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Correlation analysis for forced vibration test of the Hualien LSST program

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ABSTRACT: The correlation analysis for a forced vibration test of a 1/4-scale containment SSI test model constructed in Hualien, Taiwan was carried out for the case of after backfilling. Prior to this correlation analysis, the structural properties were revised to adjust the calculated fundamental frequency in the fixed base condition to that derived from the test results. A correlation analysis was carried out using the "Lattice Model", which was able to estimate the soil-structure interaction effects with embedment. The analysis results coincide well with test results and it is concluded that the mathematical soil-structure interaction model established by the correlation analysis is efficient in estimating the dynamic soil-structure interaction effect with embedment. This mathematical model will be applied as a basic model for simulation analysis of earthquake observation records.

1 INTRODUCTION

A Large Scale Seismic Test (LSST) Program has been conducted in Hualien, Taiwan (Tang et al. 1991), to investigate soil-structure interaction effect during strong earthquakes, and to verify several analytical theories through earthquake observations. Before starting earthquake observations, forced vibration tests were conducted in 1992 before backfill and in 1993 after backfill to define basic dynamic characteristics of the soil-structure system. Test results were reviewed and it was concluded that this soil-structure interaction system had principal axes (Morishita et al. 1993). The directions of the major and minor axes were off-set from the NS and EW directions due to soil inhomogeneity. Based on this conclusion, two models were established which correspond to each principal axis (D_1, D_2). The blind prediction and post-correlation analysis for the forced vibration test were carried out as the analytical phases of an International LSST Program. This paper describes the results of correlation analyses for forced vibration tests after backfill with first floor (FF) horizontal excitations conducted in the Hualien LSST Program.

2 DYNAMIC CHARACTERISTICS OF MODEL STRUCTURE

2.1 *Dynamic characteristics with fixed base condition*

The dynamic characteristics of the model structure with fixed base were derived from forced vibration tests (Ishibashi et al. 1994). These tests yielded pure structure characteristics which exclude soil-structure interaction effects.

For first floor excitation, the dynamic equation of motion for sway(z), rocking(θ) and elastic deformation(x) is given as EQ (1) and the elastic deformation vector (x) is given by EQ (2).

$$M(\ddot{x}+I\ddot{z}+H\ddot{q})+C\dot{x}+Kx=0 \quad ; \quad x=\sum_{n=1}^{N}x_n q_n \qquad (1),(2)$$

where M, C, K are mass, damping and stiffness matrix and I, H are unit and height vector, respectively. X_n is the n-th mode vector and q_n is the n-th time function. Multiplying by the transposed first mode vector from the left side ($X_1^T \times$), and considering the orthogonal condition for different mode vectors, the dynamic equation of motion of the first mode is given by :

$$X_1^T M X_1 \ddot{q}+X_1^T MI\ddot{z}+X_1^T MH\ddot{\theta}+X_1^T CX_1\dot{q}+X_1^T KX_1 q=0 \qquad (3)$$

Following expressions are then introduced for simplicity.

$$\overline{\omega}^2=\frac{X_1^T KX_1}{X_1^T MX_1},\ 2h\overline{\omega}=\frac{X_1^T CX_1}{X_1^T MX_1},\ \alpha=\frac{X_1^T MI}{X_1^T MX_1},\ \gamma=\frac{X_1^T MH}{X_1^T MX_1} \qquad (4)$$

Furthermore, steady state time functions are expressed as :

$$q=Qe^{i\omega t},\ z=Ze^{i\omega t},\ \theta=\Theta e^{i\omega t} \qquad (5)$$

Applying these expressions to EQ (3), the first mode response of elastic deformation component for sway and rocking input motion can be derived as :

$$Q=\frac{\omega^2(\alpha Z+\gamma\Theta)}{\overline{\omega}^2-\omega^2+2ih\omega\overline{\omega}} \qquad (6)$$

The dynamic equation of motion with only elastic deformation (fixed base condition) is given by EQ (7) and elastic deformation vector ($\overline{x}$) is given by EQ (8).

