Ground Improvement by Stone Columns - A Case Study

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ABSTRACT

Stone columns have been widely used as a cost-effective, fast and environmentally friendly ground improvement method. Stone columns improve the load-bearing capacity, reduce settlement and mitigate liquefaction of soft subsoil under structures like liquid storage tanks, earthen embankments, raft foundations etc. This paper first presents the basics of the stone column technique and discusses the design considerations, applications, advantages and limitations of this method. Then a case study of stone column installation under oil tank foundations and auxiliary buildings for a bunker terminal project in the Middle East is elaborately explained. Geotechnical investigation data of the project site revealed subsurface conditions comprising of very loose to loose and medium silty sand with low SPT N values for the top 13m depth in some boreholes. This necessitated ground improvement to meet the high bearing capacity requirement of 250kPa and 300kPa under marine gas oil tank, fuel oil tank and other structures and to achieve settlement criteria of a maximum uniform settlement of 50mm and 100mm during operation and hydrotest, respectively. As the soil profile varied across the tanks, stone columns of 0.9m in diameter with a grid spacing of 2-3m square and varying treatment, depths have been used. The design procedure, construction method and verification or confirmatory tests adopted for the successful delivery of the project is also covered in this study.

Keywords: Ground improvement, Stone columns, bearing capacity, oil tank.

RÉSUMÉ

Les colonnes en pierre ont été largement utilisées comme méthode d'amélioration des sols rentable, rapide et respectueuse de l'environnement. Les colonnes en pierre améliorent la capacité portante, réduisent le tassement et atténuent la liquéfaction du sous-sol mou sous les structures telles que les réservoirs de stockage de liquide, les remblais en terre, les fondations des radeaux, etc. Cet article présente d'abord les bases de la technique des colonnes en pierre et discute des considérations de conception, des applications, avantages et limites de cette méthode. Une étude de cas sur l'installation de colonnes de pierre sous les fondations de réservoirs de pétrole et les bâtiments auxiliaires pour un projet de terminal de soutes au Moyen-Orient est expliquée en détail. Les données d'investigation géotechnique du site du projet ont révélé des conditions souterraines comprenant du sable limoneux très lâche à lâche et moyen avec de faibles valeurs de SPT N pour la profondeur supérieure de 13 m dans certains forages. Cela a nécessité une amélioration du sol pour répondre à l'exigence de capacité portante élevée de 250 kPa et 300 kPa sous le réservoir de gazole marin, le réservoir de mazout et d'autres structures et pour atteindre les critères de tassement d'un tassement uniforme maximum de 50 mm et 100 mm pendant le fonctionnement et l'hydrotest respectivement. Comme le profil du sol variait d'un réservoir à l'autre, des colonnes de pierre de 0,9 m de diamètre. avec un espacement de grille de 2-3m carré et un traitement variable, des profondeurs ont été utilisées. La procédure de conception, la méthode de construction et les tests de vérification ou de confirmation adoptés pour la bonne exécution du projet sont également couverts dans cette étude.

1.Introduction

Due to the rapid increase in infrastructure growth, construction is now carried out in poor ground conditions, which was otherwise considered uneconomic to develop. Structures constructed on such soils may experience problems, such as excessive settlements, large lateral flow and slope instability. A number of methods are available to improve soft soils, such as stone columns, soil-cement columns, vacuum pre-consolidation, pre-fabricated vertical drains, lime treatment etc.. Among all these methods stone column techniques or vibro replacement method has gained popularity worldwide in improving weak foundation soil and has been in use for the last few decades. It has a successful history in developing stable ground, which allows safe and economic construction of residential and light commercial and industrial structures. This ground improvement technique also found effective applications under large area loadings like embankments, tank farms and fills for the control of total and differential settlements.

