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Prediction of pile running during the driving process of large diameter pipe piles

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ABSTRACT

Offshore platforms in deep seas require extremely long large diameter pipe piles (LDPPs) to support the loads generated from the structure itself, wind and waves. One of the construction issues related to the installation of a LDPP into a seabed is pile running. Unexpected pile running during the LDPP driving process may break the steel wires connected to the heavy hammer or may cause the loss of the hammer into the sea. An analytical method to predict the occurrence of pile running is proposed in this paper. The framework for determining the calculation parameters from a laboratory or field test are established. The dynamic resistance of the surrounding soil during the pile driving process is considered through analysis of the soil sensitivity and the induced excess pore water pressure. Three case studies were conducted to verify the accuracy of the proposed method. Good agreement indicated that the proposed method is capable of predicting pile running during the driving process of LDPPs in layered soil deposits.

1. Introduction

Steel pipe pile is widely used to construct the foundations of offshore structures because it requires less installation effort than a closed-ended pile under the same soil conditions (Szechy, 1959; Salgado et al., 2002; Randolph, 2003; Paik and Salgado, 2003). As some of the offshore platforms are very heavy and are among the tallest manmade structures on the earth (Sadeghi, 2007), the structures require large diameter pipe piles (LDPPs) to support the loads generated from the weight of the structure itself, wind and waves. If the LDPPs are in two or more segments, in-situ pile splicing is required, which requires additional construction time and disrupts the continuous pile driving process. When the LDPPs are driven into clay layers, the splicing time causes the excess pore water pressure to dissipate, the shear strength of the soil to increase (Jahr and Tefera, 2015), and the resistance to the pile driving to increase, which can lead to premature refusal (Randolph, 2005; Li et al., 2013).

One solution to this problem is to use a single segment of LDPP and drive it continuously into the seabed. As the LDPP could be very heavy (700 t or more), pile running may occur. Pile running occurs when the pile penetrates a soft clay layer quickly due to the weight of the structure and the limited soil resistance. Since the driving of the LDPP into the seabed requires a super-heavy hammer (up to 200 t), the unexpected pile running may break the steel wire or even cause the hammer to be lost in the sea (Yan et al., 2015). Dover and Davidson (2007) reported that a case of pile running from 15.5 to 18.3 m occurred in the comprehensive seismic retrofit of the Richmond-San Rafael Bridge due to a layer of soft to firm and normal to slightly over-consolidated Young Bay Mud that was present at approximately 36 m of depth.

A typical pile running condition in a three-layer soil deposit is illustrated in Fig. 1. The LDPP is assumed to begin penetrating into the seabed from the mud line (surface of seabed), see step (1) in Fig. 1. Then, the LDPP penetrates into the seabed under its self-weight until it is balanced by the resistance from the surrounding soil mass in a firm clay layer, see step (2). After that, hammer impaction is required to induce additional penetration, see step (3). If there is a relatively soft clay layer beneath the first firm clay layer, which is the main reason pile running occurs, the end bearing resistance of the LDPP when it penetrates the interface between the two layers will suddenly drop. If the skin friction is unable to balance the dead weight of the LDPP, the LDPP will sink into the soft clay layer, see step (4) in Fig. 1. The pile may continue to run until one of the following conditions occurs: (a) the LDPP runs into another stiff soil layer, which generates larger end

