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ANALYSIS OF SOIL-STRUCTURE INTERACTION OF A MODEL STRUCTURE ON STIFF SOIL IN HUALIEN, TAIWAN

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ABSTRACT

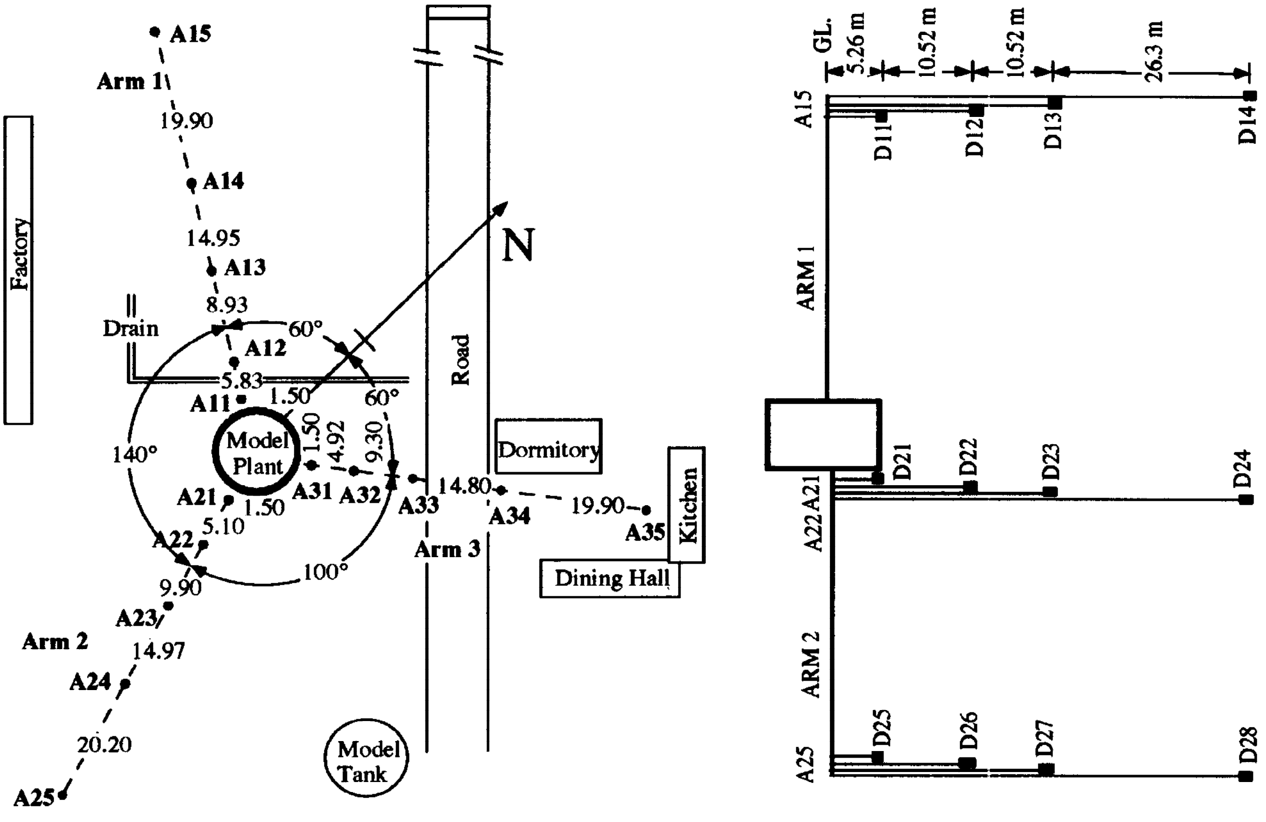
This paper presents results from forced vibration tests, microtremor observations and earthquake response analysis of a containment model constructed on stiff soil in Hualien, Taiwan. Soil stiffness degradation during earthquakes is observed and analyzed. The dynamic behavior of the soil-structure system is simulated successfully with two numerical models: a sway-rocking model, whose soil parameters were evaluated on the basis of the Continuum Formulation Method and a Finite Element model, using the program SASSI with the flexible volume substructuring approach. An empirical relation between the peak ground velocity of different earthquakes and the soil stiffness coefficients of the sway-rocking model is derived. A comparison with results of a previous study, involving a rigid tower on soft soil site in Chiba, Japan is offered.

