INTERNATIONAL JOURNAL OF
COASTAL & OFFSHORE ENGINEERING
IJCOE Vol.2/No. 5/ Winter 2017 (25-32)

Effect of Pile Bending Stiffness on Static Lateral Behavior of a Short Monopile in Dry Sand

Saeed Darvishi Alamouti*[1], Mohammad Reza Bahaari[2], Majid Moradi[3]

[1]*Phd candidate, university of Tehran, Saeed_darvishi@ut.ac.ir*
[2] *Associate professor, university of Tehran, mbahari@ut.ac.ir*
[3] *Assistant professor, university of Tehran, mmoradi@ut.ac.ir*

ARTICLE INFO

Article History:
Received: 26 Mar. 2016
Accepted: 15 Mar. 2017

Keywords:
Short monopole
flexural stiffness
static loading

ABSTRACT

Monopiles are common foundations for offshore structures such as wind turbines and they are commonly used as fender piles in port structures. In such structures, especially in OWTs, the ratio of pile length to diameter (L/D) is small which makes the pile behave as a rigid structure. However, the pile flexural (bending) stiffness still affects the pile load-displacement characteristics and maybe should not be ignored in the pile design. In this study, the effect of pile flexural stiffness on a short monopile subjected to static lateral load is investigated. The modeled pile has aspect ratio of 5 (L/D=5) which is driven into medium sand. The main characteristics of pile static lateral behavior including lateral resistance, stiffness, deflections, bending distribution and toe-kick are investigated and results are discussed. Results show that in the studied case, the pile behavior pattern is in the middle of flexible and completely rigid pile and therefore bending stiffness has meaningful effects on some important parameters related to monotonic performance.

1. Introduction

A monopile is a single large diameter steel pile which is driven into the soil about 4-6 times of its diameter [6]. Today, monopiles are the most commonly used support structures for offshore wind turbines. As well as wind turbines, they are frequently used as fender piles to facilitate vessels berthing in ports. In literature, monopiles are often divided into two main categories; short rigid piles and slender long piles. The main factor that determines rigidity of monopiles is aspect ratio (ratio of pile diameter to embedded length) [5]. Typical offshore pile says L/D ~ 30 – 50 or more whilst wind-farm monopile says L/D ~ 4 – 8 [3]. The aspect ratio affects pile behavior and its failure modes under lateral loading (Figure 1).

One of the main discrepancies between short and long piles is failure mechanism, as shown in Figure 1. In long piles failure is governed by structural capacity of pile whereas in short piles it is governed by soil ultimate resistance. This means that in short piles the effect of flexural stiffness could be negligible and only the diameter and penetration length of the pile (which determine lateral capacity) are important design parameter. However, it should not be concluded that the flexural stiffness (i.e. the effect of pile thickness) is allowed to be completely ignored. In present study, effect of pile bending stiffness (only variable thickness, fixed length and diameter (L/D)) is explored in pile behavior under eccentric lateral Load in dry sand for a rigid short pile with aspect ratio of 5. Results for load-displacement response, mudline rotation and displacement, pile body deflection, distribution of moment and toe-kick are presented and discussed.

