SEISMIC BEHAVIOR OF CONCRETE BRIDGE PIER CONSIDERING SOIL-PILE-STRUCTURE INTERACTION

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ABSTRACT :
Seismic behavior of a structure is highly influenced by the response of foundation and ground. Hence, the modern seismic design codes recommend that the response analysis should be conducted by taking into consideration the whole structural system including the soil-structural interaction. 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. This paper, investigates the use of 3-node fiber based beam elements for modeling of pile using full-scale lateral loading test on single pile and 3D FEM analysis of single pile and full-scaled bridge pier system. The finite element analysis carried out on the single pile and full-scale bridge pier exhibited that 3-node beam element can adequately simulate the behavior of concrete piles and the whole bridge systems very similar to that of full 3D analysis where piles are modeled by 20-node solid elements.

KEYWORDS:
Soil-structure interaction, Finite element analysis, Concrete bridges, Concrete piles, Seismic behavior

1. INTRODUCTION

Following the recent earthquakes like Kobe Earthquake in 1995, it has been evident that soil-structure interaction (SSI) can have detrimental effects on structures (Mylonakis and Gazetas, 2000). 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 SSI using 3D finite element method (FEM) (Wakai et al., 1999; Jeremic et al. 2004; Maki and Mutsuyoshi, 2004). 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. This paper, investigates the adequacy of using 3-node fiber based beam elements for modeling of pile based on 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 Tuladhar et al. (2007).

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. LATERAL LOADING TEST ON FULL-SCALE CONCRETE PILE

The experimental program consists of lateral loading test on two full-scaled concrete piles embedded into the ground. Both of the test piles were hollow precast prestressed concrete piles with a diameter of 450mm and a thickness of 70mm (Figure 1). 12 prestressing steel bars of 7mm diameter were used for longitudinal reinforcements and spiral hoop reinforcements with a diameter of 3mm and pitch of 100mm were used as lateral reinforcements. Strain gages were attached to the longitudinal reinforcements. Compressive strength of concrete (f_c') was 79MPa and yielding stress (f_y) of longitudinal prestressing steel was 1325MPa. Effective prestress on concrete piles was 5MPa. The test piles were embedded up to 12.8m from the ground level (GL). The head of the pile and the loading point were 1.2m and 0.6m from GL, respectively. Standard Penetration Test was done at the test site. The SPT-N values obtained from the test are shown in Figure 2 along with soil type. The depth of water-table was 1.3m from the ground level.

A load displacement relationship for the monotonic test (SP1) is show in Figure 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 78mm. Other experimental details and results are explained in Tuladhar et al. (2007).

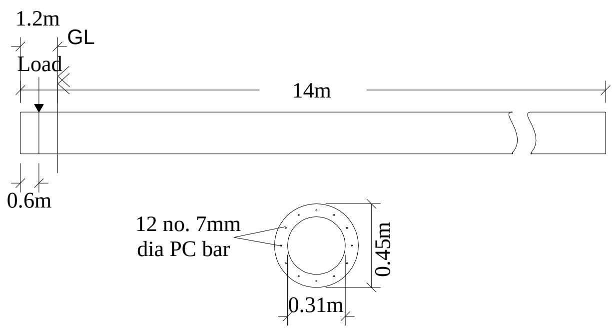


Figure 1 Details of test pile

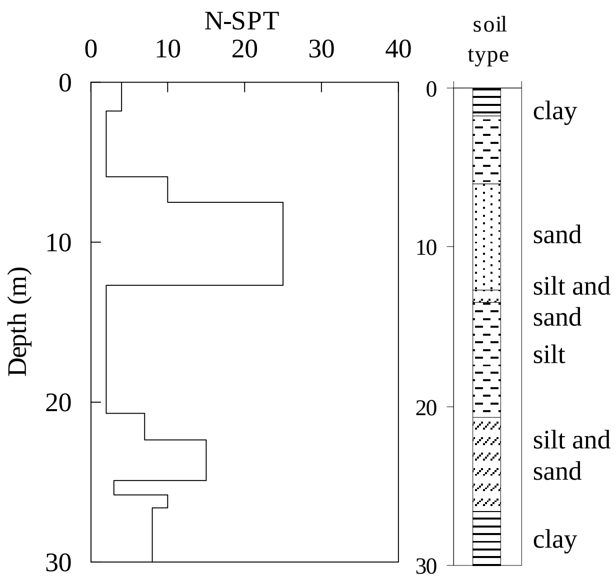


Figure 2 SPT-N profile at test site

3. 3D FINITE ELEMENT ANALYSIS OF 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. Soil properties used in the analysis are shown in Table1.

