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Investigation of Effective Parameters on the Settlement and Lateral Spreading of Shallow Foundations on the Sloping Liquefiable Soil

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ABSTRACT: The settlement and lateral spreading of the building due to the occurrence of the liquefaction phenomenon in previous earthquakes have caused significant damage to structures and their infrastructure. Numerous studies have been performed to evaluate the settlement of shallow foundations located on the liquefiable soils as a horizontal model. In fact, in most cases, there is a mild slope in the layers that can be affected by the settlement and lateral spreading of the foundation. In this research, the displacements of the structure and shallow foundation/ground surface on the sloping liquefiable three-layers soil with different relative densities have been investigated parametrically, applying three-dimensional finite element (FE) simulations using OpenseesSP. The layers are subjected to the realistic destructive event with scaled peak ground acceleration of 0.35g. A multi-yield-surface plasticity model was selected for the analysis conducted in this research based on constitutive laws applicable to all types of soils. The purpose of this study is to investigate the effect of parameters including the slope of soil layers, the density of liquefiable layer, groundwater level, foundation contact pressure, and length to width ratio of the foundation on the settlement and lateral spreading of the liquefiable sloping model. The results are shown that increasing the slope of the ground increases the difference between the settlement of the two sides of the foundation and increases the lateral displacements. Decreasing the relative density of the liquefiable layer increases the excess pore water pressure and the settlement of shallow foundation. The results also are shown that lower the groundwater level is increased the effective stress and reduces the vertical and horizontal displacements. Besides, increasing the contact pressure is amplified the foundation of static and dynamic volumetric strains and increases the settlements. Shallow foundations with larger length-to-width ratios experience lower settlements due to smaller shear strains.

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1- Introduction

Lateral spreading of mildly sloping ground and liquefaction induced by earthquakes can cause major destruction to foundations and buildings, mainly as a result of excess pore water pressure generation and softening of the subsoil. Recently, most of researches has been done on the lateral spreading of soils with mildly slopes, but a comprehensive investigation has not yet been performed to evaluate the effects of lateral spreading of structures on shallow foundations with considering the soil-foundation-structure interaction effect. Of course, there are many studies related to the effect of mild angle on the seismic responses with soil-pile interaction1-] 3]. Although recent advances in computational modeling of liquefaction-induced ground deformation are quite promising, challenges remain in this critical yet unresolved problem. On the other hand, some recent advances in computational modeling of liquefaction-induced ground deformation were focused on the structure located on the soil layers without any slope ground [4, 5]. In this study, the structure and foundation are modeled in three dimensions using the finite element method on sloping liquefiable soil layers and the effects of parameters such as slope ground angle, liquefiable layer density, groundwater-surface position, contact pressure on the foundation and the ratio of length to width of the foundation on the settlement and lateral spreading has been investigated quantitatively and qualitatively by considering the effects of structure-foundation-soil interaction.

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2- Numerical modeling

To model the structure and the soil under shallow foundation, we used the finite element parallel Opensees [6] software. As shown in Figure 1, the soil model has a length and width of 60 and 48 meters, respectively and a height of 26 m, which consists of 1720 elements and 2230 nodes. The top layer is Monterey sand with high permeability and density of 85% with 2 meters thickness and the middle and bottom layers of Nevada sand with a density of 50% and 90% and a thickness of 4 and 20 meters, respectively. The groundwater level is considered at a depth of one meter from the ground surface. Besides, the models are simulated with a mildly sloping ground from 0 to 2^{o} relative to the horizon and also are subjected to the scaled Port Island (1995 Kobe) event with PGA=0.35g along the base in the longitudinal direction (shown in Figure 2). In 3D, the soil domain is represented by

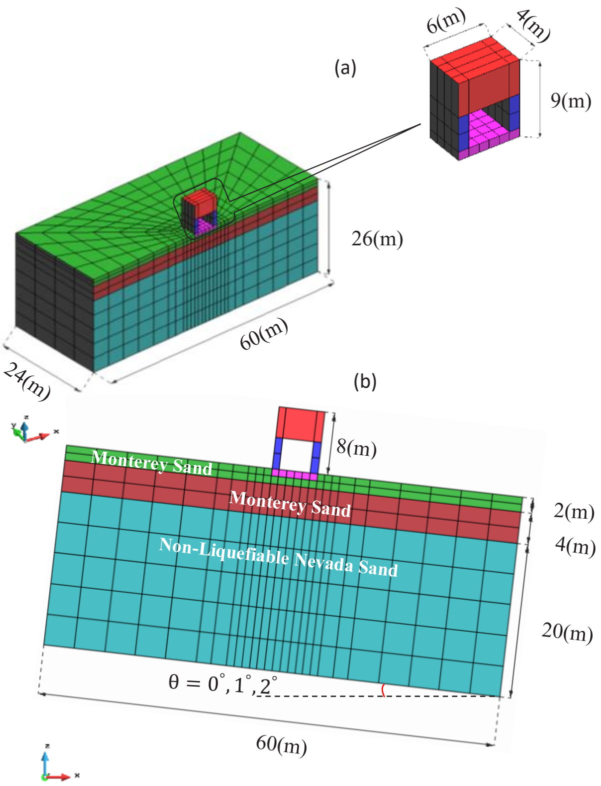

Fig. 1. (a) Meshing soil-structure 3D view (b) Meshing soil-structure side view

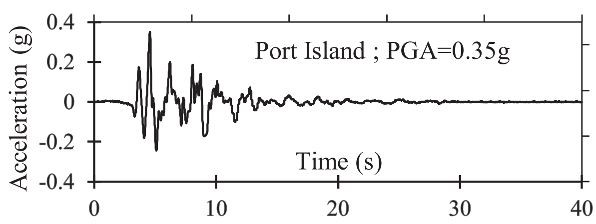

Fig. 2. Horizontal acceleration history for the Kobe (1995) with scaled PGA of 0.35 g, of the input events