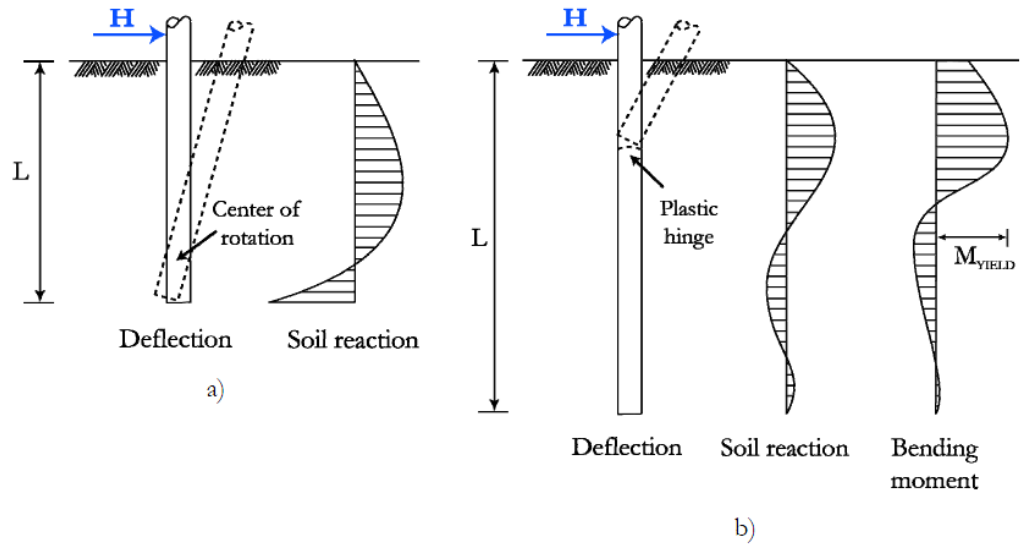


Figure 1: Failure modes of a free-headed laterally loaded pile, after [Broms, 1964]. a) Short pile (rigid-body rotation) b) Long-pile (formation of plastic hinge) [4].

Pile model

In current practice, the analysis and design of monopiles is carried out by winkler model (Figure 2). In this approach, the pile is modeled as a beam on a set of nonlinear, uncoupled soil-pile resistance springs characterized by p-y curves (API). In p-y curves, soil reaction pressure p(z) at each depth z, is a function of pile lateral displacement y(z). In sandy soils, p-y curve is expressed as below equation:

$$p = AP_u \tanh(\frac{kz}{AP_u} y)$$

Where

A is a factor to account for cyclic or static loading condition evaluated by: A=0.9 for cyclic loading and A=3-0.8z/D≥0.9 for static loading.

P_u is ultimate resistance and k is soil initial subgrade reaction modulus.

In this study, the standard homogeneous dry Firouzkooh (no. 161) sand at relative density of 60% is used for sand modeling. A summary of physical properties of the sand is presented in table 1[8].

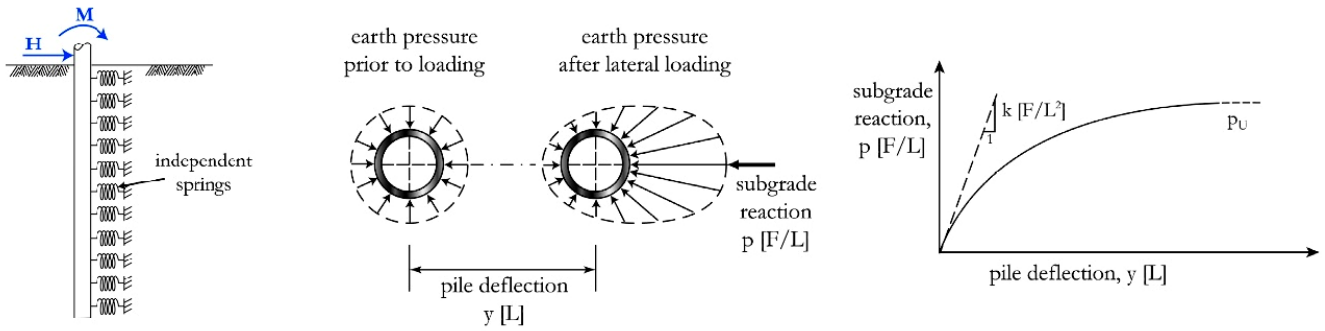
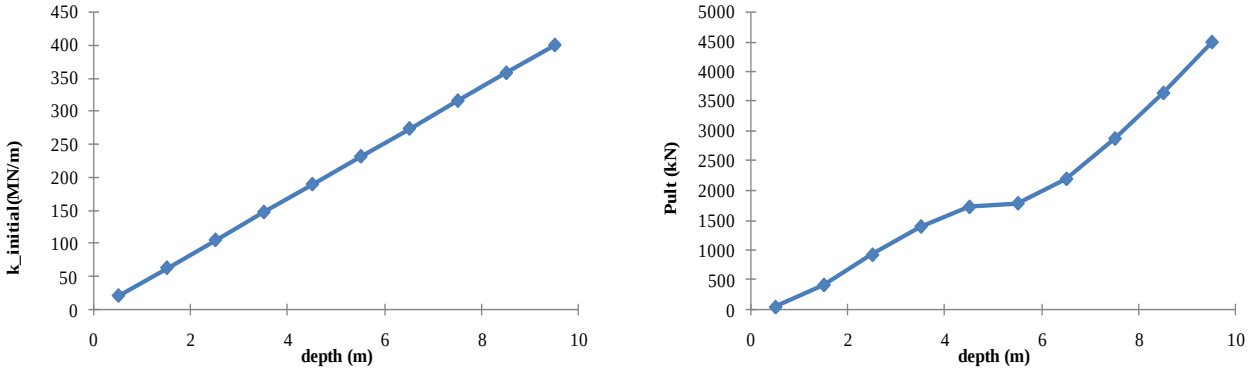


