Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
Published by Research Publishing, Singapore.
doi: 10.3850/GRF-25280825_isgsr-021-P023-cd

ISGSR2025

PILE RUNNING RISKS FOR OFFSHORE FOUNDATIONS IN CLAY

AP Dyson

School of Engineering, University of Tasmania, Australia. E-mail: Ashley.Dyson@utas.edu.au

A Tolooiyan

School of Engineering, University of Tasmania, Australia. E-mail: Ali.Tolooiyan@utas.edu.au

K Gavin

Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands. Email: K.G.Gavin@tudelft.nl

Large offshore structures such as deep-sea platforms and offshore wind turbines are frequently dependent on foundation systems requiring significant penetration into the seabed. Typical deep offshore foundations include large-diameter open-ended monopiles and spudcans capable of supporting considerable structural loads. Drop-fall hazards, large settlements under self-weight and pile running are all major hazards during foundation installation. Each occurs when driving forces exceed the shaft resistance and end bearing capacity. Assessing the risks posed by drop-fall are compounded by the presence of soils whose properties are heterogeneous and vary rapidly with depth.

This paper assesses drop-fall and pile running rates for large offshore piles in the presence of spatially variable clayey deposits, where the end-bearing resistance of the pile is negligible. A simplified analytic procedure is used to determine the velocity and run depth, based on a combination of well-accepted bearing capacity equations and Newton's second law. The method differs from traditional static bearing capacity analyses due to the consideration of continuous pile running velocities with depth. The role of depth-dependent variations in undrained shear strength has the capability of both initiating and arresting drop-fall. In the case of large driven piles whose bearing capacities at depth are primarily controlled by shaft friction, it is shown that drop-fall distances are largely robust to variations in shear strength, while velocity profiles at the near-surface where the end bearing resistance dominates are susceptible to sizeable fluctuations in drop-fall velocity. A set of worst-case scenarios is presented whereby piles penetrate under driving or self-weight from the mudline, such that velocities increase before the accumulation of shaft resistance. Despite pile skin friction providing the primary resistance compared to end-bearing resistance in the cases presented, the run depths and velocities considered continue to show surprising variability. Comparative results of clayey and sandy soils are presented with reference made to the importance of accurate in-situ test results in assessing velocity scales of fluctuation.

Keywords: Drop-fall velocity; pile running; driven pile; spatially variable soil resistance.

1. Introduction

Large-diameter driven monopiles are widely used in the oil, gas and offshore wind sectors to support superstructures exposed to extreme offshore environmental loads (Randolph and Gourvenec 2017). The diameter of these piles ranges from 2.0 to 3.5 metres for oil and gas projects and up to 7.5 metres for large offshore wind turbines (Byrne, Gavin et al. 2018). Installation commonly occurs through the use of large hydraulically powered hammers as the driving force. For single-segment piles that can be in excess of 700 tonnes, pile running poses a significant risk. Pile running, occurs when a pile penetrates rapidly through soft soil layers or transitions from a hard to a softer layer due to a significant drop in soil resistance. In soft clays, the low shear strength and minimal friction along the pile shaft results in rapid penetration. When a pile tip moves from a harder layer into a softer layer, the sudden loss of end-bearing support causes the pile to sink quickly. During running, the sum of the end bearing capacity and skin friction is less than the driving force due to the pile self-weight and force provided by the hammer impact. The pile will continue to descend until a stiff soil layer is reached, or the skin friction increases to a level sufficient to balance the driving forces of the pile.

Pile free-fall is most commonly encountered when the seabed is composed of layered soils exhibiting significant variability from one layer to the next, where the fluctuations of soil properties may not be readily evident from bore logs. Small variations in sandy and clayey lenses may be the difference between piles free falling or ceasing their run. For this reason, pile running investigations are amenable to probabilistic methods that are capable of capturing spatial trends and fluctuations with depth. Soils with spatially varying shear strengths have been evaluated using random field theory, providing predictions of bearing capacity distributions via Monte Carlo simulation (Fenton & Griffiths, 2003, 2007; Naghibi et al., 2014). For deep foundations, Fenton and

Griffiths (2007) noted that cases where the end bearing capacity does not play a significant factor in the total capacity of the pile can effectively ignore spatial variability. The reason being that skin friction is strongly controlled by arithmetic averaging of soil strengths. As expected, the variance of the pile ultimate capacity increases with the magnitude of fluctuations in shear strength (Phoon et al., 1990). In this research, a simple predictive analytic pile running method combined with random field theory is used to assess pile velocity profiles for spatially variable soils as a function of undrained shear strength and friction angle. In considering worst-case velocities, pile running is considered as a result of driving from the mudline, as opposed to wished-in-place geometries. Through Monte Carlo simulation, both individual pile running profiles and distributional trends are considered and presented herein.

