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Centrifuge Modeling of Monopiles Subjected to Lateral Monotonic Loading

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***Abstract*—**The type of foundation commonly used today for berthing dolphins is a set of tubular steel piles with large diameters, which are known as monopiles. The design of these monopiles is based on the theories related with laterally loaded piles. One of the most common methods to analyze and design the piles subjected to lateral loads is the p-y curves. In the present study, centrifuge tests are conducted in order to obtain the p-y curves. Series of tests were designed in order to investigate the scaling laws in the centrifuge for monotonic loading. Also, two important parameters, the embedded depth L of the pile in the soil and free length e of the pile, as well as their ratios were studied via five experimental tests. Finally, the p-y curves of API are presented to be compared with the curves obtained from the tests so that the differences could be demonstrated. The results show that the p-y curves proposed by API highly overestimate the lateral load bearing capacity. It suggests that these curves need correction and modification for each site as the soil conditions change.

***Keywords*—**Centrifuge modeling, monopile, lateral loading, p-y curves.

I. Introduction

DOLPHINS are divided up into two main categories in terms of resisting and transferring the loads resulting from ship impact: rigid dolphins and flexible dolphins. In flexible dolphins, the energy due to ship impact is dissipated through deformations of a large-diamater pile called monopile [1]. Monopile is a tubular steel pile with diameter ranging from 1 to 6 m. These piles, which are driven partially into the soil, show the same behavior as the cantilever beams [2]. In general, three criteria must be met in order to analyze and design a pile under lateral loads. First, the stress applied to the soil must be less than its ultimate strength. Second, the lateral deformation of the pile must be within the allowable limit. Finally, the pile must not yield structure-wise. Since the design of these kinds of piles generally includes very large lateral deformation, the lateral displacement criteria will govern the load-bearing capacity before soil reaches its ultimate load-bearing capacity [3]. Thus, one of the most common methods for analysis and design of a pile under lateral load is a traditional method called p-y curves which usually models the pile as an elastic bending element and the soil as series of non-linear springs [4]. The common p-y curves are semi-experimental, and they show the relationship between the lateral forces p applied by the pile to the soil element and the lateral displacement y of this element [5]. Murchison, O`Neill, and Reese have done the most prominent studies regarding the p-y curves, forming the basis for the p-y curves given in API [5]-[7]. The most important problem with this method is the ignorance of the continuity of soil due to modeling of the soil in the form of discrete springs. Therefore, the effects of upper or lower layers on a certain layer are ignored [8]. Of additional concern regarding p-y curves method is that the properties of pile including the pile stiffness, the conditions of pile head, and the pile shape are not considered in these curves [9]. Centrifuge modeling is one way to overcome the problems associated with the traditional p-y curves and model the interaction of soil and pile with a reasonable accuracy [10], [11].

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In the present study, five tests were conducted considering two parameters, the embedded depth *L* of pile into the soil and the free length e of pile. The p-y curves in API were then plotted and compared with the curves obtained from the experiments so that the differences would reveal and the necessary modification could be applied. Also, the variation of deflection *y* along pile for one of the tests (Test 1) is presented.

II. Design Method

The p-y method is a method for determining the pile deflection and (ultimate) lateral bearing capacity as a result of lateral load acting on a foundation. Soil resistance is modelled using non-linear springs [12]. Murchison's and O'Neill's p-y curves for lateral resistance of soils (sandy soils) presented by API in terms of displacements [6], [7], can be plotted using (1)

$$P= A.\ P_{u.}\ tgh[\frac{k.z}{A.P_u}y] \qquad (1)$$

where: y = The lateral displacement, "m", P_u = The ultimate lateral resistance of soil, "kN", z = The distance from a given point to the soil surface, "m", k = The initial modulus of subgrade reaction, "kN/m^3", A = An empirical coefficient that varies according to the type of loading.

$$A= (3-0.8z/D)\geq 0.9 \qquad \text{For Monotonic Loads} \qquad (2)$$

where: D= The diameter of monopile, "m", z = The distance from a given point to the soil surface, "m", P_u is the minimum value of the following (3) and (4):

$$P_{us}= (C_1.z + C_2.D)\gamma.z \qquad (3)$$

$$P_{ud}= C_3.D.\gamma.z \qquad (4)$$

$$P_u = min \{P_{us}, P_{ud}\} \tag{5}$$

where: z = The distance from a given point to the soil surface, "m", γ = The specific weight, "kN/m^3", D = The diameter of monopile, "m", k = The initial modulus of subgrade reaction, "kN/m^3", C_1, C_2, C_3= Coefficients which are dependent on the angle of internal friction.