$$M\left(\ddot{\overline{x}}+I\ddot{z}_0\right)+C\dot{\overline{x}}+K\overline{x}=0 \quad ; \quad \overline{x}=\sum_{n=1}^{N}X_n\overline{q}_n \qquad (7),(8)$$

where $\overline{q}_n$ is the n-th time function. Multiplying by the transposed first mode vector from the left side ($X_1^T \times$), and considering the orthogonal condition for different mode vectors, the dynamic equation of motion of the first mode is given by :

$$X_1^T MX_1\ddot{\overline{q}}+X_1^T MI\ddot{z}_0+X_1^T CX_1\dot{\overline{q}}+X_1^T KX_1\overline{q}=0 \qquad (9)$$

Applying EQs (4), (5) to EQ (9), it is concluded that the first mode response of the elastic deformation component of the dynamic system with only elastic deformation (fixed base condition) for unit base sway acceleration input ($\ddot{z}_0$=1) is given by :

$$\overline{Q}=\frac{-\alpha\ddot{z}_0(=1)}{\overline{\omega}^2-\omega^2+2ih\omega\overline{\omega}} \qquad (10)$$

Comparing EQ (6) and EQ (10), the first mode response of the elastic deformation component with fixed base condition for unit base sway acceleration input ($\overline{Q}$) is given by the first mode response of the elastic deformation component of the dynamic system with sway, rocking and elastic deformation for sway and rocking input motion (Q) as :

$$\overline{Q}=Q\times\frac{-\alpha\ddot{z}_0(=1)}{\omega^2(\alpha Z+\gamma\Theta)}=Q\times\frac{-\alpha}{\omega^2(\alpha Z+\gamma\Theta)} \qquad (11)$$

2.2 *Mathematical model of structure*

Fig.1 shows a cross-section of the test structure. The mass matrix and the height vector of the model structure are evaluated from design drawing geometry, and are shown in Fig.2. The mode shape for the elastic deformation component is represented by the ratio of rotational angle (θ) to horizontal displacement (u) at the roof floor (RF). The observed mode ratio (θ/u) derived from the test results are shown in Fig.3. It is nearly equal to 0.00055 (rad./cm), except in the frequency range below 5Hz, which is used as a first mode vector of elastic deformation (X_1). Using these data, values of α and γ defined by EQ (4) are obtained. From EQ (11), resonance curves with fixed base condition ($\overline{Q}$) are obtained by applying measured sway (Z), rocking (Θ) and elastic deformation resonance curves (Q). Resonance curves with fixed base condition derived from the test results after backfill are shown in Fig.4, in which regression results for the one-degree-of-freedom resonance curve are also shown. Natural frequencies and damping factors obtained by the regression method are summarized in Table 1. As averaged values of the test results with first floor excitation, natural frequency and damping factor are 9.59 Hz and 1.4 %, respectively.

Calculated mode ratio by the flexural and shear beam model is shown in Fig.5, in which the geometrical coefficient for shear deformation (κ) is considered as a parameter. From this figure, the value 0.00055 rad./cm of mode ratio is derived when the geometrical coefficient for shear deformation (κ) is equal roughly to 0.5. Calculated fundamental frequency for the fixed base condition at the foundation top is shown in Fig.6, in which Young's modulus is $E_0 = 288$ ton/cm^2 and the geometrical coefficient for shear deformation (κ) is considered as a parameter. From this figure, the fundamental frequency is 10.37 Hz when the geometrical coefficient for shear deformation (κ) is equal to 0.5.

