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KW1/5

Practical evaluation method for soil springs under inhomogeneous soil conditions (Hualien LSST program)

Kobayashi T.[(1)], **Yamanaka T.**[(2)], **Sugawara Y.**[(3)]
(1) Kajima Technical Research Institute, Japan
(2) Kajima Information Processing Center, Japan
(3) Tokyo Electric Power Company, Japan

ABSTRACT

A Large-Scale Seismic Test (LSST) Program is being conducted in Hualien, Taiwan, to obtain earthquake-induced soil-structure interaction data. The forced vibration test results indicated a fairly large amount of response amplitude perpendicular to the exciting directions. The reason for these phenomena is suggested to be strong irregularity of soil properties in the vicinity of the model structure in the horizontal direction. The practical evaluation method for soil springs under inhomogeneous soil conditions was proposed and simulation analyses were conducted.

1. INTRODUCTION

A Large Scale Seismic Test Program (LSST) to study the soil-structure interaction effect during earthquakes has been conducted on a 1/4-scale nuclear reactor containment structure at Hualien, Taiwan, as an extension of the same kind of program conducted at Lotung, under the control of an international consortium [1]. Fig.1 shows a section of the model structure.

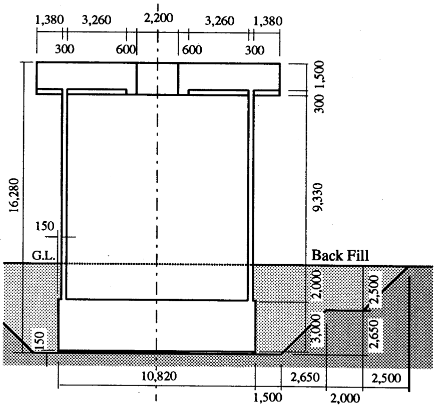


Fig. 1 Section of the model structure

Before starting earthquake observations, forced vibration tests were conducted before backfilling (FVT-1) and after backfilling (FVT-2) using an exciter to obtain the basic dynamic characteristics of the soil-structure interaction system. For both NS and EW excitations, the resonance curves before backfilling had two peaks and a fairly large amount of response amplitude appeared perpendicular to the exciting directions, even though the model structure was axi-symmetric [2]. After backfilling, the response also had a large amount of response amplitude perpendicular to the exciting direction [3].

These phenomena indicate that there was strong inhomogeneity of the soil properties in the vicinity of the model structure in the horizontal direction [3]. The concept of principal axes was introduced to minimize the components perpendicular to the exciting direction, and the test results were transposed to these axes : D1 and D2 [4].

This paper proposes a practical evaluation method for soil springs under inhomogeneous soil conditions, and this method is used to conduct correlation analyses of forced vibration tests after backfilling.

2. REVIEW OF SOIL CONDITIONS

Because there was no concept of inhomogeneity of soil properties at the Hualien site at the time of the soil investigation, the measuring plan was oriented to be of the axi-symmetric type and all the soil property and geometry data after backfilling were reduced as shown in Fig.2 [5]

However, the forced vibration test results and their analysis results indicated that there is an inhomogeneity in the supporting layer.

During model construction, Hualien was subjected to the heavy rains of several typhoons, and the excavation pit was filled with water to a depth of about 3 m. This caused the excavation slopes to collapse, except for the north-east quadrant. During the vibration test before backfilling, it was observed that the slope of the N-E quadrant appeared to be stiffer, and those of the other three quadrants were softer. A schematic view showing the soil condition of the slope around the model structure is shown in Fig.3 [3].

