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Evaluation on Hualien prediction and correlation analyses of forced vibrations

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ABSTRACT

In the Hualien Large Scale Seismic Test Program ongoing, the blind predictive and the subsequent correlative analyses of the forced vibration tests have been conducted by the consortium participants in order to validate the technical basis for the SSI analysis approaches. The present paper deals with the analytical phase of the forced vibration tests of the structure after backfill to evaluate the SSI methodologies ranging from the simple soil-spring representations to more complex FEM, the thin layer method , and the substructural techniques such as SASSI. Since the forced vibration tests were executed to investigate the dynamic basic characteristics of the soil-structure system under low strain level, this study provides a basic evaluation of the methodology with comparison of different soil-structure system characterization within each technique. Although the unified soil and structure models were utilized for each type of numerical tools in the present prediction study, there showed a significant difference in the frequency responses, indicating that both analysis methodologies and modeling procedures may cause uncertainties in the dynamic SSI analyses employed in aseismic design of nuclear power plants. Characterized by the representation of soils, the analysis results using FEM and SASSI appeared to reflect the stiffer model for soil-spring model. Since these prediction analyses results implied the necessity for conducting the correlation study, most of the participants carried out the post-test correlation analyses by modifying the soil and/or the structure models. Overall, the correlation study has been satisfactorily done for horizontal excitation at roof.

INTRODUCTION

The dynamic soil-structure interaction has a great effects on seismic behaviors of nuclear power plants. However, there has been lack of database recorded during strong motion earthquakes and have been uncertainties in the SSI analyses employed in their aseismic design. The present paper deals with the international cooperative program of the soil-structure interaction research that started in 1990. This seismic test program of a quarter-scale reinforced concrete containment model structure constructed at Hualien (See Fig.1), a seismically active site along the east coast in Taiwan, is being conducted by the international consortium consisting of EPRI, Taipower, CRIEPI, Korean Group, CEA, EdF, Framatome and TEPCO[1]. This Hualien LSST program followed the Lotung LSST one performed under the extremely soft soil conditions, where all investigators concluded that the structure responded almost as a rigid body[2,3,4]. Although the Lotung LSST program has yielded the significant findings of the validity of various SSI analysis methodologies and quantifying uncertainties associated with SSI parameters[5], it essentially needed for a stiff soil site experiment. As well as the Lotung LSST, the main objectives of the Hualien LSST program are not only to study the actual behaviors of the soil-structure system during the large earthquakes but also to validate the technical basis for the SSI analysis approaches introduced in the aseismic design of the nuclear power plants. For the latter objective, the blind predictive and the subsequent correlative analyses have been performed by the consortium participants at the stages of both the forced vibration tests and the earthquake observations. The scope of the present paper is to summarize the blind predictive and the correlative analyses results of the forced vibration tests after backfill (FVT-2 [6,7]).

Since the forced vibration tests were executed to investigate the basic characteristics of the dynamic soil-structure system under low strain levels, this study provides a basic evaluation of the methodologies with comparing different soil-structure system characterization within each technique. As linear modeling techniques, the methodologies employed by the consortium participants ranged from the practical simple approach to the more complicated 3-dimensional one. Paying attention to the modeling assumption of the soils, the analyses methods employed by the consortium participants were categorized into : 1)Soil-spring ; 2)Thin layer ; 3)Hybrid in which soils are represented by FE ; 4)Hybrid in which soils are discretized by FE ; 5) SASSI ; and 6) FEM. To investigate the effect of the representation of the soil-structure system on the numerical results, the unified soil model and the unified structural condition were given to all the participants of the Hualien project for the blind prediction analyses[8,9]. This unified model made it possible to compare the prediction analyses results under the same conditions, therefore, it revealed a significant difference in the analyses results specific to the numerical techniques. Furthermore, although a comparison of predictions and measurements showed overall good, since there appeared insufficient correlation between the analyses and the measurements, the post-test correlation analyses have been conducted by modifying the soil and/or structure models.

