EXPERIMENTAL STUDY ON NATURAL BAMBOO GEOGRID ENCASED STONE COLUMN

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ABSTRACT

As bamboo is easily available and cheaper in India with respect to polyester geogrid and also environment friendly, an attempt has been made to use natural bamboo material to improve the soft ground conditions. Stone column has been adopted as ground improvement technique and bamboo encasements are prepared to encapsulate the stone columns. Narrow bamboo sticks of 10 mm width with proper finishing are collected to prepare the encasement. Laboratory model tests have been performed on end bearing stone columns installed in soft marine clay. Partial and full length natural bamboo geogrid encasements are prepared to encapsulate the stone columns. Size of the stones used to model the stone columns is ranging from 2 mm to 10 mm. Partial bamboo encasements of 2D and 3.5D length are chosen for the experiments where 'D' is the diameter of column. Experimental results indicate improved load carrying capacity of stone column with increase in the length of bamboo encasement. Full length encasement prepared with polyester geogrid is also used to investigate the effectiveness of the natural bamboo geogrid encasement. Higher load carrying capacity is observed by using stiffer bamboo geogrid encasement at the same applied pressure. It is evident from the laboratory investigation that bamboo encasement can be an effective alternative at a cheaper cost than the polyester geogrid encasement. A finite element analysis has been performed using software 'PLAXIS 2D Professional' (2011) to find out the radial deformation of stone columns without and with full length encasement. Tensile strengths of bamboo geogrid as well as polyester geogrid are used to model the encasements in the finite element analysis. Reduced radial deformation is observed with increased stiffness of the encasement. An analytical study has also been performed with some simplified assumptions. It is observed from the analytical study that with increasing applied pressure, lesser hoop strain is developed in the full length bamboo geogrid encasement compared to the polyester geogrid encasement.

Keywords: Stone column, bamboo geogrid, encasement, hoop strain

INTRODUCTION

Bearing capacity of poor grounds can be improved adequately by installing stone columns encased with suitable reinforcements. It not only provides effective stiffness to the soil but also helps in quick drainage and creates the opportunity for faster construction with reduced settlement. Ordinary stone columns (OSCs) are unable to stand due to insufficient confinement from the surrounding soft soil and fail by bulging. Encasing it with suitable reinforcement compensates the lack of confinement and composes it as an effective ground improvement technique. Analytical, numerical as well as laboratory investigations were carried out by various authors to find out the efficiency of stone columns as soft ground improvement technique. In this regard, several attempts were made with different types of encasements. Hughes et al. (1975) investigated the reinforcing effect of a stone column in soil and derived the ultimate load capacity of ordinary stone column. Briaud (1991) derived the ultimate load capacity of encased stone column. Ayadat and Hanna (2005) investigated the performance of non-woven geofabric encapsulated sand columns and observed the columns to be failed before the stress in the geofabric material had reached its failure point as well as modified the equation for ultimate load carrying capacity. Mandal and Kamble (1998a) conducted model tests on encased stone columns. Mandal and Kamble (1998b) carried out centrifuge modeling on encased stone column. Black et al. (2007) performed laboratory model study to evaluate the performance of a peat deposit treated by both standard and reinforced stone columns and observed significant enhancement in the load-settlement response. The reinforcement methods adopted were: (a) jacketing the model stone columns with tubular wire mesh; (b) providing a metal internal bridging rod; and (c) installing a concrete plug. Gniel and Bouazza (2009) carried out small scale isolated and group column tests on geogrid encased sand column in enlarged oedometer cell designed based on the unit cell idealization concept. Fiber glass and aluminium mesh were used as geogrid. Wu and Hong (2009) conducted triaxial compression tests on 140 mm hight, 70 mm diameter dry sand samples encased in geotextile sleeves. Gniel and Bouazza (2010) conducted model studies using uni-axial and bi-axial geogrid as well as geogrid-geotextile composite to achieve more robust encasement of higher strength. Murugesan and Rajagopal (2010) used woven and nonwoven geotextile to encapsulate the stone columns and conducted model tests on single as well as group of stone columns installed in clay bed prepared in controlled condition in a large scale testing tank. Murugesan and Rajagopal (2006) carried out parametric study using the finite element program 'GEOFEM' on encapsulated stone column and found that with increasing diameter effect of encasement decreases. Yoo and Kim (2009) reported different finite element modeling approaches using finite element software 'ABAQUS'. Khabbazian et al. (2010) performed finite element analysis using ABAQUS 2006 on encased granular columns and found that optimum length of encasement was a function of the stress applied. Pulko et al. (2011) carried out analytical study on non-encased and encased stone columns considering the column as an elasto-plastic material, soil as an elastic material and geosynthetic encasement as a linear-elastic material and achieved very good agreement with elasto-plastic finite element analyses. Rathiel et al. (2004) reported that 60,000 geotextile-encased sand columns with diameter of 80 cm, length ranged from 4 m to 14 m, area ratio (column area to the influence area) between 10 to 20% were installed to improve the ground at the plant site of the Airbus Company in Hamburg-Finkenwerder. Ringtrac casings with stiffness ranging between 1700 and 2800 kN/m were adopted as the encasement material.

