Physical Modelling in Geotechnics

Centrifuge modelling of laterally loaded pile with large load eccentricity

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ABSTRACT: Piles that are implemented as the foundation of offshore structures mostly undergo significant horizontal load and bending moment. The common method of designing piles under lateral loading is based on the p-y curves method, with its current relationships derived for flexible piles. However, many studies have revealed that the existing p-y relationships are not much reliable when it comes to designing monopiles. In this paper, three centrifuge tests were performed on a flexible pile with a substantial eccentricity in order to determine to what extent this behavioral difference depends on the loading eccentricity. The p-y curves were achieved for a flexible pile in sand in terms of different depths. Moreover, the effects of load eccentricity were investigated on the pile response. The p-y curves obtained were then compared to those recommended by American Petroleum Institute (API) and hyperbolic models. The initial stiffness of the obtained p-y curve is lower than that of the API curves in most cases. According to the results, while the loading eccentricity can affect the soil reaction, the current p-y method is an acceptable method for the design of flexible piles under lateral loading. Additionally, the hyperbolic function could also be a simple, more suitable model to predict the p-y curves in sand.

Keywords: Pile, Lateral load, Eccentricity, p-y curve, Centrifuge test, Sand.

1 INTRODUCTION

Piles rarely undergo pure vertical loads as they often experience a horizontal load component. In some cases, large horizontal loads, such as wind, waves, earth pressure, inclined structural loads, and earthquakes, may occur. Thus, these piles should be analyzed and designed to resist lateral loads. Moreover, the foundations of offshore structures undergo significant bending moments due to their nature and load eccentricity.

The limit state method, the subgrade reaction method, the *p-y* method, the elasticity method, and the finite element method (FEM) are among the methods adopted to design laterally loaded piles (Fan and Long, 2005). The *p-y* method is the most commonly used technique to design piles under lateral loading, in which the nonlinear behavior of the soil is analyzed by assuming piles to be elastic beams on a nonlinear spring subgrade. Among the proposed *p-y* curves of sandy soils, the API instruction (API, 2014) provides the most well-known relation, which has been validated by testing flexible piles without load eccentricity (O'Neill and Murchison, 1983). The pile displacement *y* and soil resistance *p* are related using the hyperbolic tangent function as:

$$p = Ap_u \tanh(\frac{kz}{Ap_u} y) \quad (1)$$

where *z* is the soil depth, *A* is an empirical coefficient, *k* is the initial modulus of the subgrade reaction, and P_u is the ultimate lateral resistance dependent on soil properties and pile diameter. The hyperbolic *p-y* curve proposed for sand has also been introduced as (Georgiadis et al., 1992):

$$p = \frac{y}{\frac{1}{zn_h} + \frac{y}{p_u}} \quad (2)$$

where n_h is a soil density-related coefficient. The *p-y* method has a significant limitation for large-diameter piles with high eccentricity due to failure mechanism differences (Doherty and Gavin, 2012). However, the modification of the ultimate lateral resistance (Zhang et al., 2005) and initial subgrade modulus (Kallehave et al., 2012) could be a solution.

Research on laterally loaded piles primarily focused on the effects of the pile diameter on *p-y* curves and rarely considered the load eccentricity effect. However, there is evidence that load eccentricity has no significant effect on the *p-y* curve of monopiles (Klinkvort and Hededal, 2014). Thus, the present study performs three centrifuge tests with high load eccentricity on long piles to realize to what extent load eccentricity could individually influence *p-y* curves.

2 PHYSICAL MODELLING

This study implemented displacement-controlled and monotonic lateral load on piles. These tests were carried out at an acceleration of 40*g* using the Actidyn C67-2 centrifuge test machine at the University of Tehran (Moradi and Ghalandarzadeh, 2010).

2.1 Pile description

The model pile had a diameter of 16 mm. A pile with a diameter of 64 cm was simulated, considering the acceleration of 40*g*. This size is consistent with the reference pile diameter in the API instruction. The stainless steel 304 open-ended pile had an elasticity modulus of 207 GPa and a wall thickness of 0.5 mm. The pile was designed to show flexible behavior under lateral loading. A total of six strain gauge pairs with a spacing of 5 cm were used along the pile to measure the bending moment with the half-bridge connection.

