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Lateral displacement and pile instability due to soil liquefaction using numerical model

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Abstract Pile instability due to liquefaction of loose sand is considered one of the most important causes of bridge failures during earthquakes. In this study, the 3D finite element program DIANA 9.3 is implemented to study the seismic behavior of piles penetrated into liquefiable sandy soil. This model is supported by a special Line–Solid Connection element to model the interface between pile and surrounding soil.

Extensive studies were performed to investigate the effects of soil submergence, pile diameter, earthquake magnitude and duration on pile lateral deformation and developed bending moment along pile shaft. Study results show that earthquake magnitude and time duration have a particular effect on the pore water pressure generation and hence pile lateral deformation and bending moments. They also show the benefits of using relatively large piles to control the lateral displacement. Recommendations are presented for designers to perform comprehensive analysis and avoid buckling and plastic hinge failures.

1. Introduction

The seismic performance of piles in liquefiable soil, their analysis and design is considered one of the most sophisticated geotechnical problems. The behavior of piles in liquefiable soil is a function of soil properties, pile properties (diameter, length and material), depth of liquefiable layer, the characteristics of applied earthquake motions, relative stiffness between piles and the surrounding soil. The dynamic design of such piles and their durability against soil liquefaction, during and after earthquakes, can be considered one of the main challenges that face structural and geotechnical engineers. Beside the excess dynamic lateral loads due to seismic excitation, excess pore

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water pressures may generate and cause soil liquefaction; hence extra lateral loads are transmitted to piles. In addition to this, the pile may lose its lateral supports due to lack of soil shear strength. The conditions may become more complicated if the unsupported length of the pile is increased, which in turn can lead to the instability of the piles [1–4].

Failure of piled foundations has been observed in the majority of recent strong earthquakes. The failure of end bearing piles in liquefiable areas during earthquakes is attributed to the effects of liquefaction induced lateral spreading [1,2]. The down slope deformation of the ground surface adjacent to the pile foundation seems to support this explanation. All these theories of pile failure treat the pile as a beam element and assume that the lateral loads due to inertia and slope movement cause bending failure in the pile.

Amiri [2] presents a wide summary for historic cases of earthquakes, which induced pile damage due to lateral spreading of soil. This review presents the most famous and catastrophic pile foundation damages of bridges, where lateral movement has been observed. These lateral movements exceed 1.00 m in some cases. It includes damages during the Great Alaskan (USA, 1964), the Edgecumbe (New Zealand, 1987), the Kobe (Japan, 1995), the Luzon (Philippines, 1990) and the Niigata (Japan, 1964) earthquakes. For each earthquake, the physical nature of the event, pile foundation types, the subsurface soil condition beneath the bridge foundations and the types of the damages are discussed.

Meyersohn [1] proposed that three distinctive failure modes can be recognized in piles subjected to lateral spreads resulting from soil liquefaction. In the first one, lateral pile deflections induced by horizontal soil displacement may result in the pile reaching its bending capacity, thus developing a plastic hinge Fig. 1a. On the other hand, the lack of sufficient lateral support due to the reduced stiffness of the liquefied soil and the lateral deflection imposed on the pile may result in buckling Fig. 1b. Another type of failure is shown in Fig. 1c, where it involves excessive rigid body rotation of the pile, which is a characteristic of large diameter piles and piers. This type of response to lateral soil displacement arises primarily from a lack of sufficient restraint at the bottom of the pile, either due to an inadequate embedment length or due to low resistance of the foundation material against lateral movement. With increasing soil movement, this form of pile response may be followed by the formation of a plastic hinge at the lower interface, or by a premature collapse of the foundation due to a combination of excessive rotation and lack of lateral support.

In this study, an advanced numerical model has been used to simulate the sophisticated problem of the mutual seismic interaction between liquefiable loose sand formation and piles. The prepared numerical models are based on the finite element methodology using program DIANA 9.3 (2008). The proposed model is able to represent the soil–structure interaction system under seismic excitation and submerged conditions. Through 3D analysis, the pile is modeled as a beam element and the surrounding soil layers are modeled as solid elements. The model is supported by special 3 + 3 node Line–Solid Connection element, which is utilized to model the interface between the pile and the surrounding soil in three-dimensional configuration.

Extensive studies have been carried out to investigate the seismic interaction of the piles considering soil submergence condition, pile diameter, earthquake magnitude and duration. The characteristics of the soil dealt with are cohesionless soil having relative densities from loose to medium sand to very dense sand. Three artificial generated earthquake records have been used as the control motion at the bed-rock surface. A practical wide range of maximum base acceleration is selected (α = 0.05–0.20 g), considering earthquake durations of 10, 20 and 40 s. Both pile lateral deformation and the developed bending moment along pile shaft are studied. Recommendations and conclusions are presented for the designer to avoid both buckling and plastic hinge failures.

2. Previous studies

Most previous studies performed and examined centrifuge tests as an experimental modeling technique. On the other hand, a few number of researches deal with the numerical solution approach to investigate the pile response and behavior in such conditions.

Meyersohn [1] conducted an analytical study of pile foundation response to lateral spreads using computer code B-STRUCT. The analysis results have been compared with field observations of pile deformations underground failure conditions. The results of the study have been used to develop dimensionless charts. These charts allow the determination of the failure mechanisms of piles with respect to the relative stiffness and pile axial load. Another set of charts have been developed to determine surface soil displacements related to excessive bending conditions and plastic hinge formation.

Popescu and Prevost [3] showed that the VELACS project offers a good opportunity to verify and validate various

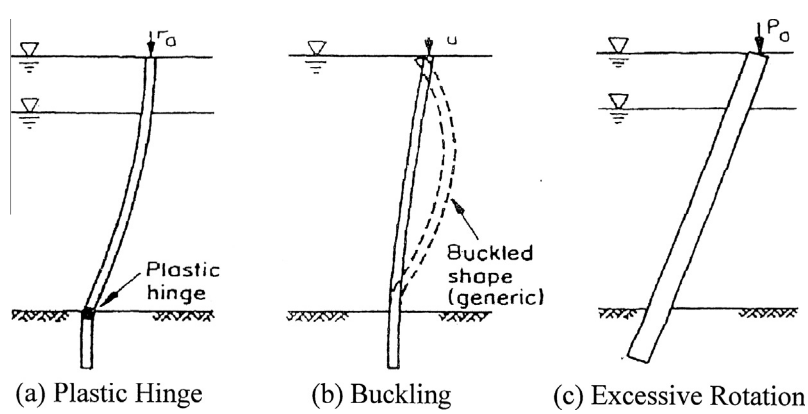

Figure 1 Pile failure mechanisms (after Meyersohn, 1994 [1]).