KINEMATIC AND INERTIAL EFFECTS ON NONLINEAR RESPONSE OF PILE-FOUNDATION IN LAYERED SOIL

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1. INTRODUCTION

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 and the layer interface is near to surface, both inertial and kinematic interaction effects can be crucial in the behavior of pile foundation at this zone. Therefore, the objective of this paper is to clarify these interaction effects at layer interface and their interrelationships with the fundamental periods of the soil and the structure. The layered soil comprises of a soft layer underlain by a stiff soil stratum.

2. MODELLING AND RESPONSE ANALYSIS

A 2-D seismic nonlinear soil-structure interaction analysis is conducted based on BEM-FEM hybrid technique[1]. A typical bridge of the Hanshin Expressway and its idealization in the zone of interest are shown in **Fig. 1**. The pier and piles are modeled by beam elements, the neighboring soil is discretized by FEM with the vertical side boundary offset 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], these modifications take account the sway motion at both ends of each element and the bending moment-axial force relationship, respectively. The nonlinear soil behavior is characterized by the Hardin-Drnevich hyperbolic model and the Mohr stress circle criterion. **Table 1** shows the analyzed cases and soil classification according the current design specifications. In each case, we performed a nonlinear analysis of the total system (model of **Fig. 1**) and free head piles system (kinematic effect, without footing and superstructure). The input motion used in the analysis is the Kobe-JMA-NS record. The characteristic length for deformation of a pile in homogeneous stratum with Vs=100 m/s (case A) is 6 m (G.L. –8 m), which is calculated according to the substructure design specifications for highway bridges. It suggests that at soil layers interface (G.L. –7 m, case B), both kinematic and inertial effects should be concerned in the response. **Fig. 2** shows the maximum internal forces along a pile, which corresponds to external pile with maximum compressional forces[4]. The interface induces a strong inertial effect (proportional approximately to the difference between total and free head pile responses) at, or nearest to this zone as can be appreciated in maximum shear force graphic (especially at G.L. -5 m). With respect to free head pile bending moment at interface level, it becomes sharper for case B over the homogeneous stratum cases, which clearly indicates the kinematic effect at this zone. **Fig. 3** shows the bending moment-rotation hysteresis to evaluate the kinematic effect at this level. The difference in the responses of 3 cases can be attributed to different frequency contents by each case; therefore to revise this point, the fourier transform of pile top accelerations are presented in **Fig. 4**. In the same figure, the response spectrum of JMA-NS record and the fundamental periods of the fixed based superstructure, the free soil and the soil-pile-superstructure system are also depicted. These fundamental periods are calculated by 1-D idealization, where the springs to simulate the pile-soil interaction in the soil-pile-superstructure system are calculated by following the substructure design specifications for highway bridges. A comparison with complete linear analysis is presented to check the variation of the frequency contents in the response due to the nonlinear behavior. According to the linear analysis, the peaks for the case B appear around 1.9 and 2.85 Hz, which is apparently dominated by the superstructure and deeper soil fundamental frequencies (peaks between 2.5 and 3 Hz are very similar for case B and case C). However, a definitive pattern is not visible in the nonlinear analysis. Therefore, it can be recognized that the frequencies contained in the response are dominant by the inelastic behavior. **Fig. 5** indicates that the maximum linear acceleration is reduced greatly due to nonlinear behavior. At interface level, the inertial effect appears at peak responses (around 7.8 and 8.1 s.), which confirms its presence even at interface zone. In order to detect the transient feature of response at interface level, the normalized variation of frequency contents with time are shown in **Fig. 6**. This was performed by wavelet transform application; herein the Daubechies 10th order wavelet function was used. We can see that the pattern of the free soil and pile figures is very similar, which also confirms the considerable effect of kinematic interaction. **Fig. 7** shows the rotational ductility for case B, where the free head case has larger

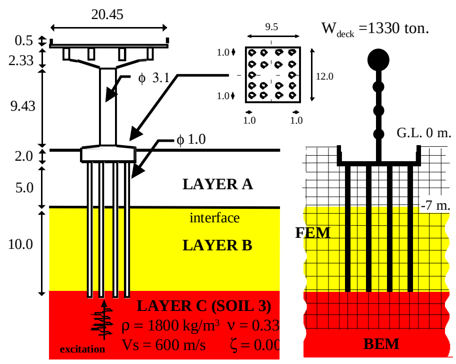

Fig.1 The Hanshin Highway and its model

Table 1. Studies profiles

CASE	LAYER A	LAYER B	Type
A	SOIL 1		II
B	SOIL 1	SOIL 2	II
C	SOIL 2		III

SOIL 1
ρ = 1500 kg/m³　ν = 0.45
Vs = 100 m/s　ζ = 0.05

SOIL 2
ρ = 1600 kg/m³　ν = 0.37
Vs = 200 m/s　ζ = 0.05

KEY WORDS: inertial interaction, kinematic interaction, pile nonlinear behavior, layered soil
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value than the total case at interface zone.

3. CONCLUSIONS

The inertial and kinematic effects have been shown to be important during seismic excitations near the interface of soils with sharply different stiffness. If strong seismic excitation is anticipated, the pile section near layer interfaces should be designed with the necessary ductility and strength to prevent its failure due to both interaction effects.

