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Soil Investigation and FVT Analysis in Hualien LSST SSI Research

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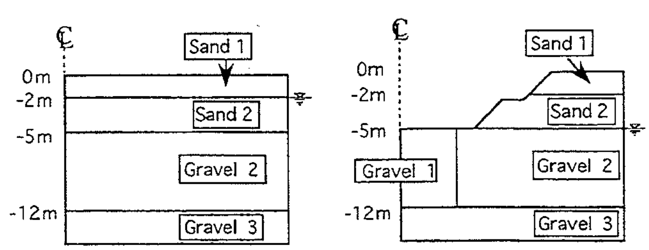
SYNOPSIS An international joint research program, Large-Scale Seismic Test (LSST) Program at Hualien, Taiwan, is ongoing, where a large-scale model structure partly embedded in gravelly layer was constructed, in-depth site soil geotechnical investigation was performed at every one of four construction stages, that is, before excavation, after excavation before structure construction, after structure construction before backfill, and after backfill, forced vibration tests (FVTs) of the model structure before backfill (FVT-1) and after backfill (FVT-2) were performed, and seismic observation of the dynamic SSI (soil-structure interaction) system is underway. This paper describes the change of the shear wave velocity (Vs) accompanied by the construction stage progress, and predictive and correlative FVT analyses, taking above-mentioned Vs change into account.

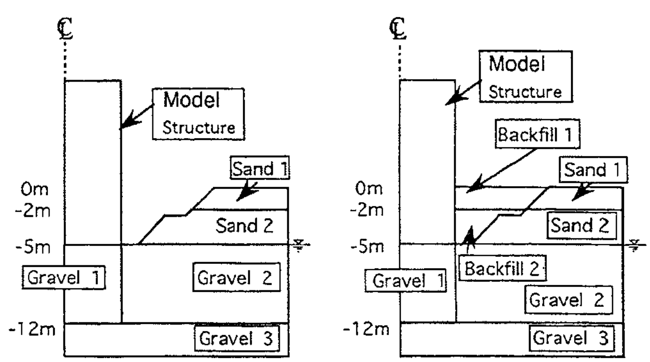
INTRODUCTION

The Hualien project called "HLSST" (Tang et al.1991) is an international joint research program to evaluate the aseismic design of nuclear structure. The model structure of considerable size, constructed on gravel layers in a high seismic region in Taiwan, is observed in Large-Scale Seismic Test(LSST) to investigate the Soil-Structure Interaction(SSI) behavior during large earthquakes.
HLSST consists of (1)geotechnical investigation, (2)model construction, (3)sensors installation, (4)forced vibration test and its simulation, and(5)monitoring structure and ground response during earthquake and its simulation.
To evaluate the change of Vs of the model structure foundation ground during the construction process, the field tests were conducted in four phases: before excavation (stage 1), after excavation (stage 2), after model construction (stage 3), and after backfill (stape 4) as shown in Fig.1.
This paper describes the numerical soil model for SSI analysis, and SSI analysis of the forced vibration test before backfill (FVT-1).

ANALYTICAL SOIL MODEL OF THE FOUNDATION GROUND AND THE BACKFILL

The significant change of Vs was observed during the model construction process. The change of Vs of the foundation ground during the model construction process is mainly dependent on the unloading and loading of overburden pressure due to the construction process.(Kokusho et.al. 1994) Fig.2 shows the soil model to be used in the SSI analysis for the construction stage 4 (=after backfill). Taking account of the site soil geotechnical investigation results, the ground just beneath the model foundation named Gravel 1 (G.L.-5~-12m) was modeled as a single soil zone with a uniform soil property. Vs of this zone





(1) construction stage 1 (Before excavation)
(2) construction stage 2 (After excavation and before construction)
(3) construction stage 3 (After construction and before backfill)
(4) construction stage 4 (After backfill)

