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Inelastic Response of Soil-Pile-Structure Interaction System under Lateral Loading: A Parametric Study

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ABSTRACT

Soil-structure interaction is the key to study the behavior of structures under static or dynamic loading. The pile foundation is adopted to transfer loads from the structure to the soil when the structure is embedded in a weak soil stratum. Soil-pile system has a nonlinear behavior; thus, it is more complicated to understand. This study focuses on the numerical investigation of interaction of soil–pile–structure system (ISPS) and interaction of soil–pile system (ISP) under lateral loads. Nonlinear static analysis is carried out considering the lateral capacity of ISPS and ISP systems under lateral loading using pushover analysis. A parametric study concerning different types of axial loading, pile length and pile radius, as well as longitudinal steel ratio in different types of sand is conducted to observe the response of (ISPS) and (ISP) systems. Besides that, lateral capacity deflection and moment curves, as well as the formation of plastic hinge are evaluated for ISPS and ISP systems for a typical pile and various soil types and their results are presented. The results show that the lateral capacity is influenced by the parametric study.

KEYWORDS: Interaction of soil-pile-structure system ISPS, Interaction of soil-pile system ISP, Nonlinear analysis, Lateral loading, Lateral capacity, Plastic hinge.

INTRODUCTION

One of the most important studies attracting the interest of structural and geotechnical engineers as well as that of researchers is the study of the interaction between structures and soil under lateral loading. What makes this study difficult is the non-linearity of soils of the basis and the interaction between soil and piles (ISP), whether in the case of static loading or under the event of an earthquake. Numerous researches have used the FEM method as a numerical method to simulate the non-linearity of soil-pile interaction. Various studies found that the interaction between soil and piles (ISP) under horizontal loading relates to pile dimensions, soil characteristics and vertical loading (Mukherjee and Dey, 2019; Khodair and Abdel Mohti, 2014; Hussein Tahghighi and Kazoo Konagai, 2006).

Sahar Ismail et al. (2020) found that engineers should optimize column and raft dimensions if they aim at providing overall structural stability, while they should use bigger raft sizes if they want to reduce the foundation rocking component. Badry et al. (2016) studied the seismic soil-structure interaction of a pile group, comparing the peak responses of a building under fixed base condition and flexible base condition. Others have directed their research to study the response of structures through experiments and numerical studies, such as Patel and Amin (2019), Chang and Kim (2019), Haiyang et al. (2019), Goktepe et al. (2019) and Kildashti et al. (2016).

Visuvasam and Chandrasekaran (2019) worked on the elastic response of a super-structure considering soil–pile–structure interaction using PLAXIS program. The group effect of piles and pile-soil interaction on the seismic response of structures was also

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investigated. Equivalent static analysis of reinforced concrete moment-resisting framed structures resting on sandy soil with various relative densities and pile spacings has been conducted. Results were presented in terms of the most significant design parameters, such as pile lateral displacement, rocking of raft foundation, structural inter-story drifts and story lateral displacements. Hajimollaali et al. (2015) worked on the seismic behavior of pile groups located in soil slopes, also known as pile-slope systems. The main objective of the present study is to explore a reasonable and practical correlation between the safety factor of soil slope and seismic lateral displacements of pile groups in the slope, in order to achieve a better understanding and a framework for seismic analysis and design of pile groups in soil slopes. A decrease in strength and stiffness of soil decreases safety factor of the system and as a result of this decrease, pile group displacements increase. Mohanad Talal Alfach (2019) conducted a detailed analysis of micropiles' parameters and showed a slight effect of pile-micropile spacing. The use of inclined micropiles leads to the attenuation of internal forces induced in the piles and the micropiles themselves.

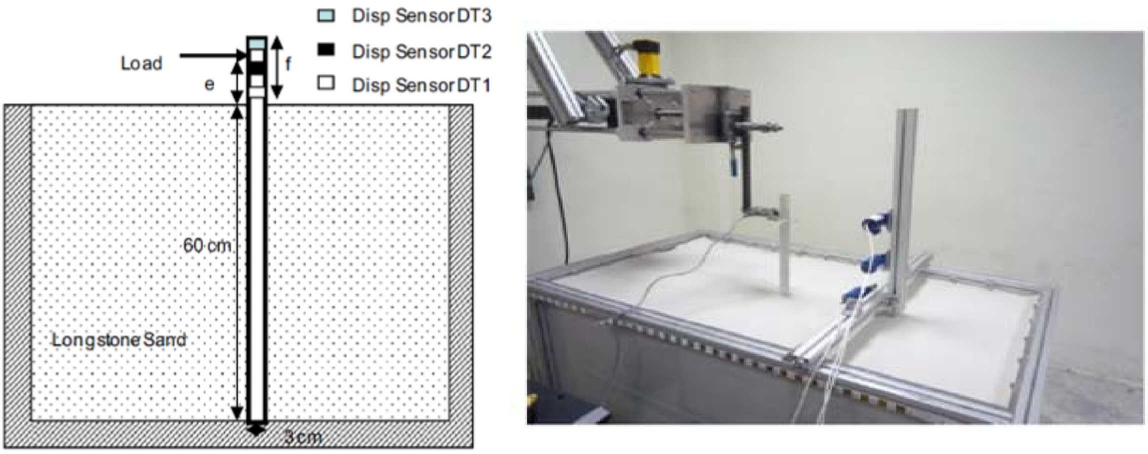
The present study is limited to an equivalent static analysis of a reinforced concrete moment-resisting bridge resting on sandy soil with various relative densities, pile lengths, pile diameters, longitudinal steel ratios and axial force levels. Results were presented in terms of the most significant design parameters, such as lateral capacity of (ISP) and (ISPS) systems, performance point, formation of a plastic hinge, over-strength factor, ductility and response modification factors.

NUMERICAL SIMULATION

Validation of the Model Used in the Numerical Study

Many researchers used SAP2000 software for modeling the behavior of soil-pile interaction. Chau et al. (2009) set up a 2-D finite element model with nonlinear gap elements between pile and soil, using SAP2000 to simulate the shaking table test on a 2×2 pile group embedded in liquefiable soils. Fabrizio et al. (2019) made a comparison between the experimental results obtained from ambient noise measurements on the free-field and the bridge deck and the results obtained from the different numerical models (SAP2000, Abaqus) with the measured dynamic response of the viaduct for evidence of coupled soil-structure interaction and site response in continuous viaducts from ambient vibration tests. Avik et al. (2019) performed a nonlinear time history analysis and the analysis results were compared with the experimental results. They used SAP 2000 software for modeling a single-story steel structure placed on a concrete pile cap with SSI, which is supported by four end bearing concrete piles. They found that the acceleration responses of the structure for both the experimental setup and the FEM model match reasonably well.

Nonlinear analysis of soil-pile interaction, based on the experimental test performed by Kampitsis et al. (2015), was used for validation of the model that was built with SAP 2000. In these tests, a vertical pile is placed in a sand mass of uniform density. Dry unit weight and relative density of the specimen were measured to be γ_s = 16.2 kN/m^3 and Dr = 0.94, respectively. Laboratory results indicated mean values of peak and critical-state angles of φ_p= 56° at very small stress levels (10kPa) and φ_{cv} = 32°, respectively. The material and strength characteristics of the sand have been documented in Anastasopoulos et al. (2010). The single pile was a hollow aluminum 6063-F25 cylinder of 3 cm external diameter, 2.8 cm internal diameter and 60 cm length. The elasticity modulus of the pile is E_0 =70 GPa and the yield stress of the aluminum is 215 MPa. The pile was fixed at the base of the sandbox to ensure verticality during the sand running process. However, its length was sufficiently long for the bending failure (plastic hinge) not to be affected by the tip boundary conditions. The load is applied to the pile at a distance e= 32 cm from the ground surface. The experimental setup is portrayed in Fig.1. For more details on the laboratory testing process, the reader is referred to the studies of Gerolymos (2012) and Giannakos (2013). In Fig. 2, the calculation of lateral force acting at 32 cm above the ground level with the corresponding displacement at the ground surface is obtained from the numerical model and compared with the results obtained from the experiment. It is observed that the tangent stiffness at a low load level is overestimated compared to the experimental result and the ultimate capacities are predicted precisely. One can deduce that the proposed numerical model can be employed providing a minimum calculation effort while retaining good precision for the obtained results for the soil–pile inelastic system (Gasmi Houda, 2018).



(a) (b)

Figure (1): Pushover model setup; (a) geometry and (b) instrumentation

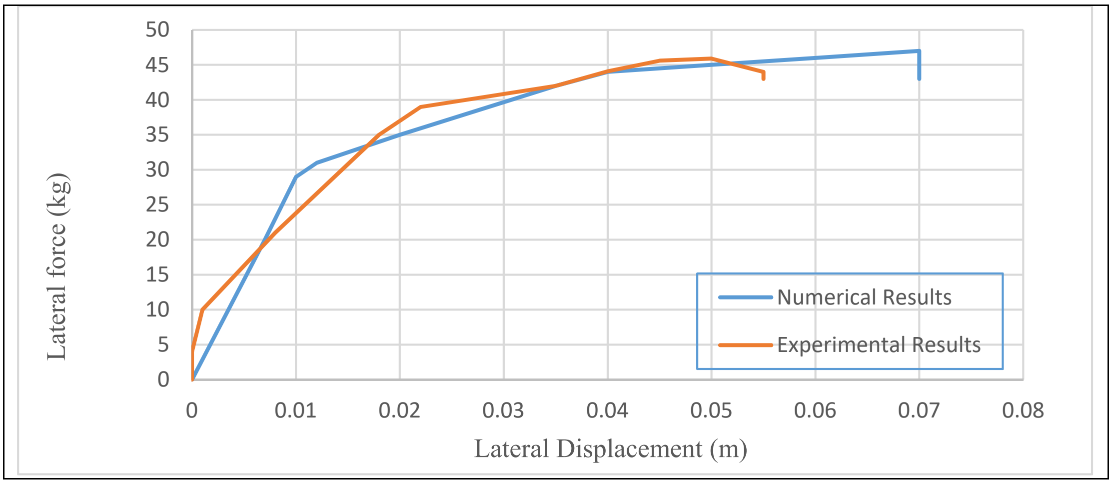


Figure (2): Experimental and numerical force-displacement curves at pile head

NUMERICAL ANALYSIS

Figure 3 shows a single column that extend to 3 m above and 5 m below ground. The column has a uniform section and steel reinforcement. It carries a total weight of 500 kN that is assumed to act at a superstructure of mid-adequate capabilities for the present study. The SAP 2000 software allows for strength and stiffness degradation in the components by providing the force deformation criteria for hinges used in the numerical analyses. The material properties of the structure, piles and soils are given in Tables 1 and 2.

