Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

5-4-9

EXPERIMENTAL VALIDATION OF SOIL-STRUCTURE INTERACTION ANALYSIS

Ikuo KATAYAMA[1], Tsuneo OHSUMI[1], and Yoshiaki TERAMURA[2]

[1]Advanced Engineering Operation Center, Tokyo Electric Power Services Co., Ltd.,
3-1, Uchisaiwai-Cho 1-Chome, Chiyoda-Ku, Tokyo 100, Japan

[2]Trainee at TEPSCO, Tokyo Electric Power Co., Inc.,
1-3, Uchisaiwai-Cho 1-Chome, Chiyoda-Ku, Tokyo 100, Japan

SUMMARY

We verified the three-dimensional dynamic hybrid computer code for soil-structure interaction analysis, HASSI-4, by using a forced vibration test result and earthquake response records obtained at the same model. After getting good fit of the calculated results to the recorded motions, we examined the capability of typical two-dimensional analysis codes using the same recorded motions. These codes not only modulated the characteristic frequency but also resulted in excessive damping, resulting into serious underestimate of the structural response. These facts clearly account for the needs to treat the soil-structure interaction phenomena of three-dimensional structures as three-dimensional.

INTRODUCTION

In the dynamic soil-structure interaction analysis of heavy structures, basically three-dimensional soil-structure interaction problems have been reduced to that of two dimensions. However, the conversion of the problems into two-dimensional problems has usually caused serious modulation of dynamic characteristics of structural systems (Ref. 1). Especially for such vibration system whose fundamental vibration characteristics would be seriously affected by soil compliance, the above conversion has to be based upon some concrete reason.

The authors first tested a newly developed three dimensional dynamic analysis code, HASSI-4, developed by using a hybrid finite element method, through the simulation analyses of the recorded motions obtained in forced vibration test and real earthquake response observations of a small scale concrete structural model. In the next step, some typical two-dimensional dynamic codes were used to simulate the earthquake response records and the results were compared with those previously obtained by three-dimensional code. The discussion follows in regard to the above comparative studies.

OUTLINE OF HASSI-4

We have developed HASSI (Hybrid Analysis Code for Soil-Structure Interaction) since 1982. The features of the HASSI lies in that it provides us with realistic dynamic response of three-dimensional super-structures and near-field soil regions by using frequency domain solution. It provides mathematical boundary conditions to permit radiation of energy away from the foundation of the structure into the half-space through a system identification technique (Ref. 2). The details of the

HASSI-4 is described in Ref. 3. The HASSI-4 permits (1) Linear response analysis of the soil-structure system subject to the prescribed triaxial free-field surface acceleration input motions at the structure and soil interface, (2) Linear time domain response or frequency response analysis of the system subject to simultaneous forced vibration forces prescribed at multiple locations.

SITE INVESTIGATIONS AND SOIL PROPERTIES

As the test site for the vibration test of model structures with 3 m diameter and 10 m height, we selected a 50 mx60 m yard in the bare plain of 2 kmx2 km graded by excavation to the height about 40 m above sea level and the yard is underlain by well cemented mudstone in the depth more than 70 m within the yard, the sufficient depth to form elastic half-space for the model. The aquifer table was 14 m below the surface, where a remarkable contrast in soil impedance between the upper and the lower sand layer existed. The results of in-situ geophysical survey and laboratory tests used for subsequent analyses are shown by the soil classification, S and P wave velocity profile, and distribution of natural unit weight are summarized in Fig. 1. Figs. 2 shows the shear modulus and damping ratio versus shear strain relationships fitted on Hardin-Drnevich type curves, for the upper-most layer in concern.

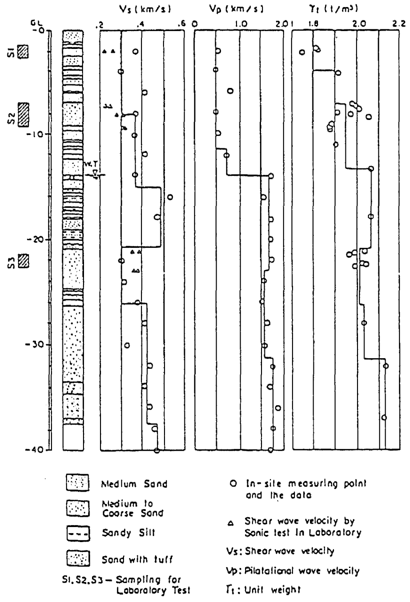


Fig. 1 Summary of soil condition of sub-surface layers

SIMULATION OF FORCED VIBRATION TEST

Test results and numerical model The details of the test performed and the results are given in Ref. 4. The displacement response per unit exciting load was plotted in Fig. 3 for this case of model 2C. The numerical model of the forced vibration test is shown in Fig. 4(a), where far-field interface was chosen at four times the radius of the cylinder. The size of the mesh is effective for the frequency up to 20 Hz.