It has been observed that no investigation has been carried out using bamboo made geogrid as encasement material for stone columns. In the present study, laboratory model tests have been conducted on end bearing stone columns without and with encasement. Bamboo geogrid encasements of varying lengths are used to encase the stone columns. A full length polyester geogrid encasement has also been prepared for the model test to find out the efficacy of natural bamboo geogrid encasement. Finite element analysis as well as analytical study has also been performed.

EXPERIMENTAL STUDY

Material Properties

Properties of soft clay, granular materials for stone columns and the tensile properties of geogrid elements are determined prior to the laboratory experiments. The properties of soft marine clay and stones are given in Tables 1 and 2 respectively.

Table 1 Properties of soft marine clay

Properties	Value
Liquid limit (%)	82
Plastic limit (%)	42
Plasticity index (%)	40
Shrinkage limit (%)	22.35
Specific gravity	2.58
In situ vane shear strength (kPa)	10
Moisture content before testing (%)	61
Bulk unit weight (kN/m^3)	18
Optimum moisture content (%)	28.2
Optimum dry density (kN/m^3)	14.5
Clay content (%)	72
Pre-consolidation pressure (kPa)	18

Table 2 Properties of stone

Properties	Value
Grain size (mm)	2 to 10
Dry density (kN/m^3)	16
Friction angle	43°

The grain size distribution curves for clay and stone are shown in Fig. 1.

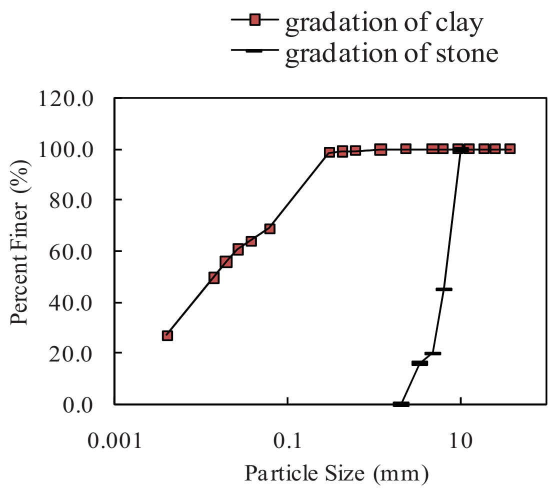

Fig. 1 Grain size distribution curve for clay and stones

Two types of geogrid, natural bamboo geogrid made with well fabricated bamboo sticks and polyester geogrid are used for the model tests.

Tensile strength of the bamboo geogrid is determined according to ASTM D4595-11 specification for wide-width strip method. Wide width specimens of 200 mm width and 100 mm gauge length are prepared by attaching the narrow bamboo strips from both directions with highly adhesive 'Fevi kwik'. Bamboo geogrid wide width specimen before and after the tensile strength test are shown in Figs. 2 and 3 respectively.

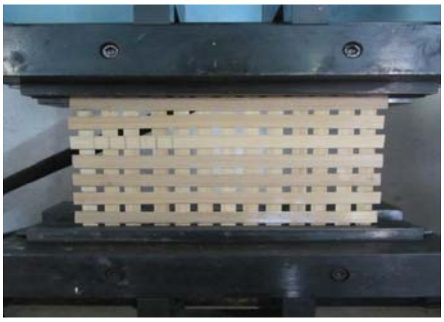

Fig. 2 Wide width bamboo grid specimen before tensile test as per ASTM D4595-11

Fig. 3 Wide width bamboo grid specimen after tensile test

Response of the wide width bamboo grid in tensile strength test is shown in Fig. 4.

