Computers and Geotechnics 59 (2014) 87–97

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Influence of stone column installation on settlement reduction

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ARTICLE INFO

Article history:
Received 2 August 2013
Received in revised form 20 December 2013
Accepted 2 March 2014
Available online 26 March 2014

Keywords:
Stone columns
Installation
Settlement reduction
Numerical modelling
Anisotropy
Destructuration

ABSTRACT

The paper presents numerical simulations investigating the settlement reduction caused by stone columns in a natural soft clay. The focus is on the influence of the soft soil alteration caused by column installation. A uniform mesh of end-bearing columns under a distributed load was considered. Therefore, the columns were modelled using the "unit cell" concept, i.e. only one column and the corresponding surrounding soil in axial symmetry. The properties of the soft clay correspond to Bothkennar clay, which is modelled using S-CLAY1 and S-CLAY1S, which are Cam clay type models that account for anisotropy and destructuration. The Modified Cam clay model is also used for comparison. Column installation was modelled independently to avoid mesh distortions, and soft soil alteration was directly considered in the initial input values. The results show that the changes in the stress field, such as the increase of radial stresses and mean stresses and the loss of overconsolidation, are beneficial for high loads and closely spaced columns but, on the contrary, may be negative for low loads, widely spaced columns and overconsolidated soils. Moreover, whilst the rotation of the soil fabric reduces the settlement, in contrast the soil destructuration during column installation reduces the improvement.

1. Introduction

Stone columns are one of the most common ground improvement techniques to improve soft soil deposits. They reduce the total and the differential settlements, accelerate consolidation, improve the bearing capacity and the slope stability and reduce the liquefaction potential. The improvement is achieved through the inclusion of gravel or crushed stone, which has a higher stiffness, strength and permeability than the natural soft soil. In addition, column installation also modifies the properties of the surrounding soil. However, design of stone columns does not usually consider those installation effects and is usually based on their performance as rigid inclusions [1–3]. In this paper, the term 'installation effects' refers to the changes in the state of soil due to column installation. Some authors [4] account for certain changes in the stress state due to installation by assuming a higher value of the coefficient of earth pressure at rest than that for the natural soil. The paper discusses the influence of the installation effects on the settlement reduction, which is nowadays one of the major concerns in an accurate design of stone columns [5].

Stone columns are installed using a deep vibrator, either electric or hydraulic, similar to those used for vibrocompaction or vibroflotation. However, the alteration caused by the vibrator is completely different in each ground improvement technique because of the different soil characteristics. In vibrocompaction, the vibrator is used in granular soils, and the vibration compacts the surrounding soil. The soil densification is the most important effect of vibrocompaction, and has been mainly analysed using field measurements [6,7], as it is difficult to model the process numerically [8]. In contrast, stone columns are typically used in soft cohesive soils, as these cannot be compacted. The density of clay increases only after consolidation by the application of monotonic, long-term loads. Therefore, the installation effects of stone columns are not usually considered and the main effect is assumed to be the cavity expansion induced by the vibrating poker. There is also a range of soils that fall in between the two extremes discussed above, in which densification is still possible, but additional granular material is needed to ensure an effective improvement, e.g. to

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http://dx.doi.org/10.1016/j.compgeo.2014.03.003
0266-352X/

