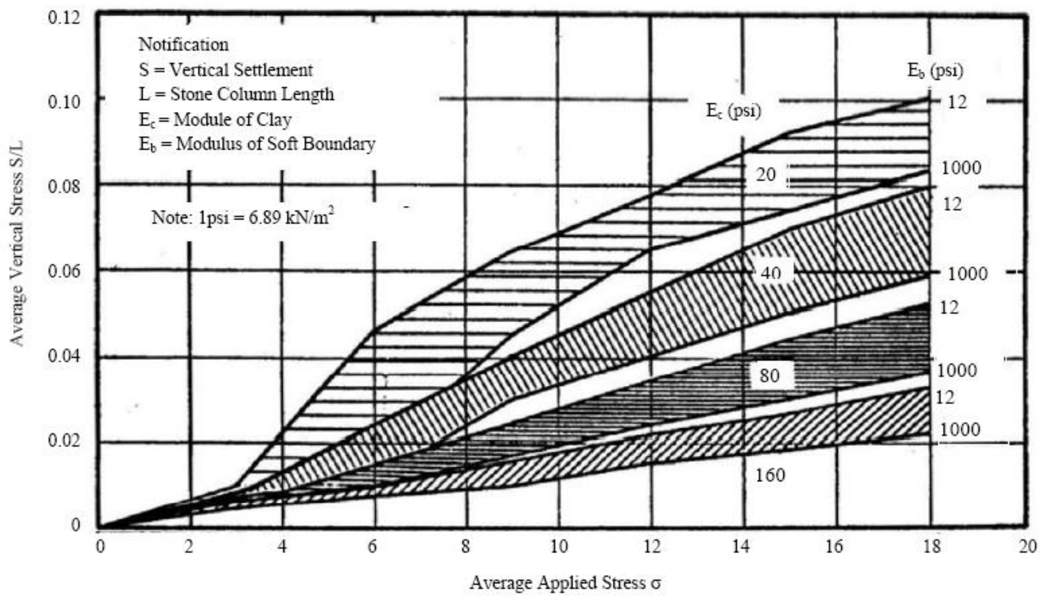


Fig. 9. Nonlinear finite element unit cell settlement curves: as = 0.25, L/D= 10 [11].

2) Simplified nonlinear finite element analysis

The Nonlinear Finite Element Analysis is based on the designs charts which are presented in Fig. 8 and Fig. 9 [20]. Due to (12) and (13), the initial average stress and the change in stress in the clay are 1560kg/m^2 and 4503kg/m^2, respectively. Using Table I, the drained Poisson's ratio of the clay is assumed to be 0.40. Note that the value of Poisson's Ratio selected has a remarkable effect on the calculated value of E_c: larger value of υ gives smaller values of Ec. The modulus of elasticity of clay for the applicable stress range is calculated by (17)

$$E_c = (1+\upsilon) \times (1\text{-}2\upsilon) \times (1+e_0) \times \sigma_{avg} / (0.435 \times (1\text{-} \upsilon) \times Cc) \quad (17)$$

$$\sigma_{avg} = (1560\text{kg/m}^2 + 4503\text{kg/m}^2) /2) = 3031.5\text{kg/m}^2 \quad (18)$$

Ec =14400kg/m = 20 psi

TABLE I: TYPICAL POISSON'S RATIO VALUES OF CLAY FOR DRAINED LOADING [11]

Soil Consistency	Poisson's Ratio
Very soft	0.35 - 0.45
Firm to Stiff	0.30 - 0.35
Stiff over consolidated Clays	0.10 - 0.30

The ratio of the length to diameter of stone column is taken as

$$L/D= 6m/ 1m = 6 \quad (19)$$

Interpolating from Figs. 8 and 9 for different S/L values are given in (20) and (21).

L/D=5, σ =12.2 psi and E_c=14400kg/m^2 = 20 psi =>> S/L= 0.078 (20)

L/D=10, σ =12.2 psi and E_c=14400kg/m^2 = 20 psi =>> S/L= 0.08 (21)

Thus, the effective ratio of the stone column settlement to the stone column length is obtained based on (20) and (21).

