



Hualien earthquake analyses using ring exciting thin layer method

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ABSTRACT

As a participant of the international project of Hualien Large Scale Seismic Test Program, the blind prediction analysis on the earthquake of January 20, 1994, and its subsequent correlation study have been performed using the ring exciting thin layer technique developed by the authors. The present paper introduces first the ring exciting thin layer method for simulating the response of the soil-structure system to the earthquake ground motions. Since the ring exciting thin layer method using the Green's functions for ring loads is characterized by the cylindrical walls model, it realistically allows axisymmetric irregular soil profiles such as backfills. As results of the prediction analysis, there appeared a significant difference between the analysis and the observation, therefore, the correlation study has been conducted by modifying both the soil model and the structure one. To modify the soil model, we initially addressed the confining stress-dependency of the gravel just beneath the foundation. Furthermore, we considered the strain-dependency of the soil properties due to the secondary non-linearity during the earthquake. These revised parameters were established on the basis of the dynamic triaxial tests using the samples obtained by the in site freezing method.

INTRODUCTION

An international cooperative program of the Hualien Large Scale Seismic Tests was initiated to study the actual seismic behaviors of the soil-structure system at a stiff soil site, as well as, to verify the SSI analyses methodologies employed for the seismic response predictions of nuclear power buildings[1]. Participating this project ongoing, we have performed the earthquake blind prediction and correlation analyses by employing the ring exciting thin layer method. The ring exciting thin layer method, proposed by Tajimi[2], was already introduced at SMiRT13 for the impedance analysis[3], where the simulation analysis of the forced vibration tests before backfill (FVT-1) was also described. It was concluded in Ref.3 that the ring exciting thin layer method has a great potential for simulating the dynamic responses of a soil-structure system to forced vibrations under axisymmetric irregular profiles of soils. This paper presents the ring exciting thin layer method for simulating the dynamic responses of a soil-structure system to earthquake ground motions. In the present study, the earthquake blind prediction and the subsequent correlation analyses have been successfully performed by employing the proposed method. This correlative study involving modification of the soil and structure models has been done for not only the earthquake observation but also the forced vibration test after backfill(FVT-2[4]). In particular, the soil model was revised on the basis of our careful insight of the geotechnical investigation data to accurately account for the effects of the effective confining stress-dependency and of the strain-dependency due to second non-linearity

ANALYSIS METHOD

1) General description

The ring exciting thin layer technique, extended from the point exciting thin layer one[5], is based on the Green's function approach employing the ring load solutions to describe the soil-foundation interaction[2]. As introduced in the point exciting thin layer method, the exact displacement functions and a linear variation of the displacement are defined for the thin layered strata in the horizontal and in the vertical direction, respectively. The point exciting thin layer technique is, however, limited to the horizontally layered soil models, whereas the present ring exciting thin layer method allows the axisymmetric irregular profiles of soils by employing the multiple cylindrical walls model, shown in Fig.1. At SMiRT13, the authors introduced the impedance analysis method utilizing the multiple cylindrical walls model in order to conduct the blind prediction and the correlation analyses of the forced vibration tests before backfill[3]. Subsequent to that paper, the present one outlines the ring exciting thin layer method to simulate the responses of a soil-structure system to earthquake ground motions. Since the present method is based on the thin layer technique, the linear response analysis is performed in frequency domain.

2) Earthquake response analysis method of soil-structure system

A typical multiple cylindrical walls model of soils is illustrated in Fig.2. The displacement vector of the rings $\{U\}_i$ at the interfaces of the i -th cylindrical wall subjected to the harmonic base motions and, at the same time, to the external ring loads $\{P\}_i$ acting at the interfaces is expressed ;

$$\{P\}_i = [R]_i (\{U\}_i - \{U\}_i^x) \quad (1)$$

, where $[R]_i$ is the stiffness matrix of the i -th cylindrical wall given in Ref.2, $\{U\}_i^x$ denotes the response of the i -th cylindrical wall to the harmonic base motions in the x -direction, corresponding to the dynamic response of the one-dimensional shear soil column assumed by use of the same soil parameters as the cylindrical wall. The internal force vector induced to satisfy the continuous condition of the neighboring cylindrical walls, shown in Fig.3, is ;

