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A simple method for earthquake response analysis of soil-pile-foundation-structure systems

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ABSTRACT

This paper studied a simple and highly precise method for estimating earthquake responses of soil-pile-foundation structures so that an investigation into the realization of nuclear reactor buildings supported by piles could be carried out. Effects of pile groups, non-linearity of soil surrounding the piles and embedment effects of the foundation were considered. The simulation of the response of a pile-foundation structure which was observed during the 1995 Hyogo-ken Nanbu Earthquake showed good agreement.

1. INTRODUCTION

It is required under current design codes that nuclear reactor buildings be sited on bedrock in Japan. However, such suitable rock sites are limited. With an aim of extending siting options, the possibility of nuclear reactor buildings supported by piles is being investigated. In order to realize nuclear reactor buildings supported by piles, a simple and precise method for evaluating seismic responses of soil-pile-foundation structures must be established for design purposes. When considering the magnitude of design seismic motion, the non-linearity of soil and structures cannot be ignored. It is necessary to establish a method with which nonlinear analyses can be made.

2. BASIC CONCEPT OF ANALYTICAL MODELS

A new numerical model was proposed by expanding the concept of the present design model (Sway Rocking model). The proposed model is shown in Fig.1. A building and its piles are modeled by bending shear beams and lumped masses. The pile group is condensed into a single beam. Soil surrounding the piles and the foundation is modeled by interaction springs and viscous dampers. Driving forces evaluated from responses of a free field act on the underground masses. The major advantage of the model lies in its ability to simulate the non-linearity of both soil and structure with little computing effort. A similar model was proposed by Penzien et al.[1], which is often used for seismic designs of ordinary structures. However, the soil-pile and soil-foundation interaction springs which are derived from many assumptions are not always highly precise. In this study, dynamic interaction springs are evaluated using the thin layer element method (TLEM)[2] which can accurately evaluate the radiation condition and the stratification of soil. Therefore, the precision of the interaction springs is improved. However, there are some problems when the stiffness of the springs are computed by TLEM. With an increase in the number of piles, CPU time increases. Non-linearity of soil surrounding the piles cannot be taken into consideration. When a building is embedded, it is difficult to make an accurate evaluation.

Therefore, for the purpose of solving the three aforementioned problems, a practical evaluation method for interaction springs was investigated as described in a following section.

3. MODELING OF INTERACTION SPRINGS

The soil is divided into 10~20 thin layers. A soil stiffness matrix of the pile groups is computed using TLEM. This full matrix is reduced on the assumption that horizontal displacement of each pile is equal at the same depth. Then, the reduced matrix is simplified by substituting two types of springs, lateral and shear spring. These interaction springs are represented by complex functions of frequency. However, in order to use them in a nonlinear analysis, it must be expressed with a coefficient which does not depend on the frequency. In the proposed model, the interaction spring ($k(\omega)$) is approximated as

$$\mathrm{Real}(k(\omega)) \fallingdotseq K - \omega^2 M, \qquad \mathrm{Imag.}(k(\omega)) \fallingdotseq C_{const} + C\omega \qquad (1)$$

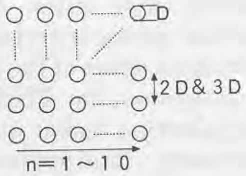
where K is the static stiffness, M is the additional mass and C is the damping coefficient. The approximation is carried out using the least square method. Fig.2 shows a typical case of $k(\omega)$ and this approximation. Due to the result that frequency dependency is small for the shear spring, the additional mass of the shear spring is neglected.

3.1 Effects of Pile Groups

Values of interaction spring per pile are changed when the number of piles in the group is changed. If the interaction springs for a great number of piles can be estimated from those of a small number of piles, it should be possible to develop an analytical model at low cost.

Fig.3 shows variations of the normalized coefficient K_n / K_1, M_n / M_1, C_n / C_1 (K_n, M_n, C_n; spring coefficients per pile a pile group consisting of n piles, K_1, M_1, C_1; coefficient of single pile) for the number of piles n. With an increase of the number of piles, the spring coefficients per pile decrease in proportion to n^{α} (exponent of n). However, the value of α is different depending on the depth. Fig.4 shows a case where the K_n, M_n, C_n are normalized by the value of a pile group which consists of 25 piles. α is almost equal at any nodes. From this result, the values of spring coefficients for a large number of piles can be estimated using equations (2) and (3), which are independent of depth.

