International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:13, No:6, 2019

Numerical Investigations on Group Piles' Lateral Bearing Capacity Considering Interaction of Soil and Structure

Mahdi Sadeghian, Mahmoud Hassanlourad, Alireza Ardakani, Reza Dinarvand

Abstract**—**In this research, the behavior of monopiles, under lateral loads, was investigated with vertical and oblique piles by Finite Element Method. In engineering practice when soil-pile interaction comes to the picture some simplifications are applied to reduce the design time. As a simplified replacement of soil and pile interaction analysis, pile could be replaced by a column. The height of the column would be equal to the free length of the pile plus a portion of the embedded length of it. One of the important factors studied in this study was that columns with an equivalent length (free length plus a part of buried depth) could be used instead of soil and pile modeling. The results of the analysis show that the more internal friction angle of the soil increases, the more the bearing capacity of the soil is achieved. This additional length is 6 to 11 times of the pile diameter in dense soil although in loose sandy soil this range might increase.

Keywords**—**Lateral bearing capacity, pile group, oblique pile, soil-structure interaction, depth of fixity.

I. Introduction

THE piles are structural vertical or oblique elements driven deep into the subsurface layers to transfer vertical loads or lateral loads from the superstructure to strong soil layers. However, sometime lateral loads may even be greater than vertical loads in process of foundation design for the following cases:

- Lateral earth pressure on retaining wall
- Wind load on giant wind turbines
- Lateral load caused by collision of ships with berth mooring structures
- Loads generated due to the movement and braking of cars on bridges

In these cases, piles, or in other words, monopiles must be analyzed under lateral loads. Pile-soil interaction should also be considered for a more precise analysis.

In deck structures, which are subject to lateral loads caused by waves and ship collisions, large and thick piles are used to resist against huge loads. These piles are called 'monopiles'. Monopiles are also used as foundation for wind turbines in the sea. Displacement at the top of the monopile (drift) and bending moment along the pile are very crucial for the design of these structures and need to be carefully computed.

To structurally design piles and to predict deformations along it, the following methods are commonly used:

- Soil modeling with linear or nonlinear spring [1]-[4]
- Strain wedge method in the soil [5]-[8]
- Three-dimensional finite element simulation in continuum media [9]-[12]

In the first method, which is known as the p-y method, analysis of piles under lateral loading is accomplished by using beams on the non-linear Winkler springs model. In this procedure, the soil-pile interaction along the depth is identified by a series of discrete non-linear springs achieved from the p-y curves. This method is simpler than the other methods. However, as mentioned by Reese and Van Impe [13], the p-y curve method does not consider stiffness of the pile, soil continuity, cross-sectional shape of the pile, and conditions of the pile head.

As mentioned above, one of the methods for estimating the response of a flexible pile under lateral loading is Strain Wedge (SW). The equations used in this approach are according to the one-dimensional Beam on Elastic Foundation (BEF), where the response parameters of a pile can be determined from the aspect of the 3D soil-pile interaction behavior [14]. The SW method is more complex than the p-y method and gives trustworthy results only for flexible piles [15]. Parameters belonging to the SW model are associated with a visualized three-dimensional passive wedge of soil that expands against the pile [16]. Consequently, the SW Model has the power to supply a theoretical connection between the more complicated three-dimensional soil-pile interaction and the simpler one-dimensional BEF characterization [17].

The third method forms the basis for a three dimensional numerical simulation of soil-pile interaction analysis. In 2017, Awad et al. studied the behavior of single pile in rock with ECM and FEM software [18]. Also, in 2017, Sadeghian et al. investigated the behavior of dolphin structures under lateral loading considering soil-pile interaction [19]. The main problem with 3D numerical simulation is the high amount of data needed about the soil parameters and pile properties. This required information must be derived via numerous tests. Other disadvantage is the time required for the analysis to be run. However, one of the most important advantages of this method is its high precision compared to other methods [20].

In 2009, Asgarian and Lesani studied depth of fixity in

Mahdi Sadeghian, Master of Geotechnical Engineering, Imam Khomeini International University, Qazvin, Iran (corresponding author; e-mail: Sadeghian.Mah@gmail.com).
Mahmoud Hassanlourad and Alireza Ardakani areAssistant Professors at Imam Khomeini International University, Qazvin, Iran (e-mail: Hassanlou@eng.ikiu.ac.ir, a.r.ardakani@gmail.com).
Reza Dinarvand, Master of Geotechnical Engineering, Imam Khomeini International University, Qazvin, Iran (e-mail: RezaDinarvand1991@gmail.com).

monopiles for marine structures and proposed 6-10 times the diameter of a pile for vertical piles [20]. Also, in 2014, Hamedi et al. conducted studies on the parameters affecting the single monopile and the depth of fixity in marine structures, and finally proposed 4 to 5 times the diameter of the pile for dense sandy soil and 6 to 7 times the diameter of the pile for loose sandy soil [21].

