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A REVIEW ON PERFORMANCE ENHANCEMENT OF STONE/GRANULAR COLUMNS

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ABSTRACT

Use of stone columns beneath foundation is one of the widely used ground improvement techniques which is employed for mitigation of problems such as excessive total and differential settlement, low bearing capacity etc., arising in weak cohesive soils. Stone columns also serve as vertical drains thus speeding up the process of consolidation. Load carrying capacity of ordinary stone column primarily depends on lateral confinement offered by surrounding soil. Hence, in case of very soft soil under loading stone column undergoes excessive bulging which leads to failure of overlying structure. Penetration of surrounding soil in stone column or squeezing of stones in surrounding soil reduces drainage capacity and angle of internal friction of stone column material which in turn, reduces rate of consolidation and load carrying capacity of stone column. In few cases, it has also been observed that adopted installation procedures results in remolding of surrounding soft clay due to vibrations or impact, thus reducing passive pressure offered by it, further reducing capacity of stone column. To overcome above stated limitations, various remedial measures which are put forward have been discussed in this paper. Geosynthetic encasement is now extensively used to increase the capacity of stone column and is advantageous in very soft soils. It drastically reduces settlement of bed, without affecting drainage path. Another technique to enhance performance of stone column is use of circumferential nails. Effect of size and spacing of nails has varying effect on increase in capacity of stone column. Base enlargement is also a conceptualized method especially

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for increasing load carrying capacity of stone column by formation of spherical bulb at the tip. Use of internal reinforcement such as lateral circular disks of geogrid or geotextile, wire mesh of aluminum, steel and plastic etc. has found to improve load carrying capacity of stone column, with increase in capacity when reinforcement in column is increased. A theoretical model has also been discussed which is proposed to predict load carrying capacity of internally reinforced stone columns. Also, semi-rigid stone columns making use of cementing materials and under reaming has been presented for use in black cotton soil. Mixing of randomly synthetic fibers have proved to enhance the performance of stone column. Variation of capacity based on percentage of fiber and length of fiber has been presented in this paper. This paper identifies the conceptual methods which are more suited for general practice, and scope for further research.

Keywords: stone columns, granular columns review, ground improvement

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ABSTRACT: Use of stone or granular columns is widely adopted technique for improvement of ground and aid in consolidation. However, applicability of these methods in very soft clays is not practicable. Also, if the required strength of ground is more than minimum possible spacing of columns, then the columns need to be strengthened with the help of other techniques. Several techniques to improve stone/granular column capacity are presented in this paper. Major objective of the failure prevention methods for stone/granular columns is to arrest the bulging. Experiments carried out by researchers with use of various reinforcement methodologies such as encasement, lateral reinforcement, nailing, skirting, inclusion of fibre and cement etc. are presented.

INTRODUCTION

Due to increase in infrastructure growth, the building industry has been forced to look for cheaper land for construction. As a result, lands with poor ground conditions such as low lying areas of marine and estuarine quaternary deposits which possess very poor geotechnical properties due to their low strength are being considered for construction [1].

A number of soil improvement techniques are available, of which, stone column technique is preferable owing to the advantage of reduced settlements provided by it as well as accelerated consolidation settlements due to reduction in flow path lengths. Another advantage of this method is simplicity of construction [2].

McKenna [3] reported ineffectiveness of stone columns in embankment due to soft clay squeezing into voids of aggregate thus having very little effect on pore pressure built up. Chummar [4] reported failure of stone columns by excessive settlement in very soft silty clay layers. The possible causes of stone column were less limit capacity of stone columns and low cohesion of sensitive silty clay.

Stone columns are usually limited to clays having undrained cohesion (Undrained, Unconsolidated shear strength) C_u 15kN/m^2 [5]. Further developments in stone columns for their implementation in clays having cohesion lesser than the stated value include external reinforcements [6], internal reinforcement [7, 8] Modification of geometry [9, 10], Modification of stone column material [10, 11] and secondary improvement of soil around stone column to improve performance of stone column [12].

METHODS TO IMPROVE PERFORMANCE

Various methodologies are tested to increase stability and load carrying capacity of stone column. These include reinforcement of stone column with high-modulus materials, modification in geometry of stone column, mixing of additives in aggregates and reinforcement of soil in unit cell of stone columns.

