The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
 ISBN 978-0-367-14328-2

Numerical modeling of the offshore wind turbine monopile foundation under environmental loading

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ABSTRACT: Prediction of dynamic performance of an offshore wind turbine requires consideration of many different design parameters. Beside the superstructure, foundation also plays an important role both functionally and financially in their design. In this study, numerical dynamic analysis of an offshore wind turbine with a monopile foundation is performed under wave action that may lead to liquefaction around pile diameter due to the cyclic stresses induced by the pile displacements. The effects of foundation characteristic such as monopile diameter and its embedment depth are investigated. The results in terms of displacements, excess pore water pressure, and inertial forces are presented and discussed. Findings are considered to give better estimation of the dynamic performance and liquefaction susceptibility of the offshore wind turbines foundations under cyclic loads induced by the pile displacements.

1 INTRODUCTION

The interest in wind energy has been growing all over the world since it is a sustainable option in pursuit of renewable energy. Due to higher wind speeds and open areas, offshore wind farms are becoming widespread to provide renewable energy in Northern European countries. The EU capacity is predicted to grow to 150 GW by 2030 (Haiderali and Madabhushi 2013).

Offshore wind turbines (OWTs) are critical structures because of their economic impacts and vital role in renewable sustainable energy industry. Therefore, having a better understanding of the performance of these structures under various loading conditions is a necessity. Structural performance of superstructure of offshore wind turbines has been widely studied, but studies focusing on their foundation behavior are rather limited. The high amount of wave and wind loads during the lifetime of these structures can be critical on the performance of the offshore wind turbine foundations. To properly evaluate effects of environmental loads on performance of wind turbines, soil-pile-structure coupled effects need to be considered. Liquefaction possibility around the pile foundation is a phenomenon that has been studied mostly under seismic motion by different researchers (Chang et al. 2013). Although seismic motion is a random dynamic load, most of the liquefaction studies in geotechnical laboratory tests are performed under cyclic load which has the similar nature as a sea-wave load. In this regard, the liquefaction susceptibility under wave cyclic loads is investigated in this study according to the monopile structural properties (Erken et al. 1995, Corciulo et al. 2017). This investigation under the action of wave cyclic loads is a need according to the increase of interest for installation of these structures in seismically prone areas. Because offshore wind turbines are generally installed on monopile foundations, this foundation type is investigated in the present study (Byrne et al. 2017). The effect of monopile diameter and the monopile embedment depth are the factors that are investigated under wave loads by considering soil-monopile-structure interaction in the present study. Two pile dimeters namely 3 m and 5 m piles were considered with embedment depths of 20 m and 15 m. In the first part, the effect of monopile diameter with the constant 20 m pile embedment depth and in the second part the effect of pile embedment depth for 5 m diameter monopile are investigated.

2 NUMERICAL MODELING AND ANALYSIS

In the present study, numerical analyses are performed using open source finite element software OPENSEES, capable of analyzing both structural and geotechnical systems subjected to dynamic motions and loads (Mazzoni et al. 2010).

2D dynamic fully coupled u-p analysis (considering coupling effect of solid deformation and pore water pressure) is performed for the soil-monopile-structure system. The Pressure Dependent Multi Yield material defined as a soil constitutive model by Yang et al. and implemented in OPENSEES is adopted in this study (Yang 2000, Chang et al. 2013, Mazzoni et al. 2010). In order to choose the appropriate parameters for the mentioned constitutive model and generate realistic soil response, the calibrated values defined by previous researchers by verification of the model parameters with undrained cyclic simple shear test, are considered for the sandy soil layer (Karimi and Dashti 2016). The 9-4 quad u-p element (9 nodes for solid deformation and 4 corner nodes for pore water pressure determination) is considered to capture the pore water pressure generation which is the critical issue in liquefaction studies. Soil properties at the location of wind turbine assumed for this study are presented in Table 1.

In this study, the prototype wind turbine was located at a water depth of 20 m and it was supported with a monopile foundation as shown in Figure 1-a. Free Field Analysis (FFA) is the first step of analysis. In this regard, the soil medium is modeled by using the previously mentioned material properties and the appropriate elements to consider the pore water pressure

Table 1. Soil properties for Nevada sand.

