ARTICLE IN PRESS

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ScienceDirect

Soils and Foundations xxx (2018) xxx–xxx

www.elsevier.com/locate/sandf

Comprehensive group pile settlement formula based on 3D finite element analyses

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Received 27 December 2016; received in revised form 8 July 2017; accepted 14 August 2017

Abstract

In the past, formulas for the settlement of group piles considered only a few input parameters and offered only a limited approximation of the actual settlement. Nowadays, however, thanks to the fast-growing performance of personal computers, it is possible to create large 3-dimensional finite element models with a better and more reliable settlement approximation. On the other hand, 3-dimensional finite element methods for piles are not very common in practice since the required procedure is comparatively cumbersome, expensive and needs a bit more expertise. In order to address this issue, a pile settlement formula was developed in the present study based on about 120 finite element model configurations. The group pile settlement formula incorporates the dimensions of a rectangular raft, namely, the diameter, length and spacing of the piles, vertical uniform pressure, soil moduli up to five layers, ultimate pile-soil resistance, pile-tip resistance and elastic modulus of the piles. In addition to this, the average deflection rate of the raft is estimated. The reliability of the finite element model is verified through laboratory-scale group pile tests. The proposed formula is also checked against five well-documented case studies. The formula may help engineers optimize group pile configurations more efficiently by applying the quality of the 3D finite element estimation to practice.

Keywords: Group pile formula; TNO DIANA; Settlement; PLAXIS 3D; Subgrade modulus

1. Introduction

The demand for pile foundations has increased with the fast development of tall and heavy structures in growing cities. As a result of this, accurate estimations of group pile settlements have become more important. In particular, strict foundation raft settlement or deflection rate requirements dictated by national codes have initiated the search for more sophisticated methods.

For the last 60 years, numerous approaches have been proposed for estimating the settlement of group piles. The leading approaches can be categorized as follows (Dung et al., 2010): (1) The empirical or semi-empirical approach (Meyerhof, 1976; Vesic, 1977), (2) The equivalent raft or pier approach (Terzaghi and Peck, 1967; Fellenius, 1991; Poulos, 1993; Yamashita et al., 2015), (3) The interaction factor approach (Poulos and Davis, 1980; Randolph and Wroth, 1979) and (4) The numerical analysis approach (Chow, 1986; Clancy and Randolph, 1996). The comparison and prediction capabilities of these methods have been well-documented in a study by Dung et al. (2010). Their study reports that the relative standard deviation in settlements calculated by the four different methods is in the range of 50%. Such a deviation in group pile settlements indicates a major problem with accuracy. Besides these methods, Shahin (2014) used recurrent neural networks calibrated with in-situ full-scale pile load tests to predict pile settlements.

Peer review under responsibility of The Japanese Geotechnical Society.
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https://doi.org/10.1016/j.sandf.2017.11.012
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There are various factors that can influence the settlement of group piles. One of them is the pile installation method. The effects of the pile installation method have been investigated by several researchers (Housel and Burkey, 1948; Cummings et al., 1950; Lambe and Hom, 1965; Lo and Stermac, 1965; Orrje and Broms, 1967; Hanna, 1967; Fellenius and Broms, 1969; Koizumi and Ito, 1967; D'Appolonia and Lambe, 1971; Fellenius, 1984, 2006). These studies were mostly targeted at solving problems such as the gain in bearing capacity or the loss due to pile driving (usually in clay), post-pile displacement due to negative skin friction and the development of pore pressure. In recent years, some researchers have developed rate-dependent models for soft soils which are helpful for modelling the effects of pile installation (Zhu and Yin, 2000; Grimstad et al., 2010; Sivasithamparam et al., 2013). Ottolini and Dijkstra (2014) reported that until that time there had been no efficient numerical model that considered the installation effects especially on the settlement of group piles. A recent study by Phuong et al. (2016) demonstrated that the installation of a single displacement pile could be modelled well with the material point simulation method (MPM). The numerical results reported in their study were verified by centrifuge tests. It has been reported that the MPM, in conjunction with the hypoplastic constitutive model (formulated by Von Wolffersdorff, 1996) makes it possible to model the large strains developing around a pile tip during pile driving. According to the study, the bearing capacity of a single pile increased about 2.5 times, while the void ratio around the pile tip decreased by about 5% (=compaction) after pile driving.

