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NONLINEAR SEISMIC ANALYSIS OF SUBGRADE PILES WITH SOIL DURING STRONG GROUND MOTIONS

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SUMMARY

During strong ground motions in the Hyogoken Nanbu earthquake (1995), the substantial soil deformation and the big inertial forces from superstructure are considered to have concern with bridge piles damage. Piles and surrounding soil are supposed to have experienced nonlinear, with possible contribution of axial force fluctuation in the pile behavior. In the present study, we investigate 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 by the two-dimensional nonlinear time domain FEM-BEM hybrid technique. The RC pile nonlinearity is represented by the one component model for the pile idealization and by the modified Q-hyst model for the hysteretic rule. The modification of Q-hyst model takes into account the relationship between bending moment-curvature depending on axial force. The nonlinear soil behavior is characterized by the modified Hardin-Drnevich hyperbolic model and by the Mohr stress circle criterion. The study of a typical Hanshin Highway bridge indicates that the soil behavior is practically insensitive to RC piles behavior and the presence of piles changes the soil behavior especially at interface zone across soil layers. Furthermore, the presence of axial force affects the pile nonlinear behavior and the heavy damage in the Hanshin disaster may possibly be due to tension force and bending moment interaction.

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. Actually, the bridges are designed to resist severe loading conditions for which inelastic action is an inherent component of the system response. Clearly, the origin of nonlinearly can be in either the superstructure or the foundation depending upon the system properties. Furthermore, foundation nonlinear behavior can originate from the phenomenon of nonlinear soil-pile interaction or yielding of the piles themselves. Therefore, during strong motions, both, piles and surrounding soil have possibility to come into nonlinear behavior and the varying axial load affects the pile response. In brief, 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:

- Differences between RC linear and nonlinear behavior on the pile response 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 and varying axial force.
- Changes in soil behavior due to RC linear or nonlinear behavior.

In the present study, we perform a two-dimensional (2-D) seismic nonlinear analysis in time domain for a typical pile-supported Hanshin Highway bridge. An axial load has an important effect on the primary bending moment-

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curvature relationship of a reinforced concrete section. Therefore, in this study, the definition of primary bending moment-curvature is based on the criterion that the pile yield strength depends upon the axial force and the bending moment.

METHODOLOGY

Soil-structure interaction effects are considered by using a 2-D nonlinear soil-structure interaction system based upon the time domain FEM-BEM (Finite Element Method-Boundary Element Method) hybrid technique developed by Takemiya and Adam [5]. The FE region is considered as the non-homogeneous nonlinear zone while the BE region is considered as linearly elastic domain. Therefore, the far field is modeled by BEM and the near field that includes pile foundations by FEM. The coupling between the two fields is established in the sense of weighted residual technique, where the BE region is treated as a super finite element and its stiffness matrix is computed and assembled into the global stiffness matrix. 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 FE soil edge elements to mitigate the wave reflection there.

The inelastic behavior of pile is represented by one component model proposed by Giberson [1], with the consideration of sway motion at both ends of each element as was presented by Takemiya and Shimabuku [7]. The RC hysteresis model is treated by the Q-hyst model of Saidi and Sozen [4], which is modified so as to take into account of the relationship between bending moment and axial force. At each computational step, the yielding moment is defined from a conventional bending moment-axial force interaction diagram and the correspondent hysteresis curve is defined considering constant stiffness Ko as illustrated in Figure 1. Furthermore, to simplify the rules of model, the largest excursion point in both directions is viewed as the largest excursion point in either direction. The soil nonlinear behavior is characterized by Mohr stress circle criterion and the hyperbolic model originally proposed by Hardin and Drnevich [2], which was refined by Takemiya *et al.* [6] to be more suitable for computational simulation in 2-D problems for irregular seismic loading.

The equation of motion is solved step by step by the Newmark-Wilson method taking care of the nonlinearity by the iterative Newton-Raphson procedure. The assumed Mohr stress circle criterion to evaluate the out-of-balance load is presented in Figure 2. In this criterion, the soil is assumed linear in both normal stress direction σ_x and σ_z , whereas, the shear stress τ_{xz} and shear strain γ_{xz} adhere to modified Hardin-Drnevich relations. Therefore, the out-of-balance stress tensor only considers the out of balance shear stress $\Delta\tau_{xz,u}$. As the normal stresses σ_x and σ_z change with the variation of τ_{xz} from one iteration to next, the effect of nonlinear behavior of the normal stress is implicitly taken into account.

