SOIL LAYERING EFFECTS ON SEISMIC NONLINEAR RESPONSE OF PILE FOUNDATION

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This paper investigates the effects of the soil layering on the pile foundation response with emphasis on the kinematic and inertial interactions. The analysis is conducted based on the time domain FEM-BEM 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 this study provide useful data for a better prediction and understanding of the behavior of piles embedded in layered soil.

Key Words : *pile nonlinear behavior, layered soil, kinematic interaction, inertial interaction*

1. INTRODUCTION

Structures sited on soft soils are founded by deep foundations. Those are demanded on the lateral resistance against earthquake loading, especially for highway bridges as confirmed in recent big earthquakes. The pile failures arise from large inertial forces developing in the superstructure (inertial effect) or substantial ground deformations (kinematic effect). When a pile foundation is in a layered soil with sharply different stiffness, both inertial and kinematic interaction effects can be important in the behavior of pile foundation. Therefore, the objective of this investigation is to clarify these interaction effects and their interrelationships with the fundamental periods of the soil and the structure. The investigated cases included stiff soil underlain by softer layer and soft superficial layer on stiff soil stratum with different depths of the boundary between soil layers.

2. METHOD OF ANALYSIS

We perform a 2-D seismic nonlinear soil-structure interaction analysis in time domain FEM-BEM 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). In the model, the deeper soil is modeled by BEM, the pier and piles are discretized by beam elements, neighboring soil by FEM, and the vertical boundary is offset far from the area of interest.

The inelastic behavior of pier and piles are represented by the modified one component model[2)] and the modified Q-hyst model[3)], where the axial load variation is considered in the evaluation of the yield bending moment at each computational step from the bending moment-axial force interaction diagram. The nonlinear soil behavior is characterized by the Hardin-Drnevich hyperbolic model and the Mohr stress circle criterion.

3. COMPUTATIONAL RESULTS AND DISCUSSION

A typical bridge of Hanshin Highway and the idealization of soil-superstructure-pile system in the zone of interest are shown in **Fig. 1**. The piles' rows are called A, B, C and D for reference. The length of pile elements is taken the same with the size of soil elements. Since the plane strain condition is assumed, a width of 24 m (twice width of the footing) is considered in the third direction. The site shown in **Fig.1** refers two layers soil deposits denoted by layer A and B underlain by much stiffer soil denoted by layer C. The layer C is assumed to have the same properties of the elastic extending half-space (BE) with the shear velocity (Vs) of 600 m/s, the mass density (ρ) of 1.80 ton/m^3 and the

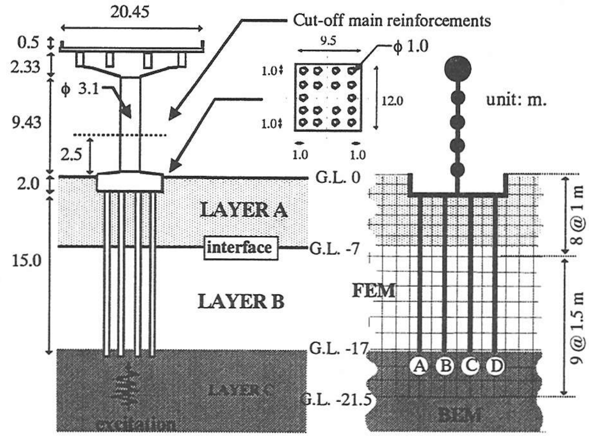


Fig. 1. Hanshin Highway and its idealization.

Table 1. Studied profiles.

Layer \ Case		Soil-11	Soil-21	Soil-12	Soil-22	Soil-12-s	Soil-21-s	Soil-12-d
V_s (m/s)	A	100	200	100	200	100	200	100
	B		100	200		200	100	200
ρ (ton/m^3)	A	1.5	1.6	1.5	1.6	1.5	1.6	1.5
	B		1.5	1.6		1.6	1.5	1.6
ν	A	0.45	0.37	0.45	0.37	0.45	0.37	0.45
	B		0.45	0.37		0.37	0.45	0.37
Distance from pile top to interface (m)		---	5	5	---	2	2	9