Encasement of column

Encased stone column is widely adopted method in the field for ground improvement in very soft soils. First use of encasement of stone column in widening of railroad embankment in the year 1996 is documented by Raithel and Kirchner [13]. A number of case histories are reported by Raitel et al. [14], Alexiew et al. [15] and Araujo et al. [16].
The concept of encasement of stone column is put forward probably by Van Impe and Silence [17].

The preliminary details of this technique were provided by Kempfert et al. [18], and later updated by Raithel and Kempfert [6], Raithel et al. [14], Alexiew et al. [19] and Pulko et al. [20].

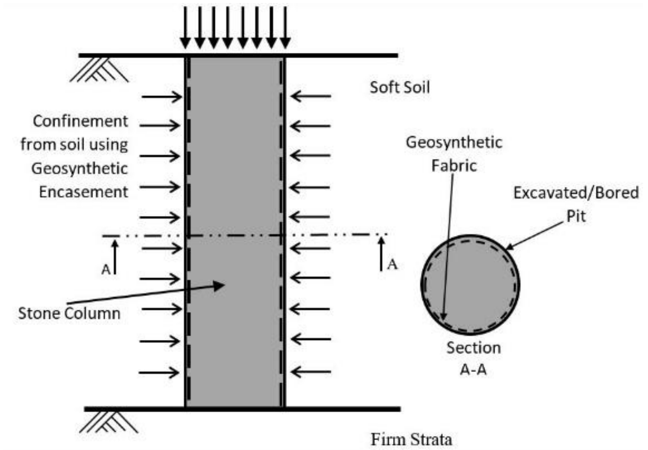

Fig. 1 Schematic diagram of encased stone column (Modified after Murugesan and Rajagopal [2])

It has been found out that encasement of stone column significantly increases the performance of stone column with reduction in settlements, acceleration of settlements and increase in shear strength [6]. Stiffer is the reinforcement, better is the performance of stone column [21]. Effect of thickness and stiffness of reinforcement in stone column helps for liquefaction mitigation has been studied by Tang et al. [22].

While theoretical and numerical models highlight the suitability of encasement of stone columns for better performance, well documented case histories of successful utilization are rather limited. Hence the well documented data sets of field performance are still required [5].

Inclusion of lateral reinforcement

Reinforcing stone columns with geogrids prevents bulging. 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 stone column aggregates. Based on numerical analysis, it has been suggested that the greater the number of reinforcement layers and the closer the spacing, the lesser will be the bulging [7].