Figure 2: Winkler model and Graphical definition of p and y, after Reese *et al*., 1974 [4]

Table 1: Physical properties of Firouzkooh #161 sand

USC Name	Gs (kg/m^3)	emax	emin	φ (degree)
SP	2.658	0.874	0.574	36.5

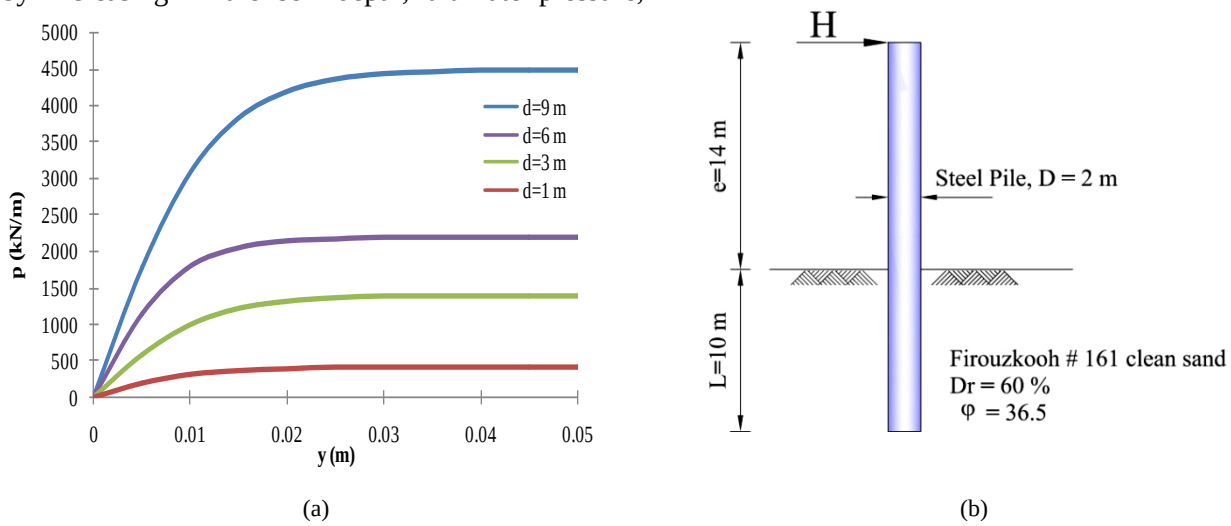
Depth varying initial subgrade reaction modulus and the ultimate resistance of Firouzkooh sand is presented in Figure 3 for static condition. Initial subgarade reaction increases linearly in depth but the variation of ultimate pressure is not linear.



(a) (b)

Figure 3: a) soil initial subgrade reaction modulus. b) Soil ultimate pressure

API p-y curves for this soil for some typical depth is calculated and presented in Figure 4-a. As it is shown, by increasing in the soil depth, ultimate pressure, ultimate deflection, initial stiffness and secant stiffness of the soil is increased.



(a) (b)

Figure 4: a) p-y curves for Firouzkooh (no. 161) sand in typical depths. b) Schematic sketch of modeled monopile

Monopile modeled in this study has a total length of 24 m and outer diameter of 2 m. 10 meters of the monopile is driven into the soil (L/D=5, i.e. short pile). Horizontal load is applied at highest point of the monopile resulting in load eccentricity of 14 m (e/D= 7). Schematic sketch of modeled pile is illustrated in Figure 4-b.

