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3-DIMENSIONAL SIMULATION ANALYSES OF FORCED VIBRATION TEST AT HUALIEN

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ABSTRACT

Forced vibration tests of a quarter-scaled structure model for a containment vessel were performed at Hualien. The test results indicate that resonance curves obtained by the test of the model structure before backfill had two peaks and that there was a large amount of response perpendicular to the exciting direction. These phenomena seem to arise from the strong irregularity of soil properties in the vicinity of the model structure in the horizontal direction. In order to examine these phenomena, three-dimensional simulation analyses by use of a hybrid method are carried out in this paper. The results of our iteration analyses suggest that the cross-axial coupling effects are generated by the irregularity of the soil near the foundation, and that two peaks are mainly ascribed to the existence of loosened soil just near the foundation in the soft soil region.

KEYWORDS

Soil-structure interaction; forced vibration test; quarter-scaled containment model; backfilled soil; 3-D hybrid analysis method; soil irregularity.

INTRODUCTION

An optimal aseismic design of massive structures typically seen in nuclear power plants requires a detailed understanding of dynamic soil-structure interaction effects. Numerous analytical and experimental studies on the soil-structure interaction problems have been performed by several researchers. The methods of analytical approaches to the soil-structure interaction problems have been investigated through experimental studies like forced vibration tests and earthquake observations in both actual or model structures. In order to evaluate reliability for the methodology of soil-structure interaction problems, a quarter-scaled structure model for a containment vessel was constructed at Hualien in Taiwan, which is located in the area of high seismic activity (Tang *et al.*, 1991). As the first stage of a series of experimental researches on the soil-structure interaction problems, forced vibration tests were carried out for the model structure without embedment and the model with embedment by backfilling the surrounding soil. The detailed examination of the soil properties around the model structure was carried out and reported by Kokusho *et al.* (1993, 1994). The vibration test results for the model structure have been published and discussed by Morishita *et al.* (1993, 1994) and Tanaka *et al.* (1994). The results shown by Morishita *et al.* (1994) indicate that resonance curves obtained by the forced vibration tests before backfill had two peaks and that there was a large amount of response perpendicular to the exciting direction. These phenomena seem to arise from the strong irregularity of the soil properties in the vicinity of the model structure in the horizontal direction. They suggested that there were two distinct soil zones around the model structure, a survived zone and a collapsed zone after a heavy rain brought by a typhoon. They have also reported that the coupling of the response in the two directions could be minimized by rotating the axes counterclockwise by 34 degrees for the results before backfill and by 30 degrees for the results after backfill, respectively. Luco and de Barros (1994) have also examined the forced vibration test results before backfill by use of identification approaches. They stated in their report that foundation impedance functions derived on the basis of the experimental response of the model structure were significantly different in two orthogonal directions suggesting a significant lateral variation of soil properties or a marked anisotropy.

In order to examine the cross-axial coupling of the response by the forced vibration tests at Hualien arising from the irregularity of the soil around the model structure, three dimensional analyses will be carried out in this paper. A hybrid analysis method (Yoshida *et al.*, 1990) will be used for the simulation analyses of the forced vibration test before backfill. The complicated soil region near the model structure will be modeled by the finite elements, and the layered half-space surrounding the complicated soil region will be represented by the boundary elements. The structure is assumed to be rested on the ground surface and the ground surface is supposed to be entirely flat. In the Hualien project, results for horizontal excitation at the roof and at the top of the base, and vertical excitation at the top of the base were obtained. In this paper, simulation analyses will be limited to the case of the horizontal excitation at the roof of the model structure.

SOIL-STRUCTURE MODEL

The containment model structure at Hualien is illustrated in Fig. 1. This model structure corresponds to approximately 1/4 scale of reactor buildings of commercial nuclear power plants. The model structure has a total height of 16.13m, a wall diameter of 10.82m and is founded at a depth of 5.15m below the ground surface (GL+0m). The base slab of diameter 10.82m has a thickness of 3.00m and rests on a layer of lean concrete of 0.15m. The reinforced concrete containment shell has an external diameter of 10.52m , a height of 11.63m, and a uniform thickness of 0.30m. The roof of the structure has a diameter of 13.28m and a thickness of 1.50m, and has a square 2.2 x 2.2 m access hole at its center. The total weight of the containment model structure is about 1450 ton.