In order to evaluate the p-y curve, the bending moments were computed at each gauge station with multiplying the recorded strains by the gauge constants calculated based on loading a simply supported beam at the midpoint. The experimental bending moment data were fitted with fourth-order polynomial. The equations for lateral displacements y and soil resistance P were obtained by double integration and differentiation of the fitted moment curve $M_{(z)}$ along the depth of pile z, respectively.

$$P=\frac{d^2M_{(z)}}{{d_{(z)}}^2} \tag{6}$$

$$y=\iint \frac{M_{(z)}}{E_pI_p}d_z \tag{7}$$

where $M_{(z)}$ = The moment curve during the pile, "kN.m", E_p = The modulus of elasticity of the pile, "kN/m^2", I_p = The moment inertia of the pile, "m^4".

In the equations above, the boundary conditions include the displacement of the pile head and the zero slope at the end of the pile.

III. The Concept of Centrifuge Modeling

Since most of geotechnical problems are of large dimensions and their modeling needs relatively small scale factors, the errors due to modeling (Scaling effect) is significant. Moreover, the behavioral nature of geotechnical structures is stress-dependent, meaning that they show different behaviors depending on the applied stress level. This fact also amplifies the negative effects associated with scaling; however, if a method could be found to apply stress conditions as same as the field (real world) values at the corresponding points, the problems caused by errors of scaling effect would be largely negligible. One way to do this is to use a centrifuge. Centrifuge is a set of devices which locally increases the gravitational acceleration by rotation and compensates for the decrease in stresses due to the reduction in model size. In centrifuges, based on the ratio of gravitational acceleration to the earth's gravity, the dimensions of model are reduced linearly [13].

IV. Model Instrumentation

Since there was no loading system embedded in the centrifuge, a lateral loading device was built with a stepper motor tailored to apply static loading to the soil box. Due to increased weight of the compartments during highly-accelerated rotation of the centrifuge accompanied with large forces applied during the loading, a 66-kgf.m stepper motor was chosen to be installed on the loading system. This motor generates forces associated with horizontal displacements of the pile with high-efficiency. Mechanism of the lateral loading simulator is to transfer the rotation of the stepper motor to two pulleys and a belt around them and then imposing this motion to the end of a ball screw. The ball screw transforms the rotational motion generated in the engine to a translational motion. This translational motion is transferred to the loading cell and then to the loading shaft via two rail and four wagons, and finally at the end of shaft, it imposes controlled lateral displacements on the pile. To prevent local damage on the pile, a piece of equipment was used to generate a uniform force. Moreover, a control system was embedded in the centrifuge to switch off/on the power and set the rotational direction of the engine as shown in Fig. 1.

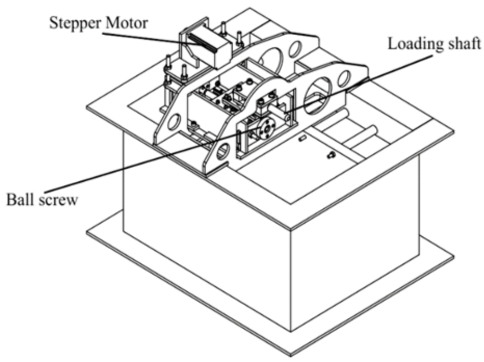

Fig. 1 Sketch of lateral loading setup

Bending occurs along a pile depending on the type of lateral loading; thus, the strain gauges had to be installed along the vertical axis of pile on two sides in order to measure the flexural strains. According to the length of the pipe, 16 strain gauges at eight stations were installed on the pile shaft. It is worth mentioning that the strain gauges were connected together as Full Bridge so that the output could directly display the input needed to calculate the bending moments in the calibration formulae via recording only one number.

