- Technical Paper -

ANALYTICAL STUDY ON INFLUENCE OF PILE MODELING ON THE RESPONSE BEHAVIOR OF CONCRETE STRUCTURES

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ABSTRACT

Seismic behavior of a structure is highly influenced by the response of foundation and ground. In this paper, 3D FEM analysis was carried out on single concrete piles and full-scaled bridge pier considering soil-structure interaction. Comparison between 20-node solid element and 3-node beam element was carried out for the modeling of concrete pile. Verification with full-scale lateral loading test on concrete piles and 3D FEM analysis showed that fiber based beam element can adequately simulate the lateral behavior of pile.

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

1. INTRODUCTION

Recent damaged caused by earthquakes suggest that soil-structure interaction can have detrimental effects on structures [1]. Hence, the modern seismic design codes stipulate that the response analysis should be conducted by taking into consideration the whole structural system including superstructure, foundation and ground.

A number of researches have recently investigated the influence of soil-structure interaction (SSI) using 3D finite element method (FEM) [2,3]. 3D FEM analysis is appealing for soil-structure interaction problems as it can model soil continua and it takes into account the damping and inertial effect 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 the computation time [4]. This paper, investigates the use of 3-node fiber based beam elements for modeling of pile using full-scaled lateral loading test on concrete piles and 3D FEM analysis.

The authors conducted comprehensive study on the behavior of concrete pile using full scaled lateral loading test on single piles. The experimental details and results of which has already been published in JCI [5].

In this research, based on the experimental results from full-scaled test on single concrete piles, 3D FEM analysis was carried out to investigate the lateral behavior of pile and soil. Adequateness of modeling the pile by 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.

Furthermore, 3D FEM analysis was also carried out on full-scaled bridge pier considering soil-structure interaction. Comparison between the modeling of pile using 3-node fiber based beam elements and 20-node solid element was also carried out for full-scaled bridge pier.

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

Lateral loading tests were carried out on two full scaled concrete piles embedded into the ground. Both of the test piles were hollow precast prestressed concrete piles (Fig. 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. Pile was embedded into the depth of 12.8m from ground level (GL). The head of the pile and the loading point was 1.2m and 0.6m from the

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ground level (GL), respectively. Fig. 2 shows the N-SPT profile at the test site. Test pile (SP1) was subjected to monotonic loading where as test pile (SP2) was subjected to reversed cyclic loading.

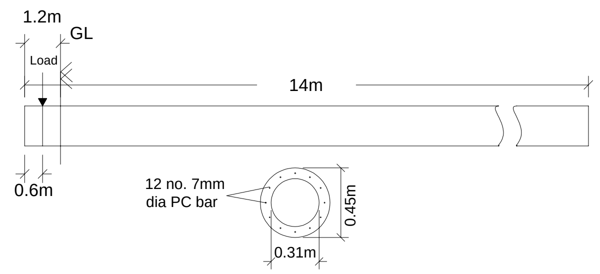

Fig. 1 Details of test piles

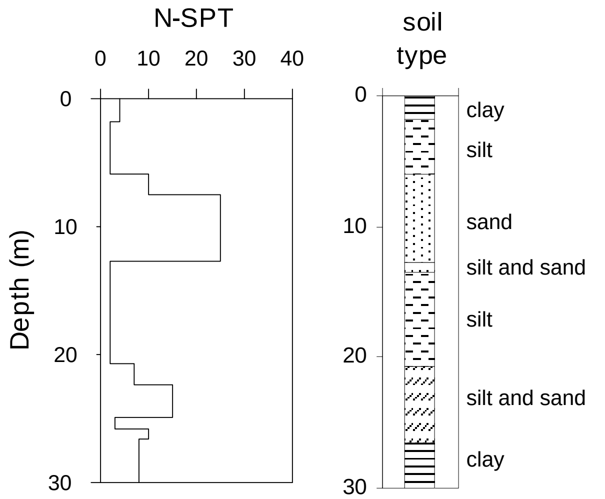

Fig. 2 NSPT profile at test site

A load displacement relationship for the monotonic test (SP1) is show in Fig. 5 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 160mm. Other experimental details and results are explained in Tuladhar et al.[5].