$$[R]_i \{U\}_i^x = \{Q\}_i \quad (2)$$

By substituting Eq.(2) into Eq.(1) and by assembling the sub-equation of Eq.(1), the following equation is formed ;

$$\{P\} = [R]\{U\} - \{Q\} \quad (3)$$

Providing that the soil model is subjected to only to the base motions, i.e., the external ring loads $\{P\} = 0$, the equilibrium relation is ;

$$[R]\{U\} = \{Q\} \quad (4)$$

The response (motions of the rings) of the soil model $\{U\}_g$ to the seismic motions is given by Eq.(4).

By employing the volume method, the response analysis of a soil-structure system to earthquake ground motions is conducted in the straightforward manner. The procedure is outlined ;

- 1) To compute the response of the multiple cylindrical walls model $\{U\}_g$ in Eq.(4)
- 2) To compute the effective input motions by use of the impedance matrix of the foundation given in Ref.2 with the mass matrix of soil volume replaced by foundation for sway and rocking motions.
- 3) To compute the response of the soil-structure system. In the present method, the structure is idealized by a stick model of lumped masses system.

PREDICTION ANALYSIS

1)Hualien large scale seismic tests

The seismic test program of a quarter scale reinforced containment model is ongoing at Hualien, Taiwan, a highly active seismic site near the Philippine Sea Plate boundary[1,6,7]. Fig.4 shows the cylindrical model structure, the soil profile with backfill, and the strong motion stations including downhole array utilized in the blind analysis. Since July,1993 to May,1996, fifteen events have been recorded. In the present international project, the blind predictive and the subsequent correlative analyses of the earthquake data recorded on January 20,1994 (M=5.6, Hypocentral distance=27km, Epicentral depth=49.5km) were conducted by the consortium members.

2)Control motion and analysis procedure

The free field acceleration records at the ground surface (A15 in Fig.4) were given as the control motions to predict the ground motions along the downhole, and at the same time, the seismic responses of the soil-structure system. Among three components, Fig.5 shows the control motion for L-component (in NS direction) at A15. Illustrated in Fig.6, at the first step of the analysis, the seismic response analysis of the free field soil system has been performed by using the one-dimensionally propagating shear wave theory (SHAKE-equivalent) to predict the motions along the downhole, and to simulate the input motions at the base of SSI model. At the second step, the response analysis of the soil-structure system has been carried out by employing the ring exciting thin layer method introduced in the present paper. The transfer functions were utilized to combine the free field soil model with the SSI model shown in Fig.6.

3)Analysis model for prediction

Since the maximum acceleration of the control motions ranged about 30-40gals, the linear dynamic analyses using the unified soil model were performed without accounting for the strain dependency of the soil properties. Hence, the unified soil model was proposed by CRIEPI for blind prediction study[8]. Figs.7 and 8 show the idealization of the structure and the mathematical model of the soils under the unified conditions, respectively, provided for conducting SSI analysis.

4)Prediction analyses results

As for the responses of the free field soil system, a good comparison of the predicted and the observed motions along the downhole array demonstrated the validity of the SHAKE-equivalent technique utilizing the unified free field soil model. As results of the response analysis of the SSI system, Figs. 9 show the transfer functions from the control motions to the responses at both base and roof of the structure. A poor correlation between the prediction using the unified model and the observation, shown in Figs.9, implies the necessity for conducting the correlation study. Since the predicted peak frequencies of the transfer functions appeared rather higher than the observations, the degradation of the system stiffness should be considered for the correlation.

CORRELATION STUDY

1)Modification of structure model

Sugawara et al. revised the structure stiffness from the forced vibration tests results using the system identification method[9]. As concluded in that paper, the stiffness of the structure was reduced to 85% of the unified one for the present correlation.