In the simulation analyses of the forced vibration test before backfill, the upper structure is modeled by a three-dimensional lumped mass system as shown in Fig. 2. The system consists of three masses and two main beams. The top mass corresponds to the mid-level of the roof-plate excluding the thickness of the roof beams, the second mass is located at the mid-height of the vessel wall where accelerometers are installed (GL+ 4.82m), and the base mass is settled at the mid-level of the basemat excluding the lean concrete. Dummy masses and rigid beams are considered when the horizontal and vertical displacements are evaluated near the edge of the roof where accelerometers are located. The roof-plate and the basemat including the lean concrete are assumed to be rigid in the present analyses. The exciter is assumed to be set at a height of 13.705m from the top of the base. The fixed-base natural frequencies of the first four modes are listed in Table 1. The Young's modulus for the concrete of the model structure is assumed here to be E=2.32x10^6 ton/m^2. This value is slightly smaller than the widely used value (E=2.88x10^6 ton/m^2) and was determined by referring to the results by Luco and de Barros (1994) who obtained the fixed-base natural

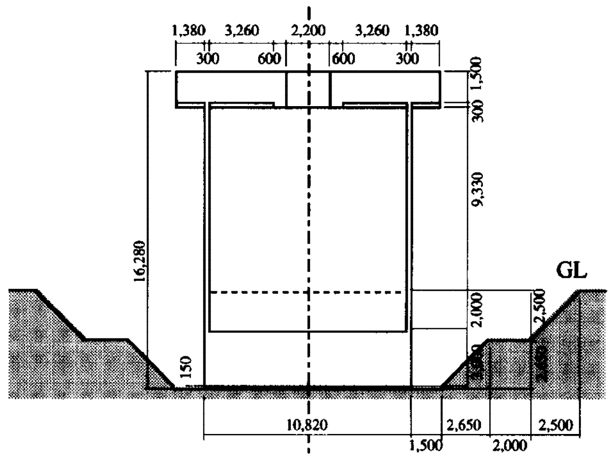
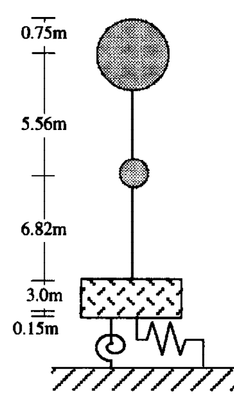


Fig.1. Cross section of the Hualien containment model structure. (before backfill)



Weight (ton)	Inertia Moment I_x, I_y (tom m)	Inertia Moment I_z (tom m)	Shearing Cross Section Area (m^2)	Geometrical Moment of Inertia (m^4)
558.7	6151.	12310.		
			9.63	126.
139.0	1815.	3630.		
			9.63	126.
781.3	5717.	11434.		

E=2.32x10^{6}ton/m^2
ν=0.167

Fig.2. Physical properties of employed lumped mass model.

Table 1. Fixed-base natural frequencies.

Mode No.	Frequency(Hz)	Type of Mode
1	9.37	Horizontal
2	19.84	Torsional
3	27.97	Vertical
4	36.58	Horizontal/Rocking

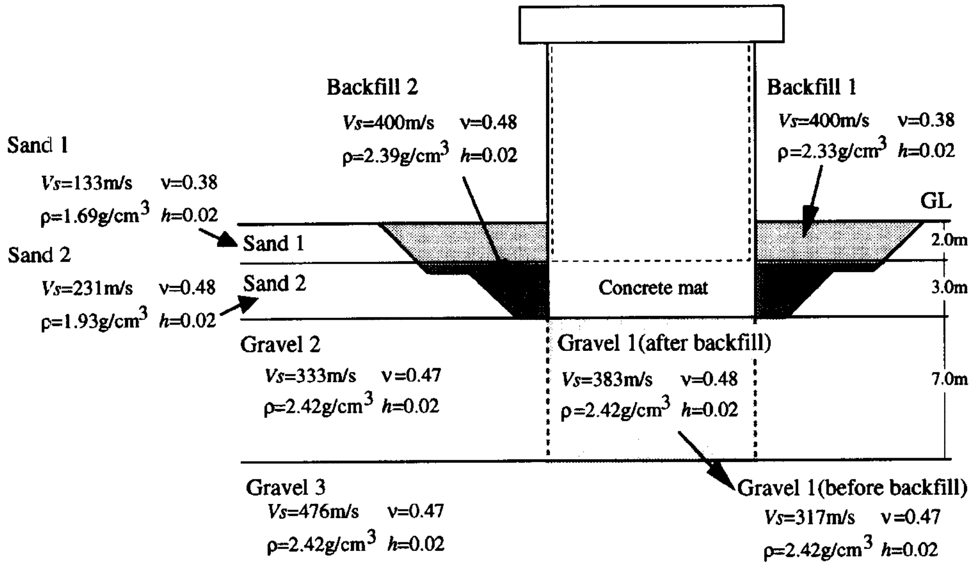


Fig. 3. Soil model in the vicinity of the Hualien containment model. (proposed by Kokusho *et al.*, 1994)

frequency for the horizontal vibration of 9.37 Hz derived from the test results using identification methods. The damping factor in the upper structure is also set to be 3.6% by referring to their results.