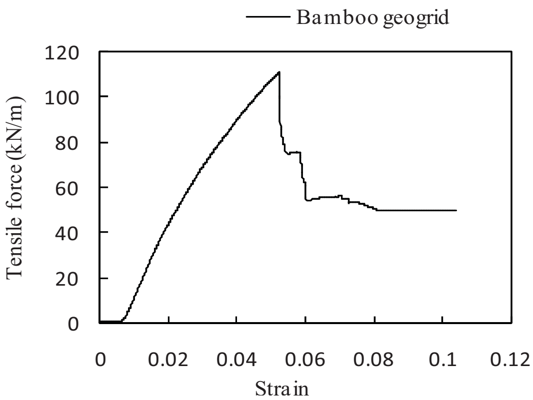

Fig. 4 Linear responses of a narrow bamboo stick in tensile strength test

Tensile strength of the polyester geogrid is also determined according to ASTM D4595-11 specification for wide-width strip method. Test specimens of 200 mm wide and 100 mm gauge length are prepared for the tensile strength test. Response of the polyester geogrid in tensile test is shown in Fig. 5.

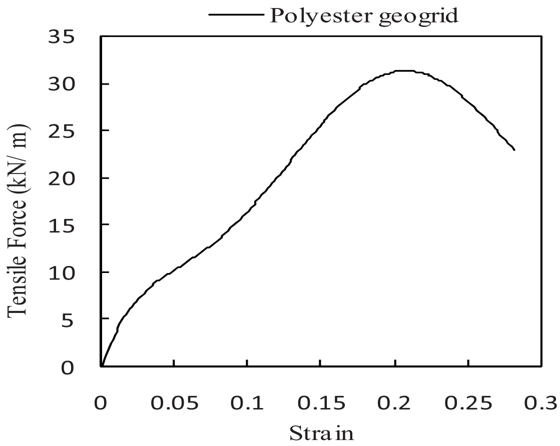

Fig. 5 Response of the polyester geogrid in tensile strength test

Properties of the natural bamboo geogrid and the polyester geogrid are given in Table 3. It is evident from the tensile strength test that bamboo geogrid is stiffer as well as the tensile strength is more than the polyester geogrid.

Table 3 Properties of geogrid

Material	Properties	Value
Bamboo geogrid	Mesh size	5 mm x5 mm
	Ultimate tensile strength	110 kN/m
	Ultimate stiffness	2200 kN/m
Polyester geogrid	Mesh size	5 mm x5 mm
	Ultimate tensile strength	32 kN/m
	Ultimate stiffness	160 kN/m

Laboratory Model Tests

Model tests are performed on end bearing stone columns without and with encasements installed in soft marine clay. All the tests are performed on 100 mm diameter stone columns. Diameter of the loading plate is chosen as two times the diameter of the stone column i.e. 200 mm. It represents a single stone column with its surrounding influence zone. The tank is designed large enough to diminish the boundary effect on the model tests. The load value is measured with a 5 ton capacity load cell and the settlement is measured with 3 LVDTs while the average of three settlement readings is implemented as the final reading. Schematic representation of the model test on a single end bearing encased stone column is shown in Fig. 6 and the laboratory test set up is shown in Fig. 7.

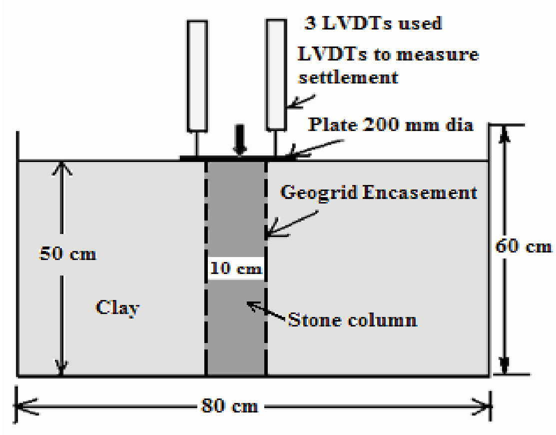

Fig. 6 Schematic of load test on a single stone column

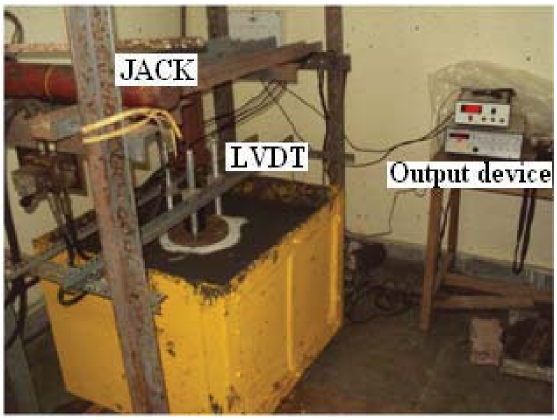

Fig. 7 Laboratory test set-up

Experimental Program

The experimental program is presented in Table 4.