Table 1. Initial stiffness, K_{py} according to Reese, Cox and Koop (1974)

	Loose (φ<30°)	Medium (30°<φ<36°)	Dense (φ>36°)
K_{py} (below water table) (MN/m^3)	5.4	16.3	34
K_{py} (below water table) (MN/m^3)	6.8	24.4	61

Table 2. Pile parameters

Pile diameter, D (m)	Length of pile L (m)	Longitudinal steel ratio
0.5	5	3%

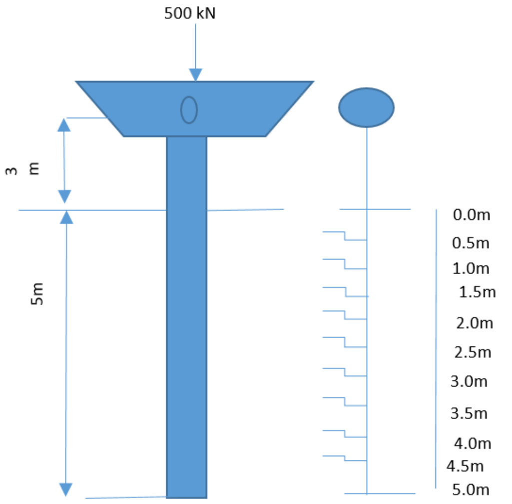


Figure (3): Interaction of soil-pile-structure configuration

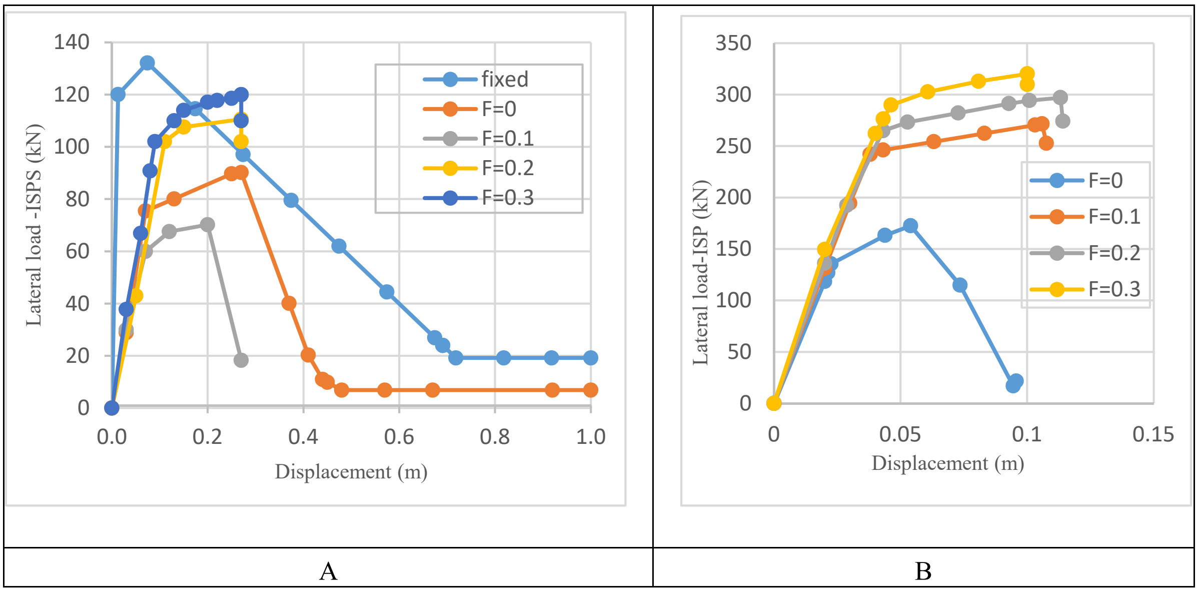
PARAMETRIC STUDY

To evaluate the impact of key parameters on the behavior of ISP and ISPS, different practical values were assumed for these parameters and are listed in Table 3.

Table 3. Parametric cases

Parameter	Axial force, *P/(f_c A_g)*	Pile diameter, D (m)	Longitudinal steel ratio	Length of pile L (m)	Type of soil
Value	0, 0.1, 0.2, 0.3	0.5 m, 0.7 m, 1 m, 1.2 m	3%, 4%, 5%, 6%	5, 7, 10	Loose, Medium, Dense

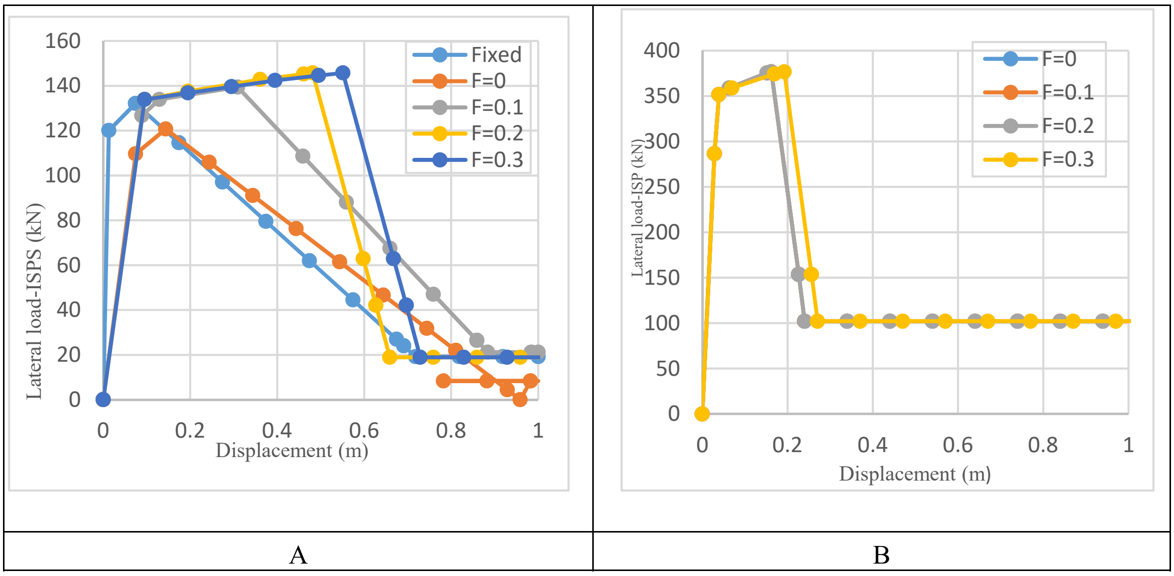
RESULTS AND DISCUSSION



A

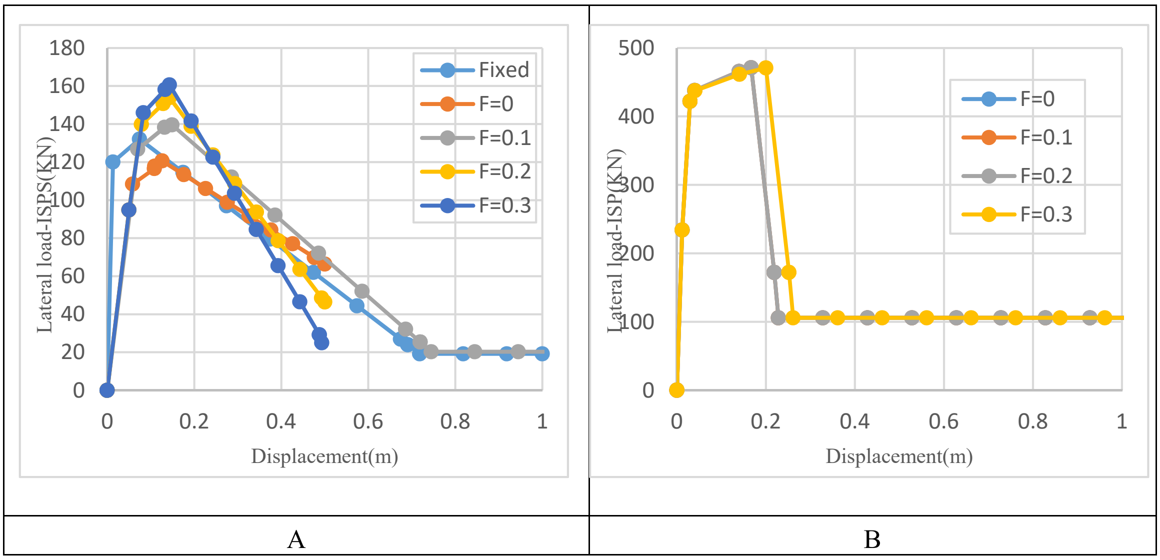
B

Figure (4): Lateral load-displacement behavior of A) ISPS and B) ISP in loose sand