Lateral spring :
$$K_n = K_{25}(n/25)^{Xl+1}$$
$$C_n = C_{25}(n/25)^{Yl+1} \quad (2)$$
$$M_n = M_{25}(n/25)^{Zl+1}$$
Shear spring :
$$K_n = K_{25}(n/25)^{Xs+1}$$
$$C_n = C_{25}(n/25)^{Ys+1} \quad (3)$$



Xl,Yl,Zl,Xs and Ys are defined as group factors of pile group, which depend on soil profiles and pile configurations. Values of these factors are shown in Table 1.

Table 1 Group factors of pile groups

Pile spacing ratio	Soil model	Xl	Yl	Zl	Xs	Ys
2D	homogeneous	-0.699	-0.504	-0.140	-0.027	-0.027
2D	layered	-0.681	-0.506	-0.175	-0.023	-0.022
3D	homogeneous	-0.660	-0.443	-0.080	-0.005	-0.009
3D	layered	-0.641	-0.442	-0.098	-0.009	-0.008

3.2 Non-linearity of Interaction Springs

With an increase of input motion, soil surrounding the piles shows plastic behavior. It is expected that non-linear characteristics of the interaction spring are different from surrounding soil under the influence of the structure response. Therefore, the characteristics of non-linearity of interaction springs are studied.

How the interaction springs change with increase of excitation on the foundation is investigated by equivalent linear analysis using two dimensional FEM (Fig.5). With an increase of the excitation amplitude, the real part of the shear spring decreases and the imaginary part increases. However, the lateral spring hardly changes. The effect of a structure is small for lateral springs. For the shear spring, reduction ratio of stiffness(◆) and damping factor(◇) versus its shear strain are plotted in Fig.6. These symbols coincide which the curve which represent G/G0-γ and h-γ of the surrounding soil. From these results, it is proposed that non-linearity is fully took into account for only shear springs and the non-linear characteristics of the surrounding soil are applied to the shear spring.

3.3 Embedment Effects of Foundation

Many studies on embedment effects of foundations without piles have been made and several simple evaluation methods have been proposed in the past. These methods would be very useful if they could be employed in our proposed model. Therefore, the applicability of these methods to pile foundations is investigated. In this study, springs which model the side wall effect of embedded foundation are investigated as soil-foundation interaction springs. Fig.7 shows the comparison between soil springs acting on a foundation with piles and those without piles, which are computed by an axi-symmetric FEM. The values for both springs correspond to each other quite well. It is clear from this result that a simple method for a foundation embedded without piles can be applied to a foundation with piles. A representative simple method for soil-foundation interaction spring is proposed by Harada et al[3]. We apply this method because the vibration effect of the surface layer on bed rock was taken into consideration. Fig.8 compares the FEM results and the approximation method. Harada's method shows a higher applicability. Since the Harada's results are dependent on frequency, it is approximated with K,M and C for the proposed model.

4. RESPONSES OF STRUCTURES SUPPORTED BY PILES

By using our proposed models, earthquake responses of two types of structure are calculated.

4.1 Responses of a Smokestack of a Steam Power Plant

In order to confirm the applicability of the proposed method, simulation analyses of observation data are carried out. The earthquake response obtained on the smokestack of the steam power plant in the Osaka Bay during the 1995 Hyogo-ken Nanbu Earthquake is simulated. As shown in Fig.9, the smokestack is supported by 273 piles, each 64.5m in length. The analysis is made using the acceleration wave observed in the ground(GL-70.8m) as an input wave. The distribution of peak acceleration computed by the proposed model corresponded well with observed values as shown in Fig.10. Furthermore, waveform of acceleration time history(Fig.11) and response spectra(Fig.12) agree with that observed. It is confirmed that the proposed model is well in agreement with the observed results.