To adjust the calculated fundamental frequency (10.37Hz) to that derived from the test results (averaged to 9.59Hz) as aforementioned, Young's modulus is revised to effective Young's modulus (E_e) as follows :

$$E_e = \eta \times E_0 = 0.86 \times 288 \text{ ton/cm}^2 = 246 \text{ ton/cm}^2$$

$$\eta = (9.59 \text{ Hz} / 10.37 \text{ Hz})^2 = 0.86 \qquad \eta : \text{apparent stiffness reduction factor}$$

3 CORRELATION ANALYSIS FOR FORCED VIBRATION TEST

3.1 *Analytical model*

There are many soil structure interaction analysis models. One that was used, or will be used in the near future, for aseismic design of nuclear power plants is selected. Here, the Lattice Model is selected for the correlation analysis of the forced vibration test for horizontal excitation after backfilling. The analytical model and the general concept of the Lattice Model are shown in Fig.7.

Unified physical constants of soil for the simulation analysis were proposed by the Technical Management Committee of the Hualien Project as shown in Fig.8. These constants were employed directly in the D_1 direction correlation analysis. D_1-Equivalent rocking stiffness ($K_{RR[D1]}$) was obtained by an axi-symmetric FEM model under supporting layer (GL-5.15m). For the D_2 direction, the rocking stiffness of the supporting soil is derived from that of the D_1 direction ($K_{RR[D2]} = K_{RR[D1]} \times 1.20$). The revised stick model of the structure which was established in previous chapter was used.

3.2 *Correlation analysis results*

Calculated resonance and phase lag curves for the D_1 and D_2 directions for first floor horizontal excitation are shown with the test results in Figs. 9～10. Calculated peak frequencies and deformation ratios are summarized and compared with the test results in Table 2. Calculated peak frequencies, damping factor, peak amplitude and deformation ratios correlated well to the test results. Impedance functions of the soil derived from the test results is compared with those of the simulation analysis models in Figs. 11～12. They showed reasonably good agreement.

4 CONCLUSIONS

The concluding remarks obtained from the analysis results are summarized as follows ;

1. The dynamic characteristics of the model structure with the fixed base condition are derived from test results, and the mathematical model of the structure was revised.
2. The results of the correlation analysis coincide well with the test results in peak frequency, damping factor, peak amplitude, deformation ratios (sway, rocking and elastic deformation) and impedance functions of the soil.
3. The mathematical model discussed in this paper is efficient for estimating a dynamic soil-structure interaction effect with embedment in forced vibration tests.

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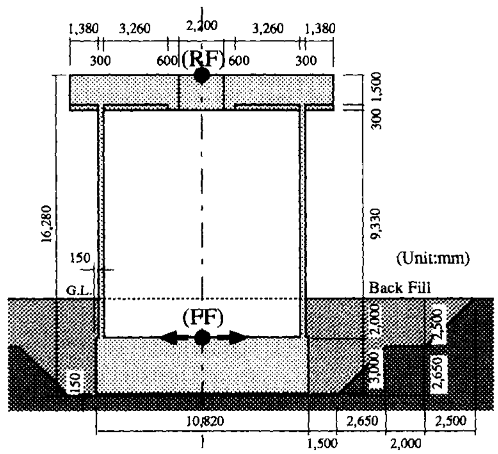