Stone columns derive their resistance by means of bulging, which causes passive pressure to be developed in the surrounding soil. The enhanced drainage effect offered by stone columns allows for the reduction of consolidation time and compressibility, and the increase of load-bearing capacity and shear strength. The theory of load transfer, estimation of ultimate bearing capacity and prediction of the settlement of stone column was developed by numerous researchers (Greenwood,1970; Hughes et al. 1974; Priebe 1976).

This paper reviews the basic mechanism of stone column technique, its construction methods and design considerations, and finally, a case study of stone column application for fuel storage tanks and its auxiliary structures employed for a project in the Middle East is also presented.

2. Stone column technique

The stone column technique, also known as vibro-replacement or vibro-displacement, is a ground improvement process where vertical columns of compacted aggregate are formed through the soils. The technique has been used since the 1950's for improving both cohesive soils and silty sands (Barksdale and Bachus, 1983). These columns result in considerable vertical load-carrying capacity and improve shear resistance in the soil mass. Stone column construction involves the partial replacement of unsuitable subsurface soils (usually 15 to 35 percent) with a compacted vertical column of stone that usually completely penetrates the weak strata. Design loads on stone columns typically vary from 20 to 50 tons.

The presence of the column creates a composite material of lower overall compressibility and higher shear strength than the native soil alone. Confinement, and thus stiffness of the stone, is provided by the lateral stress within the weak soil. When loaded, the stone columns deforms by bulging into the subsoil strata and distributes the stresses at the upper portion of the soil profile rather than transferring the stresses into deeper layer, unlike in case of pile foundation, thus causing the soil to support it. The resulting stress concentration in the stone is primarily due to the column being stiffer than the soil.

The most improvement due to stone column has been found in compressible silts and clays occurring near the surface and ranging in shear strength from 15-50 kN/m^2. The greatest economic advantage is generally realized if the depth to the bearing strata is between about (6-10 m). Stone columns, if installed in loose sands, minimize the likelihood of liquefaction of these deposits due to earthquakes because of their tendency to dilate while shearing and dissipate the excess pore pressures generated (Mitchell and Huber 1985). The component material being granular and with higher permeability, stone columns could also accelerate the consolidation settlements and minimize the post construction settlements. Moreover, in situ stress conditions get improved due to the installation of the stone columns.

3. Construction of Stone columns

The construction of stone columns involves creation of a hole in the ground which is later filled with granular material. The granular fill consisting of stone/ gravel or stone sand mixture of suitable proportion, is compacted by suitable means to create a compacted column of required strength. Stone columns can be installed either by wet or dry method as described in the below sections depending on the site characteristics (Mosley et al.1993) The equipment essentially consists of a vibrator, which is elastically suspended from extension tubes with air or water jetting systems, and supported by a crane or base machine. The system also includes provision for stone delivery, control and verification devices.

3.1 Vibro-Replacement (wet)

In the vibro-replacement (wet) method, a hole is formed in the ground by jetting water under high pressure from the vibrator tip which allows a probe down to the desired depth. The uncased hole is flushed out and then stone is added in (0.3-1.2 m) increments and densified by means of an electrically or hydraulically actuated vibrator located near the bottom of the probe. The wet process is generally used where borehole stability is questionable. Therefore, it is suited for sites underlain by very soft to firm soils and a high ground water table. Stones or gravel of size ranging from 30mm to 80mm are used as backfill material in the wet process.

