ARTICLE IN PRESS

Computers and Geotechnics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Analysis of flexible raft resting on soft soil improved by granular piles considering soil shear interaction

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A R T I C L E I N F O

Keywords:
Flexible raft foundation
Granular layer
Soft soil
Granular piles
Soil shear interaction

A B S T R A C T

This paper presents a method for nonlinear analysis of flexible raft foundation resting on a granular layer over soft soil improved by granular piles. The raft is idealized as a thin rectangular plate. The granular layer beneath the raft is idealized as incompressible shear layer. The improved ground is represented schematically as a system of elementary columns (soft and stiff springs) mutually interacting because of internal friction and/or adhesion. The accuracy of the present method is validated by comparing its results with the results of other existing analysis methods, field measurements and results of the PLAXIS 3D program and shown to be valid. A parametric study is performed to investigate the effect of various parameters on the behavior of raft resting on granular layer over soft soil improved by granular piles. It is observed that neglecting the soil shear interaction in the analysis is highly affecting raft behavior.

1. Introduction

Raft is a common foundation for some structures such as tall and heavy buildings, silos, chimneys and storage tanks constructed on soft soil. In many situations, granular piles are used to improve the soft clay beneath the raft. In such cases, understanding the behavior of the raft foundation resting on soft soil improved by granular piles is very significant for economical and safe design of the raft. Granular piles beneath the raft may be fully penetrated and resting on strong soil layer (i.e., end bearing granular piles, EBGP) or partially penetrated (i.e., floating granular piles, FGP). The floating granular piles are considered an economic alternative system to fully penetrated granular piles in case of deep soft soil layer or in case of lightly loaded structures. A granular layer of sand or sand-gravel mixture is usually placed over the top of granular piles reinforced soft soils [1].

The analysis of soil-raft interaction using different approaches are studied by many researchers (e.g. [2–11]). Most of the reported studies are conducted to study the behavior of rafts resting on unimproved ground. However, many research works are also conducted to understand the behavior of footings resting on granular piles-improved soft soils.

Balaam and Booker [12] presented solutions to evaluate settlement, moment and shear distribution of uniformly loaded rigid circular rafts resting on granular piles-reinforced soft soil by adopting a unit cell approach. Balaam and Booker [13] extended their work and proposed an interaction analysis that contains some simplifying assumptions to account for column yielding.

Prieb [14] developed a method for the analysis of rigid footings resting on end bearing granular piles improved soft soil. Prieb [14] method is considered the most common method used in the literature for calculating the settlement of soft soil reinforced by fully penetrated granular piles. The method is based on the unit cell concept and takes into consideration the angle of internal friction of the granular piles material.

Alamgir et al. [15] presented a rational analysis method for the prediction of deformational behavior of the soft ground improved by columnar elements and loaded with a uniform load. Poorooshasb and Meyerhof [16] presented a method based on the unit cell idealization. The vertical settlement is assumed uniform across the surface (i.e., rigid footing). The derivation of the equations and the model assumptions are quite similar to those of Prieb [14], but the main difference lies in the nature of the granular pile deformation characteristics. The details of the method can be found in the original reference.

Shahu et al. [17] proposed a simple theoretical approach to predict the settlement of uniformly loaded soft ground reinforced by granular piles with granular mat on top. The approach is based on the unit cell concept and incorporates the equal strain condition, the distribution of shear stresses and the load sharing between granular pile and soil. Pulko and Majes [18] developed an analytical-closed form solution for the prediction of settlements of rigid foundations resting on soft soil

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http://dx.doi.org/10.1016/j.compgeo.2017.09.007
Received 31 March 2017; Received in revised form 9 September 2017; Accepted 15 September 2017

improved by a large number of end bearing stone columns based on the unit cell concept. Pulko et al. [19] extended the work of Pulko and Majes [18] to deal with encased stone columns.

Elshazly et al. [20] proposed a method for the analysis of circular footings on granular pile-reinforced grounds and obtained the response of the system by advanced nonlinear finite element code. Madhav [21] proposed a method to evaluate the settlement of a raft on granular piles considering the radial displacement compatibilities of granular piles and performed a parametric study to investigate the influence of different parameters on the behavior of raft on granular piles.

Kirsch [22] performed a finite element analysis on two footings supported by 25 floating granular piles taking into account the installation effects. The finite element prediction is compared with field data and despite over-predicting the ultimate capacity of granular piles it predicts the settlement behavior quite well at working loads. The influence of increasing the column length and the angle of internal friction is found to be more pronounced at low area replacement ratio.

Zhang et al. [23] proposed an analytical solution for the settlement of composite foundations reinforced with floating granular piles considering the unit cell concept and the bulging deformations of granular pile.

Stuedlein and Holtz [24] presented and discussed the different methods used to predict the settlement of shallow foundations resting on aggregate pier reinforced clay. The accuracy of these methods was investigated using a database of high-quality footing load test data. Based on the database, they developed a multiple linear regression model for the prediction of footing displacements for aggregate pier reinforced clay under a wide range of pier configurations and soil conditions.

