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Soil-structure interaction analysis of Hualien LSST model in wide strain range

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ABSTRACT

This paper presents results from forced vibration tests, microtremor observations and earthquake response analysis of a nuclear reactor containment model constructed on stiff soil in Hualien, Taiwan. The dynamic behavior of the soil-structure system is simulated successfully with two numerical models. The dependencies of the soil parameters of both models on the amplitudes of the different dynamic excitations are investigated in detail. An original numerical simulation of microtremor is performed.

INTRODUCTION

The Hualien Large-Scale Seismic Test is an international project on dynamic soil-structure interaction. It is sponsored by a consortium of industrial and research enterprises from five countries (Japan, USA, Taiwan, France and Korea). The project has been initiated as a continuation of the Lotung Large-Scale Seismic Experiment [1]. Both test programs have involved construction of nuclear power plant containment models and monitoring of their earthquake response in conjunction with the surrounding soil. Whereas the Lotung Experiment has been carried out on soft soil, the Hualien Model has been constructed on stiff soil following the need to confirm and expand the findings of the previous program [2]. Hualien is located south of Lotung on the east coast of Taiwan, in a highly active seismic zone near the Philippine Sea Plate boundary.

This paper presents results from forced vibration tests, microtremor observations and earthquake response analysis of the Hualien Model. Soil-structure effects are identified from the recorded data and the dynamic behavior of the soil-structure system is simulated with two numerical models. The case study of numerical analysis of microtremor, which is included in this paper, is a step towards a methodology for accurate computation of system functions on the basis of microtremor data.

DESCRIPTION OF THE MODEL AND THE EXPERIMENTAL DATA

The test structure [3] represents a one-fourth scale model of a nuclear power plant containment. Accelerometers are installed at all points of interest on the structure and in a three-dimensional array in the surrounding soil [4].

Based on comprehensive geotechnical investigations, the Central Research Institute of Electric Power Industry (CRIEPI), Japan, created a "unified model" of the soil around the foundation [5], [6]. Subsequently, some of the soil properties were revised, following new tests and a "modified ground model" was suggested. Both models are presented in Fig. 1.

Two forced vibration tests have been conducted on the Hualien model: before backfill (FVT-1) and after backfill (FVT-2). In October 1994, the present authors conducted a series of microtremor observations of the structure and the surrounding soil.

The soil conditions in the vicinity of the foundation are anisotropic. Analysis is best conducted in the directions of the principal axes, which have been designated D1 and D2 [7], [8].

Data from five earthquakes recorded at the Hualien site are used in this study (Table 1).

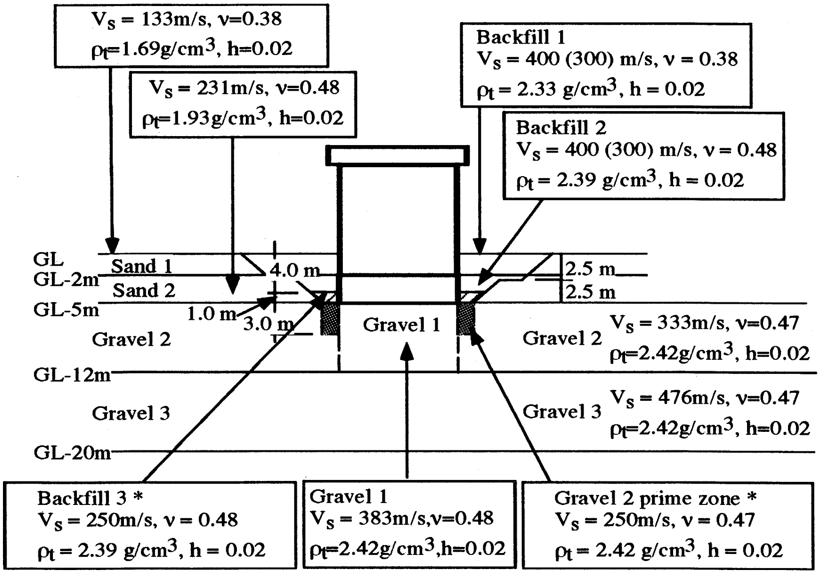
IDENTIFICATION OF SYSTEM CHARACTERISTICS AND BEHAVIOR

Figure 2 presents a formal comparison between the results of FVT-2 and analysis of microtremor. 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 of forced vibration tests to evaluate system characteristics.

