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Interpretation from large-scale shake table tests on piles undergoing lateral spreading in liquefied soils

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Abstract

Results from a benchmark test on full-scale piles are used to investigate the response of piles to lateral spreading. In the experiment, two single piles, a relatively flexible pile that moves together with the surrounding soil and a relatively stiff pile that does not follow the ground movement have been subjected to large post-liquefaction ground displacement simulating piles in laterally spreading soils. The observed response of the piles is first presented and then the results are used to examine the lateral loads on the pile from a non-liquefied soil at the ground surface and to evaluate the stiffness characteristics of the spreading soils. The measured ultimate lateral pressure from the crust soil on the stiff pile was about 4.5 times the Rankine passive pressure. The back-calculated stiffness of the liquefied soil was found to be in the range between 1/30 and 1/80 of the initial stiffness of the soil showing gradual decrease in the course of lateral spreading.

Keywords: Pile response; Liquefaction; Lateral spreading; Large-scale shake table test; Reduction of soil stiffness; Lateral soil pressure

1. Introduction

The most frequently encountered soil profile for piles in liquefied deposits consists of three distinct layers, as illustrated in Fig. 1 where the liquefied layer is sandwiched between a non-liquefied crust layer at the ground surface and non-liquefied base layer. Liquefaction during strong ground shaking results in almost a complete loss of stiffness and strength of the liquefied soil, and consequent large ground deformation. Particularly large and damaging for piles can be post-liquefaction ground displacements due to lateral spreading [7]. During the spreading, the non-liquefied surface layer is carried along with the underlying spreading soil, and when driven against embedded piles, the crust layer is envisioned to exert large lateral loads on the piles. Thus, the excessive lateral movement of the liquefied soil, lateral loads from the surface layer and significant stiffness reduction in the liquefied layer are key features that need to be considered when evaluating the pile response to lateral spreading.

In the light of the liquefaction characteristics and kinematic mechanism as above, a three-layer soil model was adopted in a previous study [4] for a simplified analysis of piles. In the adopted pseudo-static approach, the spreading is represented by a horizontal displacement of the liquefied soil whereas effects of the non-liquefied surface layer are modeled by an earth pressure and lateral force at the pile head, as shown in Fig. 1. Here, the earth pressure represents the loads that act directly on the pile while the lateral force approximates the loads that are transferred to the pile through the upper foundation. Using the secant-stiffness approach, the interaction between the liquefied soil and the pile is assumed to be specified by an equivalent linear spring (βk) where k is the subgrade reaction coefficient representing the initial stiffness of the soil while the reduction in stiffness due to liquefaction is taken into account by way of the degradation factor β.

Key parameters influencing the pile response are the magnitude of lateral ground displacement (U_G), ultimate pressure from the surface layer (p_u) and stiffness reduction in the liquefied layer (β), as indicated in Fig. 1. These

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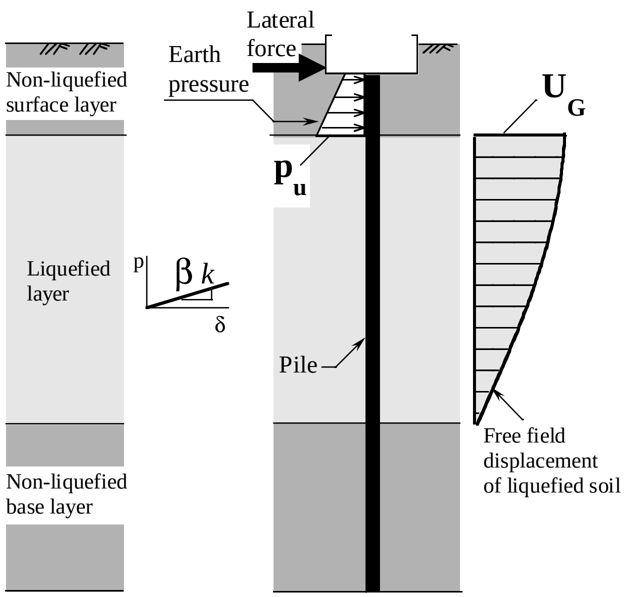

