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A Review of Methods of Increasing the Efficiency of Stone Columns to Ground Improvement

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Abstract- Soft clay soils there in many coastal areas. These soils generally have high compressibility and don't provide required bearing capacity. Various techniques are used to improve these soils. Among existing techniques, stone columns are known as quick and inexpensive method. The benefits of columns are: increasing the bearing capacity, reduction the total and differential settlements, acceleration the consolidation time and decreasing the liquefaction potential. Due to the poor performance of columns in very soft soils such as peat, various methods have been developed to increase the efficiency of the columns such as vertical encased, horizontal reinforced and construction of reinforced and unreinforced sand bed over the stone columns. This article presents a review of these existing techniques and evaluated the effectiveness of each of these methods.

Keywords- *Bulging, Encased Stone Columns, Sand Bed, Geogerid,*

I. Introduction

Deep vibratory method such as vibro-compaction and vibro-replacement are ground improvement techniques to improve the bearing capacity and settlement of weak soils. Vibro-compaction method was developed in 1936 by the Keller group to densify granular soils [1]. In this method, vibrator penetrates into the soil and by applying the lateral forces causes the soil particles to re-arrange into a denser state. This technique reaches its technical and economic limits in saturated sands with high silt contents, as fine particles attenuate the horizontal forces imparted by the vibrating poker [2]. Due to the limitations of vibro-compaction in cohesive soils, vibro stone columns were developed in the early 1950s. In this method, wen the vibrator poker penetrate the soil, the excavated borhole, backfilled in successive stages with coarse aggregate, which is compacted by re-lowering the poker. This process results in stone columns which are tightly inter-locked with the surrounding soil [3]. Stone columns can easily be constructed up to a diameter of 1.5 meter and typically replace 10–35% of the in situ soil [4]. Stone columns can be used to increase bearing capacity of the foundation, reduce total and differential settlements, increase the slopes stability, accelerate the consolidation time and decrease the liquefaction potential.

The stone columns derive their load capacity from the confinement offered by the surrounding soil. In very soft soils this lateral confinement may not be adequate and bulging occurs in the stone column. So far, several methods have been proposed to reduce the stone column bulging and subsequently increase the efficiency of stone columns in ground improvement such as vertical encasement and horizontal reinforcement of the stone column, stone column with vertical circumferential nails and construction of reinforced and unreinforced sand bed over the stone columns. In this paper a review of existing techniques to increase the efficiency of stone columns in ground improvement is done and the effectiveness of each is evaluated.

II. Vertical Encased Stone Columns(VESC)

Geosynthetic encased stone columns are used in very soft soils where insufficient lateral support is provided by the surrounding soil and excessive bulging of stone columns occurs during loading. The geosythetic material develops tensile forces which constrain the column. Due to the supporting effects of the encasement, in opposite to conventional stone columns, a special range of very soft soils (c_u < 15 kN/m²) such as peat or very soft silt/clay as well as sludge can be improved by this technique [5]. In a conventional stone column, the horizontal support of the soft soil must be equal to the horizontal pressure in the column. whereas in a GEC, the horizontal support of the soft soil can be much lower, due to the radial support effect of the geosynthetic [5].

Gniel and Bouazza [6] stated that the coarse aggregates like crushed rock may cause damage to the geotextile, furthermore, the column generally receives little compaction during installation to limit the damage caused to the geotextile by vibration, therefore geogrid encasement can be used as a more robust and perhaps stiffer alternative to geotextile and to broaden the appeal of geosynthetics in stone column ground improvement.

Gniel and Bouazza [7] compared the effect of geogrid encasement on behaviour of group column (unit cell) and isolated column using laboratory scale model testing. They conducted that The constrained conditions provided by unit-cell loading provide additional lateral confinement to the encased columns and prevent radial column failure. Whereas isolated columns failed by radial expansion below the level of encasement. They observed that fully-encased columns reduced vertical strain by about 80% when compared to clay behaviour alone. Effects of different encasement lengths in the case of isolated stone column are shown in Fig. 1.