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 5.3 Hz for Event 950501. A similar decrease of predominant frequency as ground motion becomes stronger, was observed previously by Ganev et al. [9] at a structure, built on soft soil. The reason for this effect is weakening of the soil support during earthquakes as discussed further on.

SIMULATION OF DYNAMIC RESPONSE IN THE SMALL STRAIN RANGE

The behavior of the soil-structure system was simulated using the linear sway-rocking model



Notes:

Values in parentheses are those of the Modified Ground Model

Zones designated by * have been introduced in the Modified Ground Model

Fig. 1. The unified and modified ground models by CRIEPI

Table 1. Earthquake events and peak response accelerations

Event	D1			D2		
	Ground	Basement	Roof	Ground	Basement	Roof
940120	36.65	30.22	79.47	26.56	24.93	55.09
940530	32.16	11.43	28.90	19.54	12.32	33.59
940605	24.52	24.58	61.77	28.11	22.66	52.39
950501	66.42	55.83	84.63	99.76	72.76	165.24
950502	38.56	26.12	72.72	58.43	22.74	64.46

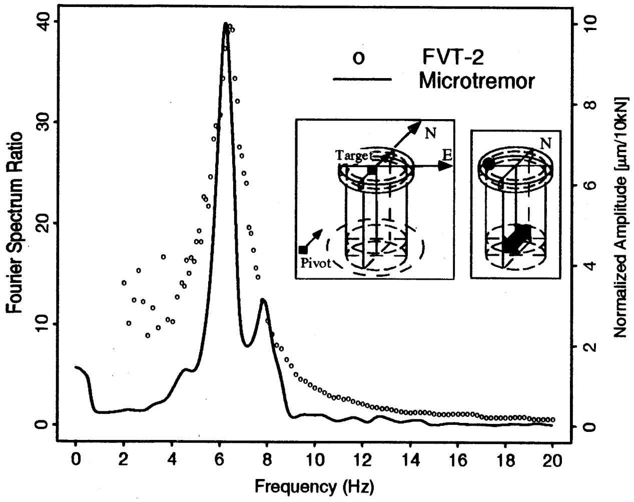


Fig. 2. Formal comparison between FVT-2 and microtremor

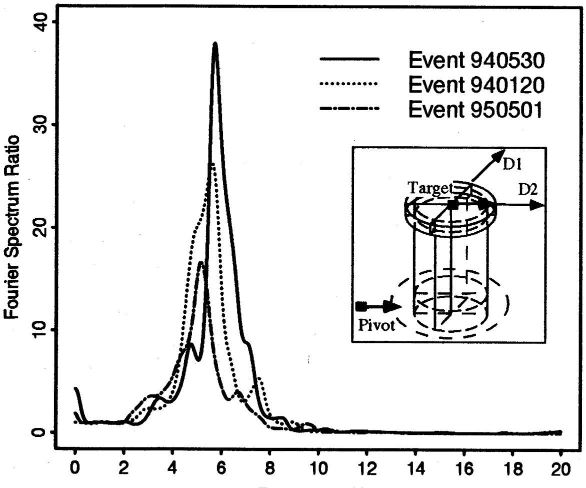


Fig. 3. Fourier spectrum ratios between the free field and the top of the structure

shown in Fig. 4. The values of the soil springs and dashpots were determined on the basis of the Continuum Formulation Method (CFM), developed by Harada et al. [10].

