Soil-pile-structure interaction analysis using 3D FEM

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Abstract

The importance of soil-structure interaction during earthquake ground motions has been emphasized by damage produced in the structures in recent earthquakes. Currently available analytical tools to consider soil-structure interaction oversimplify the interaction between the soil and structure and lack proper calibration with full-scale testing. This research aims to study the non-linear behavior of pile-soil interaction during earthquakes using 3D Finite Element Analysis based on full-scale lateral loading tests. Full-scale concrete piles embedded into cohesive soil were tested under monotonic and reversed cyclic loading. The experimental results were used as the basis for 3D Finite Element Analysis. The applicability of a three node fiber based beam element for modeling concrete piles was investigated based on the results from full-scale testing and 3D FEM analysis. The analysis showed that three node fiber based beam elements with rough mesh division and perfect bond between pile and soil can adequately simulate the behavior of concrete piles.

Keywords: Soil-structure interaction, 3D finite element analysis, seismic behavior, concrete piles

1. INTRODUCTION

Recent earthquakes, such as the 1995 Hyogo-ken Nanbu (Kobe) earthquake, have highlighted that the seismic behavior of a structure is highly influenced not only by the superstructure, but also by the response of the foundation and the ground as well. Hence, the modern seismic design codes stipulate that the response analysis should be conducted by taking into consideration the whole structural system including the superstructure, foundation and ground. For the development of a seismic response analysis method for a whole structural system, however, it is first imperative to clarify the behavior of soil and pile during earthquakes.

With the advancement in computation capability, three dimensional (3D) finite element methods (FEM) have become more appealing, as in this method the nonlinearity of pile and soil can be taken into consideration more rigorously. In addition, soil can be modeled as continuum media taking into account the damping and inertial effects of soil. However, for a structure with a large number of piles, it is computationally difficult to carry out full 3D FEM analysis using solid elements for both structure and piles. The degrees of freedom of the model will greatly be reduced if beam elements are used for modeling the pile instead of solid elements, and thus, saving computation time. This paper, investigates the use of 3-node fiber based beam elements for the modeling of piles using a full-scale lateral loading test on concrete piles and 3D FEM analysis.

The authors conducted a comprehensive study on the behavior of concrete piles using full scale lateral loading tests on single piles, the experimental details and results of which has already been published in Tuladhar et al. (2007). In this research, based on the experimental results from the full-scale tests on single concrete piles, 3D FEM analysis was carried out to investigate the lateral behavior of piles and soil. The adequacy of modeling the pile by a fiber based beam element was investigated based on the experimental results and comparison with full 3D FEM analysis with piles modeled as 20-node solid elements.

In the 3D FEM analysis, the soil was modeled as 20-node solid elements. For the modeling of the concrete pile, comparisons between 3-node fiber theory based beam element and 20-node solid element were carried out.

2. FULL–SCALED LATERAL LOADING TEST ON SINGLE CONCRETE PILE

Lateral loading tests were carried out on two full scale concrete piles embedded into the ground. Both of the test piles were hollow precast prestressed concrete piles (Figure 1). 12 prestressing steel bars of 7mm diameter were used for longitudinal reinforcements. Compressive strength of concrete (f_c') was 79 N/mm^2 and yielding stress (f_y) of longitudinal prestressing steel was 1325 N/mm^2.

The test piles were embedded into the soil to a depth of 12.8m from ground level (GL). The head of the pile and the loading point was 1.2m and 0.6m from GL, respectively. Figure 2 shows the N-SPT profile at the test site. Test pile (SP1) was subjected to monotonic loading whereas test pile (SP2) was subjected to reversed cyclic loading. A load displacement relationship for the monotonic test (SP1) is shown in Section 4 along with the analytical results. Yielding of the pile occurred at V_y = 120kN and maximum load achieved was V_u = 135kN. The maximum displacement at the failure was 75mm. Other experimental details and results are explained in Tuladhar et al. (2007).

