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Dynamic Centrifuge test and BNWF analysis on piles in dry sand

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ABSTRACT

A series of dynamic centrifuge model tests was performed on a pile-soil system for the various amplitudes of input acceleration to investigate the dynamic behavior of a pile in dry sand. The lateral response of pile foundations in sand is commonly analyzed using p-y elements attached to the pile, often using the API sand p-y relationship. The API relationship was developed for static loading conditions, with cyclic correction factors intended to represent degradation due to many slow loading cycles. However, the API model is often applied for dynamic loading conditions (e.g., earthquake shaking) because suitable alternatives have not been formulated. This study demonstrates that the API sand functional form is not ideal for dynamic analysis of piles, on the other hand, a new functional form of p-y curve better captures the nonlinear p-y behavior of piles in sand during earthquake loading.

1. INTRODUCTION

Predicting dynamic behavior of piles during an earthquake has been one of the most important challenges to geotechnical engineers. The analysis of the lateral behavior of pile foundations has been investigated using 2D and 3D modeling of pile-soil system using finite element or finite difference methods [Kim et al. (2012)]. Beam on a Nonlinear Winkler Foundation (BNWF) analysis is also well known method which is considerably less complex than other numerical methods [Boulanger et al. (1999)]. For BNWF analysis, p-y material model behavior is very important because the surrounding soil is represented entirely by nonlinear springs.

The API p-y curve (API, 1993), which was developed for static loading conditions, is usually applied for dynamic loading condition because suitable alternative have not been formulated. Researchers have investigated p-y behaviour for dynamic loading conditions. Dobry et al. (2003) reported that the API p-y curve underestimates the ultimate resistance of soil under dynamic loading. Yang et al. (2011) and Yoo et al. (2013) investigated the behavior of p-y curves under dynamic loading conditions from a series of shaking table tests. They reported that the API p-y curve not only significantly underestimates the ultimate resistance of soil for shallow depths but also overestimates the subgrade reaction modulus of soil when the displacement of a pile is less than 1%

of the pile diameter.

In this study, BNWF analysis was carried out by implementing API p-y curve and a new p-y functional form of p-y curve suggested by Choi et al. (2015). The analysis results were compared with the dynamic centrifuge test results.

2. CENTRIFUGE TESTS

The dynamic centrifuge model tests for a single pile were conducted at the Korea Construction Engineering Development Collaboratory Program (KOCED), Geo-Centrifuge Center, on a centrifuge which has a radius of 5 m, 2.5 ton payload and up to 100 g centrifugal acceleration. All tests in this study were carried out at a centrifugal acceleration of 40g.

The model container used for the centrifuge tests was an Equivalent Shear Beam (ESB) box. Fig. 1 shows the schematic layout of a single pile and instrumentation for the centrifuge tests. The model pile was fabricated with a close-ended aluminum pipe with 2.5 cm external diameter and a 0.1 cm wall thickness, and the embedment depth of a pile was 57 cm and it was fixed against translation at the base. The concentrated mass of 1.0 kg was attached to the pile at the height of 13 cm from the surface to simulate a superstructure.

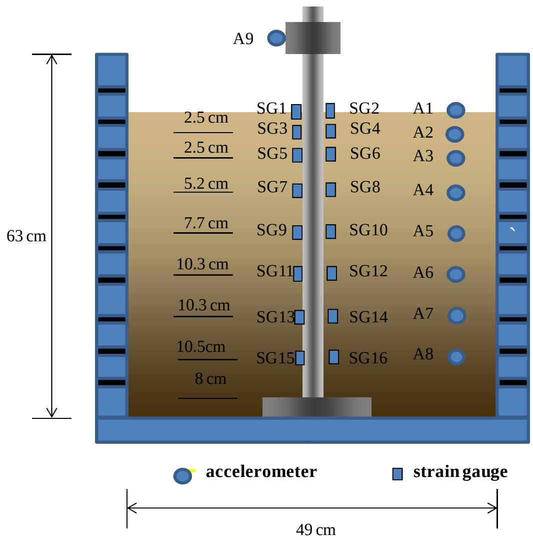


Fig. 1 Schematic layout and instrumentation for model soil-pile system (model scale)