Alternatively, dynamic analysis was performed with the program SASSI employing the flexible volume substructuring approach [11] (Fig.5). A softer annular region in the vicinity of the foundation was assumed, according to the proposition in Reference [12].

Initially, the results of FVT-2, which represent small-strain linear behavior, were simulated with both numerical models. A very good agreement was produced by the analysis with SASSI, based on the modified ground model (Fig. 6). However, in the case of the CFM simulation, better results were obtained using the soil properties of the unified model. As it can be seen in Fig. 1, the shear wave velocity and accordingly the stiffness of the backfills in the unified ground model are higher than those of the more reliable modified model and apparently exceed the actual values. The fact, that the sway-rocking model utilized such a disparity to yield a good agreement, signifies that the Continuum Formulation Method tends to underestimate the soil stiffness.

The reasons for this tendency are in the theoretical basis of the method. The soil reaction acting upon the side walls of the foundation is evaluated first for an unit thickness of the soil and then for the whole embedment depth [10]. This is equivalent to assuming a plane strain state along the vertical axis, which, when rocking is addressed, leads to neglecting of some of the shear resistance of the soil.

Following the successful simulation of FVT-2, both numerical models were validated by analyzing earthquake Event 940530, which had caused a very small relative structural response (c.f. Table 1) and no pronounced nonlinear effects.

As it was already shown, observation of ambient vibrations is an inexpensive and accurate alternative to forced vibration tests for identification of predominant system frequencies. It would be very practical to develop a methodology for accurate computation of system functions on the basis of microtremor data. In an attempt to provide an useful case study for this purpose, dynamic analysis of the soil-structure system was performed with SASSI, using the microtremor record of the ground surface as control motion. A simplifying assumption that the excitation comes from a single source was employed. The model validated by FVT-2 was used.

When evaluating the free field response with SASSI, the user is given an opportunity to exercise own judgment in defining the seismic environment [11]. Microtremors consist to a larger extent of surface waves, and the amplitude of the simulated response was found to be dependent exclusively on the ratio of participation of the Rayleigh waves. The value of this parameter was determined by trial and error in comparison of calculated and recorded microtremors at the top of the structure. It varied within a range of 10-15% for different records. Figure 7 presents a comparison between recorded and calculated microtremor at the top of the structure in the NS direction. The Rayleigh wave participation ratio in this case is 39%.

SIMULATION OF DYNAMIC RESPONSE TO LARGER EARTHQUAKES

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. Good agreement was achieved with both models for all the studied earthquakes as exemplified in Fig. 8.

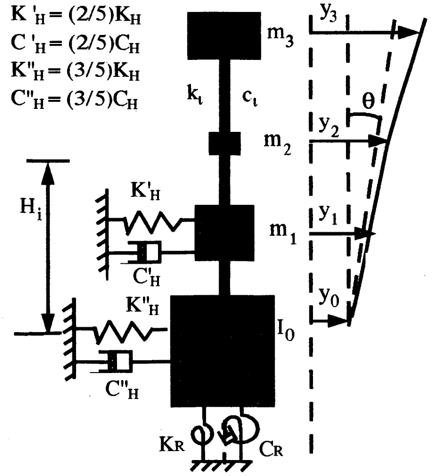


Fig. 4. Sway-rocking model (Continuum Formulation Method)

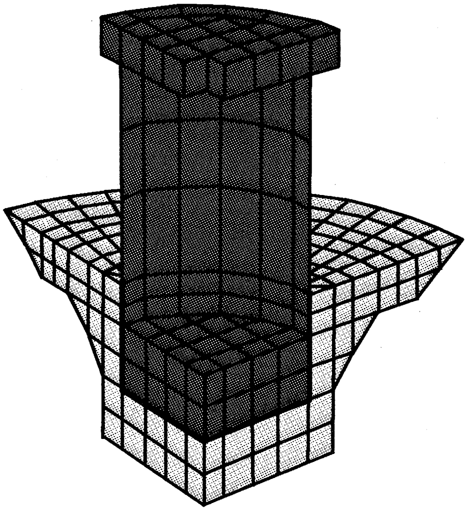


Fig. 5. Three dimensional quarter model (SASSI)