KEYWORDS

Soil-structure interaction; Microtremor; Forced Vibration Test; Continuum Formulation Method; Finite Element Method.

INTRODUCTION

For observation of soil-structure interaction effects, a 1/4 scale nuclear reactor containment model has been constructed in Hualien, Taiwan in an active seismic zone on stiff soil (Tang *et al.*, 1991). The Hualien Large-Scale Seismic Test is an internationally sponsored project, developed as a continuation of the Lotung Large-Scale Seismic Experiment, which has been carried out on a soft soil site (EPRI, 1987). The properties of the soil around and beneath the structure have been systematically investigated by in-situ tests which comprise borings, large penetration tests and PS-loggings and laboratory tests which include triaxial tests on frozen undisturbed samples (Kokusho *et al.*, 1993). Based on the geotechnical investigation, the Central Research Institute of Electric Power Industry, Japan, created a soil model of the foundation ground. This model was named "unified ground model" (Kokusho *et al.*, 1994). Part of the present study is based on it. Two forced vibration tests have been conducted on the Hualien model: in October, 1992 before backfill (FVT-1) and in February, 1993 after backfill (FVT-2). In October 1994, the present authors conducted a series of microtremor observations of the structure and the surrounding soil using eight velocity-type pickups simultaneously. Figure 1 shows the locations of the surface and downhole accelerometers at the experiment site. Ganev *et al.*, (1995b) determined the orientation errors of the free field accelerometers on the basis of earthquake data by means of the maximum cross-correlation method (Yamazaki *et al.*, 1992). Previous researchers (Morisita *et al.*, 1993; Tanaka *et al.*, 1994) have established that



a) Plan of the site

b)Vertical cross-section of the site

Fig. 1. Locations of the accelerometers at the experiment site (all dimensions in m)

the soil conditions under the model structure are inhomogeneous and non-isotropic and therefore, analysis can be conducted more conveniently in the directions of the principal axes. They are designated D1 and D2. D1 is located 61 degrees counterclockwise from the North. Basic information about the earthquake events used in this study is presented in Table 1.

Table 1. Earthquake events used in the analysis.

Event	Date mm/dd/yy	Location of Epicenter deg/min/sec		Magni-tude	Peak ground accelera-tion cm/s/s	Peak accelera-tion at the roof cm/s/s	Peak ground accelera-tion cm/s/s	Peak accelera-tion at the roof cm/s/s
		Latitude	Longitude		D1	D1	D2	D2
940120	01/20/94	24°03'36"N	121°51'00"E	5.6	36.65	79.47	26.56	55.09
940530	05/30/94	24°05'40"N	121°34'20"E	4.5	32.16	28.90	19.54	33.59
940605	06/05/94	24°27'60"N	121°50'40"E	6.2	24.52	61.77	28.11	52.39
950501	05/01/95	24°02'42"N	121°39'06"E	4.9	66.42	84.63	99.76	165.24
950502	05/02/95	24°00'44"N	121°38'24"E	4.6	38.56	72.72	58.43	64.46

of forced vibration tests to evaluate system characteristics. Compared with the forced vibration tests, the microtremor observation is easy and inexpensive to perform. Also, from a theoretical point of view, microtremor is closer to earthquake excitation than FVT, and permits the same type of analysis. Figure 3 shows Fourier spectrum ratios between the free field and the top of the structure, evaluated from earthquake records in the D2 direction. The predominant frequency of the system shifts from about 6.0 Hz for Event 940530 through 5.7 Hz for Event 940120 to 5.34 Hz for Event 950501. A similar phenomenon was observed previously by Ganev *et al.*, (1995a) at a structure, built on soft soil. The reason for the shift of the predominant frequency is weakening of the soil support during earthquakes. This phenomenon usually can be explained with three factors: soil nonlinearity, separation of soil from the structure and pore water pressure buildup. At this point, no clear evidence of separation or pore water pressure buildup has been obtained. Most probably, the soil stiffness degradation under dynamic loads is due to highly nonlinear behavior as a result of local stress concentration at the contact with the foundation.