The geotechnical investigation for the soil around the model structure has been carried out both in field and laboratory tests by Kokusho *et al.* (1993, 1994). They have proposed the final soil model after backfill to be used in the soil-structure interaction analyses in the latest paper (Kokusho *et al.*, 1994). Figure 3 shows the final soil model proposed by them. Soil properties used in the present hybrid method are determined by referring to the final soil model proposed by Kokusho *et al.* (1994).

As for the irregularity of the soil properties around the model structure in the horizontal direction, Morishita *et al.* (1994) have suggested that there exist two distinct soil zones; a harder soil zone and a softer soil zone. The

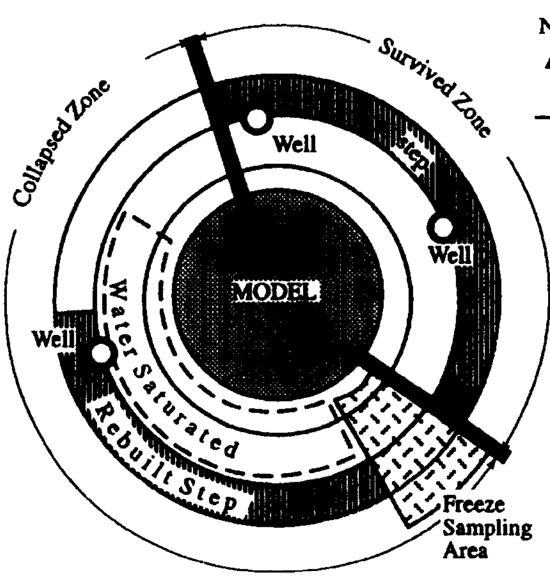
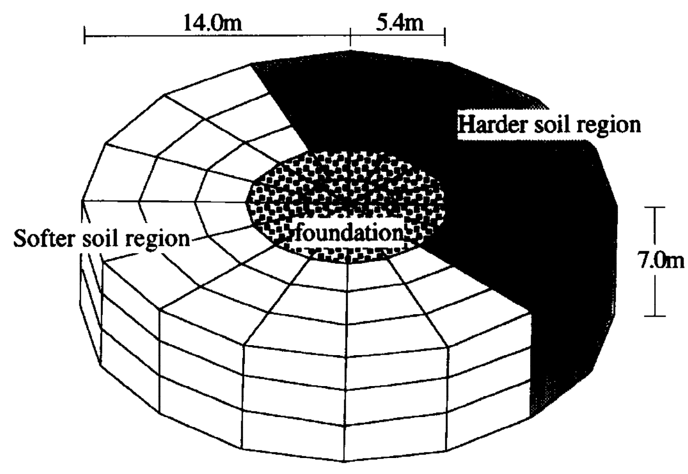


Fig. 4. Schematic view of soil condition. (after Morishita *et al.*, 1994)



Number of nodes :329
Number of finite elements :277
Number of boundary elements :120

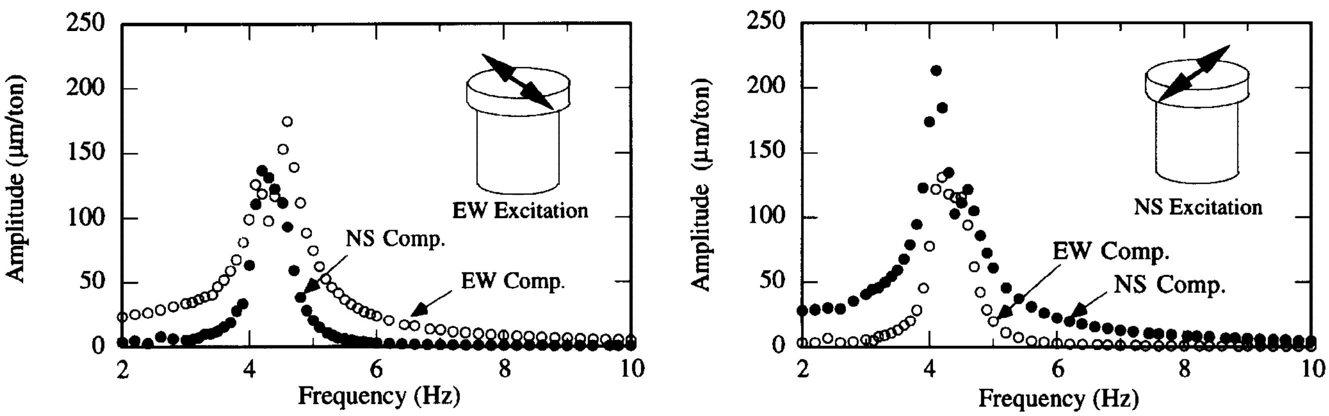
Fig. 5. Mesh layout of FEM region used for the present hybrid method.

harder soil zone corresponds to the region survived even in a heavy rain by a typhoon and the softer soil zone corresponds to the region collapsed by the heavy rain. Figure 4 is quoted from the paper by Morishita *et al.* (1994) to specify the two zones.