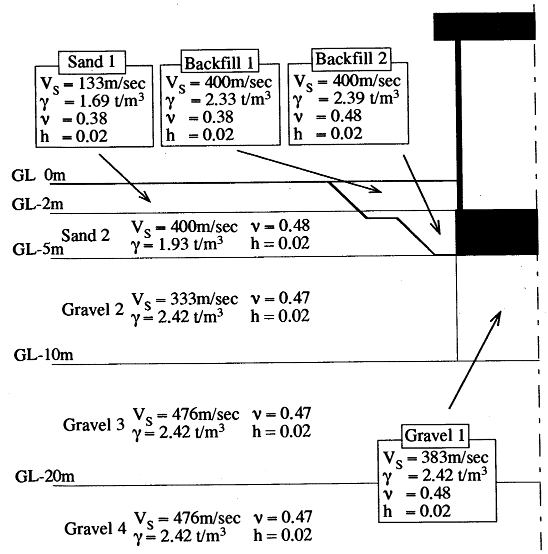
The soil properties measured after model construction and before backfilling were rearranged and it was confirmed that there are two zones just beneath the basemat, a soft zone and a hard zone, as shown in Fig. 4 [4].

Based on the concept of inhomogeneity, the complicated forced vibration test results were well followed by a simulation analysis using a sophisticated theory [6].

Thus, the measured test data are rearranged in consideration of the visual situation of the slope during FVT-1 shown in Fig.3 and the measured soil property distribution as shown in Fig.4. The rearranged soil properties and geometries based on the axi-symmetric oriented soil model (Fig. 2) are shown in Fig. 5. In Fig. 2, the shear wave velocity just beneath the basemat (Gravel 1) is 383 m/sec which is almost equal to weighted mean of the shear wave velocity of Gravel 2 and Gravel 3 with weight of 2 and 1, respectively.

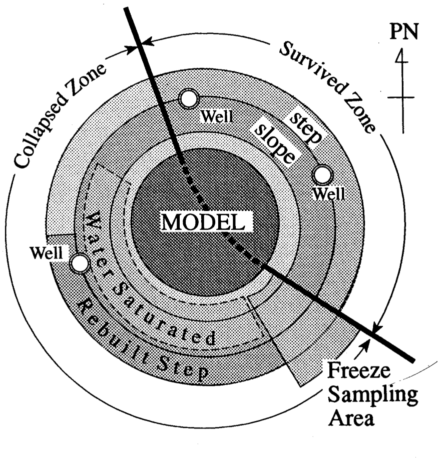
$$333 \text{ m/sec} \times (2/3) + 476 \text{ m/sec} \times (1/3) = 381 \text{ m/sec.}$$

Considering these conditions, circumferential angles of soft zone and hard zone in Fig. 5 are decided to be $4\pi/3$ and $2\pi/3$, respectively.



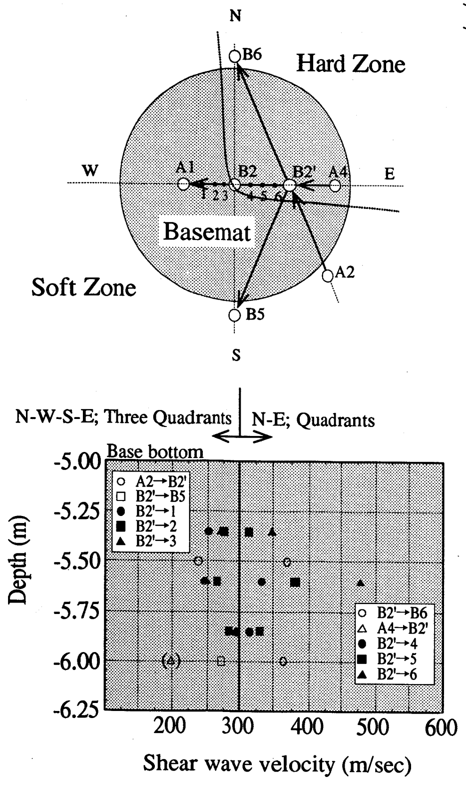
(after Okamoto et al [5])