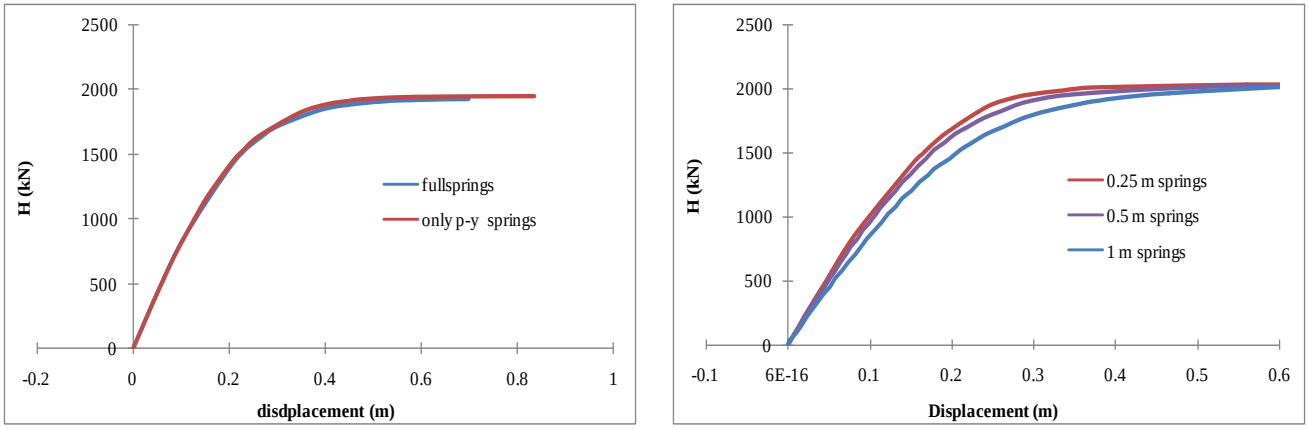
To assess effect of flexural stiffness on the pile static behavior, only the pile thickness variation is considered. Moreover, for more general sense and better comparison, perfect rigid body behavior of the pile is investigated too.

Mesh Verification

Complete system of pile-soil-interaction model includes not only the p-y curves introduced at previous section, but also t-z and Q-z curves. Mobilized soil–pile axial load transferred deflection relationship at any depth is represented by t–z curves [2]. Similarly, the mobilized tip load capacity and axial tip deflection relationship is described using a Q–z curve [2]. However, effect of pile axial performance may not affect the pile lateral behavior. To verify this assumption, pile load-deformation response at the loading point is investigated in two cases. One is the case wherein all three types of soil springs are attached to the monopile (denoted by fullsprings in the graph) and the other case is the pile with only p-y curves attached. The resulted load-deformation response is shown in Figure 5-a. It is seen that the pile axial performance affect the pile less than 1% in ultimate capacity. In other words, the only p-y model overestimates the pile capacity less than 1%. Thus, in modeling procedures of the monopile subjected to lateral loading, the effect of t-z and Q-z springs is ignored in this study.

Finite element accuracy of the modeled structure response depends on size of beam elements for discretizing of the monopile system and the intervals of the soil springs in the pile. In order to assess this accuracy, the monopile load-deformation response at the loading point is considered for different intervals of p-y springs. FE Modeling Results are plotted in Figure 5-b. This plot shows that the structure response related to 0.5 and 0.25 intervals of soil springs are so close and the results are converged after 0.5 m spring

intervals. So, the soil springs spacing of 0.5 m is considered for modeling purpose in this study. Another conclusion according to this graph is that modeling with large intervals of the springs underestimates the pile stiffness, although it doesn't have any effect on failure capacity.