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

In case SL-Mon, both the pile and soil are modeled as 20-node solid elements as shown in Figure 3a. Soil and pile were modeled up to 12.8 m depth, and 9.5m and 3.15m in length and width, respectively. 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 (Tuladhar et al., 2007).

For the case FB-Mon (Figure 3b) 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). 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. Here, perfect bond between pile and soil was assumed.

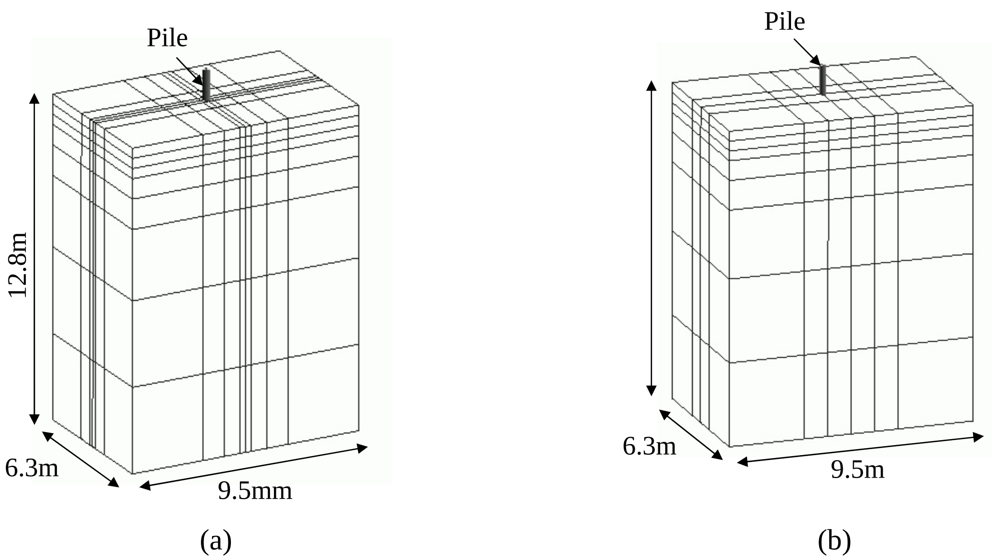


Figure 3 FEM model (a) Pile modeled as solid element (SL-Mon) (b) Pile modeled as beam element (FB-Mon)

3.2. 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 Figure 4. As shown in the Figure 4, 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 Figure 4, 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 Figure 5. The curvature at the higher displacement level slightly vary with the experimental results, however, the depth of maximum curvature obtained from the analysis is quite comparable to the experimental results.