Fig. 1. Simplified kinematic mechanism of lateral spreading.

parameters are associated with intrinsic uncertainties, however, and therefore one encounters difficulties in selecting their most appropriate values. For this reason, great efforts have been made over the past decade either to back-calculate these parameters from well-documented case histories of recent earthquakes or to evaluate them using sophisticated experiments on scaled-down soil–pile models. In this paper, results from a benchmark experiment on full-size piles are used to investigate the lateral loads from a non-liquefied surface layer on the pile and stiffness characteristics of liquefied soils undergoing spreading. The ultimate lateral pressure from the surface layer on a single pile (p_u) and characteristics of the stiffness reduction parameter (β) are examined in detail.

2. Large-scale shake table experiment

The test was conducted by the Japan Electric Power Civil Engineering Association (JEPOC) using the large-scale shake table of the National Research Institute for Earth Science and Disaster Prevention (NIED) at Tsukuba, Japan. The test was specifically designed for investigating the response of piles to large post-liquefaction ground displacements, as described in the following.

2.1. Physical model

A prototype model of piles was prepared in a laminar box with dimensions of 12 m×3.5 m×6 m (length–width–height), bottom-fixed at a large shake table. The model consisted of two single piles embedded in a deposit of saturated sand with a crust layer of sand above the water table, as shown in Fig. 2(a).

A steel pile with an outer diameter of 31.8 cm and a pre-stressed high-strength concrete pile (PHC-pile) 30 cm in outer-diameter were used in the test. The 4.9 m long piles were fixed at the base and free at the top. The piles were installed at a distance of about 15 pile-diameters and were considered therefore free of cross-interaction effects. Moment-curvature relationships of the test piles are shown in Fig. 3 where point *C* denotes concrete cracking, point *Y* indicates yielding of steel or reinforcement, respectively, and concrete crushing or the ultimate level for the PHC pile is denoted by point *U*.

The sand deposit consisted of two horizontal layers of Kasumigaura sand ($D_{50}=0.265$ mm, $U_C=2.36$ and $F_C=3\%$), both at a relative density of about 50%. The lower saturated sand layer was prepared by pouring sand into the laminar box through a water layer of about 50 cm to the prescribed height of 3.8 m from the base of the piles. The crust layer at the ground surface was prepared by placing dry sand above the water table.

A large number of accelerometers, pore pressure transducers, displacement and pressure gauges were installed to measure the response of the piles and ground. Pairs of strain gauges were installed at a regular distance of 20 cm along the pile body for measuring bending strains of the piles. In total, 227 channels were used for data acquisition in the experiment. Details of the experimental set-up and instrumentation are given in [16].

2.2. Dynamic excitation and lateral loading

The experiment was conducted in two phases, as shown in Fig. 2(a) and (b). In the first phase, the model was shaken with a sine wave excitation in the longitudinal direction (Fig. 2(a)). The applied base-input motion had peak acceleration of 0.217 g, frequency of 2 Hz and duration of the intensive part of 30 s (60 cycles). The key objective in this phase of the test was to induce liquefaction in the saturated sand deposit while keeping the response of the piles in the range of elastic deformations.

Once liquefaction was induced and the dynamic phase of the test was concluded, a rigid loading frame was attached to the outer-side of the laminar box and the liquefied portion of the deposit was subjected forcibly to a lateral movement with a rate of 4.1 cm/s at the top of the layer, as shown in Fig. 2(b). This second phase of the test aimed at subjecting the piles to large post-liquefaction ground displacements simulating piles in laterally spreading soils. It is apparent from the time scale of the applied accelerations and displacements in the subsequent loading phases shown at the bottom of Fig. 2(a) and (b) that the lateral ground movement was initiated about 6 s after the end of the shaking phase, which was approximately the time required to attach the loading frame to the laminar box. The application of lateral ground movement