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The effects of wind load direction changes on offshore wind turbine monopile response

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ABSTRACT: Monopile is the most common type of foundation for onshore and offshore wind turbines. As the wind blows in different directions, wind load alternately applies in different directions during the life cycle of the wind turbine. In this paper, the influence of the alternating change of wind load direction on the response of wind turbine piles is studied. The functional performance of the soil-pile system is simulated with a bounding surface soil behavior model presented by Dafaliad-Manzari that is implemented in FLAC3D software. The softening and hardening effects of soils due to cyclic load patterns are incorporated into the model in a convenient manner. The results show that in monopiles, alternative change in the direction of loading results in the decrease in the maximum horizontal displacement and rotation up to 16% in comparison with the uni-directional loading mode. This difference in vertical displacement is about 100%. Residual displacement and rotation in the horizontal direction also decrease 13% and 18%, respectively. Alternating change of loading causes upward moves of the monopile; the pile moves upward from its original level. In general, the change of loading direction causes a significant change in the pile response, although the values of this difference vary in different parameters and for altered loading modes.

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1- Introduction

Wind turbines are periodically exposed to a variety of lateral loads during their service life. Due to the nature of the applied forces of wind and wave loading is multi-directional. However, in most of the research in this field, one-way loading is considered to assess the response of these structures to lateral loads. On the other hand, the study on soil behavior due to alternative multi-directional loading is limited to laboratory soil samples and the application of the results for piles is questionable [1]. Since classical soil behavioral models such as Mohr-coulomb are generally unable to take into account the effects of stiffening due to reciprocating plastic strains caused by alternative loading, a model based on boundary surface plasticity called Dafalias-Manzari is applied. Dafalias and Manzeri introduced a relatively simple model to simulate soil behavior at different porosity ratios under one-way periodic loads. They use the status parameter as a fundamental variable in the boundary framework as well as the critical state theory in soil mechanics [2]. This model has 15 parameters, in which, in order to calculate the input parameters, it is necessary to perform a series of triaxial tensile and compressive tests, in both drained and not drained conditions under different confining pressures.

In this article, applying the Dafalias-Manzari behavioral model, the behavior of offshore wind turbine pile foundation is simulated in FLAC3D software and the response of thick piles under static alternating wind loads is studied in one-way and multi-directional modes. The purpose of this paper is specifically to assess the pile responses to multi-directional loading and compare them with those in unidirectional loading condition.

2- Model development and validation

FLAC3D software is applied for simulation pile-soil behavior subject to lateral loads. FLAC3D, is numerical modeling software for advanced geotechnical analysis of soil and rock. It is designed to accommodate any kind of geotechnical engineering project that requires continuum analysis. FLAC3D utilizes an explicit finite difference formulation that can model complex behaviors, such as problems that consist of several stages, large displacements and strains, non-linear material behavior, or unstable systems.

2- 1- Validation

In order to evaluate the results obtained from the software, several samples of laboratory and large-scale piles subjected to static monotonic loading are considered. The results of the simulations performed in this research using FLAC3D software are also compared with the results extracted from Abacus and SAP software. The results indicate that FLAC provides better performance and higher accuracy.

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Table 1. Differences in pile response between unidirectional and multi-directional static alternative loading and unloading

α	Y-DISP (%)		Z-DISP (%)		ROTATION (%)	
	Max	Res	Max	Res	Max	Res
15°	-14.94	-6.14	117.78	-35.45	-14.83	-11.37
30°	-15.86	-9.65	118.45	-33.63	-15.2	-14.32
45°	-16.32	-13.42	117.69	-32.73	-16.88	-18.02
60°	-26.43	-25.4	116.7	-31.8	-25.45	-29.4

2- 2- Loading process

To investigate the effect of changing the direction of alternating wind load on the response of the wind turbine pile foundation, the characteristics of a real model turbine located on the East coast of England are considered. The pile has a length and diameter of 43 and 2.5 meters, respectively, and a wall thickness of 59 mm, which is considered as one of the thickest monopiles with respect to the length-to-diameter ratio of 8.26. The pile response to the lateral wind load is examined in Toyoura sand soil with the Dafalias required parameters.