3.2 Vibro-Displacement(dry)

The vibro-displacement method is a dry process sometimes referred to as vibro-replacement. The main difference between vibro-displacement and vibro-replacement is the absence of jetting water during initial formation of the hole in the vibro displacement method. The equipment used typically consists of specially designed machines, known as vibrocats, which have vertical leaders. The vibrocats control the complex bottom feed vibrators, equipped with material lock and storage units, which deliver fill material to the vibrator by means of specialised mechanical or pneumatic feeding devices as shown in Figure 1.
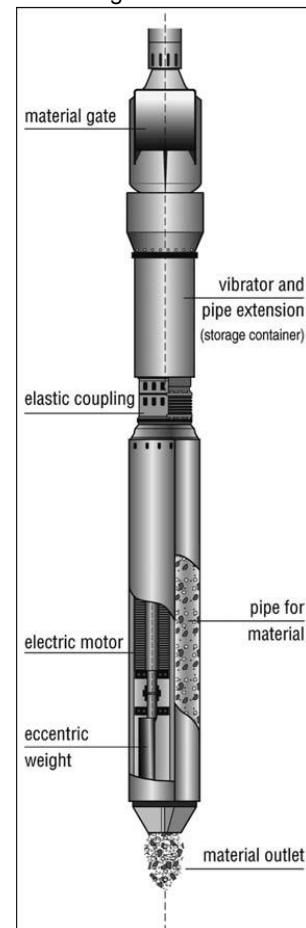

Figure 1. Details of a Bottom feed vibrator (Keller)

To be able to use the vibro-displacement method the vibrated hole must be able to stand open upon extraction of the probe. Therefore, for vibro-displacement to be possible soils must exhibit un-drained shear strengths in excess of about (40-60 kN/m^2), with a relatively low ground water table being present at the site. Grain diameter of fill material when using dry bottom feed

method ranges from 10mm to 40mm. Dry method is known to create columns with diameter ranging from 0.6m to 1.0m.

4.Basic Design Considerations of Stone Column

For purposes of settlement and stability analysis, it is convenient to associate the tributary area of soil surrounding each stone column as illustrated in Figure 2. The tributary area can be closely approximated as an equivalent circle having the same total area. For an equilateral triangular pattern of stone columns the equivalent circle has an effective diameter (d_e) of 1.05 s and for a square grid it is equal to 1.13 s, where "s" is the spacing of stone columns. The resulting equivalent cylinder of material having a diameter d_e enclosing the tributary soil and one stone column is known as the Unit cell.
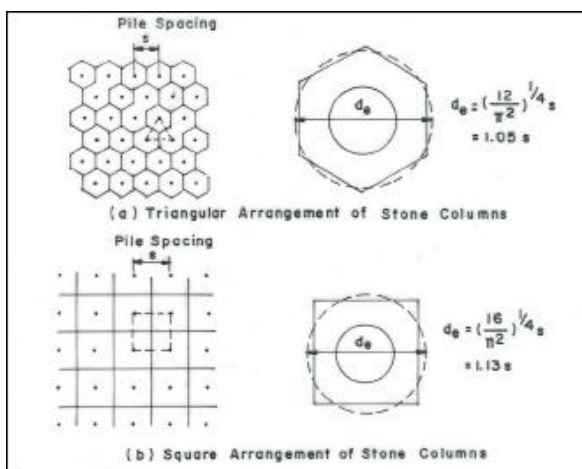

Figure 2. Typical layout of stone column

The design procedure proposed by Priebe (1995) is a widely accepted method in which the unit cell approximation is used for the analysis of stone column with the assumptions that the column is based on a rigid layer, the column material is incompressible, and the unit weight of column and soil is negligible. Hence, the column cannot fail in end bearing, and any settlement of the load area results in a bulging of the column, which remains constant all over its length.
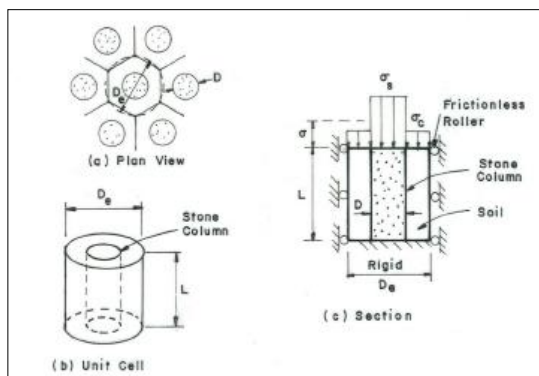

Figure 3. Unit cell idealization (Barksdale & Bachus,1983)

4.1 Area Replacement Ratio

The volume of soil replaced by stone columns has an important effect upon the performance of the improved ground. The amount of in-situ soil replaced by the granular column within a unit cell can be quantified by the area replacement ratio as which is defined as the ratio of the area of the stone column after compaction (A_C) to the total area within the unit cell (A).