II. Methodology

In this study, the Finite Element Method is used for simulation. Element type of the soil and pile are selected to be solid and shell, respectively. The pile cross-section is tubular. Dimensions of the model are chosen carefully to remove any boundary effect on the responses. Fig. 1 indicates the soil layer and monopile geometry applied in vertical and oblique pile group model analysis. The pile-soil interaction was modeled using the small sliding, surface to surface master/ slave contact pair formulation as described in software manual. As long as the pile was much stiffer than the soil, the inner and outer surfaces of the pile were defined as the master surface, while the surface of the soil around the pile and the soil inside the pile were defined as the slave surface. The contact conditions between the two surfaces were controlled by the kinematic constraints in the tangential and normal directions.

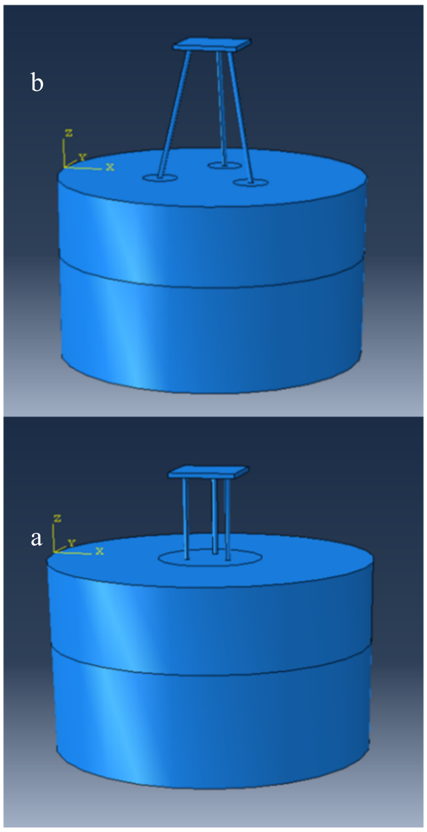

Fig. 1 3D Finite element model constructed: (a) Vertical pile group; (b) Oblique pile group

First, the soil layer was created and analyzed to obtain the initial stresses. Then, the displacements were set equal to zero and the system was prepared for monopile loading. Afterwards, the monopile was created and static lateral load was applied at monopile's head. Finally, the displacements of the head of monopiles were determined.

Parameters, such as the free length (H) and embedded length of the monopile (L), and monopile diameter (D) are known to affect the results. The soil parameters are also known to be important for final results. To study the soil effect two different soil types, namely loose and dense sandy soils were assigned to the soil layers. Tabled I and II show the soil properties and steel properties used for present numerical analysis, respectively.

TABLE I
SOIL PROPERTIES USED IN THE ANALYSIS

Sandy soil	γ (kN/m^3)	E (MPa)	C (kPa)	Ø (degree)	Poisson's ratio (ν)
loose	17	30	10	30	0.3
dense	21	80	10	40	0.3

TABLE II
MATERIAL PROPERTIES OF THE MONOPILE USED IN ANALYSIS

Pile material	Yield stress (kN/m^2)	Ultimate stress (kN/m^2)	E (kN/m^2)	Density (kN/m^3)	Poisson's ratio (ν)
St52	360,000	520,000	2.1E8	78.5	0.3

At this stage, the tube monopiles with a diameter of 0.8 m and a thickness of 34 mm were modeled in sandy soil under static loading. For this purpose, first, the monopiles were vertical with two free lengths of 17 and 28 meters and buried lengths of 17 and 28 meters in loose sandy soils. Then all of these models were analysed with oblique piles with angles of 10, 15 and 20 degrees. Then the same models were repeated in dense sandy soil. The results were recorded as load-displacement diagrams.

III. Model Verification

To verify the numerical model, four steel monopiles at the port of Pars Asalouyeh were tested under lateral loading conditions. Two of the test piles (pile 1 and pile 3) were used to validate the pile-soil interaction model in this study. The values of model input parameters, including test conditions, soil, and monopile parameters, were assumed as suggested by Seifi and Fakher [22]; as they can be seen in Tables III and IV, respectively [15]. Fig. 2 shows the 3D finite element models of the one test pile.