2)Establishment of initial soil model and FVT-2 correlation analysis

Fig.10 shows the flowchart of the modification of the soil model. As illustrated in Fig.11, the modification procedure adopted in the correlation study consisted of 2steps ;

- a) Provide the initial model corresponding to FVT-2
- b) Establish the model for the earthquake correlation

To modify the unified soil model, a careful insight was given again into the data of the geotechnical investigations systematically conducted by CRIEPI. Following factors were mainly considered ;

- a) The effective confining stress-dependency of the gravelly soils just beneath the foundation.
- b) The strain-dependency of the properties of soils just around the foundation due to the secondary non-linearity during the earthquake.

In order to accurately take into account these effects, the dynamic triaxial tests data using the samples obtained by the in site freezing method were primarily used to revise the soil model just around the foundation. Hence, the empirical relationship between the shear wave velocity and the effective confining pressure was proposed for the foundation gravel by Okamoto et al.[8] :

$$V_s \propto \sigma_c^{0.3} \quad (5)$$

Furthermore, Fig.12 represents $G-\gamma$ and $h-\gamma$ curves obtained from the dynamic triaxial tests. Table 1 summarize the relationship between the soil model employed in our study and the geological investigation data used. Shown in Table 1, the unified soil stiffness was initially given by CRIEPI on the basis of the down hole logging[8]. Furthermore, the reduced stiffness of the backfilled soils was proposed by CRIEPI in July,1995, after their additional geological investigations. In our correlation study, the stiffness and the damping of the soils just around the foundation (Gravel 1 and Backfill) were initially defined at the strain level of 5×10^{-6} under the estimated in-site effective confining pressure. To modify the soil model for Gravel 1, both the change of the effective overburden pressure and the observed excessive pore water pressure were considered. Fig.13 shows the shear velocity of foundation gravel (Gravel 1) obtained from the cyclic triaxial tests, compared with PS-loggings. At the same time, a deeper distribution of shear wave velocity in the gravelly soils from GL-12m to GL-27m was revised on the basis of the large penetration tests data[3]. Consequently, Fig.14 describes the complete soil model initially revised for the correlation analysis of FVT-2. The analyses results simulated for FVT-2 using this revised soil model showed a excellent correlation with the measurements, shown in Fig.15.

3)Earthquake correlation analysis

Consider now that the predominant frequency observed at roof during the 1/20/'94 earthquake was 5.3Hz (Peak frequency at response spectra), while the resonant frequency measured for horizontal excitation at roof was 6.1Hz and 6.3Hz in the principal axes. On the other hand, a good correlation existed between the prediction analysis based on the PS-loggings and the observations along the downhole array at the free field. These results indicated that the non-linear effect locally induced by the motions of the foundation, called secondary non-linearity, should be taken into account for the earthquake correlation analysis. Based on a discrepancy in the observed predominant frequency between the forced vibration and the earthquake, the earthquake-induced strain level of the soils just around the foundation was assumed for the correlation, shown in Figs.11 and 12. By utilizing the stiffness and damping of the soils at the assumed strain level, the earthquake correlation analysis has been successfully performed. Table 2 summarizes the analysis cases presented in this paper. A good correlation between the analysis and the observation shown in Fig.9 and Table 3 demonstrates that the ring exciting thin layer method is quite acceptable for the seismic response analysis of the soil-structure system under the axisymmetric irregular soil profiles.

CONCLUDING REMARKS

The ring exciting thin layer method has a great potential for simulating seismic responses of a soil-structure system under an axisymmetric irregular soil profiles. By adequately modifying both the soils and the structure model, the correlation analyses have been successfully performed not only for the earthquake but also for the forced vibration test after backfill. Since the properties of the sandy or gravelly soils depend on the effective confining pressure, as well as, on the strain level, the dynamic triaxial tests data using the samples obtained by the in-site freezing method are available for establishment of the soil model just around the foundation.