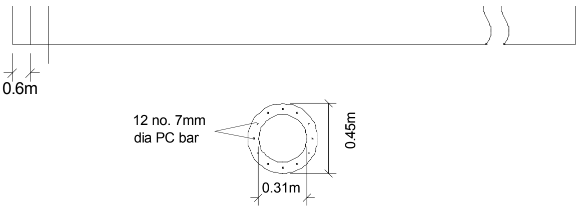


Figure 1 Details of test piles

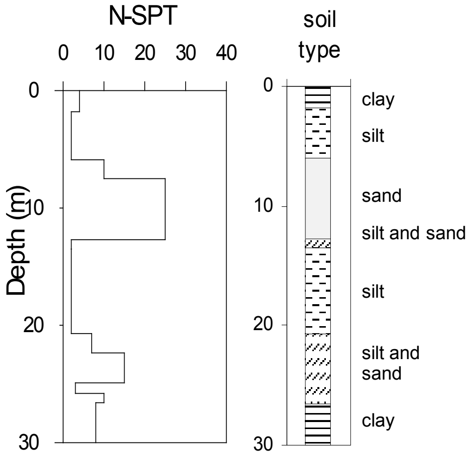


Figure 2 NSPT profile at test site

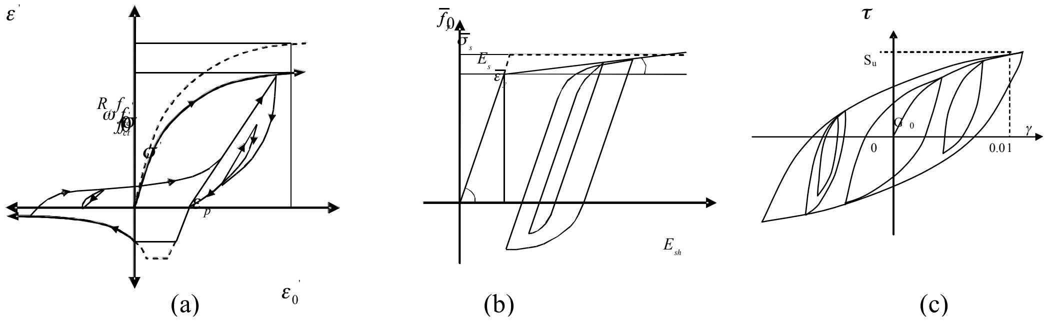
3. 3D FINITE ELEMENT ANALYSIS

The experimental study was used as the basis to study the behavior of concrete piles and soil using 3D FEM analysis.

3.1 Constitutive model for concrete and soil

Nonlinearity of concrete before cracking was modeled by an elasto-plastic fracture model (Maekawa et al., 2003). A smeared crack model based on average stress-average strain was used to model concrete after cracking. For post cracking behavior compression and tension models proposed by Maekawa et al. (2003), as shown in the Figure 3(a), were used. For reinforcement, a nonlinear path dependent constitutive model of Fukuura and Maekawa (1975) as shown in Figure 3(b) was used.

Soil elements were formulated in both deviatoric and volumetric components separately. The volumetric component of the soil element was taken here as linear elastic. For the deviatoric component, the non-linear path dependency of soil in shear was modeled by Ohsaki model (1980) as shown in the Figure 3(c).



(a) (b) (c)

Figure 3 Constitutive models for (a) concrete (b) reinforcement and (c) soil

3.2 Analytical model of concrete pile and soil

In the analytical model, soil is modeled using a 20-node isoparametric solid element. For the modeling of the concrete pile, comparison between a 3-node fiber-theory based beam element and a 20-node solid element was carried out. The analytical parameters used are illustrated in Table 1. FEM code COM3 developed by Tokyo University was used for the analysis.

Table 1 Soil properties used in the analysis

Depth from GL (m)	Soil type	Unit weight (kN/m^3)	Shear strength (kPa)	Shear Modulus (kPa)
0–6	Clay	15.7	33	20.4
6–12.5	Sand	18.6	140	154.3

3.2.1 20-node solid element model of pile

In this modeling (SL-Mon), both the pile and soil are modeled as 20-node solid elements as shown in Figure 4. Soil and pile were modeled up to 12.8 m depth, and 9.5m and 3.15m in length and width, respectively. Soil properties used in the analysis are shown in Table 1. Only half of the domain was considered taking into account the symmetry in the geometry and load. The base was fixed in all X, Y, and Z directions. The two lateral faces of the soil model, perpendicular to the direction of loading were fixed in the X direction and the remaining two lateral faces were fixed in the Y direction.