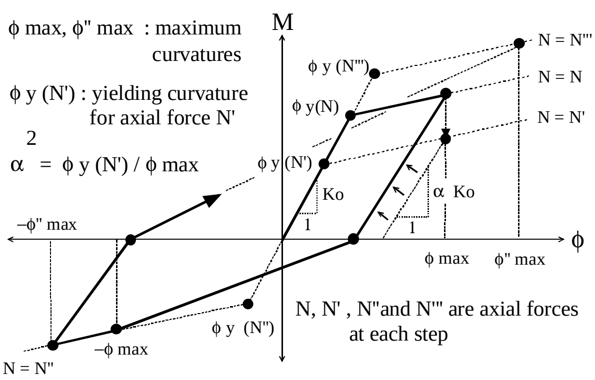

Figure 1: Modified Q-hyst model

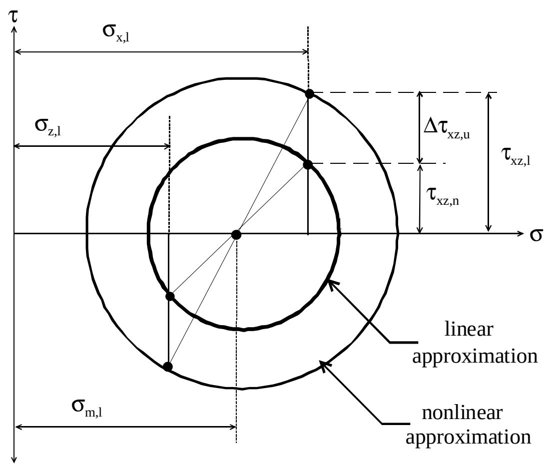

Figure 2: Modified Mohr circle for soil behavior

TYPICAL HANSHIN HIGHWAY FOUNDATION ANALYSIS

A typical bridge of Hanshin Highway and the idealization of soil-footing-pile system in the zone of interest are shown in Figure 3, 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. Near the pile foundation, the soil is modeled by quadrilateral 4 node-solid elements of 1 m. x 1 m. until G.L. –8 m. and elements of 1 m. x 1.5 m. from G.L. –8 m. to G.L. –21.5 m. The length of pile elements coincide with the size of soil elements.