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

4.2 Stress Concentration factor

When the stone column reinforced ground is loaded, concentration of stress occurs in the stone column, and an accompanying reduction in stress occurs in the surrounding less stiff soil. The distribution of vertical stress within a unit cell can be expressed by a stress concentration factor "n" defined as the ratio of the stress in the stone column (σ_s) to the stress in the surrounding cohesive soil (σ_c). The magnitude of stress concentration depends on the relative stiffness of the stone column and the surrounding soil. The value of n generally lies between 2 and 6 with values of 3–4 usual, at the ground surface. The stress concentration factor (n) increases with time of consolidation. For a given stress concentration ratio, the stress on the surrounding soil can be determined by the following equation

$$\sigma = \sigma_s\, a_s + \sigma_c\, (1\text{-}\, a_s) \tag{2}$$

4.3 Basic Improvement Factor

The improvement of soil due to a stone column is evaluated on the assumption that the column material shears from the beginning whilst the surrounding soil behaves elastically. The soil displacement due to column installation occurs to the extent that the coefficient of earth pressure Ks=1. The improvement factor (the ratio of settlement with and without column), assuming a Poisson's ratio μ_s =1/3, is given by the following equation

$$n_0 = 1 + \frac{Ac}{A}\left[\frac{5-Ac/A}{4\,K_{ac}(1-Ac/A)} - 1\right] \tag{3}$$

where K_{ac} is the active earth pressure coefficient

The relation between the improvement factor n_o, the reciprocal area ratio A/Ac and the friction angle of column material φ_c is illustrated in the following Figure.
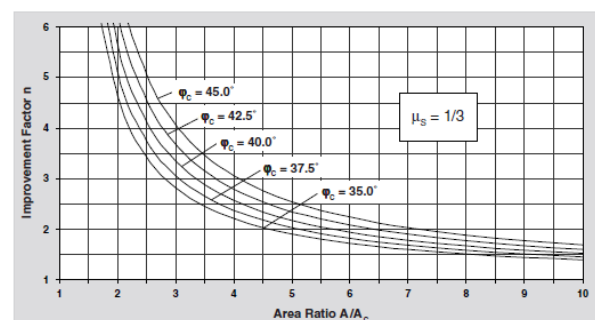

Figure 4. Design chart for Vibro replacement (Priebe,1995)

5. Failure Mechanisms and limitations

Stone columns may be constructed as either end bearing on a firm stratum underlying soft soil, or as floating columns with the tip of the column embedded within the soft layer. Either end bearing or free-floating stone columns greater than about three diameters in length fail in bulging, as shown in Figure 5. A very short column bearing on firm support will undergo either general or local bearing capacity type failure at the surface. Finally, a floating stone column less than about 2 to 3 diameters in length may fail in end bearing in the weak underlying layer before a bulging failure can develop.
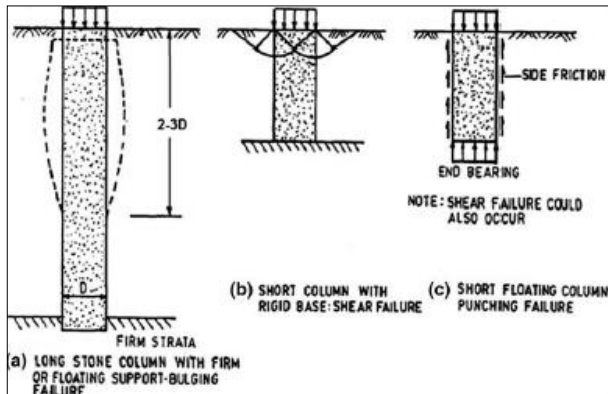

Figure 5. Failure mechanism in a single stone column(Barksdale & Bachus,1983)

When stone columns are installed in very soft clays squeezing of stones occurs due to low lateral confinement from surrounding soil and more quantity of stones are required than anticipated. The surrounding clay may also get intruded into stone aggregates and limits the bearing capacity of the column.