Fig.1 Cross section of model structure

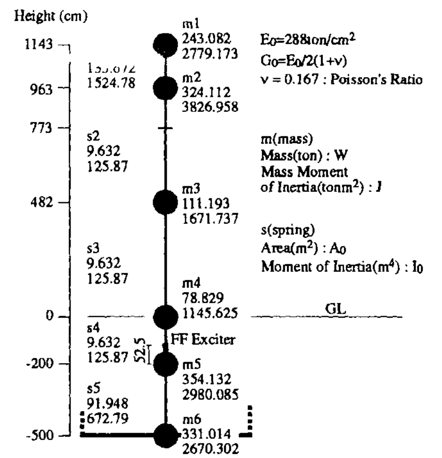


Fig.2 Lumped mass model of model structure

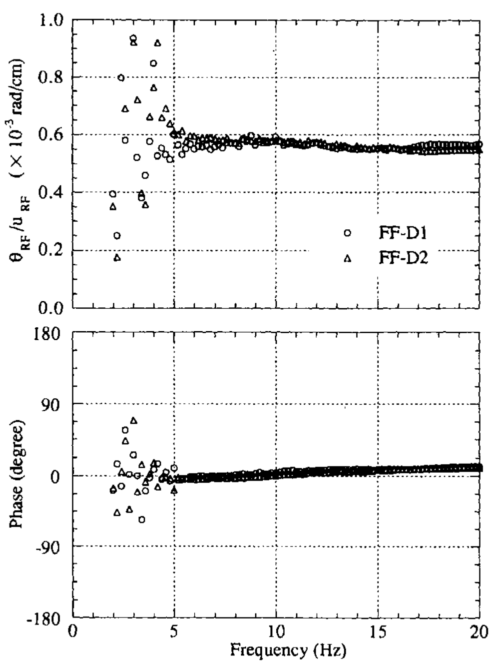


Fig.3 Observed mode ratio (θ/u) derived from test results

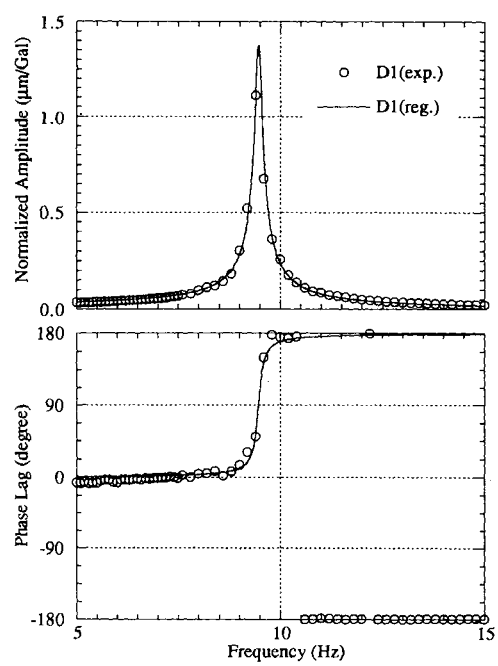


Fig.4 Resonance curves for fixed base condition (D_1-direction)

Table 1 Natural frequency and damping factor for fixed base condition

D_1 direction		D_2 direction		Average	
f_0	h	f_0	h	f_0	h
9.47	1.0	9.71	1.8	9.59	1.4

f_0: Natural frequency (Hz)
h : Damping factor (%)

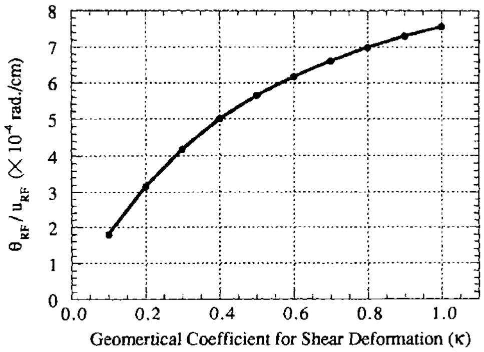


Fig.5 Mode ratio (θ/u) by beam model

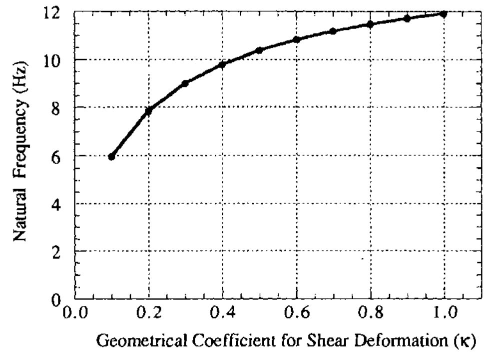


Fig.6 Fundamental frequency of fixed base condition

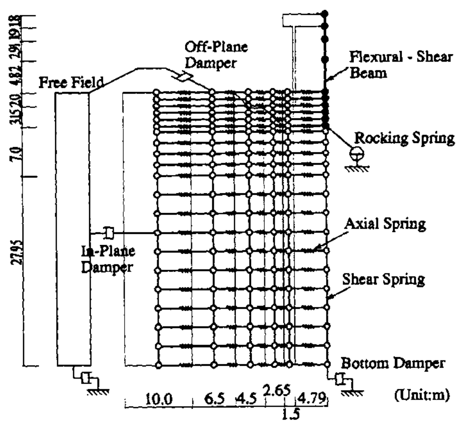


Fig.7 Analytical model (Lattice Model)