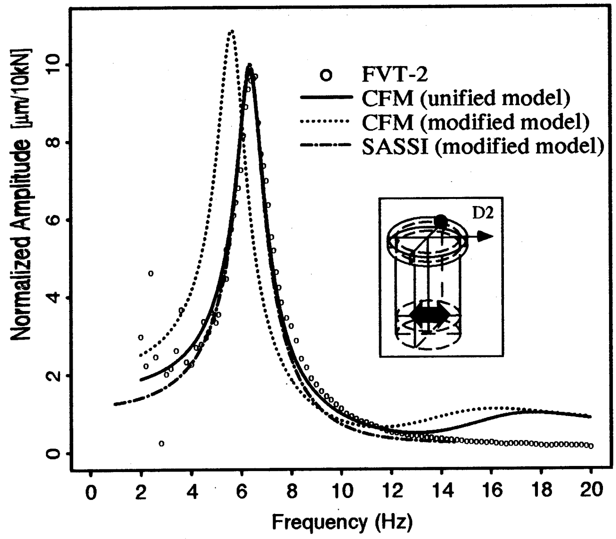


Fig. 6. Simulation of FVT-2 with CFM and SASSI

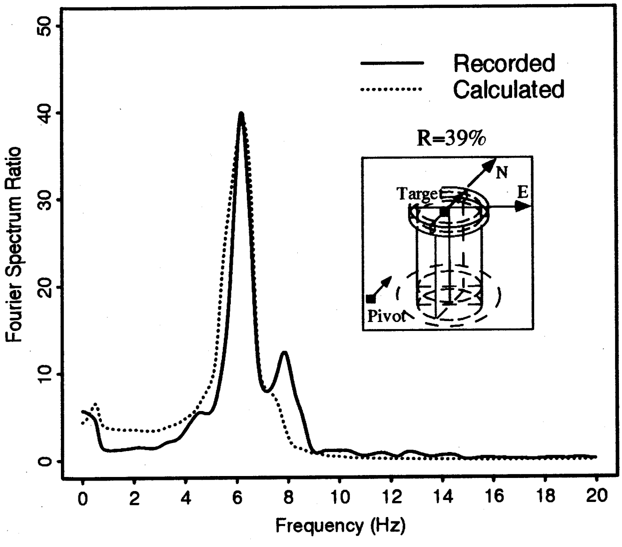


Fig. 7. Simulation of microtremor with SASSI

The soil parameters of the sway-rocking model were adjusted to fit the recorded response by a trial and error procedure, developed by Ganev et al. [9]. Best-fit values of the soil stiffness and dashpot coefficients for all analyzed cases are plotted against the peak ground velocity in Fig. 9. A general decreasing of the soil stiffness with increasing of the peak ground velocity is evident. The rocking damping coefficient exhibits a general increase in accordance with the existing theory. No conclusive explanation can be offered at this time for the decreasing of the sway dashpot coefficient.

The values denoted with superscript (*) in Fig. 9 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 (c.f. Table 1). It can be observed, that the best-fit values for Event 950502 are closer to those of the preceding stronger earthquake rather than to those of the other similar events. Apparently the soil stiffness remained weakened for some time after the occurrence of Event 950501.