Fig.1 Analytical model for stress change due to model construction procedures was determined as 383m/s by averaging measured values after backfill. On the other hand, Vs of this soil layer before backfill (stage 3) was judged to be 317m/s based on the test results. Other zones of the model, that is, Sand 1, Sand 2, Gravel 2 and Gravel 3 zones were made according to the free field measurements before excavation. Horizontally layered ground model was proposed as the unified model for FVT-1 prediction, with the Vs value of 317m/s (denoted Vs* hereafter) for the first layer just beneath the basemat from G.L.-5 to -12m. That is, Vs of the free field for the first layer (=333m/s) was neglected at FVT-1 prediction stage to make the model horizontally layered. In addition, note that 'Gravel 2 Prime' zone also illustrated in Fig.2 was introduced only for FVT-1 2nd step correlation analysis. It neither appears in the proposed unified model for FVT-1 nor for FVT-2. The backfill is divided into 2 zones, that is, Backfil 1 and Backfill 2 at the ground-water level.

The Poisson's ratio ν was calculated based on the P and S wave velocities, soil density γ_t was taken from soil samples obtained by means of the freezing sampling technique excect for that of the backfill which was taken from in-situ density test, and hysteresis damping ratio h was measured by laboratory cyclic triaxial tests.

FVT-1 PREDICTION AND CORRELATION

Outline of Model Structure, FVT and Analysis Method

The test model structure is of cylindrical shape with about 10.5 m in wall diameter, about 16 m in total height, which corresponds to about 1/4-scale of reactor buildings of commercial nuclear power plants (Fig.3). It is made of reinforced concrete and weighs about 1.44 kilotons. The model structure was constructed on the gravelly layers after the excavation of the top sand layers up to the depth of 5 m.

The forced vibration tests before backfill ('FVT-1') (Morishita et al. 1993) were carried out with the exciter having the maximum excitation force of 10 tons installed on the roof slab for NS-& EW-directional excitations and then on the basemat for NS-, EW-directional & vertical excitations.

Axisymmetric FEM code with transmitting boundary named 'TB3D' (Ueshima et al. 1982) developed in CRIEPI is used for the FVT-1 prediction and correlation, taking the application also in the FVT-2 analysis step into consideration where horizontally heterogeneous ground model has been proposed by CRIEPI (Fig.2). The model structure, too, is idealized in terms of axisymmetric solid elements. Fixed base natural frequency of this model structure was 10.0 Hz.

Roof-& base-horizontal excitation cases (denoted RF-H, BS-H each hereafter) are analyzed by 'TB3D'.

FVT-1 analysis for the same SSI system by other methodology like substructuring method is described in Ueshima et al.(1994) together with the analysis for vertical excitation case, and more detailed FVT-1 analysis results.

Procedure for FVT-1 Prediction & Correlation

(1) The 'blind prediction' for FVT-1 is performed first, where blueprints for structure construction, excitation condition and the results of site soil investigations are given to the analysts with FVT (test) results kept uninformed.

(2) FVT (test) results are disclosed to all the analysts, and 'correlation analysis' process starts, where each analyst compares predicted resonant curves with test results, studies the reasons of the discrepancies between prediction and test if any, and makes the model refinement for the next analysis step.

(3) The way of 'the first step correlation' taken in this study is as follows;

Vs and h (damping ratio) of the first layer (G.L.-5~-12m just beneath the structure base mat) are varied and identified so that the

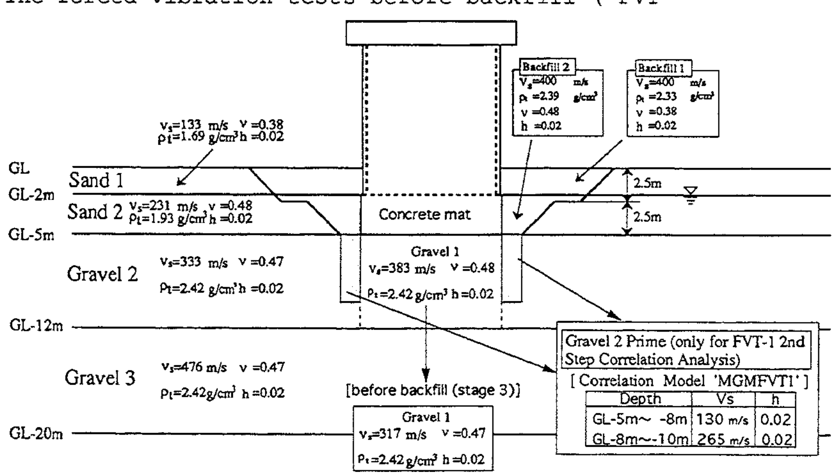


Fig.2 The soil model before and after backfill (stages 3 & 4)