A B

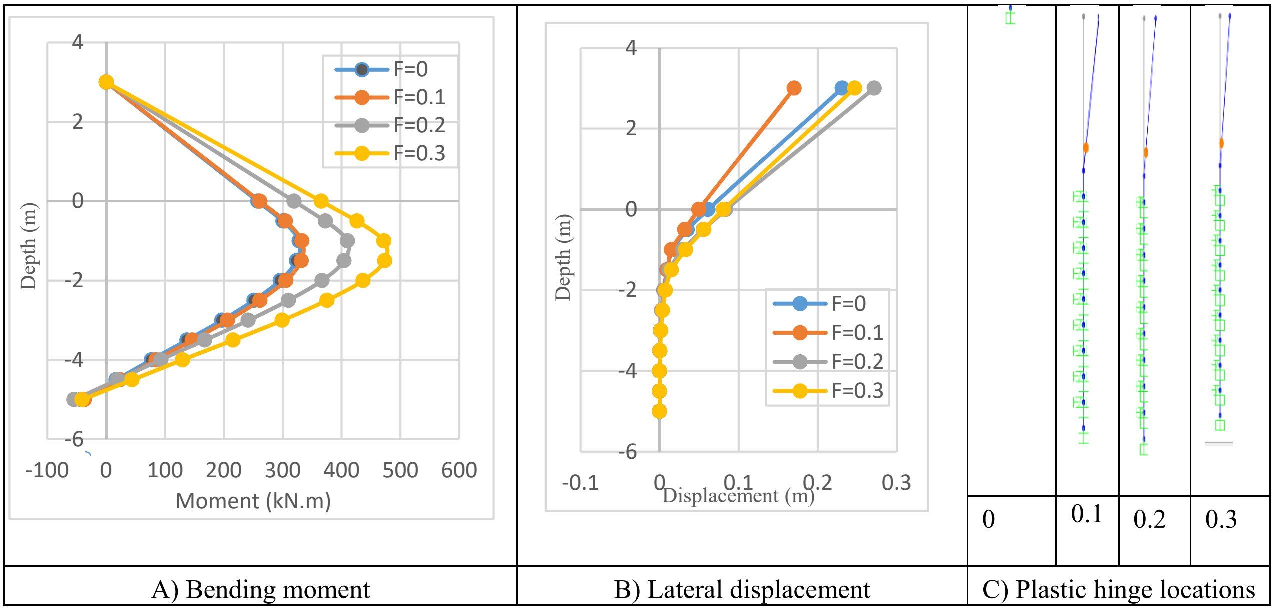
Figure (5): Lateral load-displacement behavior of A) ISPS and B) ISP in medium density sand



A B

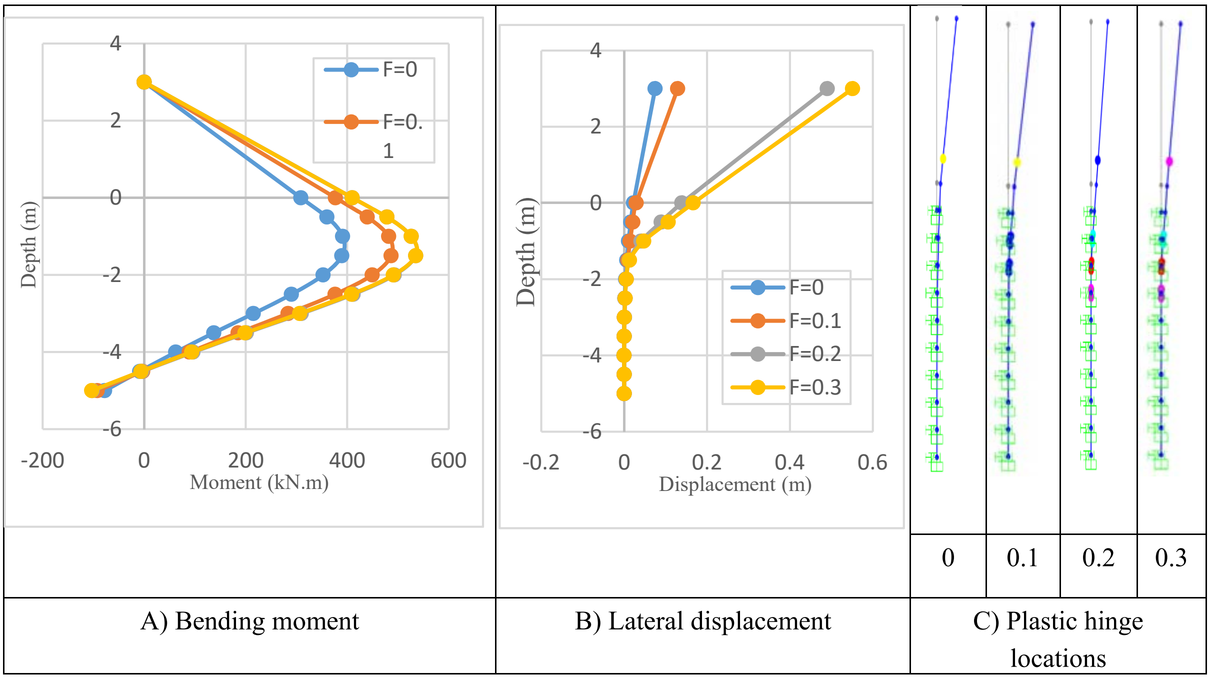
Figure (6): Lateral load-displacement behavior of A) ISPS and B) ISP in dense sand

Figs. 4A, 5A and 6A show lateral load-displacement response for the soil-pile-structure system (ISPS) and Figs. 4B, 5B and 6B show lateral load-displacement behavior for the soil-pile system (ISP) in loose, medium desnity and dense sand, respectively, under the influence of axial load. For piles in loose sand and subjected to a load level of 0.1 and less, the initial stiffness showed similar values for all cases yet the lateral capacity is increased by 83% in ISP system and by 3.3% in ISPS system. Figs. 5 and 6 show that the axial load has only a marginal influence on the lateral capacity response of pile in the case of medium desnity and dense sand in ISP and ISPS system.



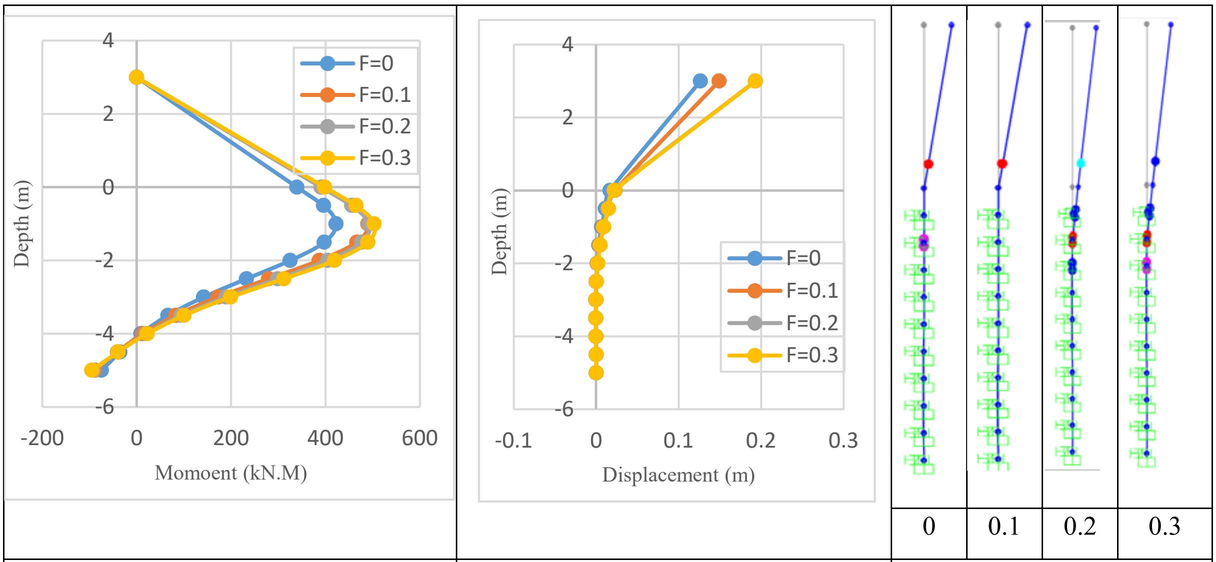
A) Bending moment B) Lateral displacement C) Plastic hinge locations

Figure (7): Behavior of present piles, embedded in loose sand and subjected to varying axial load ratios (F)



A) Bending moment B) Lateral displacement C) Plastic hinge locations

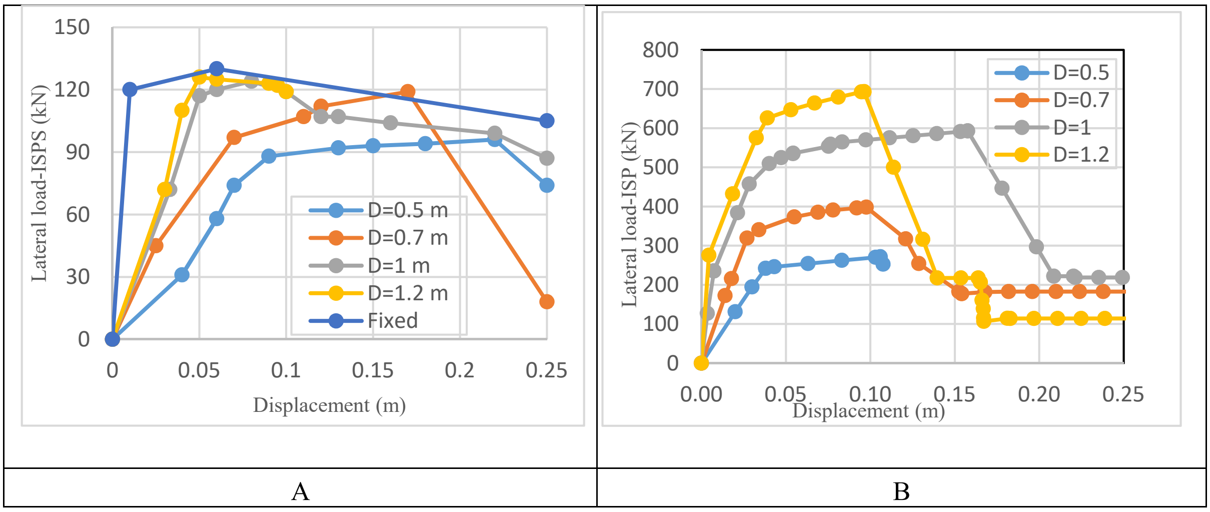
Figure (8): Behavior of present piles, embedded in medium sand and subjected to varying axial load ratios (F)



