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Soil Dynamics and Earthquake Engineering 27 (2007) 395–413

SOIL DYNAMICS AND EARTHQUAKE ENGINEERING

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Three-dimensional numerical simulation of earthquake damage to group-piles in a liquefied ground

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Received 22 August 2006; received in revised form 16 October 2006; accepted 24 October 2006

Abstract

Dynamic behavior of group-piles in liquefied ground is discussed using numerical analyses. The process of damage to a group-pile foundation in reclaimed land is simulated using three-dimensional soil–water-coupled analysis with a soil–pile-building model. This study analyzed a five-story building that tilted northeastward because of serious pile damage during the 1995 Kobe earthquake. Analyses showed that the piles yielded immediately before complete liquefaction in the reclaimed layer, when the horizontal displacement of the building reached several tens of centimeters. In the early period before complete liquefaction of the reclaimed layer, inertial effects of superstructure on pile curvatures are apparent at both the pile head and at the bottom of the reclaimed layer. In contrast, after complete liquefaction of the reclaimed layer, the kinematic effect of connected footings on curvatures of piles is considerable at the bottom of the reclaimed layer.
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Keywords: Earthquake damage; Liquefaction; Group-pile; Three-dimensional soil–water coupled analysis; Soil–structure interaction

1. Introduction

Numerous structures with pile foundations in reclaimed ground were damaged seriously during the 1995 Kobe earthquake [1,2]. Among the damaged structures, many tilted and settled in spite of the fact that no remarkable damage occurred to the superstructure. In particular, the structures adjacent to quay walls were damaged severely. Field investigations and numerical analyses of some damaged pile foundations in reclaimed ground were conducted to clarify the damage process mechanism [3,4]. Those investigations revealed that not only the pile heads, but also the lower parts of the piles had cracked or failed. This phenomenon indicates that both the inertial force from the super structure and the kinematic interaction between the piles and the ground play important roles in the piles' mechanical behavior. The pile behavior is particularly complicated when the ground surrounding a structure liquefies as a result of seismic excitations. Damage related to liquefaction might involve cases in which the pile foundation is damaged because of the lateral flow of liquefied soils; alternatively, the piles might fail at the boundary between two different soil layers, of which one liquefies and the other does not.

Some damaged buildings with pile foundations tilted, indicating that the degree of damage to the piles differed according to the piles' locations. Most precedent analytical studies of soil–pile interaction used a one-dimensional (1-D) spring–mass model (a beam on a nonlinear Winkler foundation) or two-dimensional (2-D) finite element method (FEM). These methods cannot yield a precise prediction of the failure mechanism, such as different degree of the damage in horizontal plane, because they cannot take three-dimensional (3-D) structural properties and seismic excitation into account. Therefore, 3-D

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0267-7261/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soildyn.2006.10.003

analysis is needed to discuss the horizontal distribution of damage in the group-pile and the building's direction of inclination.

Soil–pile interaction behavior has been examined recently using 3-D finite element analyses. Numerous researchers have studied static 3-D behavior of a single pile or group-pile under lateral loading using nonlinear constitutive models [5–10]. Brown and Shie [6] and Trochanis et al. [7] investigated slippage and separation effects along with overall nonlinear soil behavior on the responses of single piles and pairs of piles using a 3-D finite element elasto-plastic model that incorporates interface elements. Wakai et al. [8], Zhang et al. [9], and Yang and Jeremić [10] compared the computed $p-y$ curves with those obtained from field tests, model tests and empirical methods that are commonly used in practice. Moreover, dynamic behavior of soil–pile interaction has been investigated using dynamic 3-D finite element analysis [11–16]. Effects of soil nonlinearity and of kinematic and inertial interaction on seismic response of piles and superstructures were investigated in those studies. Most of the past analyses have been based on total stress concept; they ignored the influence of liquefaction on the responses of piles and superstructures.