Das and Deb [25] proposed a mechanical model to study the behavior of uniformly loaded circular raft resting on stone column-improved ground. The axi-symmetric condition was considered in the analysis. The raft was idealized by a circular plate. The soft clay and granular fill were idealized as the spring-dashpot element and the Pasternak shear layer, respectively. The stone columns were modeled as stiff non-linear springs. To perform an axi-symmetric analysis, stone columns are converted into equivalent concentric rings with one stone column at the center. The finite difference method is used to solve the governing differential equations. The effect of different parameters on the behavior of the circular raft over stone column-reinforced ground was also studied. Das and Deb [26] extend their work to study the response of cylindrical storage tank foundation resting on stone column-reinforced ground taking into account the separation between the bottom raft and ground under liftoff condition.

Based on literature review, most of the current studies are focusing on the settlement behavior of the improved ground. In the design of the raft foundation, not only the settlement is a significant design factor, but also the internal forces (i.e., bending moment and shear forces) are very important design factors. The flexural rigidity of the raft is also a major factor affects its behavior. Therefore, it is necessary to determine the settlement as well as the internal forces in the raft resting on soft soil improved by granular piles.

One of the drawbacks of the current analytical methods for footings resting on soft soil improved by granular piles are that it assumes a uniform load as well as a rigid foundation on a single unit cell. Elshazly et al. [27] observed that the unit cell concept could lead to erroneous estimations of the settlement of the foundation. Studies also show that the unit cell concept is only applicable to interior granular piles near the centerline where no lateral displacement is observed [28]. Another drawback is that it neglects the shear interaction between soil springs in the analysis of improved soft ground-raft interaction.

The overall objective of this study focuses on investigating the behavior of a uniformly loaded flexible raft resting on a granular layer over soft soil improved by granular piles taking into account all the granular piles, the flexural rigidity of the raft, the nonlinearity of granular layer, soft soil and granular piles, nonhomogeneity of soft soil and the shear interaction between adjacent columns (i.e., soft springs or soft and stiff springs). The effect of various parameters on the behavior of raft resting on granular layer over soft soil improved by granular piles is studied in terms of displacements, differential displacements, bending moments, load shared by granular piles, settlement reduction factor and the average stress concentration ratio.

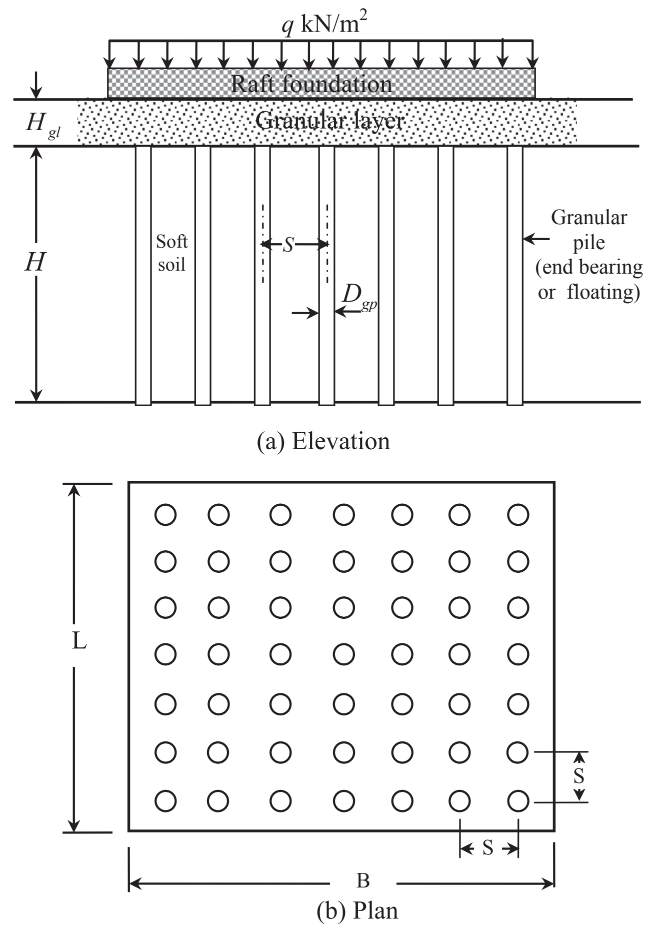

Fig. 1. The problem to be analyzed.

2. Method of analysis

Fig. 1 shows the definition sketch of raft foundation resting on a granular layer over soft soil improved by granular piles. The raft is of width B and length L and subjected to a uniformly distributed load, q. The thickness of the granular layer is H_{gl} and its shear modulus is G_{gl}. Diameter and spacing of granular piles are D_{gp} and S, respectively.

The raft is idealized as a thin rectangular plate. The granular layer is idealized as incompressible shear layer. The improved ground is represented schematically as a system of elementary columns (springs) mutually interacting because of internal friction and/or adhesion. The soft soil and granular piles are idealized as soft and stiff springs respectively. The shear interaction between adjacent columns (springs) is represented by a soil shear parameter. The length of the granular piles is considered equal to the thickness of the soft soil stratum (i.e., case of end bearing granular piles) or less than the thickness of the soft soil stratum (i.e., case of floating granular piles).

It is reported that due to the installation of the granular piles, the interface between the soft soil and granular piles material might be assumed as perfect (i.e., total adhesion) [22,29–31]. This leads to the improved ground behaving as one body. Therefore, in the present analysis, it is assumed that the value of the parameter that represents the soil shear interaction is constant and not varies from point to point