Evaluation of Soil-Structure Interaction Based on Forced Vibration Tests of Three Reactor Buildings Within a Site

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Introduction

Three BWR type reactor buildings (Unit No.1, 2, 3) have been constructed at Hamaoka site in Shizuoka prefecture, Japan, during the past fifteen years. In order to confirm and verify the seismic design procedure, forced vibration tests were performed for the completed three reactor buildings. Enough test data have been accumulated and consequently, it is now possible to consolidate these data and compare the differences of vibrational characteristics of the three reactor buildings. By making use of the test data, this paper presents the evaluation of soil-structure interaction effects through the simulation study of vibrational characteristics of the three reactor buildings and explores realistic vibration models.

Three Reactor Buildings

Fig.1 shows the layout of three reactor buildings at Hamaoka site. The Unit No.1 is located adjacent to the Unit No.2, while the Unit No.3 is apart from the other two. Some dimensions and fundamental vibration properties such as building size, depth of embedment, natural frequencies and damping factors are compared in Table 1. The size and weight increase in accordance with the unit number and the weight of Unit No.2 is about 50% of that of Unit No.3. It should be noted that the damping factor of Unit No.3 is large compared with that of Unit No.1 and 2.

The basemat of each unit is placed on Tertiary rock called "Sagara Layer". The field survey shows that the soil profile beneath each unit has almost similar condition.

Method of Forced Vibration Test and Vibration Model

The detailed procedure of forced vibration tests and modeling of soil-structure interaction systems are described in the previous papers(ref.1,2). Though the forced vibration tests were performed in two horizontal directions (NS and EW), applying sinusoidal excitation force with 2 units of vibration generators on the operating floor, the simulation analysis in this study focussed on the vibration characteristics in only NS direction considering the symmetry of the shape of the building. Soil profiles are assumed based on the field survey as shown in Fig.2. For the verification of vibration model, two kinds of models are considered for the soil-structure interaction system as shown in Fig.3. These are Rocking-Sway Model (R-S Model) and Lattice Model, respectively. R-S Model was used for the seismic analysis of Unit No.1 and 2, and Lattice Model was used for Unit No.3.

Simulation Analysis of Unit No.3

Since the soil springs which represent the soil-structure interaction effects were derived from the test results in previous studty, in this paper, the simulation analysis was carried out focussing on the evaluation method for the soil springs. After several case studies, by the new adoption of side soil springs based on Novak's theory for the evaluation of embedded surface layers (ref.3), the appropriate evaluation of soil-structure interaction was made possible both in R-S and Lattice models with base soil springs based on theoretical solution by Kobori's or Tajimi's theory (ref.4,5). An example study of the application of Novak's theory is shown in ref.6.

Fig.4 shows the comparison of frequency dependent soil springs between the values derived from the test results and this study. Result of this study shows that it can provide almost the similar trend to that of the values derived from the test results both in the horizontal and rotational springs. Fig.5 shows the comparison of resonance and phase lag curves at operating floor level in the two models (R-S, Lattice Model) with different soil springs. The analytical results with Novak's side soil spring seem to match very well with the test results, especially in the amplitude of resonance peak. A similar tendency can be seen at other measuring points.

Furthermore, in order to confirm the correspondence between R-S and Lattice model, Fig.6 shows the comparison of resonance curves at six measuring points in both models. The result shows that both models can provide fairy good agreement at each measuring point.

Comparative Study of Three Buildings

Since the vibration model was improved by adding the Novak's side soil springs through the simulation analysis of Unit No.3, the simulation method was applied to the other reactor buildings, Unit No.1 and 2.

The major purpose of this study is to explore the effect on the vibration properties of the differences in building size, weight, depth of embedment and the influence of neighbouring buildings through an unique vibration model based on the following unified concept.

1) For the analytical model of the building, each reactor building was divided into three parts, namely the S/W, I/W, and O/W, and each part was idealized by lumped mass system, in which each wall was represented by bending-shear-springs and each slab by shear springs.
2) Lattice model with Novak's side soil spring was used as a soil-structure interaction system.
3) Base soil springs were evaluated by the theoretical solution based on Kobori's or Tajimi's theory.
4) Damping factor of a reactor building was assumed to be 5%.
5) Young's modulus of concrete in each Unit are about twice of that of design values.
6) Physical parameters of the soil are used based on the values as shown in Fig.2.