Liquefaction analysis has been developed since the 1980s by many researchers. The field equations of current liquefaction analyses are based on Biot's porous media theory [17]. Although several formulations have used different unknown variables, e.g. $u-U$, $u-w$ and $u-p$ formulations, the effect of the difference is not considerable in the earthquake problem [18]. The performance of a constitutive model, on the other hand, affects analytical results to a marked degree [19]. Many researchers have proposed various types of constitutive models; they have validated their models through simulations for dynamic behavior of ground and various structures based on experimental results and case histories. Most precedent studies, however, have relied upon 2-D analysis to assess linear structures such as embankments, quay walls, etc. Few investigators have developed dynamic 3-D soil–water-coupled analyses based on effective stress concept. Ohtsuki et al. [20], and Finn and Thavaraj [21] validated their 3-D soil–water coupled analysis method for the results of shaking table tests with group-piles in liquefiable ground under gravitational and centrifugal field. The dynamic behavior of group-piles in liquefiable ground depends on the nonlinear material properties of liquefied soil and piles. Therefore, we cannot infer general findings from a limited number of experiments. We require further study of dynamic pile behavior in liquefied ground through simulations of model tests and case histories, along with soil–water-coupled analysis.

This study simulates the process of damage to a pile foundation located in a reclaimed land with 3-D soil–water-coupled analysis using a soil–pile-building model. We analyze a five-story building that tilted northeastward because of serious damage to its piles during the 1995 Kobe earthquake. First, the vertical array records observed near the damaged building are simulated to validate the numerical model and clarify the seismic ground behavior. The direction of ground motion is also simulated. Second, the time and spatial distribution of the damage to the piles are discussed through analyses of 3-D soil–pile building system. Particular attention is devoted to the influence of a change in axial force on a group-pile behavior by incorporating an axial-force-dependent pile model into liquefaction analysis. The inertial effect of the superstructure and the kinematic effect of underground girders on the damage to piles are discussed along with the effect of vertical input motion on the damage.

2. Damaged building

Fig. 1 shows the location of the investigated building on the Fukaehama artificial island at the east edge of Kobe City [22]. The damaged building was about 350 m away from the western quay wall of the artificial island. Ejected sand and water were observed everywhere on the island after the earthquake [23]. Fig. 2 shows the horizontal residual displacement of the surrounding ground and the building [22]. Measurements were conducted in this study by comparing aerial photographs taken before and after

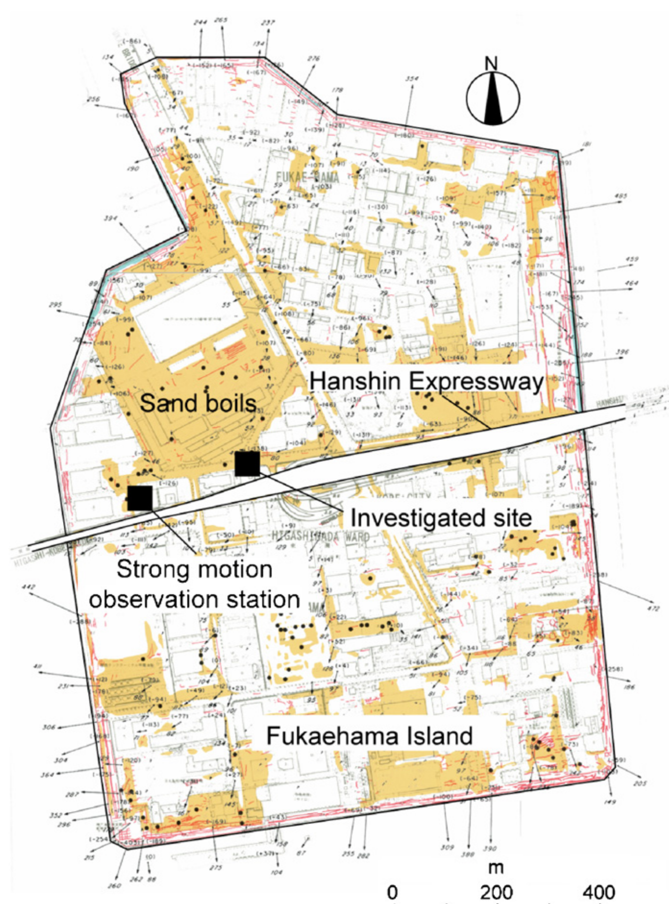

Fig. 1. Location of the investigated building (reproduced from [23]).

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