TABLE III
SOIL PROPERTIES BASED ON [15]

Soil layer	Depth (m)	γ (kN/m^3)	E (MPa)	C (kPa)	Ø (degree)	Poisson's ratio (ν)
sand	0-8	17	60	10	38	0.37
Sand and gravel	8-21	19.5	120	10	40	0.25
sandstone	21-30	18	135	10	42	0.20

To summarize the verification process, analysis results (p-y curves) from one of the monopiles were compared with the available correlations and field test results as shown in Fig. 3.

TABLE IV
CHARACTERISTICS OF MATERIALS USED IN MONOPILES [15]

Pile material	Yield stress (kN/m^2)	Ultimate stress (kN/m^2)	E (kN/m^2)	Density (kN/m^3)	Poisson's ratio (ν)
St52	360,000	520,000	2.1E8	78.5	0.3
St60	420,000	600,000	2.1E8	78.5	0.3
St70	490,000	700,000	2.1E8	78.5	0.3

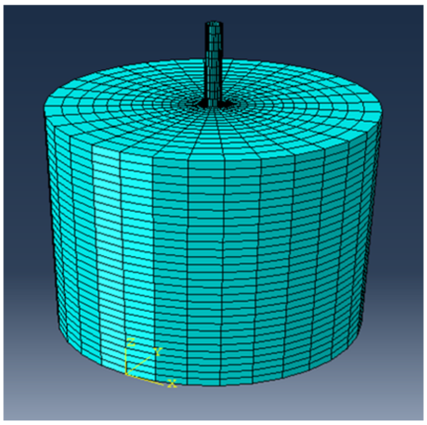

Fig. 2 Details of the finite element mesh for validation

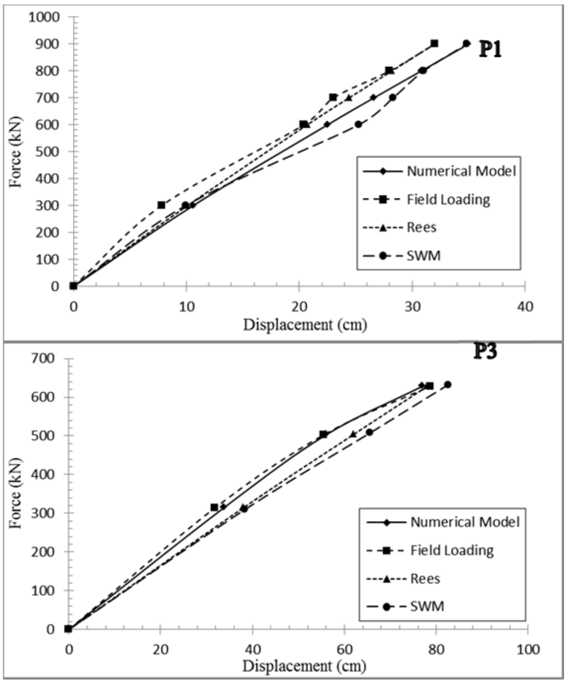

Fig. 3 Comparison of test results, theoretical methods and numerical simulation results

As it can be seen in Fig. 3 and P1 (Pile 1), the pile under 90 ton load in the test field was displaced by 32 cm and 33 cm in the numerical model. Clearly, this shows the accuracy of the numerical model. In other words, there is a reasonably good agreement between computation from numerical model and measurements form field experiments. Here, it is worth noting that the validation was done in the elastic behavior range and the pile had not reached its plastic state.

The p-y methods have also shown good agreement with field experiments. However, it should be mentioned that these graphs are drawn after calibration. Further comparison between computed and measured information was not possible, as there are not any data such as bending moment.

IV. RESULTS

A. Investigating the Effect of Soil Resistance on Critical Capacity

Fig. 4 shows the relationship between the ultimate resistance of the monopile and the internal friction angle of the soil (φ). As shown in this figure, the soil resistance, or the higher the degree of internal friction of the soil, the load capacity of the soil increases. In other words, in the present model, the resistance of the system is affected by soil fracture. As can be seen in Fig. 4, increasing soil bearing capacity is visible with increasing internal friction angle for all the examined angles of the monopiles.