In order to take the irregularity of the soil and the geometry of the model structure into account, a soil model used in the hybrid analysis is constructed as shown in Fig. 5. This figure shows the finite element mesh used in the hybrid analyses. The model consists of 320 nodes, 277 finite elements, and 120 boundary elements. The finite element region has a diameter of 28.0m and a thickness of 7.0m and is set on the underlying half-space whose shear wave velocity is 476m/s in the soil model as illustrated in Fig. 3. The foundation of the model structure is specified by the shaded zone at the center of the figure. The upper structure is connected at the center of the shaded zone. In the present study, as the foundation is assumed to be rigid, nodes of the finite element region just under the foundation are connected each other by rigid beams.

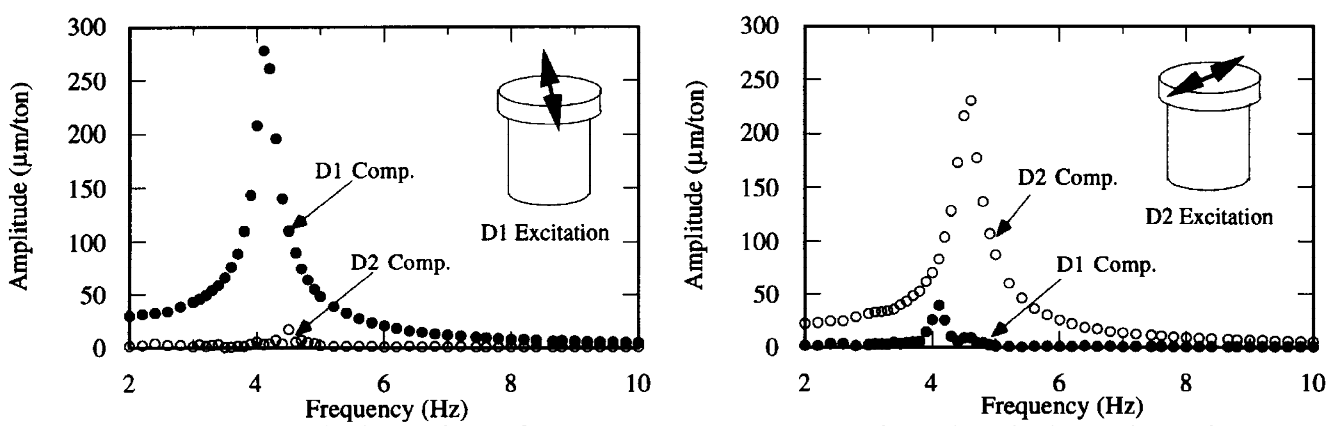
OUTLINE OF RESULTS OF FORCED VIBRATION TEST

Figure 6 shows recorded results of the forced vibration test before backfill. Figure 6 (a) corresponds to results of the EW (East-West) horizontal excitation at the roof, and Fig. 6 (b) to results of the NS (North-South) excitation at the roof. Displacement response curves are normalized by the exciting force at the roof for all frequencies and consequently show displacements due to a unit force. From these figures, it is clearly recognized that the response curves in the exciting direction have two distinct peaks at frequencies of 4.2 and 4.6, and that a large amount of response is obtained in the orthogonal direction to the exciting direction. These cross-axial coupling and twin-peak characteristics may arise from the irregularity of the soil around the model structure in the horizontal direction. Tanaka *et al.* (1994) have reported that the coupling of the response in the two directions could be minimized by rotating the axes counterclockwise by 34 degrees for the results before backfill and by 30 degrees after backfill, respectively. They named the new axes D1 and D2 directions. The



(a) EW excitation at the roof (b) NS excitation at the roof

Fig. 6. Observed displacement at the roof of the model structure before backfill.



(a) D1 excitation at the roof (b) D2 excitation at the roof

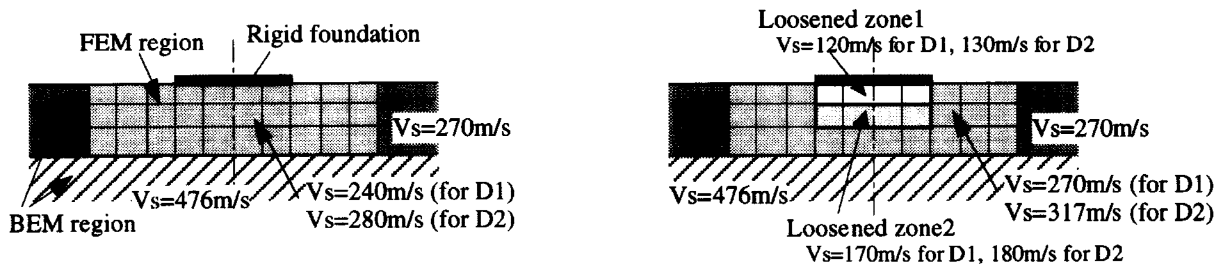
Fig. 7. Transformed displacement at the roof of the model structure before backfill.

