NONLINEAR SOIL-PILE FOUNDATION INTERACTION ANALYSIS BASED ON FEM-BEM HYBRID TECHNIQUE

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This paper investigates the effects of RC pile nonlinear behavior in view of the bending moment-axial force relationship on the response of a pile-supported bridge system. The analysis is conducted based on BEM-FEM hybrid technique. The RC nonlinear behavior is represented according the modified Q hyst model that takes into account the relationship between bending moment-curvature dependent on axial force. The results of analysis indicate that the soil behavior is practically insensitive to RC piles behavior, the presence of axial force in piles affects the pile behavior and the heavy damage in the Hanshin disaster may possibly be due to tension force and bending moment interaction.

Key Words : *soil-pile interaction, RC nonlinear behavior, bending moment-axial force interaction BEM-FEM hybrid technique*

1. INTRODUCTION

Significant damage to pile-supported bridges in the area of the 1995 Hyogo-ken Nanbu Earthquake enhanced the performance based design of soil-pile-structure systems. During strong motions, both, piles and surrounding soil have possibility to come into nonlinear behavior. Consequently, the capacity of these structures to resist seismic excitations depends on the performance of the piles and its interaction with the surrounding soil. Hence, in this paper, the investigation was focused on the following points:

- -RC nonlinear response of piles coupled with nonlinear soil.
- -Effect of axial force in the pile nonlinear response in view of the weight of superstructures.
- -Differences between outer- and inner-pile responses due to pile-soil-pile behavior.

The RC nonlinearly for the moment-curvature is based on the criterion that the pile yield strength depends upon the axial force and the bending moment. A 2-D seismic nonlinear soil-structure analysis is carried out by taking BEM-FEM hybrid technique for a typical pile-supported bridge of the Hanshin Highway.

2. METHOD OF ANALYSIS

We perform a 2-D seismic nonlinear soil-structure interaction analysis in time domain BEM-FEM hybrid technique[1)]. The far field is modeled by the boundary element method (BEM) and the near field that includes pile foundations by the finite element method (FEM). The coupling between the two fields is established in the sense of weighted residual technique.

In the model, the deeper soil is modeled by BEM, piles are discretized by beam elements, neighboring soil and footing by FEM, and the vertical boundary is offset far from the area of interest. Fictitious high damping coefficient is assumed for these soil edge FEM elements to mitigate the wave reflection there.

The inelastic behavior of pile is represented by one component model[2)] with the consideration of sway motion at both ends of each element[3)]. The RC hysteresis model is treated by the Q-hyst model[4)], which is modified so as to take into account of the relationship between bending moment and axial force (**Fig. 1**). At each computational step, the yielding moment is defined from a conventional bending moment-axial force interaction diagram and the largest excursion point in

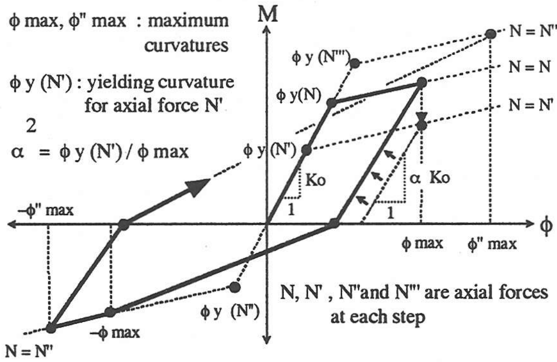

Fig. 1. RC hysteresis model for pile elements

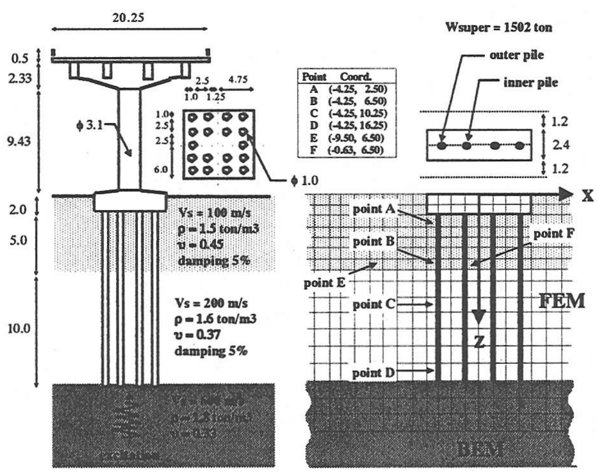

Fig. 2. Hanshin Highway and its idealization

both directions is viewed as the largest excursion point in either direction.