HUALIEN FORCED VIBRATION TESTS AFTER BACKFILL

1)General description of tests

The Hualien 1/4-scale reinforced cylindrical concrete containment model were constructed on the gravelly soils after excavating the sandy layer of 5m depth(See Fig.1). Before starting earthquake observation, the forced vibration tests of the model structure were performed for the horizontal excitation at roof and at 1st floor, as well as, for the vertical excitation at 1st floor[6,7]. An excitor of 10tons was utilized to generate the steady-state vibrating motions. The resonant frequencies observed in the tests was 6.1 - 6.3Hz and 6.5 - 6.6Hz for horizontal excitation at roof and at 1st floor, respectively, with the damping factors of about 8%[7].

2) Unified soil model for prediction

There exists uncertainties in establishment of soil model necessary for conducting SSI analyses. In the Hualien program, a series of the geotechnical investigations, both field and laboratory ones, has been carefully carried out to fully characterize the site geotechnical conditions by CRIEPI[4,5]. As results of this Hualien investigation, the unified soil model shown in Fig.1 was first proposed to conduct the blind prediction analyses of the forced vibration tests. This analytical condition given to each consortium participant made it possible to reveal the differences in numerical results due to the modeling assumptions of the soil-structure system. As for the 1/4-scale reinforced concrete test structure, its plan and section with the recommended material properties were also given to perform the prediction analyses. After comparing the predictions with the measurements, the consortium participants performed the post-test correlation analyses by modification of soil and/or structure models.

3)Structure model

The design drawings of the structure were given to each participant for the prediction analysis, shown in Fig.1. As the concrete properties, h = 2(%) and E = 2.88×10^5(kgf/cm^2) were recommended. Based on this structure model, the fixed base natural frequencies for the horizontal mode was estimated to be approximately 10.3-10.6Hz. However, after the correlation analysis of FVT using the regression method, it was suggested that the stiffness should be apparently reduced by 15% possibly due to difference in the geometry between the test structure and its design drawing [10]. At the stage of correlation study, some of the participants took account for this reduction.

ANALYSES METHODOLOGIES EMPLOYED FOR BLIND PREDICTION

A total of about 20 participants, including industry and university groups, have performed independent predictive calculations of the forced vibration tests[11-16]. Each participant employed the practical method utilized in the aseismic design of the nuclear power plants, or introduced the advanced method developed recently for the dynamic SSI research. By focusing on the representation of soils, the numerical tools employed in the present program are categorized into a group of the following methodologies :

(1)*Soil-spring model.*
Since the stiffness and the damping of the soil spring are generally based on the solutions of the wave theory of an elastic half space, and since it is easy to conduct the nonlinear response analysis of the structure by use of a stick model of lumped masses system with the soil spring, this simplified approach is often employed in the practical aseismic design of nuclear power plants.

(2)*Thin layer method.*
The ring exciting thin layer method is based on the Green's function approach employing the ring load solutions to describe the soil-structure interaction[11]. The thin layer representation using the multiple cylindrical walls model makes it possible to take realistically into account soil layering with axisymmetric irregularities of soil profiles such as embedment.

(3)*Hybrid method in which soils are represented by finite elements.*
In general, hybrid method is defined as a substructural method that combines infinite far-field model such as the boundary elements with a model of structure itself or with a model of structure including the soils adjacent to its foundation. In case of this hybrid method, the surrounding soils just around the foundation are discretized by the solid elements.

(4)*Hybrid method in which soils are not discretized by finite elements.*
This model combines infinite far-field model such as the boundary elements with a stick model of structure without representing its surrounding soils by the solid elements.

(5) *SASSI.*
SASSI is a numerical SSI code based on the substructuring technique. Both the structure and the soils just around the foundation are represented by solid elements. The soil spring representing the far field is characterized by use of the finite element technique.

(6) *FEM.*
In the present paper, FEM is defined as the direct method using finite elements. While the soils are discretized by use of axisymmetric solid elements under general boundary conditions to account for the wave radiation, the structure is represented by a stick model of lumped masses or by solid elements.

Among these methodologies that are capable of producing 3D solutions for SSI problems, the simplified approaches such as the soil-spring model, as well as, the more realistic ones such as FEM and SASSI are practically employed in the aseismic design of the nuclear power plants. On the other hand, the thin layer method and the hybrid methods have been developed to have the advanced capabilities accounting for soil layering, wave radiating and embedment effect.