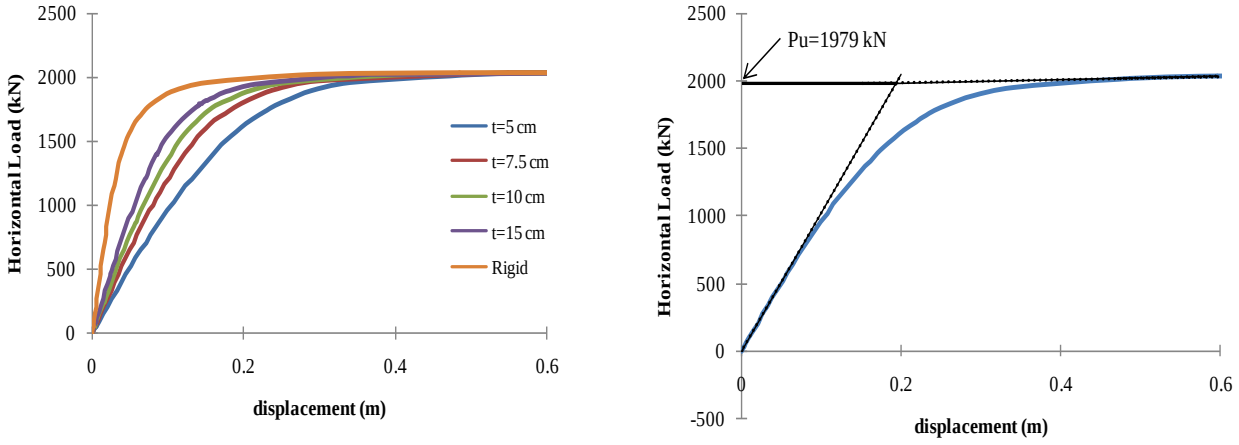


(a) (b)

Figure 5: a) Monopile load-displacement response in two cases; full springs model (p-y; t-z and q-z curves) and only p-y springs. b) Mesh verifying of modeled monopile

Results

A numerical model is set up by a powerful finite element package ABAQUS to investigate pile behavior under static lateral loading. Load-displacement behavior of pile for different flexural stiffness (which is distinguished with different pile thickness in following graphs) is illustrated in Figure 6-a. This figure shows that by increasing in bending stiffness, the pile failure capacity would not change, albeit, the ultimate capacity is affected a little. Increasing in flexural stiffness, leads to increase in pile stiffness, but near ultimate resistance, if flexural stiffness would be high, gradient of stiffness reduction would be high too. This implies that stiffness and deflection properties of short pile are important parameters to determine monopile structures ultimate resistance. In the other words, in such rigid piles, abrupt reduction in structure stiffness and bearing capacity should be avoided by specifying safe margins in pile deflections.



(a) (b)

Figure 6: a) load-displacement response of monopiles subjected to lateral load, b) asymptote-tangent method to estimate ultimate capacity

It should be noted here that the failure capacity is different from ultimate capacity. In other words, in this numerical study all piles fails in equivalent ultimate force (about 2040 kN), but they have not the same ultimate capacity, because the ultimate capacity is controlled by a predefined level of deformation. One method to estimate the ultimate capacity is asymptote-tangent method [7]. In this method, the critical load is the point on initial tangent curve which intersect the asymptote on high pile deflections (Figure 6-b). According to this criteria, ultimate resistance increases by increasing in flexural stiffness of the pile. However, the change in the values is not significant. The ultimate resistance could be compared to Broms (1964) equation for short free-head monopile. The following assumptions are made in the analysis by Broms (1 964):

1. The active earth-pressure acting on the back of the pile is neglected.

2. The distribution of passive pressure along the front of the pile is equal to three times the Rankine passive pressure.
3. The shape of the pile section has no influence on the distribution of ultimate soil pressure or the ultimate lateral resistance.

If the pile is sufficiently rigid to cause soil failure, according to mentioned assumptions the pile ultimate resistance is calculated as follow:

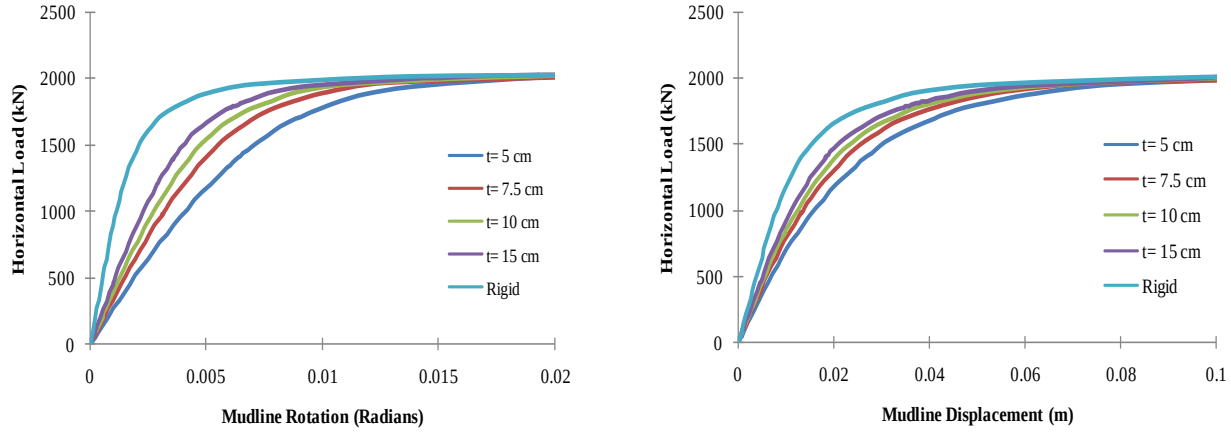
$$Hu = \frac{0.5\gamma d L^3 K_p}{e + L}$$