2.2 Soil properties and specimen preparation

In light of rich research background, standard Firoozkuh 161 sand (Farahmand et al., 2016) with a relative density of 60% was employed. Table 1 reports the properties of Firoozkuh 161 sand.

Table 1. Sand properties (*Cu: Coefficient of uniformity).

Sand type	e_{min}	e_{max}	G_s	D_{50} (mm)	*C_u
Firoozkuh 161	0.574	0.874	2.65	0.3	1.87

A soil specimen with a moisture content of 5% was fabricated within a cubic metal box with a size of 80*60*50 cm. A certain weight of the soil was distributed in the container using a sieve. Then, the soil was compacted to a relative density of 60% under layer thickness control. The added moisture is only to facilitate compaction, and the behavior of soil can be considered similar to dry sand in this model. Therefore, unsaturated soil properties such as apparent cohesion can be ignored.

2.3 Test procedure

The lateral loading system was assembled on the box and transferred to the centrifuge, as shown in Fig. 1. Then, the pile was driven into the sand with a rubber hammer at 1*g*. Although pile installation methods influence the *p-y* curve (Dyson and Randolph, 2001), the present study implemented the same installation method as those performed by earlier works at the University of Tehran.

Fig. 1. Centrifuge model setup.

To measure the pile head displacement, an LVDT was used in front of the horizontal load point. Two more LVDTs were utilized at the top and bottom of the load point to obtain integration constants in the calculation of the pile deflection. A loadcell was employed along the loading shaft to measure the horizontal load, as shown in Fig. 2.

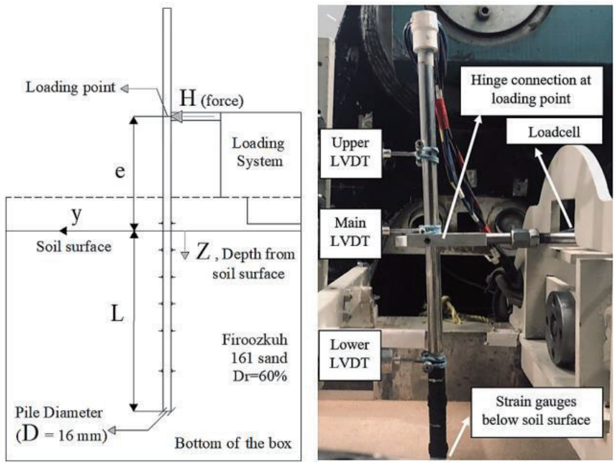

Fig. 2. Schematic figure of parameters and Configuration of instrumentation.

Unidirectional horizontal displacement as large as the pile diameter (i.e., 16 mm) was applied in all three tests with the free-headed condition. The pile length within the soil (*L*) was 18 times as large as the pile diameter (*D*), and the effects of load eccentricity (*e*) were investigated, as shown in Table 2.

Table 2. Tests program (Prototype Scale).

Test no.	Relative density (%)	e/D	L/D	e (m)	L (m)
M1	60	13.25	18	8.48	11.52
M2	60	16	18	10.24	11.52
M3	60	18.75	18	12	11.52

3 RESULTS AND DISCUSSION

3.1 Load-Displacement curves

Fig. 3 depicts the normalized load-displacement curve of the pile head. The lateral load capacity declines significantly as load eccentricity rises.

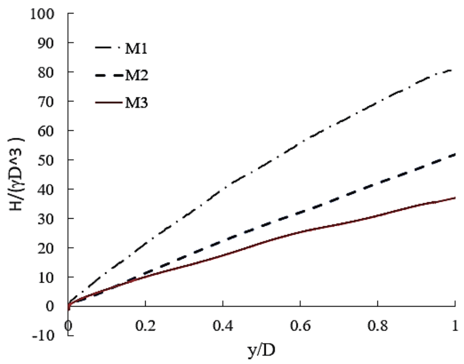

Fig. 3. Load-head displacement curves.