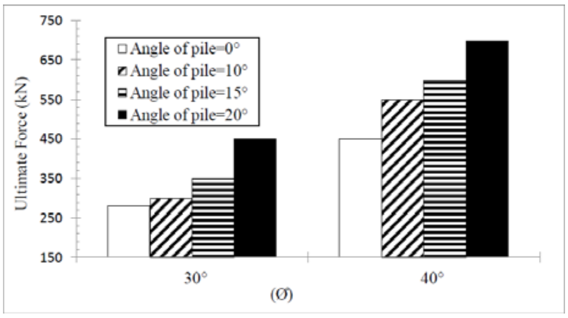

Fig. 4 Ultimate resistance of the pile group against the internal friction angle of the soil

B. Depth of Fixity

Structural and soil interactions have always been one of the challenges faced by engineers. So, in order to design the soil-related structures, a series of simplifications is required. One of these simplification and procedural rules for the design of monopiles is suggested that, instead of a complete analysis of the structure and soil, some lengths are added to the free length and consequently the soil model is removed. With regards to the contradictions and technical differences and recommendations for this issue, this subject was studied in this paper.

The depth of fixity is a portion of the pile length. This portion is added to the length of the column at the bottom. Then, the surrounding soil of the pile is removed and replaced with a fixed support at the end of the column. This is called as depth of fixity. In 2009, this length is proposed to be about 6 to10 times of the pile diameter [20].

Assembled model for studying the depth of fixity has been given in Fig. 5.

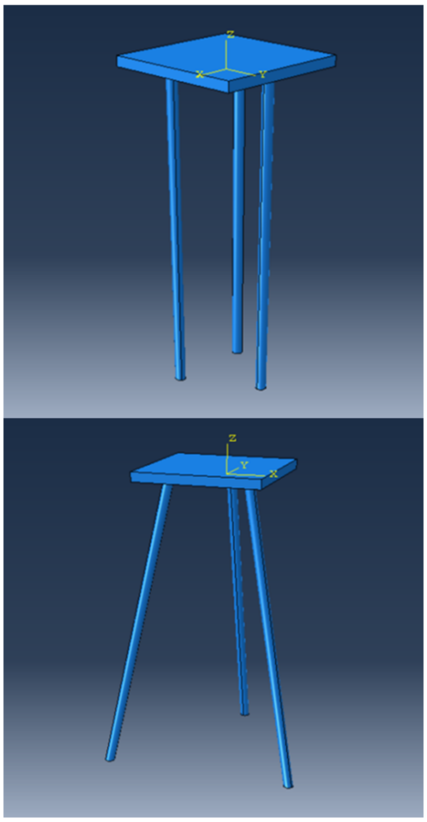

Fig. 5 Assembled model for studying depth of fixity

Fig. 6 compares the monopile–soil system behavior with its optimized interchangeable cantilever column in terms of the load-displacement diagram for vertical and oblique piles with the angle of 10 degree. In Fig. 6, H is the free length and equivalent model is the length that was added to the free length.

Studies have shown that the optimal depth of fixity can be achieved at the point where the deformation is almost zero (y_0). In other words, the effective length of the cantilever column is equal to the monopile free length (H) plus the length of the pile where its horizontal displacement is zero (y_0). Also H_b is the optimal cantilever column length that is used in the model instead of monopile and soil model and their interaction between pile and soil.

$$H_b = H + y_0 \tag{1}$$

According to the obtained results, the depth of fixity in dense sand is almost 6 to 11 times the pile diameter. However, it is more than this range in loose sandy soil. Further studies show that the depth of fixity is only applicable for flexible monopiles. In other words, this method leads to errors when applied to rigid piles. Also, this method is only acceptable in the monopile elastic behavior.

In Tables V and VI, the value of the depth of fixity in terms of the pile diameter is shown for dense and loose sandy soil. The acceptable force range is only within the range of elastic behavior of the system, or in other words, before the gradient is changed.