6. Case Study

6.1 Project Description

The project site considered for the case study is the development of a bunker terminal in the Middle East consisting of five nos of oil tanks (with diameters 20m and 26m and heights 17m and 20m) and its auxiliary structures like office building, pump station, substation etc. The geotechnical contracting company Keller had been appointed for the ground improvement works for the project site. Based on the past history of soil densification works at the vicinity of the same site stone columns has been proposed for the improvement of the project area.

The objective of the ground improvement works by stone columns is to achieve design bearing capacities of 250kPa for marine gas oil tank and 300kPa for fuel oil tank and differential settlement of 0.003 x radius of the tank. For buildings and other structures, bearing capacity of 200kPa should be achieved for a max allowable settlement of 25mm. The maximum uniform settlements to be achieved during operation and hydrotest of tanks are 50mm and 100mm respectively.

6.2 Soil Conditions

The site is located on a flat backfilled land at an elevation of 5m to 7m from Mean Sea Level. The soil investigation data reveals that the site essentially consists of medium dense, light green, calcareous, slightly gravelly, silty, fine to medium SAND with cobbles and boulders up to 13m to 15m followed by extremely weak to very weak, locally weak, light grey to greenish-grey, MARL with occasionally thinly bedded calcarenite to a depth of 30m. Furthermore, an un-symmetric pattern of N-value was observed in different boreholes(Figure 6). The groundwater table was recorded at a depth of 4.3m to 4.5m below the existing ground level.
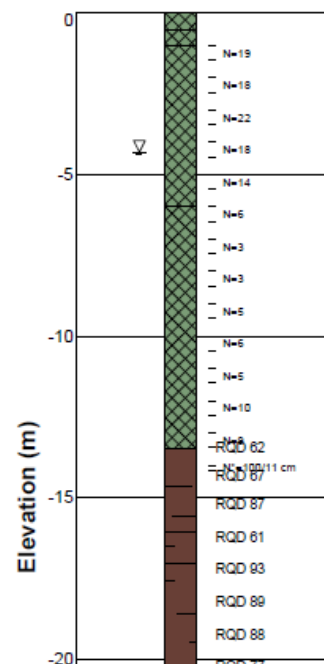

Figure 6. Generalized subsurface profile

6.3 Installation of stone columns

Based on the site characteristics, availability of equipment and past experience, the wet method of installation has been chosen for the project, as shown in Figure 7. Around 2000 stone columns of 0.9m diameter, spaced at 1.8m to 3m c/c in a square grid with varying treatment depths, were installed using depth vibrators. Due to the variation in soil profile across the tanks column depth ranging between 4.7m to 13m was used economically. Stone aggregates of grain diameter 25mm to 100mm were used as backfill material for the columns. Structural fill of 0.3m thickness has been considered as load transfer platform above the stone column heads.