4.2 Dynamic Characteristics of Nuclear Reactor Buildings Supported by Piles

Dynamic characteristics of nuclear reactor buildings supported by piles are investigated. A reactor building of PWR 3LOOP type is modeled. Fig.13 shows the schematic view of the assumed building. 4 cases shown in Table 2 are computed. The buildings are supported by piles in case1 and case 2. The same buildings are erected directly on bedrock in case3 and case4. In case2 and case3, the buildings are embedded in soil.

Maximum responses of the outer shield wall are indicated in Fig.14. Acceleration responses of the buildings supported by piles are smaller than those of buildings on bedrock. Displacements of the buildings on piles are larger than those on bedrock. However, deformations of the buildings are reduced in the pile supported case. Time histories and response spectra at base mat are compared in Fig.15 and Fig.16. Due to the fact that stiffness of the bearing piles is smaller than that of the bedrock, the predominant frequency shifts to the lower frequency. The low predominant frequency causes acceleration response to decrease and displacement to increase. Pile support is of advantage to super structures for the studied cases.

5. CONCLUSION

A simple earthquake response evaluation method which can be utilized for designs of structures supported by piles was proposed and it was confirmed to be highly precise. In the proposed model, the interaction springs are introduced so that effects of the pile groups, non-linearity of the soil surrounding the piles and influence of the foundation embedment can easily be dealt with.

The seismic response of the smokestack supported by piles observed during the 1995 Hyogo-ken Nanbu Earthquake was simulated using the proposed method. As a result, it was confirmed that the analytical results correspond quite well to the observed response.

Furthermore, the proposed simple method was applied to a nuclear reactor building which is assumed to be supported by piles. Results obtained from the cases showed that acceleration responses and deformation of the super structures can be reduced by the presence of the pile support.

REFERENCES
1. Penzien, J. et al. 1964. Seismic analysis of bridges on long piles. *Journal of the Engineering Mechanics Division, ASCE90,* No.EM3: pp.223-253
2. Tajimi, H. 1980. A contribution to theoretical prediction of dynamic stiffness surface foundation. *Proc. 7th WCEE, Vol.5* :pp.105-112
3. Harada, T. et al. 1981. Dynamic soil-structure interaction analysis by continuum formulation method. *Research Report of Institute of Industrial Science, University of Tokyo,* Vol.29, No.5