3.2 Pile deflection, moment, and soil reaction

The bending moment along the pile was directly obtained from the test results. The soil reaction p and pile displacement y can be found based on the depth z as:

$$p(z) = \frac{d^2 M(z)}{dz^2} \tag{3}$$

$$y_{pile}(z) = \iint \frac{M(z)}{E_p I_p} dz \tag{4}$$

where M is the bending moment and $E_p I_p$ is the flexural stiffness of the pile. Figs. 3-5 plot pile displacement, bending moment, and soil reaction at a given horizontal load at a prototype scale, respectively.

The pile deflection curves indicate that the pile was flexible, and a plastic hinge formed almost 0.3L below the soil surface. The bending moment results suggest that the negative bending moment zone reduced as load eccentricity increased. The soil reaction curve indicates a relatively constant trend in depth.

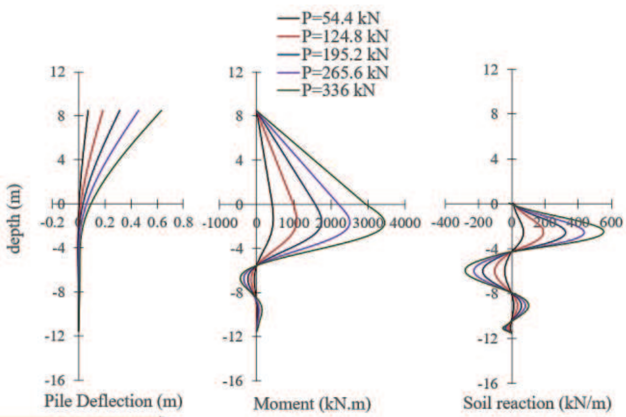

Fig. 3. Response of pile M1 at given lateral loads.

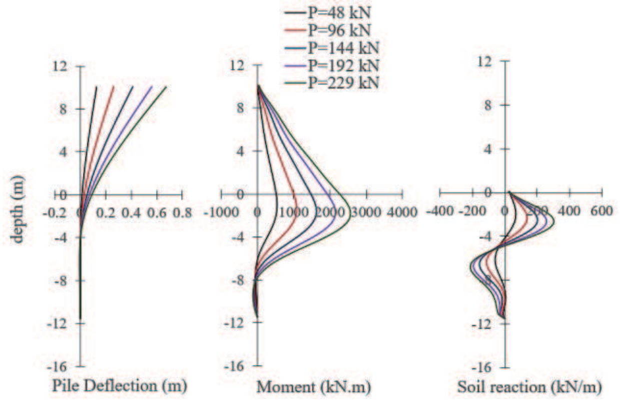

Fig. 4. Response of pile M2 at given lateral loads.

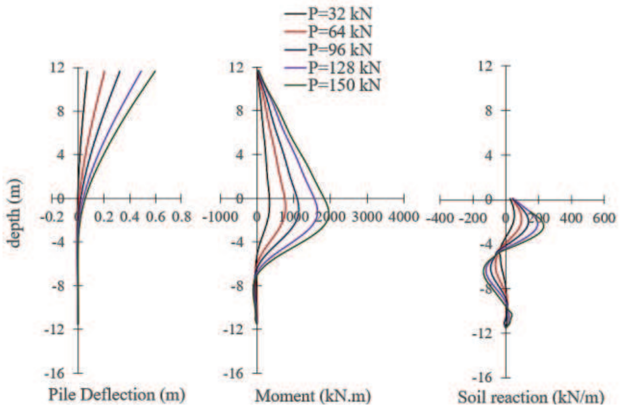

Fig. 5. Response of pile M3 at given lateral loads.

3.3 *p-y* curves

The *p-y* curve was obtained by plotting soil reaction versus pile displacement at a given depth. The *p-y* curves were compared at depths of 0.5*D*, *D*, and 2*D*, given the flexible behavior of the pile. The API curves and hyperbolic model were derived using Eqs. (1) and (2) for φ=36.5° and *D*=64 cm. This internal friction angle of sand is equal to the value tested and presented in previous research on 161 Firoozkuh sand with the same relative density and preparation method. Figs. 6-8 illustrate the *p-y* curves of the three tests. As can be seen, the initial slope of the *p-y* curve is often smaller than the API estimate. The ultimate lateral resistance p_u was found to be overestimated or underestimated, depending on the depth and load eccentricity. However, the average estimate of p_u is acceptable.