The Hardin-Drnevich hyperbolic model[5] and Mohr-Coulumb criterion characterize the soil nonlinear behavior.

The equation of motion is solved by step by step Newmark-Wilson method with the treatment of the nonlinearly by the iterative Newton-Raphson procedure.

3. COMPUTATIONAL RESULTS AND DISCUSSION

A typical bridge of Hanshin Highway and the idealization of soil-footing-pile system in the zone of interest are shown in **Fig. 2**, where the superstructure mass is concentrated at footing. Since the plane strain condition is assumed, a width of 4.8 m. is considered in the third direction. Two models are considered for analysis and its specific conditions are summarized in **Table I.** The calculation time interval at FEM zone is

Table I. Cases of analysis

Case	Pile	Footing	Soil
RC nonlinear	mod. Q-hyst	linear	H-D
RC linear	linear	linear	H-D

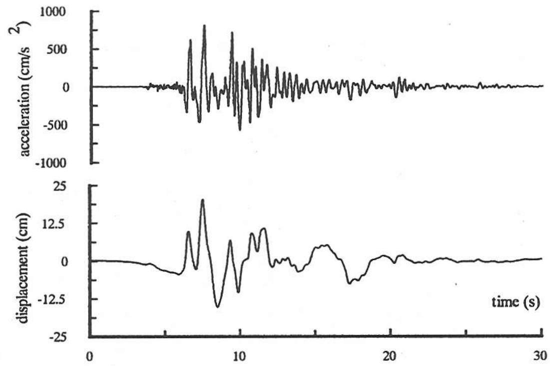

Fig. 3. Kobe-JMA-NS record

defined as 0.0025 s. and 0.001 s. for RC linear and nonlinear cases respectively. The damping coefficients for FEM edge vertical elements are assumed 25 %. The 1995 Hyogo-ken Nanbu earthquake motion, Kobe-JMA-NS component **(Fig. 3)**, is used for the input to the analyzed model **(Fig. 2)**.

The results of the two cases are depicted in **Fig. 4**. The RC nonlinear behavior is noted to be concentrated near the footing and the transition zone of soil stiffness. Pile internal forces of the RC nonlinear case become smaller compared to the RC linear case, while an increase in relative displacement due to the RC nonlinear behavior is observed. The differences between inner and outer pile responses are observed clearly for shear forces in both cases of analysis. However, these differences are not visible for bending moment and horizontal displacement responses.

The bending moment-rotation relationships for outer and inner piles are shown at specific depths in **Fig. 5** and **Fig. 6**. The RC nonlinear behavior is observed for piles both at the zone from the pile head to G.L. –4 m. and around G.L. –7 m. (interface between upper and middle soil layer). We can observe that the maximum moment at pile head of the inner pile indicates a bigger value than the outer pile. The reason of this behavior may due to the presence of lower tensional force in this maximum moment at inner pile as can be recognized in **Fig. 7**. According this figure, the maximum moment coupled with axial force is practically twice of the yielding moment and the maximum axial force of outer pile is