3. 3D FEM ANALYSIS FOR SINGLE PILE

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

3.1 3D FEM Model for Single Pile

In the analytical model, soil is modeled as 20-node isoparametric solid element. For the modeling of concrete pile, comparison between 20-node solid element and 3-node fiber based beam element was carried out.

In case SL-Mon, both the pile and soil are modeled as 20-node solid elements as shown in Fig. 3. 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 Table1. The base of the model was fixed in all X, Y, and Z directions. The lateral sides of the model were fixed in the direction perpendicular to the surface. To simulate the gap formation between soil and pile surface, a 16-node interface element is used between soil and pile surface [5].

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

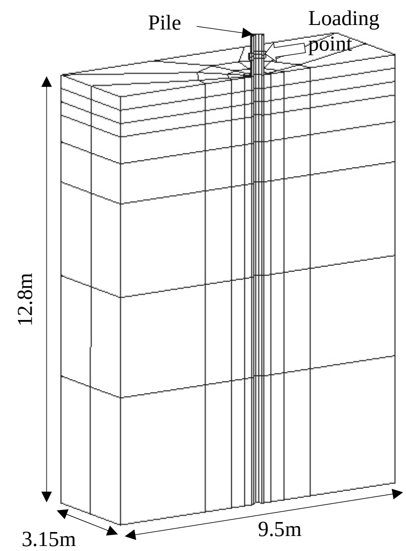

Fig. 3 FEM model with pile modeled as 20-node solid element (SL-Mon)

For the case FB-Mon (Fig. 4) soil was modeled as 20-node solid elements, whereas the pile was modeled as 3-node RC beam elements based on the fiber model [6]. 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 according to the longitudinal reinforcement arrangements. Pile section reinforcement is same for case SL-Mon and FB-Mon as shown in Fig. 4.

Soil and pile were modeled up to 12.8 m depth, 9.5m length and 6.3m width. Soil properties as mentioned in Table1 were used for the analysis. Here, perfect bond between pile and soil was assumed.

element.(FB-Rev).

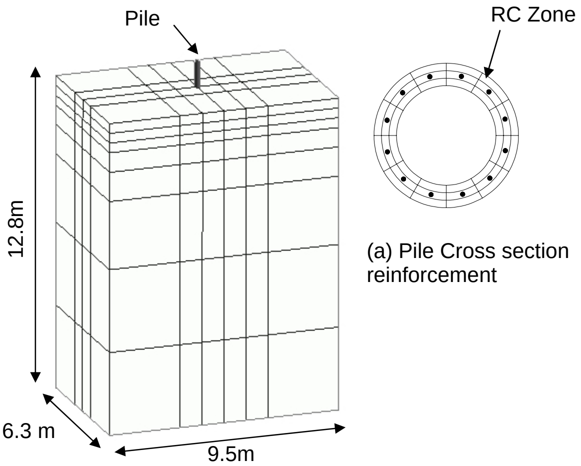

Fig. 4 FEM model with pile modeled as 3-node fiber based beam element (FB-Mon)

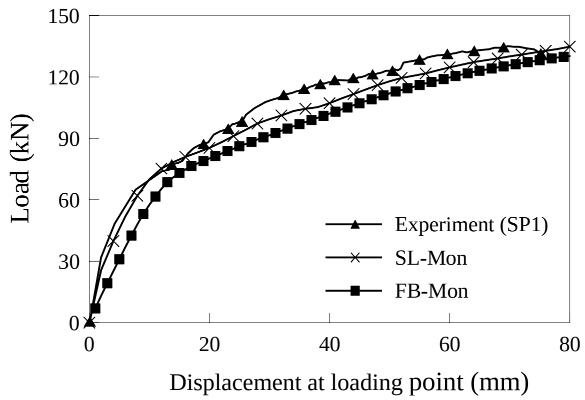

Fig. 5 Load displacement curves for monotonic loading for single pile

3.2 Constitutive model for concrete and soil

A smeared crack model based on average stress-average strain was used to model concrete after cracking. For post cracking behavior compression and tension model proposed by Maekawa et al. [6], were used. For reinforcement, nonlinear path dependent constitutive model proposed by Fukuura and Maekawa [7] was used.