The sand stiffness rises when depth increases. Based on the results, this stiffness increment becomes less when the load eccentricity increases. For example, in pile M3 with the most eccentricity, the *p-y* curves are less different at three specified depths.

According to Fig. 9, the *p-y* curves of all three tests are almost the same at a depth of *D*. A comparison of this curve to the API curve and hyperbolic model demonstrates that the hyperbolic model is in greater agreement with the experimental results.

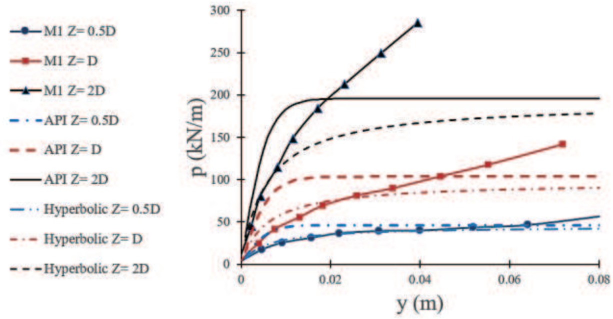

Fig. 6. Comparison between derived *p-y* curves and API and Hyperbolic model for Pile M1.

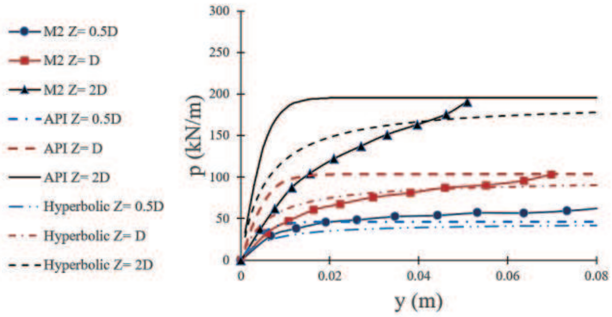

Fig. 7. Comparison between derived *p-y* curves and API and Hyperbolic model for Pile M2.

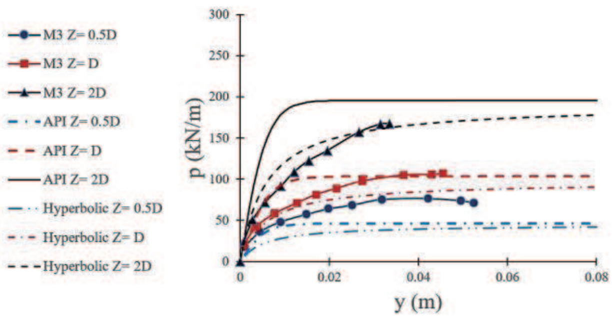

Fig. 8. Comparison between derived *p-y* curves and API and Hyperbolic model for Pile M3.

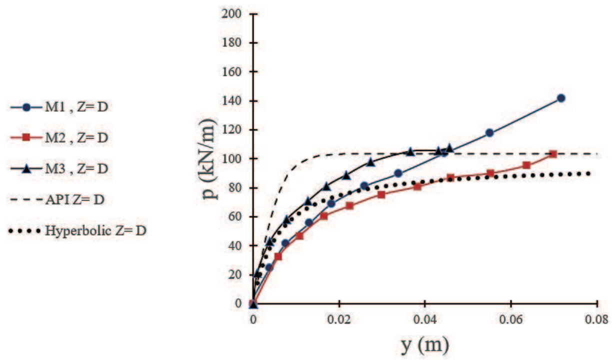

Fig. 9. Effect of load eccentricity on the *p-y* curves at *Z=D*.

4 CONCLUSIONS

The present study performed three lateral loading centrifuge tests on a flexible pile with an L/D ratio of 18 to explore the effects of load eccentricity on *p-y* curves. The results can be summarized as:

(1) The API initial soil stiffness was slightly overestimated, even for a flexible pile.

(2) The initial stiffness of the p-y curve increases with increasing depth. The experimental results demonstrate that as the load eccentricity increases, the rate of stiffness increment decreases. However, due to the high sensitivity of the *p-y* curves to the experimental conditions, this conclusion requires further research.

(3) Despite differences between the result of hyperbolic, API, and this study, the *p-y* method seems to be efficient for the lateral design of piles, even under high load eccentricity. Also, the hyperbolic function could be a simpler and more accurate model.

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