Fig. 2 Axi-symmetric oriented soil model



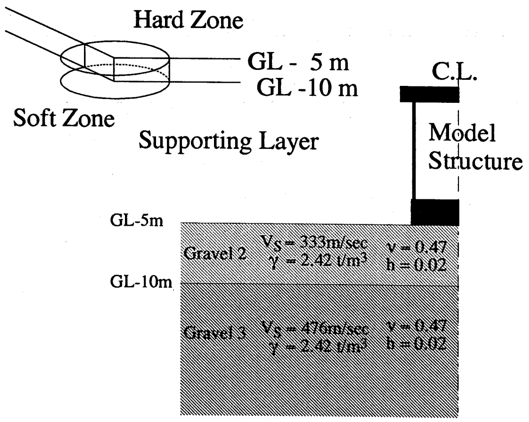
(after Sugawara et al [3])

Fig. 3 Schematic view showing soil condition around structure

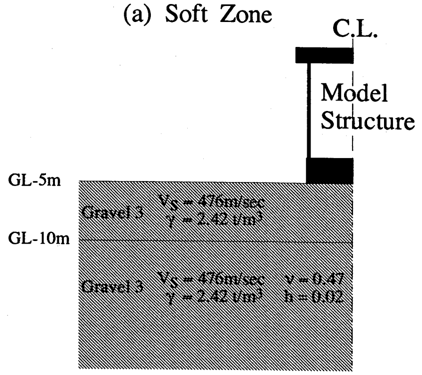


(after Yamaya et al [4])

Fig. 4 Geotechnical investigation results



(a) Soft Zone



(b) Hard Zone

Fig. 5 Rearranged soil properties and geometries

3. BASIC THEORY

(1) Moment of inertia of a sector

The moment of inertia of the sector shown in Fig. 6 round the x axis, I(θ) is given as :

$$I(\theta) = \iint_{r=0,\,t=0}^{r=R,\,t=\theta} (r\sin t)^2 r\,dr\,dt = \frac{\pi}{4}R^4\left(\frac{\theta}{2\pi} - \frac{\sin 2\theta}{4\pi}\right) \tag{1}$$

The moment of inertia of the whole circle round the x axis is given by replacing θ by 2π :

$$I(2\pi) = \frac{\pi}{4}R^4 \tag{2}$$

Defining P(θ) as :

$$P(\theta) = \left(\frac{\theta}{2\pi} - \frac{\sin 2\theta}{4\pi}\right) \tag{3}$$

where P(θ) means the ratio of the moment of inertia of the sector to that of the whole circle.

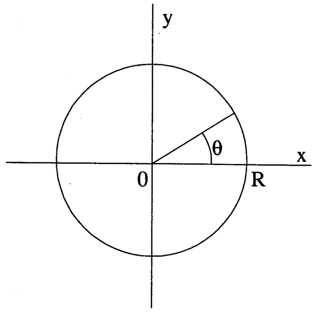


Fig. 6 x-, y-axis and a sector

(2) Minor axis (D1 direction : round x-axis)
The supporting soil at the Hualien site just beneath the base mat was idealized as shown in Fig. 7. The ratio of the moment of inertia of the hard sector to that of the whole circle is

$$ {}_{D1}P_H = 2 \times P(\frac{\pi}{3}) \cong 0.20 \qquad (4) $$

The ratio of the moment of inertia of the soft sector to that of the whole circle is :

$$ {}_{D1}P_S = 1 - {}_{D1}P_H \cong 0.80 \qquad (5) $$

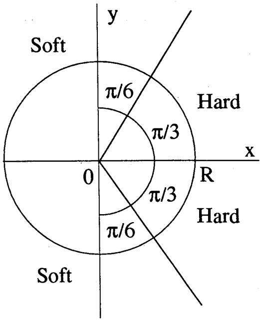


Fig. 7 Soft and hard region just beneath the base mat

(3) Major axis (D2 direction : round y-axis)
The ratio of the moment of inertia of the hard sector to that of the whole circle is :

$$ {}_{D2}P_H = \frac{1}{2} - 2 \times P(\frac{\pi}{6}) \cong 0.47 \qquad (6) $$

The ratio of the moment of inertia of the soft sector to that of the whole circle is :

$$ {}_{D2}P_S = 1 - {}_{D2}P_H \cong 0.53 \qquad (7) $$

4. APPLICATION FOR HUALIEN LSST MODEL

(1) Rocking Stiffness under Axi-symmetric Soil Conditions

A practical evaluation method for the rocking springs under complicated soil conditions such as those at the Hualien site is proposed to derive a weighted mean of the rocking springs under the axi-symmetric layered soil conditions with a soft layer (Ks) and a hard layer (KH).