2. Background - Analytic procedure

A brief description of the governing equations and the resistance to dynamic penetration presented by Sun, Wang et al. (2018) are provided. Based on Newton's Second Law of Motion, the governing equation of the soil-pile-hammer system is given by

$$\frac{1}{2}\left(m_p + m_h\right)\frac{d^2 z_{tip}}{dt^2} = G - F_s - F_{bear} - F_b - F_d \quad (1)$$

where m_p is the pile mass; m_h is the hammer mass; z_{tip} is the position of the pile tip; G is the force of the pile-hammer due to gravity; F_s is the pile sleeve resistance; F_{bear} is the end bearing resistance; F_b is the buoyant weight of the displaced soil; and F_d is the inertial drag force. The magnitude of F_d is negligible compared to the magnitude of the remaining forces, hence is neglected as follows. As such, the velocity of the pile and hammer $v_0$at the time of impact are derived:

$$v_0 = \sqrt{\frac{2\eta m_h g h_p}{m_h + m_p}} \quad (2)$$

where, h_p is the stroke of the hammer; g is the gravitational constant; and η is the blow efficiency. Comprehensive details of the hammer performance are given by Sun, Shi et al. (2022). Based on Eq. 1, Sun, Jia et al. (2016) derived the following equilibrium equation based on the principle of energy conservation, allowing velocities to be determined at calculation steps $j-1$ and j, at which the pile-hammer system displaces a distance ΔS.

$$\frac{1}{2}\left(m_h + m_p\right)\left(v_j^2 - v_{j-1}^2\right) = \left(G - F_s - F_{bear} - F_b\right)\Delta S \quad (3)$$

As such, the square of pile velocity at step j is given by

$$v_j^2 = \frac{2(G - F_s - F_{bear} - F_b)\Delta S}{m_h + m_p} + v_{j-1}^2 \quad (4)$$

The side friction, F_s, is calculated as the sum of the friction on the inner and outer pile surfaces

$$F_s = \int_0^z f_s(z)(1+\beta)\pi D \, dz \quad (5)$$

where f_s is the unit skin friction; β is the ratio between the inner and outer skin friction, typically varying between 0 and 0.5 (Dover and Davidson 2007); and D is the outer diameter of the pile. As recommended by the API method, for piles installed in clayey soils, the ±-method is used to define an adherence shaft friction factor ±, where

$$f_s(z) = \alpha \, s_u \quad (6)$$

such that s_u is the undrained shear strength; with ± defined as follows (API 2011).

$$\alpha = \frac{1}{2}\left(\frac{s_u}{\sigma'_{vo}}\right)^{-0.5}, \quad \frac{s_u}{\sigma'_{vo}} \leq 1 \quad (7a)$$

$$\alpha = \frac{1}{2}\left(\frac{s_u}{\sigma'_{vo}}\right)^{-0.25}, \quad \frac{s_u}{\sigma'_{vo}} \geq 1 \quad (7b)$$

where σ'_{v_o} is the effective overburden stress. In the case of driven piles, the remoulded undrained shear strength s_u/S_t(where S_t is the soil sensitivity) is applied.

The soil buoyancy contributes to the governing equation in Equation (3) as follows

$$F_b = (z + h_w)\gamma_w \pi D t \tag{8}$$

where, h_w is the seawater depth; γ_w is the unit weight of water; and t is the pile thickness. Compared to the shaft and end bearing resistances, the soil buoyancy provides marginal support to the pile. Similarly, the inertial drag force F_d provides minimal contribution to the forces acting on the pile and is therefore neglected in this study. The end bearing pressure $q_{tip}\,(z)$for clayey layers is calculated by

$$q_{tip}\,(z) = N_c s_u = 9 s_u \tag{9}$$

with minimal impact on the soil resistance to driving provided by the choice of bearing capacity factor N_c between 9 and 15.