The volumetric component of soil element was taken here as linear elastic. For the deviatoric component, non-linear path dependency of soil in shear was modeled by Ohsaki model [8].

3.3 3D FEM results for single pile

The 3D-FEM analysis results for the case SL-Mon and FB-Mon are compared with the experimental results in Fig. 5. As shown in the Fig. 5 20-node solid element can simulate the behavior of pile very accurately. 3-node fiber based beam element slightly under estimates the lateral load carrying capacity of the pile. This is because, while modeling the pile as a beam element, subgrade reaction from soil is underestimated as volume of the pile is being neglected. However, as shown in Fig. 5, using perfect bond between pile and soil and using rough mesh division, 3-node fiber based beam element can adequately simulate the behavior of concrete pile.

Curvature distribution along the depth of pile for case FB-Mon is compared with the experimental results in Fig. 6. The curvature at the higher displacement level slight vary with the experimental results, however, the depth of maximum curvature obtained from the analysis is quite comparable to the experimental results.

For the reversed cyclic case, Fig. 7 shows the load displacement curve from the experiment (SP2) and FEM analysis with pile modeled as a beam

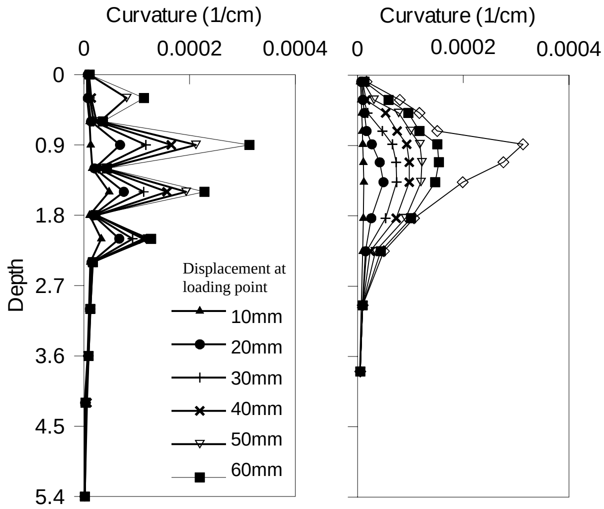

Fig. 6 Curvature distribution (a) Experiment (b) FB-Mon

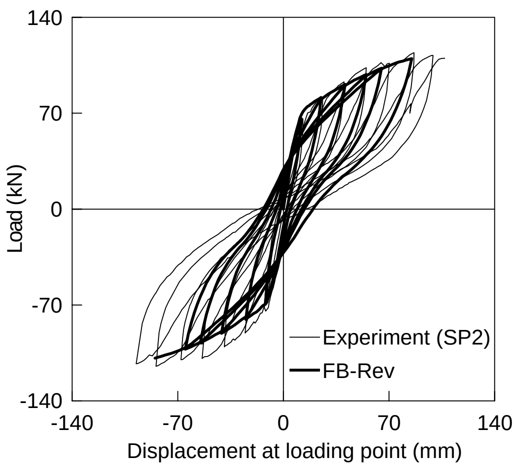

Fig. 7 Load displacement curves for reversed cyclic loading for single pile (a) Experiment (b) FB-Rev

4. 3D FEM ANALYSIS OF BRIDGE PIER CONSIDERING SOIL-STRUCTURE INTERACTION

On the basis of the experimental and 3D FEM analysis carried out on full-scale single concrete pile, 3D FEM analysis was carried out on a full-sized bridge pier considering soil-structure interaction. The bridge pier considered is being designed according to JSCE standard [9].

4.1 Description of the structure

The selected system for the analysis is a single bridge pier of (4mx2m) supported on 12 numbers of 1m diameter piles (Fig. 8). Fig. 9 shows the soil profile and summary of soil parameters used in the analysis is shown in Table 2.