MODELING OF THE SOIL-STRUCTURE SYSTEM

Analysis of the structural response to FVT-2 was used as a starting point to establish suitable models for numerical simulation. The problem was approached in two different ways as described below.

Sway-Rocking Model

The behavior of the soil-structure system was simulated using a linear sway-rocking model, according to the methodology described by Ganev *et al.*, (1995a). This model represents the soil support by means of a rocking spring coefficient K_R, sway spring coefficient K_H, rocking dashpot coefficient C_R and sway dashpot coefficient C_H. The values of these parameters were determined on the basis of the Continuum Formulation method (CFM), developed by Harada *et al.*, (1981). The soil properties of the unified ground model (Kokusho *et al.*, 1994) were used at the initial stage of this analysis.

Finite Element Model (SASSI)

Alternatively, dynamic analysis was performed with the program SASSI employing the flexible volume substructuring approach. Taking advantage of the symmetry of the structure, a three-dimensional quarter model was used, and slightly different properties of the layer below the foundation were considered for the D1 and D2 directions. A scheme of the Finite Element discretization is shown in Fig. 4. Soil properties used for analysis of FVT-2 and some of the earthquakes in the D2 direction can be seen in Table 2. The backfills were considered softer than those prescribed by the unified model. The properties of the elements of material types 2, 3, 4 and 6 (Fig. 4) reflect results from the latest geotechnical investigations, performed by CRIEPI in October 1994. At the initial stage, the properties of material types 5 and 7 were assumed equal to type 4 in accordance with the assumption for existence of a softer annular region around the foundation walls (Veletsos and Dotson, 1988). Previous analysis of the forced vibration test by Tang and Nakamura (1995), has shown, that this assumption leads to good results in the case of the Hualien model.

RESULTS AND DISCUSSION

Initially, the results of FVT-2, which represent small-strain linear behavior, were successfully simulated with both models. Figure 5 illustrates the good agreement between the recorded response and the two simulations. Subsequently, the models were validated by analyzing earthquake Event 940530, which had caused a very small relative structural response (Table 1) and no pronounced nonlinear effects. The simulation was successful. It should be noted, however, that for the SASSI analysis the backfills were considered to have lower shear wave velocity than for the CFM analysis. The higher accuracy of the Finite Element Method and the new geotechnical investigations at the Hualien site suggest that indeed, the backfills are softer than initially stipulated in the unified ground model. This means, that the Continuum Formulation Method tends to underestimate the soil stiffness.

