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Finite Element Analysis of Stone Column System: A Parametric Study

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Abstract
The performance of stone column has been studied as a method of ground improvement technique including the influence of design parameters on the settlement. The effect of area replacement ratio, influence of friction angle of stone column and influence of column stiffness has been studied with the use of finite element analysis. The study shows that settlement decreases with the increase in area replacement ratio. The friction angle has significant effect on the performance of stone column whereas the influence of column stiffness is negligible to the overall performance as it is dependent on stiffness properties of surrounding soil.

Keywords
Stone Column, Settlement Improvement Factor, Finite Element Method, Parametric Study

1. Introduction

In situ soil conditions are defining factors to carry out any construction activities. The structures should either be designed on the basis of soil properties or soil should be improved to meet the design requirement of the structure. Stone column is one of the economical and acceptable ground improvement techniques [1] that can be used with great success to enhance the settlement and bearing characteristics of soil. The decrease in the overall and differential settlement of treated soil is because of the fact that, the aggregate used in stone column has higher stiffness than that of original soil [2]. Stone columns has proved its versatility with its application ranging from isolated footings (pad/strip footings) to wide area footings/structures (embankments, raft foundation,waste water treatment plant) under different condition of loading.

In context of our country, the study has been rarely done, so an attempt is done to find the performance of stone column on the basis of load settlement response.

The main objective of this research work is to study the influence of area ratio, properties of stone column material that is friction angle and column stiffness on the overall settlement performance of stone column improved ground. This will also help for the study of usefulness of stone column in our geological setting and its effectiveness.

2. Study Area

The study area is situated at Sallaghari of Bhaktapur Metropolitan City, Bhaktapur district, Nepal. Kathmandu valley lies on metamorphic nappe and the overlying fossiliferous Tethyan sediments, both of which are part of Kathmandu complex[3]. The Kathmandu valley is filled up with late Pliocene to Pleistocene thick basin filled sediments[4]. Its basin is itself filled with thick fluvio-lacustrine deposits. Due to the products of weathering and its deposition on bed of lake, clay layer is capped by sand and silt overburden.

Figure 1: Study Area

3. Literature Review

Ground improvement techniques have been carried out from the past in order to enhance bearing capacity of soil and to reduce excessive settlement.The selection of particular ground improvement is mostly dependent on type of soil to be improved.

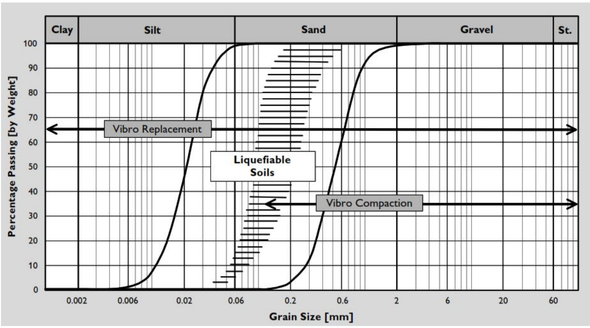

Figure 2: Use of Vibro Replacement and Vibro Compaction techniques by Priebe [5]

From the Figure 2, it can be well understood that, vibro replacement techniques is well suited for a range of soil types and its application for ground improvement cannot be denied.Numerical studies have been more pronounced during recent years.[6]Killeen & Mccabe (2014) studied the effect of small stone columns groups to study the settlement performance of pad footing along with the infinite number of stone column groups modelling it as a unit cell concept. [7] Castro (2014) presented 2D and 3D finite element analysis to study the performance of groups of stone column under a rigid footing and concluded that there is a small influence of the column arrangement on settlement performance of rigid footing and purposed a simplified modelling technique. Different design techniques have been proposed to study the performance of stone column in terms of settlement, bearing capacity and mode of failure. Unit cell concept is conventional approach to carry out analysis of stone column which uses circle of equivalent area to the zone of influence whereas Cylindrical cavity expansion theory idealizes soil as uniform, isotropic and linear elastic material which obeys Hooke's Law, then the principal total stress and strain increments in the radial, tangential and vertical direction can be calculated [8] ,which can be applied to stone column system.[9] Priebe (1995) developed a semi empirical design method to estimate the settlement of an infinite grid of end bearing stone columns. The column is assumed to be incompressible and a basic settlement improvement factor (n), which is defined as the ratio of settlements for an untreated footing to a treated footing, is developed.

$$n = \frac{s_{\text{untreated}}}{s_{\text{treated}}}$$

where $s_{\text{untreated}}$ is settlement of original ground with respect to applied load and s_{treated} is the settlement of improved ground with the application of stone column.