Fig.7 shows the comparison of resonance curves at operating floor levels in three buildings. Compared with Unit No.1 and 2, the height of the resonance curve in Unit No.3 is quite low which is supposed to be induced by the effects of embedment. The difference of test curves in each unit is well explained by the analysis. In Units No.1 and 3, the peak height and the predominant frequency correspond to that of simulated results, while in Unit No.2, the resonant peaks around 5.5Hz seem to be different from that of the analytical result which implies the cross-interaction effects between Unit No.1 and 2.

Cross-Interaction between Unit No.1 and 2

In afore-mentioned comparative study, it is suggested that the resonance curves in Unit No.2 are supposed to be influenced by Unit No.1.

Firstly, in order to evaluate the cross interaction effects, wave propagation theory was applied to compute the coupling impedance matrix assuming uniform half space of soil(ref.7). Novak's side soil spring was evaluated for the surface layered soil. Fig.8 shows the computed sway and rocking spring of the Unit No.2 both with independent and coupling conditions, indicated by solid and dotted lines respectively. Both lines show almost same values. This result indicates that the cross-interaction effects by means of supporting soil are not so significant.

Secondly, according to the phase lag curves in the forced vibration test which are not shown in this paper, the vibrations of Unit No.1 seem to be transmitted through the interface of side walls between Unit No.1 and 2 which is named to be transmitting zone. For this reason, in the analysis, the rigidity of the materials stuffed along the interface of side walls was newly introduced to the vibration model as appropriate shear springs in addition to the coupling soil springs. The vibration model is shown in Fig.9. By the excitation at operating floor level (4th floor) in Unit No.2, resonance curves at 6 measuring points both Unit No.1 and 2 were obtained. Fig.10 shows the comparison of resonance curves between analyses and test results in Unit No.1 and 2. Both in Unit No. 1 and 2, the computed results well represent the overall resonance curves of test results. This implies that the effects of the rigidity of materials in transmitting zone can not be disregarded as well as the interaction effect of surrounding soil when the vibrations are excited at the upper parts of building.

Conclusions

As the results of simulation analysis, following features can be made clear.

1) By the adoption of Novak's side soil springs for the evaluation of embedded surface layers, the appropriate evaluation of soil-structure interaction was made possible through an unique vibration model with base soil springs by Kobori's or Tajimi's theory for Unit No.1 and 3.

2) In Unit No.2, cross-interaction effects between Unit No.1 and 2 are suggested and this effects can be simulated considering the rigidity of materials stuffed along the interface of side walls in addition to the cross-interaction soil spring. However, since the rigidity of materials is considered to highly depend on the strain level, in real application to seismic design, the efficiency of the materials subjected to earthquake input will be necessary to confirmed by the accumulation of earthquake records in the future.

References

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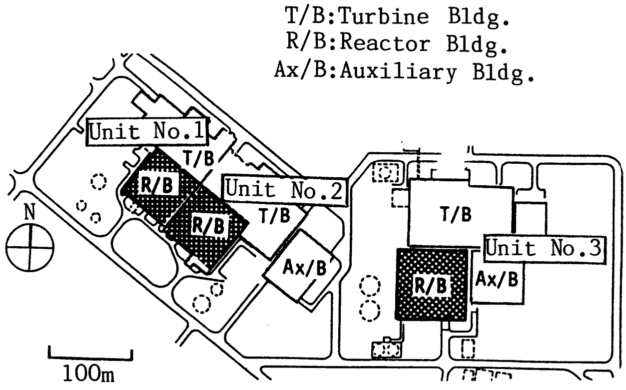
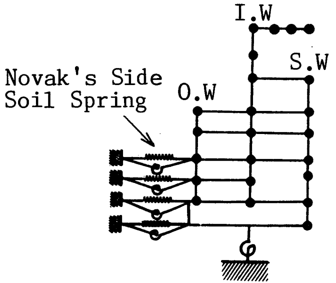


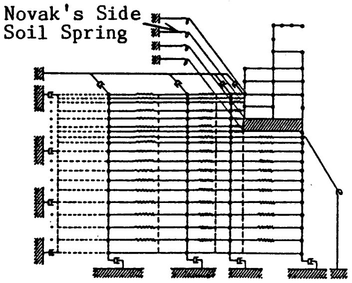
Fig.1 Layout of Three Reactor Bldgs.