To simulate the gap formation between the soil and pile surface, a 16-node interface element is used between the soil and pile surface (Figure 5). In this opening-closure model, there is no stress transfer between pile and soil during opening or tension. During closure or compression, however, high rigidity (K) is assumed to avoid the overlapping of the soil and pile elements in compression. In this case, no shear stress between the RC and soil elements is assumed.

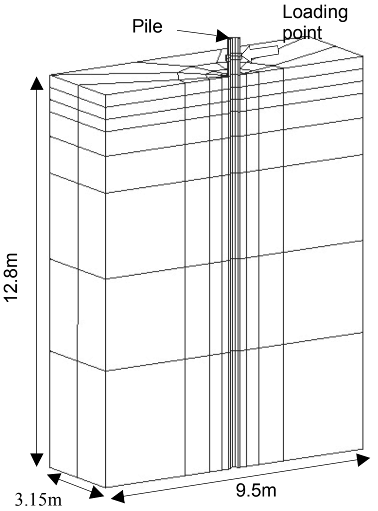


Figure 4 Finite element model for pile and soil for case SL-Mon

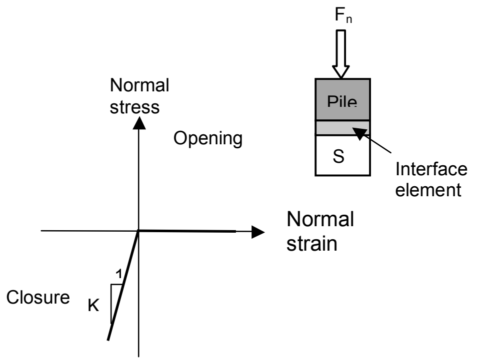


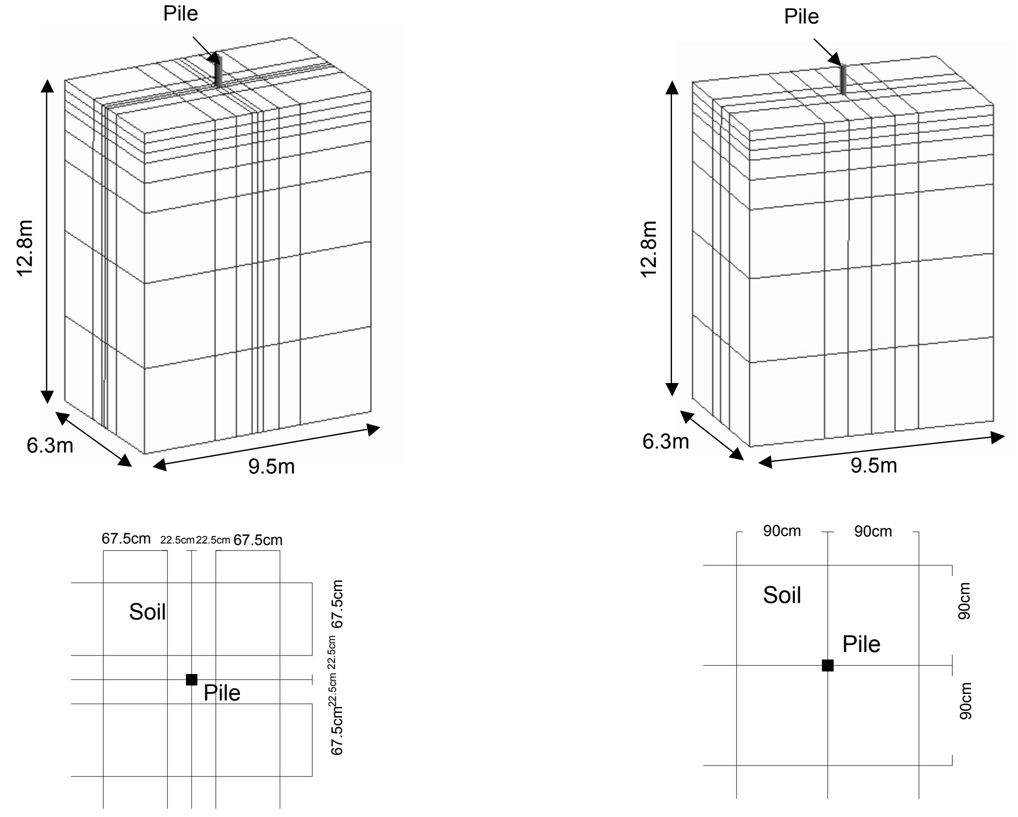
Figure 5 Opening-closure model for interface element