One of the key field of study is the effect of design parameters on functioning of stone column as it helps to understand the behaviour of stone column on different condition . So, there is need for the study of different parameters such as area ratio, friction angle and stiffness properties of stone column materials to be used and other parameters on settlement behaviour of soil improved by stone column.

4. Geotechnical Properties and methodology

The data required for the parametric analyses were taken form borehole test conducted at Sallaghari site and field and laboratory tests. The analysis was performed using finite element approach considering 3D modelling.

4.1 Finite Element Model

During the parametric study of stone column improved ground improvement technique, first the soil was modelled creating a borehole and after that structural component of model was defined ,which being stone column and raft element.The load was applied as surface load to the raft element of the model and the performance of improved and unimproved ground was studied. To reduce calculation time, symmetry of axis of model has been considered and one quarter of soil and structure has been modelled. The dimension of raft being 10m*15m, using symmetry boundary conditions along the line of symmetry, the dimension of model created is 5m*7.5m. Stone Column of diameter 0.6m has been used for study and the number of stone column used has been determined from area replacement ratio. The 3D model is shown in Figure 3 and 5.

Among the various model of soil available, Mohr-Coulomb model was used which is primarily based on cohesion and friction angle of soil. Modulus of elasticity of soil was determined from unconfined compressive strength and the correlation available from literature [10].10-noded tetrahedral elements was used to carry 3D modelling. The soil properties used in modelling is presented in Table 1.

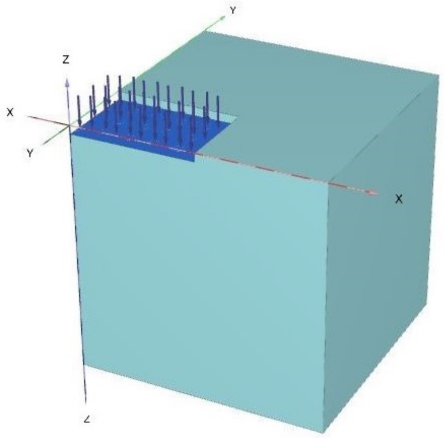

Figure 3: 3-D model

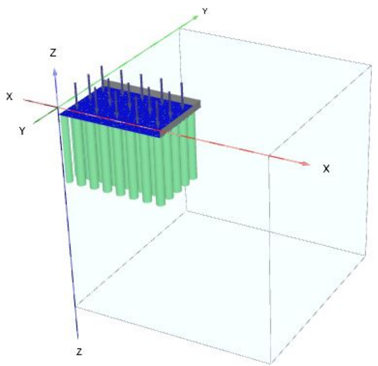

Figure 4: Structure Element

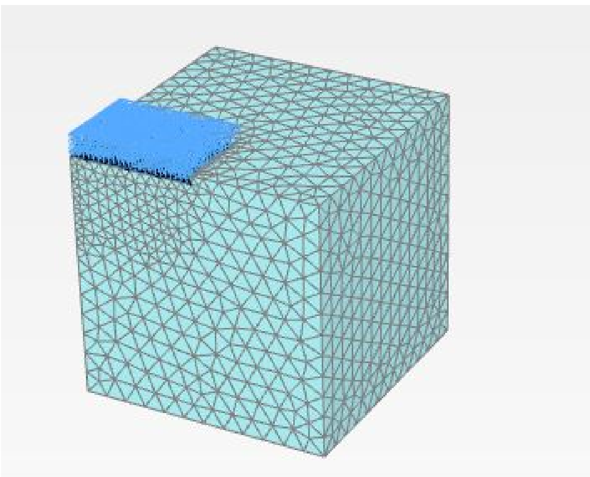

Figure 5: Mesh with Loading

5. Results and Discussion

5.1 Effect of Variation of Area Replacement Ratio

The area replacement used in this study was varied from 10% to 30%. The load was varied from 100 kN/m^2 to 200 kN/m^2.