Soil properties and geometries used for an axi-symmetric FEM for soft and hard soil conditions are shown in Fig. 5.

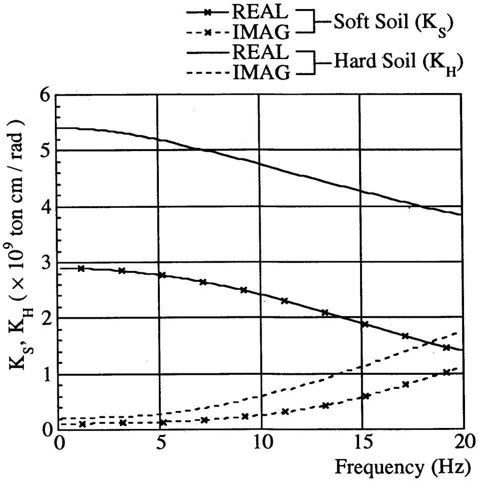


Fig. 8 Rocking Springs for Soft and Hard Soil Conditions

Frequency dependent rocking springs (Ks and KH) for soft and hard soil conditions obtained by an axi-symmetric FEM are shown in Fig. 8. KH is roughly 1.9 times of Ks.

(2) Practical Evaluation Method for Soil Spring under Inhomogeneous Soil Conditions

Rocking springs (KD1 and KD2) for the minor and major axes are practically evaluated from Ks and KH as weighted means according to the moments of inertia of the soft and hard zones in respect of the minor and major axes, respectively. The result is expressed as :

$$ \begin{Bmatrix} K_{D1} \\ K_{D2} \end{Bmatrix} = \begin{bmatrix} {}_{D1}P_H & {}_{D1}P_S \\ {}_{D2}P_H & {}_{D2}P_S \end{bmatrix} \begin{Bmatrix} K_H \\ K_S \end{Bmatrix} \qquad (8) $$

KD1 and KD2 are frequency dependent, as shown in Fig. 9. KD2 is roughly 1.2 times KD1.

(3) Simulation Analysis of Forced Vibration Test

The "Lattice Model" is adopted here as a soil-structure interaction model, for estimating the soil-structure interaction effects with embedment.

The general concept of "Lattice Model" is shown in Fig. 10. The adjacent soil zone is idealized by multi-mass-columns whose masses are connected by axial springs in the horizontal direction and by shear springs in the vertical direction. Three-dimensional effects are idealized approximately by off-plane, in-plane and bottom dampers. The rocking springs K_{D1} and K_{D2} obtained above are employed in the model. The model structure is idealized by a multi-degree-of-freedom beam model with flexural and shear deformation. The system identification results [7] are used in the idealization of the dynamic characteristics of the structure.

The horizontal and rotational response amplitude/phase lag curves obtained from the correlation analyses of forced vibration tests for the roof floor and the first floor, D1 and D2 direction excitations are shown in Figs.11~14 in comparison with the test results.

The comparisons are summarized in Table-1.

The analysis results and test results coincide well for the horizontal and rotational response amplitude/phase lag curves, peak frequency, damping ratio and displacement ratios. The response amplitudes of the analysis result are slightly larger than those of the test result.