Table 4 Experimental program

Test No.	Type
1	Plate load test on only clay
2	Load test on ordinary stone column
3	Load test on stone column encased partially with bamboo geogrid (encasement length = 2D; D = Diameter of stone column = 100 mm)
4	Load test on stone column encased partially with bamboo geogrid (encasement length = 3.5D)
5	Load test on fully encased stone column encased with bamboo geogrid
6	Load test on fully encased stone column encased with polyester geogrid

Preparation of Clay Bed

The clay bed is prepared in a model tank of size (700 x 800 x 600) mm^3 up to a depth of 50 cm. The bed is prepared in five equal layers with each layer 10 cm height. First a 100 mm layer of wet clay is filled in the test tank and leveled. The entire layer has been covered with a polythene sheet to prevent any moisture loss. Then the layer is compacted by placing a square plate of 160 mm x 160 mm on the clay bed uniformly and tapping it with a 10 kg rammer three blows every time. The tamping instruments are shown in Fig. 8. The layer is leveled before preparation of the second layer with same technique. Each layer is prepared in the same way and vane shear test is performed at each layer. After the clay bed is prepared, it is covered with a polythene sheet and left under a surcharge load of 2 kPa over the entire bed for 24 hours to ensure more uniform clay bed. It will remove the voids or cavities from the clay. The same procedure is followed to prepare the clay bed for all the tests. It has always been taken care of that the loading effort on clay is not crossing the pre-consolidation pressure at the time its preparation.

Fig. 8 Tamping instruments

Preparation of Encasement

Bamboo encasement is made of 10 mm wide and 1 mm thick well fabricated bamboo sticks. Highly adhesive 'Fevi kwik' is used for the preparation of the encasement. First the horizontal rings of 100 mm outer diameter are prepared with an overlap of 40 mm. The rings are prepared by surrounding the sticks around a 98 mm diameter wooden mould. Then the vertical sticks of required length are attached at the outside of the horizontal rings maintaining a square mesh of 5 mm × 5 mm to form the bamboo geogrid encasement of adequate height. It is also taken care of that the overlap portion of the horizontal rings must not be in a same vertical line. Three bamboo casings of length 500 mm (full encasement), 200 mm (2D) and 350 mm (3.5D) have been prepared maintaining 100 mm diameter.

Another geogrid encasement of 500 mm length is prepared with polyester geogrid. The geogrid is rolled by keeping 100 mm outer diameter with an overlap of 40 mm. Highly adhesive 'SPEB' is used to fix the encasement. Wire meshes of low tensile strength at an even spacing of 100 mm along the length of encasement are also used to prevent the slippage failure. The wire meshes are attached at the overlap portions in a same vertical plane. Pictorial view of the full length bamboo geogrid encasement and polyester geogrid encasement are shown in Figs. 9 and 10 respectively.

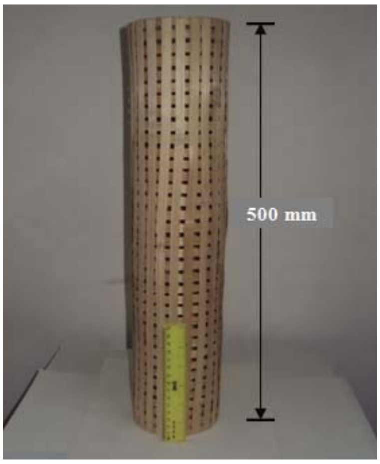

Fig. 9 Full length bamboo encasement

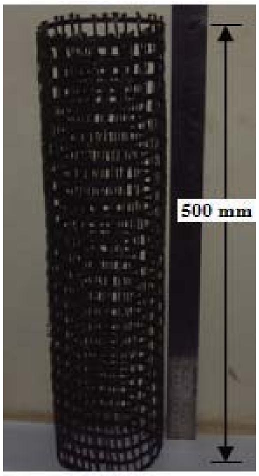

Fig. 10 Full length poly-ester geogrid encasement

Installation of Stone Column

Stone column is installed in the soft clay by replacement technique. A helical augur of 100 mm outer diameter is used to remove the soil from the center of the clay bed up to the bottom of the tank making a hole of 100 mm inner diameter. It is always taken care of that the augur remains vertical at the time of insertion into the clay. After that stones are filled into the hole in five equal layers with each layer tamped 25 times with a 15 mm diameter and 1 m long iron rod to achieve a density of 16 kN/m^3. Before filling, the stones should be slightly wet to avoid moisture absorption from the surrounding clay.