Wherein,
e denotes load eccentricity, L is embedded length, d is pile diameter and Kp is the passive pressure factor.
Ultimate resistance of modeled monopile obtained by Broms method is summarized in Table 2. Calculated value is about 25% higher than the results obtained by Winkler method and API p-y curves.

Table 2: Input parameters for ultimate resistance capacity using Broms equation

Pile diameter (d) (m)	L=5d	e=7d	γ_d (t/m^3)	phi	Kp	Hu (kN)
2	10	14.00	1.57	36.5	3.9	2524

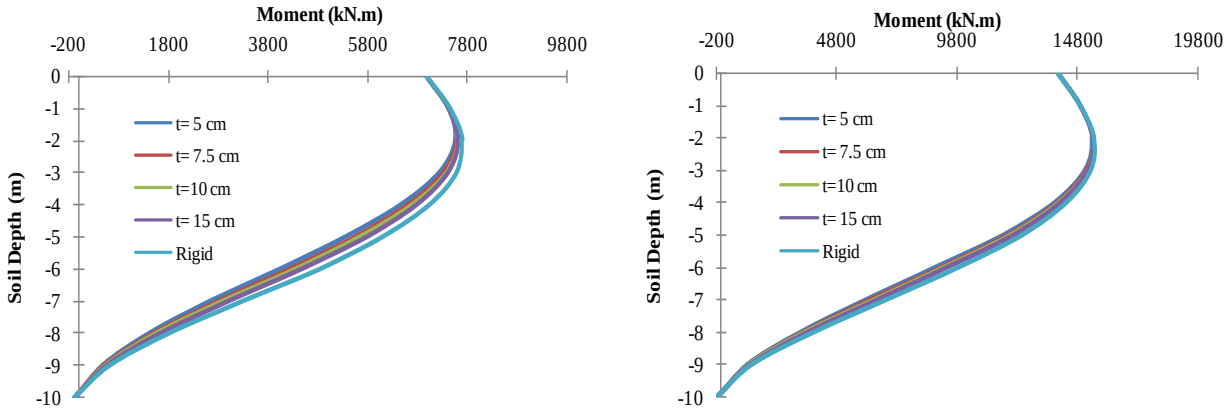
In monopiles used as offshore wind turbine foundation, mudline displacement and rotation are important parameters to meet foundation performance requirements. The load-pile rotation and load-pile displacement response at soil surface is presented in Figure 7-a and Figure 7-b respectively. Flexural stiffness has large effect on mudline rotation. H-ϕ response of the piles is different but they all converge to a same value. As H- ϕ curves show, decreasing in pile rotation in a certain value of horizontal load is not linearly dependant on the pile stiffness, i.e. in high values of stiffness the effect of pile flexibility on the rotation decreases. Pile load-displacement curves at soil surface are influenced by flexural stiffness similar to Figure 6-a. However, the curves are closer to each other versus Figure 6-a especially in higher stiffness. This means that to meet performance requirements of monopile structures (especially pile lateral bearing capacity), increasing in pile thickness is not applicable by itself.