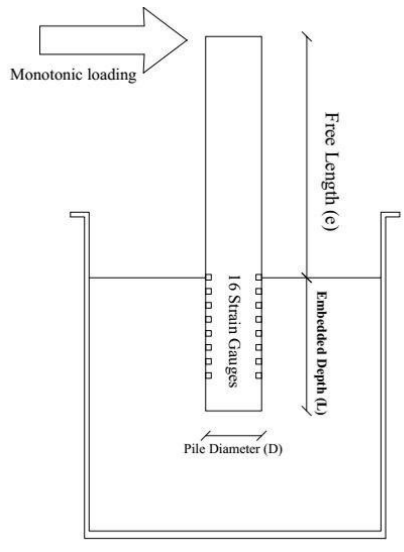

Fig. 2 Sketch of the test setup

The dimensions of soil box should be proportional to the size of monopile and its boundary conditions, so when the lateral loading as well as the corresponding displacements is applied, the walls of soil box have the minimum effect on the soil around the pile. The box has an 80-cm length, a 60-cm width and a 50-cm height made with 1-cm thick steel plates. The friction between soil materials and walls of the box is one of the effects of boundary conditions causing errors in test results. To reduce the friction, the transparent plastic sheets were used on the inside walls [14].

A. Properties and Test Program

In this study, five tests in total were done; three of which with a fixed free length and varying embedded depths, and the other two with one of the embedded depths of the previous stage fixed and varying free lengths. In Table I, the test programs of these experiments can be viewed. In all tests, the loading rate was 0.24 mm/s with a duration of 70 s.

TABLE I
TEST PROGRAM AND SPECIFICATIONS

Test No	Embedded Depth, "cm"	Free Length, "cm"	L/D	e/D	Centrifuge Acceleration
1	37.74	24.5	15.1	9.8	40g
2	30.6	24.5	12.2	9.8	40g
3	26.52	24.5	10.6	9.8	40g
4	26.52	29.5	10.6	11.8	40g
5	26.52	34.5	10.6	13.8	40g

The pile cross-section used in all experiments was a stainless steel 316 pipe which has a modulus of elasticity fairly close to the piles being used in the sea [15]. As can be seen in Table II, its mechanical characteristics are presented and compared with other types of steels. The selected pipe has a diameter of 2.5 cm and a thickness of 0.5 mm which can model an actual pile with a diameter of 1 m under a gravitational acceleration of 40 g based on the scaling law. These settings were established in all the experiments.

TABLE II
MECHANICAL PROPERTIES OF STAINLESS STEEL 316

Tube Type	Specific Weight, "KN/m^3"	Yield Stress, "MPa"	Ultimate Stress, "MPa"	Modulus of Elasticity, "MPa"
Stainless Steel	7930	290	515	207
ST52	7850	360	520	210
ST60	7850	420	600	210
ST70	7850	490	700	210

The soil used in the physical models is Firoozkooh sand no.161. The physical and mechanical properties of this soil type are given in Table III [13]. The tests were done with the relative density of 60% and the moisture content of 5% in dry conditions.

TABLE III
SPECIFICATIONS OF FIROOZKOOH 161 SAND

Sand Type	G_s	e_{max}	e_{min}	D_{50}, mm	C_u, kPa	C_c, kPa	ϕ, deg
Firoozkooh 161	2.658	0.874	0.574	0.3	1.87	0.88	36.5

V. TEST RESULTS

First, a comparison is made between the two parameters, free length and embedded depth. After that, the p-y curves obtained from the tests are presented and compared with the curves obtained from the related expressions in API. Also, the necessary modifications applied to the curves are studied and discussed.

A. Parametric Study

Embedded depth and free length were earlier introduced as the two parameters that had been changing during this study. Currently, we are going to study the effect of each of these parameters on the displacement of the pile head as well as the lateral load bearing capacity. As shown in Fig. 3, the reduction of the penetration of the pile in to the soil results in the reduction of the lateral stiffness of the pile, which could result in a reduction in the lateral load bearing capacity of the pile for a given displacement. It should be noted that the change in the stiffness and the bearing capacity of the pile is very small for a change in pile penetration, and the difference is not significant. As can be seen, the change in load bearing capacity was about 5%, while the penetration depth had been changed by 15 to 20% in comparison to the value of the earlier test.

