Three dimensional numerical simulation of piles in liquefiable ground

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ABSTRACT

This paper presents a three-dimensional finite element simulation method for the seismic response of piles in liquefiable soils using a unified plasticity model for large post-liquefaction shear deformation of sand. The unique constitutive model used is able to achieve unified description of the behavior of sand at different states under monotonic and cyclic loading during both pre- and post-liquefaction regimes. In the finite element analysis, soil is modelled through u-p form coupled brick elements and pile through second-order brick elements. Centrifuge shaking table experiments on single piles in level and in lateral spreading ground was simulated using the proposed finite element analysis method. Simulation results exhibits the method’s effectiveness in reproducing the dynamic response of both the ground and piles.

Keywords: liquefiable ground, constitutive model, seismic pile response, finite element simulation, centrifuge shaking table test

1 INTRODUCTION

The analysis of the seismic response of piles in liquefiable ground is an important and challenging topic in the field of geotechnical earthquake engineering. Various methods have been adopted, including both force and displacement based pseudo-static analysis methods often used by design codes (e.g. JRA, 2002; API, 2000), dynamic beam based one-dimensional analysis methods (e.g. Boulanger et al, 1999; Brandenberg et al, 2012), and three-dimensional dynamic continuum methods (e.g. Finn, 2004; Cheng and Jeremic 2009). As the dynamic response of piles in liquefiable soil is three-dimensional, dynamic continuum methods is able to provide more realistic representation of the actual problem. However, its application has been limited due to insufficient computation capabilities until recent developments.

In this paper, a unified plasticity model for large post-liquefaction shear deformation of sand is first formulated, based on which a three-dimensional dynamic finite element analysis method for the seismic response of piles in liquefiable ground is developed. In the finite element analysis method, soil is modelled through u-p form brick elements for soil–pore fluid coupled response and pile through second-order brick elements. The proposed method is validated against data from two centrifuge shaking table experiments on piles in liquefiable ground, one in level ground and the other in sloping ground.

2 CONSTITUTIVE MODEL

The proper reflection of ground response is essential for seismic pile response analysis in liquefiable ground. To achieve this goal, a constitutive model capable providing a unified description of sand of different densities from pre- to post-liquefaction under monotonic and cyclic loading was formulated (Wang et al, 2014).

A most unique feature of the model is a physically based formulation for the generation and accumulation of large post-liquefaction shear deformation. Volumetric strain is decomposed into mean effective stress change induced \(\varepsilon_{vc}\), reversible dilatancy induced \(\varepsilon_{vd, re}\) and irreversible dilatancy induced \(\varepsilon_{vd, ir}\), as was proposed by Shimoto et al (1997) and Zhang (2000). At zero effective stress (liquefaction) state, due to the volumetric compatibility constraint, sufficient dilatancy would be required for sand to regain effective stress, causing the generation of shear strain according to dilatancy relations.

In accordance to the decomposition of volumetric strain, the model decomposes the dilatancy rate into reversible \((D_{re})\) and irreversible \((D_{ri})\) components, and the mean effective stress change induced \(\varepsilon_{vc}\) is assumed to be elastic. The reversible dilatancy rate is defined as:
where \( d_{ir} \) is a material constant, \( d_{ir1} \) and \( d_{ir2} \) are functions that reflect the experimental observations (Zhang 2000) of the two tendencies of decrease for irreversible dilatancy rate, and \( d_{ir3} \) is a function to enhance the models ability to capture the contraction at initial loading and load reversal.

In order to allow the constitutive model to provide unified description of sand under different densities and confining pressures, it is made critical state compatible through the introduction of a state parameter in the plasticity and dilatancy terms (Been and Jefferies, 1985):

\[
\Psi = e - e_c
\]

where \( e \) is the current void ratio and \( e_c \) is the critical void ratio.

Fig. 1 shows a simulation of undrained cyclic torsional test on Nevada sand conducted by Kutter et al (1994). The model exhibits its excellent capability in simulating the cyclic mobility and post-liquefaction shear deformation generation of saturated sand, thus providing basis for the numerical analysis of piles in liquefiable ground.

![Fig. 1. Simulation of undrained cyclic torsional test for Nevada sand by Kutter et al, 1994. (a) effective confining stress and shear stress relation, (b) stress-strain relation. (Experiment data from Kutter et al, 1994).](image)

### 3 SIMULATION METHOD

For the simulation of piles in liquefiable ground, the OpenSees finite element framework is utilized due to its advanced capabilities for modeling and analyzing the nonlinear response of systems using a wide range of material models, elements, and solution algorithms (McKenna and Fenves, 2001).