For encased stone columns, the encasement is installed prior to the filling of stones. As geogrid encasements are used in the present study, it can be installed directly by simply pushing it into the hole. The installed polyester geogrid encasement is shown in Fig. 11.

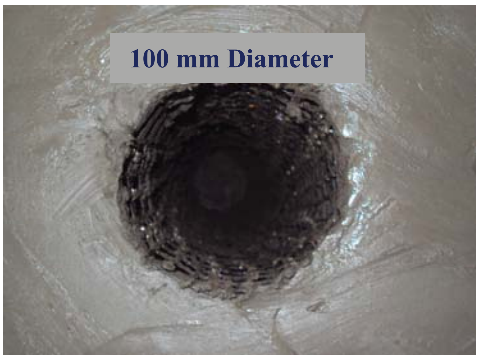

Fig. 11 Installed polyester geogrid encasement before installation of stone column.

Results and Discussions

The pressure-settlement responses on only clay, clay with ordinary stone column, stone column with partial and full length bamboo encasement as well as stone column with polyester geogrid encasement are analyzed and presented here. After the load test on ordinary stone column (OSC), it was casted with Plaster of Paris to get the deformed shape for an understanding of the failure pattern. The casted deformed shape of column is shown in Fig. 12.

Fig. 12 Casted deformed shape of ordinary stone column.

Pressure - settlement response

The pressure-settlement responses of stone column without and with full length encasements are shown in Fig. 13.

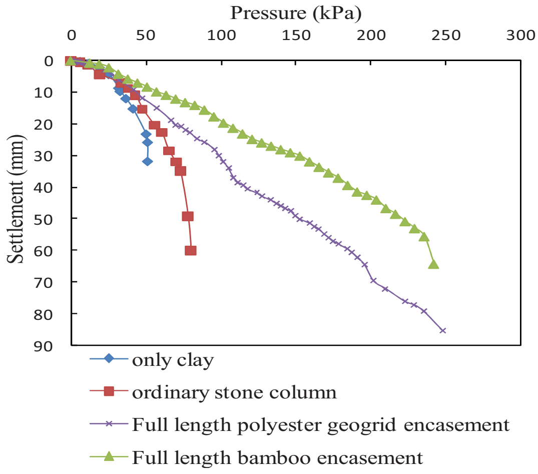

Fig. 13 Pressure-settlement responses of stone column without and with full length encasements.

Effect of encasement

Improvement in load carrying capacity of the clay bed due to ordinary stone column compared to only clay is observed from Fig. 13. Though the bearing capacity is improved, failure occurs at a low settlement value. Only clay can bear 53 kPa pressure and undergoes 23 mm settlement before failure. The ordinary stone column can carry 73 kPa pressure and undergoes 35 mm settlement before failure. In case of stone column without encasement, the surrounding soft soil is unable to provide sufficient confinement and the load cannot get distributed to the complete length of the column. Failure occurs by bulging within the top portion of the column. As a consequence it fails at a lower settlement despite greater stiffness than only clay.

Figure 13 shows remarkable improvement in bearing capacity when the stone columns are encased. As the encasements provide additional confining pressure to the column, the stone column does not bulge and the load gets distributed throughout the length of the column.

Effect of encasement stiffness

It can be observed from Fig. 13 that maximum load carrying capacity is obtained providing full length bamboo encasement for a certain settlement. At 50 mm settlement, the bamboo geogrid encased column bears 1.46 times higher load than the polyester geogrid encased column. The bamboo encasement is stiffer than the polyester geogrid encasement as observed from the tensile strength tests. As the encasement becomes stiffer, it will provide more confining pressure to the stone column at same applied pressure. As a consequence, the load carrying capacity gets improved.

The stone column encased with bamboo geogrid carries 236 kPa pressure and endures 55 mm settlement before failure. After undergoing this much settlement, some bamboo sticks break and some get detached from the rings.

Providing polyester geogrid encasement, no clear failure point is observed up to 249 kPa pressure and the column undergoes 85 mm settlement at that pressure. Load carrying capacity is less than the full length bamboo encasement for a certain settlement. As it is very flexible, radial expansion occurs for a higher point without tearing. When very large settlement is allowed, polyester geogrid encasement is better.

Effect of encasement length

Figure 14 shows the load-settlement responses of stone column with bamboo geogrid encasements of varying lengths.

