Influence of Column Position on the Bearing Capacity of Geosynthetic-encased Stone Column Supporting Railway Embankment on Soft Clay

Goushya Begum[1], Desha Shenthan[2] and B. Hanumantha Rao[3]

[1] Research Scholar, School of Infrastructure, IIT Bhubaneswar, Argul, Bhubaneswar, Odisha-752050, E-mail: gb18@iitbbs.ac.in
[2] Undergraduate Student, School of Infrastructure, Indian Institute of Technology Bhubaneswar, Argul, Bhubaneswar, Odisha-752050, E-mail: ds24@iitbbs.ac.in
[3]Assistant Professor, Department of Civil Engineering, IIT Bhubaneswar, Argul, Bhubaneswar, Odisha-752050, E-mail: bhrao@iitbbs.ac.in

Abstract. Construction on/in soft ground is feasible only after improving its strength by resorting to appropriate ground improvement technique. Stone columns and encased stone columns have been proved to be greatly effective for improving the bearing capacity of soft ground. Ensued bearing capacity is highly depended on lateral confinement wielded by the soil to the stone column along with the position of the column either below or above the ground surface. If depth of stone column insertion is more so does the cost of excavation. In this study, the performance of geosynthetic-encased stone columns (GESC) with varying insertion depths above the ground surface beneath a railway embankment has been analyzed numerically. For study purposes, GESC of 600 mm diameter with 3 m spacing embedded in soft soil underlain by an embankment is considered. The different lengths of GESC above the ground surface are replicated in the form of varying lengths. 2D finite element analysis has been performed to determine the bearing capacity and bulging of the stone column. Optimization has been done based on their effectiveness and economy. From the results, it is found that, as the position of the column raised above the ground surface, stresses on the stone column gradually decreased for the central stone column's from 715.8 kPa when it is normally oriented, while for the remaining insertion depths are 509.78, 455.03, and 409.57 kPa which in turn reduced the confinement of the GESC causing more settlements and bulging. As regards to bulging, the maximum is noticed at the centrally placed column, for all the cases analyzed, and it decreased as moved away from the center of an embankment.

Keywords: Soft clays, Geosynthetic encased stone column, insertion depths, Finite element analysis, bulging

1. Introduction

Infrastructure development is essential to boost the economic growth of a country [1]. Every construction site may not be endowed with good quality of the foundation soil. Building of infrastructure facility on/in soft ground is promising because soft soils exhibit poor bearing capacity due to less support offered by the foundation soils [2]. Excessive settlements with time is an another great impediment to progress the construction in soft grounds. These circumstance elevate that the foundation soil is rehabilitated and its engineering properties are improved by suitable ground improvement technique [3]. For clayey soils with cohesiveness less than 15 kPa, it strength is generally enhanced by stone columns. Because stone columns act as reinforcement within the soft soil, they provide additional strength by improving its bearing capacity. The top of the stone column experiences significant lateral deformation or bulging as a result of the soil's insufficient lateral confinement [4, 5, 6]. In these situations, encasing the stone column is beneficial as it increases the rigidity and decreases the deformation [7]. Geogrids are used to encase (reinforce) the stone column when the soft clays are unable to provide sufficient lateral resistance in all surrounding [8, 9, 10]. The main characteristic of stone column is its high permeability, which speeds up the consolidation process within soft ground, while rigidity of the column supports the loads of superstructure [11].

It is observed from the field that installation of GESC becomes uneconomical in particular of cases where GESC is to be implemented in already failed embankments. Transportation and hauling of failed embankment spoil is reasoned out as the chief cause for uneconomical costs. Calculation of bearing capacity of GESC for variable insertion depths above the ground becomes necessary to limit the excavation and to constrain the costs on soil transportation. Examining GESC's bearing capacity and predicting its bulging deformation for various column insertion depths are the study's core objective. By examining the lateral deformations, one must assess the variation in the bulging of stone columns. Estimating the settlement and understanding the change in bearing capacity for all the models are required to recognize the variance in bearing capacity as per the serviceability criteria. The effect of key material parameters on the stone column also plays the important role.