Static alternating load equal to the average wind force is applied as the lateral load to the pile. Load is applied to the pile head in the form of stress and after reaching the equilibrium, the unloading is done by sudden removal of the load. In the one-way mode, all loads are applied along the Y axis. Fig. 1. Loading and unloading continue until a steady state is achieved, where with increasing the number of loading cycles, no significant increase in displacement values is observed. The steady-state occurs in the first 10 cycles with a horizontal displacement value of about 4.3 cm, so the number 10 cycles can be considered as the number of convergence cycles of the displacement values.

In the multidirectional loading mode, the alternating loading in each direction is repeated until a steady state is observed, then the loading direction changes and the process is continued until the steady state. 60, 45, 30 and 15 degrees are considered for the change in the direction of loading. For multidirectional loading, first in the X direction, 10 loading cycles are applied, then the direction of loading is changed and another 10 cycles are applied, and this process continues until half of the pile circumference is covered, Figure 1.

3- Results and Discussion

The difference in pile response between the uni-directional and multi-directional loading is presented in Table 1, where the maximum and residual percentage of differences in pile head displacement and rotation is tabulated for different

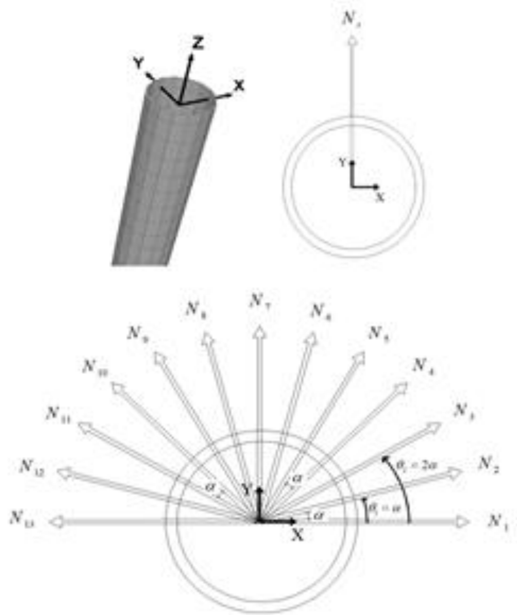

Fig. 1. . Schematic of unidirectional and multidirectional loading

loading rotation angles. As indicated in the table, the lateral displacement (Y) decreased (minus means decrease) by up to 26% due to the change in loading direction compared to unidirectional loading. Similar behavior is observed for rotation. The difference is increased with the increase in the rotation angle. For 15, 30 and 45-degree multidirectional loadings, the difference is limited to 18%, however it is decreased to 29% for 60-degree rotation angle. The reason behind this difference is that in 60-degree rotation condition, none of the loading vectors are directly in the Y-direction. Therefore, the corresponding results in 60-degree are not valid

There are the considerable differences between the maximum and residual displacement in the vertical (Z) direction. In the vertical direction (Z), the behavior between unidirectional loading and multidirectional loading is quite different; in the former pile settles while in the latter, the pile moves upward.

From soil behavioral point of view, the difference between the results of unidirectional and multi-directional conditions demonstrate the importance of the loading history. In fact, according to the applied Dafalias-Manzari behavioral model, the effect of changes in stress and strain tensors of the previous steps on the development of new deflection and volumetric strains is considered by using the stiffness and dilation modules. The observed differences between unidirectional and multidimensional states indicate the fact that the application of more varied stress paths to the soil affects the tensor parameters and the way they propagate and form.

4- Conclusions

Wind turbines are subject to cyclic wind loads, and due to the rotation of the wind direction, this loading is not applied in only one direction. In this paper, by performing numerical simulation of pile behavior in FLAC3D software and considering the Dafalias-Manzari theory, the responses of a thick offshore wind turbine under static alternating wind load subject to unidirectional and multi-directional modes are compared.

The results show that after 10 loading and unloading cycles, the deformations reach a steady state. By considering different loading directions, it is concluded that the maximum horizontal displacement and pile rotation are reduced by 16%. Permanent displacement (residual) in the horizontal direction and permanent rotation also decreased by up to 13% and 18%, respectively. The differences are increased when the angles of rotation are increased. There are the considerable differences between the maximum and residual displacement in the vertical (Z) direction. The pile moves upward in multidirectional loadings.

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