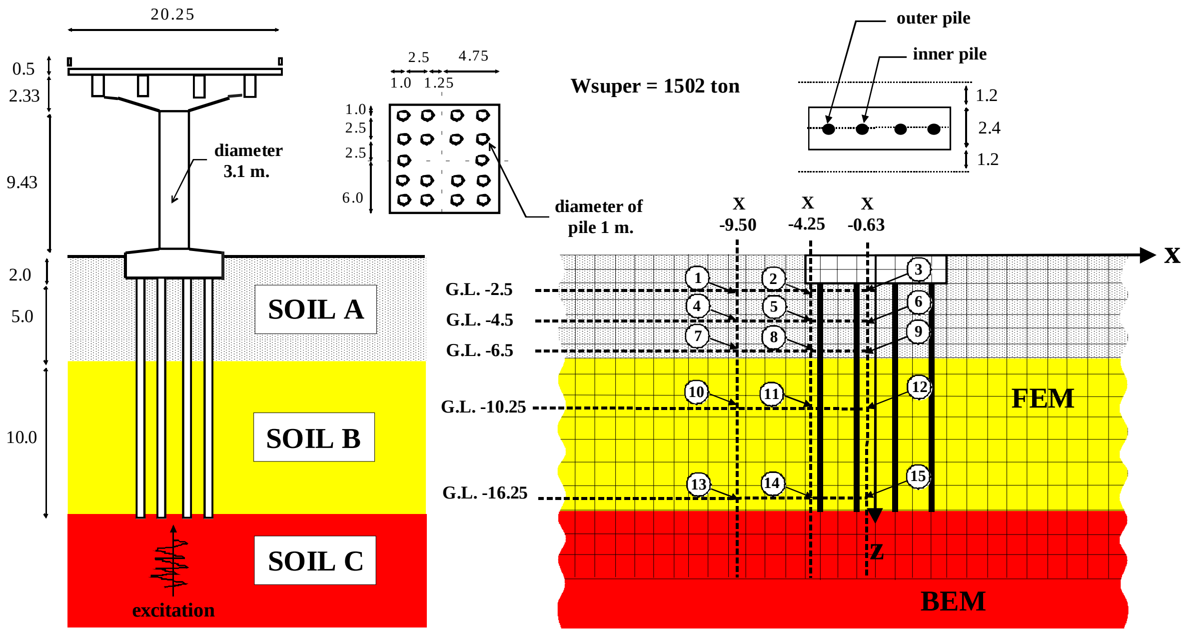

Figure 3: Hanshin Highway and its idealization

Table 1: Cases of analysis.

Case	Pile	Footing	Soil
RC nonlinear	One component model	linear	Hardin-Drnevich model
RC linear	linear	linear	Hardin-Drnevich model

Table 2: Properties of concrete and reinforcement.

	Compressive strength (σ_{ck})			270 kgf/cm^2
	Modulus of elasticity (E_c)			2.8 x 10^5 kgf/cm^2
	Strain under maximum compression stress (ε_{cc})			3.0 x 10^{-3}
	Ultimate strain of restrained concrete (ε_{cu})			3.6 x 10^{-3} kgf/cm^2
	Yield strength (σ_{sy})			3500 kgf/cm^2
	Modulus of elasticity (E_s)			2.1 x 10^6 kgf/cm^2
	Longitudinal bars	Diameter (ϕ)		29 mm
		Number	Depth 2 m. to 8.375 m.	18
			Depth 8.375 m. to 17 m.	9
	Transversal	Diameter (ϕ)		13 mm
STEEL		ctc	Depth 2 m. to 17 m.	30 cm

Table 3: Properties of soil layers.

	Density (kg/m3)	Shear velocity (m/s)	Poisson's value	Damping (%)
SOIL A	1500	100	0.45	5
SOIL B	1600	200	0.37	5
SOIL C	1800	600	0.33	0

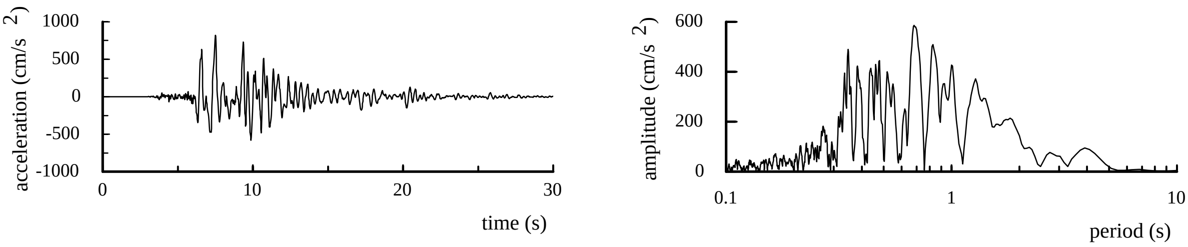

Figure 4: Kobe –JMA-NS record and their Fourier response spectra.

The differences between RC pile linear and nonlinear behavior are compared throughout two models of analysis. These specific analytical conditions are summarized in Table 1. The computation time interval at interface BEM zone (Δt_{BEM}) is assumed as 0.02 , while the FEM time increment Δt_{FEM} as 1/8 and 1/16 of Δt_{BEM} for RC linear and RC nonlinear cases, respectively.

The RC pile constitutive properties is given in Table 2, where the confined concrete characteristics are defined according the 1996 Design Specification of Highway Bridges (Part V) [3]. The yielding points of bending moment-axial force interaction diagram are derived using conventional reinforced concrete theory. The soil properties are presented in Table 3, and the fictitious damping ratio imposed on the FEM edge vertical elements is 25 %. Figure 4 shows the acceleration and their Fourier spectra for the 1995 Hyogo-ken Nanbu earthquake, Kobe Marine Meteorological Observatory record, north-south component (Kobe-JMA-NS). This record is used for the input to the analyzed models.

