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A nonlinear model for footings on granular bed–stone column reinforced earth beds

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ABSTRACT

In the present study, an attempt has been made to model and analyze a combined footing supporting column, which is to be constructed on very soft soil. In view of small bearing capacity and very large deflections, foundations are constructed after improving the original ground. Here, the ground has been improved by providing the stone columns in the soft soil and on top of this improved ground; a granular fill layer has been placed just below the footing. The footing has been modeled as a beam having finite flexural rigidity. Granular fill layer, soft soil and stone columns have been represented by Pasternak shear layer, Kelvin–Voigt body and the Winkler springs, respectively. Nonlinear behavior of these has been considered by means of hyperbolic constitutive relationships. Governing differential equations for response of the system have been derived and presented in non-dimensional form. These equations have been solved using appropriate boundary conditions by means of an iterative Gauss Elimination technique.

Parametric study has been carried out for a typical combined footing supporting five column loads, considering a possible range of various model parameters and all the results have been presented in the form of nondimensional charts, which can be used readily.

1. Introduction

Stone columns have been used extensively over the last three decades in different parts of world in numerous ground improvement and foundation projects. A stone column is constructed by filling a cylindrical cavity with granular material. The soil improvements via stone columns are achieved from accelerating the consolidation of soft soil due to shortened drainage path, load carrying capacity increase and/or settlement reduction due to inclusion of stronger granular material.

Various studies have been conducted to study the behavior of various types of foundations on stone column treated ground. Balaam and Booker [1] provided the solution for the magnitude and rate of settlement of rigid foundations supported by soil reinforced with granular piles. Schweiger and Pande [2] analyzed settlement and failure load of rafts resting on stone column reinforced soft clays. Canetta and Nova [3] considered the soil reinforced with stone columns as a composite material and presented a general method to derive the suitable constitutive law. Alamgir et al. [4] presented a theoretical approach for the prediction of deformational behavior of the soft ground improved by columnar inclusions and loaded with a uniform load. Poorooshasb and Meyerhof [5] examined the efficiency of end bearing stone columns in reducing the settlement of a foundation system. A rigid raft foundation was considered for this study. Lee and Pande [6] proposed a numerical model to analyze elastic and elastoplastic behavior of stone column reinforced foundations. Numerical predictions were made for the behavior of model circular footings resting on stone-column reinforced foundations. Elshazly et al. [7] proposed

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a method for the analysis of circular foundations on stone-column-reinforced grounds and obtained the response of such system with the help of an advanced nonlinear finite element code. Shahu et al. [8] presented a theoretical approach to analyze soft ground reinforced by granular piles with a granular mat on top. This granular mat was assumed as a rigid, smooth layer. Deb et al. [9] proposed a mechanical model to predict the behavior of a geosynthetic-reinforced granular fill over soft soil improved with stone columns. Nonlinear behavior of soft soil and the granular fill was considered. Deb [10] analyzed a footing resting on a granular bed lying on top of the stone column treated soft soil. Parametric study conducted for a uniformly loaded strip footing revealed the fact that the presence of the granular bed helps to transfer stress from soil to stone columns and reduce maximum and differential settlement. The stone column was considered to exhibit linear behavior and the flexural response of footing was not considered in the analysis. In all these studies various types of foundations have been analyzed, however, the flexural rigidity of the foundation has not been considered in the analysis.

The flexural rigidity of footings can be considered in the analysis using the concept of beams on elastic foundation. Some of the studies pertaining to this include Vallabhan and Das [11], Shirima and Giger [12], Chen [13], Maheshwari et al. [14], etc. However, in all these studies, stone columns were not used for improvement of natural ground.

In view of above, Maheshwari and Khatri [15] proposed a model for the analysis of footing having finite flexural rigidity resting on poor soil. Nonlinear behavior of stone columns was considered in the analysis. However, in this model, the natural soil was modeled as Winkler springs, which cannot simulate clayey soil (soft soil) in which large part of the settlement is due to consolidation. Therefore, in the present study, a mechanical lumped parameter model has been proposed for the analysis of footings resting on granular bed–stone column improved soft soil system. Natural soil has been idealized as a Kelvin–Voigt body to take care of its time dependent behavior. The footing has been considered to possess finite flexural rigidity. Typically, the footing is supporting five equi-spaced columns, i.e., the footing is considered to have four bays. Nonlinear behavior of natural soil, stone columns and the granular fill on top of the stone column improved ground has been considered in the analysis.

2. Soil–Foundation system under consideration and proposed model

Fig. 1 depicts the definition sketch of a combined footing of length $2L$ supporting column loads. The loads getting transferred to the footing through equi-spaced columns are Q_1, Q_2 and Q_3 as shown in the figure. The footing is resting on a granular bed on top of the stone column treated soft soil. The thickness of granular fill layer is H and its shear modulus is G. Diameter and spacing of stone columns are d and s respectively. The flexural rigidity of footing is EI.

Fig. 2 shows the proposed model for the above stated soil-foundation system. The combined footing has been modeled as a finite beam lying on a granular fill layer, which has been idealized as Pasternak shear layer. This granular fill layer is lying on a stone column improved earth bed. Nonlinear behavior of granular fill, stone column and natural soft soil has been considered in the analysis. Natural soil has been modeled as nonlinear Kelvin–Voigt body and the stone columns as nonlinear Winkler springs. For simplicity, symmetric arrangement of stone columns below the footing (Fig. 2) has been considered. However, analysis procedure is general enough to take care of any other arrangement of stone columns. A hyperbolic nonlinear stress–displacement relationship proposed by Kondner and Zelasko [16] has been considered to exhibit the behavior of granular fill and stone column. The stress–displacement response of the saturated soft soil has been represented by a hyperbolic relation as proposed by Kondner [17]. Stone column has been assumed to be installed throughout the depth of natural soil bed overlying a rigid stratum. The influence of disturbance to the soil during the installation of stone columns has been neglected in the analysis.

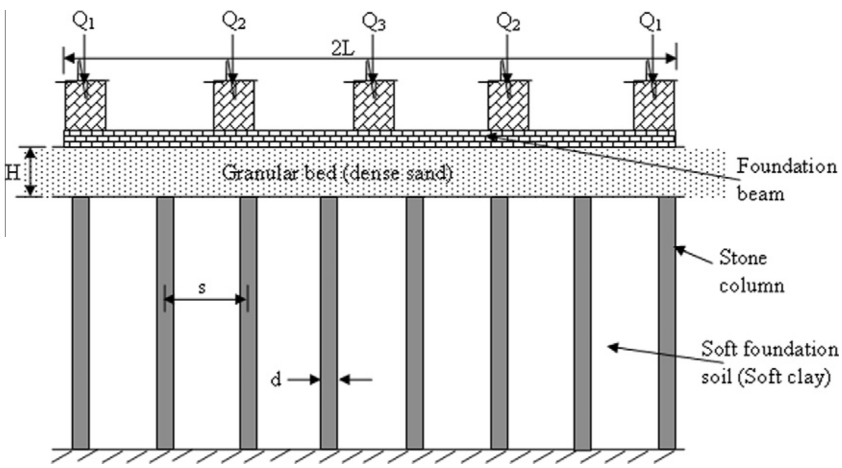

Fig. 1. Footing-granular bed–stone column reinforced soft soil system.