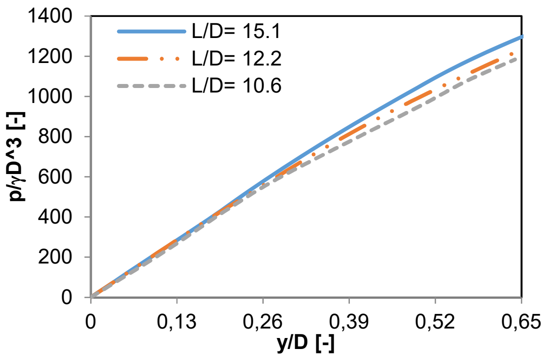

Fig. 3 Effect of embedded depth on soil (non-dimensional)

According to Fig. 4, it can also be shown that by increasing the length of pile embedded into the soil, the lateral displacement at the pile head is reduced for a given force.

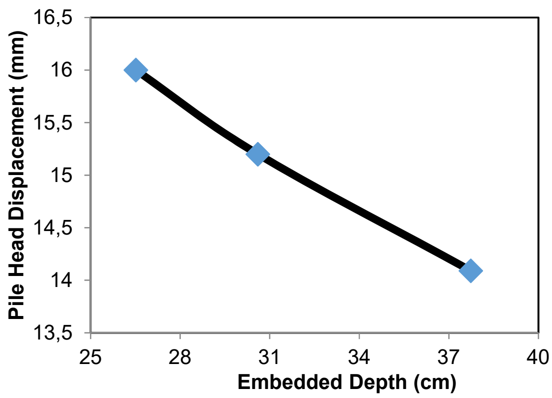

Fig. 4 Effect of embedded depth on displacements at pile head for the first three tests

As can be seen in Fig. 5, the change in free length would affect more than the change in penetration depth. In the three tests shown, the free length had been changed by approx. 15% in comparison to value of the previous test. As can be observed, with an increase in free length, the lateral stiffness of the soil, and consequently, the lateral load bearing capacity decreases. It should be noted that the variation of free length affects more considerably the lateral load bearing capacity compared to the variation of embedded depth as shown in Figs. 4 and 5.

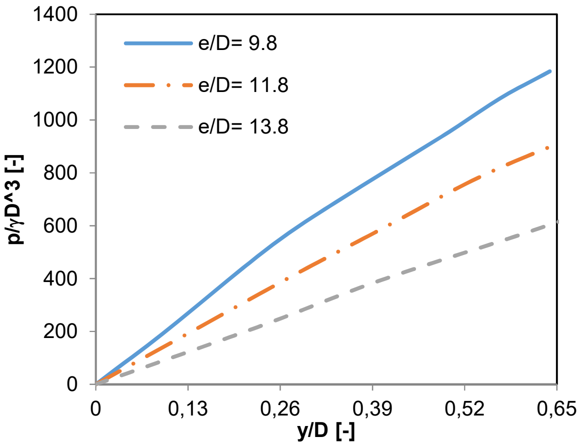

Fig. 5 Effect of free length on soil (Non dimension)

According to Fig. 6, it also can be observed that by increasing the free length, the displacement at the pile head also increases.

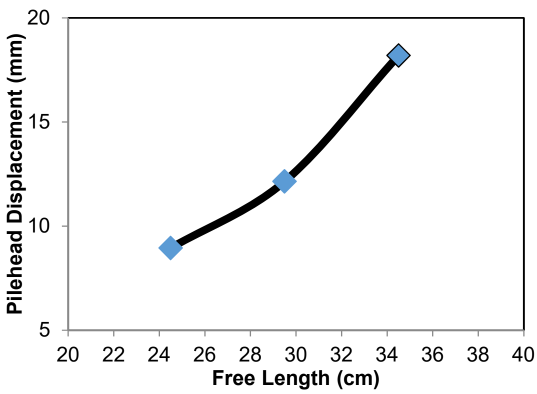

Fig. 6 Effect of free length on displacements at pile head for the second three tests

B. Comparison and Discussion on the p-y Curves

As earlier mentioned, according to the expressions and graphs given in API, the p-y curves depend on the soil depth, the pile diameter, and the soil properties such as angle of internal friction and relative density. The expressions and assumptions are based on the in situ tests done on a certain type of soil with constant properties. According to the expressions given in API and the relative density measured in the tests, the Modulus of Subgrade Reaction is calculated to be 40000 kN/m^3 for the p-y curves in API. The experimental graphs obtained from (6) and (7) and those obtained from (1) (suggested by API) are shown in Figs. 7 and 8 at the depths z=2D and z=3D.