Nowadays, engineers are trying to enhance their settlement predictions by implementing 3-dimensional finite element (3D FE) models. On the other hand, this approach is not yet widely used in engineering practice since it is relatively cumbersome and expensive.

In order to address this issue, a group pile settlement formula was developed in this study based on about 120 finite element model configurations. The group pile settlement formula incorporates the dimensions of a rectangular raft, namely, diameter, length and spacing of the piles, vertical uniform pressure, soil moduli up to five layers, ultimate pile-soil resistance, pile tip resistance and elastic modulus of the piles. The reliability of the formula was checked against another 3D FE program (PLAXIS 3D) and also against five well-documented case studies.

2. Verification of finite element model with embedded beams

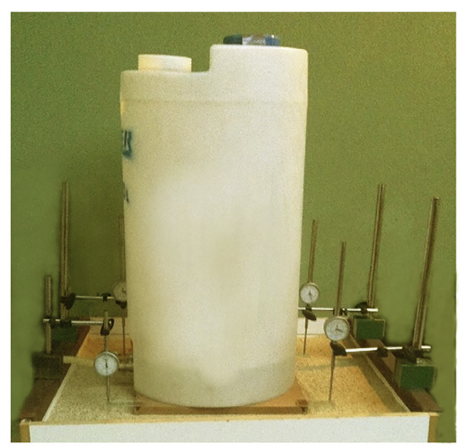
2.1. Finite element program

In this study, the TNO-DIANA finite element (FE) program is used to model the group piles. The main reason for using DIANA is its capability to model piles as embedded beam elements which have a nonlinear solid-beam slip surface (Diana User's Manual, Release 9.5). Embedded piles can be accommodated in solid elements relatively easily, because their nodes are not required to coincide with the nodes of the adjacent solid elements. A typical illustration of an embedded beam (embedded pile) is given in Fig. 1S (in the Supplementary Data file).

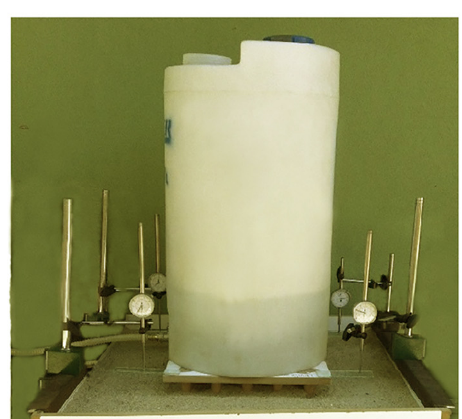
2.2. Setup of laboratory-size group pile test for verification

The verification test was performed in a 0.8 m × 0.8 m × 0.8 m MDF (Medium-Density-Fibreboard) box filled with dry sand (Fig. 1). The testing facility was used not only for the plate loading test, but also for the group pile loading test. The loading plate applied for the plate loading test was manufactured from a 0.4 m × 0.4 m × 0.02 m MDF piece. A similar size MDF plate was rigidly attached to 25 wooden piles and served as a small-size group pile foundation (Fig. 1). Each pile was 0.35 m in length and 0.02 m in diameter.

In each test, the required vertical weight was provided by an HDPE (High Density Polyethylene) cylindrical water tank located at the centre of the loading plate (Table 1 and Fig. 2). The distribution of the water pressure over the raft was expected to be quite uniform since the cylindrical water



a) Plate loading test



b) Group pile loading test

Fig. 1. (a) Plate loading test and (b) Group pile loading test.