A) Bending Moment B) Lateral displacement C) Plastic hinge locations

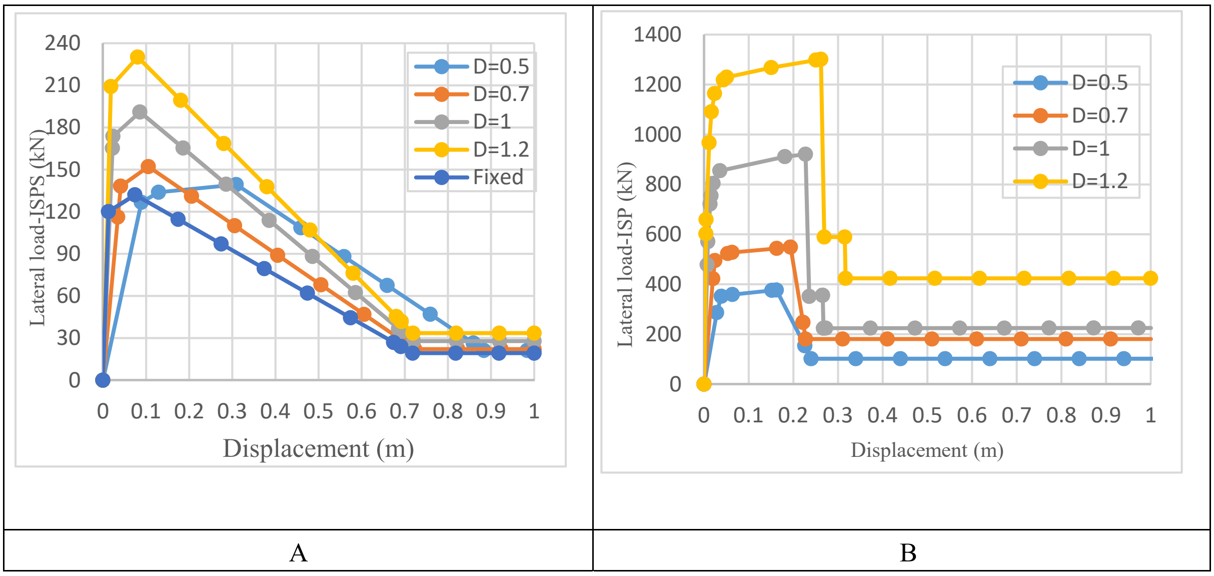
Figure (9): Behavior of present piles, embedded in dense sand and subjected to varying axial load ratios (F)

Figs. 7, 8 and 9 show the distribution of the ultimate bending moment and lateral displacement of the pile for ISPS system for different levels of axial load with different soil types. It can be seen from these figures that the ultimate bending moment is affected by the level of axial load as well as the soil type. Note that the highest loading ratios considered for dense and medium density soils were 0.1 and 0.2, respectively. Moreover, the ultimate displacement increased with the axial force level. The length segments, subjected to the maximum positive bending moment and the negative moment at the end of the pile are not affected by the axial load level. However, the equivalent depth-to-fixity is dependent upon the type of soil without being affect by the magnitude of the axial load. The value of the equivalent depth -to-fixity is 2.5 m, 2 m and 1.75 m for loose sand, medium density and dense sand, respectively. The point of formations of the plastic hinge is affected by the type of sand as well as the axial load. For the case of loose sand, the plastic hinge is formed in the base of the column without being affected by axial load. In the case of medium density and dense sand, the plastic hinge appeared in the base of the column for axial loads equal to 0 and 0.1 yet formed at 1 m from the top of the head of the pile for axial load levels of 0.2 and 0.3.



A B

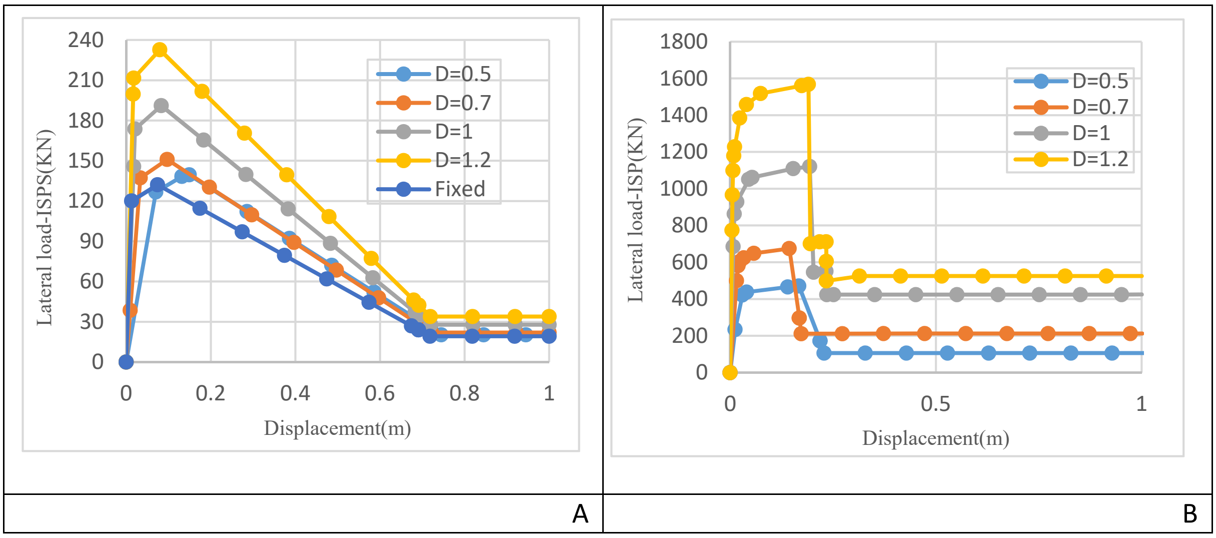
Figure (10): Lateral load-displacement behavior of A) ISPS and B) ISP, in loose sand



A

B

Figure (11): Lateral load-displacement behavior of A) ISPS and B) ISP in medium sand

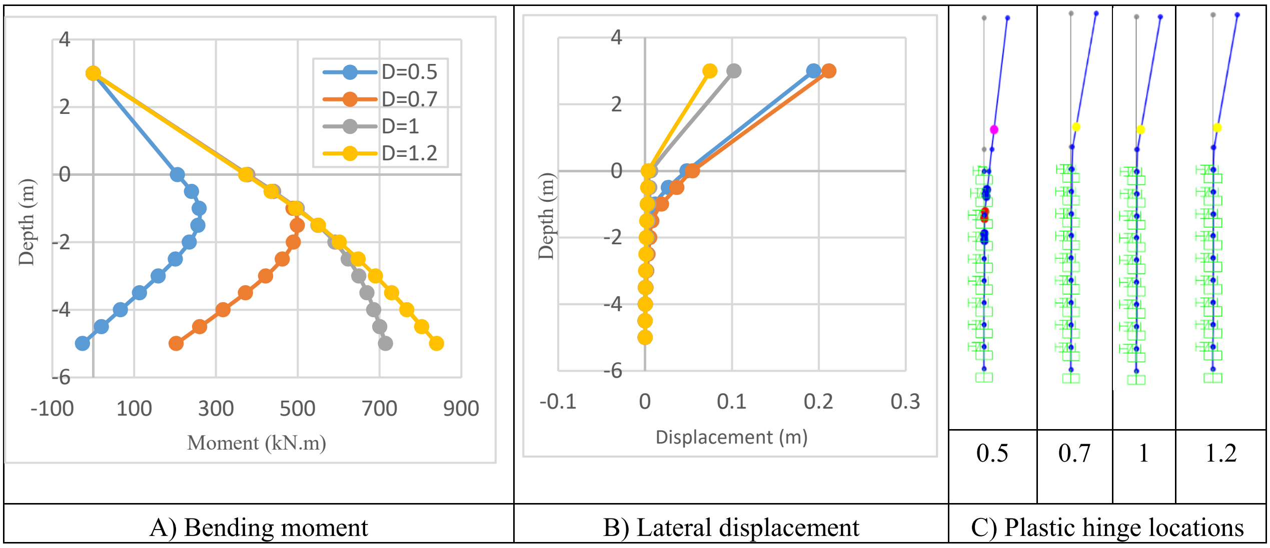


A

B

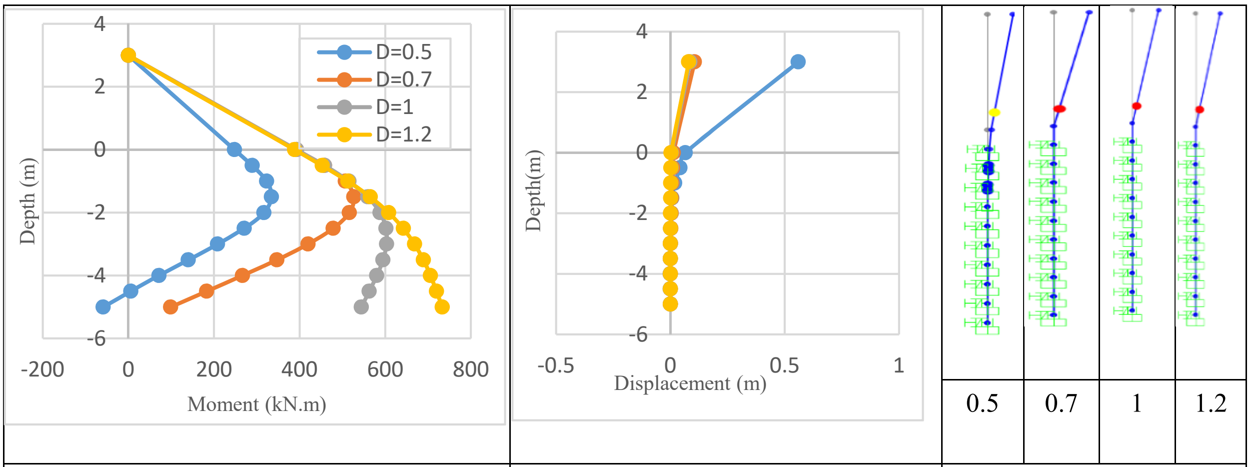
Figure (12): Lateral load-displacement behavior of A) ISPS and B) ISP in dense sand

Figs. 10, 11 and 12 illustrate the curves of (ISPS and ISP), being subjected to the same axial load level and prepared at similar reinforcement ratios yet immersed in different soils at pile diameters of 0.5, 0.7, 1 and 1.2 m. It can be concluded that a larger pile diameter gives a stiffer curve with larger yield and ultimate displacement. The lateral capacity is increased with pile diameter for ISP system, yet is stagnant for ISPS at a pile diameter equal to 1 m. For dense and medium sand, the lateral capacity in ISP and ISPS is increased with pile diameter.