3.2.2 3-node beam element model of pile

In these cases, the soil was modeled as 20-node solid elements, whereas the pile was modeled as 3-node RC beam elements based on the fiber model (Maekawa et al., 2003). Soil and pile were modeled up to 12.8 m depth, 9.5m length and 6.3m width. Soil properties as mentioned in Table 1 were used for the analysis. The base was fixed in all X, Y, and Z directions. Two lateral faces of the soil model, perpendicular to the direction of loading were fixed in the X direction and the remaining two lateral faces were fixed in the Y direction. Here, perfect bond between pile and soil is assumed.

Variations in the mesh divisions were considered as illustrated in Figure 6(a) and Figure 6(b). For the fine mesh, FB-Mon1, the mesh division around the pile was 0.5D (diameter) of the pile. Whereas, the width of mesh around the pile was considered as 2D of the pile for the rough mesh case FB-Mon2.

The applied beam elements for modeling of the pile are formulated based on the flexural theory and fiber model (Maekawa et al., 2003). In the RC beam elements, axial force and two directional flexural moments are calculated using the averaged axial strain and two directional curvatures. The cross section of the element is divided into minute cells (fibers) according to the longitudinal reinforcement arrangements.



(a)

(b)

Figure 6 Finite element model with pile modeled as 3-node beam element (a) Fine mesh (FB-Mon1) and (b) Rough mesh (FB-Mon2)

4. FINITE ELEMENT ANALYSIS RESULTS

The 3D-FEM analysis results for the 20-node solid element modeling and 3-node beam element modeling of the pile are compared with the experimental results in Figure 7. As shown in the Figure 7, the 20-node solid element with interface element between soil and pile can simulate the behavior of the pile very accurately.

For the case of the 3-node beam element modeling, case FB-Mon1 which considers fine mesh divisions (0.5D), the model underestimates the lateral load carrying capacity of the pile compared to the experimental observations, whereas, case FB-Mon2 with rough mesh divisions (2D), gives reasonable accuracy. While modeling the pile as a beam element, the subgrade reaction from soil is underestimated as the volume of the pile is being neglected. However, as no interface element is considered between pile and soil, the soil in the active side (tension side) also contributes to the total subgrade reaction from the soil. For the case FB-Mon1, where the soil around the pile is divided into fine mesh, only small portion of soil around the pile in active side (tension side) contributes to the subgrade soil reaction. Hence, the lateral load carrying capacity of pile is largely underestimated in case FB-Mon1. However, when the rough mesh is considered, the larger soil mesh in the active side (tension side) can contribute to the subgrade soil reaction. Hence, the case FB-Mon2 with the rough mesh division gives a higher lateral load carrying capacity for the pile compared to the case FB-Mon1.

Figure 8 shows the curvature distribution along the pile for case FB-Mon2. Maximum curvature for case FB-Mon2 occurred at 0.9 m from the GL, which agrees well with the experimental observations. This suggests that, if beam elements are used for the pile modeling, a realistic soil stress state can be obtained by using a coarse mesh division around the pile and considering the perfect bond between soil and pile. For the reversed cyclic case, Figure 9 shows the load displacement curve from the experiment (SP2) and FEM analysis with pile modeled as a beam element (FB-Rev).