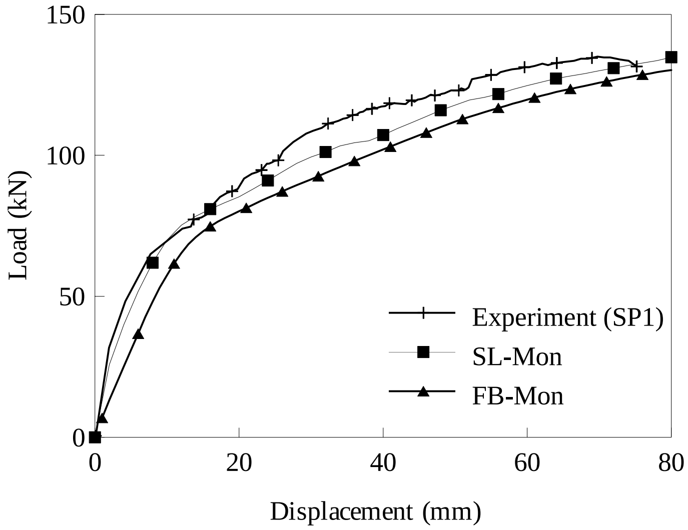


Figure 4 Load displacement curve for monotonic loading for single pile

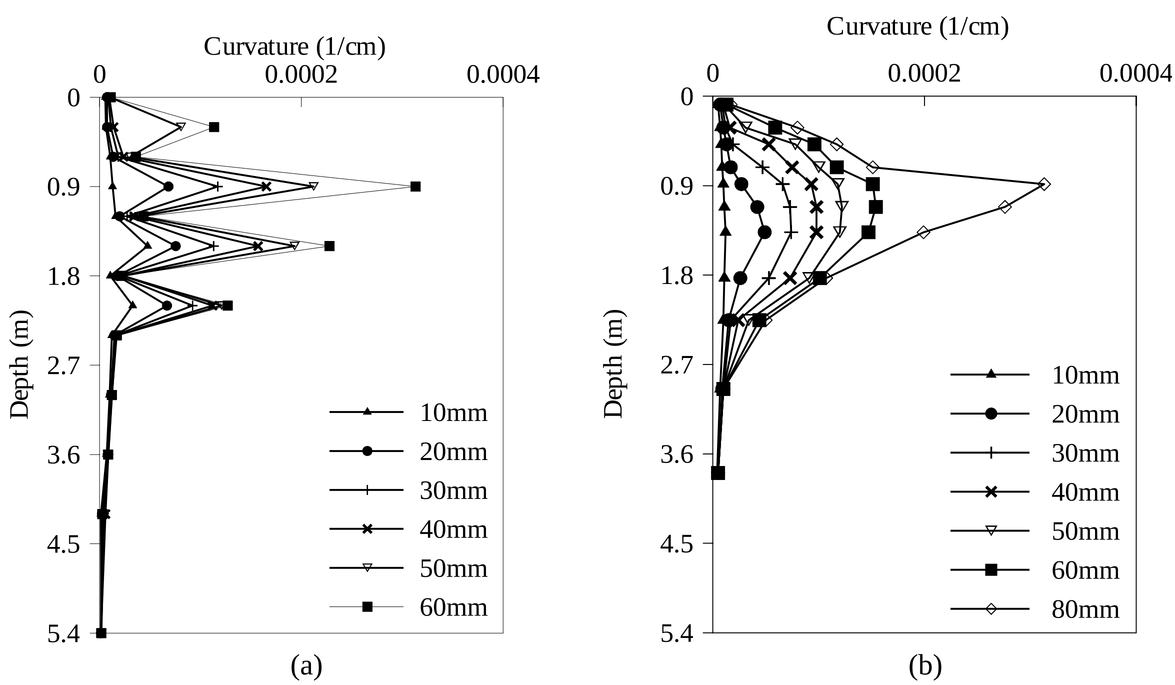


Figure 5 Curvature distribution along the depth of pile (a) Experiment (b) FbMon

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.

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 (Figure 6). Summary of soil parameters used in the analysis is shown in Table 2.

Table 2 Soil properties used in the analysis

Depth from GL (m)	Soil type	Unit weight (kN/m3)	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