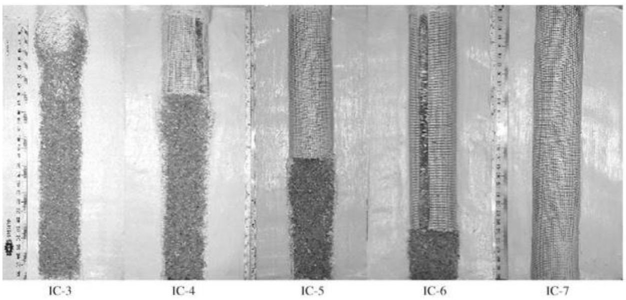

Figure 1. Photographs of extruded isolated column cross-sections. (effects of different encasement lengths) [7]

Murugesan and Rajagopal [8] performed load tests on single as well as group of stone columns with and without encasement. The loading on the ordinary stone column shows a clear failure, while the encased stone column did not show any signs of failure even at large settlement levels. Pressure-settlement responses of a group of stone columns is shown in Fig. 2. They stated finally that the encased columns act like semirigid piles.

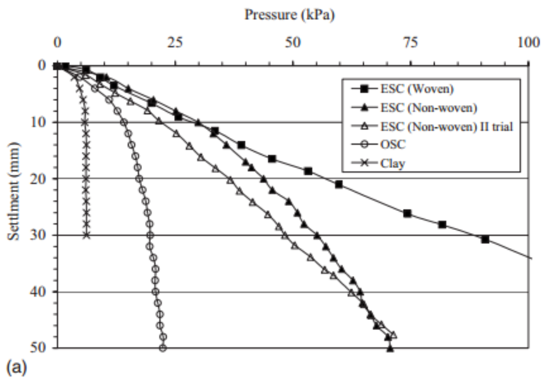

Figure 2. Pressure-settlement responses of a group of stone columns(75- mm diameter) [8]

III. STONE COLUMNS WITH VERTICAL CIRCUMFERENTIAL NAILS

Shivashankar et al. [9] suggested an alternative method to enhance the performance of stone columns in soft soils by inserting nails (small diameter steel bars) vertically along the circumference of the stone column (Fig. 2). They performed a series of laboratory model tests in a circular unit cell tank with the stone column at the centre and the soft soil surrounding it, to investigate the effect of vertical circumferential reinforcement on the strength, stiffness and bulging characteristics of stone columns in a soft soil bed. They studied influence of parameters such as depth of nails from the ground level, the number of nails, the diameter of nails, the diameter of stone column and area ratio. They observed that bulge diameter and bulge length are decreased substantially for a stone column reinforced with vertical circumferential nails. Also improvement in load-settlement characteristics observed with vertical circumferential nails. They concluded that performance of the model test is significantly enhanced by increasing the number of nails and diameter of nails.

It should be noted that the implementation of this method has not been reported so far in practice.

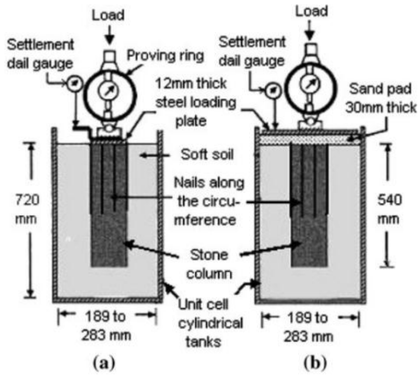

Figure 3. Test arrangement of stone columns with vertical circumferential nails : a) Load applied only on column area, b) Load applied on entire area [9]

IV. HORIZONTAL REINFORCED STONE COLUMNS (HRSC)

Stone columns can be reinforced by geosynthetic horizontal layers. This technique indicates improvement in the bearing capacity of stone columns. The degree of decrease in bulging and increase in load-carrying capacity depends on the number of reinforcement layers, the spacing between the reinforcement layers, and the angle of shearing resistance of the granular medium [10]. Based on numerical analysis, Madhav et al. [10] suggested that the greater the number of reinforcement layers and the closer the spacing, the lesser will be the bulging.

Several researchers studied the effect of horizontal layers of reinforcement in stone column material on the behaviuor of the stone column. For example, Sharma et al. [11] performed a series of tests on horizontal reinforced single stone column (HRSC) with diameter of 60 mm in a clay bed having a diameter of 300 mm and a thickness of 300 mm. Their results indicated bearing capacity increases with increasing number of reinforcement layers and reducing distance between reinforcement layers. Fig. 4 shows the stress–settlement curves for composite ground with a stone column (n=0) and with stone column reinforced with geogrids (n>0) placed at constant spacing (s=10mm). This figure clearly shows, improvement the stress–settlement behavior with increasing the reinforcement layers of geogrid.