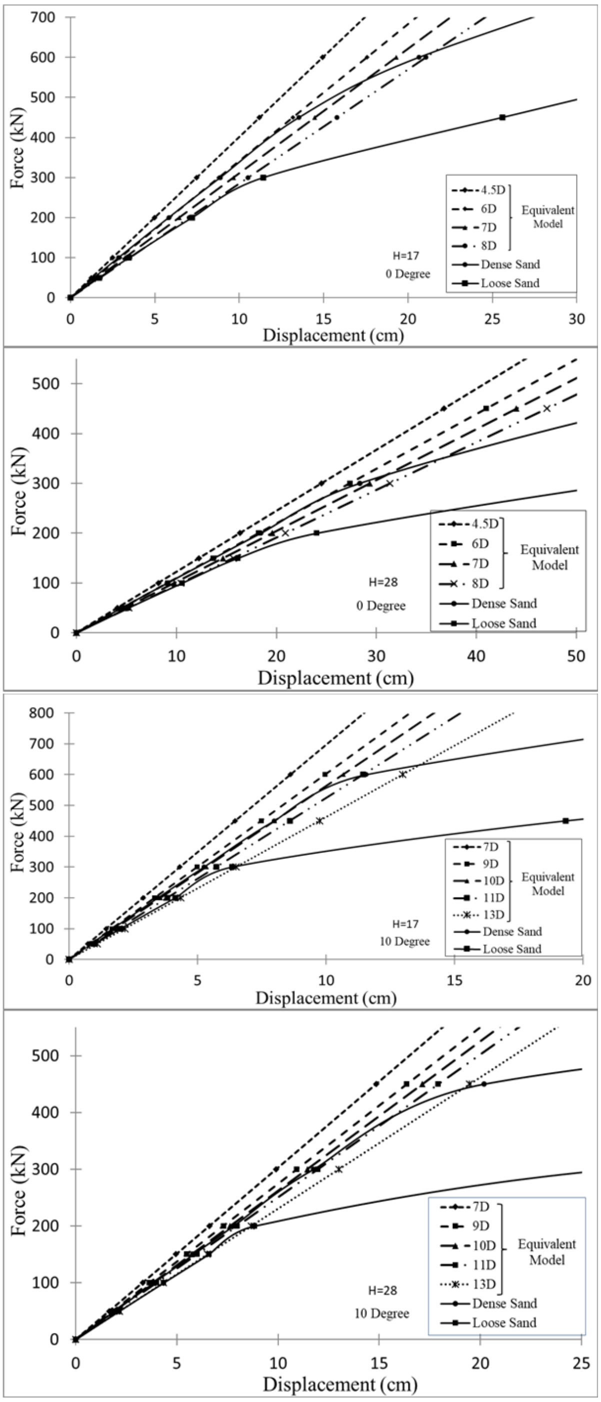

Fig. 6 Monopile-soil system versus cantilever column in terms of load-displacement behavior for vertical and oblique pile

As it can be seen from Tables V and VI, the amounts of the oblique piles' angle have been affected the depth of fixity. In this way, when the angles of the monopiles increase, the amount of depth of fixity also increases. Thus, according to the final results, in dense and loose sandy soil for vertical monopiles, the depth of fixity is approximately equal to 5-7 times, and 7-9 times the monopile diameter. Also, the depth of fixity is calculated for oblique monopiles in dense sandy soils equal to 9-11 times and 12-14 times the monopile diameter in loose sandy soil.

TABLE V
DEPTH OF FIXITY FOR VERTICAL AND OBLIQUE PILE IN DENSE SANDY SOIL

Angle of the monopile	Depth of fixity (y_0)
0°	(5.5-6.5)D
10°	(9-10)D
15°	(9-10)D
20°	(10-11)D

TABLE VI
DEPTH OF FIXITY FOR VERTICAL AND OBLIQUE PILE IN LOOSE SANDY SOIL

Angle of the monopile	Depth of fixity (y_0)
0°	(7.5-8.5)D
10°	(12-13)D
15°	(12-13)D
20°	(12.5-13.5)D

V. CONCLUSION

The depth of fixity and its simplifications for soil and pile interaction is a major concern in practice for civil engineers. This paper presents an attempt to investigate the effect of internal friction angle and also depth of fixity in both loose and dense sandy soil.

There is a possibility to replace the soil-structure interaction analysis with a simplified analysis. As a matter of fact, an equivalent cantilever column can be simulated instead of the soil-monopile simulation. To achieve this, a part of the embedded length (which is known the depth of fixity) is added to the free length. Again, the depth of fixity is a function of free length, diameter of the monopile, and the soil strength parameters. The depth of fixity in dense and loose sandy soil is estimated to be about 5-7 times, and 7-9 times the monopile diameter for vertical cantilever column. Moreover, the depth of fixity for oblique cantilever column is estimated to be around 9 to11 times in dense sandy soil and 12 to14 times the monopile diameter in loose sandy soil. With this method, researchers can significantly reduce their computing time.