Soil unit weight (kN/m^3)	Friction angle (°)	Phase transformation angle (°)	Shear modulus (kPa)	Relative Density (%)
20	34,5	26,5	72500	63

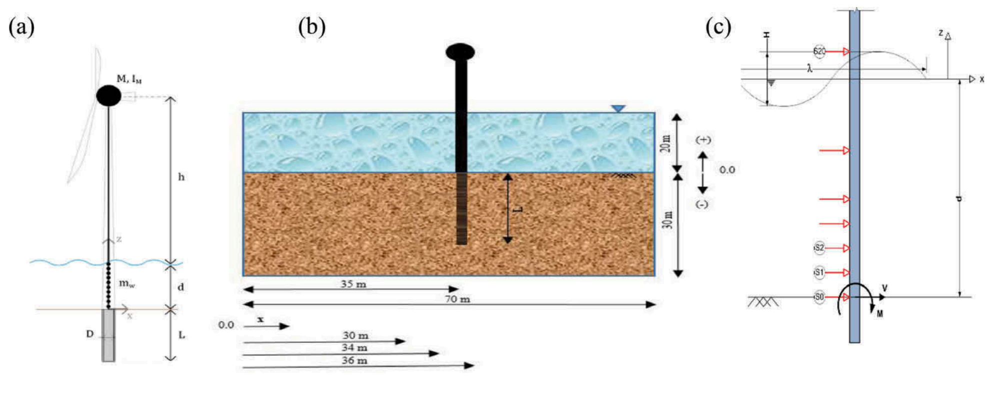

Figure 1. a) Schematic view for the reference offshore wind turbine (Corciulo et al. 2017). b) Schematic view of the problem. c) Wave force application (Massah Fard et al. 2018).

(PWP) generation in the domain. The free field boundary condition is assumed and the gravity analysis is obtained in this step for the problem. The schematic view of the problem for numerical modeling and the wave force application are presented in Figure 1-b and c. In the second step, the embedded monopile foundation is installed in the soil medium. The parameters for the 5 MW reference offshore wind turbine such as the mass of the rotor and nacelle, height of the wind turbine and seawater depth are considered in the present study. The soil-pile interaction effect is captured through the modified soil elements (Corciulo et al. 2017). The viscous boundary conditions are assumed for the base and the lateral boundaries by definition of Lysmer-Kuhlemeyer (1969) dashpots through zero-length elements (Mazzoni et al. 2010). The properties for the offshore wind turbine, foundation and seawater are presented in Table 2.

In the last step of modeling, the tower is installed. The tower modeling has two parts; the first section is below the seawater level and the second section is above the seawater level. The seawater effect is evaluated in the model by defining mass for the parts of the tower below the seawater level according to the literature reviews (Corciulo et al. 2017). After installation of the soil, monopile foundation, OWT tower, and consideration of the boundary conditions, the gravity analysis of the whole structure by considering soil-monopile-structure interaction is investigated. For consideration of the lateral hydrodynamic loads on the structure, two cases for wave loading with 9 sec wave period which is typical for North Sea (Nikitas et al. 2017) were applied for the liquefaction analysis of monopile-soil system. A summary of these cases as shown in Figure 1-c is given in Table 3. For dynamic wave load application, the viscous boundary conditions are considered at the base and lateral boundaries of the soil domain to damp out outgoing waves.

The wave loading on the monopile was estimated using linear wave theory, which is also referred as small amplitude wave theory, sinusoidal wave theory or Airy theory (DNV 2010). The estimated wave loading on the pile was calculated from water particle velocity and acceleration determined using DNV-RP-C205 (DNV 2010). The term of application is by summation of the applied shear loads and moments at the top point of the monopile foundation. The hydrodynamic force acting on each strip was calculated using Morrison's theory for fixed structures in waves and current using Equation 1:

$$f(t) = \rho(1 + C_A)A\dot{v} + 1/2\rho C_D Dv|v| \tag{1}$$

where, ρ is mass density of fluid, C_A is added mass coefficient, C_D is drag coefficient, A *is* cross-sectional area, $\dot{v}$ is fluid particle acceleration, v is fluid particle velocity, and D is diameter of cross-section. Typical added mass and drag coefficient values of 0.6 and 1.0 were assumed, respectively. The corresponding total shear load and bending moment are applied to the monopile and are presented in Figure 2 for Case-1 and Case-2.