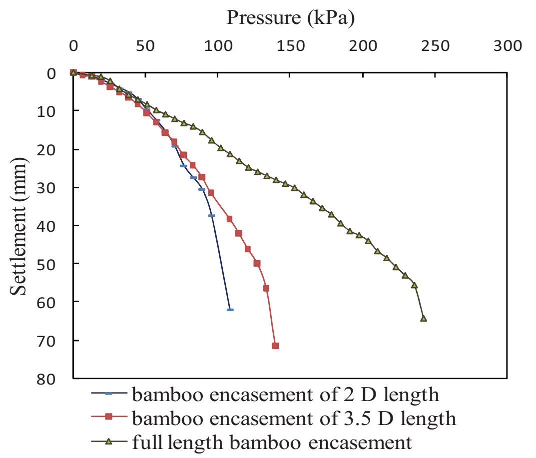

Fig. 14 Load-settlement response of bamboo encased stone columns for various encasement lengths.

It can be observed from Fig. 14 that with increasing length of encasement, the load carrying capacity gets improved. Providing partial bamboo encasement of 2D length, the stone column can endure 89 kPa pressure and undergoes 31 mm settlement before failure. The load carrying capacity gets improved compared to ordinary stone column. As bamboo encasement is stiff, after initial improvement it punches through the soil and failure occurs by bulging beneath the encasement. Failure occurs much before the maximum hoop tension gets developed in the encasement. The load cannot get distributed throughout the length of the column though greater lateral confinement is obtained at the upper portion of the column. From Fig. 13, it is observed that both the stone columns encased with 2D and 3.5D length of encasement show similar response up to a settlement of 30 mm though the column encased with 3.5D length fails at a greater pressure and settlement. Providing encasement of 3.5D length, the stone column can carry 127 kPa pressure and undergoes 50 mm settlement before failure which occurs due to the bulging of stones beneath the encasement. As the encasement is too stiff than the clay, it goes through some amount of settlement while transferring the load to a greater depth. Although failure occurs at a higher pressure in case of 3.5D length of encasement, almost punching failure takes place because of the higher stiffness and less flexibility of the encasement. The maximum pressure-settlement response is observed when the stone column is encased with full length encasement. Before failure, it gains almost 2 times greater load carrying capacity than the partial encasement of 3.5D length. As the full length encasement gets the rigid base of the tank, it provides maximum lateral confinement to the column unlike the partial encasements that go through almost punching failure much earlier the development of maximum hoop stress. Providing full length encasement, the applied pressure gets distributed throughout the length of the column.

FINITE ELEMENT ANALYSIS

An axisymmetric finite element analysis has been performed using 'PLAXIS 2D Professional' (2011) maintaining similarity with the laboratory model test. The test tank has been designed taking equivalent diameter of the rectangular tank used in the laboratory test. The equivalent diameter is 850 mm. Height of the tank adopted as 500 mm. Properties of clay, stone and geogrid are kept same as obtained from the laboratory tests. 15-node triangular elements are used to model the deformations and stresses in the soil. In the analysis, un-drained (B) Mohr-Coulomb model is used for soft clay and drained Mohr-Coulomb model is used for stone column. The geogrid elements are modeled as elastic material. 60 mm prescribed displacement is applied on the 100 mm diameter stone column to represent a rigid plate of 200 mm diameter.

Finite Element Model

The axisymmetric finite element model of fully encased stone column is shown in Fig. 15. Polyester geogrid encasement is simulated by providing geogrid stiffness as 160 kN/m whereas stiffness of 2200 kN/m is adopted to simulate the bamboo encasement.

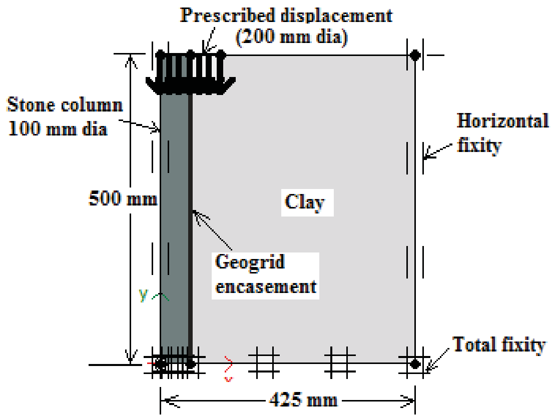

Fig. 15 Axisymmetric model of encased stone column

Results and Discussions

From the finite element analysis, radial deformations of stone column without and with full length encasements are evaluated along its depth. Radial deformations corresponding to the depth of column are shown in Fig. 16.