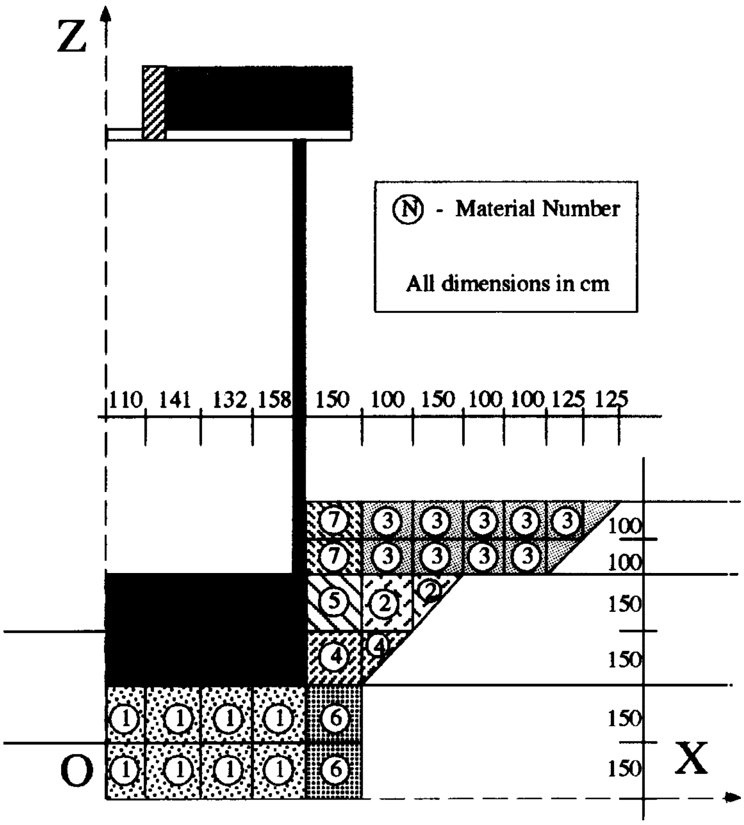


Fig. 4. Discretization of the structure and the backfill into Finite Elements.

Table 2. Soil properties used for dynamic analysis in D2 direction.

			FVT Event 950530		Event 940120		Event 950501	
Material Type	Unit weight g/cm3	Poisson ratio	Shear wave velocity m/s	Damping ratio %	Shear wave velocity m/s	Damping ratio %	Shear wave velocity m/s	Damping ratio %
1	2.42	0.48	250	5	100	5	100	5
2	2.39	0.48	300	2	300	2	300	2
3	2.33	0.38	300	2	300	2	300	2
4	2.39	0.48	225	2	225	2	200	4
5	2.42	0.48	225	2	225	2	200	4
6	2.42	0.48	225	2	225	2	200	4
7	2.33	0.38	225	2	100	2	100	4

In order to simulate properly the response of the soil-structure system during larger earthquakes, account had to be taken of the weakening of the soil support. In each case, the properties of the backfill zone were parametrically varied and identified by comparison of recorded and calculated structural response.

Modification of the Parameters of the Sway-Rocking Model

The soil coefficients of the sway-rocking model were adjusted to fit the recorded response by a trial and error

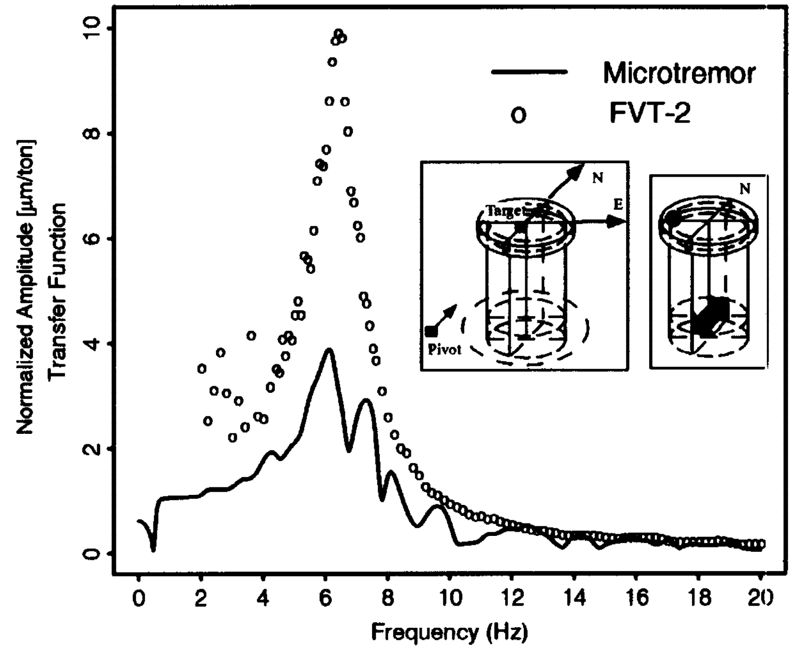


Fig. 2. Formal comparison of microtremor with FVT-2.

