Computers and Geotechnics 88 (2017) 74–94

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

High pressure jet-grouting column installation effect in soft soil: Theoretical model and field application

Hanlong Liu [a], Hang Zhou [a,*], Gangqiang Kong [b], Hongyu Qin [c], Yahui Zha [d]

[a] Key Laboratory of New Technology for Construction of Cities in Mountain Area (Chongqing University), Ministry of Education, School of Civil Engineering, Chongqing University, Chongqing 400045, China

[b] College of Civil and Transportation Engineering, Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China

[c] School of Computer Science, Engineering and Mathematics, Flinders University, 1284 South Road Clovelly Park, South Australia, 5042, GPO Box 2100, Adelaide 5001, South Australia, Australia

[d] College of Civil Engineering, Key Laboratory of New Technology for Construction of Cities in Mountain Area, Chongqing University, Chongqing 400045, China

ARTICLE INFO

Article history:
Received 5 January 2017
Received in revised form 22 February 2017
Accepted 3 March 2017

Keywords:
High pressure jet grouting column
Installation effect
Theoretical model
Cavity expansion
Limit injection pressure
Ground surface displacement

ABSTRACT

This paper presents a theoretical model for investigating the installation effect of high pressure jet grouting column in soft clay. The model is formulated by assuming the installation process as a series of pressure-controlled spherical cavity expansion in semi-infinite soil, of which the approximate solutions are derived by combining use of two fundamental solutions of spherical cavity expansion in finite spherical symmetry soil and displacement-controlled spherical cavity expansion in semi-infinite soil. The approximate solutions are then validated by comparing the predictions with FEM results as well as published results. The comparison results show that the presented approximate solutions are suitable for the problem of pressure-controlled spherical cavity expansion in semi-infinite soil, particularly in evaluating the limit expansion pressure as well as the expansion pressure-ground surface displacement relation. Subsequently, the proposed approximately solutions are applied to interpret the limit injection pressure and the grouting pressure-ground surface displacement during the installation process of HPJ-GC. Some parametric studies are also conducted. Furthermore, an instrumented field test study of HPJ-GC is conducted in the thick soft soils comprising quaternary alluvial and marine deposits of the Lianyungang-Yancheng Highway located in Jiangsu Province, China. The measured ground heave is compared with the analytical predictions using the proposed theoretical model. Reasonable agreement is achieved.

1. Introduction

High pressure jet-grouting column (HPJ-GC) is a useful and effective method, which is widely used in geotechnical engineering for various purposes, such as reducing the settlement and increasing the bearing capacity of the existing and new foundations, supporting open and underground excavations, and creating water cut-offs for dams [17,18,19,4,21,14]. The installation process of HPJ-GC can be separated into the following procedures. First, a grout pipe with small diameter nozzles, which are disposed for directing a jet of fluid such as the water-cement mixtures at an angle inclined to the axial direction of the grout tube, is inserted into the drilled borehole in the ground. Then, the fluids are injected into the subsoil through the nozzles at high speed to erode the surrounding soil, which is mixed with the injected fluid to form a gout bulb. The grout pipe is continuously rotated at a constant rate and slowly raised towards the ground surface. This allows the formation of successive grout bulb, and eventually produces a jet column of quasi-cylindrical shape. According to the number of the fluids injected into the subsoil, the HPJ-GC technique can be classified as three types: single-fluid system (grout), double-fluid system (air and grout) and triple-fluid system (water, air and grout) [12].

The first works on HPJ-GC date back to the 1970s, and in the last 40 years numerous papers have been presented. A review of the previous study shows that the most findings are restricted to the experience of individual authors though collective views have been reported in a few cases in the early stage [11]. Most of the design guidelines for HPJ-GC were based on empirical methods. No reliable theoretical improvement was presented in the next two decades. Modoni et al. [21] developed a theoretical model for revealing the mechanical phenomenon of single-fluid jet-grouting in three types of soil, as characterized by gravels, sandy soils and clayey

* Corresponding author.
E-mail addresses: hliuhhu@163.com (H. Liu), zh4412517@163.com (H. Zhou), gqkong1@163.com (G. Kong), hongyu.qin@flinders.edu.au (H. Qin), zhayahui@163.com (Y. Zha).

http://dx.doi.org/10.1016/j.compgeo.2017.03.005
0266-352X/

soils, on the basis of the theory of turbulent diffusion. They show that the grout seepage is the most important factor when the jet-grouting is conducted in gravels, while the process of injected fluid in sandy soil should be regarded as penetration. For clayey soil, the jet action is assumed as load imposed on the jet-soil interface, and the erosion process is simulated as an evolving sequence of undrained failures. The developed theoretical model for single-fluid jet-grouting was further modified and extended to the cases of double and triple-fluid system by the aid of energy method. This extended theoretical model was subsequently used for predicting the diameter of single, double and triple fluid jet-grouting columns [15,27].