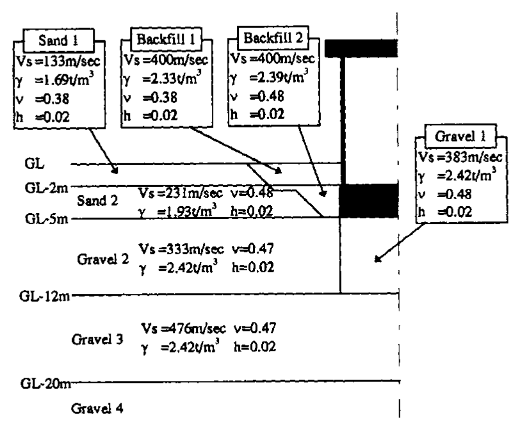


Fig.8 Soil property

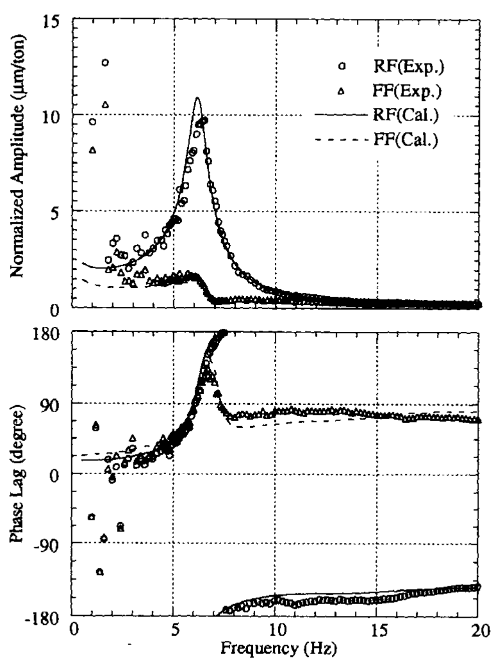


Fig.9 Resonance curves for horizontal excitation at foundation (D_1-direction)

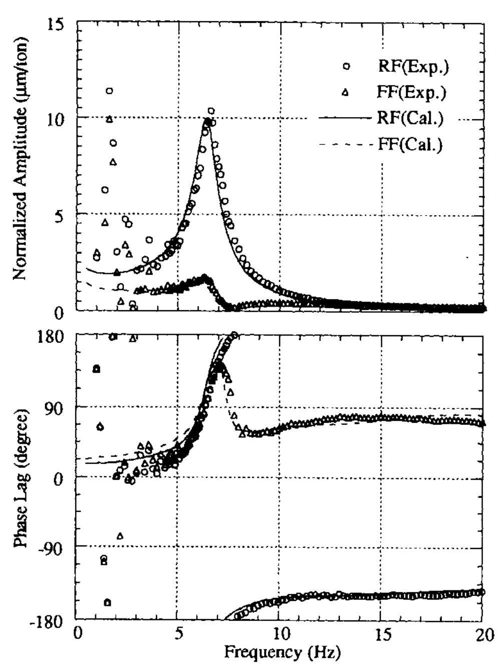
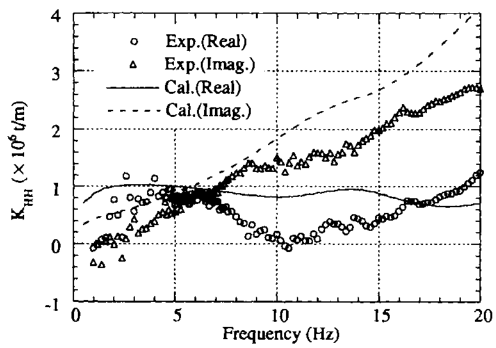