According to the graphs, it is obvious that according to the direct effect of the pile diameter on the wave force, the shear load and moment taken from the wave force to be applied at the monopile head are lowered by decreasing the monopile diameter.

Table 2. Reference offshore wind turbine parameters (Corciulo et al. 2017).

h (m)	d (m)	L (m)	D (m)	ρ_s (ton/m^3)	E_s (GPa)	A_{sec} (m^2)	I_{sec} (m^4)	M (ton)
90	20	20	5	7,85	200	0,777	2,38	350

Table 3. Wave loading cases for different pile diameter.

Wave Loading Cases	Period T (sec)	Wave length λ (m)	Still water level d (m)	Max. breaking wave height H (m)	Pile diameter D (m)
Case-1	9	105	20	12,4	5,0
Case-2	9	105	20	12,4	3,0

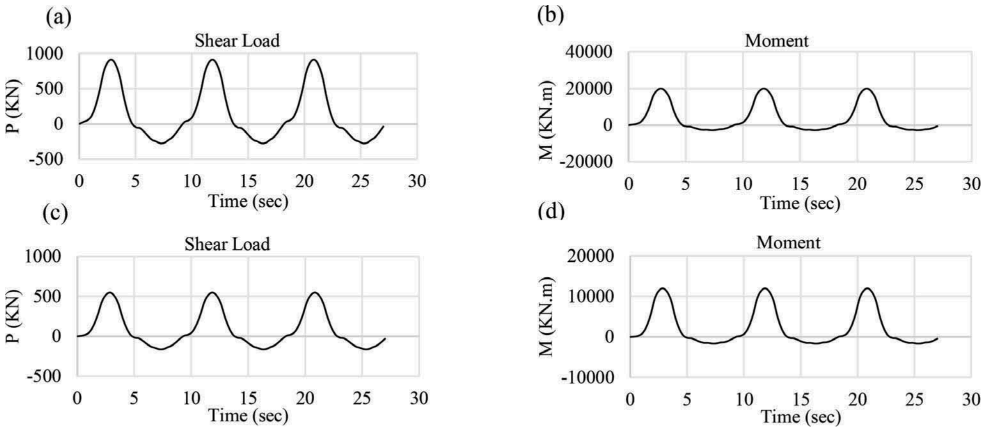

Figure 2. a, b) Shear load and moment for Case-1 (5 m diameter) c, d) Shear load and moment for Case-2 (3 m diameter).