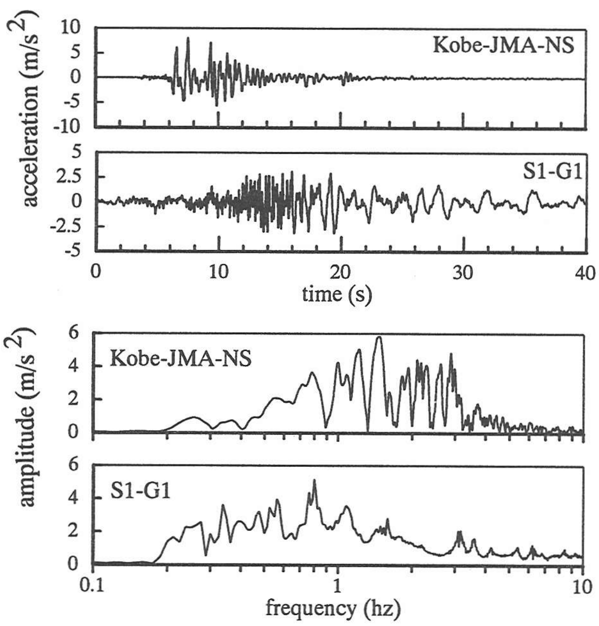
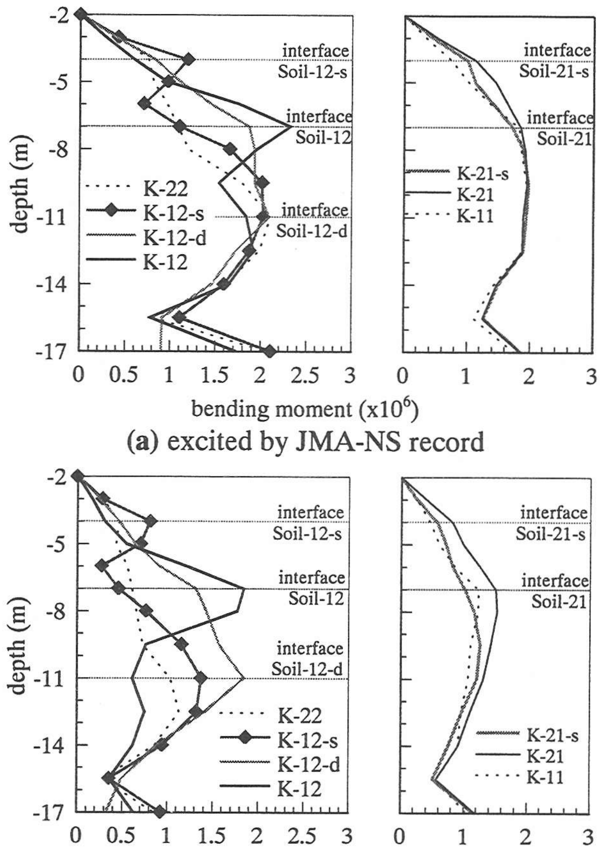


Fig. 2. Kobe-JMA-NS and S1-G1 records.

Poisson's ratio (ν) of 1/3 for all studied cases. The properties of the layer A and B are given in **Table 1**.

Two different records are used as excitation: the North-South component of the 1995 Hyogo-ken Nanbu Earthquake measured in Kobe (JMA-NS) and an artificial record denominated S1-G1, which corresponds to motion on ground 1 (bedrock) of Level II-Spectrum I of the "Japanese Seismic Design Code for Railway Structures"[4]. The respective time histories and Fourier spectrum are depicted in **Fig. 2**.

In addition to idealization given in **Fig. 1**, a structural model composed by only free head piles is also considered in order to evaluate the kinematic interaction effects. In the denomination of the analyzed cases, the letter **T** corresponds to whole system idealization (model of **Fig. 1**) and the letter **K** corresponds to the free head piles system. **Fig. 3** shows the kinematic bending moment distributions along the pile length. When the layers interface is located at G.L. –4 m or G.L. –7 m, peak values appear at this level for the K-12 or K-12-s cases (soft layer on stiff layer). However, these bending moment peaks do not appear for the K-21 and K-21-s cases (stiff layer on soft layer). The bending moment distribution for these cases and the K-11 case are almost the same. This is caused by the fact that the stiff layer underlain by soft layer leads to smaller amplification than the soft layer on stiff layer. The supporting interpretation is made from the maximum shear strain of the soil in **Fig. 4**. In



(**a**) excited by JMA-NS record

(**b**) excited by S1-G1 record

Fig. 3 Kinematic bending moment distribution.