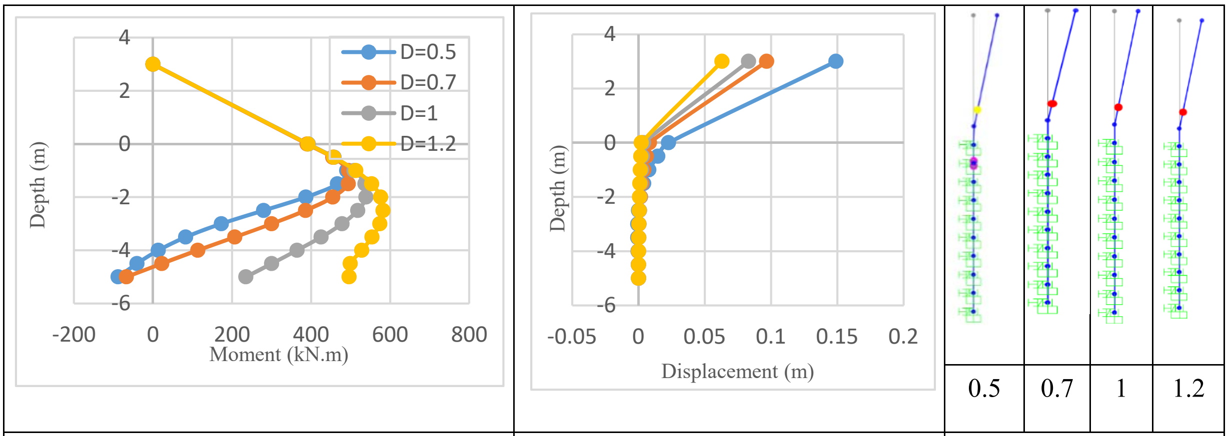
A) Bending moment B) Lateral displacement C) Plastic hinge locations

Figure (13): Behavior of present piles, embedded in loose sand at varying diamters (D)



A) Bending moment B) Lateral displacement C) Plastic hinge locations

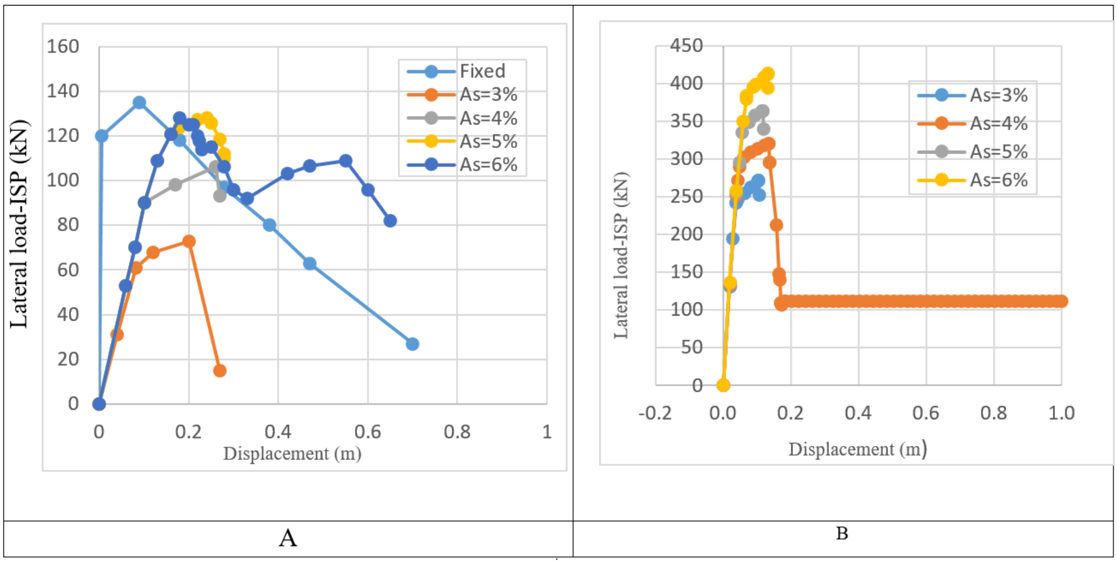
Figure (14): Behavior of present piles, embedded in medium density sand at varying diamters (D)



A) Bending moment B) Lateral displacement C) Plastic hinge locations

Figure (15): Behavior of present piles, embedded in dense sand at varying diamters (D)

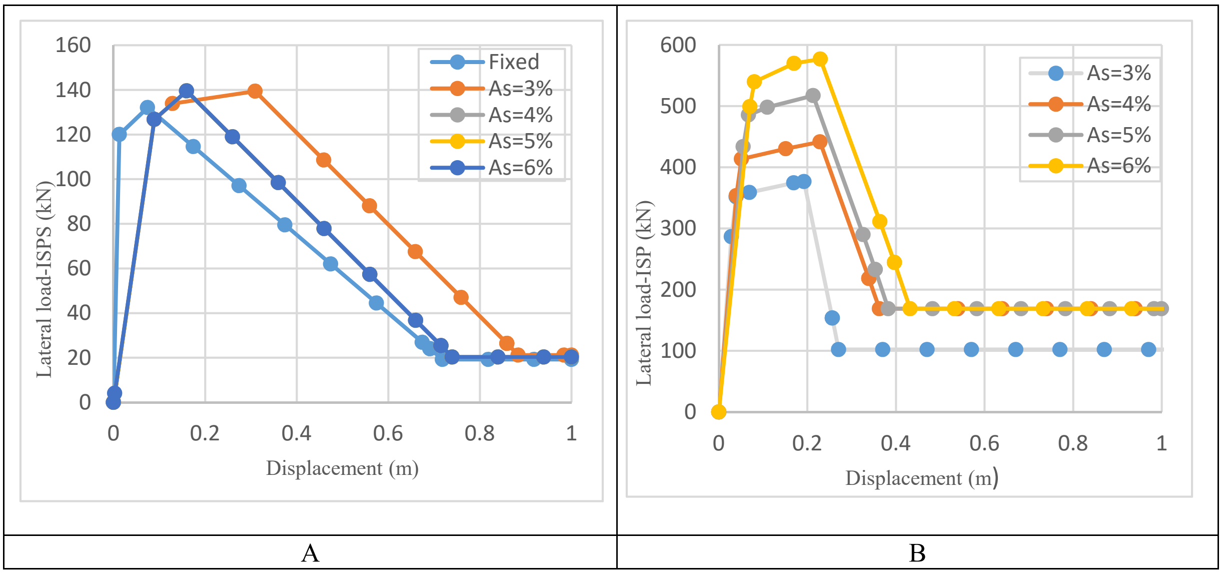
Figs. 13, 14 and 15 show the distribution of bending moment and lateral displacement of the piles within ISPS for different pile diameters with soil types. According to these figures, when the pile diameter is increased, the bending moment and the ultimate displacement are decreased. The length of segments for ultimate positive bending moment and the negative moment are affected by the pile diameter. The positions of the plastic hinge are affected by the increase in the pile diameter in loose sand but not so in dense and medium density sands.



A

B

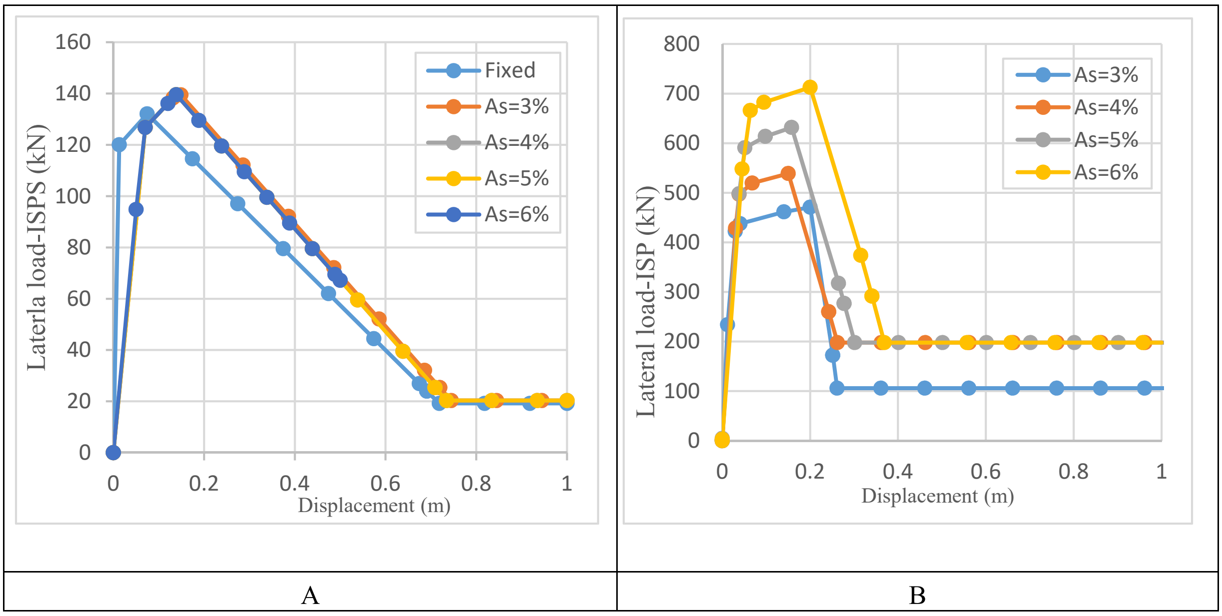
Figure (16): Lateral load-displacement behavior of A) ISPS and B) ISP in loose sand



