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Finite element modeling of soil-pile response subjected to liquefaction-induced lateral spreading in a large-scale shake table experiment

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ABSTRACT

This paper presents two-dimensional (2D) nonlinear dynamic finite element (FE) modeling of a large-scale shake table test conducted at the E-Defense shake table facility in Japan. This study explores the efficiency of 2D effective stress analyses to predict the behavior of soil-pile systems subjected to liquefaction and lateral spreading using the library of existing constitutive models and the prescribed parameters. The coupled soil-water FE model was developed in OpenSees and the analysis results are compared with measured data from the shake table experiment with the main emphasis on the response of liquefied soil and the demand applied to the piles as well as the sheet-pile quay wall. By examining the numerical analysis results, it is demonstrated that the FE model was able to reproduce the shake table model behavior with reasonable accuracy. Lastly, a mitigation strategy was modeled to investigate its effectiveness to reduce the demand on the soil-pile system.

1. Introduction

In recent earthquakes such as the 2010 Haiti, the 2010 Chile, the 2010–2011 Canterbury Sequence and the 2011 Great Tohoku earthquakes, extensive damage in pile foundations has been observed due to liquefaction-induced lateral spreading. Many researchers have investigated the basic mechanisms of this phenomenon through physical modeling including shake table experiments [1–5] and centrifuge tests [6–9]. In addition, a number of numerical simulations have been carried out based on physical experiments for validation and application using different modeling techniques [10–14].

In March 2006, a large-scale test on lateral spreading of liquefied sand behind a sheet-pile quay wall was performed at the E-Defense facility in Japan. The experimental data was analyzed by Motamed et al. [2], which studied the soil-pile interaction in laterally spreading grounds in detail. The experiment included a simple structure model supported on a 2×3 pile group located adjacent to a sheet-pile quay wall as shown in Fig. 1. The model was heavily instrumented to measure the dynamic response of the soil-pile system. Liquefaction-induced lateral spreading was achieved and the soil moved laterally about 1.1 m behind the quay wall. Based on the shake table experiment, a 2D numerical model was developed in this study using OpenSees [15] framework employing available constitutive models in its material library. The constitutive soil model used in this study was developed for granular materials subjected to cyclic loading with emphasis to undrained cases [16–18]. The suggested parameters of the constitutive model were calibrated for Nevada sand, which was significantly different from the sand used in the shake table experiment as explained in Section 3.1 in this paper. The numerical modeling produced comparable results to the experimental data and the details are presented hereafter.

In addition to modeling the behavior of the pile group subjected to the lateral flow of liquefied soil based on the large-scale experiment, this research explores the effectiveness of a mitigation measure to reduce seismic demands on the soil and the pile group. Motamed and Towhata [19] carried out a series of 1 g small-scale shake table model tests on a 3×3 pile group located behind a sheet-pile quay wall subjected to liquefaction-induced large ground deformation which was basically a 1/10 scale of the E-Defense shake table experiment. Three remedial techniques were explored in Motamed and Towhata [19], among which one of the studied mitigation measures was selected to be explored in this study. The selected mitigation strategy included installation of a mitigating sheet-pile with fixed-base boundary condition in between the pile group and the quay wall. This paper discusses the effectiveness of this method to reduce seismic demands using the OpenSees model and compared with the experimental results reported by Motamed and Towhata [19]. Lastly, a parametric study was performed to investigate the remedial effects of various types of mitigating sheet piles with different sectional properties, which are commonly used in engineering practice.

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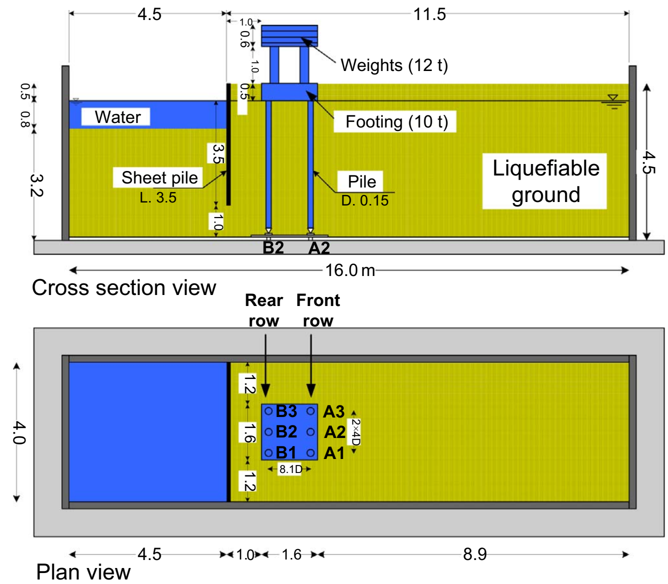

Fig. 1. Schematic illustration of large scale shake table test at E-Defense facility (unit: m) (Motamed et al. [2]).