The aforementioned constitutive model was implemented in the OpenSees framework under the name CycLiqCPSP, and is used for the simulation of sand in the analysis method. u-p form brick elements (Brick u-p, Yang et al, 2008) are used for the sand in order to achieve soil–pore fluid coupled analysis, which is essential for liquefaction analysis.

The piles are simulated using 20 node second-order brick elements. The cross section of each pile consists of 6 elements for more accurate bending curvature and moment of the pile.

A stepped approach is adopted in the assembling and analysis of the model, which is illustrated in Fig. 2. Initially, a model of the ground is generated with the proposed constitutive model and Brick u-p elements without the pile. The sides of the model are fixed against lateral displacement and the top of the model is given a free drainage boundary, and a gravity analysis
step is conducted to acquire an initial stress field. Then soil elements are “excavated” with pile and pile cap installed in their place, and goes through another gravity analysis step with the pile and pile cap. After these two gravity analysis steps, the model would be ready for the seismic analysis step. During seismic analysis, the displacements of the model on the sides are fixed with periodic boundary conditions.

Fig. 2. Staged simulation of pile in liquefiable ground.

4 SIMULATION OF CENTRIFUGE EXPERIMENTS

Two centrifuge shaking table tests on single piles in liquefiable ground were conducted and simulated using the proposed method.

The shaking table tests were conducted under 30 g centrifugal acceleration, with a HPMC solution used as the pore fluid to resolve the conflicting scale factors for dynamic and consolidation time. All units mentioned hereon are in prototype scale for clarity.

Fig. 3 shows a photo of the centrifuge model. The two centrifuge models were identical except that one was in level ground and the other in sloping ground. The ground consists of two layers, a 5m medium dense ($D_r=50\%$) layer of Fujian sand overlying a 2.5m dense ($D_r=80\%$) layer. A 6m long square pile was installed vertically in both models with a pile cap connected to the pile head. A 10.8t superstructure was placed on top of the pile. Accelerometers, pore pressure transducers and strain gauges were installed to measure the acceleration and pore pressure in the sand and bending moment of the pile. The model was constructed within a laminar box. A single direction horizontal excitation was input at the base of the model during the experiments.

Fig. 4 and 5 shows the calculated and experimental results for horizontal acceleration and excess pore pressure ratio for the model with a sloping ground, the acceleration and pore pressure results for the model in level ground was very much similar. The acceleration at the soil surface is shown in both time and frequency domains, showing good agreement between the calculated and experimental results, however the calculated maximum amplitude was larger. The pore pressure generation during the seismic event was well reflected in the numerical simulation, where the top 4m of sand had reached liquefaction after about 10s.

The pile bending moment histories at the pile head where the maximum bending moment occurred in both experiments are shown in Fig. 6. Using the proposed method for simulation of piles in liquefiable ground, the dynamic pile response was excellently reproduced. The peak bending moment in the piles in both experiments

Table 1. Material parameters for Fujian sand.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_s$</td>
<td>200</td>
<td>$\alpha$</td>
<td>40</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.006</td>
<td>$\gamma_{s,v}$</td>
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<tr>
<td>$h$</td>
<td>1.7</td>
<td>$n^s$</td>
<td>1.1</td>
</tr>
<tr>
<td>$M$</td>
<td>1.3</td>
<td>$n^e$</td>
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<tr>
<td>$d_{e,1}$</td>
<td>0.45</td>
<td>$\lambda_e$</td>
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</tr>
<tr>
<td>$d_{e,2}$</td>
<td>30</td>
<td>$\varepsilon_0$</td>
<td>0.837</td>
</tr>
<tr>
<td>$d_v$</td>
<td>0.6</td>
<td>$\zeta$</td>
<td>0.7</td>
</tr>
</tbody>
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occurred later than the time of peak input acceleration, at about 7s. The pile in the model with a sloping ground experienced significant residual moment due to the lateral spreading of the ground.

5 CONCLUSIONS

A three-dimensional dynamic finite element simulation method for the seismic response of piles in liquefiable ground was developed using the OpenSees finite element framework, with the sand simulated through a uniquely formulated unified plasticity model for large post-liquefaction shear deformation of sand. The proposed method was applied to the simulation of two centrifuge shaking table experiments on piles in liquefiable ground, and the calculation results were validated experimental data. The simulation results show that the proposed method is well adept in reproducing the seismic response of both the liquefiable ground and the piles.

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