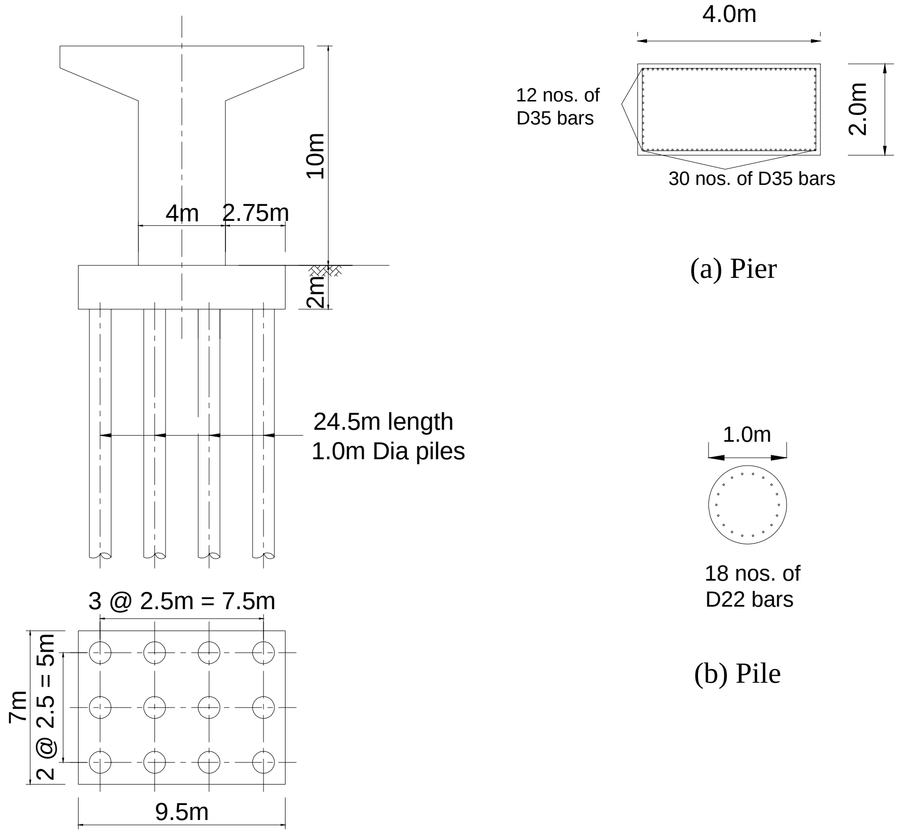


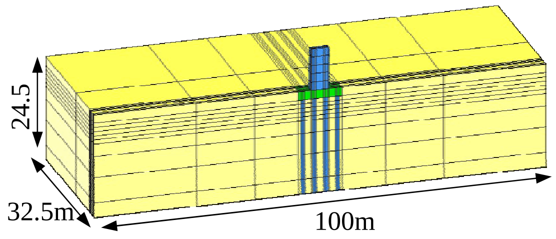
Figure 6 Details of full-scale bridge pier

4.2 Finite element modeling

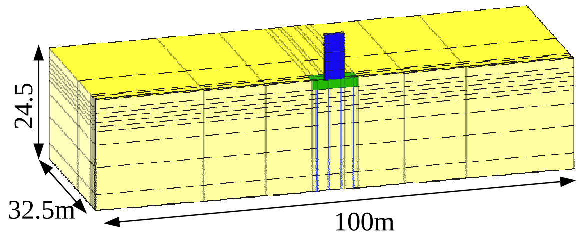
For the finite element analysis of the overall structure system (Figure 6), soil and pier are modeled as 20-node isoparametric solid elements. For the modeling of the pile, comparison between 20-node solid element and 3-node fiber based beam element was carried out. The constitutive models for soil and concrete described earlier 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.

Different analytical cases considered are shown in Figure 7. 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.



(a) Mon2



(b) Mon3

Figure 7 3D FEM models for the bridge pier

4.3. 3D FEM analysis results for full-scaled bridge pier

Load displacement curve from the analysis of full bridge pier system is shown in Figure 8. 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.

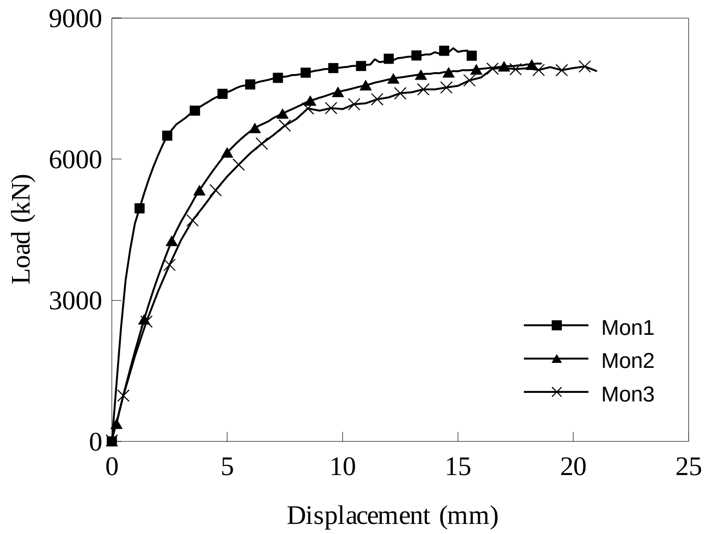


Figure 8 Load displacement curves for full bridge pier system

The horizontal soil displacement contour for case Mon2 and Mon3 for the pier top displacement of 18cm are shown in Figure 9. The range of soil deformation for both the cases agrees 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 is observed.