Strain gauges were attached on both sides of the pile to measure curvature in the pile during vibrations. Bending moments were computed from measured curvatures based on the observation that the pile behavior remained elastic during shaking. Accelerometers were used to measure the acceleration responses of the soil and the superstructure. Eight accelerometers were installed in the soil with varying depths and one accelerometer was attached to the upper mass.

The model soil was Jumoonjin sand, characterized as fine-grained uniform sand. The dry sand deposit was prepared to have a relative density of 80% to minimize changes in relative density during the shaking sequence.

A sequence of sinusoidal wave excitations was imposed on the base of the model. The amplitude of the input sinusoidal wave varied from 0.05g to 0.3g and the frequency was 1Hz in the prototype scale.

3. DESCRIPTION of BNWF ANALYSIS

Beam on Nonlinear Winkler Foundation (BNWF) analyses were carried out to analyze the lateral behavior of a pile by implementing p-y curves in OpenSees, an open source finite element modeling platform that is freely available to users. Fig. 2 shows the description of BNWF analysis. The soil-pile system is modeled utilizing displacement based beam elements for the pile and nonlinear spring elements which represents the lateral response of the surrounding soil. The vertical displacement is fixed at the bottom of the pile. Input motions from recorded acceleration along the soil depth were imposed at the end of each spring node.

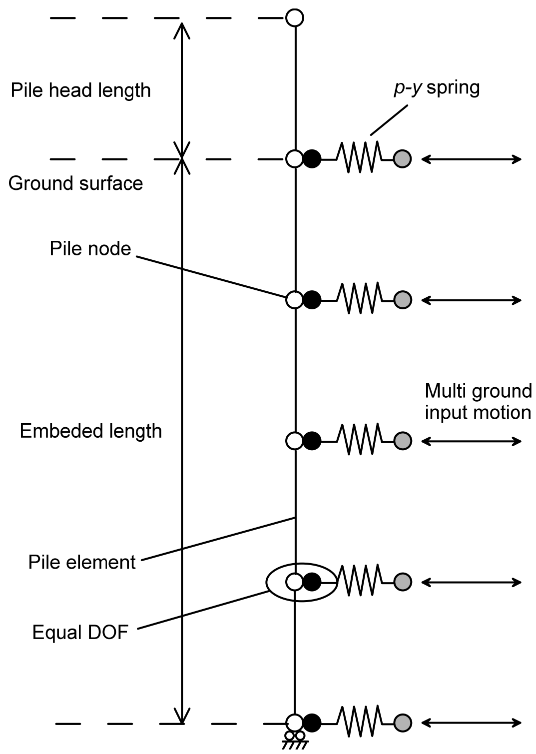


Fig. 2 Schematic diagram of BNWF analysis

4. ANALYSIS RESULTS

4.1 API sand model

The PySimple1 uniaxial material in OpenSees using soil type 2 approximates the functional form of the API sand equations, and this relation was used herein. Fig. 3 shows the comparison of the acceleration response at the upper mass between analysis results and test results in prototype scale. Three graphs at the first column show the results when the initial modulus of subgrade reaction was set to be 14,610 kPa, which is the secant modulus of the experimental backbone curve for the amplitude of input ground motion of 0.05g. It was found that the analysis result predict the centrifuge result reasonably well for the case of the amplitude of input ground motion is 0.05g. However, the analysis results overestimate the centrifuge test results for the case of the amplitude of input ground motion is 0.15g and 0.3g. For each input motion, a particular subgrade reaction modulus could be selected to provide reasonable agreement with the test data, but the appropriate subgrade reaction modulus was found to depend on shaking amplitude. For example, subgrade reaction moduli of 14,610, 10,680, and 6,481 kPa were required to provide a good match with the experimental data for input shaking intensities of 0.05, 0.15, and 0.3g, respectively. This is an undesired feature that indicates the functional form of the API sand p-y curve is incorrect.