2. Study Area

In this research, a 1500 m long broad gauge railroad line in the state of Odisha that connects Haridaspur and Paradeep has been considered. Groundwater was present at ground level, the foundation soil is a very soft clay with an undrained shear strength of 15–25 kPa, the soft clay extends to a depth of almost 17 m, and cultivation was prevalent on both sides of the embankment. These conditions were observed on the site through physical verification and were also based on the soil reports. According to data from bore holes, the foundation soil has layers of soft clay, silty clay, and sandy clay that stretch from the natural ground surface to greater depths.

3. Description of Numerical Methodology

Geosynthetic-encased stone columns with varying insertion depths beneath and into the embankment have been used to create an embankment for a railway line. SIGMA/W module of GeoStudio is used to perform finite element analysis. A two-layer soil foundation is employed, with the bottom layer being silty clay and the top layer being soft clay. The soft clay beneath the embankment is where the encased stone columns were installed. The research was performed with the assumption that the soft clay is loaded during the course of two months in four levels, namely L1, L2, L3, and L4. Approximately 15 days were needed to finish each layer. The actual duration of the construction was two months (60 days). Immediately following the construction of the embankment, the consolidation process began. The stone column's diameter is set at 0.6 m. The GESC spacing is taken into account to be 3 m, which is the ideal spacing for calculating bearing capacity (Deshpande et al., 2021). From centre to centre, the spacing of stone columns is established. A sand layer with a 0.5 m thickness is provided over the stone column. Within the sand layer, two layers of the geogrid layers with 0.5 m spacing were used. Geogrid reinforcement serves to evenly distribute the embankment surcharge weight across all the GESCs, and the blanket layer offers a high permeability drainage layer that aids in removing extra PWP. This is how surcharge stress is transferred. Few stone columns located at the toe of the embankment cannot be installed when the insertion depth varies because they impair the embankment's dimensions. Consequently, those stone columns are regarded as being in the ground itself.

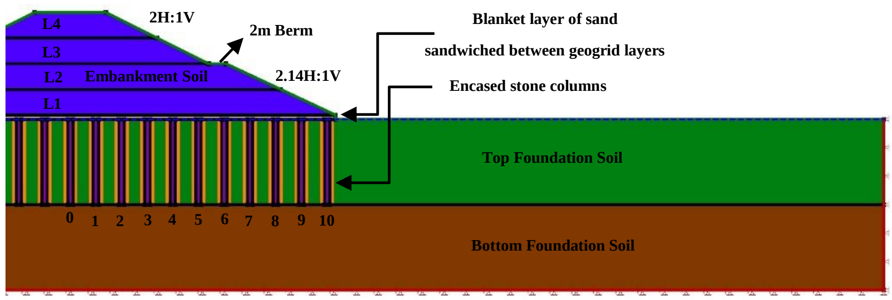


Fig. 1. Basic model of embankment on the stone columns in soft clay.

All four models have undergone finite element analysis, with the insertion depths of the stone columns changing in each case. The first type of design places the stone columns directly below the embankment as shown in Fig. 2a.

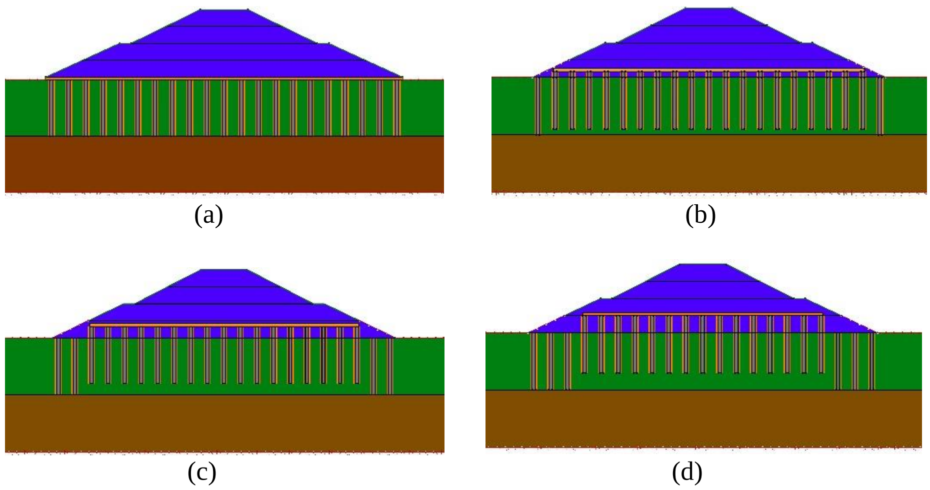


Fig. 2. Models showing different insertion depths of GESC: (a) 0 m, (b) 1 m above the ground surface, (c) 2 m above the ground surface, and (d) 3 m above the ground surface