3. Pile velocities and run depths in heterogeneous soils

Combining the analytic procedure explained above and spatially variable soil profiles, a series of pile running cases in clay were examined (Table 1) based on the pile geometry given by (Sun, Jia et al. 2016). Figure 1 highlights the variability of resistance components and associated velocities for a set of 500 Monte Carlo realisations, indicating a variety of observed pile velocities and total run depths.

Table 1. Statistical properties for random fields generated.

Parameter	***Description***	***Value***
s_u [kPa]	Mean	20, 40, 60, 80, 100
Á[kPa/m]	Depth trend	0, 0.5, 1, 2
¸/*D* [-]	Scale of fluctuation	1, 2, 5, 10, •
½[%]	Coefficient of variation	10, 20, 30, 40, 50

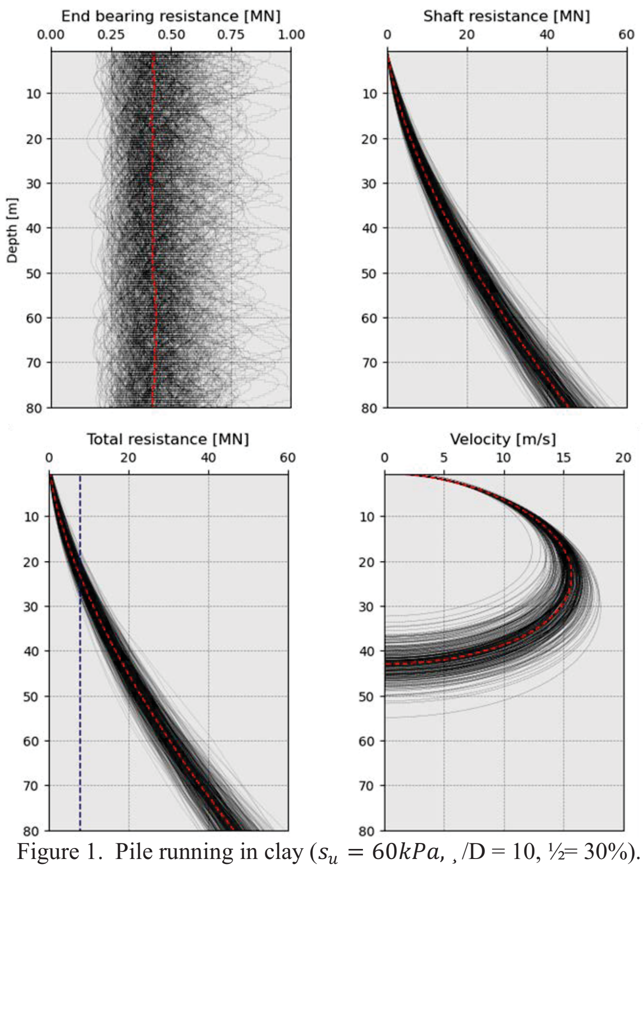

Figure 1. Pile running in clay ($s_u = 60kPa$, ¸/D = 10, ½= 30%).

A clear trend between maximum velocity and pile depth is driven by the shaft resistance, which is resilient to spatial variation and serves as the primary factor in descent of the pile.Figure 2 indicatesthe behaviour of pile running in spatially variable soils. Increasing shear strengths result in reduced free fall depths and velocities, as is expected. While the variation of results in clay remains reasonably constant, increased scatter is observed as friction angles increase in value. While each of the given cases considers a coefficient of variation of 30%, for larger friction angles, this results in a larger standard deviation, hence greater variability of pile runs.

