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Settlement performance of pad footings on soft clay supported by stone columns: A numerical study

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Abstract

The settlement behaviour of small loaded areas (such as pad and strip footings) on soft soil supported by stone columns is poorly understood. The lack of confinement associated with peripheral columns and the sharp stress decay with depth are features which are incompatible with the widely-used unit cell method for infinite column groups thereby rendering small group behaviour particularly difficult to analyse. Useful field data is virtually non-existent and although innovative laboratory modelling has been insightful, the findings cannot easily be extrapolated to field scale. In this study, a 3-D finite element analysis in conjunction with an elastic–plastic soil model is used to identify the effect of variables in the design process and interactions between them: these include column arrangement, spacing, length, and Young's modulus of the column material. A simplified method is proposed to relate the settlement of small groups to a reference unit cell settlement predicted by current analytical approaches.

Keywords: Footings; Stone columns; Settlement improvement factor

1. Introduction

It is well established that vibro-replacement stone columns provide an effective means of increasing the bearing capacity and reducing the compressibility of soft soils. The benefits arise from the fact that there is partial replacement of the host soil by a more competent material; the enhanced stiffness and strength of the compacted stone serve to relieve the soil of some of its load. Stone columns can be used in a variety of scenarios ranging from small loaded areas (e.g. footings) to wide loaded areas (e.g. floor slabs, embankments).

The optimum deployment of stone columns beneath small loaded areas (such as pad and strip footings) is arguably the most challenging aspect of stone column settlement prediction in soft soils. Sexton et al. (2013) have used 2-D axisymmetric Finite Element (FE) modelling to demonstrate that some recent analytical methods (Castro and Sagaseta, 2009 and Pulko et al., 2011 in particular) are successful in capturing the key factors influencing

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the performance of infinite column grids, which can be implemented mathematically using a *unit cell* model. However, unit cell models cannot capture the behaviour of peripheral group columns beneath footings that are not equally confined on all sides. The smaller the group, the more influential these peripheral columns become. Furthermore, the increment of vertical stress beneath footings decays much more acutely with depth than that beneath widely loaded areas, allowing partial depth treatment to be used in practice even though analytical methods are poorly developed in this respect.

A database of measured field settlement improvement factors in fine-grained soils compiled by McCabe et al. (2009) highlights a dearth of such data for strip and pad footings. High quality physical models of footings on soft clay supported by stone columns (i.e. Muir Wood et al., 2000; McKelvey et al., 2004; Black et al., 2011; Sivakumar et al., 2011; Shahu and Reddy, 2011) have been informative, although there are obvious difficulties in extrapolating model test findings to field scale, and the proportion of the area under each footing that has been replaced with stone in some of these tests has tended to lie at the high end of what might commonly be used in practice. Research in which the finite element method has been used to model ground improved with stone columns relates to wide area loading in the main, using either unit cell (e.g. Domingues et al., 2007a) or 2-D axisymmetric (e.g. Elshazly et al., 2008a) approximations. Some 3-D modelling of large column grids has also been carried out (i.e. Gäb et al., 2008); however, other than Kirsch (2008) no 3-D modelling of column-supported footings, carried out in conjunction with an advanced constitutive soil model, has been published. In this paper, PLAXIS 3D Foundation is used to model the behaviour of rigid square pad footings supported by various stone column configurations. The soil profile at the former UK geotechnical test site at Bothkennar, Scotland, is used as the basis of the modelling as it is representative of many soft soil profiles internationally for which the applicability of stone columns is of growing interest. This research identifies the roles and interactions of key factors relevant to the settlement design of small groups of stone columns, such as column arrangement, spacing and length, as well as the strength and stiffness of the column material. A simple design method predicting the settlement of groups of floating (partial depth) or end-bearing (full depth) columns is proposed, based upon geometrical corrections to unit cell settlement predictions.

2. General finite element modelling details

2.1. Column group variables

PLAXIS 3D Foundation FE software (Version 2.2) has been used in this study to capture the three-dimensional nature of small groups of columns supporting pad footings. The settlement performance of various configurations of columns was investigated by varying the number of columns (N), column spacing (s) on a square grid (with one exception) and column length (L). The combination of N and s dictated the footing width (B). The diameter of stone columns (d) is normally not a design variable as the poker is of fixed diameter (430 mm used for the bottom feed system) and a column diameter of $d = 600$ mm was adopted for the subsequent Finite Element Analysis (FEA) which is a typical average diameter of columns formed in soft soils. The area replacement ratio or area ratio is a parameter which measures the proportion of in situ soil replaced with stone columns. For a finite group of columns, the area ratio is defined as the ratio of the footing area (A) to the total area of columns beneath the footing (A_C):

$$\frac{A}{A_C} = \frac{4B^2}{N\pi d^2} \quad (1)$$

However, for an infinite grid of columns, the area ratio is defined as the ratio of the area of the zone of influence of one column ($A = s^2$ for a square grid) to the area of a single column (A_C):

$$\frac{A}{A_C} = \frac{4s^2}{\pi d^2} \quad (2)$$

The column length was increased in 1 m increments in the subsequent FEA from $L = 0$ m (i.e. an untreated footing) to $L = 13$ m to examine the settlement performance corresponding to partial depth treatment. The final analysis at

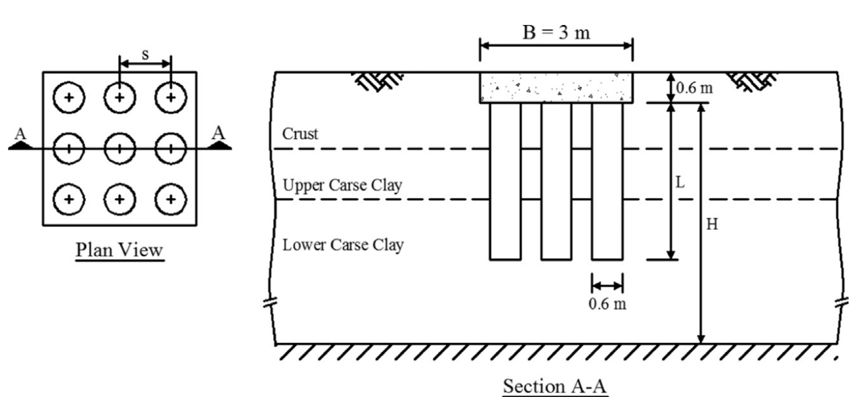

Fig. 1. Typical layout of a 3 × 3 group of columns beneath a 3 m square footing in the Bothkennar soil profile (see Section 4.1).