FVT PREDICTION ANALYSES RESULTS

1)Evaluation basis

As described in Ref.[5], the forcing functions are harmonic with known frequencies and amplitudes for the forced vibration tests. Considering that the significant factors for any of the analysis method of the forced vibration test are the stiffness and the damping of the foundation, only two parameters of the resonant frequency and the peak response amplitude are helpful in assessing various analysis methods. The comparative evaluation using these two parameters was performed in the present paper.

2)Summary of blind prediction analyses results using unified soil model

Figs.2 and 3 show the relationship between the predicted resonant frequencies and the predicted peak amplitudes normalized by exciting force for horizontal excitation at roof and at 1st floor, respectively, comparing the predictions and the measurements. Although the unified soil and structure models were used in these predictions, the resonant frequencies and the peak amplitudes were significantly scattered, indicating that the modeling assumption of SSI system would be a source of the uncertainties. Such dispersion of the predictions suggest that the uncertainty due to the analysis method should be practically considered in the aseismic design. Consequently, it might be essential to take into account such uncertainty in the probabilistic risk assessment of nuclear power plants. It is also noticed in Figs.2 and 3 that the analysis results yielded a considerable dispersion even when the same methodology was employed. In particular, there showed a large dispersion among the analysis results using the soil spring method because of the difference in modeling assumptions, i.e. an approximate manner, of soil layering and/or backfill. To summarize these predictions described in Figs 2 and 3, Table 1 presents the statistics of the analyses results using the unified model. Shown in Table 1, the coefficient of variation was evaluated to be 0.06 for the resonant frequency, however, it exceeded 0.3 for the peak amplitude. Since the frequency and the amplitude are related to the stiffness and the damping, respectively, these statistics results demonstrate that the modeling assumption has a greater effect on the damping rather than the stiffness of the model. Another finding in Figs. 2 and 3 is an insufficient correlation between the analyses with the measurements, implying the necessity for conducting the post-test correlation analyses by modifying the soil and/or the structure models.

Furthermore, it should be noticed in Figs.2 and 3 that FEM and SASSI results reflect stiffer models for the soil spring representation. In order to discuss such tendency, the predicted resonant frequency was averaged within each group of the analysis methodology. Table 2 shows difference in the predicted resonant frequency due to the analysis methodology for horizontal excitation at roof. Described in Table 2, the resonant frequencies were predicted to be 6.3Hz and 7.4Hz for the soil spring method and for FEM, respectively. This difference in the predicted frequency indicates that the finite element representation provides the stiffer model of the soils than the soil spring. Furthermore, the resonant frequency predicted by both SASSI and the hybrid method representing the soils just around the foundation by FE was 7.6Hz approximately equal to that of FEM. Consequently, it has a significant effect on the predicted response of the soil-structure interaction system how to represent the soils adjacent to the foundation. In order to clearly understand such effect, the stiffness ratio of the finite element representation to the soil spring one, k_F/k_S, was estimated on the assumption that k_F/k_S is directly proportional to $(f_F/f_S)^2$, where k = stiffness ; f = resonant frequency ; and the subscripts S and F denote the soil spring method and FEM, respectively. For the predicted frequencies $(f_S = 6.3Hz, f_F = 7.4Hz)$, the stiffness ratio k_F/k_S was estimated to be approximately 1.4. This significant ratio of 1.4 indicates that the finite element representation provides the stiffer model by 40% than the soil spring method. On the other hand, the resonant frequency predicted using the thin layer method ,7.1Hz, fell in-between the resonant frequencies calculated from the soil spring method and FEM. Depending mainly on the representation of a displacement field of soils just around the foundation, such characteristics due to the analysis methodology appeared in the prediction SSI results. For FEM, the linear variation of the displacements is generally assumed for both vertical and horizontal directions in the finite element. For the soil spring method, its stiffness and damping are generally based on the exact solutions to the elastic wave theory of a homogeneous half space. On the other hand, the thin layer element is characterized by the displacement field with the linear variation and the exact displacement functions assumed in the vertical and horizontal directions, respectively. As is well known, when soils are discretized into smaller meshes, since the displacement field defined in the finite element approximate better that given by the exact solutions, the resonant frequency calculated from FEM may approach those of the soil spring method.