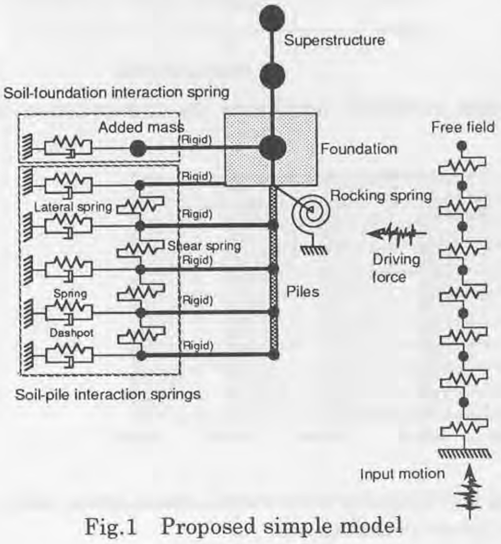


Fig.1 Proposed simple model

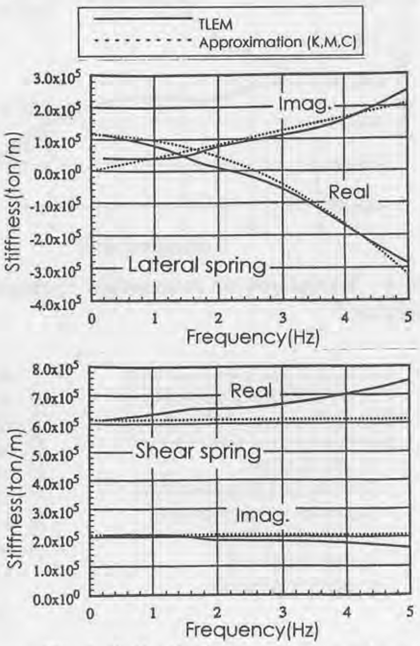


Fig.2 Soil-pile interaction springs obtained from TLEM and an approximated one

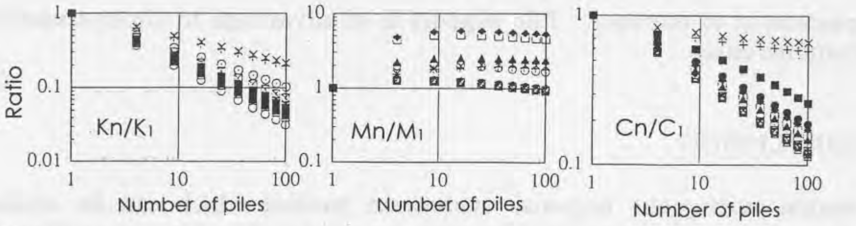


Fig.3 Variations of lateral spring coefficients per pile, which are normalized by those of single pile (Each symbol represents a node at different depth.)

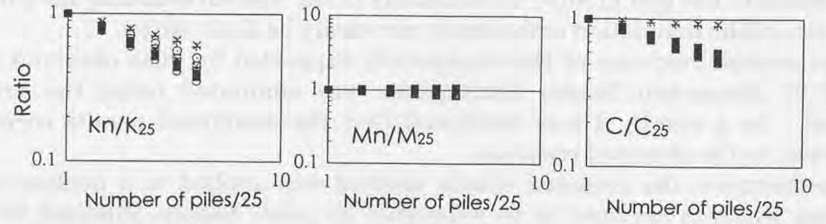


Fig.4 Variations of lateral spring coefficients per pile, which are normalized by those of 25piles (Each symbol represents a node at different depth.)

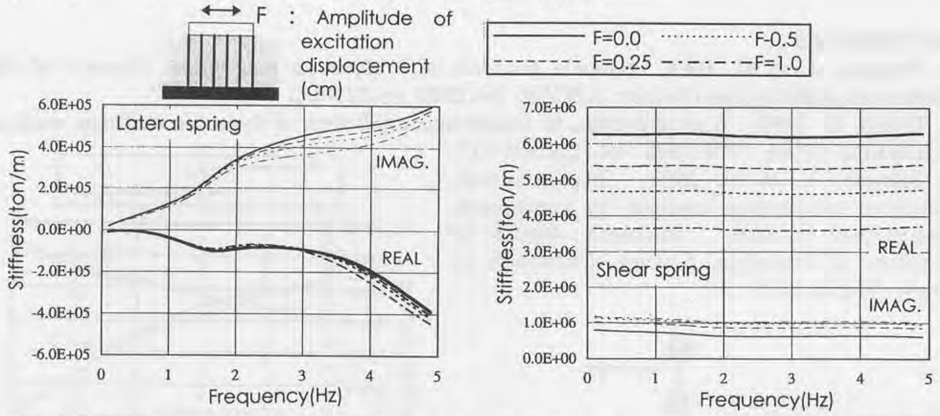


Fig.5 Variations of interaction springs when excitation amplitude for a foundation is increased

