University of Tabriz

Journal of Civil and Environmental Engineering
Volume 52 (2023), Issue 4 (Winter), 59-74

EXTENDED ABSTRACT

Seismic Modelling of Monopiles under Wave Load in the Sandy Soil

Ali Asgari [a,*], Shokoofe Alsadat Alavi [b], Aliakbar Golshani [c]

[a] *Geotechnical Engineering, Faculty of Technology and Engineering, University of Mazandaran, Babolsar, Iran*
[b] *Geotechnical Engineering, Department of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran*
[c] *Geotechnical Engineering, Department of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran*

Received: 06 February 2020; **Accepted:** 28 April 2021

Keywords:
Offshore, Monopiles, Wave load and earthquake, 3D nonlinear modeling, Dynamic analysis.

1. Introduction

Human growing demand for energy and in recent decades for clean and renewable energy, leading to the development of wind farms inshore areas and have moved to offshore areas to achieve more production. Noticed that wind farms are a series of large, expensive and same structures, their foundations are important and it's necessary to minimize the probability of failure all of them. Many wind turbines are founded on large piles called monopiles. In European countries particularly in offshore areas, dominant environmental loading on monopiles is the wave. But some of the pioneer countries in wind energy development, such as China, India and the United States are highly seismic areas. Following the occurrence of natural events of wave and earthquake in the sea at the same time, considering the behavior of monopiles under their combined effects are required. In this study, three-dimensional modeling of the soil-monopile system using Open Sees software by finite element analysis was carried out and the effect of wave load on seismic responses of monopile and its surrounding soil was investigated. The wave and earthquake loads applied simultaneously on the soil-monopile system. In the nonlinear behavior modeling for sandy soils, effects of the stiffness, permeability, dilation, and potential of soil compaction on system responses are included. Studies have shown that wave can be affected on the seismic responses of monopile significantly, in addition to amplification of monopile, rotation, shear force and bending moment, can change the location of maximum moment and shear in monopile.

2. Methodology

2.1. Soil-monopile modeling

This study is conducted to gain insight into the performance of the monopile and surrounding soil under simultaneous wave loading and earthquake using the finite element code Open Sees. Circular Steel monopile is modeled with 2-node elastic beam-column elements with 6 degrees of freedom and the soil domain is peresented by 8- node, fully coupled (solid-fluid) brick elements with 4 degrees of freedom (3 degrees related to displacements and 1 degree for pore water pressure). Rigid beam-column connections that are normal to the pile longitudinal axis, are employed to illustrate the geometric space occupied by the pile. The 3D brick elements of soil are connected to the pile geometric configuration at the outer nodes of these rigid links using the equal DOF constraint in Open Sees for translations only. A multi-yield-surface plasticity (Prevost 1985) model was chosen for the analysis conducted theory for frictional cohesionless soils in this study. To improve

* Corresponding Author
E-mail addresses: a.asgari@umz.ac.ir (Ali Asgari), saa7949@gmail.com (Shokoofe Alsadat Alavi), golshani@modares.ac.ir (Aliakbar Golshani).

the efficiency of computation, only one-half of the actual models were built (Fig. 1). The characteristic of the model parameters related to the physical pile structure and soil parameters for wave and earthquake loading in the model are given in Table 1.

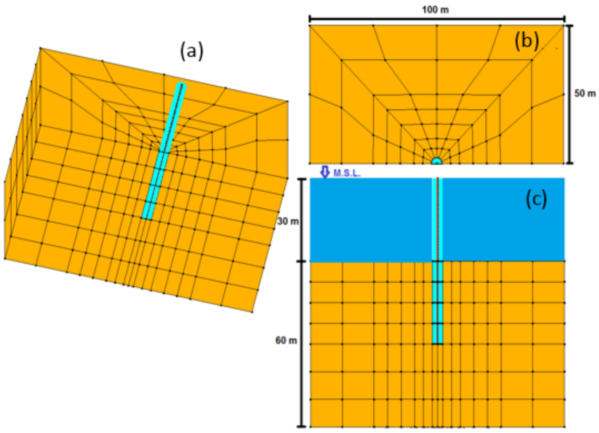

Fig. 1. FE mesh of the developed numerical model: schematic illustration in medium dense sand subjected to the wave and earthquake loading

Table 1. Monopile and sand soil characteristics

Soil Parameters	Medium Dense Sand
Mass density ρ	1900 kg/m^3
Low-strain shear modulus G_r	75 MPa
Permeability coefficient k	6.6×10^{-5} m/s
Friction angle φ	37°
Liquefaction yield strain γ_y	1%
Contraction parameter c_1	0.05
PT angle φ_{PT}	27°
Dilation parameter d_1	0.6
Dilation parameter d_2	3.0
Monopile characteristics	Value
Mass density ρ	1900 kg/m^3
Poisson's ratio	0.3
Young's modulus	2.1×10^8 kPa
Total length	60 m
Pile diameter	6 m

2.3. Wave & earthquake loading

In this study, 6 far-field earthquakes (Loma Prieta (1989) (Shake 1), Taiwan SMART1 (1986) (Shake 2), Irpinia-Italy (1980) (Shake 3), San Fernando (1971) (Shake 4), Sitka-Alaska (1972) (Shake 5) and Northridge-01 (1994) (Shake 6)) with a magnitude greater than 6 are selected. The selected accelerograms are scaled to 0.35 g to investigate the high seismic hazard level. Seismic excitation is applied at bottom of the soil model in the direction of longitudinal axis X.