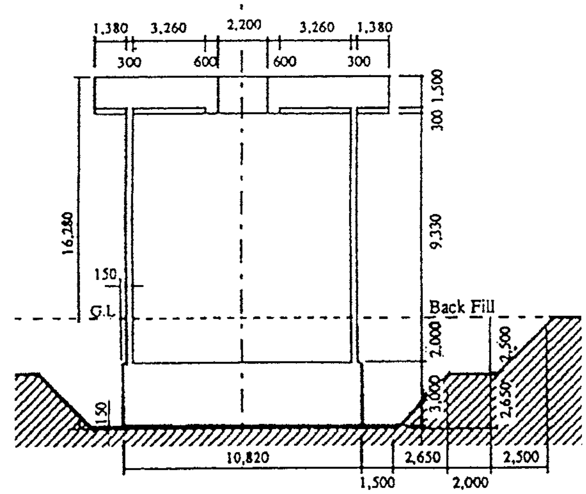
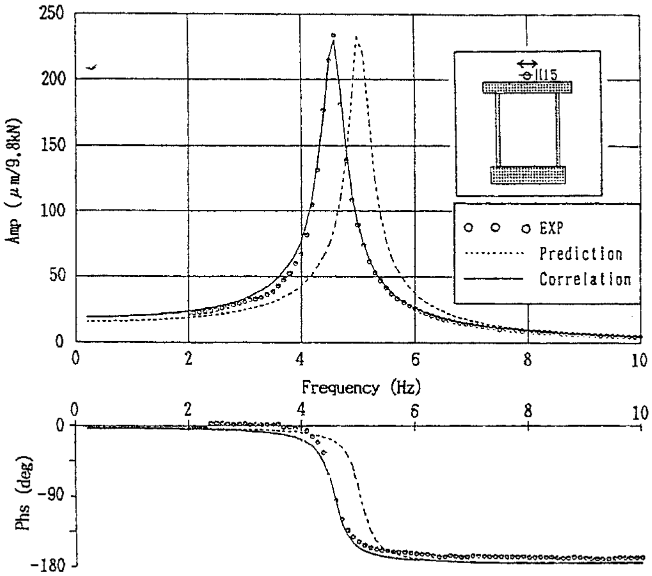


Fig.3 Cross section of test model structure

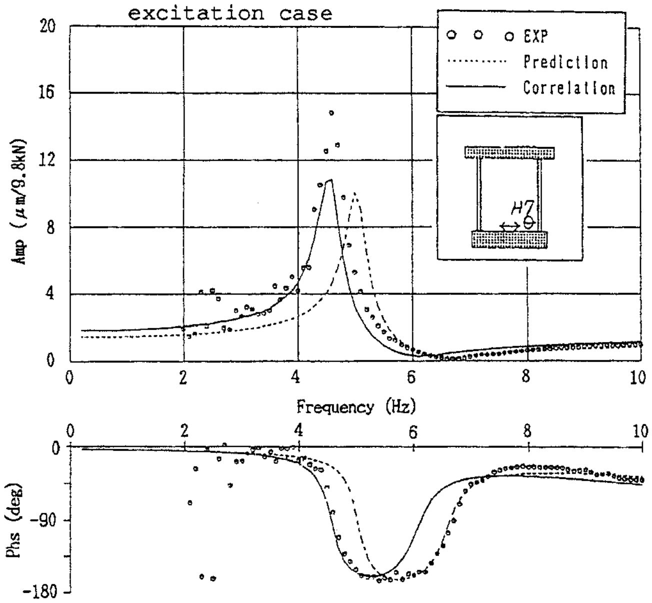
fundamental resonant frequency (f_0) and the peak amplitude of the component parallel to the excitation direction on the roof ($U_{RF,P}$) resulting from the simulation agree with the tests, a) with the first layer just beneath the basemat remaining uniform, and b) with all the other soil properties except above Vs & h of the first layer remaining unchanged.

