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Research Paper

Permeable piles: An alternative to improve the performance of driven piles

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ABSTRACT

This paper investigates the soil displacements and excess pore pressures induced by driven piles using a combined 3D finite and infinite element approach. The analyses are compared with analytical evaluations and field measurements. Consolidation analysis is conducted to illustrate the variation in pore pressure with time. A technique of drilling drainage holes on the pipe pile is proposed in this paper to accelerate the dissipation of pore pressure to improve the performance of displacement piles. It has been noticed that optimal performance of piles can be obtained by assigning openings in piles within the bottom 50% of the pile length.

1. Introduction

Piles can be installed by driving (displacement piles) or inserting (non-displacement piles), and the stress state and the developed pore water pressure in the surrounding soil differ significantly based on the installation method. In the case of non-displacement piles, a relatively uniform stress condition is formed due to the presence of casing and drilling mud. Design of such piles relies on empirical correlations [1]. On the other hand, a great amount of uncertainty exists in the design of displacement piles, since the driving mechanism is project-specific, where the soil-pile interaction (i.e., displacements, strains and stresses) is altered by geological conditions, pile properties and installation procedures. For displacement piles, a foundation pit is often excavated prior to pile driving to minimize the radial displacement and ground heave at shallow depth, especially in soft soil layers. Pore water pressure must also be carefully controlled during the installation of displacement piles to reduce the settlement at greater depth.

Empirical evaluation of displacement piles is generally carried out based on experimental evidence, either from field measurements or controlled laboratory conditions. Bozozuk et al. [2] measured the soil disturbance of sensitive marine clay in an *in situ* pile driving project. They found that vertical heave could be at a distance as far as approximately 39 times the pile diameter (d), and the developed pore water pressure was 35–40% higher than the overburden stress during the installation, which was dissipated 8 months after completion of the project. In addition to these conservative estimations, pore pressure cells [3] and piezocones [4] had been used in full scale field tests. An influencing zone of $3d$ was reported, where undrained shear strength of sensitive clay changed due to excess pore pressure, but a full dissipation was observed after 25 days [3]. Field observations of Cooke et al. [5] demonstrated that ground heave occurred up to a depth of about $10d$, below which the soil behaviour was governed by settlement and radial displacement. A recent field testing program provided evidence that the excess pore water pressure could be generated in a range of $15d$ from the pile and the radial displacement occurred within a distance of $3d$ [6]. Laboratory tests have been conducted to evaluate the displacement pattern around driven piles. For example, image-based geomechanics facilitated understanding of the penetration mechanism in plane-strain calibration chamber tests [7]. Centrifuge techniques were used for the analysis of heave/settlement of energy piles due to thermal loading [8].

The complexity of analysis of displacement piles lies in the unpredictability of soil deformation (i.e., ground heave at shallow

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depth and settlement at greater depth) and the pore water pressure development. The Cavity expansion method (CEM) [9] is a typical closed-form solution for the analysis of the soil-pile interaction problem. Vesic [10] proposed the CEM and Randolph and Wroth [11] initially used this method for evaluating the consolidation behaviour around a driven pile. Different derivations have been developed based on the CEM, such as stress rotation analysis [12]. An alternative approach using the strain path method has been developed by Baligh [13] for floating piles, which was further improved to predict ground movement induced by pile driving [14,15]. Load transfer function was also derived for axially loaded piles [16]. However, this type of analysis depends heavily on the choice of spring stiffness. The limitation of the spring-based approach has been identified for similar buried structures, where the use of springs calibrated for high stiffness pipelines could result in very conservative estimate of bending behaviour [17], and over- and under-estimated axial force on flexible pipes in loose [18] and dense sand [19], respectively.

Numerical techniques have been used greatly to facilitate the analysis of driven piles including geometric nonlinearity, material nonlinearity, and soil-pile interaction. The source-sink technique was developed to predict ground heave [20,21]. Boundary element analysis enabled 3D coupled evaluation of vertical piles subjected to passive loading [22]. Koumoto and Kaku [23] performed 3D finite element analysis for static cone penetration into clay. Advanced modelling techniques have been proposed to tackle complex interaction behaviour between pile and soil, such as introducing 1D wave equation analysis in piles (WEAP model) for wave propagation analysis during pile driving [24], using the MEPI-2D model (a Mohr Coulomb oriented failure criterion accounts for strain softening) to evaluate installation effects for driven piles [25], formulating analysis in an updated Lagrangian framework for calculating large deformations associated with pile driving [26,27], developing a Coupled Eulerian Lagrangian (CEL) approach for simulation of pile jacking [28] and implementing Convected Particle Domain Interpolation (CPDI) based on the Material Point Method (MPM) to trace material displacement during pile driving [29].