FVT CORRELATION ANALYSES RESULTS

1)Procedure for correlation

After comparing the predictions and the measurements, the correlation analyses have been subsequently conducted by the consortium participants. Most of the participants performed the correlative study by modification of the soil model and/or the structure model, utilizing the same methodology that employed in their prediction analyses. Since the predicted resonant frequency showed significantly higher than the experimental results, most of the participants reduced the stiffness of the soils and/or the structure for correlation [11-15]. The soil models were individually modified on the basis of their engineering judgment, or their careful insight of the geotechnical investigation data.

2)Summary of correlation analyses results

Figs. 4 and 5 show the relationship between the resonant frequency and the normalized peak amplitude for horizontal excitation at roof and at 1st floor, respectively, comparing the correlation analyses results with the predictions using the unified model. In these figures, the starting and the end marks denote the prediction and the correlation analyses, respectively. For roof excitation shown in Fig.4, the correlation analyses results converged into a small neighborhood of the measurements, indicating that the correlation studies were satisfactorily done under this exciting condition. Fig.4 also demonstrates that not only the more complex FEM and SASSI but also the simple soil spring approach produce an adequate frequency response prediction by establishing the appropriate soil and structure models associated with the analysis method. However, since most of the post-test correlation studies were conducted to fit the analysis with the tests only for roof excitation, the correlation analyses results went through and scattered beyond the measurements for 1st floor excitation, shown in Fig.5. A good correlation for roof excitation but a poor correlation for 1st floor excitation suggests that the frequency response to the forced vibration were sensitive to the location of the excitor, at roof or at 1st floor, even when they were conducted at low-level response. Further discussion may be needed for this issue.

CONCLUDING REMARKS

1. Not only the practical methods utilized in the aseismic design of nuclear power plants but also the advanced methods developed recently for the SSI research are acceptable for simulating frequency responses to forced vibration of a soil-structure system constructed on stiff soils by providing the adequate soil and structure models.
2. As analyses results conducted individually by a total of about 20 investigators, there showed a considerable dispersion in the predicted frequency response using the unified soil

and structure model. The coefficients of variation were estimated to be about 0.06 and over 0.30 for the resonant frequency and the peak amplitude, respectively. Such variability indicates that the analysis methodology itself is a source of the uncertainties in the dynamic SSI prediction.

3. Representation of soils adjacent to a foundation , with descretization or without descretization, has a significant effect on predicted frequency responses of a soil-structure system. FEM and SASSI give a stiffer model than the soil spring model. The thin layer model provides a stiffness between FEM and the soil spring representation.

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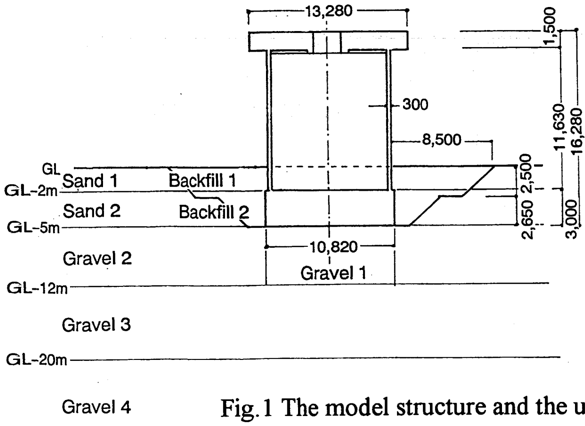

	Vs(m/s)	ρ t(t/m³)	ν	h(%)
Backfill 1	400	2.33	0.38	2
Backfill 2	400	2.39	0.48	2

	Vs(m/s)	ρ t(t/m³)	ν	h(%)
Sand 1	133	1.69	0.38	2
Sand 2	231	1.93	0.48	2
Gravel 1	383	2.42	0.48	2
Gravel 2	333	2.42	0.47	2
Gravel 3	476	2.42	0.47	2

Fig. 1 The model structure and the unified soil conditions

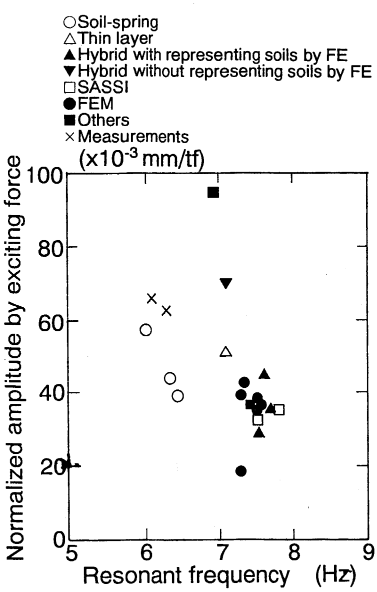

Fig.2 Relationship between Frequency and Amplitude at Resonance for Horizontal Excitation at Roof; Predictions Using Unified Soil Model, Compared with Measurements