Results of the Prediction & the Correlation

Predicted frequency response curves using the proposed unified ground model before backfill are given in the dotted lines in Fig.4a,b together with experimentally obtained ones in the dots and



a. On the roof in roof-horizontal excitation case



b. On the basemat in base-horizontal excitation case

Fig.4 Predicted and correlated frequency response curves of the components parallel to excitation direction by 'TB3D'in comparison with tests

correlated ones in the solid line. All the predicted and correlated results are summarized in Table.1 in comparison with test results.

(1) FVT-1 prediction by 'TB3D' showed the following;

1) Predicted f_0 was about 9 % higher than the test result and $U_{RF,P}$ was almost correctly predicted.

2) Prediction by 'TB3D' could be evaluated generally good from the viewpoint of degree of agreement with the test results in terms of f_0, $U_{RF,P}$, and so on. In addition, basic characteristics of the response difference appearing in the test results due to the excitation position difference in the horizontal excitation cases were well predicted. 'TB3D' could be said to have enough applicability.

(2) The first step correlation showed the following;

Table 1 Results of prediction and correlation (Analysis by TB3D) in comparison with test results

Vibration Mode (Load Pt.) 'ABBREV.'	Exp. or Anal. Prediction or Correlation	Physical Quantities			Vs&h of 1st Layer in Anal	
		f_0 (Hz)	$U_{RF,P}$ (μm/tf)	h_0 (%)	Vs(m/s) for 1st Layer(GL.-5～-12m)	h (%)
Horizontal (Roof) 'RF-H'	EXP.(RF-EW)	4.6	174.54	5.4	————	—
	Prediction	5.0	233.27	4.0	317.0	2.0
	Correlation	4.6	183.26	5.4	276.0(× 0.87)	3.3
Horizontal (Base) 'BS-H'	EXP.(RF-EW)	4.6	46.75	5.4	————	—
	Prediction	5.0	47.27	3.0	317.0	2.0
	Correlation	4.6	39.37	5.4	276.0(× 0.87)	3.3
(Further Effort) 'RF-H'	'MGMFVT1'	4.5	313.64	2.2	'MGMFVT1'	2.0
	'MGMFVT1'	4.5	178.96	5.6	ditto	3.7

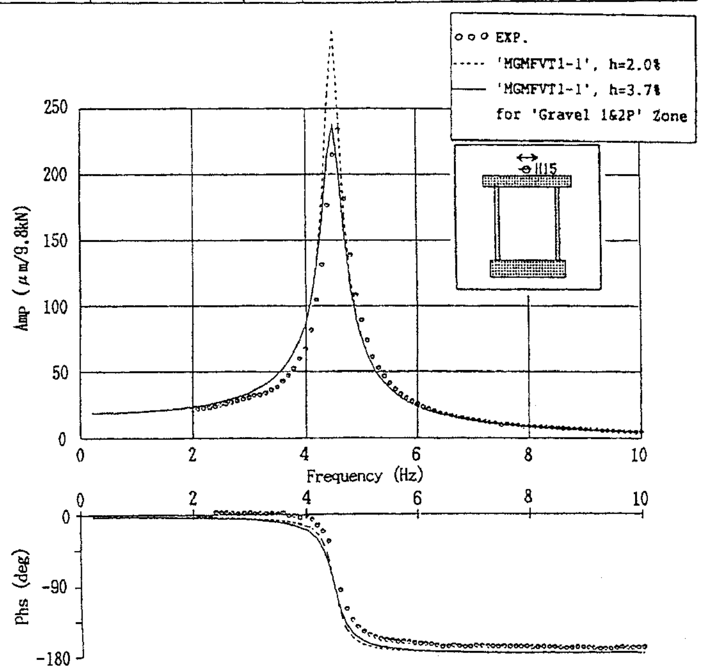


Fig.5 Frequency response curve on the roof parallel to excitation direction using modified ground model ('MGMFVT1') in roof-horizontal excitation case by 'TB3D' in comparison with tests