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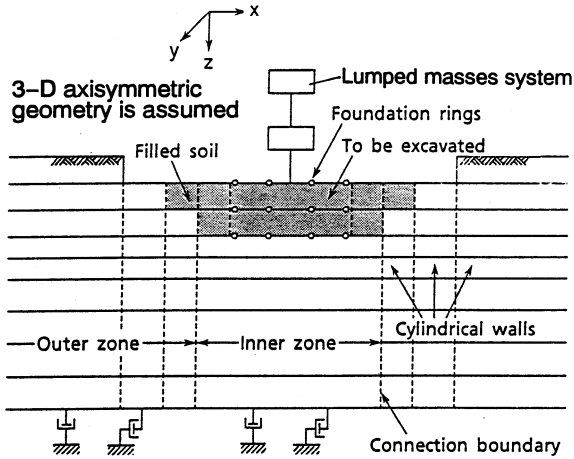


Fig.1 A typical model idealized for the ring exciting thin layer method

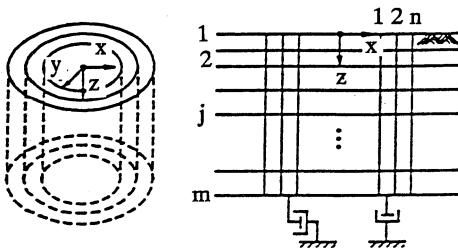


Fig.2 Structure of multiple cylindrical walls model

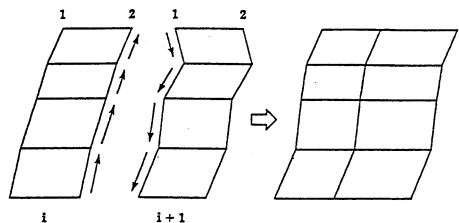


Fig.3 Connection of i-th and (i+1)th cylindrical walls

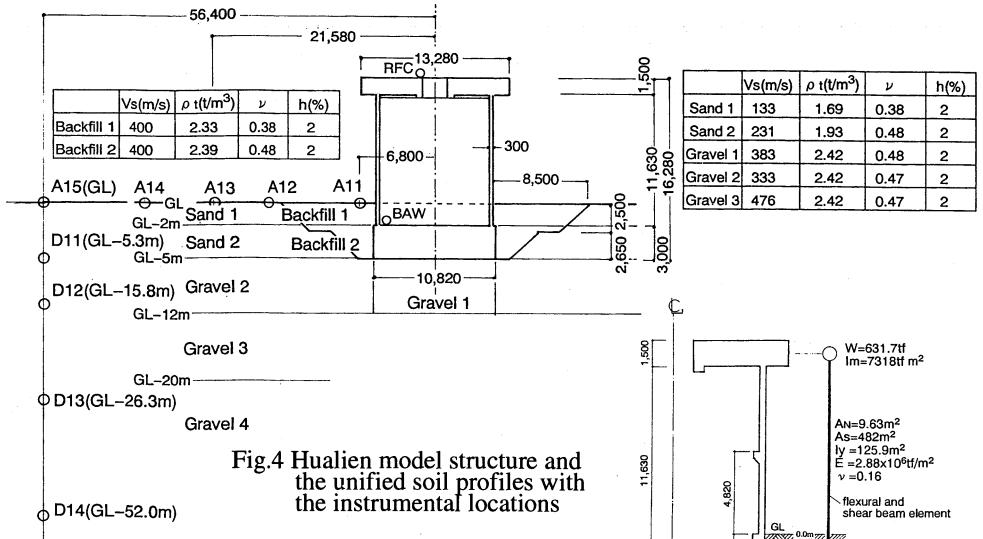


Fig. 4 Hualien model structure and the unified soil profiles with the instrumental locations

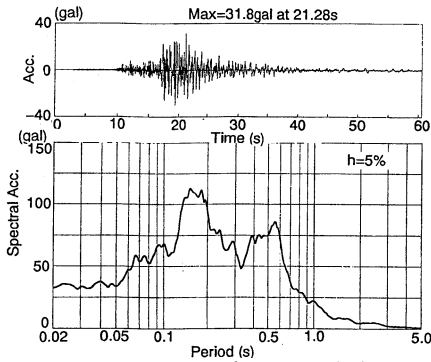


Fig. 5 Control motion at A15 given for blind analysis (L-component)