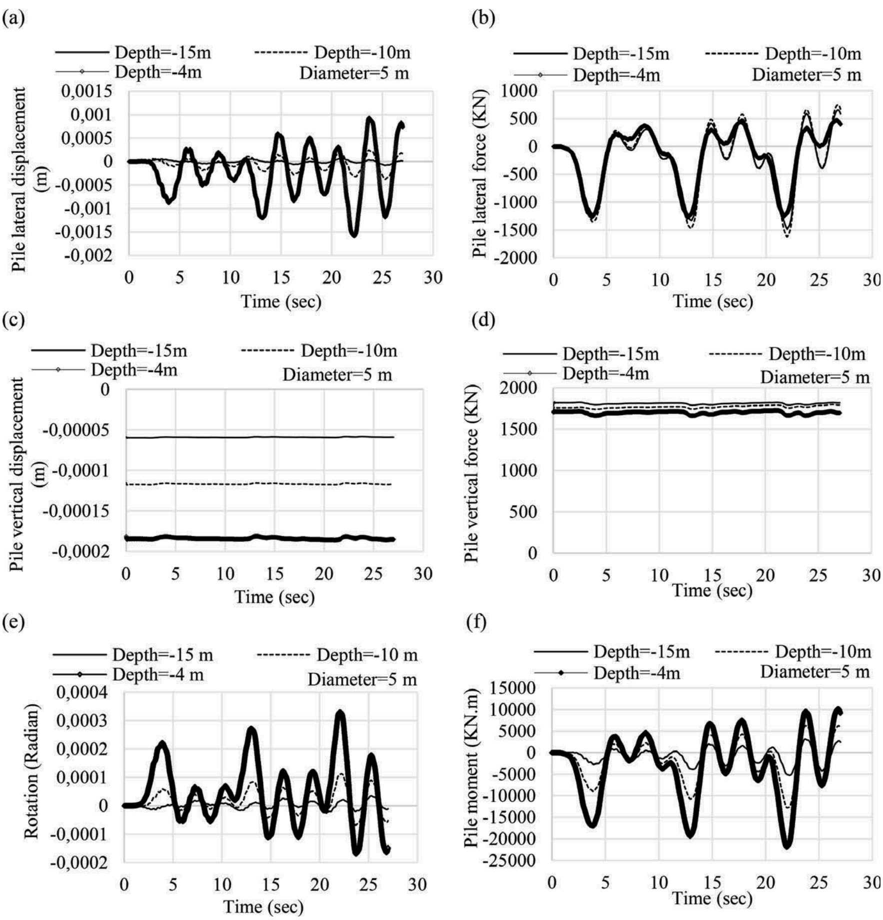

Figure 3. a) Pile lateral displacement in time. b) Pile lateral force in time. c) Pile vertical displacement in time. d) Pile vertical force in time. e) Pile rotation in time. f) Pile moment in time.

3 PARAMETRIC STUDIES

3.1 *Monopile diameter*

The main interest in this research is the monopile foundation performance by considering soil-monopile-structure interaction. In this regard, foundation diameter and its embedment depth are investigated under dynamic wave loading. In this section, the two pile diameters namely 3 m and 5 m piles were considered with embedment depths of 20 m. The performance of the monopile in term of pile deflection, inertial forces, and the soil excess PWP ratio were monitored, and they are presented in Figures 3 to 5. The graphs are presented for three different depths (-15 m, -10 m and -4 m) from the mudline surface.

According to the presented graphs, the deformation and inertial forces in most of the cases increase in the vicinity of mudline surface. The main point from the graphs is that by

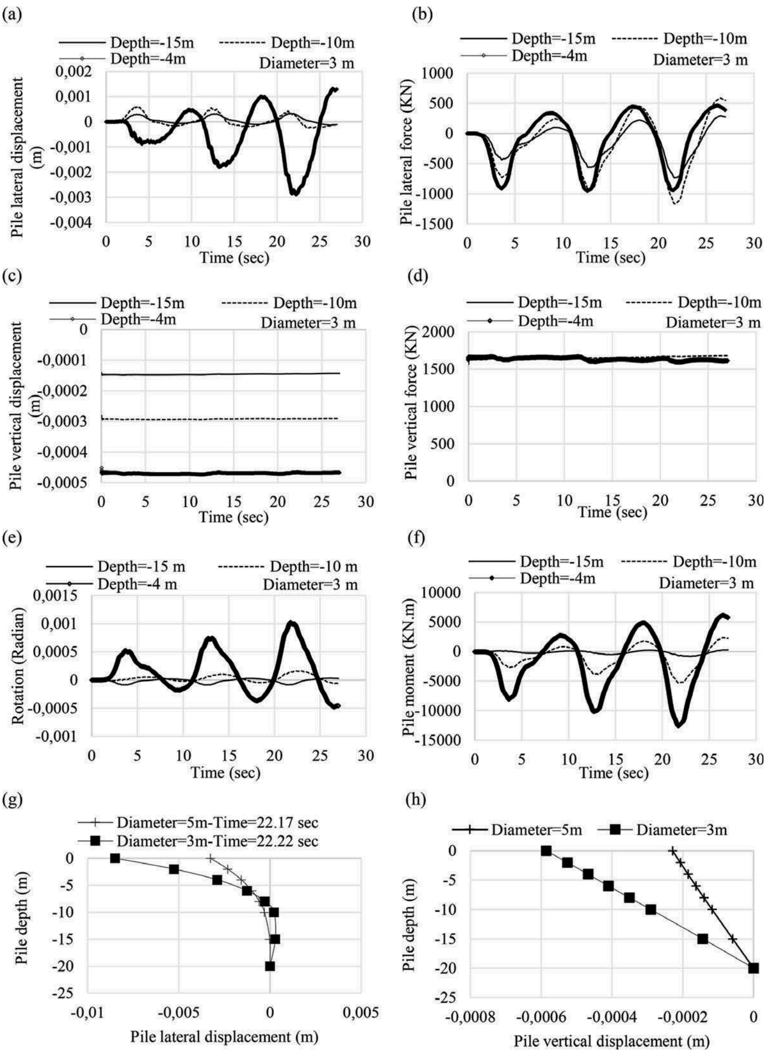

Figure 4. a) Pile lateral displacement in time. b) Pile lateral force in time. c) Pile vertical displacement in time. d) Pile vertical force in time. e) Pile rotation in time. f) Pile moment in time. g) Maximum pile lateral displacement in depth. h) Maximum pile vertical displacement in depth at last second.