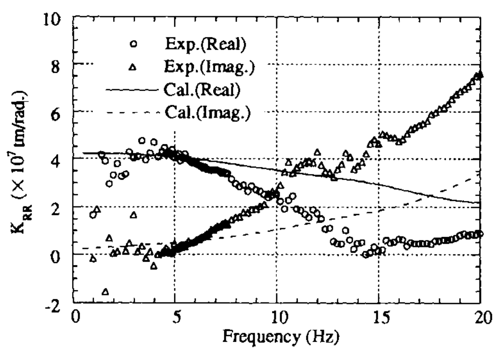
Fig.10 Resonance curves for horizontal excitation at foundation (D_2-direction)

Table 2 Calculation results for horizontal excitation at foundation

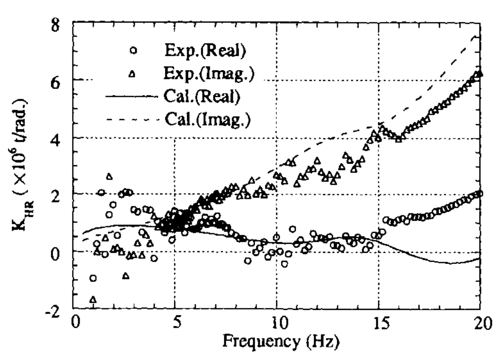
	Peak frequency (Hz)	Damping factor (%)	Peak amplitude (μm)	Deformation ratio (%) Sway	Rocking	Elastic deformation
Calculation (D_1)	6.14	8.2	10.9	4.2	55.1	40.7
Test result (D_1)	6.5	8.6	9.7	5	55	40
Calculation (D_2)	6.38	8.3	9.9	4.4	51.1	44.5
Test result (D_2)	6.6	8.1	10.4	6	48	46



(a) Horizontal impedance

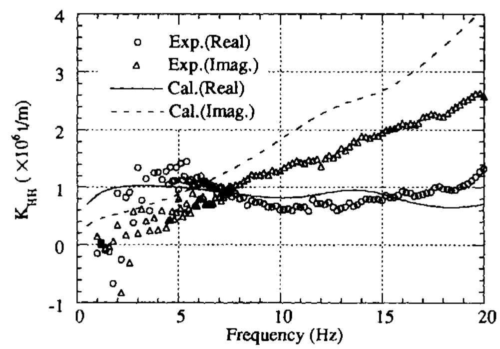


(b) Rocking impedance

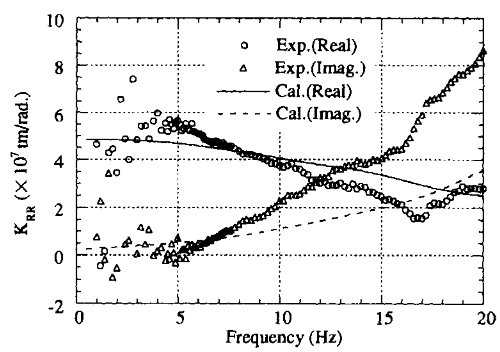


(c) Coupling impedance

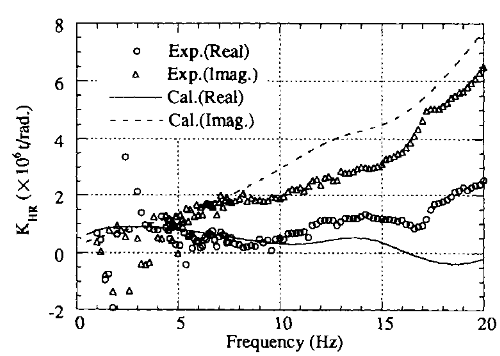
Fig.11 Impedance functions of soil (D_1-direction)



(a) Horizontal impedance



(b) Rocking impedance



(c) Coupling impedance

Fig.12 Impedance functions of soil (D_2-direction)