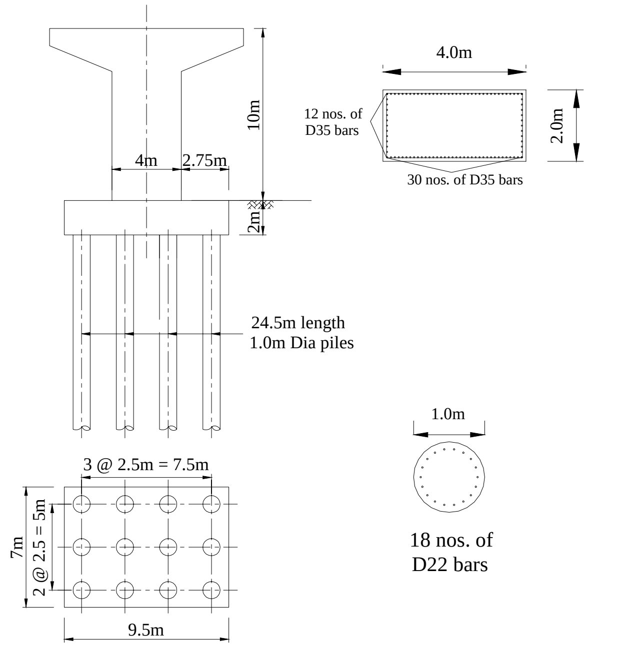

Fig. 8 Details of full-scale bridge pier

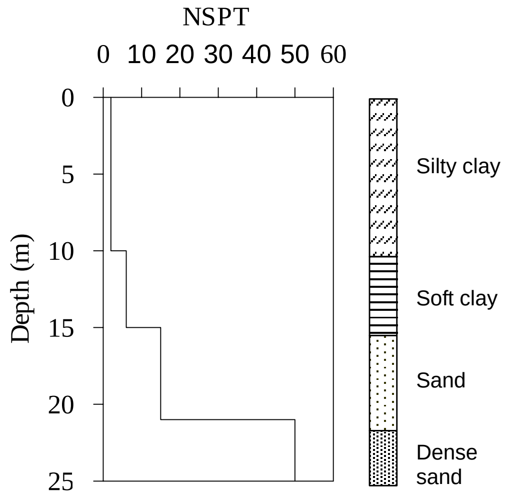

Fig. 9 NSPT profile for the bridge pier

Table 2 Soil properties used in the analysis

Depth from GL (m)	Soil type	Unit weight (kN/m^3)	Shear strength (kPa)	Shear Modulus (kPa)
0-10	Clay	17	.034	20.4
10-15	Clay	18	.051	55.7
15-21	Sand	20	.093	102.6
21-25	Sand	21	.244	268.9

4.2 Finite element modeling

For the finite element analysis of the overall structure system (Fig. 8), soil and pier are modeled as 20-node isoparametric solid elements. For the modeling of the pile, comparision between 20-node solid element and 3-node fiber based beam element was carried out. The constitutive models for soil and concrete described in Section 3.2 were used for this analysis as well. Axial compressive stress of 1N/mm^2 was considered to be acting on the pier and the footing was modeled as elastic body in all the cases.

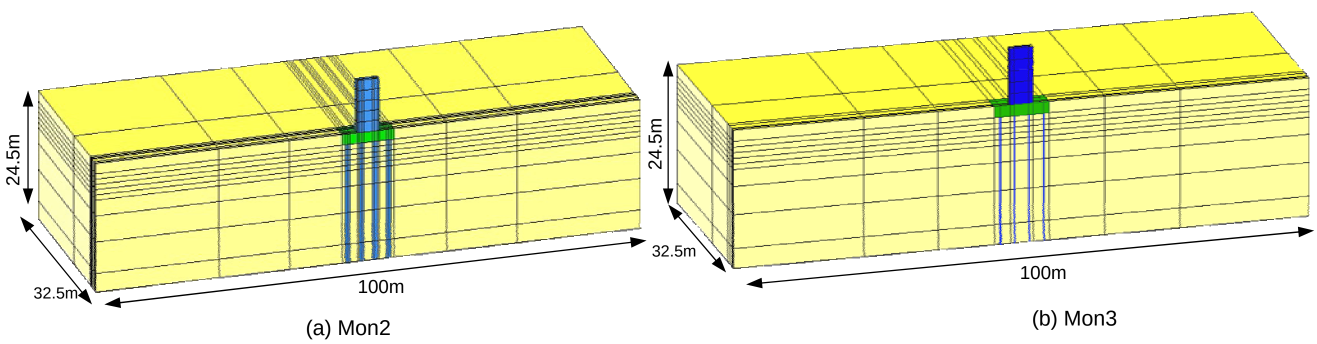

Fig. 10 Analytical models (a) Pile modeled with solid element (b) Pile modeled with beam element