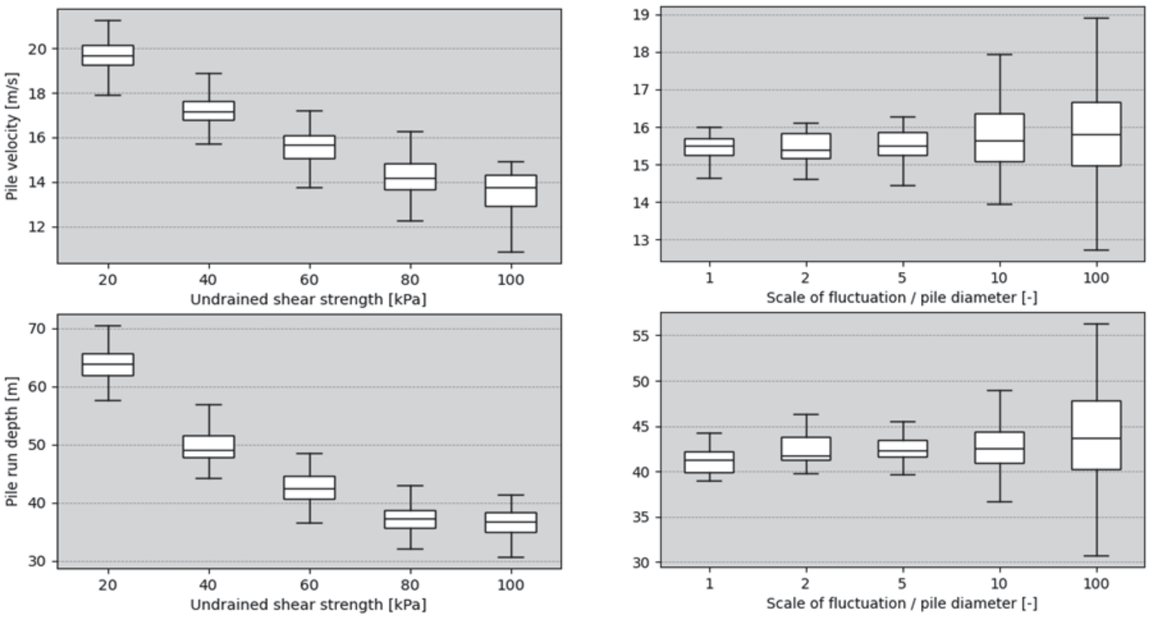

Figure 2. Effect of increasing shear strength and normalised scale of fluctuation.

4. Discussion

It is well known that thin soil lenses and heterogenous soil conditions have the capacity to dramatically impact the expected resistance to driving of large offshore piles. A simplified analytic code based on the governing equation for piles in sands and clays allows for pile running depths and velocities to be predicted. This is combined with random field generation to assess the behaviour of pile dynamics for soils exhibiting spatially variable shear strengths. The velocity profiles in clays are noted to be predominantly smooth and parabolic due to the negligible impact of pile base resistance, with large vertical scales of fluctuation produce significant variation in both the pile run velocity and final run depth for large diameter pipe piles.

References

API (2011). "2GEO Geotechnical and foundation design considerations." American Petroleum Institute, Washington, DC, USA, page120.

Byrne, T., K. Gavin, L. J. Prendergast, P. Cachim, P. Doherty and S. Chenicheri Pulukul (2018). "Performance of CPT-based methods to assess monopile driveability in North Sea sands." Ocean Engineering **166**: 76-91.

Dover, A. and J. Davidson (2007). Large Diameter Steel Pipe Piles Running under Self Weight in Soft Clay: Predicted vs. Observed Behavior—Richmond San-Rafael Bridge Seismic Retrofit. Ports 2007: 30 Years of Sharing Ideas: 1977-2007**:** 1-10.

Randolph, M. and S. Gourvenec (2017). Offshore geotechnical engineering, CRC press.

Sun, L., T. Jia, S. Yan, W. Guo, Y. Ren and Z. Lei (2016). "Prediction of pile running during the driving process of large diameter pipe piles." Ocean Engineering **128**: 48-57.

Sun, L., J. Shi, Y. Zhang, X. Feng, Y. Tian and R. Wang (2022). "Analytical method for predicting pile running during driving." Applied Ocean Research **125**: 103234.

Sun, L., Y. Wang, W. Guo, S. Yan, J. Chu and X. Liu (2018). "Case study on pile running during the driving process of large-diameter pipe piles." Marine Georesources & Geotechnology **36**(6): 709-721.