4. REFERENCES

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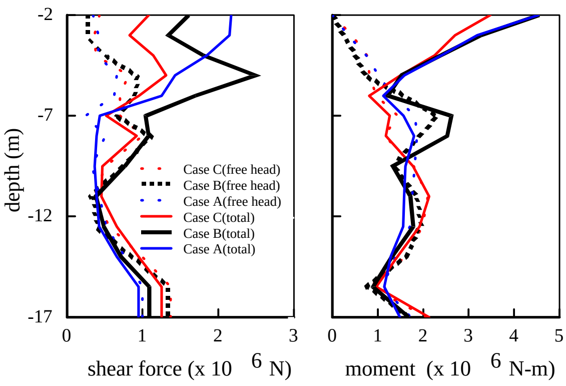

Fig. 2 Pile maximum internal forces

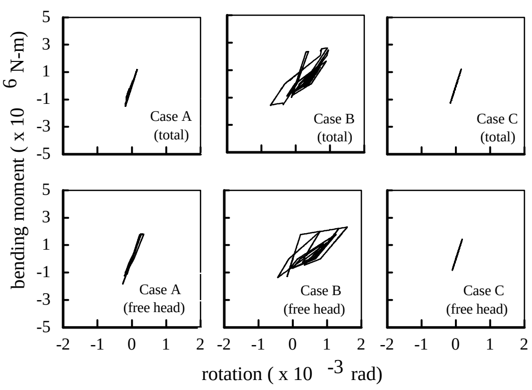

Fig. 3 Moment-rotation hysteresis of pile at G.L. –7 m

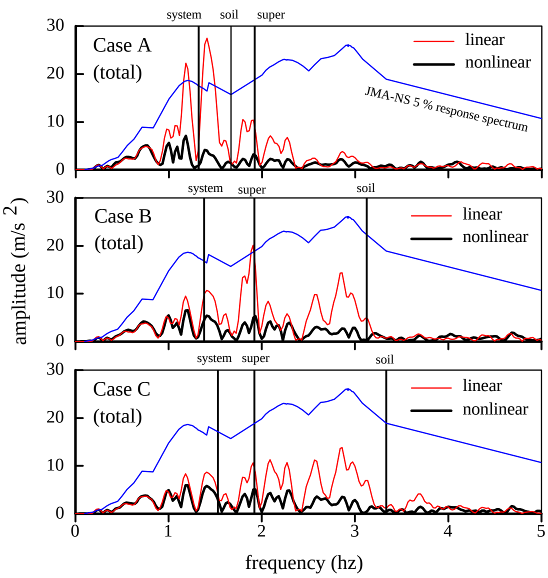

Fig. 4 Fourier amplitudes of pile top acceleration

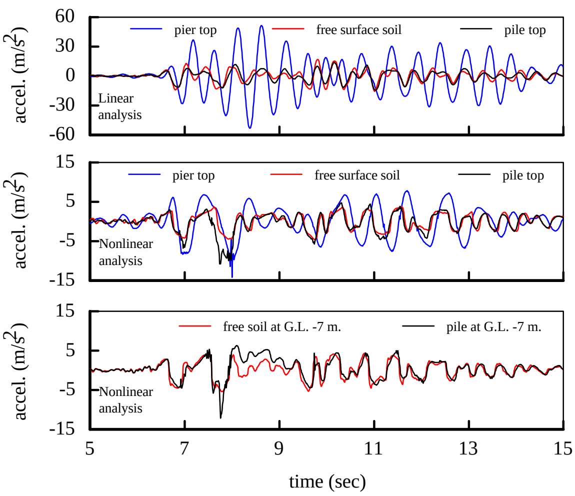

Fig. 5 Case B (total) acceleration time history

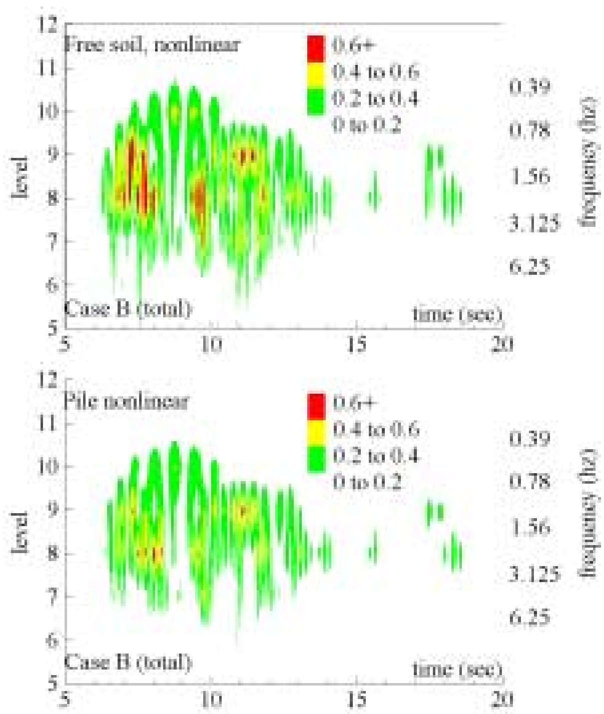

Fig. 6 Transient acceleration feature at interface level

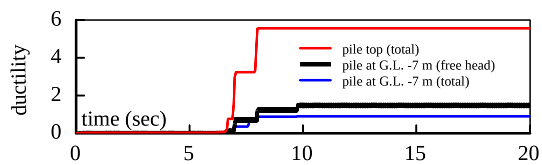

Fig. 7 Ductility at top of pile for Case