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Nomenclature

a	Radius of the cavity during loading
a_O	Radius of the cavity at the initial unloaded state
c_u	Undrained shear strength
D	Outer diameter of the LDPP
e	Coefficient of restitution
E_u	Elastic modulus of soil
F_b	Buoyancy from the sea water
F_s	Side skin friction
$f_s(z)$	Unit skin friction along depth z
f_{sd}	Dynamic skinning resistance of the surrounding soil
F_t	End bearing resistance
G	Total gravity of pile and hammer
g	Gravitational constant
G_u	Shear modulus of soil
h_p	Stroke of the hammer
h_w	Depth of seawater
K_O	Coefficient of effective earth at rest
K	Coefficient of permeability
m_h	Weight of the ram (unit in kg)
m_p	Total weight of the LDPP
N_q, N_γ	Bearing capacity factors
$q_u(z)$	Ultimate unit bearing capacity of the pile
S_t	Sensitivity of soil
t	Wall thickness of the LDPP
u_O	Hydrostatic pore water pressure,
u_w	Excess pore water pressure
v_O	Instantaneous velocity of the hammer and pile after impact
β	Ratio between the inner and outer skin friction
γ_s	Unit weight of soil
$\gamma_{s'}$	Effective unit weight of soil
γ_w	Unit weight of water
δ	Soil-pile friction angle.
η	Efficiency of the blow
μ	Poisson's ratio
σ_v	Total stress
$\sigma_{v'}$	Effective stress
ϕ	Internal friction angle of the soil

bearing resistance to stop the running pile, see step (5) in Fig. 1, or (b) the LDPP runs in the same soft clay layer and the skin friction increases until it balances the weight of the LDPP. After the pile running, the hammer impacts are required again for further penetration of the LDPP, see step (6) in Fig. 1.

To the best knowledge of the authors, the theoretical analysis of pile running has seldom been analyzed in literature, with the exception of a very simplified method proposed by Yan et al. (2015). In this method, the speed of pile running and the influence of the pore water pressure in the surrounding soil on the reduction in skin friction were not considered. Some efforts have been made in recent years to investigate the installation and loading behaviors of pipe piles in sand, e.g., Paikowsky and Whitman (1990), Jardine et al. (2005), Lehane and Gavin (2001), Paik and Salgado (2003), Jeong et al. (2011), Cho et al. (2012) and Li et al. (2013). This is because the accuracy of the prediction on the end bearing resistance of the open-ended pipe piles is influenced by many uncertainties, such as the physical properties and succession of soil layers, the pile diameter, the skirt wall thickness, the roughness of the wall surface, and even the properties of the hammer (Kraft, 1991; Yan et al., 2011). The complicated behavior of soil plugging (Yu and Yang, 2012) is an additional issue to consider.

An analytical method is proposed in this paper to calculate the pile driving process of the unplugged LDPP in layered soil deposits and thus to predict the pile running behavior. The framework for the determination of the calculation parameters from the field test data has been established. Three case studies were conducted to verify the accuracy of the proposed analytical method.

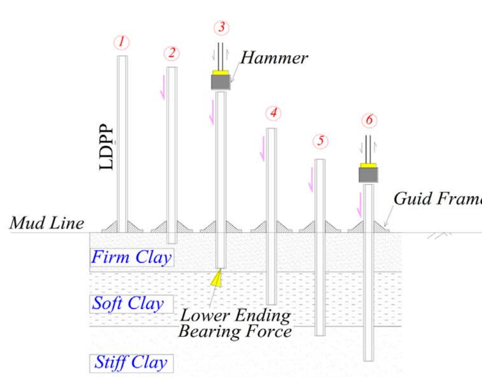
2. Analytical method

2.1. Theoretical derivation

For the pile driven by the hammer impact, the Hiley-formula (Hiley, 1925) has been widely used to assess the energy transferred from the hammer to the pile. The formula was derived based on the principle of energy conservation from the hammer blow to the work done in overcoming the resistance of the surrounding soil to the penetration of the pile. The pile driving process can be separated into two phases: (1) the energy transfers from the hammer to the pile-hammer system and (2) the pile and hammer sink together into the soil embedment.

During phase (1), the energy to the pile is calculated by the energy of the hammer multiplied by the efficiency of the blow, representing the ratio of energy after impact to striking energy of the ram. By assuming the pile and hammer moved down together and neglecting the energy dissipated from the pile compression, the following equilibrium could be derived based on the Hiley-formula,

$$\eta m_h g h_p = \frac{1}{2}(m_h + m_p)v_0^2 \tag{1}$$



(1) Initial position of the LDPP (2) penetration under self-weight (3) hammer impact pile driving
(4) pile running (5) end of pile running (6) hammer impact pile driving

Fig. 1. Schematic illustration of pile running.