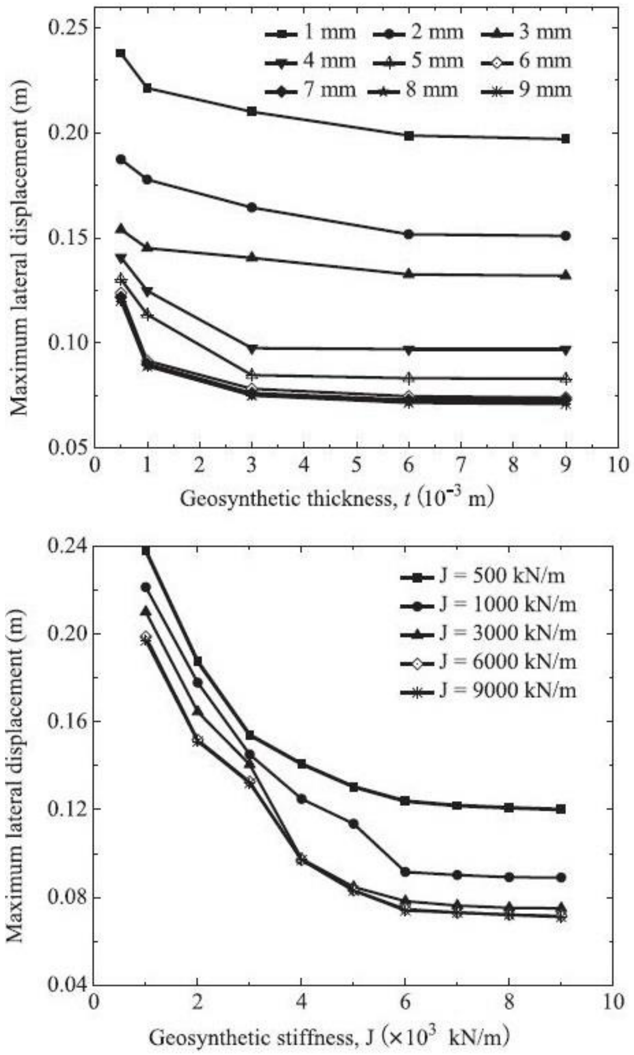

Fig. 2 Effect of thickness and stiffness on lateral displacement (Tan et al. [22])

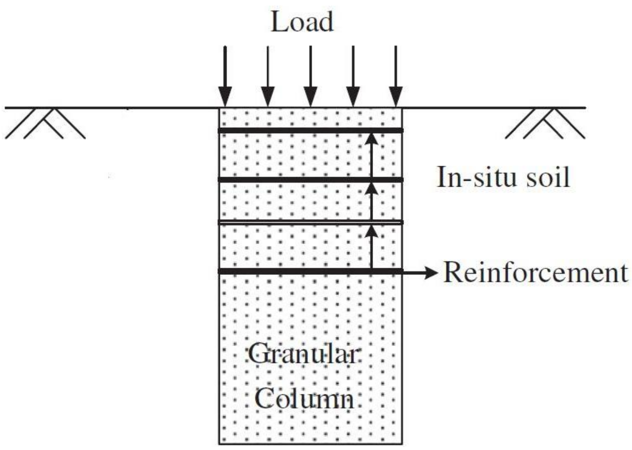

Fig.2 Schematic diagram of lateral reinforced column (Modified after Wu & Hong [23])

Sharma et al. [7] conducted a number of plate load tests on clay bed alone, granular pile alone and composite ground. The behaviour of the pile is observed to be improved with an increase in the number of geogrids and a decrease in the spacing of the geogrids. Bulge diameter and bulge length is also found to be decreased with reinforcement of the granular pile.

Findings by Ali et al. in model study of stone columns reinforced by lateral circular discs confirm to the findings of Sharma et al. [7]. The study is conducted on two types of columns (1) floating type [23, 24] and (2) end bearing type [24]. The bearing capacity of composite ground is observed to be increasing with increase in reinforcement length of column with best configuration being placement of lateral circular disks at spacing equal to $d/2$, where d is diameter of stone/granular column, for both floating and end bearing type. It is observed that development of hoop stresses (by encasement) is more effective way of confinement as compared to friction mobilization (by lateral disk reinforcement) [24].

Adydat et al. [8] used wire mesh prepared by plastic, steel and aluminium for their study of stone column reinforcement. Load carrying capacity is observed to be increasing with the increase in number of meshes and with increase in ductility of the material. 75% increase is noted for aluminium mesh. They proposed design procedure for the stone columns installed in soft soil and internally reinforced by meshes taking into account geometry and spacing of reinforcing elements and strength of soil and reinforcing elements.

An analytical procedure for analysis of laminated granular piles is proposed by Wu and Hong [25]. They conducted parametric studies on the stiffness of reinforcement, strength of reinforcement and effects of granular column radius. The results indicated that possibility of slippage in column is higher when strength and stiffness of the reinforcement increases with the constant confining pressure. With increase in confining pressure, the likeliness of slippage occurrence reduces. During experimental validation, they observed that embedment of granular column in soil results in increased column strength as compared to constant confining pressure [25].