test results transformed into the new directions from the original NS and EW directions are illustrated in Fig. 7. It is clearly seen in the figures that the cross-axial coupling in the response curves disappear by rotation of the recorded results and that the new response curves show only one peak. The results shown in these figures also indicate that the soil-structure system can be assumed to have axi-symmetric characteristics in the D1 and D2 directions. We will start our simulation analyses by utilizing the results in the D1 and D2 directions.

COMPARISONS OF SIMULATION RESULTS WITH OBSERVATIONS

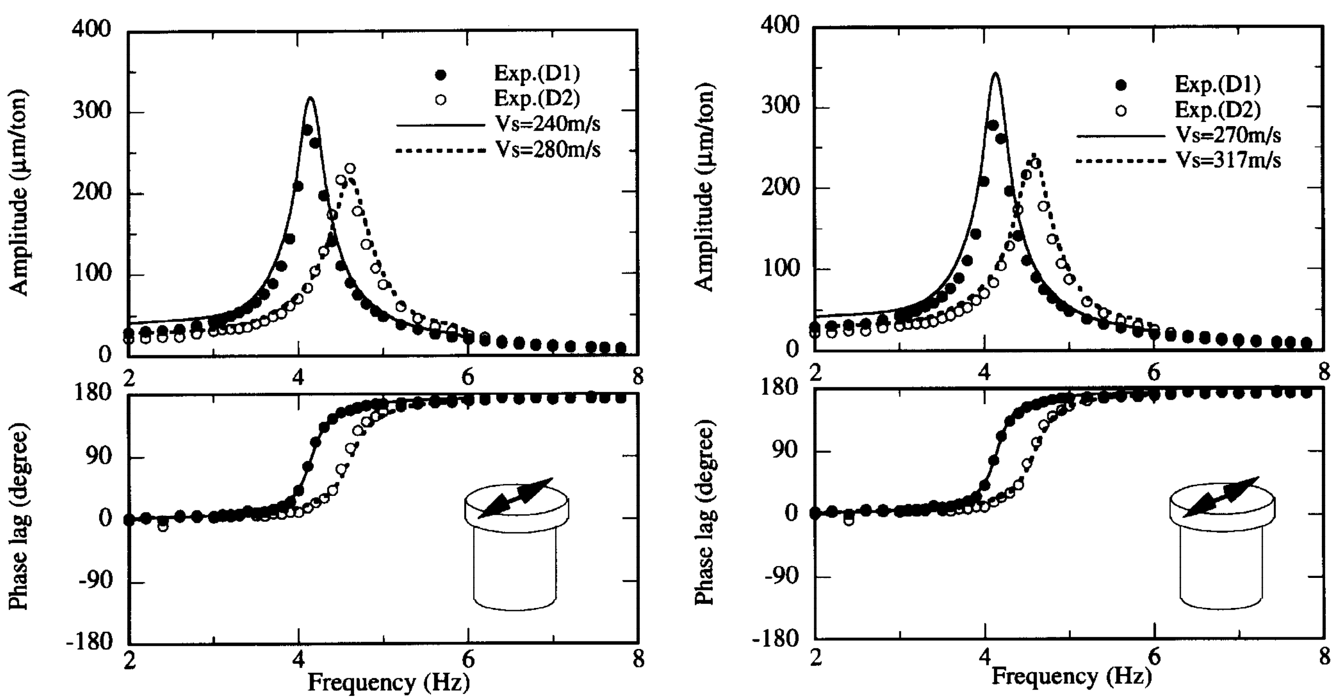
Axi-symmetric soil model

First, simulation analyses are carried out using the three dimensional hybrid method by assuming that soil properties in the FEM region are uniform and have almost axi-symmetric characteristics. Two soil models, one for the D1 excitation and the other for the D2 excitation, are determined by referring to the soil model proposed by Kokusho *et al.* (1994) as shown in Fig. 3. The properties of the underlying half-space are supposed to be identical with those by Kokusho *et al.* Soil properties of the surface layer except the shear wave velocity are also assumed to be similar to those by Kokusho *et al.* By changing the value of the shear wave velocity of the surface layer in the FEM region, simulation analyses were performed by a trial and error method. Final shear wave velocities of the two soil models are shown in Fig. 8 (a) and obtained response curves are compared



(a) Uniform soil model (b) Uniform soil model with loosened zone

Fig. 8. Employed soil models for the present hybrid analysis.