Different analytical cases considered are shown in Fig 10. In case Mon1, pier alone is modeled with fixed foundation. Whereas in case Mon2 and Mon3, the soil-structure interaction is also considered by modeling the soil and pile system. For case Mon2, soil and pile are all modeled using 3D 20-node solid elements. To simulate the gap formation between pile and soil, 16-node bond element was used between pile and soil surface. For the case Mon3, pier and soil are modeled by 3D solid element where as for the modeling of the pile, beam element was used. Here, perfect bond is assumed between pile and soil.

For both the cases, soil and pile were modeled up to 24.5m depth, and 100m and 32.5m in length and width, respectively. Only half of the domain was considered taking into account the symmetry in the geometry and load.

4.3 3D FEM analysis results

Load displacement curve from the analysis of full bridge pier system is shown in Fig. 11. Case Mon1, where soil-structure interaction is not considered, shows yield displacement of 20mm at the yielding load of 6200 kN. The ultimate load for the case Mon1 is 8300 kN at 150mm displacement. Large initial stiffness was observed in case Mon1 compared to Case Mon2 and Mon3 where soil-structure interaction were considered. However, at ultimate stage behavior of the system is more governed by the pier, hence the maximum load for all the cases are comparable. Case Mon2 and Mon3 gave a very similar load displacement behavior. This shows that 3-node beam element modeling of pile can give comparable results to the modeling of the pile as 20-node solid element. The ultimate load and maximum displacement for case Mon2 and Mon3 were 8000 kN and 18.6 mm and 8100 kN and 22 mm, respectively.

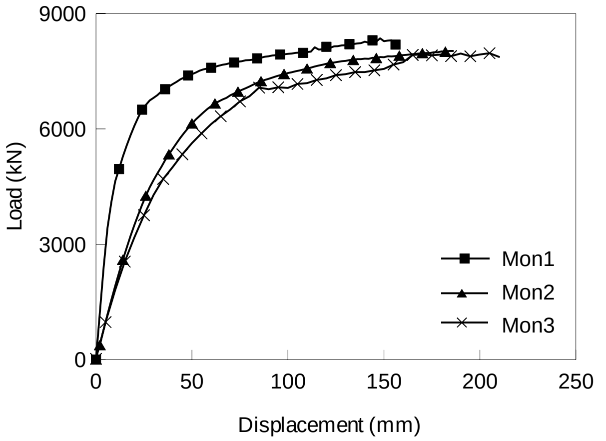

Fig. 11 Load displacement curves for full bridge pier system

The horizontal soil displacement contour for case Mon2 and Mon3 for the pier top displacement of 18cm are shown in Fig. 12. The range of soil deformation for both the cases agree quite well. For the case Mon3, where pile is modeled as 3-node beam element, perfect bond is assumed between pile and soil, whereas for the 20-node solid element modeling (Mon2) gap formation is simulated by introducing bond element between pile and soil surface. Hence, for the case Mon3, localized deformation of soil near the piles are observed.