RESULTS

The results of the two cases are depicted in Figure 5. The RC nonlinear behavior is noted to be concentrated near the footing and the interface zone between upper and middle soil layer (G.L. –7 m.). 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 in both cases of the analyses are observed clearly for shear forces at any depth and for the bending moment at pile head. However, these differences are not visible for horizontal displacement responses.

The bending moment-rotation relationships for outer and inner piles are shown at specific depths in Figure 6 and Figure 7, respectively. The RC nonlinear behavior is observed for inner and outer piles at the zone from the pile head to G.L. –4 m. and around G.L. –7 m. 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 tension force in this maximum moment at inner pile as can be recognized in Figure 8. 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 around three times of the maximum inner pile axial force.

Figure 9 shows the pile-dissipated energy, which is calculated from the bending moment-rotation hysteresis in Figures 6 and 7. We can see that the total dissipated energy at pile head is larger than at other positions. Furthermore, a difference between outer and inner pile dissipated energy at pile head is clearly noted. Table 4 presents the rotational ductility at the same places, where the highest ductility occurs in the inner pile at G.L. –3 m.; however, in reality, the possible failure occurs at pile head, since the dissipated energy governs the damage at substructure level as was recognized by Takemiya and Shimabuku [7].

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 presented in the following figures. The maximum shear strains and stresses are shown in Figure 10. 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 indicate yield shear force than the inner piles at this zone as can be noted in Figure 5. The soil stress-strain curves at fifteen locations are drawn in Figure 11, whose locations are indicated in Figure 3. We can note that the difference between these curves at same depth is only presented for points 7, 8 and 9, which correspond to transition zone of soil stiffness. The maximum shear strain is around 3% and occurs at point 7, but at the confined soil (point 9) is around 1.5%. To clarify this behavior the energy dissipated at G.L. –6.5 m and G.L. –16.25 m. are presented in Figure 12, where the energy dissipated by confined soil (point 9) is clearly smaller than dissipated by external soil (points 8 and 9). On the other hand, at G.L. –16.25 m, it is not observed and the points 10, 11 and 12 present similar quantity of dissipated energy. It confirms the pile-soil-pile coupled behavior at the interface zone of soil layers.

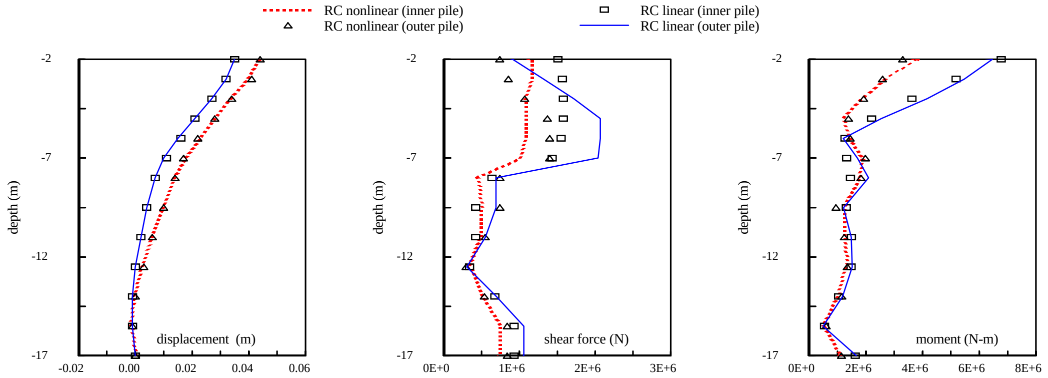

Figure 5: Pile maximum relative displacements and maximum internal forces.