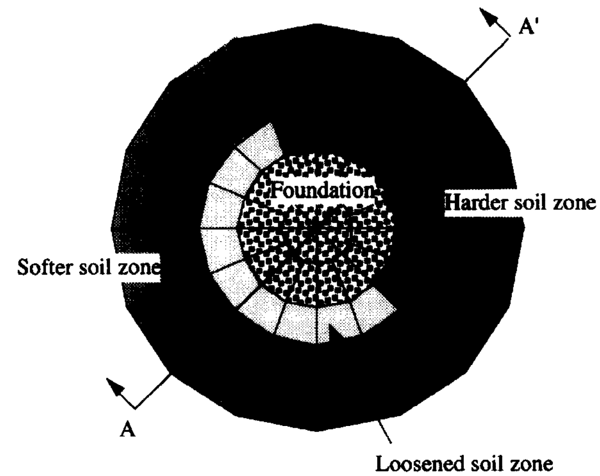
(a) Uniform soil model (b) Uniform soil model with loosened zone

Fig. 9. Comparison of horizontal response curves excited at the roof in the D1 & D2 directions.

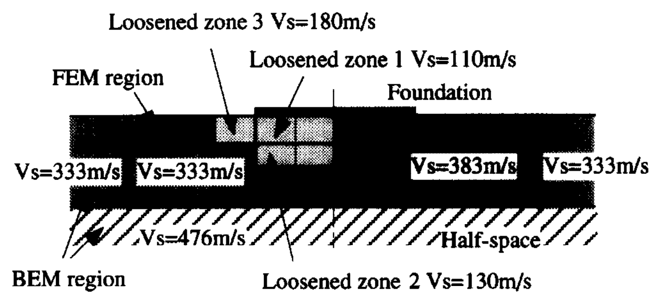
with the observed results excited at the roof in the D1 and D2 directions in Fig. 9 (a). The shear wave velocities of 240 m/s and 280 m/s correspond to the D1 and the D2 directions, respectively. These values of the shear wave velocity in the surface layer are less than that of 317 m/s proposed by Kokusho *et al.* (1994) who have determined the value based on laboratory and field tests. This reduction of the shear wave velocity may be ascribed to loosening effects under the foundation. Therefore, taking account of these loosening effects just beneath the foundation, new soil models were introduced as shown in Fig. 8 (b). Figure 9 (b) shows response curves obtained by using the new soil models. From this figure, it can be concluded that loosening effects must be considered in simulation analyses for the forced vibration test before backfill if we employ the soil model based on the soil testing results.

Irregular soil model

After the preliminary analyses assuming the axi-symmetric soil properties, we executed simulation analyses by use of the soil model considering the irregularity of soil near the model structure. The final soil model proposed by Kokusho *et al.* (1994) in Fig. 3 is used as our reference and starting model here again because their model was derived on the basis of soil testing results. As for the soil irregularity near the model structure, Morishita *et al.* (1994) have pointed out that the soil deposits near the foundation can be divided into two regions; a harder region and a softer region.

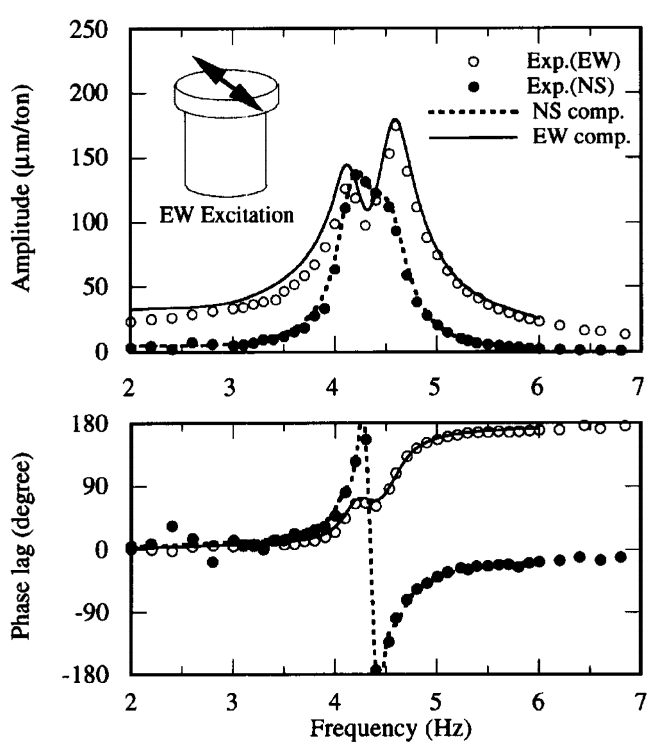


(a) Bird's-eye view of FEM region (irregular soil model)