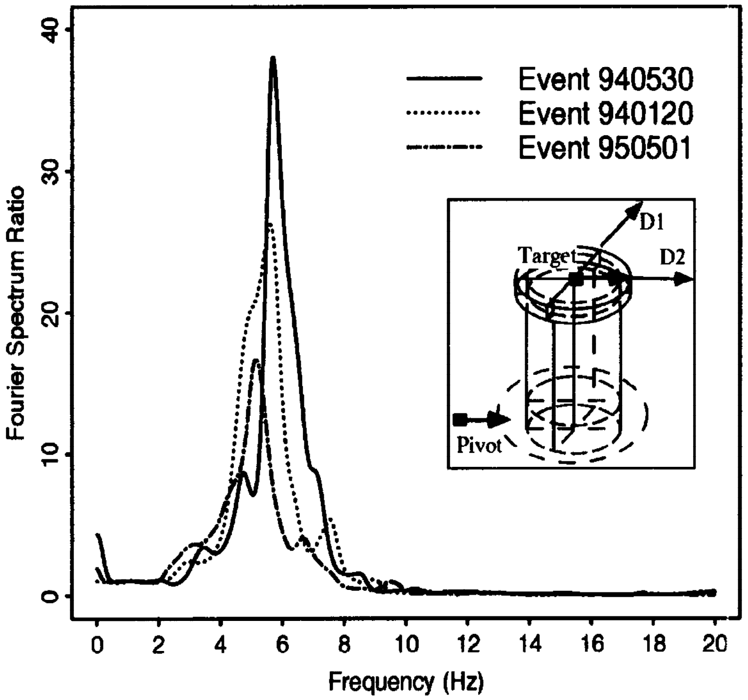


Fig. 3. Fourier Spectrum ratios between the free field and the top of the structure.

SOIL-STRUCTURE INTERACTION EFFECTS

Figure 2 presents a formal comparison between the results of FVT-2 and a transfer function, evaluated from microtremor. The NS-direction is used for this illustration, because the microtremor observations in the North-South and East-West directions were carried out at different times and rotation to the principal axes would not be completely accurate. The predominant frequency of the system is identified as 6.4 Hz from FVT and 6.3 Hz from microtremor. This good agreement shows, that microtremor observation can be used successfully instead procedure, developed by Ganev *et al.*, (1995a). The best-fit values of the soil stiffness coefficients for all the analyzed earthquake records are plotted against the peak ground velocity in Fig. 6. This empiric relation is similar to the one, derived by Ganev *et al.*, (1995a) using data from a model structure built on a soft soil site in Chiba, Japan. It should be pointed out, however, that in the case of the Chiba tower, larger earthquake records were available and separation of structure from the soil was detected. As no separation has been proven in the Hualien case, it follows, that the mechanism of soil support degradation is different. The values encircled in Fig. 6 and denoted with K^*_R and K^*_H are from Event 950502. The size of this earthquake is commensurate with the moderate Events 940120 and 940605, but it occurred within a day after the larger Event 950501 (Table 1). From Fig. 6 it can be seen, that the soil stiffness during Event 950502 was much smaller compared to the one during the other similar events. Actually, the values of the stiffness coefficients are closer to those of the preceding stronger earthquake. This signifies, that the soil support remained weakened for some time after the occurrence of Event 950501. As no newer data are available, at present it can not be concluded whether the soil stiffness has been restored with time. The same phenomenon was observed by Ganev *et al.*, (1995a) at the soft soil site in Japan. In that case, the analyzed data showed that the degradation of the soil stiffness was, in general, reversed.

Modification of the Parameters of the Finite Element Model

Monitoring the alteration of the springs of the sway-rocking model gives a general idea of the decreasing of the soil stiffness. At the same time, the analysis with SASSI enables a more precise assessment with regard to which particular backfill region undergoes changes during earthquakes. Compared to the model used for small strain level, the model which fits best the response of the moderate Event 940120 has softer elements of type 1 and type 7 (Fig. 4), which are in zones, where the local stress concentration is likely to be the highest, considering the rocking motion. For the larger Event 950501 the stiffness of the whole annular region decreases (Table 2). This supports the supposition that the soil stiffness degradation is caused by local nonlinear effects.