Monitoring the alteration of the springs of the sway-rocking model gave a general idea of the decreasing of the soil stiffness. At the same time, the analysis with SASSI enabled a more precise identification of best-fit values of the shear wave velocity (respectively shear modulus) and the damping ratio of each soil region. The maximum shear strains in the near-field soil from the ground surface to a depth of 1.0 m were evaluated for the horizontal components of all the analyzed earthquakes. Empirical relations of the strain and the stiffness and damping of the backfill were then constructed. For comparison, the nonlinear elastic behavior of the same region was evaluated also analytically using the Ramberg-Osgood model [13]. A comparison is offered in Fig. 10. A disagreement can be observed, particularly at strains larger

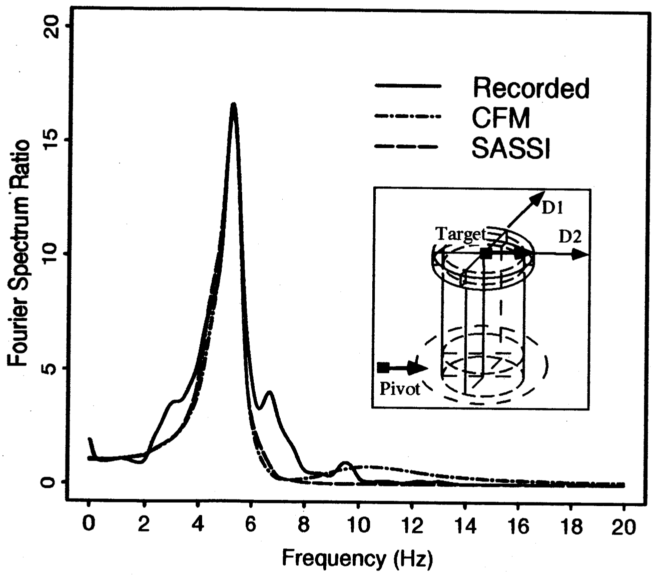


Fig. 8. Earthquake response analysis
(Event 940605, D2-direction)

than 4×10^{-4}. It is obvious that the dynamic behavior of the soil support in this case can not be described adequately with the nonlinear elastic theory. Neither pore water pressure buildup nor separation of soil from the structure were detected, although relevant analysis was performed. Therefore, it is logical to blame the soil stiffness degradation on local nonlinear effects, which are typically difficult to incorporate in a numerical model. Such rationalization is concurrent with the results of Tatsuoka et al. [14], who have shown experimentally that well-graded gravel can be brittle under dynamic loading and local deformations can decrease its stiffness by up to 70%.

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. 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 weakening of the soil stiffness, at this stiff soil site is attributed to local nonlinear effects, differently from what has been previously observed by the same authors at a soft soil site [9].

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). Empirical relations between the peak ground velocity of different earthquakes and the soil stiffness and damping coefficients of this model were derived. They were used to demonstrate that the soil stiffness remained weakened for certain time after a large earthquake. 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. Using best-fit parameters of the supporting soil, identified in the analysis, empirical relations of the shear modulus reduction and damping ratio with the shear strain were constructed. Comparison with the theoretical curves evaluated on the basis of the Ramberg-Osgood model showed that the nonlinear elastic theory could not describe adequately the dynamic soil behavior in this case.

It was demonstrated that microtremor observations can be a good alternative to forced vibration tests in the small strain range. An original numerical simulation of microtremors was performed. The participation ratio of Rayleigh waves in the ambient vibrations was determined by a parametric study.