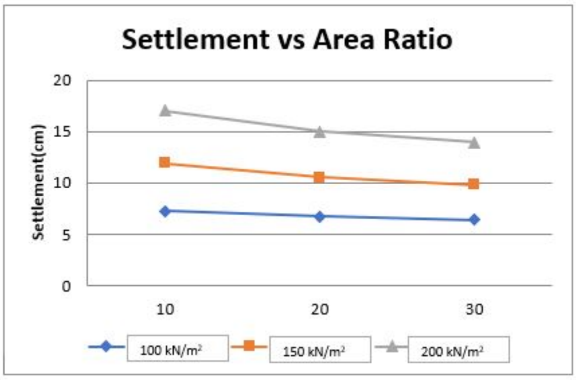

Figure 6: Plot of Settlement Vs Area Ratio

For applied load of 100 kN/m^2, it can be seen that the value of settlement decreases from value of 7.26 cm to 6.38 cm for increase in area replacement ratio from 10% to 30%. Similarly for load of 150 kN/m^2, the value of settlement decreases from 11.9 cm to 9.8 cm and for load of 200 kN/m^2, the settlement decreases from 17 cm to 13.9 cm, for increase in area replacement ratio from 10% to 30% respectively. Form the above Figure 6, it can be concluded that as the area ratio increase, the settlement decreases for the corresponding applied load . As area ratio increase, more soil is replaced by stone column increasing the load carrying capacity of soil and decreasing the settlement. Decrease in settlement is more pronounced for higher loading condition.

5.2 Effect of Stone Column Friction Angle

Another parameter that is often used for the study of stone column is friction angle parameter of stone column. Different researchers have used the value of friction angle of stone column ranging from 35 degree to 50 degree[11]. In this parametric study, stone column friction angle was varied from 35 degree to 50 degree with interval of 5 and effect was studied.

Table 1: Input Properties

Parameter	Soil	Stone Column	Raft
Depth(m)	0.0-15.0	0.5-5.5	0.0-0.5
Material Model	Mohr-Coulomb	Mohr-Coulomb	Linear Elastic
Density of Concrete, γ_{con}, kN/m^3			25
Unsaturated Weight, γ_{unsat}, kN/m^3	17.8	19.5	
Saturated Weight, γ_{sat}, kN/m^3	20	22.14	
Modulus of Elasticity, E, kN/m^2	8.80E+03	2.50E+05	2.00E+07
Cohesion, Cref, kN/m^2	7.3	0	
Friction angle, ϕ, Degree	29.67	38	
Poisson ratio, ν	0.33	0.35	
Drainage Type	Drained	Drained	