A good agreement between numerical analysis and recorded response was achieved for all the studied earthquakes. An example of the simulation of the D2 component of Event 950501 is presented in Fig. 7. It compares the recorded and calculated Fourier spectrum ratios between the free field and the top of the structure. The simulation with sway-rocking model appears to agree better with the observed response than the SASSI simulation. The reason for this is that due to computation time and data storage limitations the frequency step of the SASSI analysis had to be chosen much larger that the one of the CFM analysis.

CONCLUSIONS

The dynamic behavior of a nuclear reactor containment model in Hualien, Taiwan was investigated, using data from forced vibration tests (FVT), microtremor observations and earthquake records. It was demonstrated, that microtremor observations can be a good alternative to forced vibration tests in the small strain range.

A shift of the predominant frequency of the soil-structure system during earthquakes was observed. This phenomenon signifies degradation of the soil stiffness under large dynamic loads. The response of the containment model to FVT and earthquakes was simulated successfully with a sway-rocking model, whose soil parameters were evaluated on the basis of the Continuum Formulation Method (CFM). An empirical relation between the peak ground velocity of different earthquakes and the soil stiffness coefficients of this model was derived. It was used to demonstrate that the soil support remains weakened for certain time after a large earthquake. A comparison with the results of Ganev *et al.*, (1995a) from analysis of a rigid tower on a soft soil site in Japan shows very similar phenomena. There is, however, some difference in the mechanism of soil stiffness degradation. In the case of the soft soil, separation of soil from structure was detected and proven to be a more influential factor than nonlinearity. The weakening of the soil support, observed at the stiff soil site is attributed to local nonlinear effects.

Dynamic analysis was performed also with the Finite Element Method, using the program SASSI with the flexible volume substructuring approach. This model produced a very good agreement with the recorded response and was used to investigate which zones of the backfill undergo changes during earthquakes.