REFERENCES

[1] Matlock, H., & Reese, L.C. (1960) "Generalized solutions for laterally loaded piles". J. Soil Mech. Found. Div., 86: pp. 63–91.
[2] Reese, L.C., Cox, W.R., Koop, F.D., (1974) "Analysis of laterally loaded piles in sand". Proceedings of 6th Annual Offshore Technology Conference, Houston, TX, pp. 473-483.
[3] O'neill, M., Murchison, J., (1983) "An evaluation of p-y relationship in sands", report GTDF02-83, Department of Civil Eng., University of Huston, May 1983.
[4] Lesny, K., Paikowsky, S.G., Gurbuz, A., (2007) "Scale effects in lateral load response of large diameter monopiles", Geo-Denver 2007: New peaks in geotechnics. Colorado: ASCE; 40.
[5] Reese, L.C., Cox W.R., Koop, F.D., (1975) "Field testing and analysis of laterally loaded piles in stiff clay". In: Proceedings of 7th offshore technology conference, Richardson, TX, No. 2312; pp. 671–690.
[6] Kim, Y., Jeong, S., Lee, S., (2011) "Wedge failure analysis of soil resistance on laterally loaded piles in clay", J. Geotech. Geoenviron. Eng.; 137: pp. 678–694.
[7] Norris, G., (1986) "Theoretically based BEF laterally loaded pile analysis", In. Proceedings of the 3rd international conference on numerical methods in offshore piling, Paris, France; pp. 361–386.
[8] Ashour, M., Norris, G., Pilling, P., (1998), "Lateral loading of a pile in layered soil using the strain wedge model", J. Geotech. Geoenviron. Eng.; 124: pp. 303–315.
[9] Brown, D.A., Shie, C.F., (1991) "Some numerical experiments with a three dimensional finite element model of a laterally loaded pile", Comput. Geotech.; 12: pp. 149–162.
[10] Fan, C.C., Long, J.H., (2005) "Assessment of existing methods for predicting soil response of laterally loaded piles in sand", Comput. Geotech.; 32: pp. 274–289.
[11] Chik, Z.H., Abbas, J.M., Taha, M.R., (2009) "Lateral behavior of single pile in cohesionless soil subjected to both vertical and horizontal loads", Eur. J. Sci. Res.; 29: pp. 194–205.
[12] Kim, Y. & Jeong, S., (2011) "Analysis of soil resistance on laterally loaded piles based on 3D soil–pile interaction", Comput. Geotech.; 38: pp. 248–257.
[13] Reese, L.C. & Van Impe, W.F., (2011), "Single piles and pile groups under lateral loading", 2nd Edition. London: Taylor & Francis Group.
[14] Ashour, M., & Ardalan, H., (2011), "Employment of the -Multiplier in Pile-Group Analysis", Journal of Bridge Engineering.
[15] Hokmabadi A.S., Fakher A., Fatahi. B. (2012) "Full scale lateral behaviour of monopiles in granular marine soils" Marine Structures, 29: pp. 198–210.
[16] Ashour, M., & Norris, G., (2000) "Modeling Lateral Soil-Pile Response Based on Soil-Pile Interaction", Journal of Geotechnical and Geoenvironmental Engineering.
[17] Randolph, M.F., (1981) "The response of flexible piles to lateral loading", Géotechnique, 31, pp. 247–259.
[18] Awad, A.S., Antonopoulos, I., Sadeghian, M. (2017), "Case study: Geotechnical design of bored piles in rock for the Kawarau Falls Bridge", Proc. 20th NZGS Geotechnical Symposium. Eds. GJ Alexander & CY Chin, Napier.
[19] Sadeghian, M., Hassanlourad, M., Ardakani, A., (2017), "Investigating the behavior of dolphin structures under lateral static loading considering soil-structure interaction", 1st National Conference on Highway and Transportation Engineering, Guilan University. (in Persian)
[20] Asgarian, B., Lesani, M., (2009) "Pile–soil-structure interaction in pushover analysis of jacket offshore platforms using fiber elements" J. of Constructional Steel Research, 65: pp. 209–218.
[21] Hamedi, F., Hassanlourad, M., Hassanlourad, Mo., (2016), "Investigation of lateral loaded mono-pile behavior considering soil and structure interaction", Sharif Scientific Journal, 32.2(3.1), pp. 71-78. (in Persian)
[22] Seifi, H., Fakher, A., (2007) 'Feild study of monopile behavior at Pars Asalouyeh Petrochemical Port', Proc. 9th Marine Industries. (in Persian)