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Exploring influence of sectional flexural yielding on experimental pile response analysis and applicability of distributed plastic hinge model in inelastic numerical simulation for laterally loaded piles

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ABSTRACT

This study used model pile load testing and numerical analysis to investigate the experimental analysis results of pile and soil responses for lateral load testing due to the flexural yielding of a pile, and to examine the applicability of the distributed plastic hinge model to the numerical simulation of inelastic pile response. A lateral load test on an aluminum model pile in sand was conducted as an analysis case. The pile was loaded to a large lateral pile-head displacement, a displacement under which some of the pile sections yielded and thus the pile had inelastic flexural deformation. The test results showed that before the pile yielded, the depth of maximum moment increased with increasing load due to soil nonlinearity; after the pile yielded, the depth of maximum moment varied less and the plastic region expanded upward and downward around this depth with increasing pile displacement. In deducing the responses of the pile and soil for the pile-soil system, the actual nonlinear flexural rigidity of the pile section built based on the bending test was essential to retrieve rational ones. In addition, the distributed plastic hinge model was shown to be effective to model the inelastic pile responses and capture the development of plastic zones in the pile.

1. Introduction

When piles are subjected to large lateral loading, they are easily damaged due to high bending stresses induced in them. For a yielded pile, conventional elastic analysis needs to be modified to consider the influence of flexural yielding of the pile section.

For investigating the interaction between pile and soil, many studies based on lateral pile load testing have been carried out. Most of these studies focused on the development of relationships of soil reaction and lateral pile displacement (called *p–y* curves) for different soil conditions (e.g., [1–5]). In their analyses, the test piles were assumed to be elastic and the pile responses were analyzed based on the beam theory. However, for a pile load test in which the pile might yield, the nonlinear sectional flexural property of the pile should be considered to obtain correct experimental pile responses and *p–y* curves. Chiou et al. [6] analyzed the inclinometer data of a full-scale lateral load test on a precast concrete pile. The pile in the test experienced a high degree of flexural nonlinearity, even finally reached flexural failure due to large bending curvatures. In deducing the experimental pile responses and *p–y* curves, the nonlinear moment–curvature relationships computed from section analysis were used. Ozden and Akdag [7] conducted *p–y* analysis for concrete model piles using equivalent pile bending stiffness values which were calibrated from the measured pile-head displacements for the effect of pile-section flexural nonlinearity. In those analyses for *p–y* curves described above, the nonlinear sectional flexural properties adopted could contain uncertainty because they were estimated from section analysis or calibration, but not directly from experiments. These test piles used were concrete piles whose sectional properties may be influenced by many factors, such as stirrup confinement and nonlinear properties of concrete and steel [8,9], such that the analysis results obtained contained uncertainty from the sectional flexural property adopted.

On the other hand, for numerical simulation of a pile under lateral loading, the Winkler-beam model is easy in engineering practice. For modeling the flexural nonlinearity of the pile, either nonlinear beam element or plastic hinge method can be applied, in which the latter is commonly employed in structural analysis. The plastic hinge method utilizes a point hinge to simulate the plastic deformation. There are two main categories of plastic hinge modeling: concentrated plastic hinge model and distributed plastic hinge model. The concentrated plastic-hinge model is usually used in structural modeling when the locations and the ranges of plastic

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regions are well defined. But this type of modeling is not appropriate for piles because they are embedded in soils so that the locations and the ranges of plastic regions are not clear and cannot be determined beforehand. Therefore, Chiou et al. [10] introduced the distributed plastic hinge model to piles. Without a precise position of plastic regions, the distributed plastic hinge model that places many plastic hinges along potential plastic regions can effectively model the development of the plastic regions. This model has been applied to many numerical analyses of pile-supported structures (e.g., [11–12]). Chiou et al. [10] also used a field pile test to verify their model; however, other tests under different test conditions with well controlled measurements are still necessary for more demonstration of the model.

Therefore, this study had two purposes: (1) to investigate effects of flexural yielding on the pile response and soil reaction analysis results based on the bending strain measurements of lateral load testing of piles, and (2) to demonstrate the effectiveness of the distributed plastic hinge model. To this end, we designed a model pile load test as an analysis case. In the test, the pile was loaded to yield and the pile bending strains were recorded. The test data were analyzed and the experimental pile responses and associated *p*–*y* curves obtained using linear and nonlinear sectional flexural properties were compared. Also, pushover analyses based on the distributed plastic hinge model were conducted to simulate the inelastic pile responses during the testing. To obtain the actual flexural property of the pile section for the above analyses, a bending test was performed to determine the complete nonlinear moment–curvature relationship of the pile section.