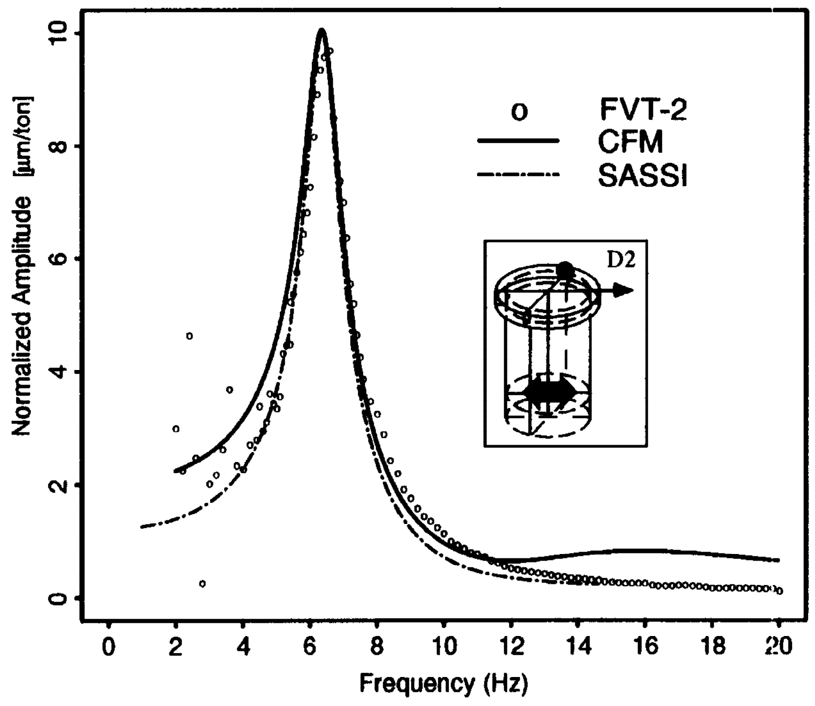


Fig. 5. Simulation of FVT-2 with CFM and SASSI

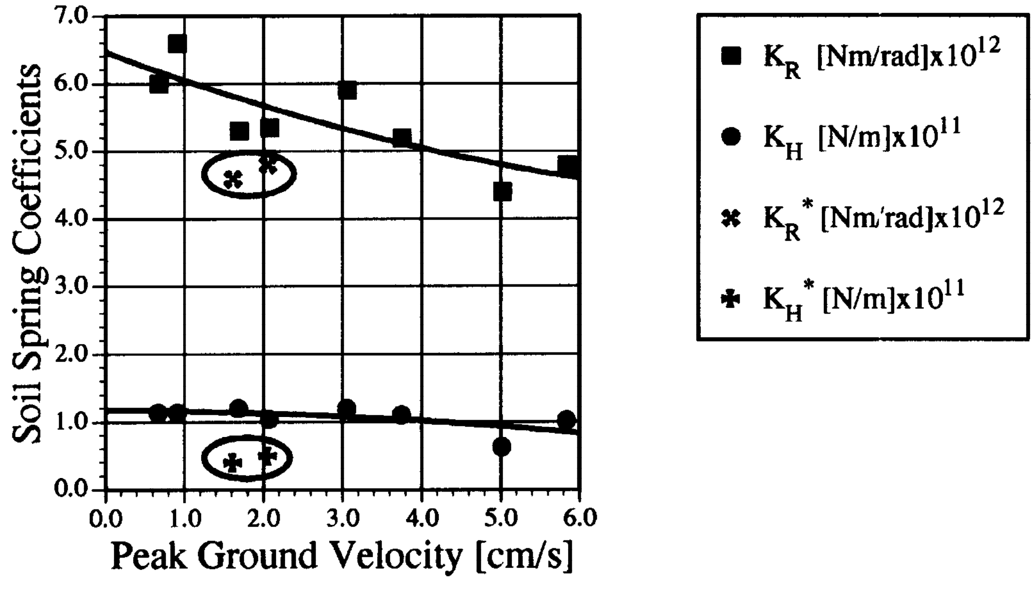


Fig. 6. Empirical relation between the peak ground velocity and the soil stiffness coefficients of the sway-rocking model.

Comparing the backfill properties used to achieve best-fit results with the two numerical models, it was concluded, that the Continuum Formulation Method tends to underestimate the soil stiffness.

REFERENCES

EPRI (1987). *Proceedings: EPRI/NRC/TPC Workshop on Seismic Soil-Structure Interaction Analysis Techniques Using Data from Lotung, Taiwan*, Palo Alto, California.

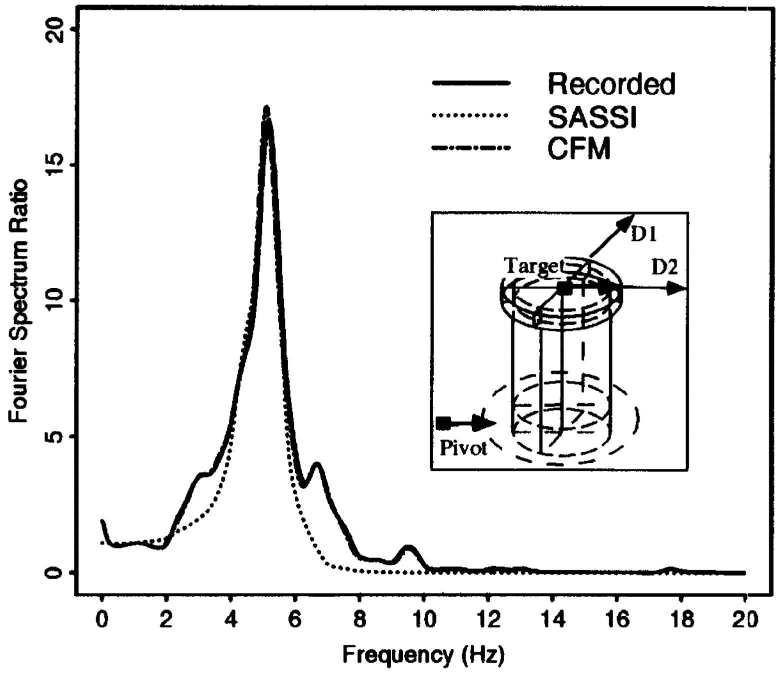


Fig. 7. Simulation of the D2-component of Event 950501 with CFM and SASSI.

