Dynamic coupled analysis of large-diameter steel piles located in liquefiable soil layers

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ABSTRACT

Many shores in Iran are at risk of earthquakes, and due to the dynamic loading of the earthquake, these saturated soils are prone to liquefaction. In this study, the behavior of two-layered saturated sand with different relative densities and the interaction effects of soil and pile under dynamic loads has been considered. For this purpose, a constitutive model presented in the multi-surface framework has been applied. In addition, the equations governing the saturated environment have been solved in a completely coupled way based on the finite element method. According to the obtained results, liquefaction will occur in the upper layers no matter the loading frequency when their liquefaction potential is high. Nevertheless, at depths and layers where the liquefaction potential is low, the pore pressure is strongly dependent on the loading frequency, so that with an increase in the frequency of the dynamic loads, the water pore pressure increases less. Also, based on the analyses performed under different frequencies, it is observed that at a dynamic loading frequency, increasing the pile length has little effect on the displacement of the pile head but can significantly affect the displacement of the buried parts. Therefore, the larger the ratio of the pile length in the liquefiable soil to the total length of the pile, the greater the possibility of more displacement in the buried end of the pile; And as a result, it can lead to instability of the structure.

KEYWORDS

Numerical modeling, Liquefaction, Layered soil, Soil-pile interaction, Multi-surface constitutive model

1. Introduction

Most marine structures should be constructed on large-diameter piles with sufficient penetration into the subsurface layers. The shallower deposits at such places usually consist of soft clayey or loose to medium sandy soils, which are highly susceptible to various liquefaction forms. Due to the rapid growth of marine structures, the effect of liquefaction on the large-diameter piles has to be investigated in more depth. In this study, a robust numerical approach was used to investigate the behavior of large-diameter piles of such structures during liquefaction; and the effects of inertial and kinematic interactions were considered using a coupled formulation and simultaneous modeling of the pile and adjacent soil. There have been some previous studies in this area [1-17], which we tried to cover their shortcomings in this study, and some of their results have been used to verify and compare the results.

2. Methodology

The constitutive relation employed in this study was established on the original basis of Prevost, in which a multi-surface method is implemented for cyclic hysteretic response [18] (Figure 1).

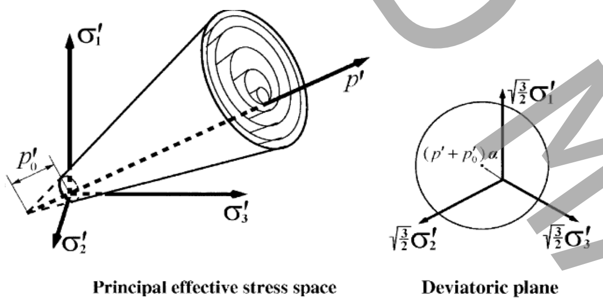

Figure 1. Conical yield surface in the space of principal stresses and on the deviatoric plane

A numerical model was created by means of the finite-element program OpenSeesPL [19]. Based on the sensitivity studies, the extents of the model in x, y, and z directions were selected at 60, 30, and 35 m, which are suitable to diminish boundary effects (Figure 2). For the zone round the pile, mesh magnitude was selected comparatively fine, which becomes coarser to outside boundaries.

To validate the model in replicating logical results, a centrifuge test performed by Wilson [20], named Csp3 for Event J, was used; the behavior of excess pore pressure, superstructure acceleration, and bending moment of the pile were compared with those of the centrifuge test. The results of the constructed model agree with those of the physical model in terms of accelerations, excess pore pressure ratio (R_u), and pile bending moments. Consequently, the model can capture soil and pile responses appropriately under earthquake loading and liquefaction.

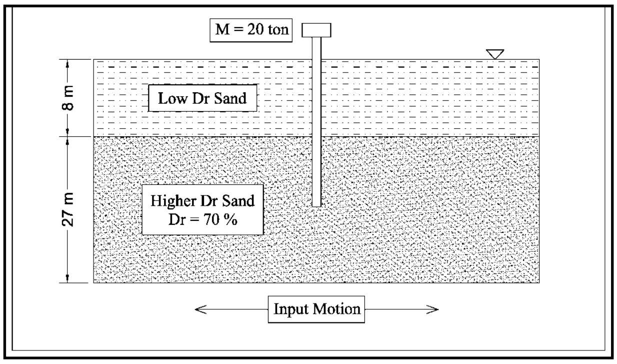

Figure 2. The soil layer state considered in the current investigation

3. Discussion and Results

R_u normally is likely to decline with depth. This tendency can be explicated from the difference in soil's density (and stiffness, of course) for different layers. For the upper section of the model, relative density is smaller, resulting in greater oscillations of soil particles. Consequently, the soil's assembly densifies, and pore water is enforced to get out of the soil pores. The pressure of pore water surges through this procedure.

Moreover, the loading frequency does not influence the liquefaction development in the upper soil layer. According to this point, liquefaction can happen in every portion of the soil from the ground surface down to the depth of 8 m in all cases. Therefore, the incidence of liquefaction for the upper layer (low relative density) seems irrelevant to the frequency of base motion.

Investigating the soil's horizontal movement at x = 5:5 m from the pile for different frequencies reveals that the intensity of vibrations decreases with a surge in the loading frequency. This decline is in accordance with variations of Ru. The amplitude of fluctuations of soil elements has special importance prior to liquefaction compared to its value after liquefaction. The cause is that shear wave wandering from unfathomable areas of the ground through soil medium is damped somewhat after liquefaction, and the breadth of soil vibration declines, accordingly. In addition, Haeri et al. [21] and Lu et al. [19] pointed out such an occurrence in their work.

4. Conclusions

The main conclusions of the paper are:

- When the loading frequency is equivalent to or smaller than the soil's natural frequency, it is more likely for deeper zones of soil to liquefy, in addition to the liquefaction of upper deposits. Consequently, it is suggested to use a lengthier pile and increase its embedment in such circumstances.

- When the loading frequency is high, it takes longer to liquefy the soil. In other words, excitation with a higher frequency applied for a longer period could have a similar effect to loadings with lower frequencies applied in shorter times.

- When a deposit of cohesive material is present above a relatively looser deposit of sand, the sand layer may liquefy in a shorter time. R_u will rise to a value greater than one, and sand loses its shear strength. Displacements and bending moments in the embedded pile will increase accordingly.

- In conditions where clay is placed in the loose sand bed, the maximum displacement of the pile head could have a 50% growth compared to the condition with no clay. Thought, this large value occurs before liquefaction due to the extreme softness of the clay layer.

5. References

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