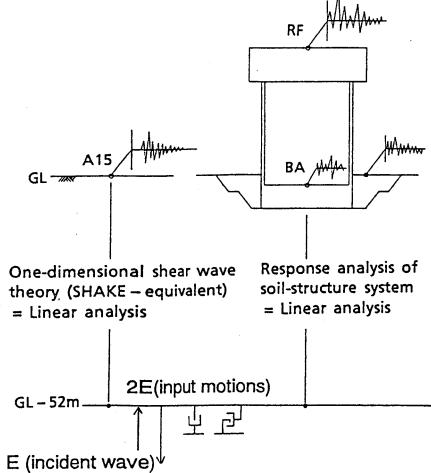


Fig. 6 Analysis procedure

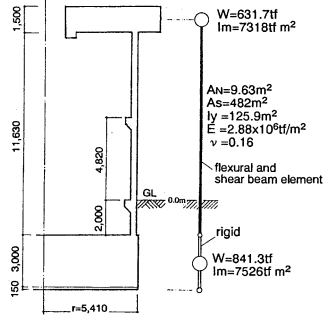


Fig. 7 Idealization of structure

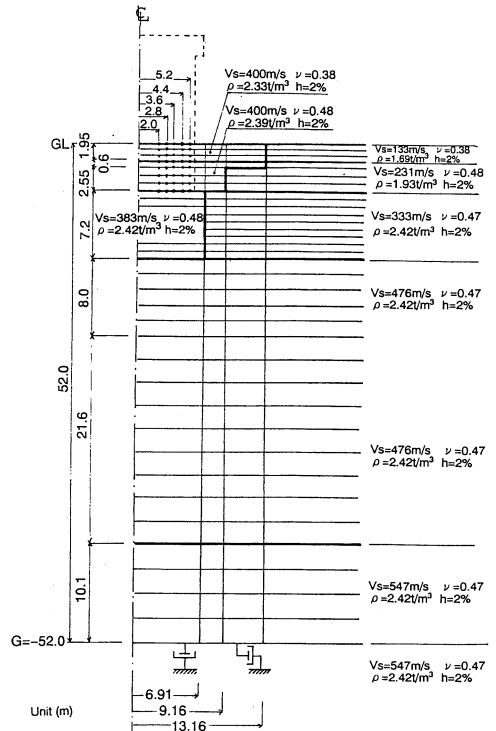


Fig. 8 Mathematical model of the soils under the unified soil conditions

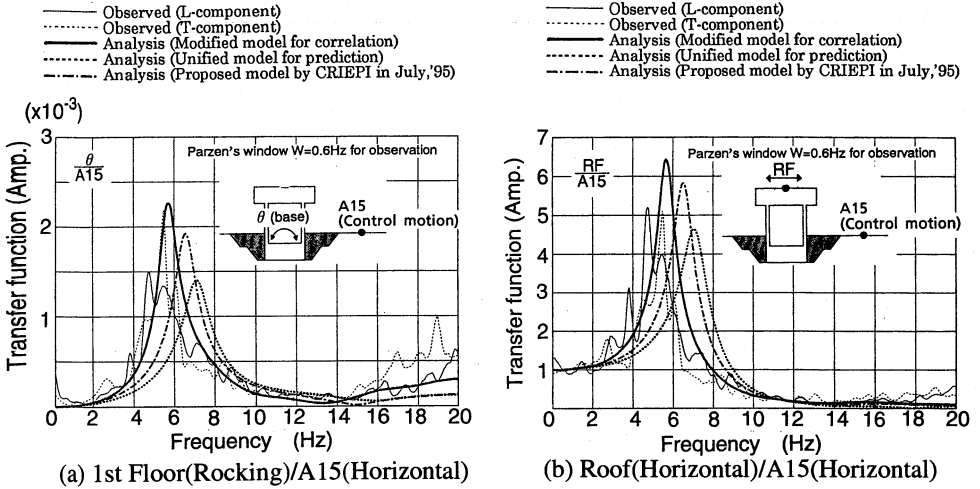


Fig.9 Computed and observed transfer functions of amplitudes from the control motion to rocking motion at 1st floor and horizontal motion at roof