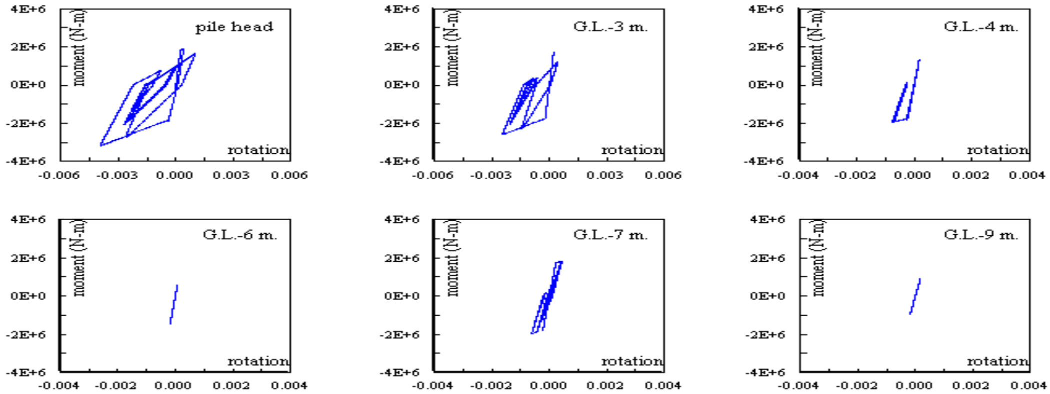

Figure 6: Bending moment-rotation hysteresis of outer pile.

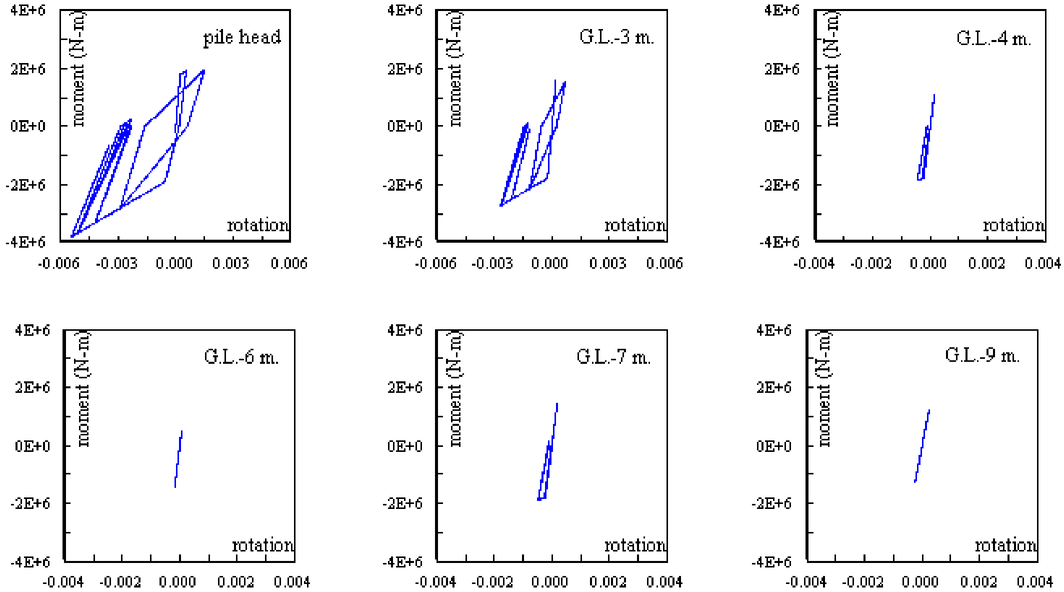

Figure 7: Bending moment-rotation hysteresis of inner pile.

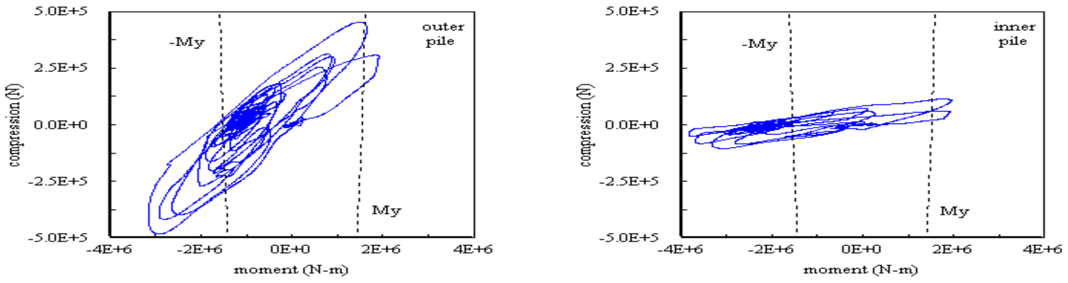

Figure 8: Bending moment-axial force relationship at pile head.