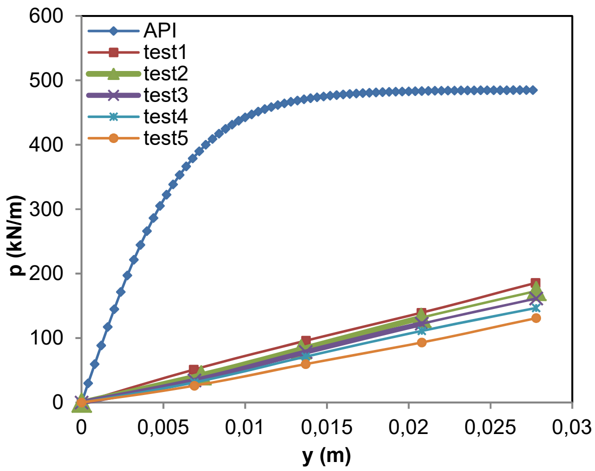

Fig. 7 Experimental and API p-y curves at z=2D

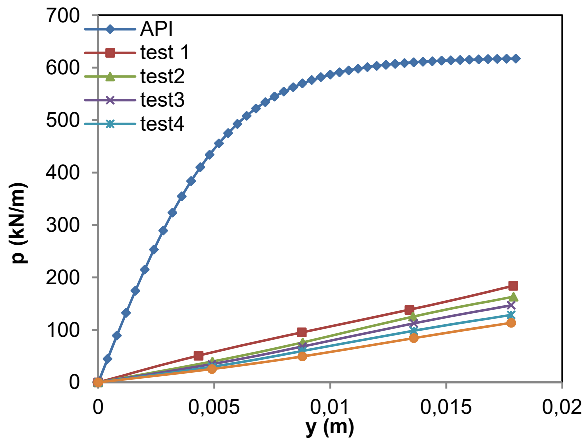

Fig. 8 Experimental and API p-y curves at z=3D

As can be seen in graphs above, the lateral load bearing capacity increases as depth increases in such a manner that the bearing capacity increases by 25% in deeper depths. It can be also observed that due to the loading applied to the monopile, the behavior of monopile is fully linear elastic, and the ultimate lateral load bearing capacity has not been reached.

Observation of the p-y curves presented in the API and the p-y curves obtained from the tests shows a significant difference between them in terms of the lateral load bearing capacity. Consequently, the API curves need to be modified. Accordingly, the initial modulus of subgrade reaction k was modified because the pile diameter, the desired depth and also the soil type could not be changed. The modified API curves are shown in Figs. 9 and 10. By decreasing k, a better agreement can be seen with the force values obtained from the tests. Hence, if better results are desired from API curves for the piles with large diameters, the soil under study should be tested to evaluate the initial modulus of subgrade reaction k. In preparation of the traditional p-y curves, some factors such as variation of embedded depth and free length were not taken into account; however, it is evident in the experimental p-y curves that increasing the embedded depth (or decreasing the free length) would enhance the lateral load bearing capacity of the pile. Based on the comparison between API and experimental curves, k = 3500 kN/m^3 was found to be the desired value to approach the results of the first test. It should be noted that the calculated value was the same for both of the depths, and this value would not change with an increase in z.