Table 1. Input parameters in this research

Input parameters	value
first layer density (%)	85
second layer density (%)	30, 50*, 68
Third layer density (%)	90
Slope (Degree)	0, 1*, 2
Groundwater level(m)	-1*, -2, -4
Foundation contact pressure (kPa)	80, 130*, 180
Ratio of length to width foundation	1, 1.33*, 2

*Parameters related to the base model

20-8 node, effective-stress, fully coupled (solid-fluid) brick elements and the soil foundation, as well as structures, were modeled using 8-node brick elements with three degrees of freedom and materials with elastic properties of steel and aluminum. The height of the structure is 8 m and also the length and width of the foundation are 8 and 6 meters and its thickness is 1 m, respectively. The contact pressure of the foundation are varied from 80 to 180 kPa and the frequency of the structure with a fixed base is equal to 2.5 Hz.

3- Results and Discussion

The parameters studied in this research are shown in Table 1. To examine slope ground angle effects on the seismic response, vertical and horizontal displacements time history at the left, and right edge of the foundation for depth 1 m are depicted in Figure 3(a-c). According to this figure, it is observed that with increasing the slope angle, the settlement on the right side of the foundation is remarkably increased, but in contrast to the left side of the foundation is reduced. The reason can be attributed to the movement of soil mass in sloping lands due to the direction of the slope. The excess pore pressure-time histories of the middle of the liquefiable soil layer are depicted in Figure 3(d), where the ground slope angle was varied from 0 to 2^{o} ; there is an evident tendency for the excess pore pressure to decrease and lateral displacement to increase as the ground slope angle increases. Lateral displacement would be expected to decrease with an increase in pore pressure dip in ground angle that expect; however, the presence of a driving static shear stress component induced by ground slope increases lateral displacement, resulting in a greater lateral displacement than the horizontal model($\alpha_f = 0°$). For more detail of the results, refer to Ref. [7].

4- Conclusions

The results of this study show the following:
Increasing the slope intensifies the static shear stresses due to the weight of the soil mass in the direction of the slope and increases the lateral displacements of the foundation. Also, increasing the slope of the ground increases the difference in vertical displacements between the two sides of the foundation and increases the rotation of the foundation. As the density of the liquefied layer decreases, the amount of settling increases, which is due to the contractile tendencies of soft sand, which increases the excess pore pressure and cyclic shear strains, and strengthens the volumetric and shear strains and increases the settling. The decrease in groundwater level has reduced the vertical and horizontal displacements of the foundation, which is due to the increase of effective stress. Due to the increase of contact pressure, the foundation settlement increases, which can be attributed to the increase in static and dynamic shear stresses transferred from the foundation to the soil, which strengthens the static and dynamic volumetric strains and increases the settlement. Foundations with larger length-to-width ratios experience smaller settlement due to smaller shear strains and reduced off-plate drainage potential due to the increased length-to-width ratio of the foundation.

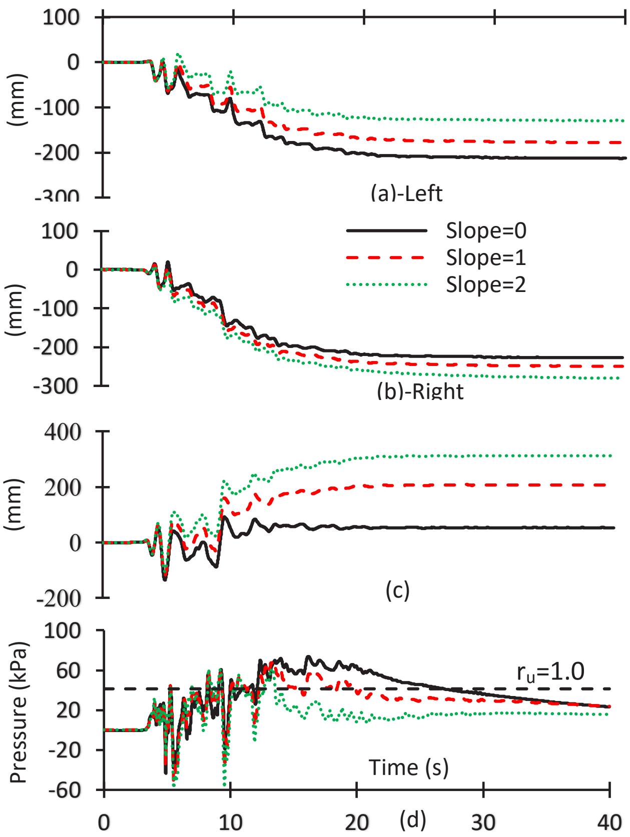

Fig. 3. (a, b) Vertical displacement time history at the left, and right edge of foundation (c)Time history of lateral displacement for depth 1 m (d) Excess pore pressure at the middle of liquifiable layer for various ground inclination angle θ=1-2°.

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