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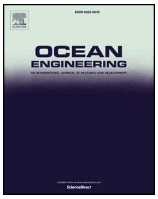

Assessment of bearing capacity of axially loaded monopiles based on centrifuge tests

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ABSTRACT

The monopile has been widely used to support offshore and coastal structures. A series of centrifuge tests has been performed to investigate the bearing capacity of large diameter monopiles in sandy soil. Both static tests and cyclic tests have been conducted for open-ended and close-ended model piles, and the effects of influence factors, such as loading rates, embedment depths, and loading histories are considered. The piles are then loaded by a sequence of compressive-tensile loadings to estimate the tension capacity, from which the shaft friction is derived. The cyclic load tests are performed with five varying load intensities, and the accumulated settlement is assessed. The centrifuge tests indicate that the pile bearing capacity tends to increase with the initial penetration depth, and the stress state of soil greatly influences the pile behavior. The tensile shaft friction is smaller compared to the compression test. The capacities of the piles reduce significantly under the axial cyclic load, and the maximum cyclic load intensity should be limited to 75% of the ultimate bearing capacity. The API design method is used to calibrate with the centrifuge test results. The method overestimates the bearing capacity at larger depths, and a conservative reduction factor is required.

1. Introduction

The use of large diameter monopiles as deep foundations for offshore structures and coastal facilities continues to be widespread due to the increased exploitation of ocean energy resources. The offshore monopiles are typically hollow steel pipe piles with larger diameters (Negro et al., 2017). In China, more than 5000 pipe piles are used in the construction of Hangzhou Bay Bridge (Yu and Yang, 2011), and the monopile-supported intertidal wind turbine contributes for 56.69% of the installed wind capacity; in Europe, the monopile foundation is the most widely used offshore wind foundation with a market share of 87% by the end of 2017 (Wang et al., 2018a). The monopiles are driven into the ground and provide considerable bearing capacities in service conditions. New challenges are brought to the design of monopile foundation considering the requirements of deeper penetration depths and complex offshore soil conditions. Understanding the response of large diameter monopiles under axial loadings is essential for proposing proper design methods and ensuring safety in the service conditions.

The bearing mechanism of the monopile foundation is a complex problem involving large amount of uncertainties. During the installation, soil enters the pipe pile from the pile tip to form a soil plug, and the behaviors of the soil plug significantly affect the pile bearing capacity. The early design methods for predicting the bearing capacity of pipe pile were derived from the close-ended piles. In recent years, more efforts have been put on the investigation of bearing behavior of monopiles and mechanisms of the soil plug (De Nicola and Randolph, 1997; Lehane and Gavin, 2001; Paik and Salgado, 2003; Paik et al., 2003). After driving, if a pile is in the fully coring mode with the incremental filling ratio (IFR) equals to 1, soil enters the pile at the same rate to the same or higher level as the ground surface (Kikuchi et al., 2007); if a pile is in the fully plug mode with the IFR equals to 0, the soil plug resists additional soil entering the pile, and the pile behaves similarly as a close-ended pile. In the fully plug mode, the plug capacity is estimated to be 68% of the base capacity of a close-ended pile, and the difference is attributed by the compressibility of the soil plug (Yu and Yang, 2011). In practice, the IFR is between the two limiting values, referring to partially plug mode. The small-diameter pipe pile and the larger embedment depth are assumed to facilitate the formation of soil plug (Paik et al., 2003). Therefore, these factors have major impacts on the overall vertical bearing capacity of a large diameter pipe pile, and they are necessary to be considered in the analysis of design methods.

Researchers have put considerable efforts in investigating the bearing behaviors of the axially loaded monopiles. Han et al. (2016) performed fully instrumented field test on a close-ended pipe pile

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driven in a multilayered soil profile, and both static and dynamic load tests were conducted. The tests results were calibrated with several design methods. Lehane et al. (1993) documented a set of field tests in examining the shaft friction of a pipe pile. It was found that the position and initial state of soil had significant influence on the stress developed, and the pile loading induced changes of radial effective stress. The design recommendation was given to estimate the shaft resistance. Besides the field tests, a series of large-scale laboratory tests were performed to study the pile bearing capacity. The base resistance of pipe piles are investigated by an instrumented model test conducted in a large testing chamber (Lehane and Gavin, 2001). The test assessed relative contributions of plug resistance and annular resistance to the overall base resistance for a pipe pile. The base resistance had a direct relationship to the cone tip resistance and the IFR. In addition, centrifuge tests were performed to enrich the database (De Nicola and Randolph, 1997; Nicola and Randolph, 1999). It was observed in the tests that the shaft friction degraded in tension tests compared to the compression tests, the close-ended pile experienced a larger degradation, and the base resistance was correlated with the cone resistance. Recently, the influence of soil plug in the dynamic responses of monopiles are investigated, and an analytical model is proposed to predict the dynamic velocity response (Liu et al., 2018). A series of field tests were performed in stratified soils to investigate the axial resistance of monopiles, and the methods in predicting shaft frictions were put forward by correlating with the standard penetration test (Kou et al., 2016).