Vs S-Wave Velocity (m/sec)	γ Unit Weight (t/m^3)	h Damping Factor (%)	GL 0 (m)
165	1.8	5	-5.0
620	2.1	5	-10.0
660	2.1	5	-20.0
700	2.1	5	-30.0
800	2.1	5	-60.0
870	2.1	5	-100.0
920	2.1	5	

Fig.2 Soil Profile



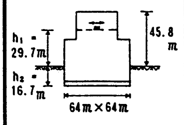
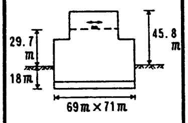
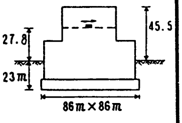
(a) Rocking-Sway (R-S) Model

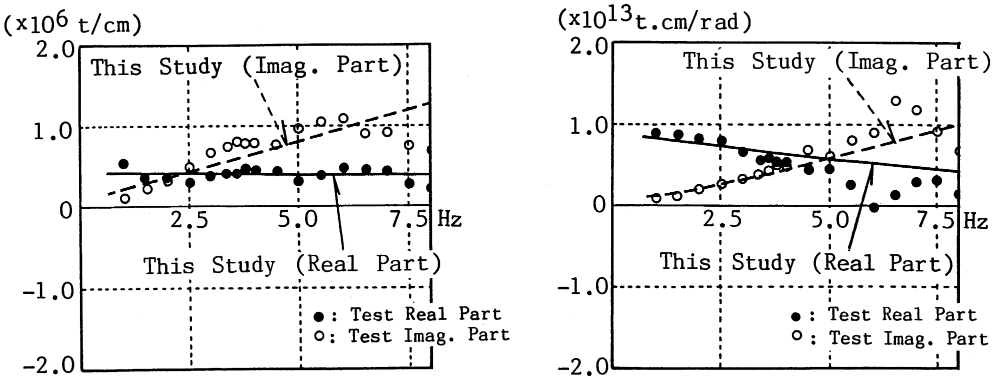


(b) Lattice Model

Fig.3 Vibration Models

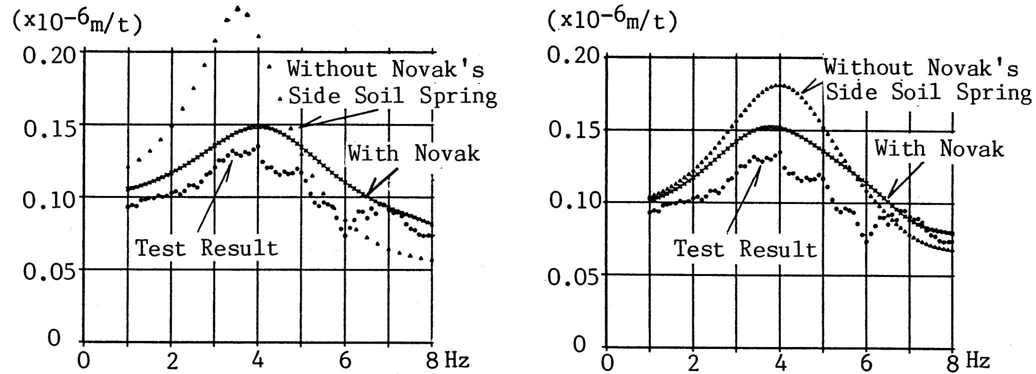
Table.1 Comparison of Three Reactor Bldgs.

	Unit No.1	Unit No.2	Unit No.3
Size of Bldg.			
Weight	15.7x10^{4}ton (0.4)	21.2x10^{4}ton (0.54)	39.5x10^{4}ton (1.0)
Embedment Ratio h_2 : (h_1+h_2)	1 : 2.8	1 : 2.7	1 : 2.2
Natural Freq.	5Hz	5.2 - 5.8Hz	3.8Hz
Damping Factor for 1st Modes	20%	20%	40%