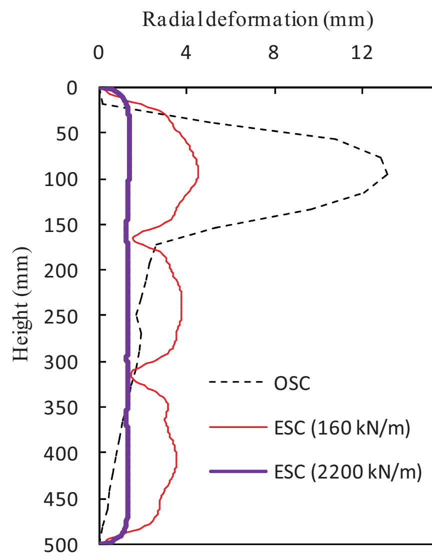

Fig. 16 Radial deformation of stone column without and with encasement (OSC = Ordinary stone column; ESC = Encased stone column)

It can be observed form Fig. 16 that radial deformation of stone column gets reduced when it is encased with geogrid reinforcements. More uniform and minimum radial deformation is obtained with increasing stiffness of the encasements. Ordinary stone column (OSC) fails by bulging within almost 2D length of the column with a significant radial deformation of around 13 mm. Geogrid encasements provide excess lateral confining pressure to the columns and prevent its radial deformation. As the stiffness increases, more hoop tension gets generated in the encasement and it provides more confining pressure to the stone column.

ANALYTICAL STUDY

In case of fully encased stone columns, the applied load on the column gets distributed throughout the length of column. It can be assumed that the load is transferred uniformly causing a uniform lateral deformation along the entire length of the column. For more simplicity, it can also be assumed that the volume always remains constant while the uniform lateral deformation takes place. Wu and Hong (2009) reported the similar concept. The schematics of the simplified assumption are shown in Fig. 17.

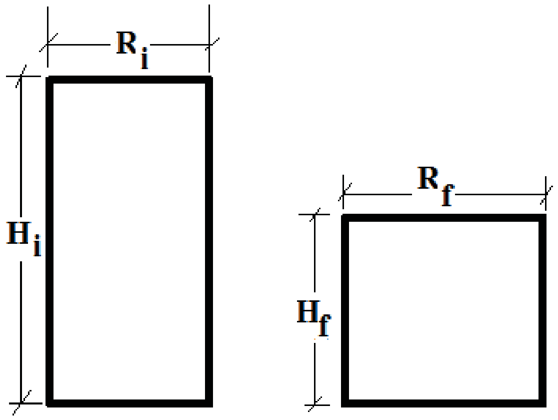

Fig. 17 Uniform lateral deformation of stone column (simplified assumption).

where:
R_i = initial radius of the column
H_i = initial length of the column
R_f = final radius of the column after deformation
H_f = final length of the column

If axial strain of the fully encased stone column = ε_l

$$\varepsilon_l = \frac{H_i - H_f}{H_i} \tag{1}$$

Hence,

$$H_i = \frac{H_f}{1-\varepsilon_l} \tag{2}$$

If volume is constant at the time of deformation,

$$\pi R_i^2 H_i = \pi R_f^2 H_f \tag{3}$$

Therefore,

$$R_f = R_i\sqrt{\frac{H_i}{H_f}} = R_i\sqrt{\frac{\frac{H_f}{1-\varepsilon_l}}{H_f}} = R_i\sqrt{\frac{1}{1-\varepsilon_l}} \tag{4}$$

If circumferential strain or hoof strain = ε_r

$$\varepsilon_r = \frac{2\pi(R_f - R_i)}{2\pi R_i} = \frac{R_f - R_i}{R_i} = \frac{R_i\sqrt{\frac{1}{1-\varepsilon_l}} - R_i}{R_i} = \frac{1-\sqrt{1-\varepsilon_l}}{\sqrt{1-\varepsilon_l}} \tag{5}$$

From the tensile force verses strain curve as obtained from the tensile strength test, the tensile strength of geogrid can be obtained corresponding to the hoop strain determined using equation (5).

If the encasement is considered as a thin cylindrical element, the generation of circumferential hoop stress in the encasement is shown in Fig. 18.

