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Pile response to liquefaction-induced lateral spreading: a shake-table investigation

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ABSTRACT

Case histories have shown that the liquefaction-induced lateral spreading is one of the main causes of damage to pile foundations subjected to seismic loading. This study will investigate the effect of lateral spreading on a single pile behind a quay wall. A shake-table experiment on a single pile embedded in a fully saturated sand stratum is conducted. The ground surface and pile head displacement are in close agreement prior to liquefaction. Upon liquefaction, soil acceleration is clearly attenuated. Simple liquefied lateral soil pressure analysis approaches (uniform and triangular) are calibrated using the experimental results. Subsequently, a Beam on Nonlinear Winkler Foundation (BNWF) model is proposed, and the response is compared to the experimental results. It is found that the proposed BNWF model better predicts the observed pile response compared to the simple soil pressure approaches. A parametric study through the BNWF model is performed to explore the effect of several salient factors on the pile behavior. On this basis, it is shown that a larger pile bending stiffness decreases the lateral spreading-induced deformation, and a larger pile diameter for the same stiffness results in a higher displacement and bending moment.

1. Introduction

Post-earthquake investigations indicate that pile foundations suffer severe damage due to liquefaction-induced lateral spreading. Such damage was observed for strong earthquakes in the past [1–3]. As a consequence, the pile behavior under lateral spreading remains a topic of much research interest [4–8]. Deeper insight into the response of pile foundations to lateral spreading promises to improve current design methodologies and avoid catastrophic failure during future earthquakes. Pile foundation response to lateral spreading is a complicated problem of soil-structure interaction. A large amount of research has been dedicated to this problem, including shake-table experiments [9–18], centrifuge tests [19,20], and field tests [21].

To date, a number of reported shake-table experiments employed the quay wall to trigger liquefaction-induced lateral deformation [12–17]. To reveal the failure mechanism of pile foundations behind the quay wall, Sato and Tabata [13] performed two large-scale shaking table tests with lateral spreading of liquefiable sand. The test results indicated that residual deformation due to an earthquake greatly influences the pile deformation. A similar 1-g shaking table model test on a 3×3 pile group behind the quay wall was conducted to investigate the behavior of the pile foundations subjected to liquefaction-induced ground deformation [14]. Further, the experimental data of a series of shake table tests on a pile group were presented and analyzed under different quay wall constraint conditions [15]. The results demonstrated that the fixed-end quay wall mitigation measures can effectively reduce the soil displacement and further improve seismic performance of the pile foundations. More recently, using the E-Defense facility, a large-scale shake table test on a pile group located adjacent to the quay wall was completed to explore the seismic behavior of the pile group [16]. Tang et al. [17] and Haeri et al. [18] performed the shake table test on a pile foundations to investigate the lateral soil pressure on the pile due to liquefaction-induced lateral ground deformation.

However, there is no universal agreement for estimating liquefaction and lateral flow pressure on pile foundations [17,18,22–24]. Due to the complexity of the involved computational analyses [25–27], numerous simplified procedures have been developed [28–30]. Nevertheless, limited discussions have been reported so far regarding the influence of pile bending stiffness and diameter on the pile response due to lateral spreading.

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In this study, a shake-table experiment was conducted and the experimental data were analyzed. Two simple liquefied lateral soil pressure profiles [22,23] were calibrated. In addition, a Beam on Nonlinear Winkler Foundation (BNWF) model was adopted to simulate the pile response in the experiment. Next, a parametric study was performed using the BNWF model. Finally, the reported results were utilized to draw insights and conclusions, and future works are proposed.

2. Description of the shake-table experiment

A shake-table experiment on a single pile behind a quay wall (Fig. 1) was performed at the Institute of Engineering Mechanics (IEM), China Earthquake Administration, located at Harbin. The shake-table experiment employed a rectangular laminar container that was 3.5 m long, 2.2 m wide, and 1.7 m high.

The soil profile consisted of a horizontal saturated 1.5-m thick sand stratum (Fig. 2). The water table was at the ground surface. The sand stratum was prepared using the water sedimentation method [31]. Relative density (D_r) of the sand stratum was 45–50%, and the saturated density was approximately 1900 kg/m^3. Table 1 summarizes the material properties of this sand.

Before construction of the soil stratum, a steel pipe pile with a 0.088-m diameter was installed, unconstrained at the top and connected to the container base. In an attempt to achieve a fixed-end condition, the pile was inserted into a socket at the base,

Table 1
Material properties of Harbin sand.

Specific gravity (g/cm^3)	2.5
Maximum void ratio (e_{max})	0.89
Minimum void ratio, (e_{min})	0.37
Coefficient of curvature, (C_c)	0.91
Coefficient of uniformity, (C_u)	2.98
Mean particle diameter, D_{50} (mm)	0.51
Fines content, F_c (%)	2

Fig. 1. Shake-table experiment.

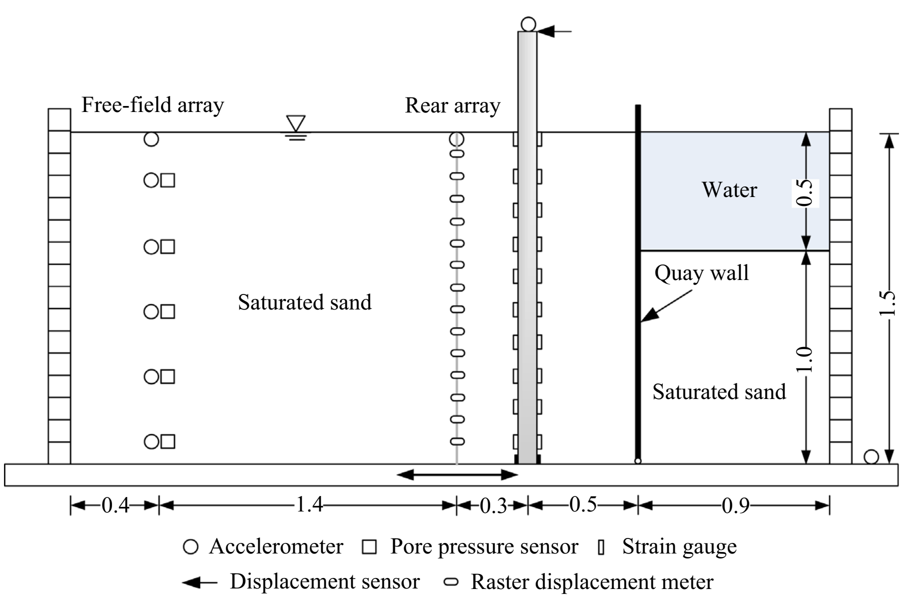

Fig. 2. Experimental setup (unit: m).