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Shaking table test on reinforcement effect of partial ground improvement for group-pile foundation and its numerical simulation

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Abstract

In this paper, particular attention was paid to the seismic enhancement effect of group-pile foundation with partial ground improvement method that is used for existing pile foundations in practical engineering. A model test on a full system with a superstructure, a nine-pile foundation and a sandy ground was conducted with the shaking table test device. The model pile is made from aluminum and the model ground is made from Toyoura Sand. The shaking table test device is 120 cm in width and 160 cm in length. The maximum acceleration is 1 g and the maximum displacement is 5 cm. The maximum payload is 16 kN and the highest frequency is 10 Hz. The model ground is carefully prepared to obtain a ground with controllable unified density. Before the shaking table test, the pattern of the partial ground improvement for an existed group-pile foundation is carefully selected using numerical tests with a 3D elastoplastic static finite element analysis. In the analysis, the nonlinear behavior of ground and piles are described by the cyclic mobility model (Zhang et al., 2007) and the axial force dependent model (AFD model) proposed by Zhang and Kimura (2002) can take into consideration of axial-force dependency in the nonlinear moment–curvature relations. The applicability of the numerical analysis has been verified in previous works by comparing the numerical results with a real-scale field tests (Kosa et al., 1998). Based on the results from the numerical tests on seismic enhancement effect of group-pile foundation with ground improvement, an optimum pattern of partial ground improvement of an existing pile foundations has been picked out for shaking table test. A numerical analysis using the program DBLEAVES (Ye, 2007) is also conducted for the same optimum pattern for comparison purposes. The effectiveness of the partial ground improvement method has been proved by both the shaking table test and the numerical analysis.

Keywords: Group-pile foundation; Shaking table test; Seismic enhancement; Partial ground improvement; Soil–pile interaction; Numerical test

1. Introduction

In order to clarify the mechanical behaviors of pile foundations at their ultimate state during strong earthquakes, a great volume of research based on the tests on group-pile foundation subjected to lateral loading either in model scale or in real-scale has been conducted. For instance, Tokimatsu et al. (2007) conducted a shaking table test using E-defense, one of the largest shaking table test

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devices in the world, to estimate the effects of dynamic interaction among soils, pile foundation and superstructure. Shirato et al. (2008) also conducted a large-scale shake table experiment on the nonlinear behavior of pile-groups subjected to lateral loading during huge earthquake. Motamed et al. (2009) conducted a shaking table test using E-Defense to investigate the behavior of pile group behind a sheet pile quay wall subjected to liquefaction-induced large ground deformation.

Uno et al. (2011) reported their results on shaking table tests of bridge pile foundation in liquefied ground, focusing on the sectional force which occurred in the middle part of pile. Ishizaki et al. (2011) conducted a dynamic centrifuge model test to investigate the mechanical behavior of a pile-supported building with semi-rigid head connection in liquefiable soil. Bhattacharys et al. (2011) reported the results of dynamic centrifuge tests to study the transient bending moments in piles during liquefaction. Tazoh et al. (2011) conducted centrifuge tests to investigate the seismic behavior of batter pile foundation.

Also, many engineering problems related to pile foundation subjected to lateral loading have been investigated. Kimura et al. (2007) reported their research work on the development and application of sheet piles with H-joint steel pile in the construction of foundations for structures. Shirato et al. (2006) made a careful investigation into the effects of the stress-dilatancy behavior of soil on load transfer hysteresis in the soil–pile interaction. Khan et al. (2008) investigated the static stability of a sheet pile quay wall improved by cement treated sea-side ground with centrifuge model tests. Khan et al. (2009) also conducted dynamic centrifuge tests to verify the behavior of a sheet pile quay wall stabilized by sea-side ground improvement. Tomisawa and Miura (2007) researched the mechanical behavior of a pile foundation constructed in composite ground. Motamed et al. (2010) did an experiment on large pile groups in sloping ground subjected to liquefaction-induced lateral flow using 1G shaking table tests. Uzuoka et al. (2008) reported their interesting results about the effects of seepage and inertia on rate-dependent reaction of a pile in liquefied soil. Hara et al. (2010) conducted an experimental study on the application of piled geo-wall, a composite of independent reinforced soil structures with pile foundation, as a seismic enhancement measure for embankments. More detailed remarks on the research on pile foundation engineering can be found by referring to the work by Kusakabe and Kobayashi (2010).

It is known that during a strong earthquake, the dynamic behavior of a group-pile foundation is related not only to the inertial force coming from superstructures but also to the deformation of the surrounding ground. Therefore, in the seismic evaluation of group pile foundations, it is necessary to understand the behaviors of both group-pile foundations and superstructures simultaneously during a major earthquake. Needless to say, a full-scale loading test is the most accurate way to determine the mechanical behaviors of deep foundations, but this is extremely expensive and time consuming. Numerical simulation also plays a very important role in determining these behaviors, and a large number of numerical studies have been performed in this field. Ye (2007) developed a three-dimensional static and dynamic finite element analysis code named DBLEAVES based on a finite deformation scheme. In order to confirm the applicability of the proposed numerical method, a real-scale field test of 9-pile foundation subjected to horizontal cyclic loading (Kosa et al., 1998) was simulated with a three-dimensional (3D) soil-water coupling finite element method (FEM) using the DBLEAVES. The results are quite convincing and the applicability of the DBLEAVES has been firmly verified by a comparison of the numerical results with the field test results (Jin et al., 2010).

In this paper, numerical tests on the seismic enhancement effect of existing group-pile foundations with ground improvement are first conducted to find out the optimum pattern of ground improvement around existing pile foundations. In the numerical tests, three influential factors are considered; that is, the depth, the thickness (or height) and the width (or length) of the ground-improvement zone around the pile group. The numerical tests are conducted in the static push-over condition. The main purpose of the research is firstly to find the optimum pattern for partial-ground improvement around an existing pile foundation, and secondly, to confirm the efficiency of seismic enhancement by the partial-ground improvement method both by shaking table tests and numerical analyses. As a consequence, the applicability of the DBLEAVES for evaluating the seismic behavior of pile foundations is verified again. In the numerical analyses, the nonlinear behaviors of ground and pile are described by cyclic mobility model (Zhang et al., 2007) and axial force dependent model (AFD model) proposed by Zhang and Kimura (2002), respectively.

2. Numerical tests on the reinforcement effect of ground improvement around existing pile foundations

Cement-treated ground improvement around existing group-pile foundations, as shown in Fig. 1, is one way to effectively increase the seismic resistance of pile foundation with some distinct advantages: it is low cost, and requires relatively little time and little space for construction. Some researchers and the applications of this method can be found in the works by Maeda et al. (2008) and Adachi (2009). The problem, however, is how to find out the optimum pattern since this depends on the size and the position of the improved ground zone. In this section, numerical tests on a group-pile foundation are conducted using the DBLEAVES (Ye, 2007). Calculations are conducted in the static loading condition. Based on the numerical tests results, the optimum size and position of the ground improvement zone are determined with the static analyses by judging the validity of the ground improvement in different conditions.

Fig. 2 shows the geological profile of ground and the 3D-FEM mesh used in the numerical tests. The ground is