1) The 'correlated Vs' of the concerned layer for the RF-H excitation case by 'TB3D' (= 276 m/sec) corresponds to 13 % reduction from the Vs* (=317m/sec) which was proposed as the average of the crosshole method, but it also could be regarded within scattering range (Fig.5 of Kokusho et al. (1994)).
The 'correlated h' was 3.3 %, which looks a little large taking h_{min} (= 2 % for the layers at this site) into account.
2) Estimation of the strain level of the bedding layer just near the contact plane during the actual test using the approximate formula brought a little less value than 1×10^{-6}, which still remains in the elastic range. That is, above 'Correlated Vs and h' could not well be explained only from the viewpoint of shear modulus reduction and/or damping ratio increase due to their dependency on the soil strain level near the contact plane.

FURTHER EFFORT TO CORRELATE PREDICTION WITH TEST

As for the way of the first step correlation, the basis to do so is not necessarily sufficient from the viewpoint of geotechnical investigation. As one of other measures to make up for the system frequency gap between the prediction and the test putting confidence in the geotechnical site soil investigations, 'Gravel 2 Prime' zone as shown in Fig.2 was introduced. As the zone was left exposed to the air at the level of G.L.-5 m even during FVT-1 experiments, Vs distribution of this 'Gravel 2 Prime' zone was judged natural to be taken from the site soil investigation carried out during 'Construction Stage 2'. Modified model with this newly introduced 'Gravel 2 Prime' zone is named 'MGMFVT1' (Modified Ground Model for FVT-1).
The analysis using 'MGMFVT1' was carried out only for RF-H excitation case, which showed the following (Fig.5 & Table.1) ;
(1) The analysis using 'MGMFVT1' brought an excellent f_0 agreement without any further ground model modification. The fact that the analysis introducing 'Gravel 2 Prime' zone was successful indicated that it is important to perform the site soil investigation along the construction process when the confining pressure of the concerned soil zone is anticipated to change, and to incorporate the investigated result appropriately to the analysis ground model.
(2) Analyzed $U_{RF,P}$ was larger than the test when h=2% for all the soil zones. To get peak amplitude agreement between the analysis and the test, damping ratios (h) for only 'Gravel 1' and 'Gravel 2 Prime' zones were gradually increased and finally the agreement was got when it was increased up to 3.7%.
(3) The result showed that the structural response subjected to forced excitation is affected largely by the shear rigidities not only of the soil zone just beneath the basemat but of the neighboring soil zone.

CONCLUSION

(1)Detailed site soil investigation at every one of four construction stages disclosed that Vs of the foundation ground changes during the model construction process due to the unloading and loading of overburden pressure. Soil model for FVT-1 & FVT-2 analysis was proposed, taking above Vs change along the construction process into account.
(2) The predictive and correlative FVT analyses revealed the following;
1) Predictions by axisymmetric FEM could be evaluated generally good from the viewpoint of degree of agreement with the test.
2) In the analysis of RF-H excitation case by axisymmetric FEM, predicted resonant frequency (f_0) was about 9 % higher than the test and predicted resonant amplitude ($U_{RF,P}$) almost agreed with the test. Vs and h of the layer just beneath the contact plane having 7 m depth were varied and identified so that analyzed f_0 & $U_{RF,P}$ agree with the test. 'Correlated Vs' was 13 % reduction from the given Vs*, and 'correlated h' was 3.3 %, both of which could not well be explained only from the viewpoint of shear modulus reduction and/or damping ratio increase due to their dependency on the soil strain level near the contact plane.
3) Further analysis was made to make up for the system frequency gap between prediction and test with modifying the ground model so that the Vs change of the gravel zones along the construction process is well incorporated. It brought a successful analysis result, indicating the importance of the in-depth site soil investigation along the construction stages, and of its appropriate incorporation to the analysis ground model.

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