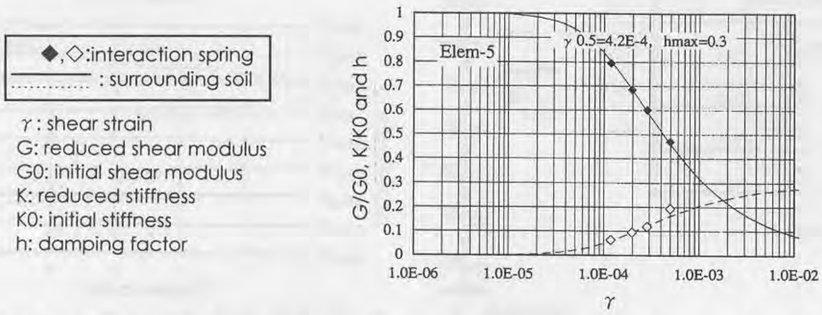
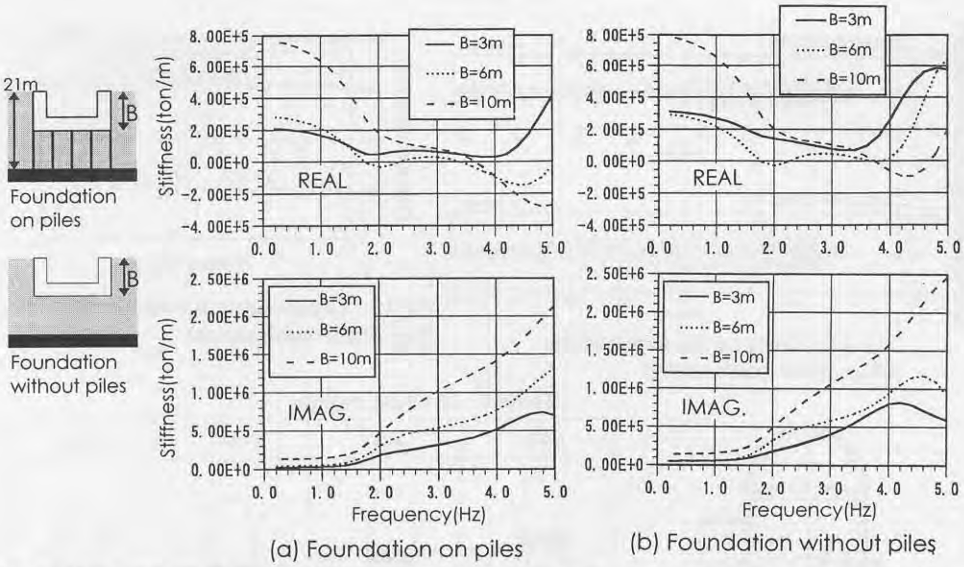


Fig.6 Relationship of shear spring coefficient and damping factor versus shear strain which is compared with nonlinear characteristics of the surrounding soil



(a) Foundation on piles

(b) Foundation without piles

Fig.7 Comparison of soil-foundation interaction springs for foundation on piles and those without piles

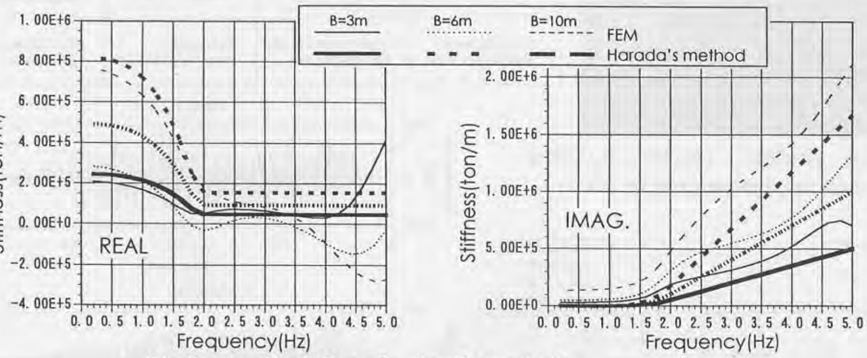


Fig.8 Applicability of a simple method

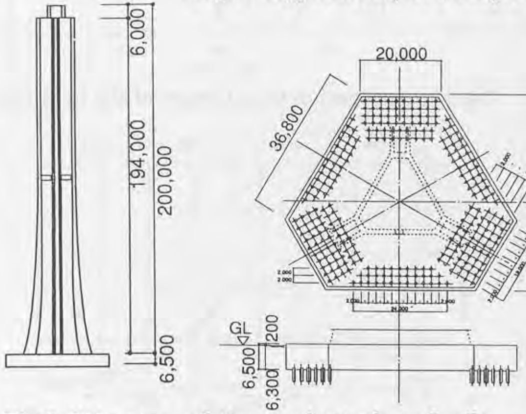


Fig.9 Side view of the smokestack and pile configuration (unit : mm)

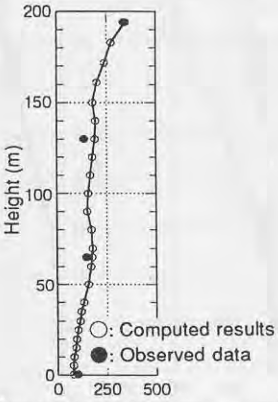


Fig.10 Comparison between maximum acceleration response of observation results and analytical ones