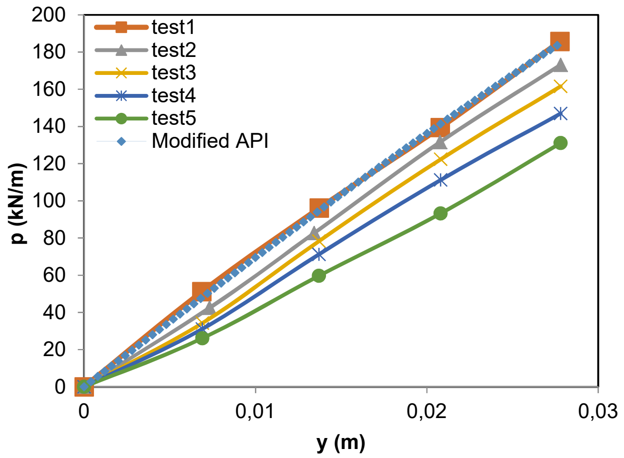

Fig. 9 Experimental and API p-y curve at z=2D

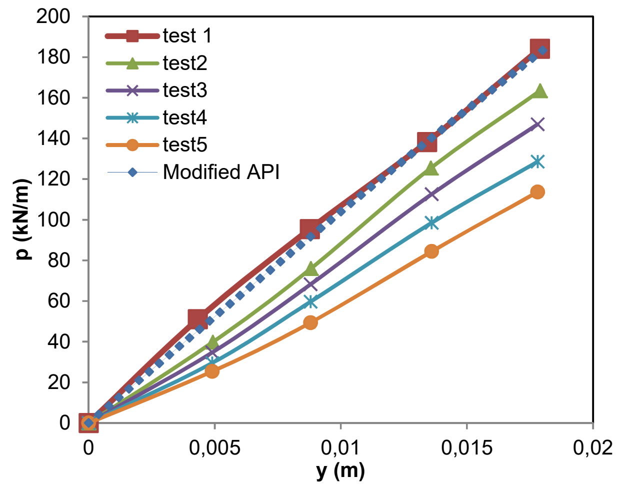

Fig. 10 Experimental and API p-y curve at z=3D

The difference in load capacity between API and experimental values is about 40% at z=2D and 30% at z=3D, suggesting that the calculations made by API have been overestimated and conservative. Therefore, some modifications need to be made to the API values through adjusting the soil Modulus of Subgrade Reaction k to the above-mentioned value in order to match with the results. In the other tests, the modified values have been also calculated for k; for example, in the third test, k is found to be 3000 kN/m^3 which is smaller than the value calculated in the first test.

The variation of deflection y along pile is shown in Fig 11. As can be seen, a plastic hinge is formed at the depth of 0.4 m due to flexible behavior of this monopile.

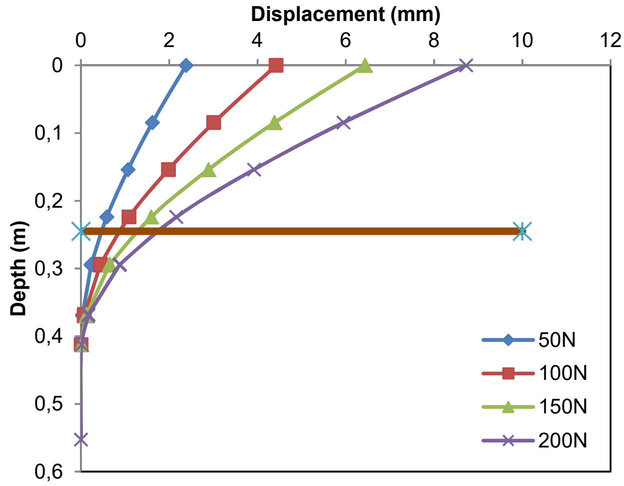

Fig. 11 Deflection versus depth of pile in test 1 (the brown horizontal line represents the soil surface)

VI. Conclusion

In this study, five tests were conducted to determine the effect of free length and embedded depth on the lateral load bearing capacity of piles. Accordingly, the curves of force-displacement as well as p-y curves were extracted during each test. Based on these curves and the ocular observations, the following results were obtained from the tests:

(1) The lateral behavior of pile-up to the maximum displacement of 0.65D was linear, and the non-linear zone was not reached.

(2) The displacement of the pile head is going to be reduced as embedded depth increases, and is going to be increased as free length increases.

(3) The effect of free length on the displacements is greater than that of penetration depth.

(4) The initial stiffness predicted by API has been evaluated approximately 11.5 times greater than the soil stiffness, and the difference even becomes greater in larger diameters; therefore, Modulus of Subgrade Reaction, k, needs to be modified in API. In fact, the value of Modulus of Subgrade Reaction should be calibrated through testing the soil. In the other words, the calculations made by API have been overestimated and conservative.

(5) API standard does not directly take into account the changes in embedded depth and free length to create the p-y curves; however, it was found during the tests that changes in these two parameters affect the load bearing of the pile at different depths and alter the shape of p-y curves.

(6) Modulus of Subgrade Reaction k not only depends on the lateral load but also on the geometrical properties of the pile including the diameter.

(7) By increasing depth from 2D to 3D, Modulus of Subgrade Reaction does not change, indicating that this parameter does not depend very much on the soil depth.

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