2. Description of E-Defense shake table experiment

The shake table model of the soil-pile system was constructed in a large semi-rigid box with the dimensions of 16 m×5 m×4 m, and the soil configuration was a horizontal ground consisted of uniform liquefiable Albany Silica sand with the relative density of 60% underlain by a thin denser sand layer (Dr=70%). The basic properties of the soil profile are listed in Table 1 [20,21]. Similar to Kazama et al. [21], uniform shear wave velocity (V_S) of 120 m/s and Possion's ratio (γ) of 0.3 were adopted in this study. A LSP-2 type steel sheet pile quay wall was used, which deformed laterally and triggered the liquefaction-induced lateral spreading. Behind the quay wall, six hollow steel piles with outer diameters of 0.1524 m and thicknesses of 0.002 m were connected to the base using a hinge connection (i.e. zero displacement and moment). The piles were used to support the 12 t weight of the superstructure and the 10 t weight of the pile cap as illustrated in Fig. 1.

The large-scale model was subjected to two-directional ground motions (i.e. longitudinal and vertical) as presented in Fig. 2. The records obtained at the JR Takatori station during the 1995 Kobe earthquake were scaled down by 20% and chosen as the input motions. The maximum amplitudes of the horizontal and vertical components were 0.6g and 0.23g, respectively. More details on the shake table experiment can be found in Motamed et al. [2].

3. OpenSees numerical model

The 2D numerical model was built using OpenSees framework, which is an open source finite element software developed by UC Berkeley for earthquake engineering simulation [15] and post-processing was performed with GiD [22]. The discretization of the model is

Table 1
Soil properties of Albany silica sand [20,21].

Depth (m)	0.0 - 4.0	4.0 - 4.5
Relative density, Dr (%)	60	70
Density, ρ (t/m^3)	1.67	1.70
V_s (m/sec)	120	
Permeability, k (m/sec)	8.50E−05	
Void ratio, e	0.558	
Possion's ratio, γ	0.3	

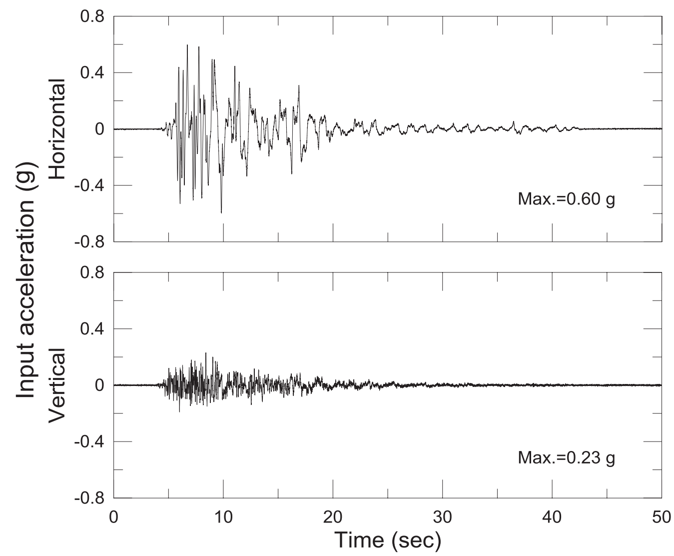

Fig. 2. Acceleration time histories of input motion.

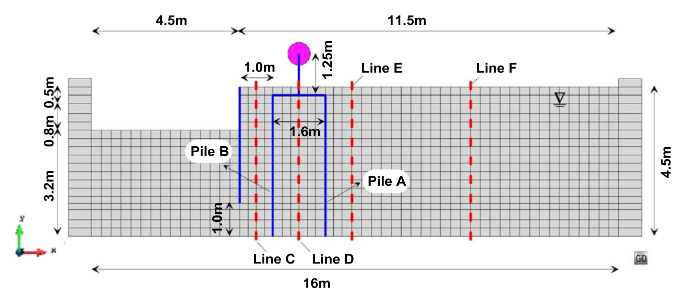

Fig. 3. FE model discretization of shake table experiment.

illustrated in Fig. 3. The maximum allowable soil element size of 0.5 m was determined to fit 20 elements within one shortest wavelength, i.e. 10 m, of the propagating shear wave [23,24]. In this manner, the propagating waves can be well captured in the analysis. The shortest wavelength within soil profile was calculated using the shear wave velocity of 120 m/sec and the maximum frequency content, i.e. 12 Hz, of the ground motion. Additionally, a convergence study was carried out to investigate the possibility of using finer mesh schemes with maximum element sizes of 0.25 m or 0.1 m. However, these models with refined discretization encountered convergence problem during dynamic analysis due to the fact they had redundant elements within one wavelength as reported by Zerwer et al. [23]. This finding reflects that the discretization of our model was sufficiently fine.

3.1. Elements, materials and boundary conditions

In the FE model, the saturated soil was simulated as a two-phase material using QuadUP elements [18] based on the Biot's theory [25] for porous media, in which displacement of the soil skeleton (u) and pore pressure (p) are the primary unknowns (u-p formulation). The out-of-plane thickness of the soil elements was set to be the same as the width of the container in the shake table test (i.e. 4 m) in order to capture the pinning effects around the piles when the soil is liquefied. The constitutive behavior of the soil was captured by the PressureDependMultiYield02 (PDMY02) material [16–18] available in OpenSees to simulate the response characteristics of sand. The parameters needed for the constitutive soil model as presented in Table 2 were selected based on a combination of recommended values from the constitutive model developer [18] and correlations with the measured parameters from the shake table experiment [20,21]. The low strain shear modulus of soil (G_{max}) was calculated based on