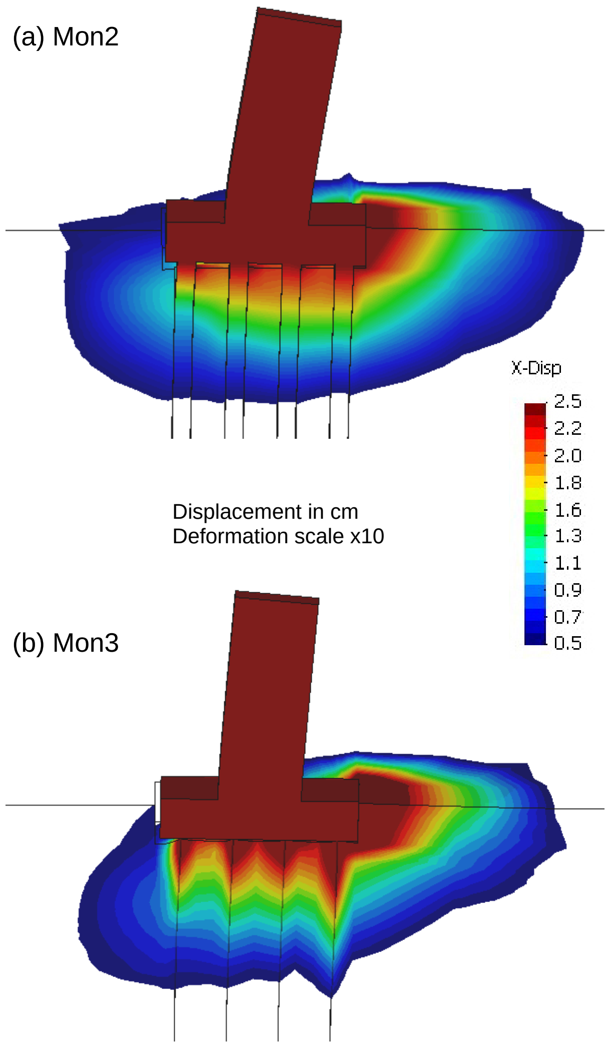

Fig. 12 Displacement contour for horizontal soil displacement (a) Mon2 and (b) Mon3

Reversed cyclic analysis was also carried out for both the models. Load-displacement curves for case Rev2 (pile modeled as solid element) and case Rev3 (pile modeled as beam element) is shown in Fig. 13. This shows that the beam element modeling of pile can simulate the hysteretic behavior of the pile reasonably well.

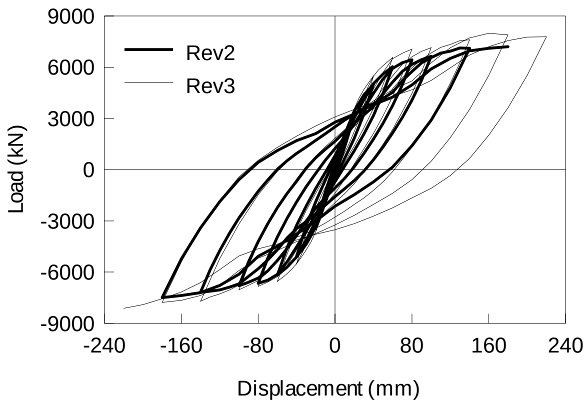

Fig. 13 Load displacement curve for reversed cyclic loading on bridge pier (a) Rev2 and (b) Rev3

5. CONCLUSIONS

In this study, on the basis of full-scaled lateral loading test on concrete piles, 3D FEM analysis was carried out on single concrete piles subjected to lateral loading. In the analysis soil is modeled as 20-node solid element, whereas for the modeling of pile comparison between 20-node solid element and 3-node fiber based beam element was carried out.

The 3D FEM analysis was further extended to full-scaled bridge pier system considering the effect of soil-structure interaction. From the analysis of single concrete pile and full-sized bridge pier, following conclusions can be drawn:

(1) 3D FEM analysis on single concrete piles subjected to lateral loading showed that 20-node solid element modeling of pile can simulate the behavior of pile very precisely.
(2) However, for the analysis of whole structural system with large number of piles complete 3D modeling of pile may not be feasible due to computational limitation. The 3-node fiber based beam element showed reasonable accuracy in simulating the behavior of concrete piles subjected to lateral loading. The lateral load carrying capacity of pile by 3-node fiber based beam element might slightly be underestimated as the subgrade reaction from soil is underestimated as volume of the pile is being neglected.
(3) 3D FEM analysis on full scale bridge pier system showed that 3-node beam element can simulate the behavior of the whole structural system very similar to that of full 3D analysis by modeling pile as 20-node solid elements.

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