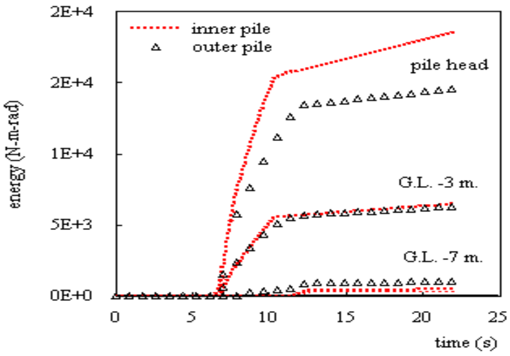

Figure 9: Energy dissipated by RC pile.

Table 4: Rotational ductility of piles.

θmax / θy	inner pile	outer pile
pile head	9.04	8.45
G.L. -3 m.	9.65	9.53
G.L. -4 m.	1.58	2.96
G.L. -7 m.	1.79	2.68

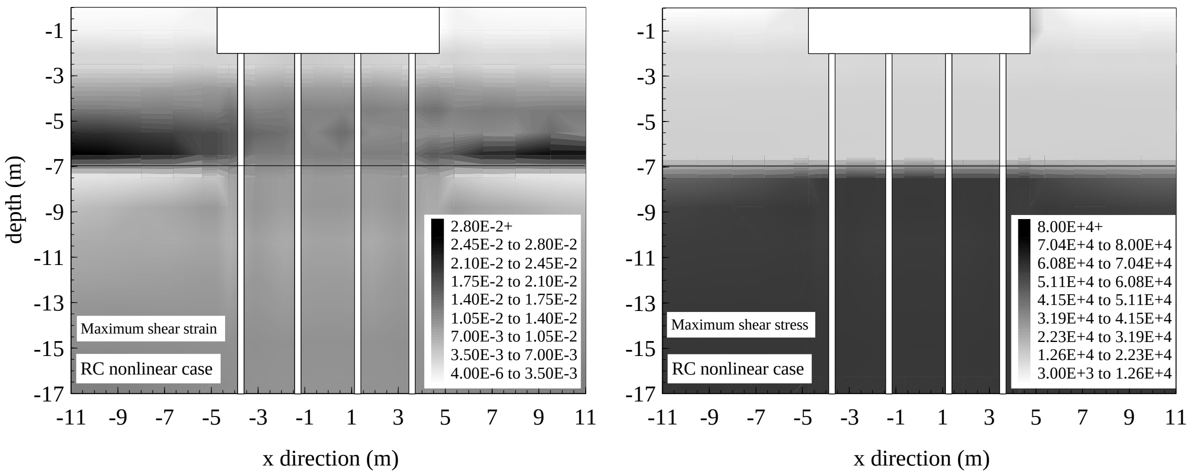

Figure 10: Maximum soil shear strain and shear stress.