A

B

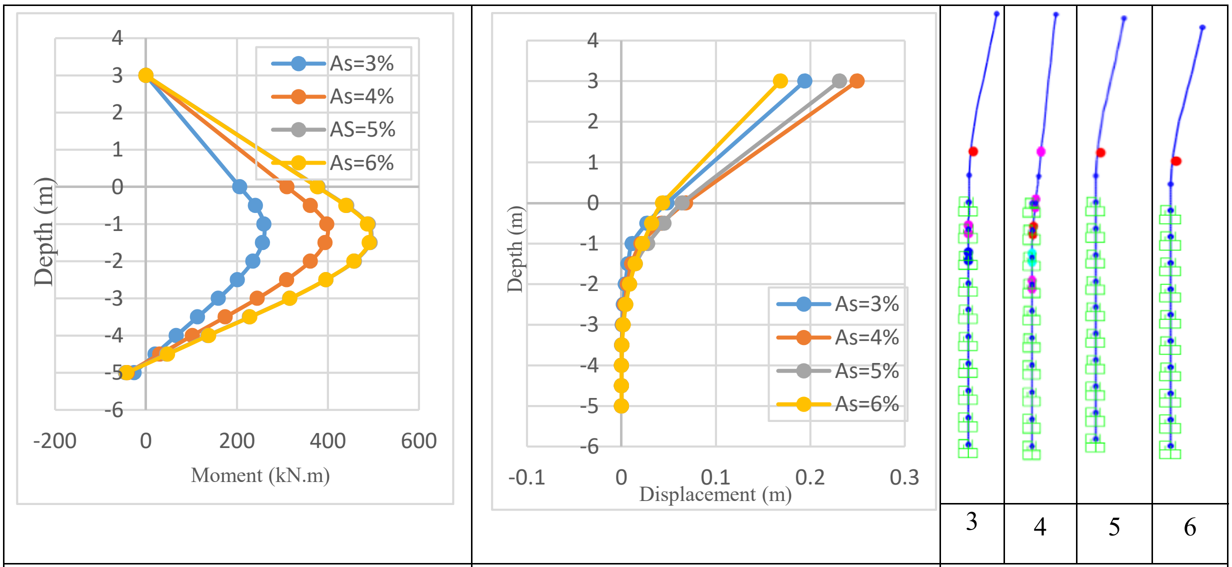
Figure (17): Lateral load-displacement behavior of A) ISPS and B) ISP in medium density sand



A B

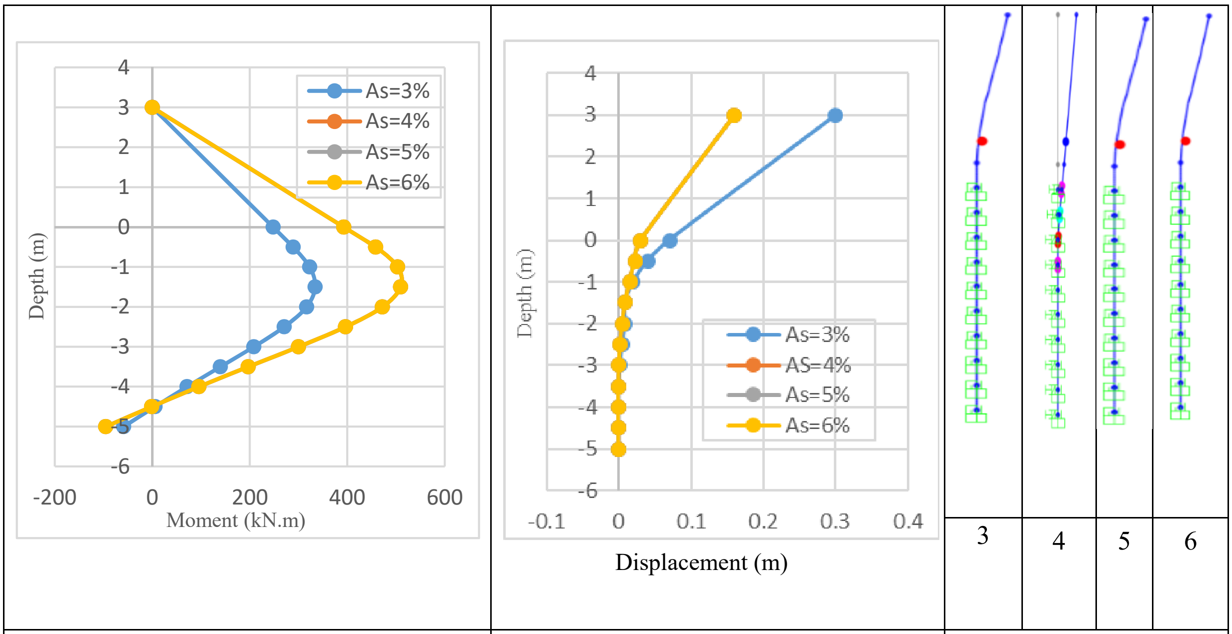
Figure (18): Lateral load-displacement behavior of A) ISPS and B) ISP in dense sand

Figs. 16, 17 and 18 illustrate the lateral capacity in the two systems (ISPS and ISP) under the effect of longitudinal steel ratio ($A_s = 3\%, 4\%, 5\%$ and 6%) with different sand types (loose, medium density and dense). For higher longitudinal steel ratio, the lateral capacity was enhanced in ISP regardless of the type of soil but not so for ISPS; especially in medium density sand. Moreover, the lateral capacity showed close values for ISPS in loose sand for reinforcement ratios at 3 and 4% as well as for those at 5 and 6%.



A) Bending Moment B) Lateral displacement C) Plastic hinge locations

Figure (19): Behavior of present piles, embedded in loose sand and subjected to varying longitudinal steel ratio (As)

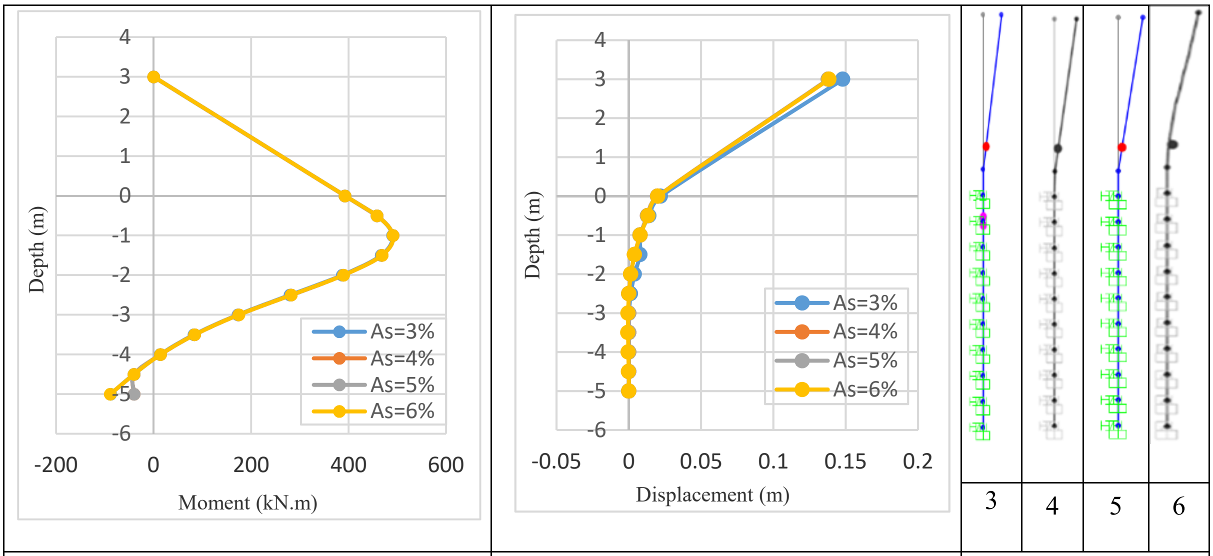


A) Bending moment

B) Lateral displacement

C) Plastic hinge locations

Figure (20): Behavior of present piles, embedded in medium density sand and subjected to varying longitudinal steel ratio (As)



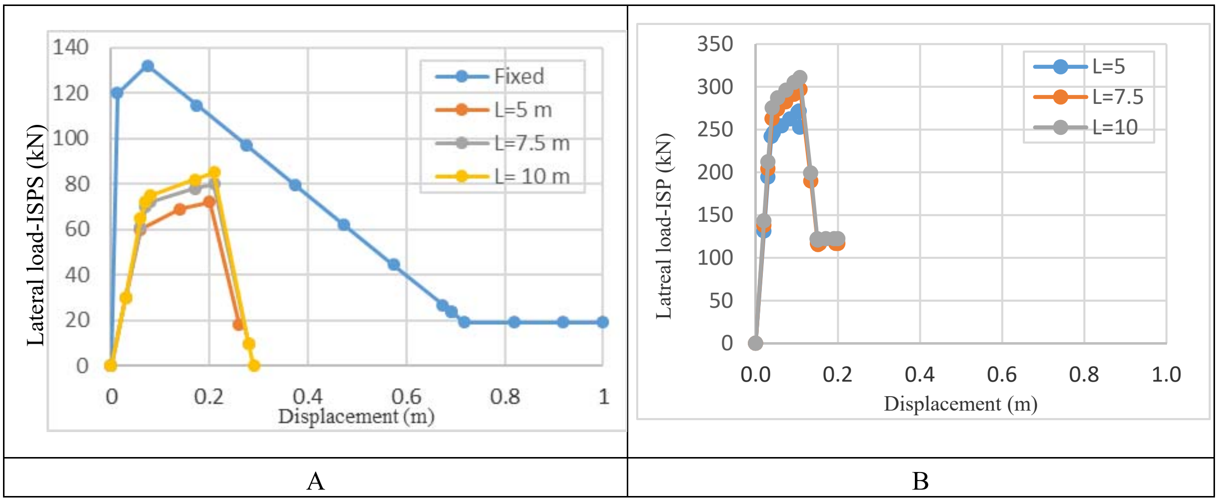
A) Bending moment

B) Lateral displacement

C) Plastic hinge locations

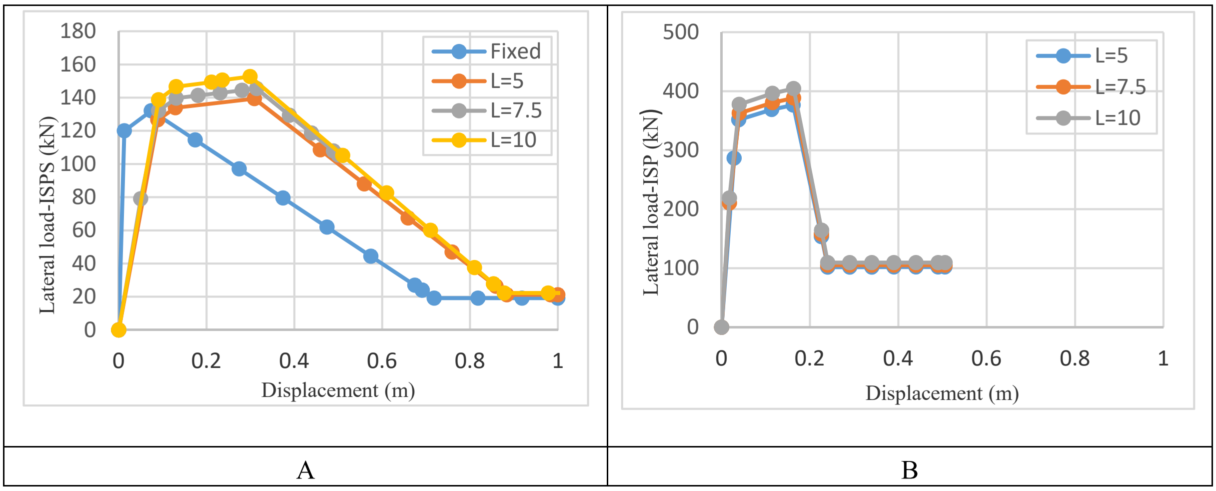
Figure (21): Behavior of present piles, embedded in dense sand and subjected to varying longitudinal steel ratio (As)