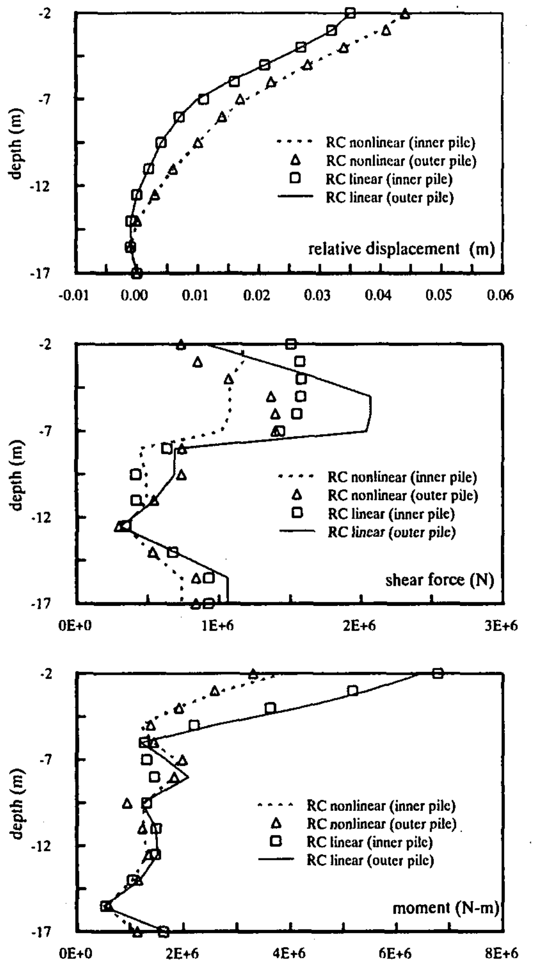

Fig. 4. Pile maximum relative displacements and internal forces

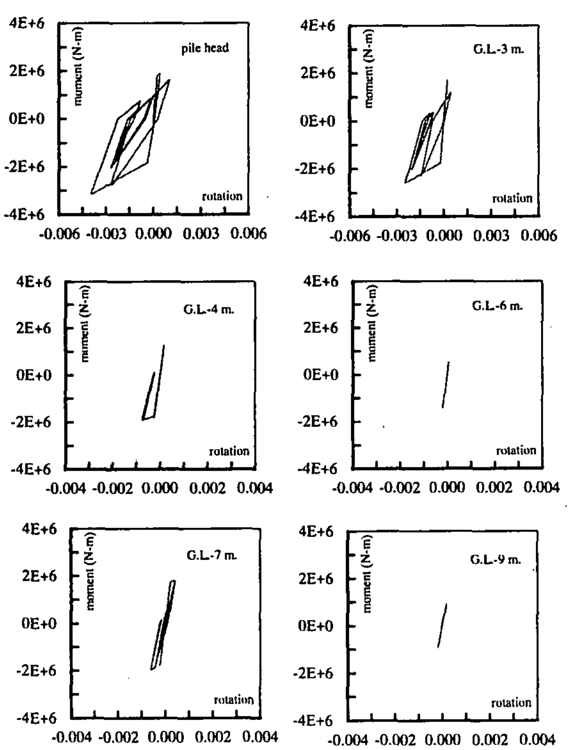

Fig. 5. Bending moment-rotation hysteresis of outer pile

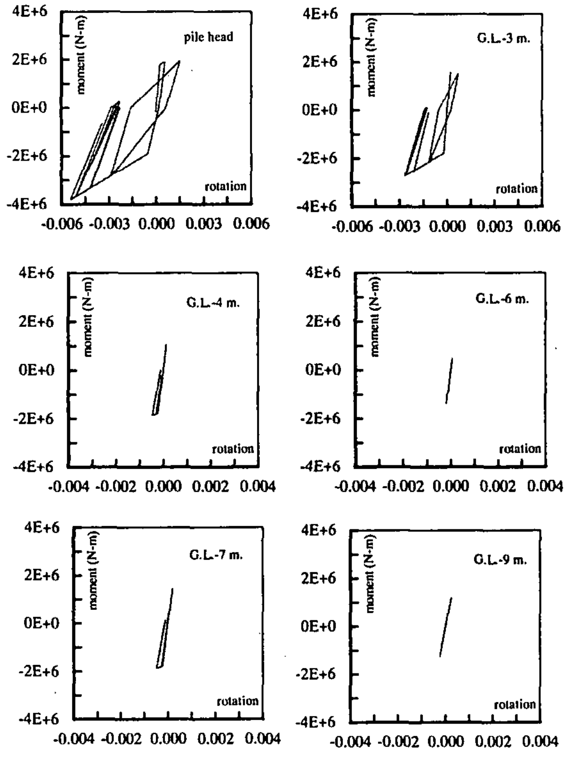

Fig. 6. Bending moment-rotation hysteresis of inner pile

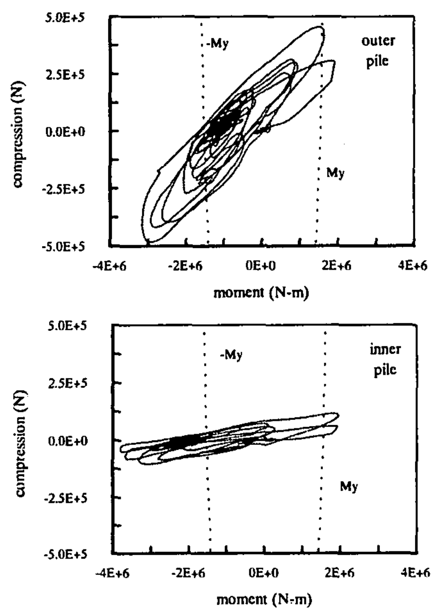

Fig. 7. Bending moment-axial force relationship at pile head

around three times of the maximum inner pile axial force.