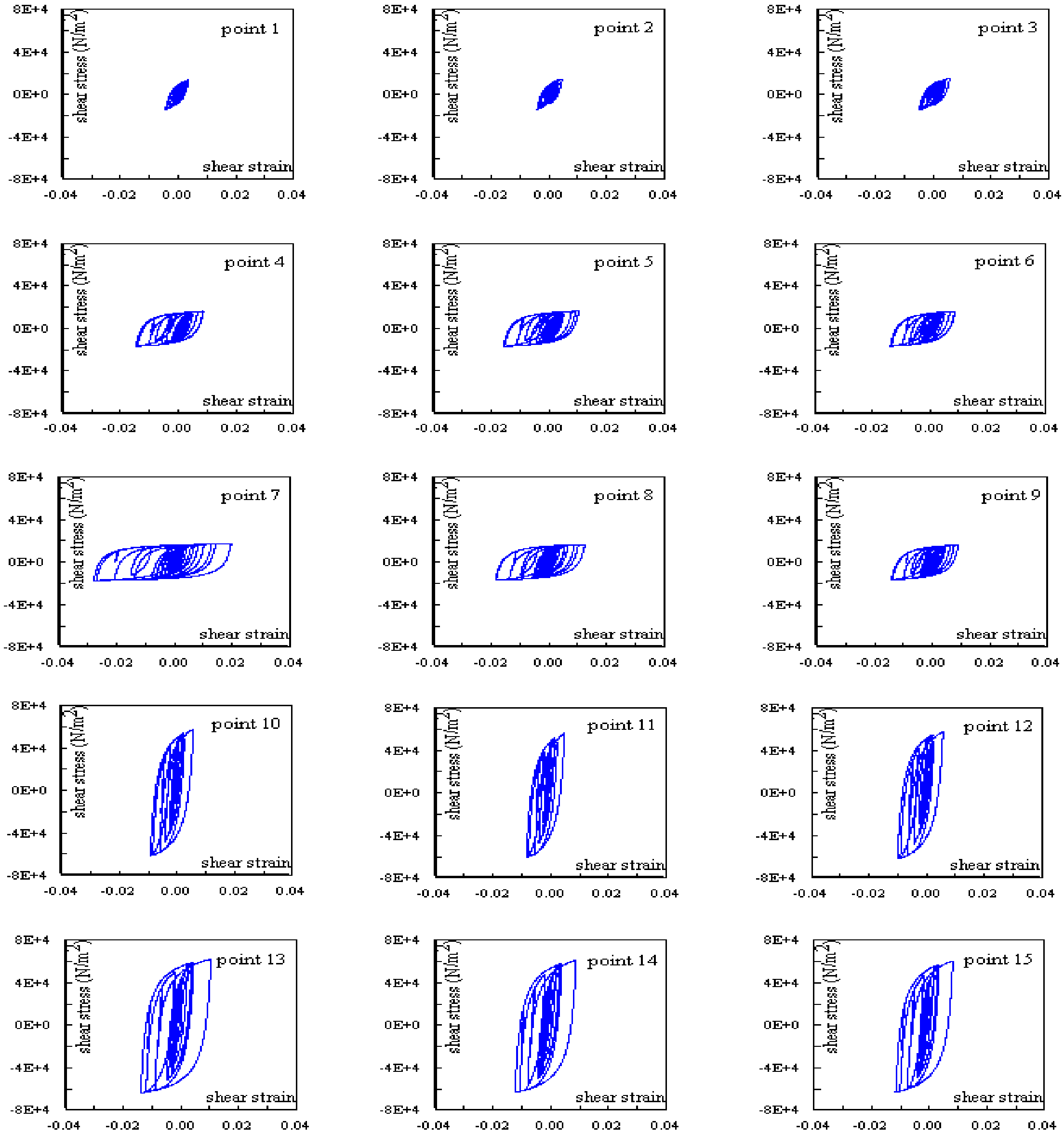

Figure 11: Soil stress-strain hysteresis for RC nonlinear case.

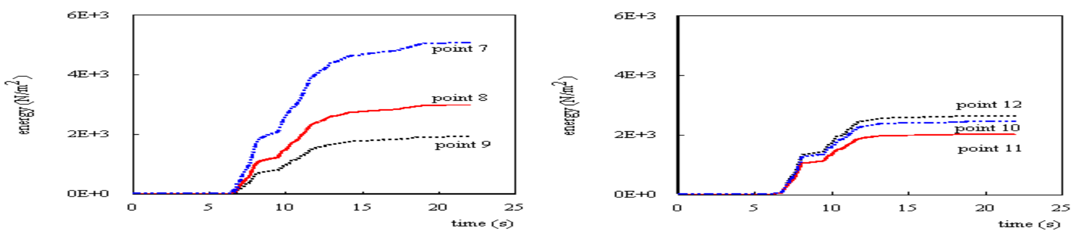

Figure 12: Dissipated energy by soil.

CONCLUSIONS

In this study the problem of nonlinear soil-pile foundation interaction was addressed. The RC pile nonlinear behavior including axial force effects and its interaction with surrounding soil was focused. Based on the analysis undertaken above, the following conclusions are drawn:

(1) Regardless the RC linear or nonlinear, the soil behavior is almost the same.

(2) The presence of piles changes the soil stiffness at interface zone across soil layers with in-phase behavior of soil confined by piles.

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

(4) The presence of axial force in piles affects the pile nonlinear behavior, which gives rise to severer damage on structures due to tension force and bending moment interaction.

(5) The outer piles present a bigger shear force compared to inner piles at the interface zone across layers indifferent of the RC linear or nonlinear behavior.

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