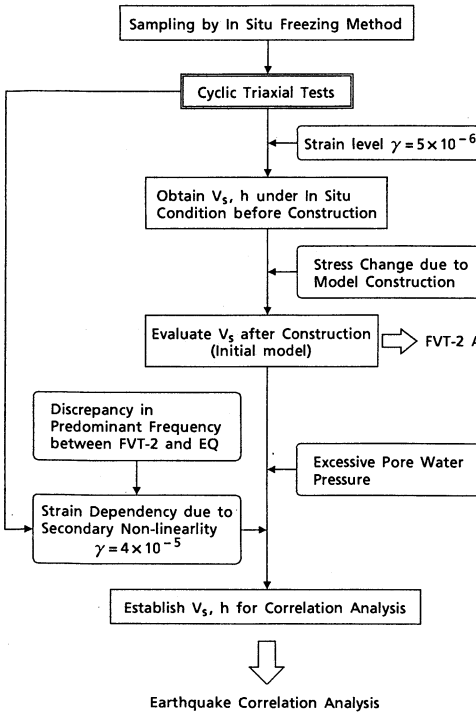


Fig.10 Flowchart of soil model modification for correlation

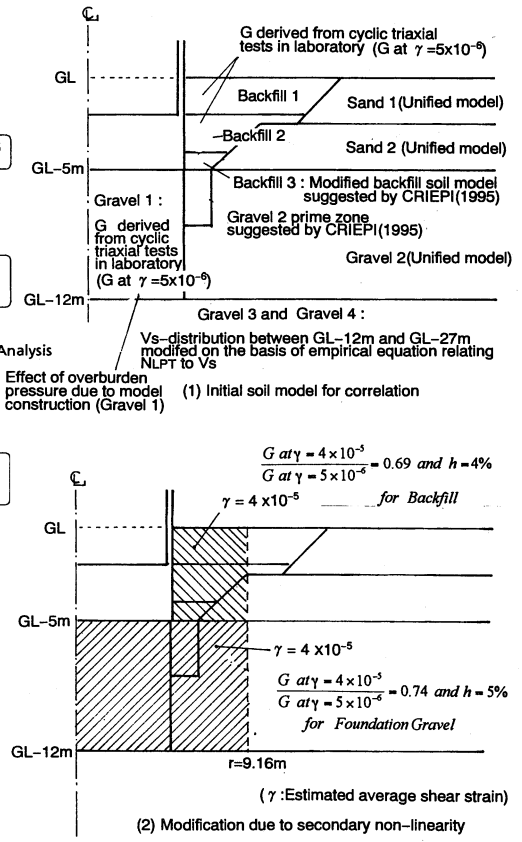


Fig.11 Establishment process of soil model for correlation

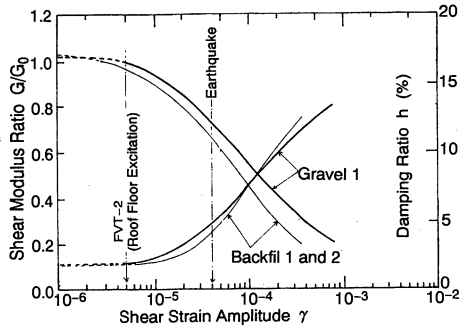


Fig.12 G- γ and h- γ characteristics of Gravel 1 and Backfill

Structural stiffness
 $E = 2.88 \times 10^9 \times \eta = 2.448 \times 10^9 (\text{tf/m}^2)$
 (Reduction factor $\eta = 0.85$; Sugawara et al. 1995)