In the second model, the embankment is designed so that the top 1 m of the stone column are elevated above the ground level; thus, the GESC is buried about a 9m underground. The uppermost 1 m of the stone columns will be set into the embankment, while the remaining 9 m will be placed into the ground within the foundation. The embankment is built on top of the sand layer, which is built on top of the stone columns that were positioned vertically. The stone columns of the third model are raised up to a height of 2 m into the embankment, with the remaining 8 m of their total length housed in the foundation. Those ESCs that affects the outline of the finished embankment's profile should be placed in the foundation itself. Final model, stone columns are set into the ground starting at the 3 m elevation into the embankment. The aforesaid scenario is depicted in Figs. 2a-d.
A linear elastic model with drained parameters was used to model the foundation layers and stone column material. The material properties of both foundation layers alter later when the stone columns are placed, necessitating consideration of the elastic plastic model with effective parameters w/pwp. While the geogrid encasement is modelled as a linear elastic model with effective parameters based on the change in pwp, the sand layer uses an elastic plastic model with effective drained parameters. The material model studied for embankment is elastic plastic with effective w/pwp characteristics. The various geotechnical characteristics of foundation layers, stone columns, sand, and embankments are listed in Table 1.
Regarding the boundary conditions, foundation's bottom side is subject to fixity in the X and Y directions, whereas the foundation's left and right most vertical sides are subject to fixity in the X direction.
For the normally aligned stone column model, mesh size is taken as 1.5 m, and between the stone columns, "mesh generates along line". For more accuracy in the results to be displayed, the number of edge length divisions was set to six. As a result, the mesh is cut into six individual bits and placed between the stone columns. Due to length variation, it is difficult to construct divisions for the remaining models; as a result, the entire geometry is thought of as having 1 m mesh size. The interface element is made available for geogrids using the create interface element, and the 0.11 m thick geosynthetic material is then used.

Table 1: Properties of the materials (Deshpande et al., 2021)

	E (kPa)	μ	γ (kN/m^3)	c′ (kPa)	ϕ′ (°)	e	k_x (m/d)	k_y / k_x
Soft clay (top soil)	2000	0.4	15	20	10	1.2	3.51×10^{-5}	0.5
Silty clay (bottom soil)	20,000	0.3	19.5	45	15	0.76	3.51×10^{-5}	0.5
Embankment soil	10,000	0.3	19	25	25	0.38	12.96	0.667
Stone column	40,000	0.3	22	0	34	0.3	0.001	1
Sand	20,000	0.3	22	43	26	0.38	-	-

4. RESULTS AND DISCUSSION

4.1 Model validation

Since the article [12] claims that a 3 m spacing yields the highest effective stress values for stone columns, validation is done using stone columns that are typically placed with 3 m spacing to measure the effective stress.

Fig. 3 shows the effective stress versus time graph of the centrally placed GESC modelled in the present study. By using web plot digitizer, the value of effective stress turned out to be 131 kPa roughly and the value obtained by the present analysis is 142 kPa. The error percentage from both the results is about 7.74% which is due to Geo-Studio version update and the point selection on the stone column. Since choosing the precise center point would not be realistic, the position on the stone column that is about in the middle has been selected.

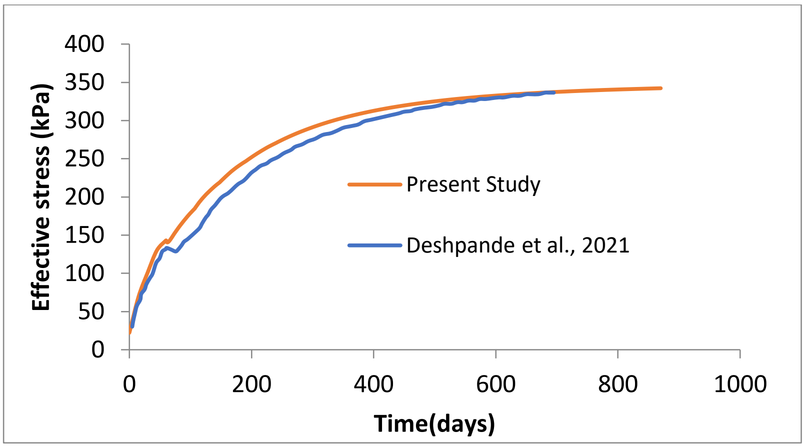


Fig. 3. Validation of effective stress evolution with time

4.2 Stress estimation

The total stresses on the stone column is analysed by selecting a point exactly at the center of the stone columns on top of the GESC. As a result, stress is obtained for all the stone columns and models with different insertion depths. Fig.4 illustrates the variance in total stress for several stone columns and types.