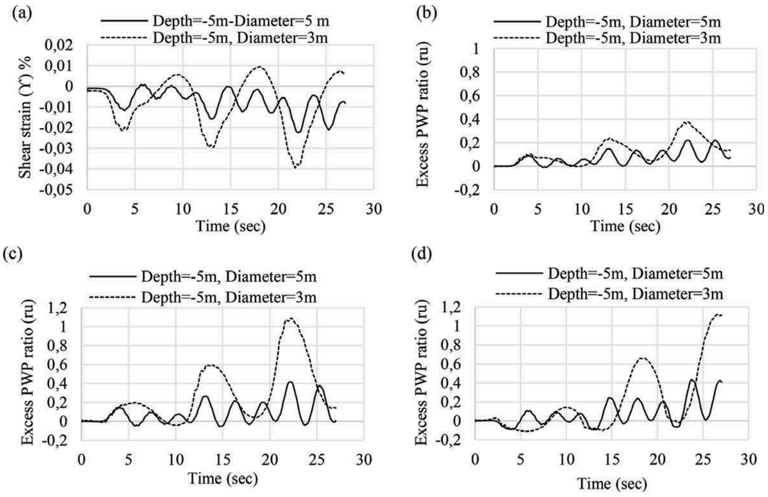

Figure 5. a) Shear strain in time at x=30 m and -5m depth. b) Excess PWP ratio in time at x=30 m and -5m depth. c) Excess PWP ratio in time at x=34 m and -5m depth. d) Excess PWP ratio in time at x=36 m and -5m depth.

increasing the diameter of the foundation, the lateral and vertical displacements decrease although the wave load amplitude increases. According to Figure 4-g, the performance of higher diameter monopile foundation is close to that with a rigid foundation, which was also mentioned by previous researchers (Haiderali and Madabhushi 2012). The lateral displacement in lower diameter monopile foundation decreases by increasing the depth and at a point, it becomes zero and this point is located at about the middle of the height of the foundation. This point is not the case for the larger diameter monopile because of its rigid behavior. As it is presented in Figure 5, a higher amount of shear strain is observed for the monopile with lower diameter value at 5 m, and 1 m (front and back sides of the foundation according to Figure 1-b) distance to the foundation. The higher shear strain value has a direct effect on the excess pore water pressure ratio and gives a higher value for a lower diameter foundation. The excess PWP increases by time and close to the mudline surface and foundation perimeter, which indicates potential liquefaction. This presents that the liquefaction susceptibility investigation is an important issue and needs to be considered for OWT monopile foundation design.

3.2 *Embedment depth of the monopile foundation*

According to the huge size of these offshore monopile foundations, the embedment depth of the monopile is another factor for evaluation of the system performance. In this regard, the pile forces and pile deformation are investigated by considering two different embedment depth values for the monopile with 5 m diameter and the results are classified in Figure 6. Figures 6-a,b and c are related to 5 m diameter monopile with 15 m embedment depth for the foundation.

By investigation of the results for embedment depth of the monopile foundation, it seems not a factor as important as the monopile diameter for large diameter foundations. The lateral and vertical displacements for both embedment depth values have similar performance. The excess PWP ratio increases from the depth about 10 m to the surface and according to Figure 6-h, closer to the pile perimeter has larger values. According to the similar performance of both monopiles with these two different embedment depth values, D/L value (ratio of monopile diameter to embedment depth) seems an important factor for design consideration and needs to be more investigated.