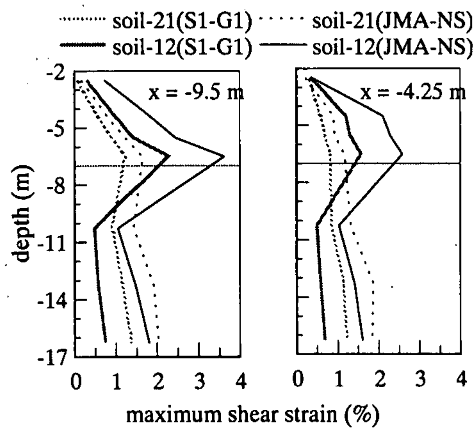
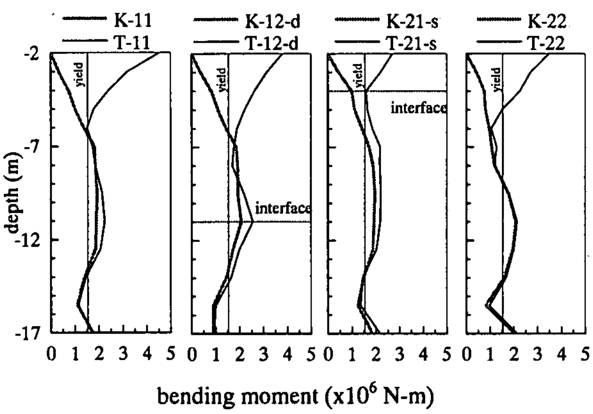
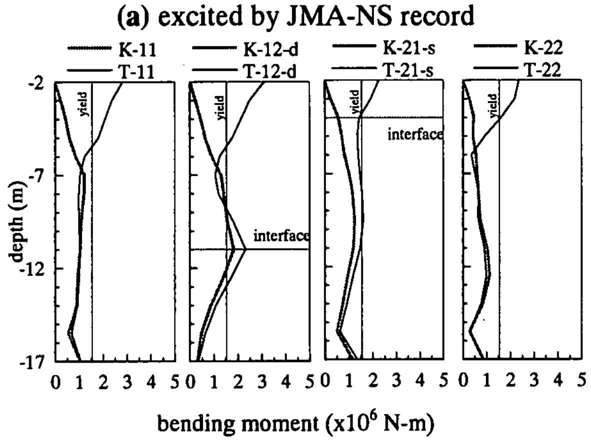


Fig. 4 Maximum shear strain of soil.

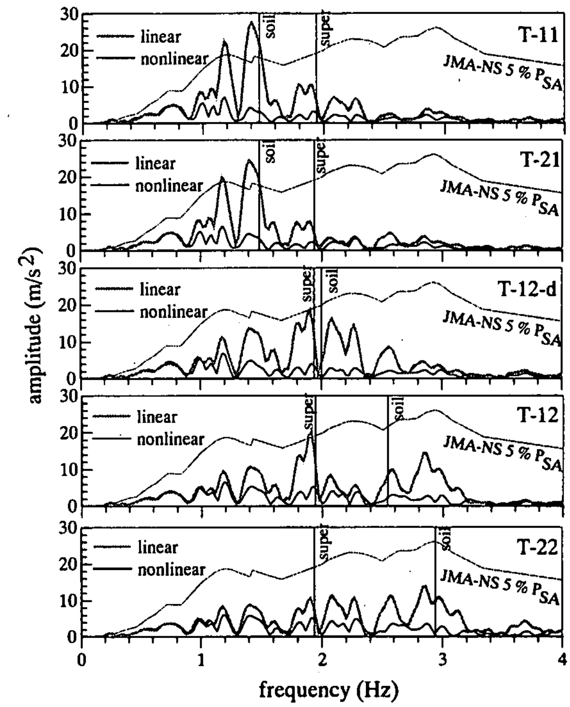


(a) excited by JMA-NS record

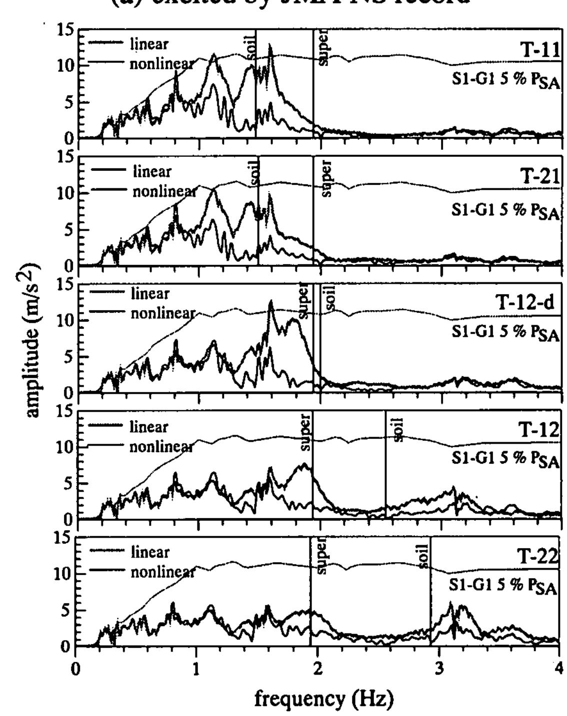


(b) excited by S1-G1 record

Fig. 5 Kinematic and total maximum bending moment along the piles.



(a) excited by JMA-NS record



(b) excited by S1-G1 record

Fig. 6 Comparison between linear and nonlinear Fourier amplitudes of pile top acceleration.

this figure, x=-4.25 m corresponds to soil near the outer side of external pile and x=-9.5 m to soil far away from the foundation. It is noted that the Soil-12 profile generates a larger response than the Soil-21 profile especially at interface between layers. Therefore, a soft superficial layer underlain by a stiff soil stratum is crucial to this behavior.