Wu and Hong [12] reported an analytical method that investigated the stress–strain relation of granular columns reinforced with horizontal reinforcement. Nazari Afshar and Ghazazi [13] performed a series of tests on ordinary stone column (OSC), horizontal reinforced stone column (HRSC) and vertical encased stone column (VESC) with various diameters. Their results show that lateral bulging decreases using geotextiles and increasing strength of reinforcement. In addition, for both VESC and HRSC, the stress concentration ratio of the columns also increases.

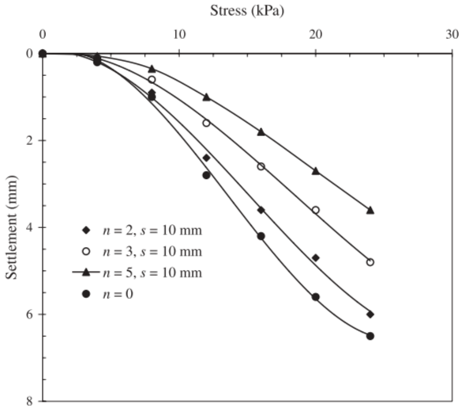

Figure 4. Effect of number of geogrids (n) on the stress–settlement response of composite horizontal reinforced ground [11]

V. GRANULAR BED ON STONE CLOUMNS IMPROVED GROUND

For drainage purposes, as well as distribution of the stresses coming from superstructures a granular layer of sand or gravel, with the thickness of 30 cm or more, is usually placed over the top of the stone columns [14]. Bulging and subsequent failure of granular pile occur near top of the granular pile due to high stress concentration in this region. These stresses are significantly influenced by the presence of granular bed [15].

Shahu et al. [15] developed a theoretical approach to analyze the behavior of soft ground reinforced by granular piles with granular mat on top, under a rigid foundation. The granular mat is assumed to be rigid and smooth. They concluded that placement of the granular bed on top of granular pile reinforced ground, leads to a desirable reduction in stress concentration ratio near the top of the pile and to reductions in normalized displacements, percentage load carried by granular pile at top and interface shear stresses.

Ambily and Gandhi [16] describes results of numerical analysis on effect of sand pad thickness on load sharing between column and soil (stress concentration ratio) (SCR) for both flexible and rigid loading condition in a unit cell. They concluded that in the case of rigid load, SCR decrease with increase in the t_{sand}/d (t_{sand} and d are sand thickness and stone column diameter, respectively) up to a value of 0.75 beyond wich the effect is negligible. Whereas in the case of flaxible load, SCR increasee with increase in the tsand/d up to a value of 0.8 to 1.25 beyond wich the effect is negligible (Fig. 5).

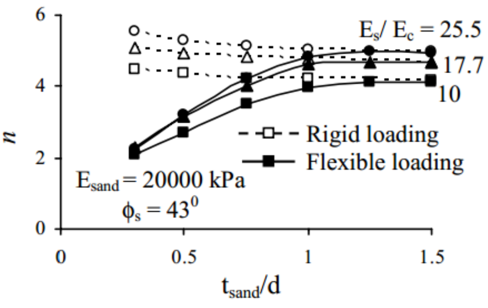

Figure 5. Effect of sand bed thickness on stress concentraion ratio [16]

Nassaji and Asakereh [17] carried out numerical simulations using Flac3D on granular bed-stone column improved ground and investigated the effects of granular bed on bearing capacity, settlement and bulging. Their results indicated that placement of the granular bed over the stone column improved ground significantly increases the bearing capacity and decreases the settlement of the ground and these effects increases with increasing thickness of the granular layer. The effects of different thickness of granular bed (t) on the lateral bulging of the stone column at a pressure load of 100 kPA is shown in Fig. 6, where D_f is footing diameter.