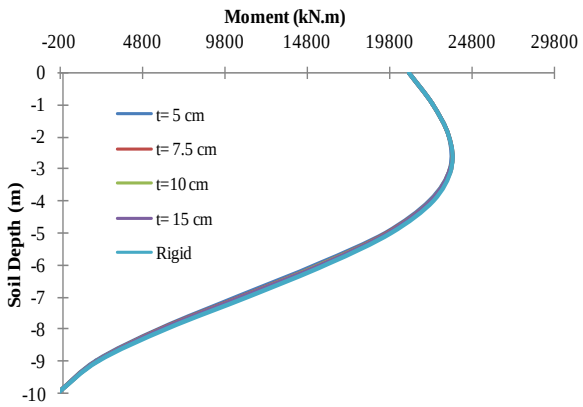
(a) (b)

Figure 7: monopiles load-deformation response at soil surface level. a) load-rotation curves, b) load-displacement curves

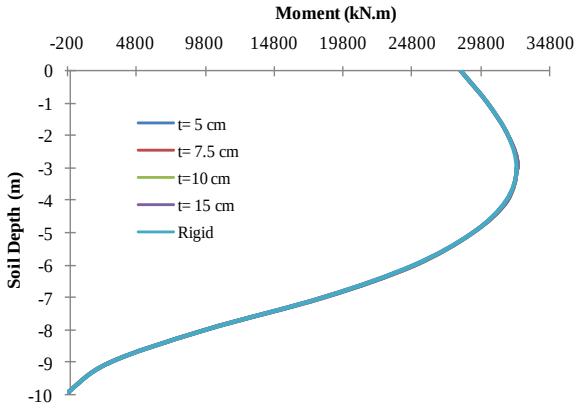
Bending moment distribution along embedded portion of monopile is presented in below graphs (Figure 8) for different levels of horizontal load. In surface level, moment value in all modeled monopiles are equal because the eccentricity is the same for all of them and effect of geometric nonlinearity in negligible.



H=500 kN



H=1000 kN



H=1500 kN

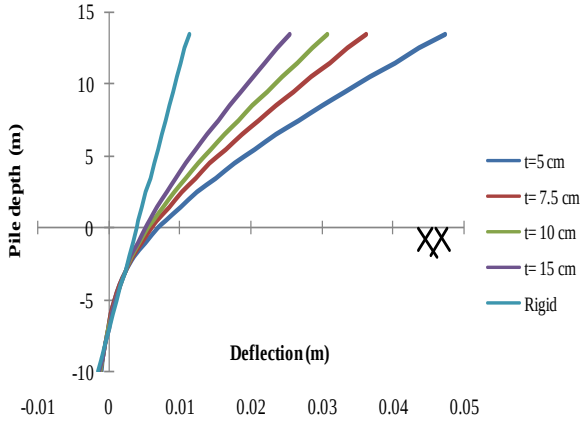
H=2030 kN

Figure 8: Moment distribution in piles at different horizontal load levels

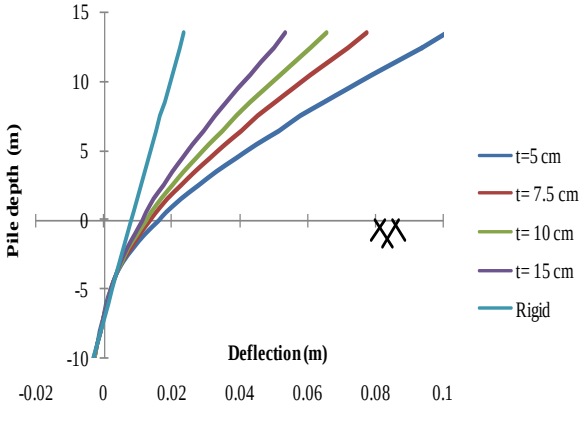
However, flexural stiffness has influenced the distribution, maximum value and location of maximum value of bending moment in low levels of horizontal load. Increasing in flexural stiffness leads to increasing in maximum bending moment value and depth. In high levels of horizontal load, this influence decrease and become negligible.

Figures 9 show monopile deflection lines under horizontal loading in 3 different load levels. As these graphs indicate, the monopile does not show rigid behavior in any flexural stiffness. However, it does not show flexible behavior too. In fact its behavior is between perfect rigid and flexible but it is more tendentious to rigid. In free portion of monopile (i.e. from soil surface to top end) flexural bending has large influence on deflections. But in embedded portion, the more is pile depth, the less is flexural stiffness effect on deflections. This is because of confinement effect of the soil as well as decreasing in bending moment.