Figs. 19, 20 and 21 show the distribution of the ultimate bending moment and lateral displacement of ISPS of piles prepared at different longitudinal steel ratios and immersed in different soil types. The percentage of increase in both ultimate bending moment and the lateral displacement with higher reinforcement ratio depended upon the type of the soil. The ultimate bending moment for piles in the loose sand was stagnated; especially for close reinforcement ratios at 5% and 6% yet that of piles in sands of medium and high density were not affected by reinforcement ratios. The lateral displacements are increased with higher reinforcement ratio only when the piles are immersed in loose sand. The deflected shapes for the piles presented in Figs. 19-21 (C) indicated that the plastic hinge location and hence the equivalent depth-to-fixity was influenced by the type of soil rather reinforcement ratio of the piles.



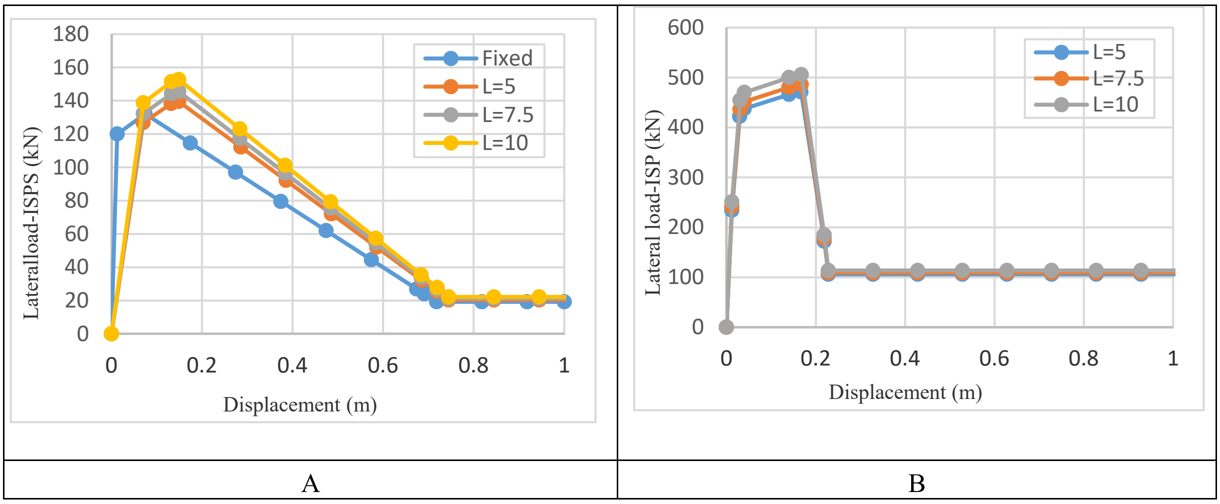
A B

Figure (22): Lateral load-displacement behavior of A) ISPS and B) ISP in loose sand



A B

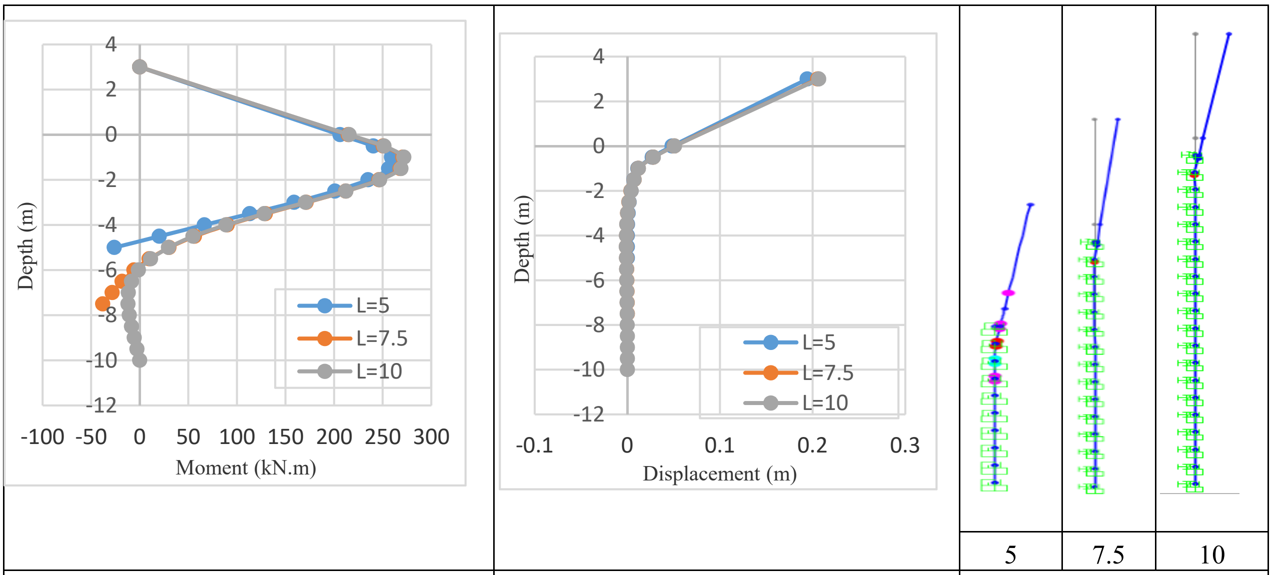
Figure (23): Lateral load-displacement behavior of A) ISPS and B) ISP in medium sand



A B

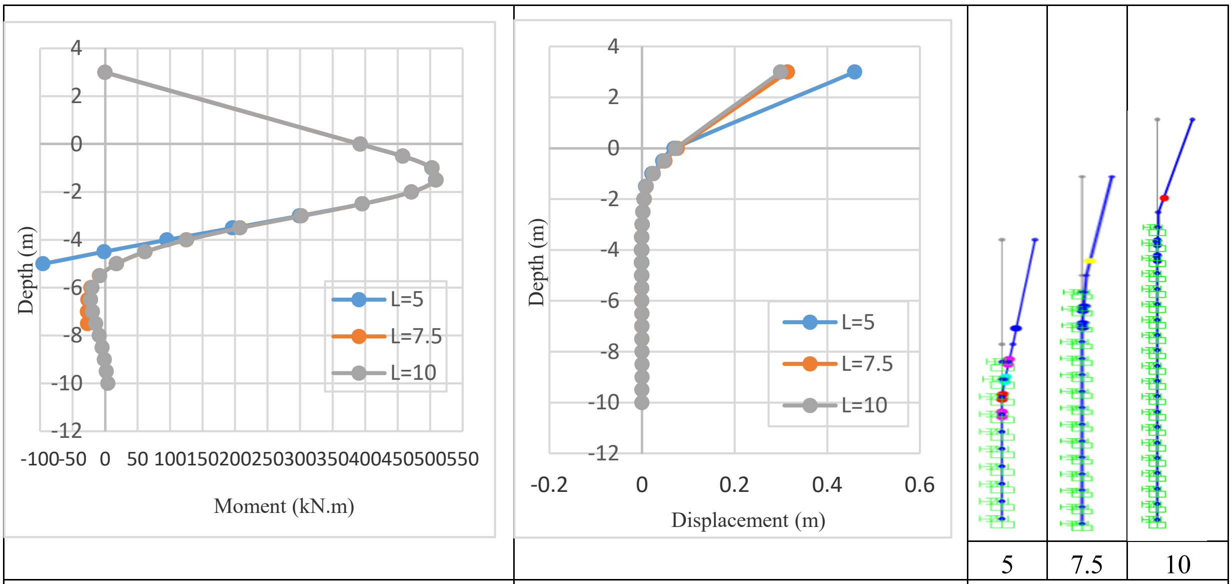
Figure (24): Lateral load-displacement behavior of A) ISPS and B) ISP in dense sand

Figs. 22, 23 and 24 show the lateral capacity in the two studied systems (ISPS and ISP) for different piles' length ($L = 5\ m, 7.5\ m\ and\ 10\ m$) with the different sand types (loose, medium density and dense). Regardless of the type of the soil, the lateral capacity was increased with pile length.