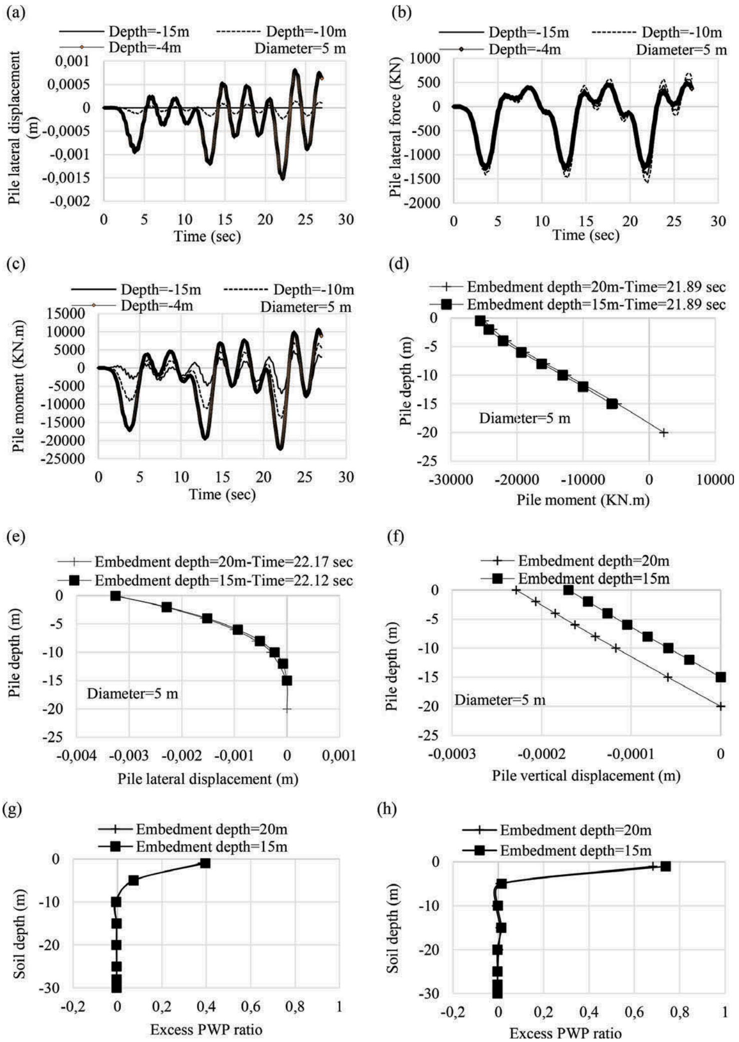

Figure 6. a) Pile lateral displacement in time. b) Pile lateral force in time. c) Pile moment in time. d) Maximum pile moment in depth. e) Maximum pile lateral displacement in depth. f) Maximum pile vertical displacement in depth at last second. g) Excess PWP ratio in depth at last second at x=30 m. h) Excess PWP ratio in depth at last second at x=34 m.

4 CONCLUSION

A 2D FE model is developed for the dynamic analysis of an offshore monopile foundation in sandy soil layer by considering soil-monopile-structure interaction. For verification of modeling approach adopted, free field analysis of the soil column and modeling of a cyclic simple shear test according to the literature review were performed in the first stage. Later the adopted soil constitutive model in previous stage was considered for the dynamic analysis of the soil-monopile-structure system under wave action. The effect of two different parameters, diameter and embedment depth of the monopile foundation in two cases is investigated under wave-induced dynamic load. Based on the results presented, increasing the monopile diameter decreases its deformation values and liquefaction tendency of the soil around it. Excess pore water pressure ratio values increase close to the mudline surface and around the perimeter of the monopile foundation, which leads to liquefaction happening for the smaller diameter monopile foundation. The results demonstrate that liquefaction susceptibility is a case which needs to be considered in the design of OWT monopile foundation. The maximum lateral displacement in all cases is at the monopile head and by increasing depth, it reduces and becomes zero at a point along the monopile foundation with lower diameter according to its flexible performance. The embedment depth of the monopile foundation is related to the diameter value of monopile foundation and for the large diameter monopile, similar performance is observed for deformations, inertial forces and excess PWP ratio. The presented results are valuable to help guidelines to determine optimum diameter of pile foundation for regions that are susceptible to liquefaction. Because of the computational duration of the nonlinear analyses and as the densification of the sand around the monopile foundation was not of interest for this research, the analyses are in short duration of three times of the considered wave period. In the graphs, the excess pore water pressure was in an increasing trend and it can be a point along the effect of wind and seismic loading which are in different frequency ranges to be considered for the future work of this ongoing research.

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