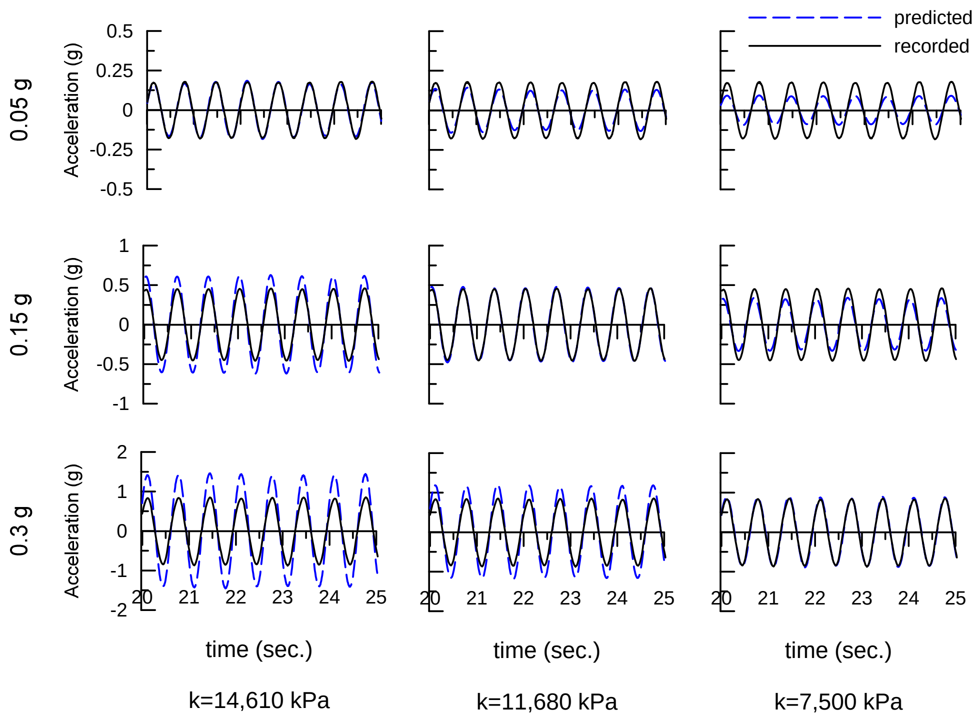


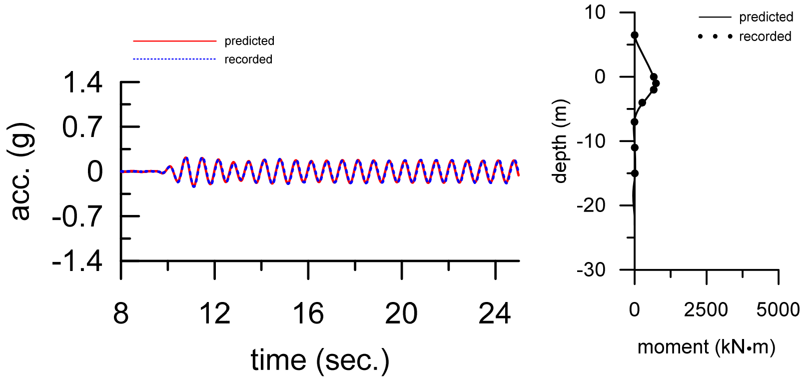
Fig. 3 Comparison between analysis results using API p-y curve and centrifuge test results