Ganev, T., F. Yamazaki, and T. Katayama (1995a). Observation and numerical analysis of soil-structure interaction of a reinforced concrete tower. *Earthquake Engineering and Structural Dynamics* **24**, 491-503.

Ganev, T., F. Yamazaki, T. Katayama and T. Ueshima (1995b). Soil-Structure Interaction of a Containment Model in Hualien, Taiwan. *Proceedings of the Twenty-third JSCE Earthquake Engineering Symposium*, pp. 397-400, Tokyo, Japan.

Harada, T., K. Kubo and T. Katayama (1981). Dynamic soil-structure interaction analysis by Continuum Formulation Method. *Report of the Institute of Industrial Science* **29**, University of Tokyo, Japan.

Kokusho, T., K Nishi, T. Okamoto, T. Kataoka, Y. Tanaka, K. Kudo, H. T. Tang and Y. H. Cheng (1993). Geotechnical investigation in the Hualien Large Scale Seismic Test project. *Transactions of the Twelfth International Conference on Structural Mechanics in Reactor Technology*, Vol. K1, Stuttgart, Germany.

Kokusho, T., K. Kudo, T. Okamoto, Y. Tanaka, T. Kawai, Y. Sawada, H. Yajima and K. Suzuki (1994). Soil-structure interaction research of a large-scale model structure at Hualien, Taiwan (Part 1). *Proceedings of the Ninth Japan Earthquake Engineering Symposium* , Vol. 2, pp. 1369-1374, Tokyo, Japan.

Morisita, H., H. Tanaka, N. Nakamura, T. Kobayashi, S. Kan, H. Yamaya and H. T. Tang (1993). Forced vibration test of the Hualien Large Scale SSI model. *Transactions of the Twelfth International Conference on Structural Mechanics in Reactor Technology*, Vol. K02/1, pp. 37-42, Stuttgart, Germany.

Tanaka H., T. Sugiyama, T. Kobayashi and H. Yamaya (1994). Forced vibration test of the Hualien Large Scale SSI model (Part 2). *Proceedings of the Ninth Japan Earthquake Engineering Symposium* ,Vol. 2, pp. 1387-1392, Tokyo, Japan. (In Japanese).

Tang, H. T., J. Stepp, Y. Cheng, Y. Yeh, K. Nishi, T. Iwatate, T. Kokusho, H. Morishita, Y. Shirasaka, F. Gantenbein, J. Touret, P. Sollogoub, H. Graves and J. Costello (1991). The Hualien Large-Scale Seismic Test for soil-structure interaction research. *Transactions of the Eleventh International Conference on Structural Mechanics in Reactor Technology*, Vol. K, pp. 69-74, Tokyo, Japan.

Tang, H. T. and N. Nakamura (1995). Analysis of the forced vibration test of the Hualien Large Scale Soil-Structure Interaction model using a Flexible Volume Substructuring Method. *Proceedings of the Third JSME/ASME Joint International Conference on Nuclear Engineering, (ICONE-3)*, Vol. 4, pp. 2053-2058, Kyoto, Japan.

Veletsos, A. and K. Dotson (1988). Horisontal impedances for radially inhomogeneous viscoelastic soil layers. *Earthquake Engineering and Structural Dynamics*, **16**, 947-966.

Yamazaki, F., L. Lu and T. Katayama (1992). Orientation error estimation of buried seismographs in array observation. *Earthquake Engineering and Structural Dynamics*, **21**, 679-694.