Equipment used comprised of a vibrator, long heavy tube, power supply system and a high-pressure water pump. Extension tubes are added as necessary, and the whole assembly is suspended from a crane. With the electric power and water supply switched on, the vibrator is lowered into the ground. The probe was penetrated to the desired depth and was hold for designed time or designed amperage, whichever occurred earlier before extraction. Then the vibrator was pulled up in short steps of 0.5m vertical interval, and the resulting crater was filled with stone aggregates and compacted to form the stiffer column.
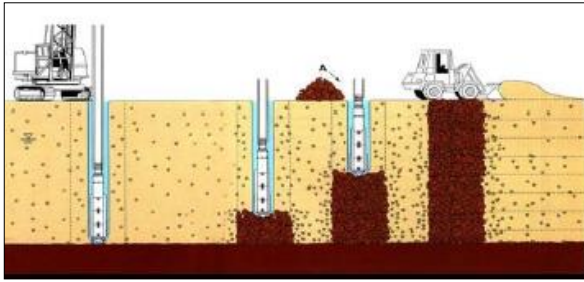
Figure 7. Wet top feed method of stone column installation (Keller Foundation)

6.4 Monitoring and Verification

The complete process of probe penetration and stone column formation was monitored using real-time automated computerized data logging system. The instrument keeps a computer record of the installation process in a continuous graphical mode, as shown in Figure 8 and information including date and time of installation, power consumption, reference number of the probe and maximum depth can be retrieved for each stone column. The consumption of backfill material was also recorded at different stages of the project to verify the effectiveness of installation works.

For the verification of ground improvement works Zone Load Tests and Plate Load Tests were conducted within the treatment area at various footing locations. Zone load tests were performed on a group of stone columns at selected location using a 2.5m x 2.5m concrete footing loaded up to 1.50 times design bearing pressure. From the working zone load tests, modulus of elasticity of the improved ground after stone column works is estimated using the values obtained from the load-settlement graph. These improved E-Modulus values were used to calculate the post improvement settlement and compared with target limits.

Plate Load Tests were performed by using a steel plate of 700mm diameter. The test plate was loaded to a maximum of 1.50 times the design load using a hydraulic jack with a ram area of 70.9 cm^2. Settlements were measured using dial gauges mounted on the plate with their spindles on the datum beams. The test results indicate that the settlement values are within the limit of the maximum value of 25mm.

7. Conclusion

Stone column or vibro replacement is a well-established ground improvement technique and proven to be effective in improving the bearing capacity and reducing post construction settlement in weak soil strata. Stone columns are applicable in a wide range of soils except for soils with a very low undrained cohesion offering very small lateral support. Depending upon the structure it supports (individual footing or rigid slabs), stone columns can be installed in small or large groups with varying grids. The case study of the stone column discussed in the present paper shows that vibro replacement is effectively applied under tank foundations meeting the higher bearing capacity requirements and stringent settlement criteria. Care must be taken to achieve optimum design in terms of spacing and depth of the stone column to obtain the economic benefit of this simple and environmental friendly technique. Real time monitoring , supervision and quality tests in the field should also be in focus to save time and cost of the project.
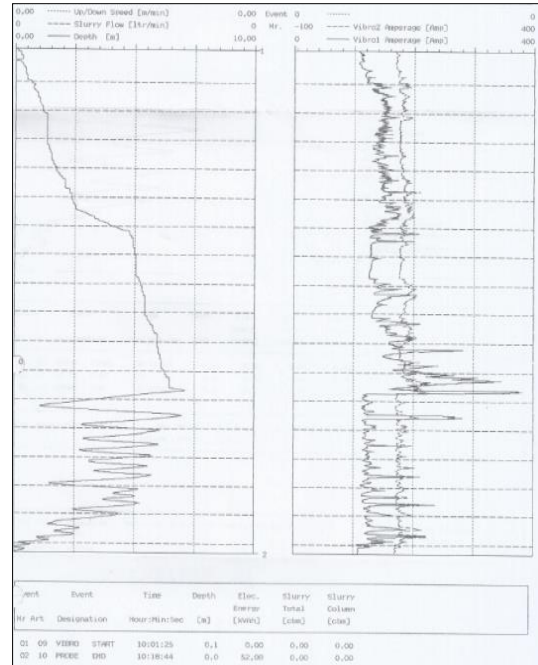

Figure 8. Real time monitoring of stone column installation (Keller)

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