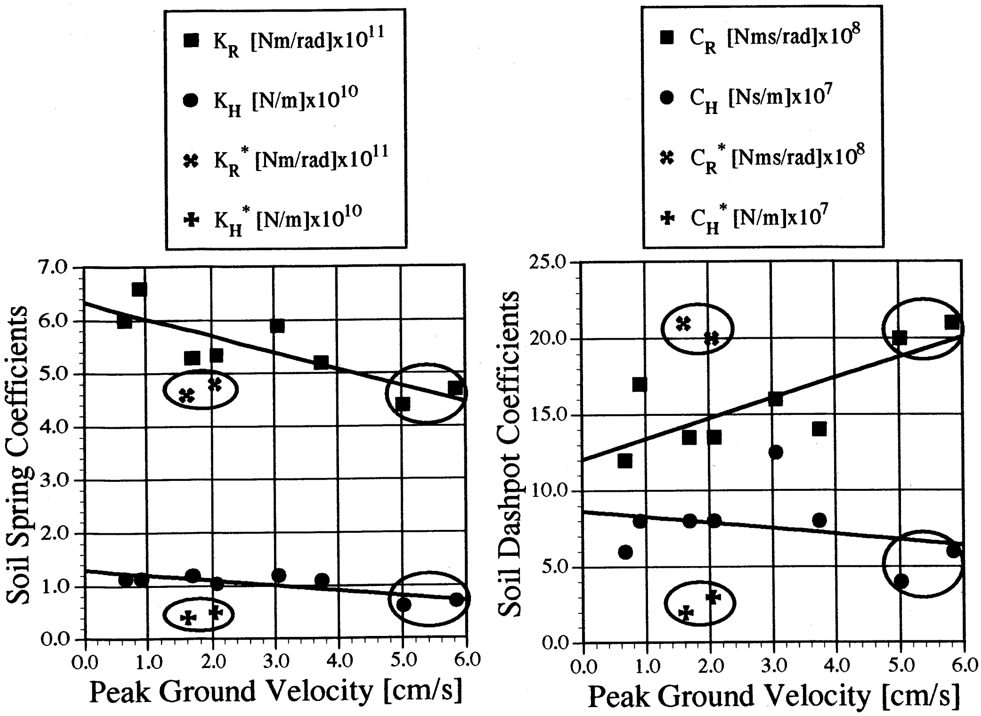


Fig. 9. Empirical relations between the peak ground velocity and the parameters of the sway-rocking model

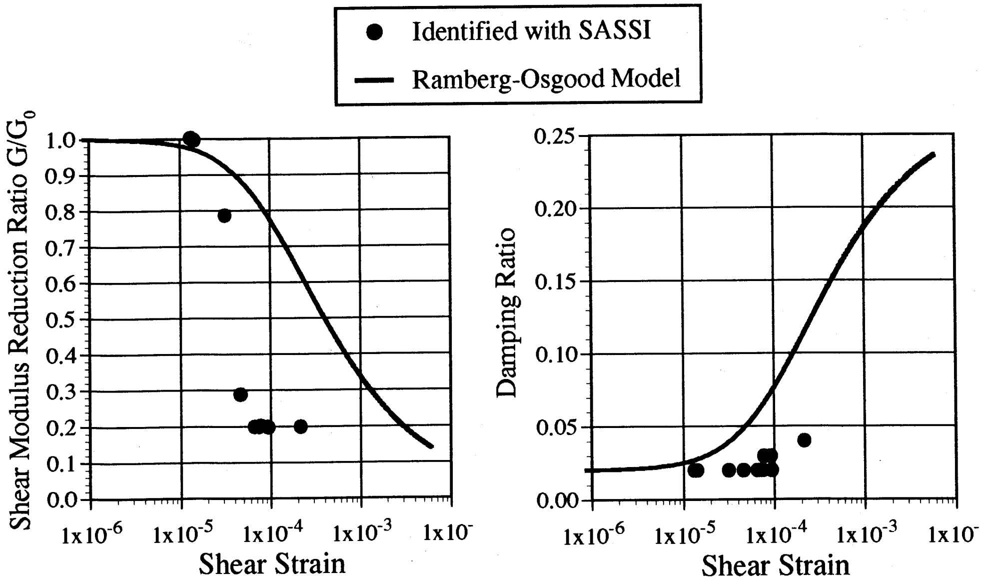


Fig. 10. Nonlinear behavior of the backfill region

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. The reasons for this tendency are in the theoretical basis of the method and it should be expected upon application of other similar and popular methods of analysis as, for example, the Novak model [15]. This conclusion has an important implication to design and might be of particular interest to the practicing engineers.

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