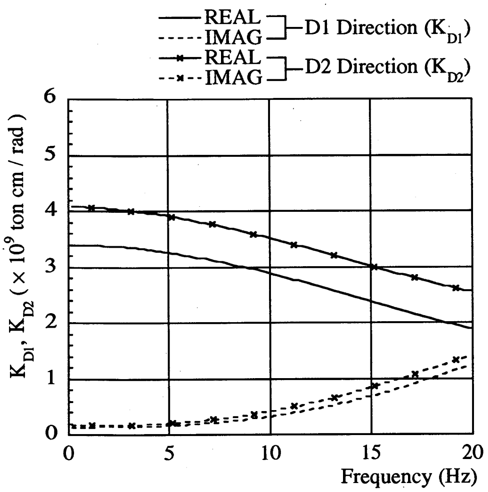


Fig. 9 Rocking Springs for D1 and D2 Directions

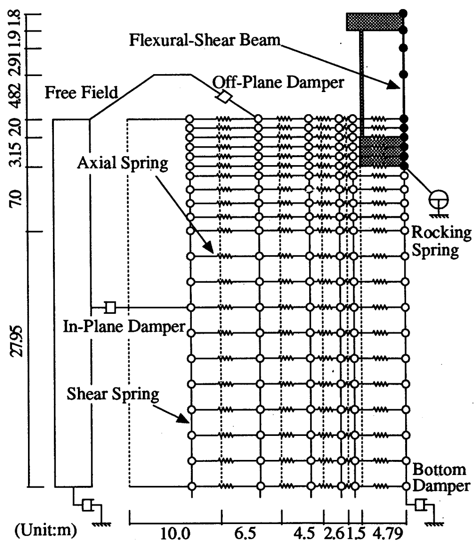
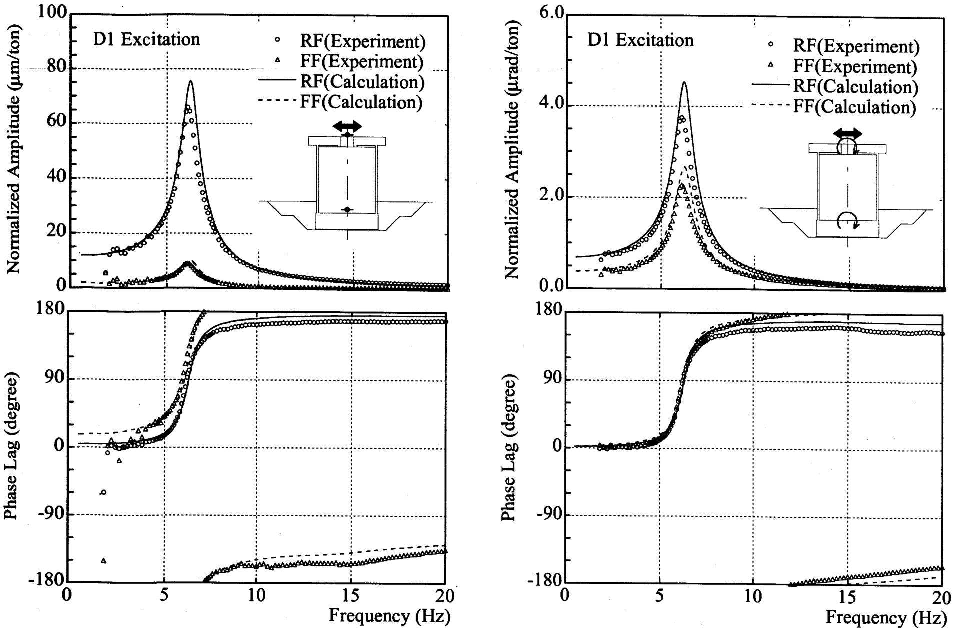