In previous research, most of the tests were performed within short periods of time after installation, but there is limited amount of open literature describing the monopile bearing capacity in a relatively longer term (Zakeri et al., 2014). The bearing capacity of the monopile may increase with time after the installation due to the setup effect that takes place along the pile shaft (Bullock et al., 2005; Lee et al., 2010), and the state of stress of soil prior to the loading sequence will influence the stress path and failure state during the tests (Kraft Jr., 1991). The increase of the vertical resistance may be attributed to the factors of dissipation of pore water pressure in saturated conditions, thixotropy effects, aging effects, and multiple unloading & reloading sequence of the pile (Karlsrud, 2012). Therefore, influences of load sequences and histories should be considered in the design phase.

Besides the loading sequence, the pile embedment depth has great influence on the bearing capacity. The larger contacting area contributes to larger shaft frictions. Moreover, the soil will plug more at larger embedment depths (Klos and Tejchman, 1981; Paikowsky and Whitman, 1990). The short open-ended pile has lower bearing capacity compared to the close-ended pile; however, as the embedment depth increases, the bearing capacity of open-ended pile tends to approach that of the close-ended pile due to the increment of soil plug capacity. Estimations of the relationship between the ultimate bearing capacity and the pile embedment depth is necessary.

In service conditions, external loadings are always cyclic in nature (Wang et al., 2018b). An axial cyclic loading acting on the pipe pile may be caused by crossing vehicles in costal facilities, by wind or wave for offshore structures, and by changing water levels in bridge foundation applications (Wichtmann, 2005). Under cyclic loadings, the stress state of soil will change significantly and result in large residual deformations. The cyclic shearing of the surrounding soil tends to cause larger differential accumulated settlements due to the spatial fluctuation of the state variables. The bridge or wind turbine foundations are sensitive to these differential settlements, and hence the investigation of the cyclic bearing behaviors of the large diameter monopile is essential. A series of laboratory tests and field tests were performed to examine the pile cyclic bearing behavior (Han et al., 2016; Poulos and Chua, 1985), and it was pointed out that the cycle loading to cause failure and the accumulated pile axial deformation were essential factors in consideration of the cyclic performance of the monopile.

The current design methods are largely empirical and heavily rely on calibrations with load tests of piles with relatively small diameters. Meanwhile, tinvestigations of the cyclic behaviors of the pipe pile are not common. Therefore, more high quality tests are required by considering influence factors to extend understandings in the behaviors of large diameter monopile under vertical loadings. In this study, a series of centrifuge tests is performed to provide important information to offshore geotechnical design. The purpose of this study is to: 1) investigate the ultimate axial bearing capacity of the monopile; 2) clarify the influence of pile dimensions; 3) examine the effects of loading rate and loading sequence to the static behaviors; 4) demonstrate the behaviors of the monopile under axial cyclic loadings.

2. Current design methods

The total axial ultimate bearing capacity of the pipe pile (Q_t) is the summation of shaft capacity (Q_s) and base capacity (Q_b):

$$Q_t = Q_s + Q_b = \pi D \int \tau_Z dz + \frac{\pi D^2}{4} q_b \tag{1}$$

where, τ_z is the local unit shaft friction; q_b is the ultimate unit base resistance; D is the pile diameter; z is the embedment depth. Several design methods have been put forward based on the empirical data from pile tests.

2.1. API method

American Petroleum Institute (API) issues the practice for fixed offshore platforms (RP2A-WSD, 2011), giving the design method in predicting the pile axial bearing capacity. Det Norske Veritas (DNV) recommends the practice for offshore wind turbines (Construction, 2008), which adopts the similar method with API in assessing the pile bearing capacity. It is assumed in the practice that the inner unit shaft friction of a pipe pile equals to the outer unit shaft friction. The soil characteristics are the major influence factor in this design method.

The local unit shaft friction is calculated from:

$$\tau_f = K_f \sigma'_{v0} \tan \delta \tag{2}$$

where, K_f is the coefficient of lateral earth pressure, which is assumed to be 0.8 for open-ended piles in unplug mode and 1 for close-ended piles or plugged open-ended piles; σ'_{v0} is the vertical effective stress; δ is the friction angle at the pile-soil interface.

The unit tip resistance is given as:

$$q_b = N_q \sigma'_{v0} < q_l \tag{3}$$

where, σ'_{v0} is the vertical effective stress at the pile tip level; N_q is the dimensionless bearing factor; q_l is the limiting tip resistance. These values are suggested in practice.

2.2. FHWA method

The Federal Highway Administration (FHWA) proposes a relatively conservative method (Paikowsky and Whitman, 1990). The calculation procedure is similar to the API method, and the smaller result is due to the assumption that the inner friction of the pipe pile is 1/3 to 1/2 of the outer shaft friction. The plug mode is considered in this method:

$$\begin{cases} plugged\colon Q_t = \pi D \int \tau_{Zo} dz + A_t q_t \\ unplugged\colon Q_t = \pi D \int \tau_{Zo} dz + \pi D \int \tau_{Zi} dz + A_{ann} q_t \end{cases} \tag{4}$$

where, τ_{zi} is the inner unit shaft friction; τ_{zo} is the outer unit shaft friction; q_t is the unit tip resistance; $A_{t,}$ A_{ann} are tip and annular areas of the pipe pile, respectively.

2.3. Chinese method & FinnRA method

The Chinese method (Construction, 2008) is the most widely used