Nomenclature

A	area
a_r	area replacement ratio: $a_r = A_c/A_l$
a, b	constants of the hyperbolic fits for the installation effects/absolute and relative effectiveness of destructuration in S-CLAY1S
c	cohesion
c_u	undrained shear strength
E	Young's modulus
E_m	oedometric (constrained) modulus: $E_m = [E(1-\nu)]/[(1+\nu)(1-2\nu)]$
e	void ratio (state parameter)
H	embankment height
K_0^{NC}	coefficient of lateral earth pressure at rest in normally consolidated conditions
K_0	coefficient of lateral earth pressure at rest
K_i	coefficient of lateral earth pressure after column installation
L	column length and thickness of the soft soil layer
M	slope of the critical state line
N	column spacing ratio: $N = r_l/r_c$
n	improvement factor
p_a	applied vertical pressure
p'	effective mean stress
p'_m	preconsolidation pressure (state parameter)
p'_{mi}	intrinsic preconsolidation pressure (state parameter): $p'_{mi} = p'_m/(1+\chi)$
q	deviatoric stress
r	distance from column axis
r_l, r_c	radius of the unit cell, of the column
s_z	settlement
s_{z0}	settlement without columns
α	inclination of the yield surface (state parameter)
β	settlement reduction factor/relative effectiveness of rotational hardening in S-CLAY1
β^*	ratio of the settlement with and without installation effects
χ	amount of bonding in S-CLAY1S (state parameter)
γ	unit weight
ε	strain
η	stress ratio: $\eta = q/p'$
θ	Lode's angle
κ	slope of swelling line from $e - \ln p'$ diagram
λ	slope of post yield compression line from $e - \ln p'$ diagram
λ_i	slope of intrinsic post yield compression line from $e - \ln p'$ diagram
μ	absolute effectiveness of rotational hardening in S-CLAY1
ν	Poisson's ratio
σ'	effective stress
ϕ	friction angle
ψ	dilatancy angle
OCR	overconsolidation ratio
POP	pre-overburden pressure

Subscripts/superscripts

0	initial
CS	at critical state
d, v	deviatoric, volumetric
e, c, s, l	embankment, column, soil, elementary cell
p	plastic
r, z, θ	cylindrical coordinates
unsat, *sat*	unsaturated, saturated

avoid liquefaction [9]. In this paper only a purely cohesive soft soil is considered.

Experimental studies have shown some of the effects of column installation, e.g. the increase of pore pressures and horizontal stresses, and the remoulding of the surrounding soil has been measured in the field [10–14]. There have also been attempts to investigate these effects through physical modelling of the process by means of centrifuge testing [15,16], but the soils used are reconstituted and hence not fully representative of natural clays.

Modelling the problem theoretically is complex, and although the cavity expansion is a well-studied problem (e.g. [17,18]), there are few numerical analyses of the installation effects of stone columns [19,20]. The authors have recently studied this numerically using advance soil models to reproduce the behaviour of natural structured soft soils [21].

Beyond the changes in the state of soil due to column installation, the knowledge of the influence that those changes have on the soil improvement is very limited. Schweiger [22] found that, if those changes are considered, the settlement of a circular footing was reduced but only for high load levels. The improvement is caused by the increase of mean stress in the clay, which enables the soil to carry more load and in turn provides a better lateral support for the columns. Column installation was modelled imposing a volumetric strain field, which is similar to input post-installation values of the soil density and the lateral earth pressure. However, this approach needs of approximate estimations of the volume change. Later, Kirsch [19] simulated the settlement reduction caused by installation effects of a group of floating columns in a sandy silt. He distinguished between individual installation effects, which were modelled applying a small cavity expansion (2–8%), and a global installation effect in an enhanced zone around the group of columns with a higher stiffness (around twice the initial one). Those installation effects give a further reduction of the settlement of 40% and 5–25%, respectively. In the work above, the installation effects were somehow back-calculated from field measurements.

To clarify the influence that the changes in the state of soil due to column installation have on the settlement reduction caused by the columns on soft cohesive soils, the authors carried out numerical simulations using two advanced constitutive models, namely S-CLAY1 [23] and S-CLAY1S [24], which have been especially developed to represent natural structured soft soils, a common type of soils to be treated with stone columns. The Modified Cam clay model (MCC) [25] has also been used for comparison. The paper presents the "unit cell" models used to study several column spacings and embankment heights, in which a curve fitting of the initial stresses and state variables is used to account for the installation effects. The settlement reduction achieved for the different cases is analysed. The comparison of the settlement improvement with and without installation effects demonstrates the influence of the changes in the stresses and soil structure, both fabric and interparticle bonding. The main positive and negative changes in the soil state due to column installation are highlighted. Depending on the analysed case, the effects of column installation either improve or reduce the settlement reduction of the stone column foundation.

2. Numerical model

The finite element code Plaxis v9 [26] was used to develop a numerical model of a reference problem that could help to