4.2 Proposed model

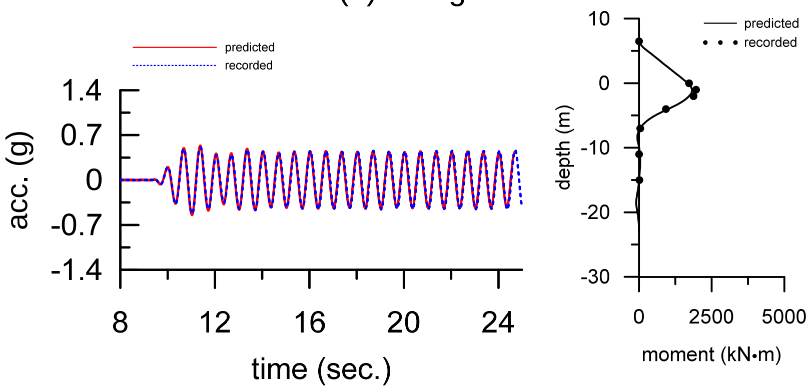
Choi et al. (2015) suggested a new functional form that better captures the nonlinear behavior of p-y curves under dynamic loading conditions is using the bounding surface plasticity theory.

Fig. 4(a) ~ (c) shows the comparison between the analysis results using the new functional form of p-y model and the centrifuge test results in terms of the acceleration at the upper mass and the bending moment along the depth of the pile.

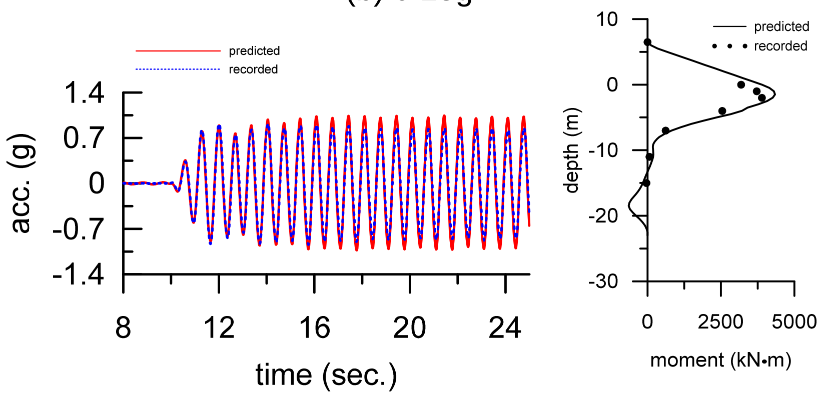
The analysis results predict the centrifuge results within error of 2% and 4% for the amplitude of input ground motion of 0.05g and 0.15g, respectively. In case of 0.3g input motion, the prediction is 20% larger than the measurements. Nevertheless, these results show a significant improvement compared to the analysis results using API p-y curve because a single set of input parameters is able to capture the response over a range of shaking intensities.



(a) 0.05g



(b) 0.15g



(c) 0.3g

Fig. 4 Comparison between analysis results using proposed p-y model and centrifuge test results

5. CONCLUSIONS

In this study, a series of dynamic centrifuge tests and beam on a Nonlinear Winkler Foundation (BNWF) analysis which considering the surrounding soil as spring elements was performed to investigate the lateral behavior of a pile under earthquake loading condition. The spring elements were modeled using both the API p-y curve and the new functional form of p-y curve. The analysis results were compared with the centrifuge test results.

The API p-y curve was significantly different from the experimental p-y backbone curve because the API p-y curve not only underestimates the ultimate resistance of soil but also overestimates the subgrade reaction modulus at the small displacement range. The BNWF analysis results implementing the API p-y curve as spring elements indicates that the API p-y curve is inappropriate to predict the behavior of piles under earthquake loading condition.

The new functional form of p-y curve was proved to capture the experimental p-y backbone curve reasonably well. The BNWF analysis results implementing the new functional form of p-y curve predicts the dynamic centrifuge test results within error of 20 % in terms of the acceleration at the superstructure and the bending moment distribution along the depth of a pile.

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