Differences between the RC linear or nonlinear cases are not clearly observed in the soil behavior. This implies that the effect of the RC behavior in the soil is apparently small in spite of relatively weak upper soil layer stiffness. Therefore, only the results of the RC nonlinear case are

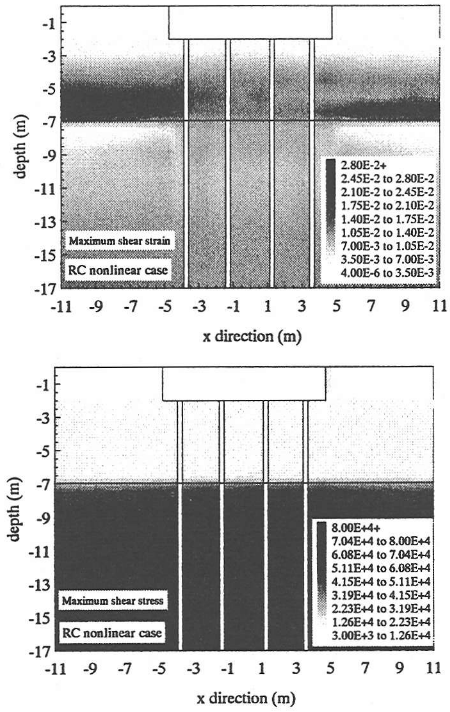

Fig. 8. Maximum shear strain and maximum shear stress

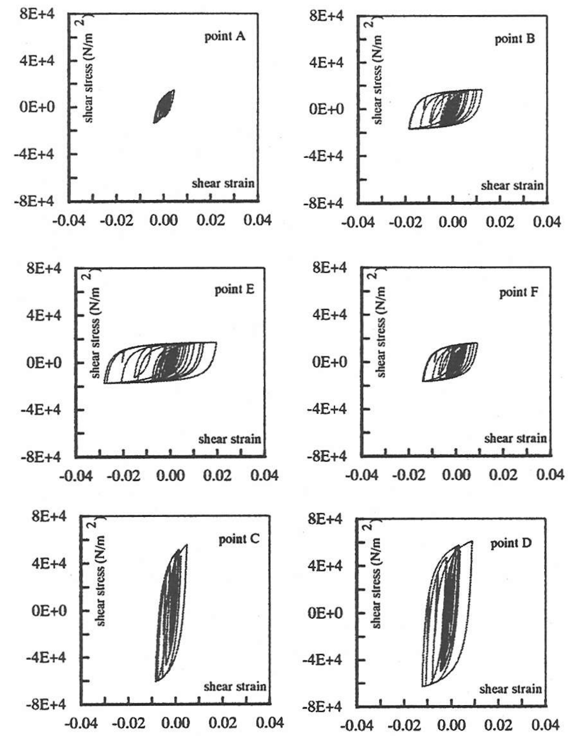

Fig. 9. Soil stress-strain hysteresis for RC nonlinear case

presented in the following figures. The maximum shear strains and stresses are shown in **Fig. 8.** This figure indicates that the maximum soil shear strain are concentrated at the zone where soil stiffness drastically changes, but it is not so in the soil confined by piles due to pile-soil-pile behavior during excitations. As consequence of this behavior, the outer piles present yield shear force than the inner piles at this zone as can be noted in **Fig. 4.** The soil stress-strain curves at six locations are drawn in **Fig. 9** whose locations are indicated in **Fig. 2.** We can note that the energy dissipated by confined soil (point F) is smaller than external soil (point B and E) of piles, which confirms the pile-soil-pile coupled behavior at this zone.

4. CONCLUSION

The results of a typical pile foundation of the Hanshin Highway analysis lead to following conclusions:

(1) The effects of the RC linear or nonlinear behavior in the soil are apparently small.

(2) The RC nonlinear behavior is concentrated at pile footing connection zone and transition zone of soil stiffness with clearly different internal piles forces in comparison to the RC linear case.

(3) The presence of axial force in piles affects the pile nonlinear behavior, which can produce a severe damage on structures due to tension force and bending moment interaction.

(4) The piles change the soil stiffness locally resulting in bigger shear force at outer piles indifferent of the RC linear or nonlinear behavior.

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