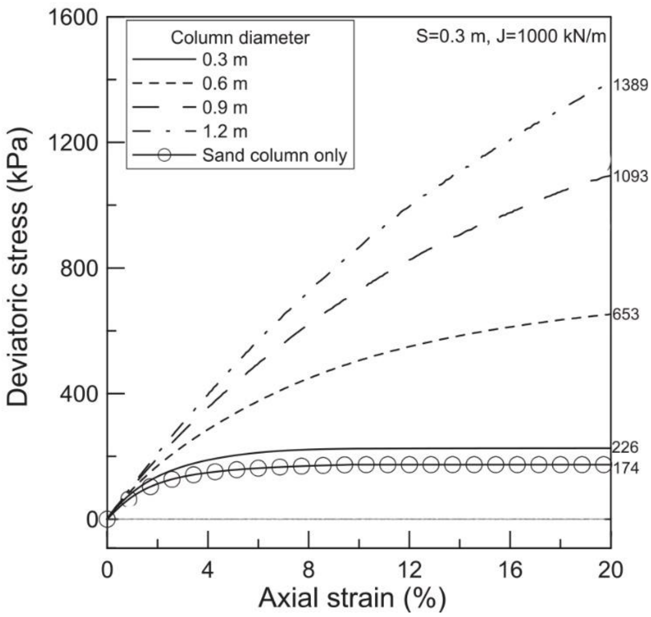

Fig. 3 The effect of column diameter on horizontally reinforced sand column behavior (Hong & Wu [26])

Hang and Wu [26] performed numerical analyses of granular columns reinforced with horizontal layers of reinforcement. They revealed that for equal reinforcement spacing, the column with smaller diameter has more strength gain. Confirming to the results of Wu and Hang [25], it is observed that increase in stiffness of the reinforcement might cause interfacial slippage at reinforcement and granular soil interface. It is also observed that high stiffness reinforcement for reinforcing small diameter column may be unnecessary.

A numerical study is performed by Hosseinpour et al. [27] to compare the laterally reinforced and encased granular columns. Their observations are consistent with observations of Sharma et al. [7] and Ali et al. [24]. It is noted that settlement achieved by inclusion of lateral reinforcement disks in columns at spacing $d/4$ is equal to settlement achieved by encased columns, with only half amount of material used. Also, reinforcements placed at spacing greater than $d/2$ does not remarkably improve efficiency, which is in consistent with results of Ali et al. [24].

An advantage of horizontal reinforcement is that the tensile failure of reinforcement will not cause the collapse of the entire column. But fabrication of horizontal reinforcement layers in full scale sand column is deficient in practical applications. Hence a further research to thoroughly study merits of horizontal reinforcement is required [26].

Circumferential Nailing

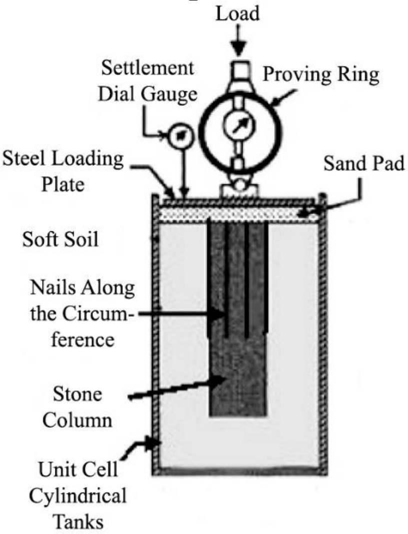

Fig. 4 Test arrangement for circumferential nailing (Modified after Shivashankar et al. [28])

Use of geosynthetic as reinforcement can be limited by relatively large settlements that occur as a result of minimal compaction received during installation to avoid damage to the encasement material and geotextile strain during loading [1]. Circumferential nailing is suggested as an alternative method by Shivashankar et al. [28].

Increase in stiffness and strength of stone column with application of circumferential nails is observed. Optimum depth of circumferential nails is suggested as $3d$, with increase in stiffness of stone column as depth of nails increases. Bulge diameter and length is found to be decreased substantially, and it is noted that the nailing technique can be used by advantage with smaller area ratios [28].

Babu et al. [29] studied effect of number of nails on load carrying capacity of stone columns. As the number of nails increase, confinement effect increases thus increasing load carrying capacity. The minimum depth of nails is suggested $3d$ to $4d$ and no significant increase is observed beyond this depth [29].

In the studies of Nayak et al. [12], the effect of nail diameter, nail depth and number of nails on load carrying capacity, bulging and settlement is observed. Their observations are in good agreement with work of Shivashankar et al. and Babu et al.