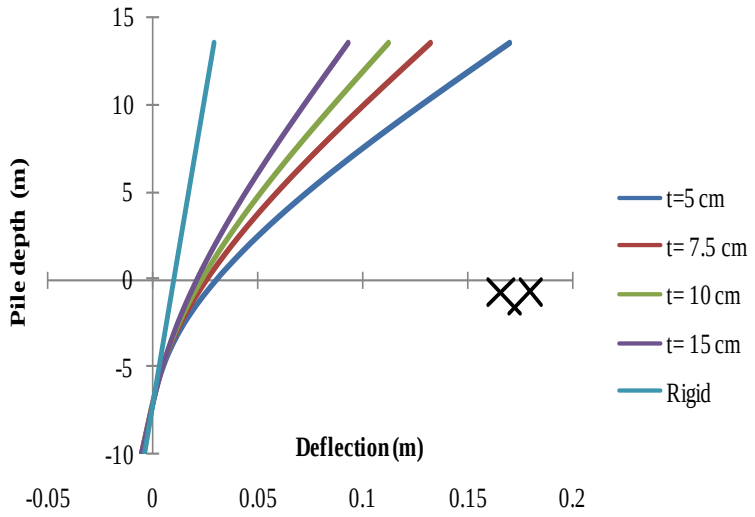
As the plots show, pile deflections near the bottom of the pile are similar in all cases. This means that pile toe-kick (deflection at the pile end respect to pile initial position) is not influenced by the flexural stiffness (Figure 10). However, the pile zero-toe-kick is one of the main criteria to determine lateral resistance of the rigid piles which denotes the effect of pile deflection shape on lateral capacity. So it could be concluded that in rigid piles (which flexural stiffness is negligible) toe-kick is probably only a function of pile diameter (and embedded length), not bending stiffness.



H=500 kN



H=1000 kN



H=1500 kN

Figure 9: Deflection lines of monopiles at different horizontal load levels

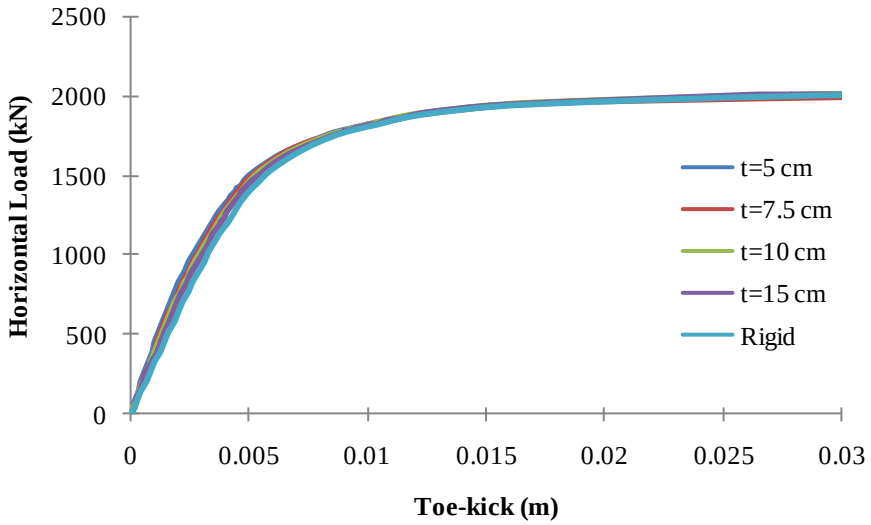


Figure 10: Monopiles toe-kick response subjected to lateral load

Conclusion

The effect of pile flexural stiffness on a short monopile subjected to lateral loading was investigated by state-of-art method (p-y curves) in medium sand. Standard parameters of firouzkooh (no. 161) sand were used in soil modeling. The monopile lateral ultimate resistance is not affected by pile flexural stiffness although ultimate capacity is affected a little. The monopile stiffness is affected largely from bending stiffness; however, this effect decreases gradually in higher bending stiffness values. Pile lateral displacement and rotation performance at the soil surface is affected by flexural stiffness, but the effect on rotation is more evident. It is notable that in higher stiffness values, the monopile fails in lower deflections which means that in higher stiffness (or more rigid piles) pile behavior is controlled more by soil performance and general behavior is displacement controlled. Effect of bending stiffness on distribution of bending moment along pile length is very low especially in high levels of lateral load. Monopile deflection lines are influenced by bending stiffness considerably. However, in higher soil depths, this effect decreases due to decreasing in moment magnitude. The effect on monopile toe-kick is not significant.

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