Fig. 5 shows the kinematic and total bending moment distributions along the pile length, where the vertical lines correspond to the yield bending moment under static axial load. Since the pile active length *la* for the inelastic behavior can be defined approximately as the depth at which the kinematic and total bending moments are equals, *la* is derived as 4~5 m for the structure-pile foundation in homogenous profile (Soil-11 and Soil-22). In a rigorously performed linear analysis, the kinematic and total bending moments at depths are almost identical since the loads transmitted from the superstructure attenuate very rapidly with the depth. However, when both surrounding soil and piles reach their yielding state, the kinematic and total bending moments are different even at deep elevations as noted for the structure with piles embedded in the Soil-21-s and Soil-12-d profiles. At the interface level of the Soil-21-s profile, the differences between L-21-s and K-21-s responses are due to the superstructural inertia force since its pile active length is larger than thickness of first soil layer. However, at the layer's interface level of Soil-12-d profile, the deep location of interface indicates that difference between K-12-d and L-12-d can not be generated by the inertial forces from the superstructure.

Since the behavior of superstructure-pile-soil system might be dependent on the frequency characteristics of the structure, ground and input excitation; the response frequency contents of the analized cases for the whole system are investigated. The Fourier transforms of the acceleration at top of pile D are depicted in **Fig. 6**. In this figure, the results of a complete elastic (pier, pile foundation and soil in linear behavior) and inelastic analyses are shown. The pseudo-acceleration spectrum (P_{SA}) with 5 per cent of damping is also reported. Additionally, the natural soil frequency and the fundamental frequency of a structure with fixed condition at its base are depicted by vertical lines. From the results of linear analysis, the following considerations are noted. The peaks between 2.5 Hz and 3.5 Hz are dominated by the characteristics of the layer with Vs=200 m/s, which corresponds to the L-12, L-12-s and L-22 cases. The peaks between 1.0 Hz and 1.5 Hz are caused by the properties of the layer with Vs=100 m/s as was observed for the L-11, L-21-s, L-21 and L-12-d cases. The peaks between 1.8 Hz and 2.0 Hz are governed by the superstructure (fundamental frequency of structure with fixed condition at its base is 1.94 Hz). Since the analysis is linear, the relationship between the natural frequency of soil (f_{soil}) and the structural frequency (f_{super}) is obtained. In the situation of $f_{super} > f_{soil}$ (L-11, L-21-s and L-21 cases), the vibration frequency from the superstructure are reduced since the soil filters these frequencies from the excitation. Consequently, the response is governed by the predominant soil mode, which corresponds to layer with Vs=100 m/s. When f_{super} is very close to f_{soil} (L-12-d case), the response is amplified at this frequency neighborhood. In the situation of $f_{soil} > f_{super}$ (L-12, L-12-s and L-22 cases), both superstructure and natural soil modes have an important contribution to the response. However, if the Fourier response spectrum of linear and nonlinear analyses is compared, it is noted that the inelastic behavior reduces greatly the maximum responses. The clearly defined frequency characteristics of the elastic analysis disappear in the nonlinear analysis with peaks at low frequency range. For the Kobe-JMA-NS excitation, the peaks appear around 0.8 Hz, 1.2 Hz, 1.4 Hz and 1.94 Hz. The peaks at 1.94 Hz for the L-12-s, L-12 and L-22 cases can be attributed to the condition of $f_{soil} > f_{super}$ and the condition of the spectral densities of the input motion which are concentrated in the frequency range larger than 1 Hz (see **Fig. 2**). Therefore, it is able to say that the input excitation "directly arrives" to the superstructure even for the inelastic behavior. For the S1-G1 excitation, the peaks correspond to frequencies around 0.8 Hz, 1.1 Hz and 1.6 Hz. Here the effects of superstructure (f_{super}) do not appear due to the spectral densities of this input motion are concentrated in frequency range shorter than 1 Hz (see **Fig. 2**). Therefore, the response frequencies are concentrated in the short frequency range and are greatly changed by the inelastic behavior of structure and surrounding soil.

4. CONCLUSION

The shallow soft layer underlain by a stiff soil stratum is crucial to pile behavior. The magnitude of the kinematic bending moment developed in the pile is appreciable at this interface. The ground composed by shallow stiff layer underlain by a soft layer does not generate peak values at layers interface, but develops significant inertial bending moments even at depth. Therefore, if strong seismic excitation is anticipated and the ground is composed of soft layer on stiff layer, the pile sections near layer interface should be designed with the necessary strength and ductility.

The response frequencies are greatly changed by the inelastic behavior of structure and surrounding soil with maximum responses concentrated in the short frequency range.

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