The applied wave on the monopile is calculated based on Airy wave theory, a simple & quick way to describe the kinematics of sea waves. The wave load is evaluated from sea mean level to sea bed at intervals of 1 meter using the Morrison equation that is included drag & inertia terms. Wave load applied on monopile's body in variable depth and over time.

2.4. Verification

Lack of access to a complete model of the soil-pile system under the joint action of seismic and wave loading, make us to using two individual models, one under seismic load (Asgari et al. 2013) and another under lateral load- Roscoe centrifuge test (Rosquoët et al. 2004) - to validate the performance of the framework developed in this study, under seismic and cyclic lateral load, respectively. Comparison of Results illustrated the used framework can calculate the accumulation of lateral displacement of pile buried in dense sand under cyclic lateral load and also evaluating the response of pile buried in saturated sand under seismic loading.

3. Results and discussion

3.1. Effect of the wave on the seismic displacement & rotation of monopile

In brief, as the Fig. 2 shows that the presence of the sea wave causes a noticeable intensification on the seismic response of the monopile (displacement & rotation), but the changes of lateral displacement is more significantly rather than rotation. These results are consistent with the findings from the published literature (Bargi et al. 2011). Also, the largest increase in displacement is not necessarily associated with the largest increase in the rotation.

3.2. Influence of the wave on the seismic shear force & bending moment of monopile

The sea wave affects the form and magnitude of shear force in the monopile at the longitudinal axis, even in some cases the location of maximum shear force changes. In addition, the presence of the wave increases the magnitude of bending moment especially in the middle of the monopile's length.

3.3. Effect of the wave/earthquake on the water pore pressure and the stress-strain & stress path

The influence of the wave load on the pore water pressure (PWP) in the shallow depth is more significant than that in the deeper depth. Similar behavior is observed at changes of Shear stress-strains and stress path curves. As the depth increases, the dilative event generates in the soil and the pore water pressure decreases gradually. The presence of waves not only changes the minimum and maximum value of pore water pressure but also changes the pattern of increasing & decreasing PWP. On the other hand, the changes in (PWP) after peak ground acceleration (PGA), follows the pattern of the wave load.

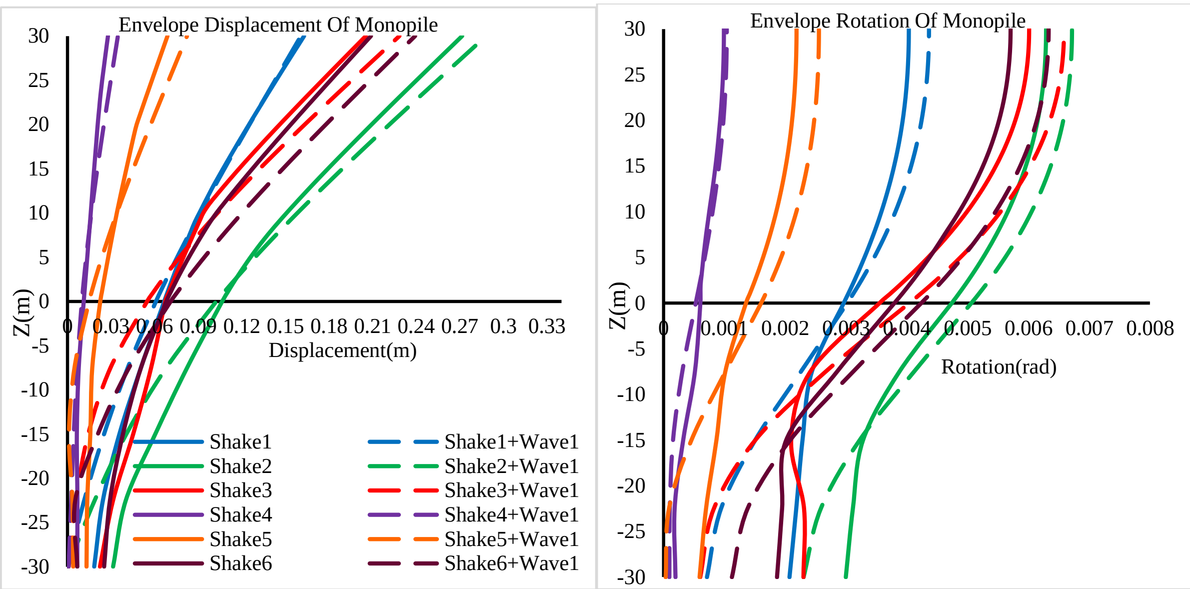

Fig. 2. Effect of the wave on the seismic displacement & rotation of monopile

3.4. The wave effect on the seismic response of the soil

The soil farthest away from the monopile is observed to undergo more displacement under the wave and seismic loads. This trend will be changed as a weak earthquake occur which the effect of sea wave may be predominant. On the hand, the lateral displacement decreases as distance from monopile increases. Besides, soil displacement near the monopile trend to follow wave load pattern after the predominant period of earthquakes.

4. Conclusions

The presence of wave causes a noticeable intensification of the monopile seismic deformation, which is intensified by moving towards the monopile head. Also, the presence of a wave increases the maximum shear force and bending moment of the monopile under the earthquake. The maximum shear force of the monopile occurs under the effect of seismic load in the distance between half and the end of its buried length, which may be closer to the end of the monopile buried length in the presence of a wave at this location. Also, the presence of a wave may change the location of the maximum bending moment under seismic loading from sea level to one-fourth of the buried length of the monopile. The Superposition Principle is not applicable to monopile responses-either force or deformation-under combined wave and earthquake loading. On the other hand, the monopile response under the combined effects of earthquake and wave loads is not equal to the sum of its responses under earthquake and wave due to the nonlinear behavior of the soil.

5. References

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