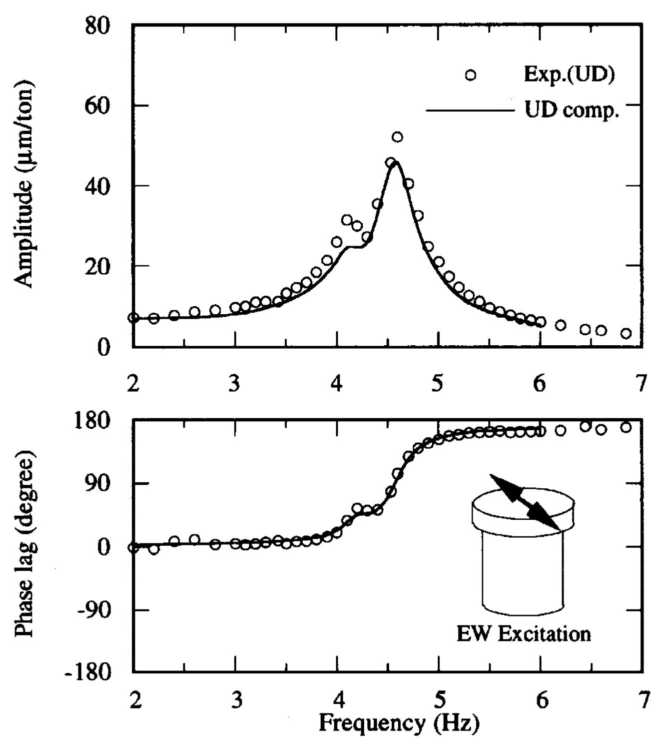


(b) A-A' section

Fig. 10. Employed properties of irregular soil model for the 3-D hybrid analysis.



(a) Horizontal components at the roof

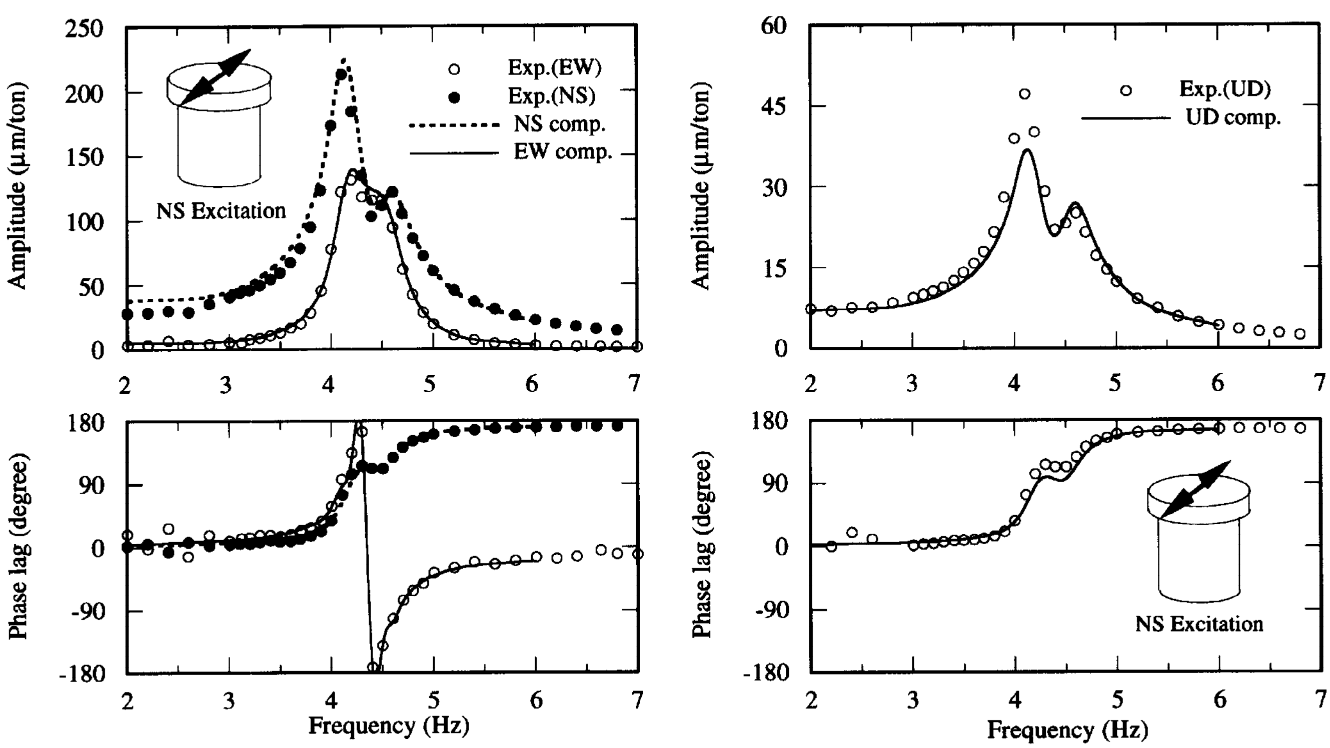


(b) Vertical component at the roof

Fig. 11. Comparison of response curves excited at the roof in the EW direction.