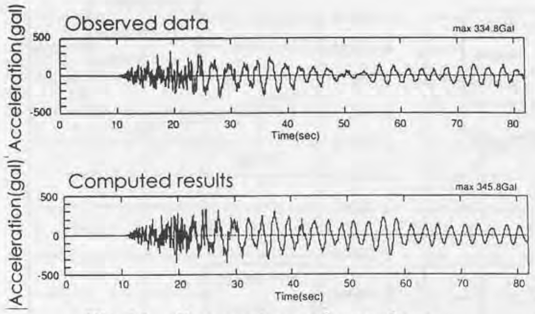


Fig.11 Comparison of waveform (Top of the smokestack)

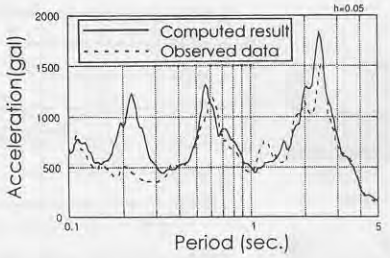
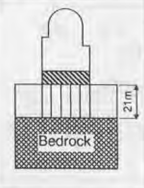
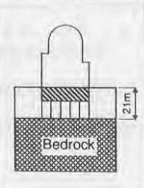
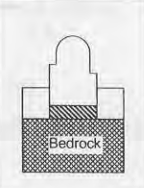


Fig.12 Comparison of response spectra (Top of the smokestack)

Table 2 Studied models

CASE 1	CASE 2	CASE 3	CASE 4
			
· Non embedment · Supported by piles	· A base mat is embeded · Supported by piles	· Embedment · Supported on bedrock	· Non embedment · Supported on bedrock

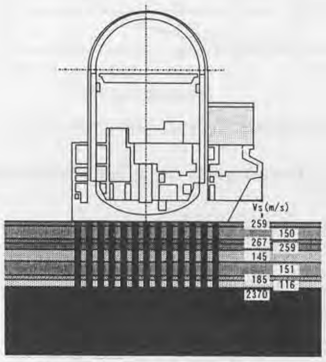


Fig.13 Nuclear reactor building assumed to be supported by piles

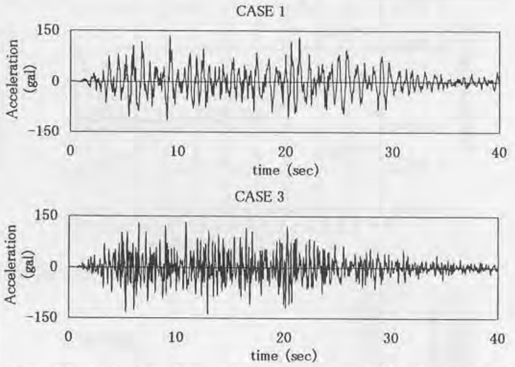


Fig.15 Acceleration time history of the base mat

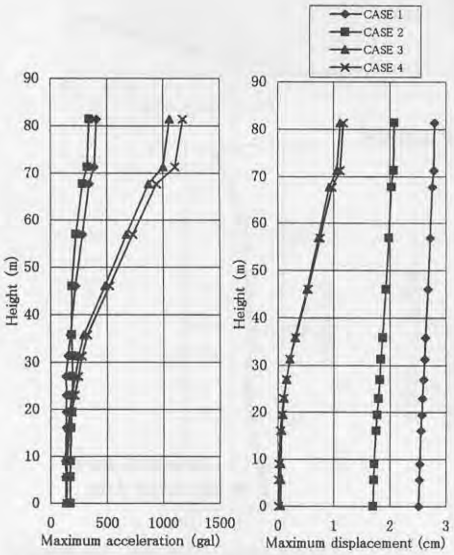


Fig.14 Maximum response of the outer shield wall

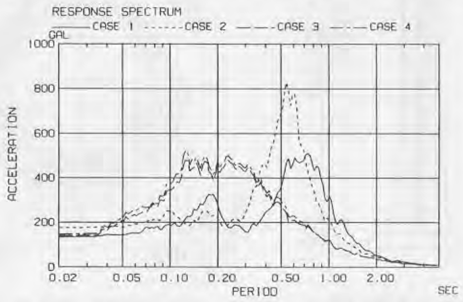


Fig.16 Response spectra of the base mat