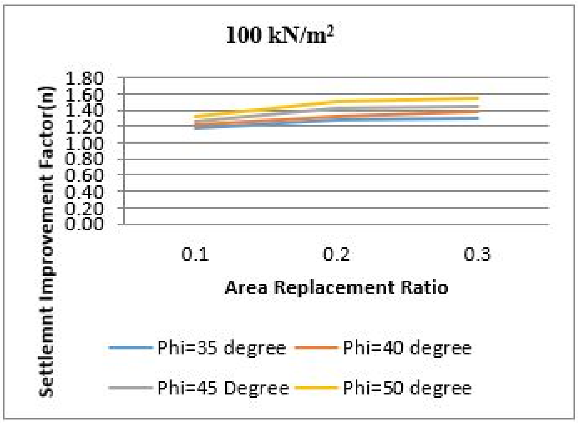

Figure 7: Influence of Friction Angle for Load of 100 kN/m^2

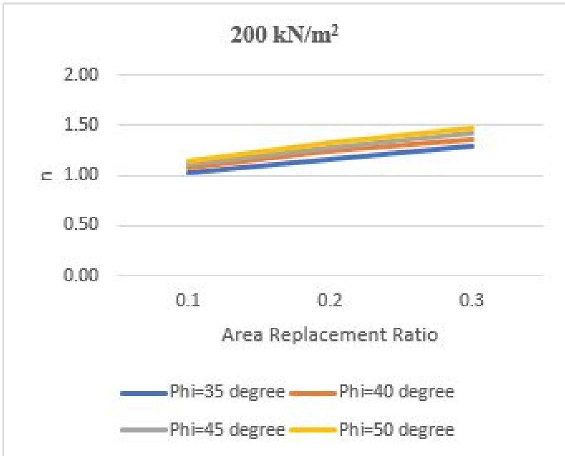

Figure 9: Influence of Friction Angle for Load of 200 kN/m^2

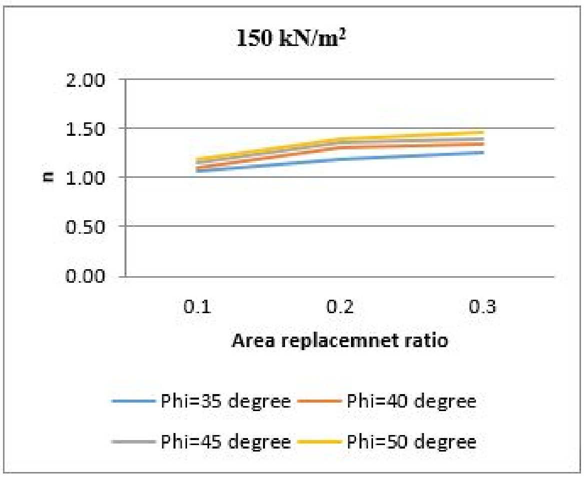

Figure 8: Influence of Friction Angle for Load of 150 kN/m^2

Figure 7,8,9 indicates the influence of friction angle on the overall functioning of improved ground with stone column. It can be clearly seen that as friction angle increases, settlement improvement factor increases. It is because of the fact that settlement reduces as friction angle increases. At a load of 100 kN/m^2 settlement improvement factor increases from 1.18 to 1.31 for the area ratio of 10% and 1.28 to 1.50 for area ratio of 20% and 1.30 to 1.55 for area ratio of 30%. Hence significant improvement of settlement improvement factor can be found with increase in friction angle of stone column.

5.3 Influence Of column stiffness

Use of stone column as ground improvement is generally carried in soil of less stiff. The stiffness of stone column is directly related to lateral support provided by surrounding soil since aggregate used as a stone column is a cohesion-less material. In this study, the stiffness of stone column is varied from modular ratio of 10 to 50 keeping the stiffness properties of stone column with the application of load varying from 50kN/m^2 to 300kN/m^2. After that the plot of load vs settlement was plotted to study the effect of column stiffness.

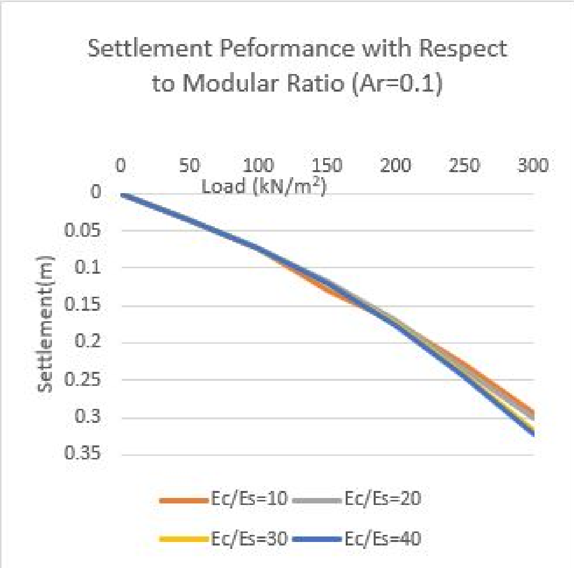

Figure 10: Performance of stone column for area ratio 0.1

Figure 11: Performance of stone column for area ratio 0.2

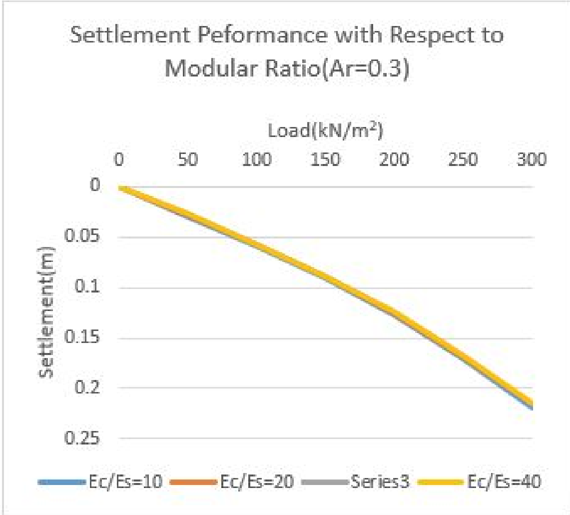

Figure 12: Performance of stone column for area ratio 0.3

From the Figure 10,11,12 it can be clearly seen that the modular ratio does not have effect on the performance of stone column rather it is function of surrounding soil and is dependent on the properties of surrounding soil of which ground improvement is being done.

6. Conclusion

- With increase in area replacement ratio, settlement improvement factor increases. The selection of suitable area ratio depends on project requirement.
- The settlement improvement factor increases as friction angle of stone column increases. It is because of the fact that , as friction angle increases settlement decreases.
- Performance of stone column is not totally dependent on stiffness properties of stone column and is related to stiffness properties of surrounding soil as it provides the lateral support to the stone column.

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