=>> For L/D=6, σ =12.2 psi and E_c=14400kg/m^2 = 20 psi

$$S/L = ((0.08-0.078) \times (6-5) / (10-5)) + 0.078= 0.0784 \quad (22)$$

The embankment settlement from the finite element method is taken as

$$S_t = 0.0784 \times 6m = 471mm \quad (23)$$

$$S_t / S = 471mm / 1139mm = 0.413 \quad (24)$$

VIII. COMPARATIVE PARAMETRIC STUDY

Increasing the diameter and decreasing the space significantly will impact and reduce the settlement. To consider these changes the diameter is increased from 1m to 1.2m and the space is reduced from 2m to 1.8m, thus,

One-Dimensional Analysis

$$S_t = 690 \text{ mm} \quad (25)$$

Nonlinear finite element method

$$S_t = 300 \text{ mm} \quad (26)$$

Moreover, the shape of pattern impacts on the settlement, diameter and space are 1m and 2m, respectively, but the pattern is changed from triangle to square pattern,

One-Dimensional Analysis

$$S_t = 855 \text{ mm} \quad (27)$$

Nonlinear finite element method

$$S_t = 480 \text{ mm} \quad (28)$$

As is seen, the one dimensional analysis leads to higher settlement. This may relate to low accuracy of finite element model. It is suggested to model the nonlinearity of material properties, interface slip and suitable boundary conditions to obtain to improve accuracy.

The results of the finite-element analysis have been defined by a detailed comparison with the results of one dimensional analysis. However, reference [20] states that the best settlement evaluation is the average of the finite element and One-Dimensional Analysis.

D = 1m S = 2m, triangular pattern

$$S_t = (471mm + 825) / 2 = 648mm \quad (29)$$

$$S_t / S = 648mm / 1139mm = 0.569 \quad (30)$$

D = 1.2m S = 1.8m, triangular pattern

$$S_t = (690mm + 300) / 2 = 495mm \quad (31)$$

$$S_t / S = 495mm / 1139mm = 0.435 \quad (32)$$

D = 1m S = 2m, square pattern

$$S_t = (855mm + 480) / 2 = 648mm \quad (33)$$

$$S_t / S = 668mm / 1139mm = 0.586 \quad (34)$$

In this case, the final results of samples analysis indicate that the settlement of unimproved soil with stone columns is approximately double of the similar soil reinforced with stone column. It is also shown that with using triangle pattern when the diameter increase and the space between stone columns decrease, the lowest settlement occurs.

IX. SUMMARY AND CONCLUDING REMARKS

Stone columns play a main role in the area of ground improvement. Stone columns are the best and applicable ground improvement technique in the areas consisting soft and soft compressible silts and clays, and also for loose silty sands.

Based on the available literatures and critical reviews on stone columns, some conclusions are made bellow:

In areas with cohesive soils, the stone columns generally constructed by ramming or vibro-replacement method either wet process or dry process. Stone columns act as a cost efficient method of ground improvement offer considerable contract program savings over other ground improvement techniques. In this method, the portions of the soils that are weak and unsuitable are replaced with compacted dense aggregate columns which are stiffer and stronger than the unimproved native soil. It often completely penetrates into the weak layers, and an increase in bearing capacity will occur. Beside of this, the stone columns act as drains and significantly reduce the time for primary consolidation to occur as well as total settlements and liquefaction potential. Based on the outcomes of past studies with physical modeling, mathematical analysis and full-scale testing, various parameters that influence overall performance of the technique have been highlighted. These are column length, strength of the column material, area replacement ratio, column spacing, strength of the column material, and installation method.

A one dimensional analysis as well as simplified FE modeling are introduced and then examined with an illustrative example. The results show that the one dimensional analysis has higher settlement reduction than the FEM. However, the accuracy of the finite-element results may arise because in finite element technique, nonlinear material properties, interface slip and suitable boundary conditions can all be realistically modeled. It requires further research in order to get a deeper understanding of the applications. Additional studies by the authors are planned to improve the accuracy of the presented simplified FEM using the most recent available commercial software.

To that end, the results indicate that the settlement of unimproved soil with stone column is approximately double for the reinforced soil with stone column. In addition, when the diameter of triangle pattern increases and the space decreases the lowest settlement occur.

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