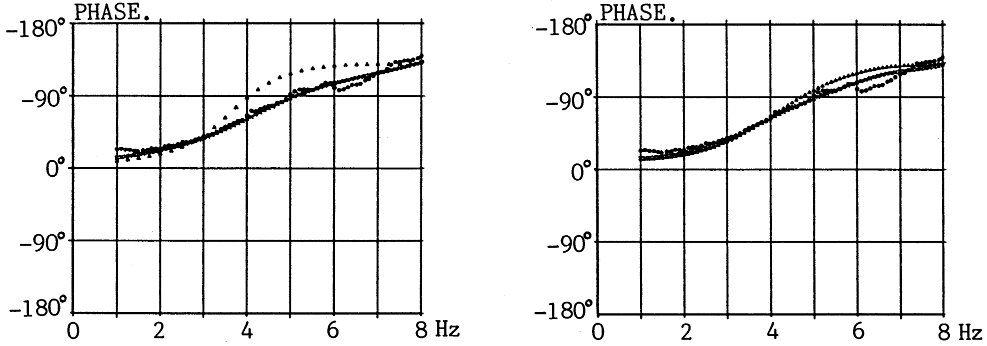


(a) Sway Spring (b) Rocking Spring

Fig.4 Comparison of Soil Spring (Unit No.3)

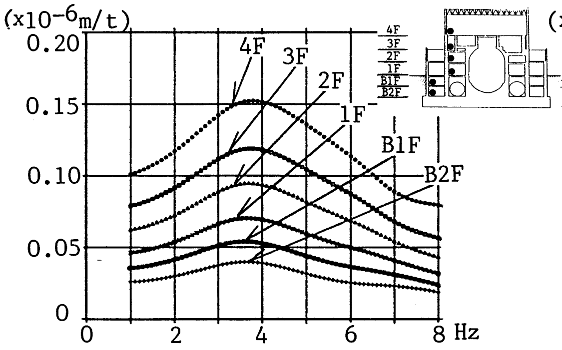


(a) Resonance Curve

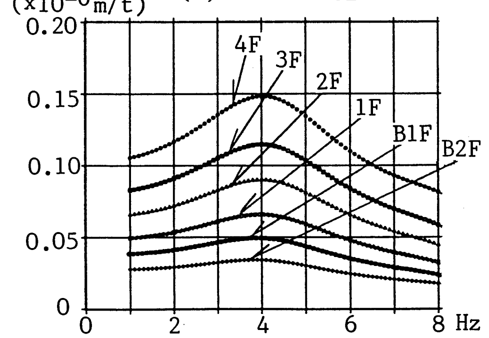


R-S Model (b) Phase Lag Curve Lattice Model

Fig.5 Comparison of Resonance and Phase Lag Curves (Unit No.3,IW.4F)

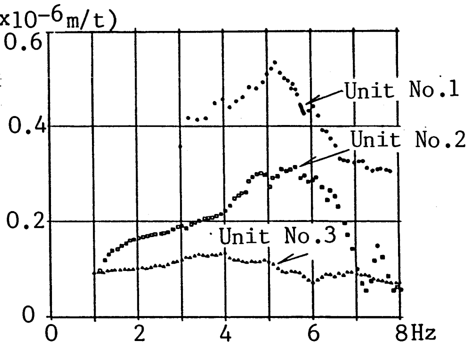


(a) R-S Modeldel

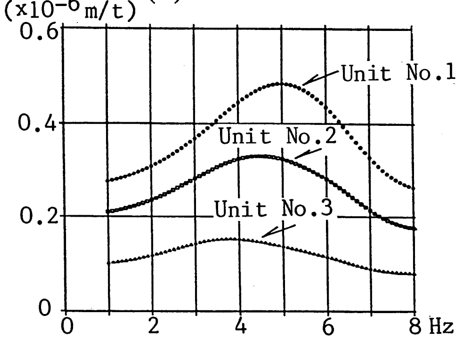


(b) Lattice Model

Fig.6 Comparison of R-S and Lattice Model (Unit No.3,IW,B2–4F)

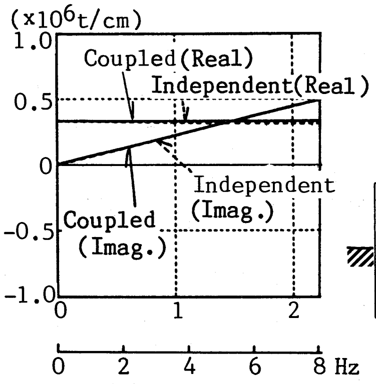


(a) Test Resultult

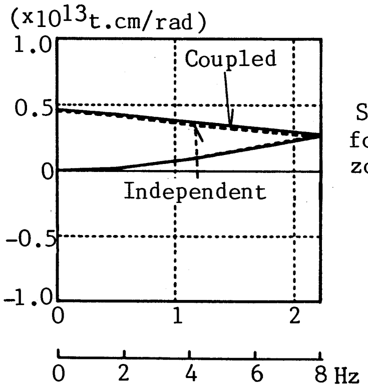


(b) Analytical Result

Fig.7 Comparison of Three Reactor Buildings (Unit No.1,2:5F,No.3:4F)