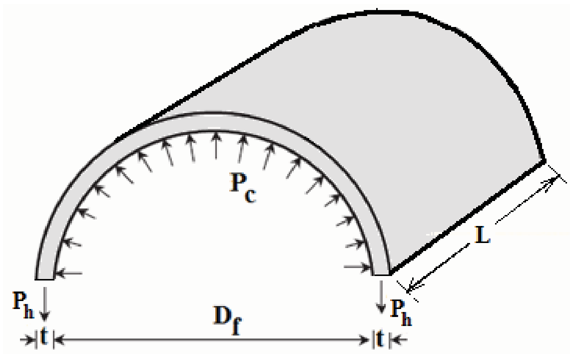

Fig. 18 Hoop stress generation in a cylindrical geogrid encasement.

If confining pressure = P_c and hoop stress = P_h,

$$P_h \, x \, t \, x \, L \, x \, 2 = P_c \, x \, D_f \, x \, L \tag{6}$$

$$P_h = \frac{P_c \, x \, D_f}{2t} = \frac{T}{t} \tag{7}$$

where:
D_f = final diameter of the stone column
L = length of the encasement
T = tensile strength of the geogrid per unit length at the corresponding hoop strain
t = thickness of the thin cylindrical encasement

The axial strain (ε_l) can be determined from load verses settlement curve obtained from the laboratory load testing on fully encased stone column. The hoop strain can be determined using equation (5) at any stage of loading. Tensile strength (T) at the corresponding hoop strain can be determined from the graph obtained from tensile strength test of geogrid. At any stage of loading, the hoop stress in geogrid as well as the confining pressure can easily be determined using Eq.7.

Application of the Analytical Study

The analytical solution is applied in the present laboratory investigation to determine the hoop strain in the full length encasements at any stage of loading. The pressure-hoop strain response of the full length bamboo geogrid encasement and the polyester geogrid encasement are shown in Fig. 19.

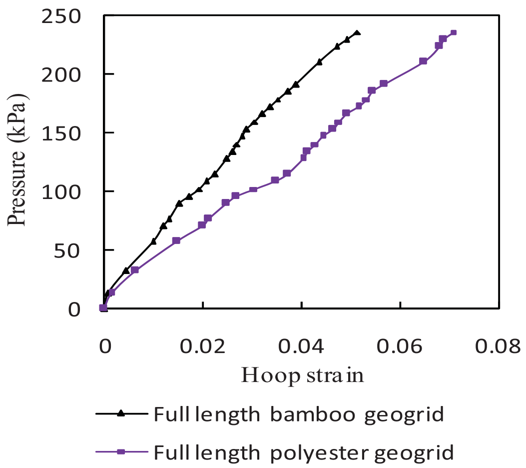

Fig. 19 Pressure-hoop strain response of the full length encasements.

It can be observed from Fig. 19 that bamboo geogrid encasement is subjected to smaller hoop strain compared to the artificial geogrid encasement. As pressure increases, the difference in hoop strain also increases. At the same applied pressure, more hoop stress gets developed in the bamboo geogrid encasement as well as it prevents more lateral bulging of the stone column. It is obvious that the load carrying capacity of bamboo geogrid encased stone column will be more.

CONCLUSIONS

From the present laboratory investigation, it can be concluded that we can use natural geosynthetic material like well fabricated bamboo sticks as encasement material effectively to improve the capacity of stone columns treated ground to a greater extent. Some major findings are mentioned here.

Ordinary stone column (OSC) cannot get sufficient confining pressure from the surrounding soft soil and fails by bulging at a low applied pressure. It is required to encase it with suitable geogrid reinforcements to provide sufficient lateral confinement. As the stiffness of encasement increases, the load carrying capacity of encased stone columns (ESCs) gets improved.

Full length bamboo geogrid encasement can produce better results than the conventional polyester geogrid encasement because of its high tensile strength and stiffness. Although bamboo geogrid encasement can fail by breaking due to its less flexibility, a very high amount of load will be needed to cause this type of failure.

Bamboo encasement is more effective for the soft clay grounds where it can reach up to a relatively hard stratum beneath the soft soil. The encasement is very stiff. It is observed from the laboratory investigation that bamboo encasement of partial lengths may fail by punching much before the generation of ultimate hoop stress though it is better than the ordinary stone column.

From the finite element analysis, it is observed that the ordinary stone column (OSC) fails due to huge radial deformation within almost 2D length of the column. The applied load cannot get distributed along the length of the column to a higher depth. As stiffness of the encasement is increased, the radial deformation of stone column gets reduced as well as becomes more uniform throughout the length of the column.

From the analytical study, the hoop strain developed in the encasements can be determined at any stage of loading. It is observed that at the same applied pressure, lesser hoop strain is developed in the full length stiffer bamboo geogrid encasement compared to the polyester geogrid encasement.

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