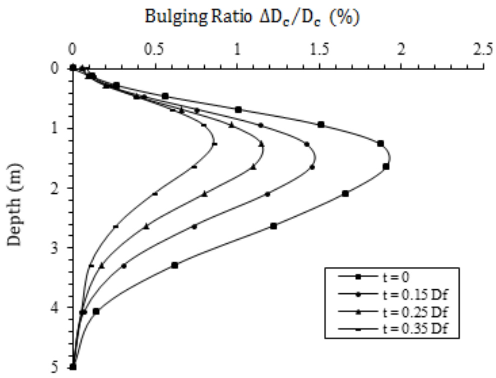

Figure 6. Bulging ratio versus the Depth for different thickness of granular bed at pressure of 100 kPa [17]

According to Fig. 7, they stated that a granular layer acts as a stress distributor, and transfers the applied stresses to depth of the column, where more support takes place from the surrounding soil. This causes that lower bulging occurs in the column.

VI. REINFORCED GRANULAR BED ON STONE CLOUMNS IMPROVED GROUND

Further improvements can be achieved by reinforcement of the granular bed over the stone columns improved ground.

Deb et al. [18] reported results of a series of laboratory model tests on unreinforced and geogrid-reinforced sand bed resting on stone column-improved soft clay. They concluded that the placement of sand bed increases the load-carrying capacity and decreases the settlement of the stone column improved soil and the inclusion of geogrid as reinforcing element in the sand bed significantly improves the load-carrying capacity and reduces the settlement of the soil. They observed decrease in bulge diameter and increase in depth of bulge due to placement of sand bed over stone column-improved soft clay. Also further decrease in maximum bulge diameter and increase in depth of observed due to application of geogrid (Fig. 8)

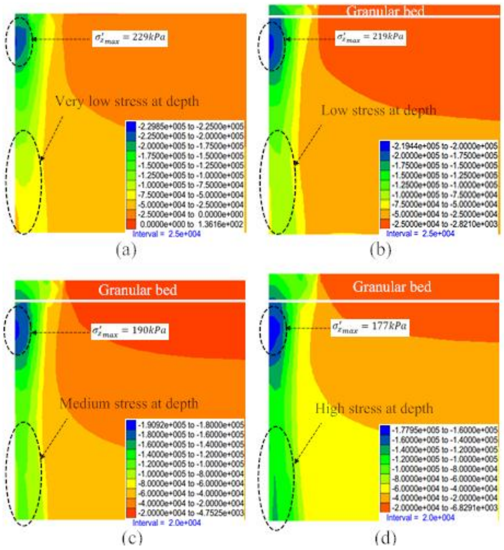

Figure 7. Effective stress contours for different thickness of granular bed at pressure of 100 kPa: a) t = 0, b) t = 0.15 D_f, c) t = 0.25 D_f, d) t = 0.35 D_f [17]

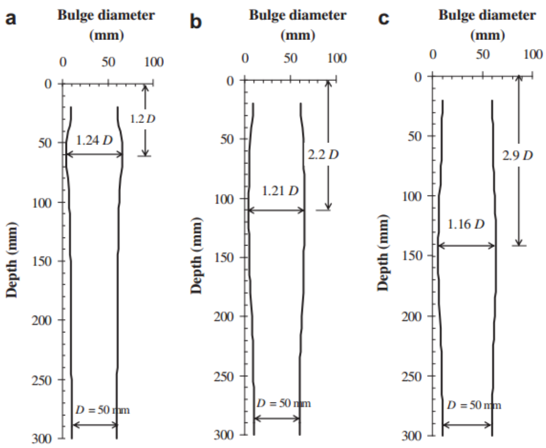

Figure 8. Bulging of the stone column when soft clay has been improved with (a) stone column alone (b) stone column with 30 mm unreinforced sand bed (c) stone column with 30 mm geogrid-reinforced sand bed [18]

VII. CONCLUSIONS

In this paper a review of existing techniques to increase the efficiency of stone columns in ground improvement is done. Based on performed studies, the following conclusions are drawn:

- Geosynthetic encased stone columns are a convenient option in very soft soils where insufficient lateral support is provided by the surrounding soil and excessive bulging of stone columns occurs during loading.

- A granular layer acts as a stress distributor, and transfers the applied stresses to depth of the column, where more support takes place from the surrounding soil.

- Decrease in bulge diameter and increase in depth of bulge occurs due to placement of sand bed over stone column-improved soft clay. Further decrease in maximum bulge diameter and increase in depth of can be achieved due to application of geogrid.

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