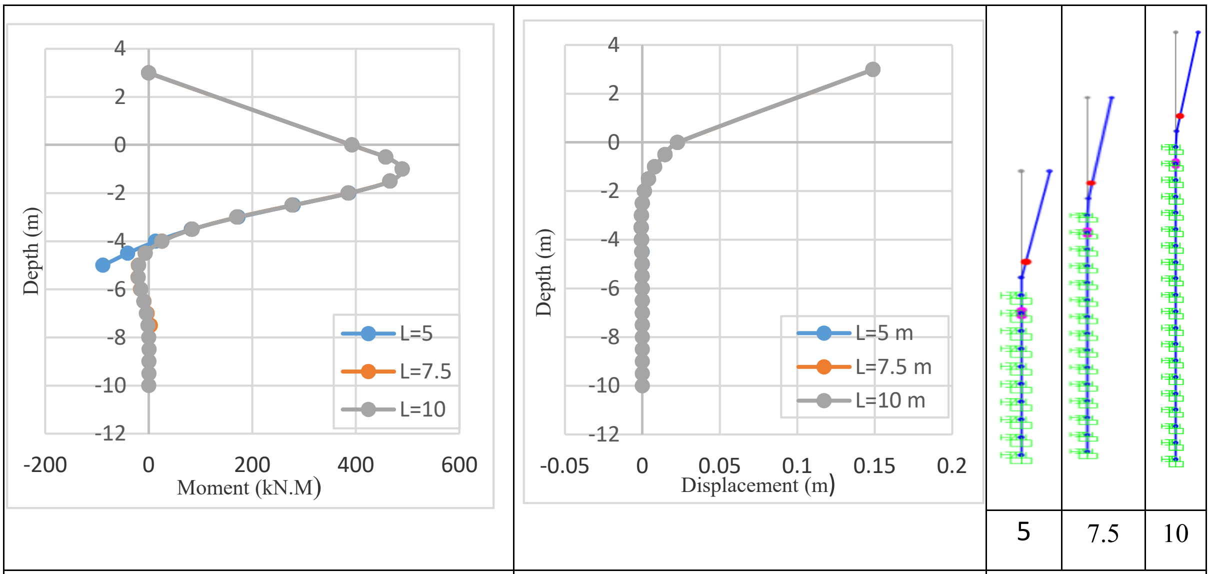
A) Bending moment | B) Lateral displacement | C) Plastic hinge locations

Figure (25): Behavior of present piles, embedded in loose sand and subjected to varying length of pile (L)



A) Bending moment | B) Lateral displacement | C) Plastic hinge locations

Figure (26): Behavior of present piles, embedded in medium sand and subjected to varying length of pile (L)



A) Bending moment

B) Lateral displacement

C) Plastic hinge locations

Figure (27): Behavior of present piles, embedded in dense sand and subjected to varying length of pile (L)

Figs. 25, 26 and 27 show the distribution of ultimate bending moment, lateral displacement and position of plastic hinge for ISPS for different lengths of the pile and soil types. The ultimate bending moment and the lateral displacement are not affected by the increase in the length of the pile regardless of the sand type. However, the location of the plastic is influenced by the pile length as well as the type of the soil. The equivalent depth - to-fixity is not affected by the type of sand and the increase in the pile length.

CONCLUSIONS

The following conclusions are drawn from the analysis of static nonlinear soil-pile-structure interaction and soil-pile interaction. These conclusions can be made related to the influence of the axial force, pile diameter, longitudinal steel ratio, length of pile and type of soil:

- In most cases, the lateral capacity of the fixed system is lower compared to the lateral capacity in the ISPS system when increasing the axial load, pile diameter, longitudinal steel ratio and length of the pile in all types of sand.
- Axial load and type of sand influence the lateral capacity in the ISP system more than in the ISPS system. The pile diameter in ISPS and ISP systems influences the lateral capacity. The longitudinal steel ratio influences the lateral capacity in the ISP system, but in the ISPS system, its effect appears just in loose sand. The lateral capacity is not influenced by the length of the pile.
- The ultimate bending moment and the lateral displacement at the top of the column increase with the increase in axial load, longitudinal steel ratio, but are not affected by the augmentation in the length of the pile.

Also, the equivalent depth-to-fixity is affected by the increase in the pile diameter and the type of sandy soil. The formation and the position of plastic hinges are affected by the type of sand, axial load level, pile diameter, longitudinal steel ratio and length of the pile.

REFERENCES

Anastasopoulos, I., Georgarakos, P., Georgiannou, V., Drosos, V., and Kourkoulis, R. (2010). "Seismic performance of bar mat-reinforced soil retaining wall: shaking table testing *versus* numerical analysis with modified kinematic hardening constitutive model". Soil Dynamics and Earthquake Engineering, 30, 1089-1105.

Avik Samanta, and Arabinda Swain. (2019). "Seismic response and vulnerability assessment of representative low-, medium- and high-rise buildings in Patna". Structures, 19, 110-127.

Badry, P., and Satyam, N. (2016). "An efficient approach for assessing the seismic soil-structure interaction effect for the asymmetrical pile group". Innov. Infrastruct. Solut. J., Springer. Doi: 10.1007/ s41062-016-0003-1.

Chang, M., and Kim, J.K. (2019). "Pseudo-dynamic test for soil-structure interaction analysis using shake tables". KSCE J. Civ. Eng., 10, 15-20. Https://doi.org/ 10.1007/s1220 5-019-1631-8.

Chau, K.T., Shen, C.Y., and Guo, X. (2009). "Nonlinear seismic soil-pile-structure interactions: shaking table tests and FEM analyses". Soil Dyn. Earthq. Eng., 29 (2), 300-310.

Chiou, J.S., and Chen, C.H. (2010). "Displacement ductility capacity of fixed-head piles". Proceedings of 5th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Missouri University of Science and Technology, Rolla, MO, 9-10.

Chiou, J. S., Tsai, Y. C., and Chen, C. H. (2012). "Investigating influencing factors of the ductility capacity of a fixed-head reinforced concrete pile in homogeneous clay". Journal of Mechanics, 28 (3), 489-498.

Fabrizio Garaa, Marco Regnia, Davide Roiab, Sandro Carbonaria, and Francesca Dezib. (2019). "Evidence of coupled soil-structure interaction and site response in continuous viaducts from ambient vibration tests". Soil Dynamics and Earthquake Engineering, 120, 408-422.

Gasmi Houda, Bouzid Tayeb, and Yahiaoui, D. (2018). "Key parameters influencing performance and failure modes for soil–pile–structure system interaction under lateral loading". Asian Journal of Civil Engineering. https://doi.org/10.1007/s42107-018-0033-4.

Gerolymos, N. (2012). "A macro-element model for nonlinear static and dynamic response of piles". Technical Report for PEVE 2008 Research Project (Contract Number 65/1694). Laboratory of Soil Mechanics, NTUA.

Giannakos, S. (2013). "Contribution to the static and dynamic lateral response of piles". (Doctoral Dissertation, National Technical University of Athens, 2013).

Goktepe, F., Celebi, E., and Omid, A.J. (2019). "Numerical and experimental study on scaled soil-structure model for small shaking table tests". Soil Dyn. Earthq. Eng., 119, 308-319.

Haiyang, Z., Jisai, F., Xu, Y., Su, C., and Xiaohui, C. (2019). "Earthquake responses of a base-isolated structure on a multi-layered soft soil foundation by using shaking table tests". Eng. Struct., 179, 79-91.

Hajimollaali, H., Elahi, H., and Sabermahani, M. (2015). "A study on correlation between safety factor of pile-slope systems and seismically-induced displacements of pile groups". Jordan Journal of Civil Engineering, 9 (3), 371-380.

Hussein Tahghighi, and Kazoo Konagai. (2007). "Numerical analysis of nonlinear soil-pile-group interaction under lateral loads". Soil Dynamics and Earthquake Engineering, 27, 463-474.

Kampitsis, A. E., Giannakos, S., Gerolymos, N., and Sapountzakis, E. J. (2015). "Soil-pile interaction considering structural yielding: numerical modeling and experimental validation". Engineering Structures, 99, 319-333.

Karthigeyan, S., Ramakrishna, V.V.G.S.T., and Rajagopal, K. (2006). "Influence of vertical load on the lateral response of piles in sand". Computers and Geotechnics, 33 (2), 121-131.

Karthigeyan, S., Ramakrishna, V.V.G.S.T., and Rajagopal, K. (2007). "Numerical investigation of the effect of vertical load on the lateral response of piles". Journal of Geotechnical and Geoenvironmental Engineering, 133 (5), 512-521.

Khodair, Y., and Abdel-Mohti, A. (2014). “Numerical analysis of soil-pile interaction under axial and lateral loads”. International Journal of Concrete Structures and Materials, 8 (3), 239-249.

Kildashti, K, Dolatshahi, K.M., and Mirghaderi, R. (2016). “A case study on the pile–soil–structure interaction of a long-span arched structure”. Struct. Infrastruct. Eng., https://doi.org/10.1080/15732 479.2016.11536 65.

Meyer, B.J., and Reese, L.C. (1979). “Analysis of single piles under lateral loading”. Preliminary Review Copy, Research Report 244-1, Center for Highway Research, The University of Texas at Austin, Austin, Texas, 1-145.

Mohanad Talal Alfach. (2019). “Reinforcement of the seismic interaction of soil-damaged piles-bridge by using micropiles”. Jordan Journal of Civil Engineering, 13 (2), 197-213.

Mukherjee, S., and Dey, A. (2019). “Analysis of laterally loaded fixed-headed single pile in multilayered soil using P-Y approach geotechnical applications”. Lecture Notes in Civil Engineering 13, https://doi.org/10.1007/978-981-13-0368-5_5 Springer Nature Singapore Pte, Ltd.

Patel, K.N., and Amin J.A. (2018). “Performance-based assessment of response reduction factor of RC-elevated water tank considering soil flexibility: a case study”. Int. J. Adv. Struct. Eng., 10, 233-247.

Reese, L.C., Cox, W.R., and Koop, F.D. (1974). “Field testing and analysis of laterally loaded piles in sand”. Proceedings of the VI Annual Offshore Technology Conference, Houston, Texas, 2 (OTC 2080), 473-485.

Reese, L.C., Cox, W. R., and Koop, F. D. (1974). “Analysis of laterally loaded piles in sand”. Proceedings of 6th Offshore Technology Conference, Houston, Texas. 2, 473-483.

Sahar, I., Kaddah, F., and Raphael, W. (2020). “Seismic soil structure interaction response of mid-rise concrete structures on silty sandy soil”. Jordan Journal of Civil Engineering, 14 (1), 117-135.

SAP2000, Version 8. (2002). “Basic analysis reference”. Computers and Structures, Inc., Berkeley.

Tahghighi, H., and Konagai, K. (2005). “Impedance-based winkler spring method for soil-pile interaction analysis”. Jpn. Soc. Civ. Eng. (JSCE), J. Earthquake Eng., 28[CD-ROM].

Visuvasam, J., and Chandrasekaran, S.S. (2019). “Effect of soil–pile–structure interaction on seismic behavior of RC building frames”. Innovative Infrastructure Solutions, https://doi.org/10.1007/s41062-019-0233-0.