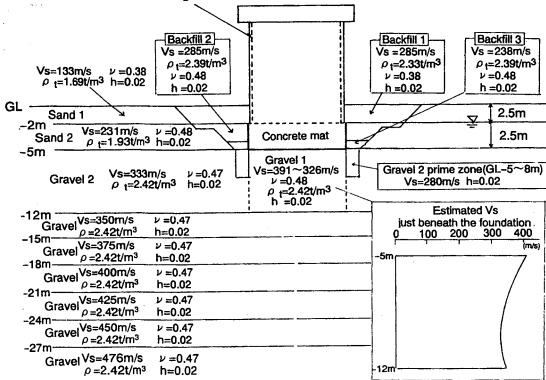


Fig.14 Complete soil model modified for correlation analysis of FVT-2

Table 1 Evaluation of soil stiffness from geotechnical investigations

		In-Site Test			Laboratory Test		
		Wave-logging				Large Penetration Test	Cyclic Triaxial Test
		Down hole	Cross hole	Suspension			
Unified Model for Blind	Gravel 1, Gravel 2*	○					
	Gravel 3, Gravel 4	○					
	Backfill	○					
Modified Model by CRIEPI '95	Gravel 1, Gravel 2*			○	○		
	Gravel 3, Gravel 4	○			○		
	Backfill			○	○		
Modified Model for Correlation	Gravel 1, Gravel 2*			○	○		
	Gravel 3, Gravel 4	○			○		
	Backfill				○		

* Gravel 2 prime zone

Table 2 Arrangements of earthquake analysis cases

Analysis model	Soil-structure system		Free field
	Soil model	Structure model	Soil model
(1) Unified model for blind prediction	Unified	Design	Unified
(2) Soil model proposed by CRIEPI '95	Proposed by CRIEPI '95	Design	Unified
(3) Modified model for correlation	Modified for correlation	Modified after Sugawara et al	Modified in FVT-analysis

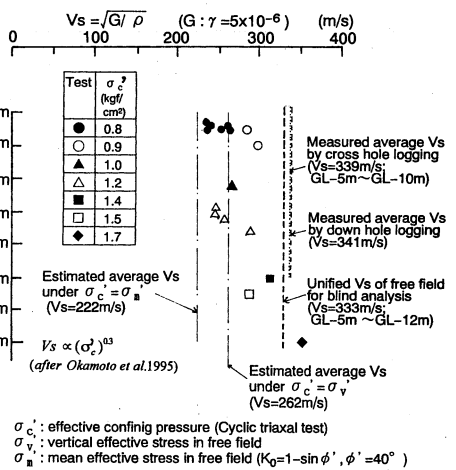


Fig.13 Shear wave velocity of Gravel 1 obtained from dynamic triaxial test, compared with PS-loggings

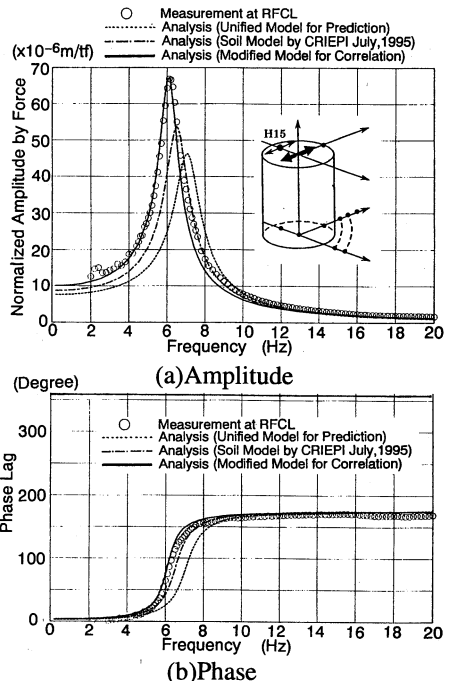


Fig.15 Computed and measured frequency responses for FVT-2 (RF-NS)

Table 3 Computed and observed peak acc. at roof during the earthquake

	L(NS)-comp.	T(EW)-comp.
Observed	67.3	78.1
Unified model for Prediction	81.1	105.8
Modified model by CRIEPI '95	80.0	93.2
Modified model for Correlation	67.5	78.1

(Unit : gal)