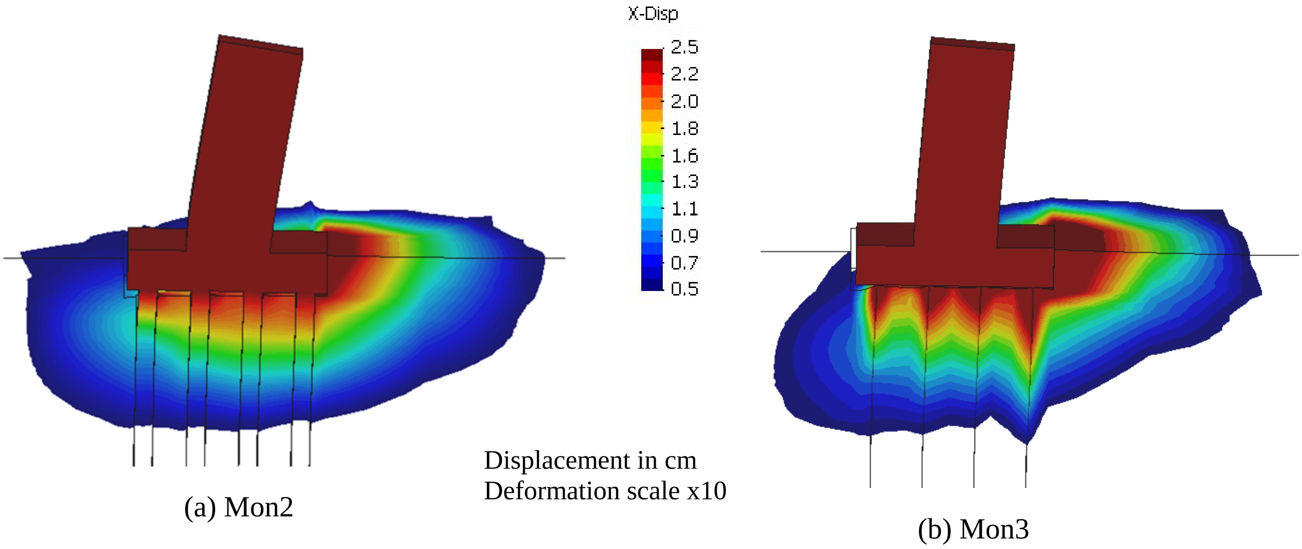


Figure 9 Displacement contour for horizontal soil displacement

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 Figure 10. This shows that the beam element modeling of pile can simulate the hysteretic behavior of the pile reasonably well.

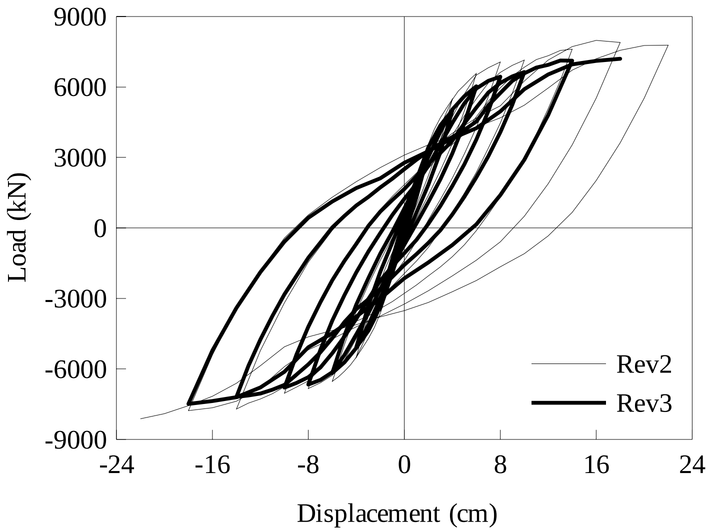


Figure 10 Load displacement curve for reversed cyclic loading on bridge pier

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.

REFERENCES

Fukuura, N. and Maekawa, K. (1975). Computational Model of Reinforcing Bar under Reversed Cyclic Loading for RC Nonlinear Analysis. *Proceedings of Japan Society of Civil Engineers* **35**, 291-295.

Jeremic, B., Kunnath, S. and Xiong, F. (2004). Influence of Soil-foundation-structure Interaction on Seismic Response of the I-880 viaduct. *Engineering Structur*es **26.** 391-402.

Maekawa, K., Pimanmas, A. and Okamura, H. (2003). Nonlinear Mechanics of Reinforced Concrete, Spon Press, London.

Maki, T. and Mutsuyoshi, H. (2004). Seismic Behavior of Reinforced Concrete Piles under Ground. *Advanced Concrete Technology* **2:1**, 37-47.

Myloankis, G. and Gazetas, G. (2000). Seismic soil structure interaction: Beneficial or Detrimental? *Journal of Earthquake Engineering* **4:3**, 277-301.

Ohsaki, Y. (1980). Some notes on Masing's Law and Non-linear Response of Soil Deposits. *Journal of the Faculty of Engineering, The University of Tokyo* **35:4**, 513-536.

Tuladhar, R., Maki, T. and Mutsuyoshi, H. (2007). Cyclic Behavior of Laterally Loaded Concrete Pile Embedded into Cohesive Soil. *Earthquake Engineering and Structural Dynamics* **37:1**, 43-59

Wakai, A., Gose, S., and Ugai, K. (1999). 3-D Elasto-plastic Finite Element Analysis of Pile Foundations Subjected to Lateral Loading. *Soils and Foundations, Japanese Geotechnical Society* **39:1**, 97-111.