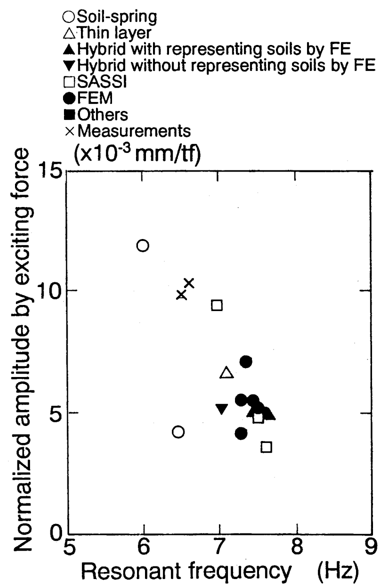

Fig.3 Relationship between Frequency and Amplitude at Resonance for Horizontal Excitation at 1st Floor; Predictions Using Unified Soil Model, Compared with Measurements

Table 1 Summary of Blind Prediction Analyses Using the Unified Soil and Structure Model

Exciting condition	Total number	Resonant frequency			Displacement at resonance (Normalized amplitude by force)		
		Average (Hz)	Dispersion (Hz^2)	Coefficient of variation	Average ($\mu m/tf$)	Dispersion ($\mu m^2/tf^2$)	Coefficient of variation
Horizontal excitation at roof	19	7.22	0.236	0.067	43.3	274.3	0.382
Horizontal excitation at 1st floor	15	7.22	0.198	0.062	5.89	4.38	0.355

Table 2 Difference in Predicted Resonant Frequency due to Analysis Methodology ; for Horizontal Excitation at Roof

Methodology	Total number	Predicted averaged resonant frequency (Hz)
Soil spring	3	6.3
Thin layer	1	7.1
Hybrid with representing soil by FE	3	7.6
Hybrid without representing soil by FE	1	7.0
SASSI	2	7.6
FEM	6	7.4

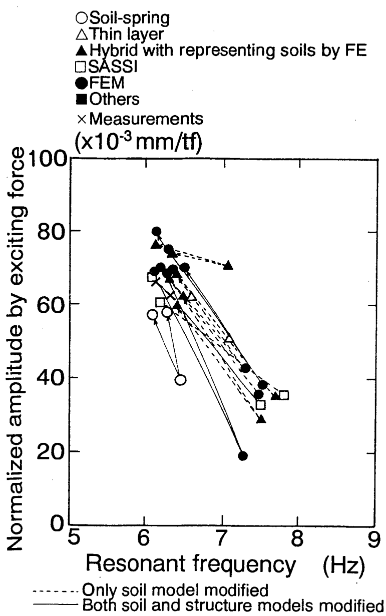

Fig.4 Approach of Correlation Analyses Results to Measurements from Predictions Using Unified Model ; Frequency and Amplitude at Resonance for Horizontal Excitation at Roof

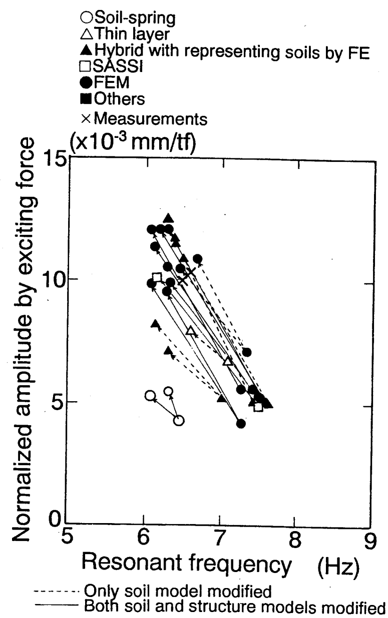

Fig.5 Approach of Correlation Analyses Results to Measurements from Predictions Using Unified Model ; Frequency and Amplitude at Resonance for Horizontal Excitation at 1st Floor