Fig. 10 General concept of Lattice model

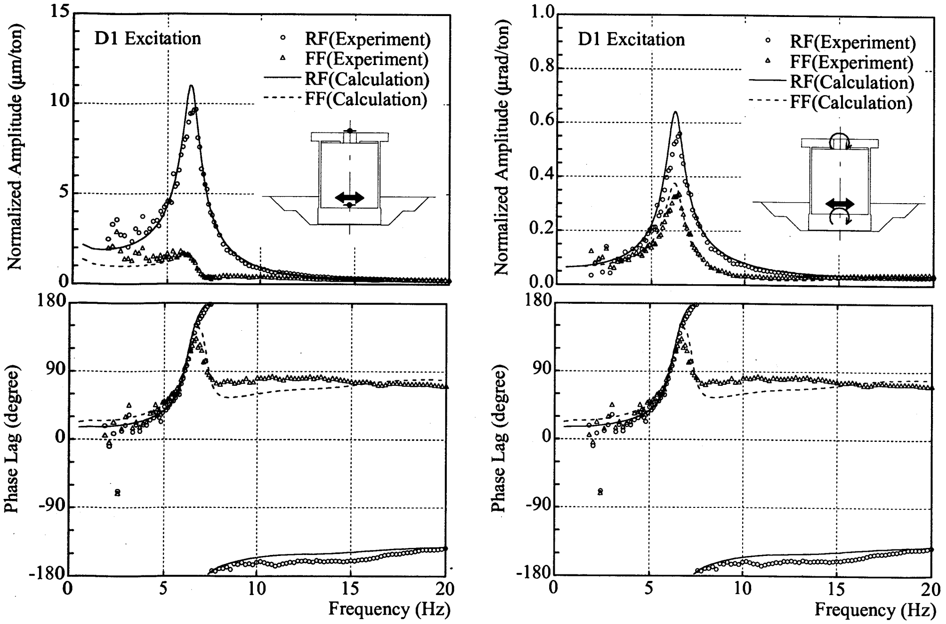
Table-1 Comparison between Test Results and Calculation Results of Roof Floor Response

Excitation Direction		Peak Frequency (Hz)	Damping Ratio (%)	Normalized Amplitude (μm/ton)	Displacement Ratios (%) Sway	Rocking	Super Structure
RF D1	Calculation	6.24	7.69	75.57	6	55	39
	Test	6.10	8.20	65.90	7	52	41
RF D2	Calculation	6.40	8.04	69.25	7	51	42
	Test	6.30	8.20	62.70	8	49	43
FF D1	Calculation	6.24	7.77	11.03	4	53	43
	Test	6.50	8.60	9.70	5	55	40
FF D2	Calculation	6.40	8.13	9.95	5	49	46
	Test	6.60	8.10	10.40	6	48	46



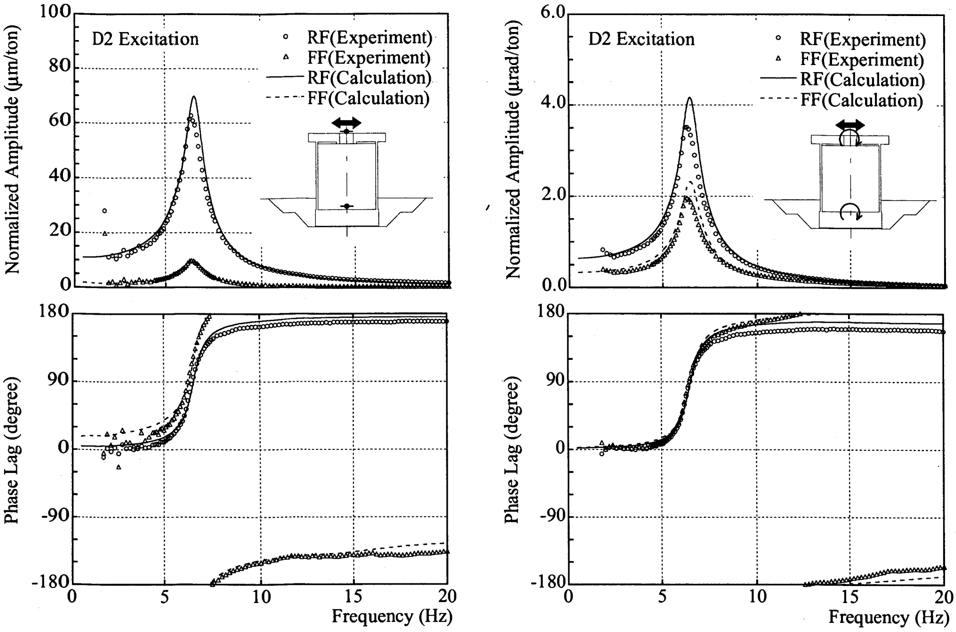
(a) Horizontal response (b) Rotational response