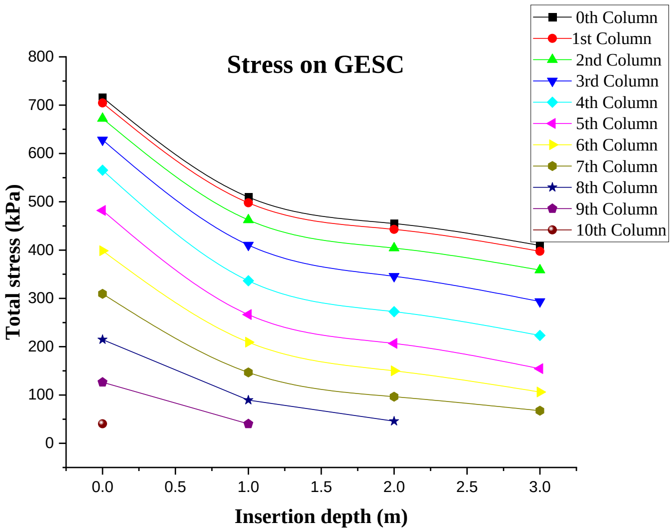


Fig 4. Variation of Total stress on GESC for variable insertion depths

The normally placed stone column is represented by the number 0 on the X-axis, while the insertion depth of 1m into the embankment is represented by the number 1. Similarly, the numbers 2 and 3 denotes an insertion depth of 2 and 3 m respectively. The central stone column is represented by the number 0, while the stone columns to the right adjacent to it is represented by number 1.

As per the results shown in Fig. 4, the central stone column always carries a heavier load. The load carried by the stone columns reduced as they progressed farther from the central stone column. Additionally, it is found that the bearing capacity for different insertion depths decreases, indicating that the pressure acting on those GESC decreases as the insertion depths rises, the load supported by the stone columns gradually decreases from the central stone column to the end stone column near toe of an embankment.

The central stone column's bearing capacity is 715.8 kPa when it is normally oriented, while for the remaining insertion depths are 509.78, 455.03, and 409.57 kPa. As a result, the pattern has a diminishing tendency.

4.3 Bulging and lateral deformation

The diameter of the GESC is affected by the surcharge load. Due to the decreased support provided by the soft foundation soil, there is an influence on the position of the stone column both before and after the application of load throughout its length. Bulging and lateral deformation of the stone column are estimated after the total consolidation time of 3 years. Figs. 5,6,7 and 8 show the bulging and the lateral deflection experienced by all the stone columns to the right side of the central stone column designated as 1 to 10 in Fig. 1. For the analysis purpose, the total length of the GESC on both left and right sides are taken into consideration. The difference in those values minus the diameter of the stone column gives the bulging.

The variation in lateral deformation and bulging are shown over the 10 m length of the GESC. Proper bulging is seen in the center stone column when it is inserted normally and the lateral deformation is more in the last stone columns. The deformation is seen tilting to the right because the right half of the GESC group is considered for the analysis. Here most of the deformations started from the same point which is 0.03.