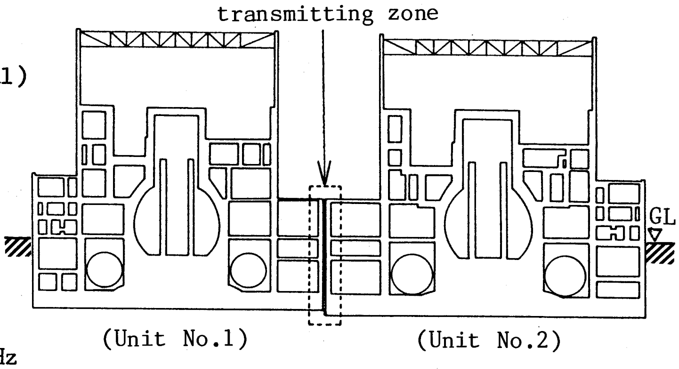


(a) Sway Spring

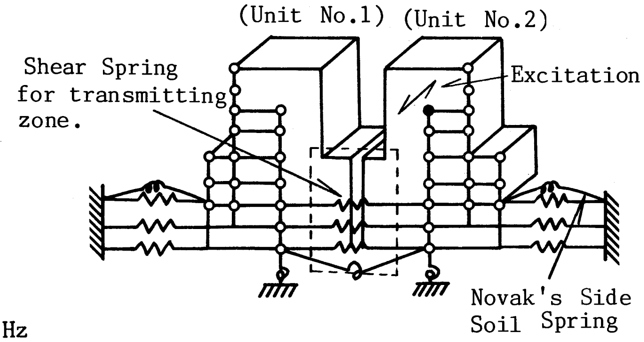


(b) Rocking Spring

Fig.8 Soil Spring (Unit No.2 excited by Unit No.2)

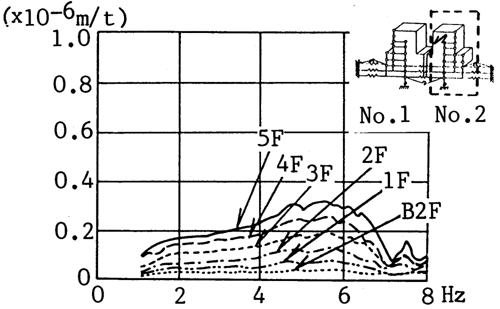


(a) Section of Unit No.1 and No.2

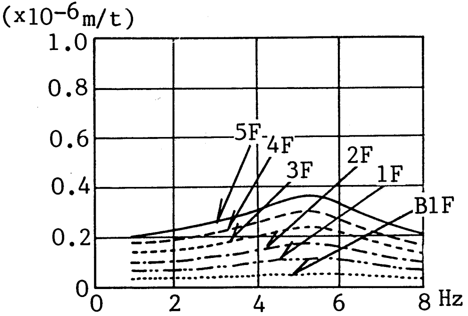


(b) Vibration Model

Fig.9 Vibration Model for Cross-Interaction

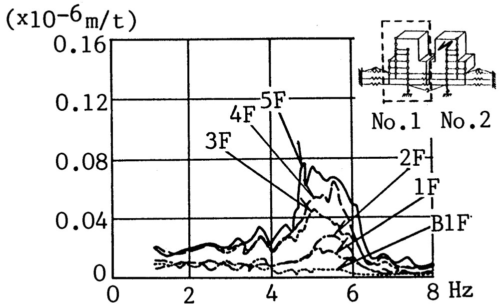


(a) Test Result

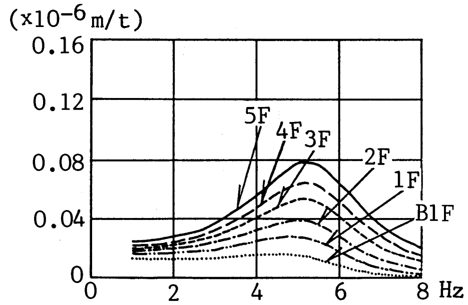


(b) Analytical Result

Unit No.2 excited by Unit No.2



(a) Test Result



(b) Analytical Result

Unit No.1 excited by Unit No.2

Fig.10 Comparison of Resonance Curves (Unit No.1 and No.2 excited by Unit No.2)