In this paper, a 3D finite element model with infinite element boundary conditions has been developed in the Dynamic/Explicit analysis mode of ABAQUS to address large mesh distortions in the vicinity of the pile. Numerical simulation is calibrated against soil displacement responses and pore water pressures during pile driving obtained from analytical solutions and experimental measurements. The consolidation behaviour with time is also evaluated. Excess pore water pressure dissipates with time after pile installation, so that the bearing capacity of the pile can be further mobilized based on the principle of effective stress. Measures that can accelerate soil consolidation could potentially help the driven pile to reach its maximum resistance in a shorter time span. Therefore, an alternative is proposed to improve the performance of pipe piles by drilling drainage holes around the pile circumference. An extra drainage path is allowed in the lateral direction at the pile. Numerical calculations are used to evaluate the efficacy of the proposed strategy. Further parametric study has been conducted to investigate the most efficient location and ratio of permeable area on the pile.

2. Pile driving analysis

2.1. Soil displacement

A pile foundation provides resistance to support the vertical load transmitted by the superstructure. Therefore, it is a general practice to calculate the soil displacement due to loading in the vertical direction (major principal stress, σ_1), which induces the increase in the minor principal stress (σ_3). Additionally, pile driving causes the increase in σ_3 due to cavity expansion [9,11] around the pile and the variation in σ_1 needs to be determined.

During the pile driving process, the increase in vertical stress ($\Delta\sigma_1$) due to lateral expansion (increase in horizontal stress, $\Delta\sigma_3$) may exceed the overburden stress, which causes the occurrence of ground heave. At greater depths, the induced vertical stress is less than the overburden stress, so that the soil will settle and move laterally (see Fig. 1). By drawing an analogy to an expanded cylindrical cavity, Randolph [1] suggested that the pile driving process occurs under undrained conditions. The radial displacement, δ_r, at final installation can be estimated as:

$$\delta_r = r - \sqrt{r^2 - r_0^2} \tag{1}$$

in which, the value r_0 represents the pile radius and r corresponds to the distance from the pile centreline.

2.2. Pore water pressure

For saturated elastic-perfectly plastic materials, pore water pressure increment can be evaluated from the Henkel equation based on cavity expansion theory [9]. The Henkel pore water parameter a can be substituted by the Skempton pore pressure coefficient A as follows:

$$a = 0.707 \cdot (3A - 1) \tag{2}$$

The excess pore water pressure around the pile circumference in the plastic zone (i.e., the radius of the plastic zone is $R_p = r_0\sqrt{E/[2(1+\mu)c_u]}$ as a function of pile radius r_0 and soil parameters including the modulus of elasticity E, the Poisson's ratio μ, and the undrained shear strength c_u) is subsequently estimated as:

$$\frac{\Delta u}{c_u} = 2\ln\left(\frac{R_p}{r}\right) + 1.73A - 0.58 \tag{3}$$

The maximum pore pressure occurs at the soil-pile interface, where the distance from the pile r is then reduced to r_0.

$$\frac{\Delta u_{\max}}{c_u} = \ln\left[\frac{E}{2(1+\mu)c_u}\right] + 1.73A - 0.58 \tag{4}$$

3. Numerical method

Different modelling techniques have been developed to solve the convergence problems to simulate pile driving, where excessive distortions of element mesh in the close vicinity of the pile often occur. Advanced numerical tools, such as the updated Lagrangian framework [26,27], Coupled Eulerian Lagrangian (CEL) approach [28] and Convected Particle Domain Interpolation (CPDI) method [29], are effective to provide solutions for 2D plane strain

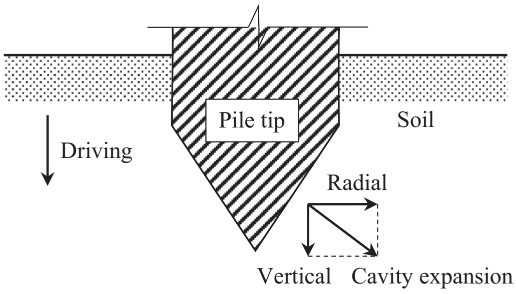

Fig. 1. Displacement of the surrounding soil due to cavity expansion.