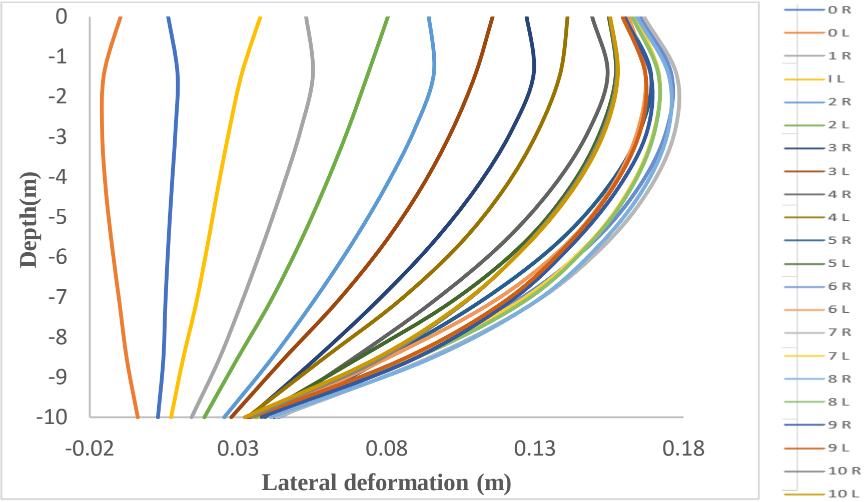
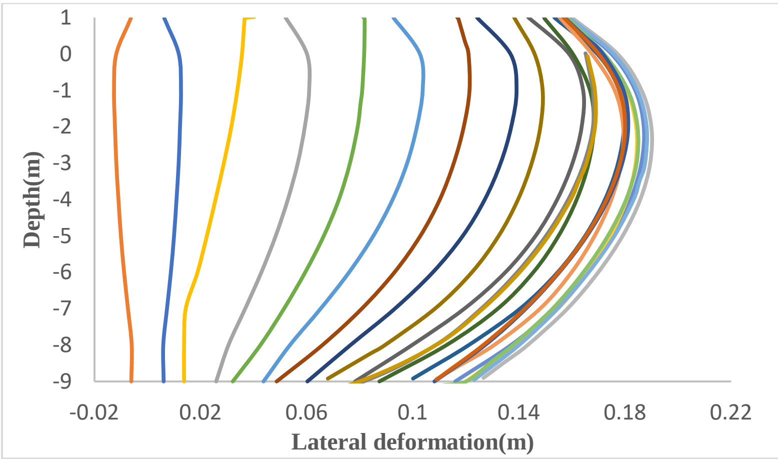


Fig 5. Predicted lateral deformations for normal alignment of GESC

In the case where the stone columns are situated 1 m higher than the normal stone columns. This graph also shows the same deformation with some minor variations. The highest deflection shown in this case more than of the normal one.



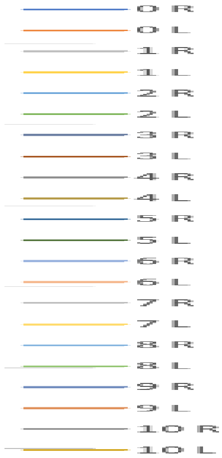


Fig 6. Predicted lateral deformations for insertion depth 1 m above the ground surface

Fig. 7 shows the values for the stone column whose top is 2 m higher than the foundations top. The bulging for the centrally placed stone column is carried out throughout the length of stone column. The last two stone columns which are in the ground as normal stone columns shows deflection similar to the normal stone columns situated at that position but the lateral deformation is slightly more than the normal stone column's highest.

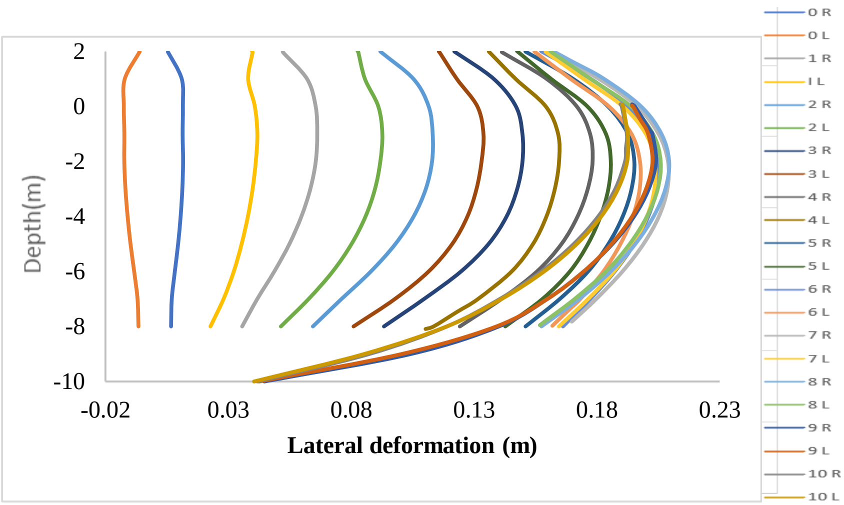


Fig 7. Predicted lateral deformations for insertion depth 2 m above the ground surface.