Properties of the soil in the harder region are assumed to have the same ones as the soil beneath the foundation proposed by Kokusho *et al.* (1994) to be used for simulation analyses of the soil-structure model after backfill. Properties of the soil in the softer region are supposed to correspond to those in the surface layer far from the foundation. Soil properties employed in the BEM region are also assumed to be identical with those in the softer region. Loosening effects near the foundation in the softer region in addition to beneath the foundation are also taken into account in the present analyses. The damping ratios of the soil in the loosened zones are assumed to be 3%. Properties of the final soil model used in the present 3-D hybrid method are shown in Fig. 10. The boundary between the harder and softer regions is similar to that of the soil zoning suggested by Morishita *et al.* (1994). Shear wave velocities specified in this figure were obtained by comparison of the calculated response curves with those by the EW component of test results excited at the roof in the EW direction. We had to iterate changing the values of the shear wave velocity by 27 times to acquire the values in this figure. When the model structure is excited in the EW direction at the roof, comparison of calculated horizontal response curves at the roof with observed results are depicted in Fig. 11(a). In this figure, displacement response curves are normalized by the exciting force and phase lag curves denote the phase lag of response at a measuring point to the exciter. Results obtained by the present hybrid method show surprisingly good agreement with the test results both in the EW component and the NS component. The displacements in the NS direction are generated by the irregularity of the soil near the foundation. Figure 11 (b) shows comparison of frequency response curves in the vertical direction when the structure is excited in the EW direction at the roof. The vertical displacements correspond to the rocking motion of the structure and have different values according to the location of measuring point. This figure depicts the vertical response near the East edge of the roof. It is clearly found from this figure that good agreement can be seen in the vertical response, too. It should be noted through our iteration analyses that the first peak at around 4.2 Hz of the EW response is mainly influenced by the existence of the loosening zone near the foundation.

Using the same soil model as shown in Fig. 10, calculated horizontal response curves at the roof are shown in Fig. 12(a) in comparison with the test results when the structure is horizontally excited in the NS direction at the roof. Figure 12(b) also depicts the vertical response near the North edge of the roof. Calculated results for the NS excitation at the roof demonstrate amazingly good agreement with those of the test results even though the soil properties used in the analysis were determined based on the comparison with the EW excitation. It can be concluded from these figures that the cross-axial coupling effects seen in the test results were generated by the irregularity of the soil near the foundation, and that two peaks shown in the response curves in the exciting direction were mainly ascribed to the existence of loosened soil just near the foundation in the soft soil



(a) Horizontal components at the roof (b) Vertical component at the roof

Fig. 12. Comparison of response curves excited at the roof in the NS direction.

region. It should be mentioned that the principal axes of the irregular soil model used in the present analyses are almost identical with those reported by Tanaka *et al.* (1994).

CONCLUSIONS

In this paper, results of simulation analyses for the forced vibration test of the large-scaled containment model structure without embedment at Hualien were presented by utilizing a three-dimensional hybrid method. Response curves obtained by the forced vibration test indicated the strong cross-axial effects and two peaks. To explain these effects, three dimensional soil models, that could express the irregularity of soil properties near the foundation were employed in the analyses.

Analyses were carried out by assuming that the model structure was on a uniform surface layer on the uniform half-space in the first step. According to the analysis results, the shear wave velocities of the surface layer were smaller than the value based on soil testing results. To account for the difference, it became clear that loosening effects under the foundation must be introduced in simulation analyses for the forced vibration test before backfill when using the soil model on the basis of the soil testing results.

In the next step, simulation analyses were carried out by using a soil model considering the irregularity near the model structure. Properties of the soil model were determined by a trial and error method, starting with the soil model based on soil testing results. The configuration of the irregularity was determined by a paper on the forced experiment at Hualien. Results obtained by the present hybrid method utilizing the final soil model in this study showed surprisingly good agreement with the test results of both NS and EW excitations at the roof. The cross-axial effects expressed in the test results can be captured almost perfectly by the present hybrid method using the final soil model.

We can draw our conclusions through our iteration analyses that the cross-axial coupling effects seen in the test results were generated by the irregularity of the soil near the foundation, and that two peaks shown in the response curves in the exciting direction were mainly ascribed to the existence of loosened soil just near the foundation in the soft soil region.

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