Skirting

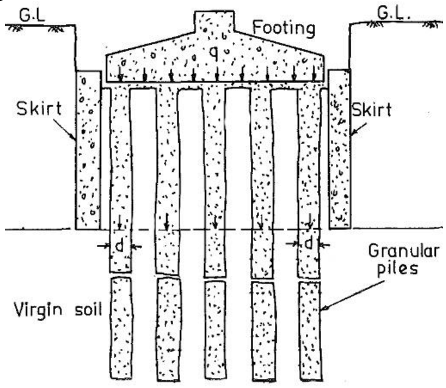

Fig. 5 Granular piles supporting skirted foundations (Modified after Rao & Ranjan [30])

Rao and Ranjan [30] put forward an innovative concept of skirting granular piles to reduce the settlement. This technique can be used with advantage in large diameter tank foundations, to reduce number of granular piles to be provided below tank rafts [31]. This method is suggested to be effective for both cohesive and non-cohesive soil deposits. A number of case histories where skirting is used along with granular piles are discussed. Depth of skirt suggested by them is four to five times diameter of granular pile.

Fibre Reinforcement

Basu [32] performed experimental analysis on behavior of random fiber mixing in granular pile, with parametric studies to observe effect of fiber content, fiber length and fiber depth on load carrying capacity of granular pile. Experimental work of Basu is later validated by Samadhiya et al. [33] by numerical analysis. It is found that the load carrying capacity increases with increase in fiber content, fiber length and fiber depth. The optimum fiber depth is found to be $3d$.

Similar study is conducted by Rakesh and Jain [34] on expansive clays. Their conclusions are in good agreement with those of Basu and Samadhiya et al. Based on their experimentation, Rakesh and Jain recommended 1% fiber content and 30mm fiber length to felicitate the proper mixing.

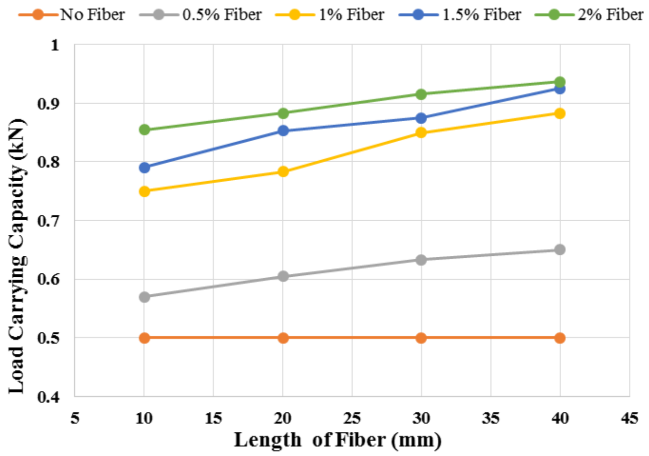

Fig. 6 Ultimate load for different fiber lengths and fiber content (Rakesh and Jain [34])

Cementing

Effect of low level cementing of sand column is studied by Juran and Riccobono [35]. They concluded that though low level cementation can significantly increase settlement response and load carrying capacity of reinforced soil due to effective cohesion provided by intergranular cementation, the brittleness of the compacted sand also increases, implying severe limitations on the allowable axial strain of an isolated column.

Cemented stone column with and without under reaming is studied by Golait et al. [10]. They observed significant improvement in load carrying capacity and settlement performance of reinforced ground when cementation is used. Under reaming of column resulted in increase of load carrying capacity.

CONCLUSION

Improvement of performance of stone column or granular columns in highly compressible soils can be achieved by a number of methods stated above. The major conclusions include:

1) Reinforcement is required in the part where bulging is prone to occur. Reinforcement up to depth of $3d$ to $5d$ is sufficient for the improvement.
2) The primary objective of the reinforcement is to increase the stiffness of the stone column or granular pile. Increase in the stiffness of reinforcements in all techniques increases the performance of stone column.
3) Increasing the density of reinforcement results in increased stiffness and hence increased the performance of stone column.
4) Lateral movement of stone column can be arrested by use of various reinforcements, thus settlements of improved ground can be reduced.
5) Studies on the field applications of the stated methods is needed to understand the practical performance of the stated methods.

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