Numerical Modeling of Monopile Foundations under Cyclic Horizontal Loading

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Abstract

Large-diameter steel monopiles may be economically justified for foundations of offshore wind turbines in deep water. The lateral loads from wind loading and wave loading cause progressive deformation of cohesionless soil. Excessive permanent deformation of soil may cause monopiles to lose structural function. A three-dimensional numerical model using the finite element method with stiffness degradation depend on number of cycle was established to simulate the accumulative deformation of pile-soil systems under long-term cyclic loading. The effects of pile geometry, soil properties and loading conditions are discussed.

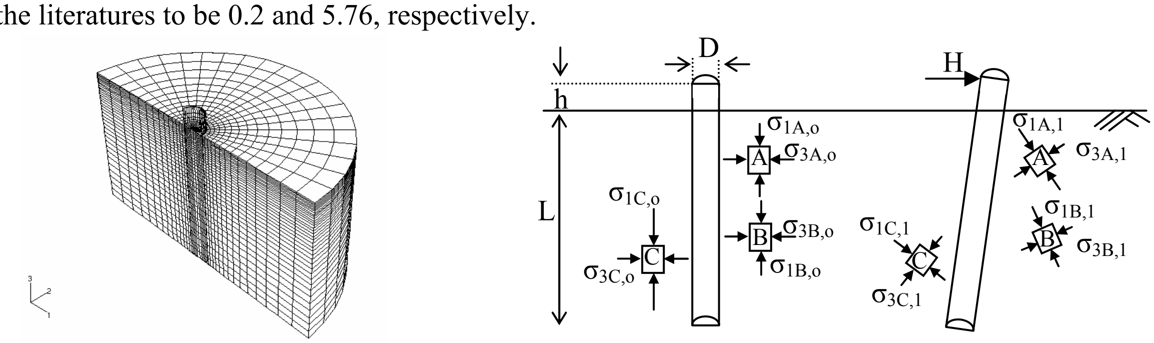
Numerical model

A three dimensional finite element model was established and calculated using the program ABAQUS[1] and is presented in Figure 1(a). The material behavior of the steel monopile was assumed to be linearly elastic. The material behavior of sand was assumed to be elasto-plastic with stress-dependent stiffness. The frictional behavior of the boundary surface between pile and soil was modeled by contact elements. With fitted dimensions the calculated behavior of the pile is not influenced by the boundaries [2].

Accumulated displacement under cyclic loading can be interpreted as a decrease in the secant stiffness modulus of each soil element. When elastic strain is negligible, the secant modulus E_{sN} of each soil element can be formulated with plastic strain in the first cycle, $\varepsilon^a_{p,N=1}$, and the N^{th} cycle, $\varepsilon^a_{p,N}$. Combined with the approach to describe plastic strain obtained in the cyclic triaxial tests of Huurman [3], the decrease in stiffness can be represented by the following equation:

$$\frac{E_{sN}}{E_{s1}} \cong \frac{\varepsilon^a_{p,N=1}}{\varepsilon^a_{p,N}} = N^{-b_1\left(\frac{\sigma_{1,cyc}}{\sigma_{1,f}}\right)^{b_2}} \qquad (1)$$

Here N is number of cycles; b_1, b_2 are regression parameters; $\sigma_{1,f}$ is main principal stress at failure in static test; $\sigma_{1,cyc}$ is cyclic stress in the main principal direction. The cyclic stress of each soil element can be determined from the stress variation before and after lateral load, as shown in Figure 1(b). For dense sand, b_1 and b_2 are determined from cyclic triaxial test results reported in the literatures to be 0.2 and 5.76, respectively.

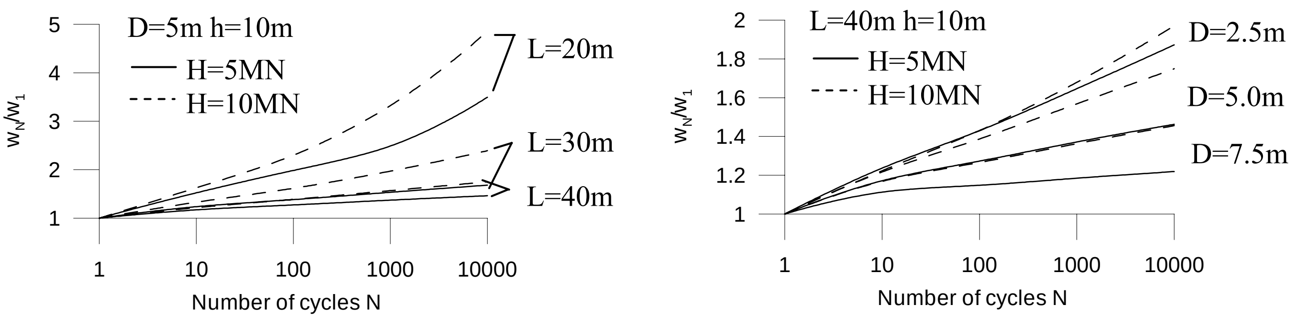


(a) Finite element model of monopile foundation (b) Stress variation of soil element

Figure 1. Numerical model of monopole foundation

Simulation results

The accumulated displacement of a pile at ground surface after N cycles, w_N, is simulated by a numerical model and the effect on pile geometry is demonstrated in Figure 2. The increasing rate of accumulated displacement, w_N/w_1, of a pile with small diameter and short embedded length is more significant than that of a pile with large diameter and long embedded length.



(a) Effect of embedded pile length

(b) Effect of pile diameter

Figure 2. Effect of pile geometry on accumulated rate of lateral displacement

The effect of loading conditions is demonstrated in Figure 3. The accumulated rate of lateral displacement, w_N/w_1, increases with the increasing load eccentricity.

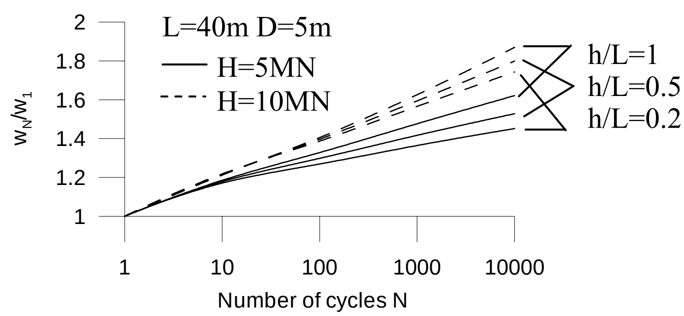


Figure 3. Effect of load eccentricity on accumulated rate lateral displacement

Discussion

Accumulated displacement of a pile is quantified using a numerical model based on a cyclic triaxial test. In reality, amplitude of lateral load varies with wave height and wind velocity. Pile behavior under a storm with variable load amplitudes will be the object of further research.

References

[1] Abaqus, User's Manual. Version 6.5, 2005.

[2] Abdel-Rahman, K. & M. Achmus: *Finite Element Modelling of Horizontally Loaded Monopile Foundations for Offshore Wind Energy Converters in Germany*. International Symposium on Frontiers in Offshore Geotechnics (ISFOG), Perth, Australia, 2005.

[3] Huurman, M.: *Development of traffic induced permanent strains in concrete block pavements*. Heron, 41(1): 29-52, 1996.

[4] Achmus, M., Abdel-Rahman, K. & Y-S. Kuo: *Numerical Modeling of Large Diameter Steel Piles under Monotonic and Cyclic Horizontal Loading*. International Symposium on Numerical Models in Geomechanics (NUMOG X), Rhodes, Greece, 2007 (in preparation).