In spite of such rewarding theoretical developments, there is still a relevant degree of uncertainty about the use of HPJ-GC technique in practical engineering, arising from the lack of reliable theoretical methods for evaluating the installation effects. It should be noted that the injection of high pressure fluid induces deformation of surrounding subsoil. In an urban environment, sometimes the deformation is so significant that it may cause damage to the existing foundations, underground services or tunnels, the pavement structure of highway. Evaluating and controlling the soil stress and deformation are important design considerations. A review of the previous work shows that no relevant theoretical model is presented for capturing the HPJ-GC installation process, although some theoretical models for the similar problems such as the compaction grouting and deep mixing soil-cement column were proposed. One typical method for compaction grouting was developed by Graf [16]. In this approach, the compaction grouting pressure is assumed to cause conical shearing of the soil above the grout bulb, and thus the grouting process is controlled by the weight of the cone of soil above the grout bulb as well as the undrained shear strength of soil. Based on Graf's method, Wong [34,35] developed a simplified analytical model for the failure of Mohr-Coulomb soil caused by compaction grouting, which is usually used to predict the limit injection pressure. El-Kelesh et al. [13] presented a model by the combing the cavity expansion model and Wong's simplified analytical model to determine the limit injection pressure. However, the assumption of the elastic-perfectly plastic soil is taken and the soil stress history cannot be well considered. Furthermore, three theoretical models only consider the limit pressure of grouting, but not the soil displacement. More recently, Shen et al. [27,28,29,30], Wang et al. [31,32] and Yuan et al. [41] investigated the jet-grouting induced soil displacement using the cavity expansion model, while they also used the elastic perfectly plastic model for describing the soil behavior.

In addition, Chai et al. [7] proposed a theoretical method to predict the lateral displacement induced by the deep mixing soil-cement column installation based on the theory of an infinitely long cylindrical cavity expansion in an infinite soil. Subsequently, Chai et al. [47] modified the method by combining use of the original method derived based on the cylindrical cavity expansion theory in an infinite medium and a correction function, which is introduced to consider the influence of the limited length of the columns. The correction function was obtained through the comparison of the spherical and cylindrical cavity expansion solution for a single column installation. However, Chai et al.'s solution does not well consider the effect of the free surface of the ground since an assumption of zero vertical displacement at the free surface is used when deriving the solution. In other words, the normal stress at the free surface induced by the imaginary spherical cavity expansion is not eliminated in the solution and it could not be used to predict the ground heave. Also, Chai et al assumed the soil to be elastic perfectly plastic and cannot consider the soil stress history.

In terms of the lack of theoretical models for the installation effect of HPJ-GC and the limitations of the presented theoretical models for the similar problems (compaction grouting and deep mixing soil-cement column), this paper aims to present theoretical models for capturing the mechanism of the installation effect of HPJ-GC. The presented theoretical models are then validated by comparing the predictions with the previous results, FEM results as well as the field test results monitored in the part of the existing Lian-Yan expressway, namely the Guan Yun section, of which the embankment is reinforced by the HPJ-GC technique.

2. Mechanism of HPJ-GC installation process in the highway embankment

This paper concerns more about the application of HPJ-GC technique in the improvement of the highway embankment (see Fig. 1), and thus the mechanism for such an engineering background is described here. According to Modoni et al. [21], the jet-grouting has three types of mechanisms for various soils, namely, grout seepage for gravels, penetration for sandy soils and erosion process for clayey soils. Improving soft soil ground remains one of the significant challenges in highway construction, the third type of jet-grouting mechanism, namely the erosion process for clayey soils, is selected in this study. For this type of mechanism, a shear failure zone forms around the nozzles of the injection pipe, where the soil is seriously disturbed during the injection of the high pressure fluid. The soil in this zone is mixed with the injected fluid and the mixture forms the final columns. Beyond the failure zone, the soil is in plastic state due to the expansion of the grout bulb. As the distance from the grout bulb increases, the deformation becomes essentially elastic. This type of mechanism can be modeled by the well-known cavity expansion theory [6,40,9,5,24,8,44,45,46,42,20,43]. Solutions to cavity expansion have been of interest in the area of geomechanics, where they have been used to conduct approximate analyses of the stresses and deformations induced by the pile installation, and to interpret the in-situ test such as the CPT test and pressuremeter test. Numerous analytical, semi-analytical and numerical solutions have been proposed for the cavity expansion problem [33,23,6,40,10,37,5,44,45,46,42]. A review of these published solutions show that all of the solution are derived based on the assumption of infinite medium. This indicates that the previous cavity expansion solutions may have limitations when applied to study the problem of jet-grouting in semi-infinite ground. Although some methods, such as the virtual image approach [25], are incorporated into the cavity expansion theory to predict the displacement by considering the effect of the semi-infinite soil, the limit pressure of cavity expansion in semi-infinite soil cannot be well considered.

3. Conceptual model for HPJ-GC installation process

It is assumed that the high pressure jet grouting in the ground can be modeled by the spherical cavity expansion in a semi-infinite soil (see Fig. 2). In this case, the problem of high pressure jet grouting is reduced to solve the boundary value problem, particularly to give the solution of the grouting limit pressure and the grouting pressure-soil surface displacement relation, which play important role in the guideline of the HPJ-GC installation in practice. However, a rigorous elastic-plastic analytical solution for the stress and displacement induced by the pressure-controlled cavity expansion in semi-infinite soil is difficult, if not impossible, to find theoretically. This paper avoids pursuing the exact elastic-plastic solution but relaxing some factors when deriving the limiting grouting pressure (or cavity expansion pressure) and grouting pressure-soil surface displacement relation. The influence of these relaxed factors on the resolution of the solution will be discussed by comparing with the FEM results in the subsequent analysis.