2. Lateral load testing

The model pile-soil system consisted of an aluminum model pile embedded in sand, as displayed in Fig. 1. The model pile was a pipe of outer diameter 101.6 mm, thickness 3 mm and length 1.6 m. The basic properties of the pile are listed in Table 1. The layout of instrument sensors is shown in Fig. 2. The strain gauges were attached to the pile at elevations of 0.01, 0.25, 0.40, 0.55, 0.70, 0.85, 1.00, 1.15, 1.30 and 1.45 m from the bottom, each with four gauges orthogonally on the four faces of the pile. Vietnam sand was used in the test and its basic properties are listed in Table 2. The soil was prepared to be fully saturated in a box of inner dimensions of 2.64 m × 2.64 m × 1.52 m. The thickness of the soil specimen was about 1.27 m and the relative density of the soil was about 73.1%, which is categorized as dense sand [13].

The model pile-soil system was designed to be a semi-flexible pile system because of the limited thickness of the soil specimen. In order to produce significant lateral displacement at the pile top, the pile tip was fixed in the test to have zero displacement

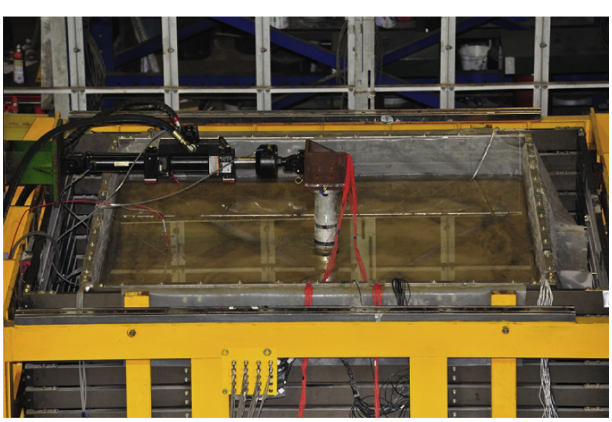

Fig. 1. The model pile test.

Table 1
Basic properties of the aluminum model pile.

Outer diameter (mm)	101.6
Inner diameter (mm)	95.6
Thickness (mm)	3
Length (mm)	1600
Density (g/cm^3)	2.7
Yield tensile strength (kg/cm^2)	1505
Ultimate tensile strength (kg/cm^2)	1935
Shear strength (kg/cm^2)	1197

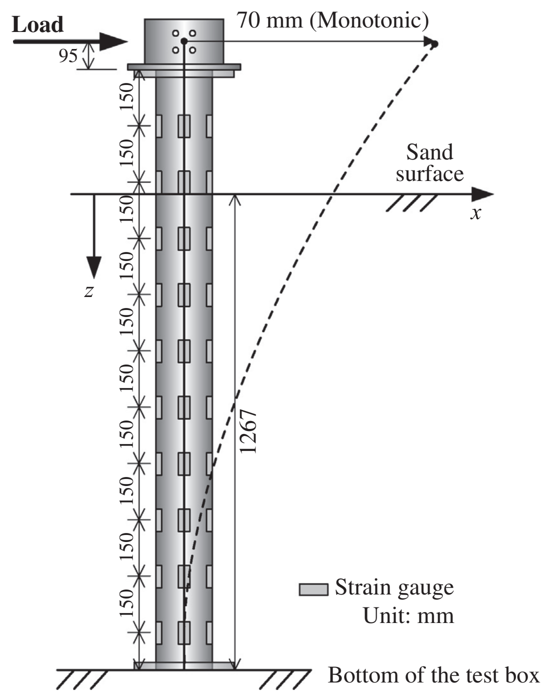

Fig. 2. Test layout.

Table 2
Basic properties of Vietnam sand.

Shape	Angular
Color	White
Specific weight G_s	2.65
D_{10} (mm)	0.17
D_{60} (mm)	0.31
Uniform coefficient C_u	1.82
e_{max}	0.951
e_{min}	0.650

and rotation at the pile tip. Therefore, the pile displacement could be computed by integrating the measured bending strains along the pile. For this pile-tip condition, the pile-soil system was regarded as a pile embedded in a hard rock or a very stiff soil with shallow overburden.

For the lateral load test, an actuator was mounted onto the top of the pile. The actuator was controlled to push the pile with specified displacement increments. The pile was monotonically loaded beyond the yield point of flexure upon a large lateral displacement. As shown in Fig. 2, the maximum pile-head displacement was 70 mm (about 70% pile diameter).

3. Sectional flexural properties

To retrieve the actual flexural property of the model pile, the bending test on another model pile with the same type as that used