Fig.11 Response amplitude/phase lag curves for D1 direction roof floor excitation



(a) Horizontal response (b) Rotational response

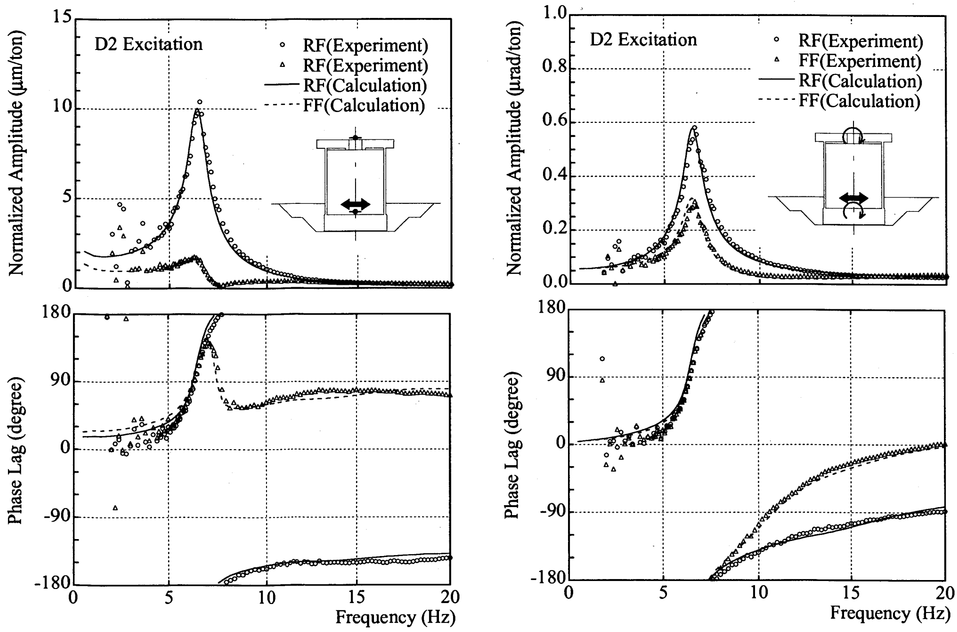
Fig.12 Response amplitude/phase lag curves for D1 direction first floor excitation



(a) Horizontal response

(b) Rotational response

Fig.13 Response amplitude/phase lag curves for D2 direction roof floor excitation



(a) Horizontal response

(b) Rotational response

Fig.14 Response amplitude/phase lag curves for D2 direction first floor excitation

5. CONCLUSION

The supporting soil of the Hualien LSST model was concluded to comprise two regions, a soft region and a hard region, based on forced vibration test results, soil investigation results and visual observation of the slope during a forced vibration test before backfilling.

For this inhomogeneous soil condition, a practical evaluation method is proposed for evaluating the rocking soil spring.

In this method, first the rocking soil springs for uniformly layered soft and hard soil conditions were obtained using axi-symmetric FEM as K_S and K_H, where original soil data obtained from soil investigations are directly used. Next, the rocking soil springs K_{D1} and K_{D2} for the minor and major axes are obtained from K_S and K_H weighted according to the moments of inertia of the soft and hard zones in respect of the minor and major axes.

A correlation analysis was conducted for the forced vibration test after backfilling by a "Lattice Model" using K_{D1} and K_{D2} as rocking soil springs and also using system identified results in the mathematical model of the model structure.

Correlation analysis results and test results coincide well for peak frequency, damping ratio, response amplitude and displacement ratios. It is thus concluded that the mathematical soil-structure interaction model ("Lattice Model") employed here is efficient in estimating the dynamic soil-structure interaction effect with embedment, and that the proposed practical evaluation method for soil springs for an inhomogeneous soil condition is also efficient.

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