Fig. 8 shows the bulging and deformations of the GESC which are placed 3 m above the foundation. The columns whose top is 3 m higher than the foundations top showed bulging but not throughout the column length. The last three GESCs 8th, 9th and 10th show the deformations same as that of normal location.

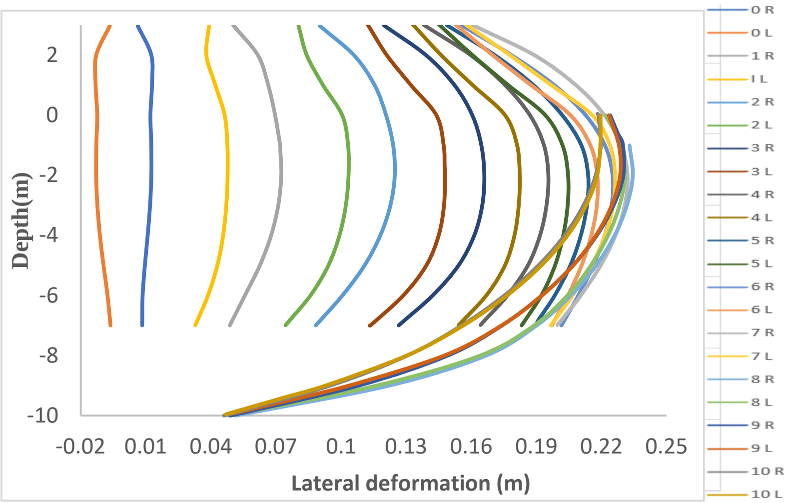


Fig 8. Predicted lateral deformations for insertion depth 3 m above the ground surface.

4.4 Stress vs settlement graphs

Fig. 9 depicts the variation of total stresses versus settlement of each stone column after the consolidation period of 3 years. For normally placed stone columns the variation of total Y stresses and settlement is linear straight line whereas for the stone columns placed above the foundation shown a nonlinear pattern, as the stone columns near the toe are placed in the foundation. As the loads coming on the stone columns decreases, the total stresses on the stone column decreases, if they are placed farther away from the center and also if the insertion depths are increased.
From the results, it can be seen that the settlement increases as the insertion depth increases. This is due to lack of rigidity of an embankment resulting in bulging and more settlements.

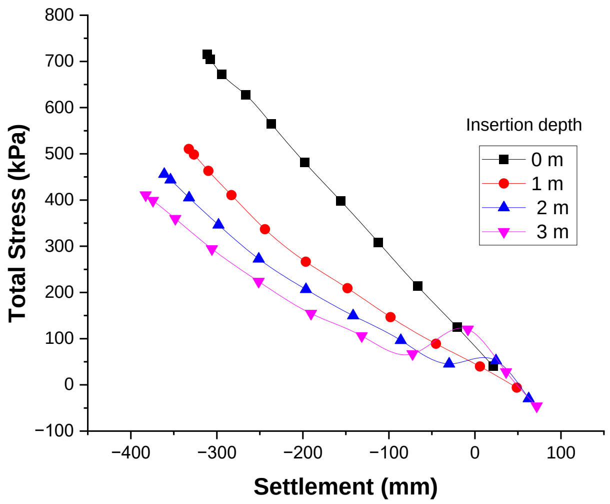


Fig 9. Total Stress versus settlement for the GESC.

5. CONCLUSIONS

In this work, a case study demonstrating the advantage of adopting geosynthetic-encased stone column as a ground improvement technique for a railway embankment built over the soft clay is investigated. Based on the analysis of results and interpretation of the same, the following conclusions are drawn:

- The load on the centrally placed column is evidently found more and it gradually decreased on columns placed towards the toe of an embankment.
- As regards to insertion depth impact, the bearing capacity is found maximum for the columns placed at the ground level and it decreased with an increase in insertion depth above the ground surface i.e., 715.8 kPa for normally orientation, and 509.78, 455.03, and 409.57 kPa for 1m,2m and 3m rise.
- It is found that bulging is highest in the central column, while the lateral deformation is greatest for the columns near to the toe of the embankment.
- For columns placed at ground surface, deformations noticed are not minimal. Whereas deflection is seen at the center of the stone column and deformation is almost equal at the top and bottom of columns with the varying insertion depths.
- With an increase in insertion depth, settlement increased and the total stresses decreased.

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