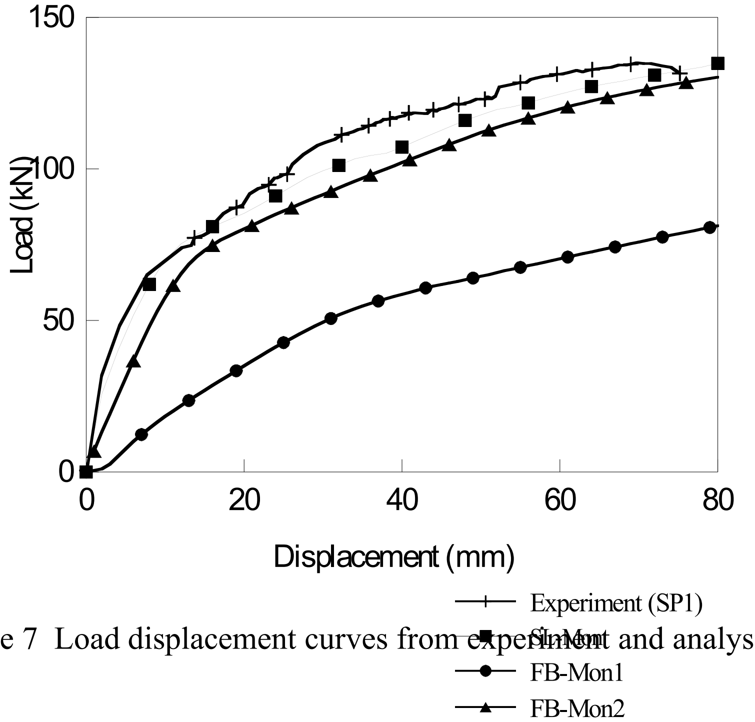
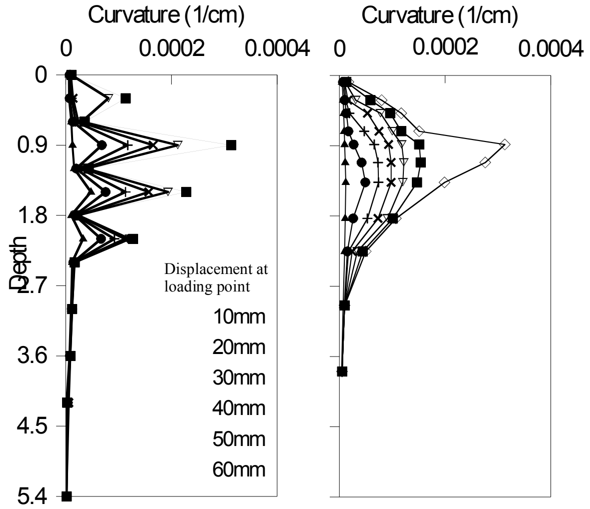


Figure 7 Load displacement curves from experiment and analysis



(a) (b)

Figure 8 Curvature distribution (a) Experiment (b) FB-Mon2

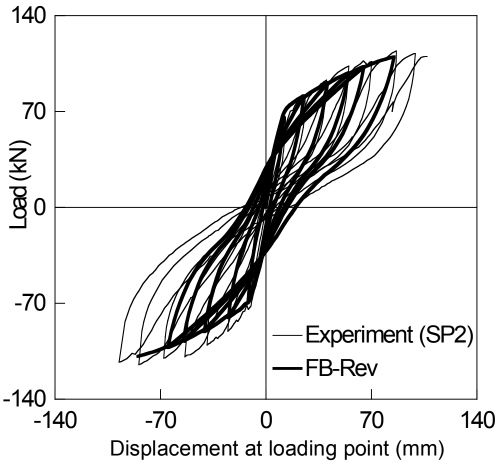


Figure 9 7 Load displacement curves for reversed cyclic loading (a) Experiment (b) FB-Rev

5. CONCLUSIONS

In this study, on the basis of full-scale lateral loading tests on concrete piles, 3D FEM analysis was carried out on single concrete piles subjected to lateral loading. In the analysis, the adequacy of modeling of concrete piles with 3-node beam elements was tested by comparing with experimental and full 3D analysis results.

From the 3D FEM analysis it was found that the 3-node fiber based beam element shows reasonable accuracy in simulating the behavior of concrete piles subjected to lateral loading. The use of a beam element in modeling the pile reduced the number of elements in the model and hence could save the computation time by 60%. 3-node beam element modeling for piles ignores the volume of the pile, hence the subgrade reaction of soil on the surface of pile is smaller and it underestimates the lateral load carrying capacity of the pile when a fine mesh division is used. Reasonable accuracy can, however, be obtained by using a rough mesh division (2D) in the soil around the pile and assuming perfect bond between soil and pile.

5. REFERENCES

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