Simulation results The strain dependent properties of the 1st layer were used for the analysis because of an essential influence of the soil near the surface on the response. The degraded properties of S-wave velocity, 210 m/s (degraded from 300 m/s for small strain) and the corresponding material damping, 6 % of critical damping, the unit weight, 1.8 t/m^3, and the poisson's ratio, 0.211, were estimated and used for HASSI-4. The resultant displacement amplification curves (solid lines) and the experimental data (open circles) are simultaneously plotted in Figs. 4(b) and 4(c), for the observation points, T and B. These figures show a good agreement between the calculated and the observed values in the range higher than the peak frequency. The poor fit in the lower frequency side of the peak was improved as shown by triangles, when the shear modulus and damping ratio were

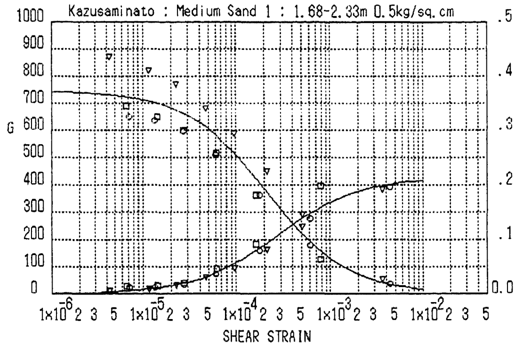
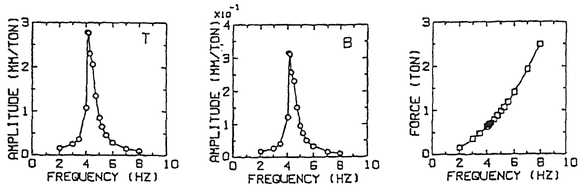
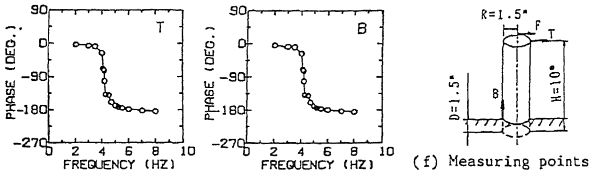


Fig. 2 Shear modulus, damping ratio versus strain relationship

modulated by considering estimated working strain levels at the frequency range.

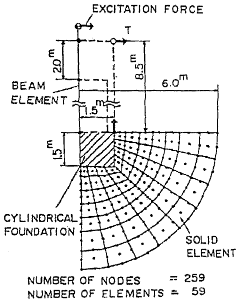


(a) Amplitude at T (b) Amplitude at B (e) Vibration force

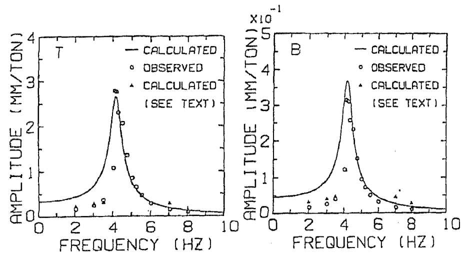


(c) Phase at T (d) Phase at B (f) Measuring points

Fig. 3 Test result of Model 2C



(a) Numerical model



(b) Amplitude at T (c) Amplitude at B

Fig. 4 Results of simulation of Model 2C

SIMULATION OF EARTHQUAKE RESPONSE MOTION OF MODEL 2C

Earthquake response records By using the model 2C, the observation of its response for earthquakes was performed with seismic instrumentation as schematically shown in Fig. 5. The horizontal components of recorded acceleration motions in the small local earthquake occurred just beneath the site on January 17, 1987, are shown in Fig. 6.

Input motions for numerical model The cross correlation analysis of these recorded motions showed that the correlation of each free field ground motion with the structural response was sufficiently small if compared with the cross correlation of each free-field ground motion, and that the spatial variation among free field ground motions was evident. Even if the motions at S1 point only 1.5 m away from the structure, their correlation with the motions at the roof top of the model was very small. Therefore, S1 ground motions were selected as the input motions for simulating the structural response on the same numerical model used for the vibration test case.

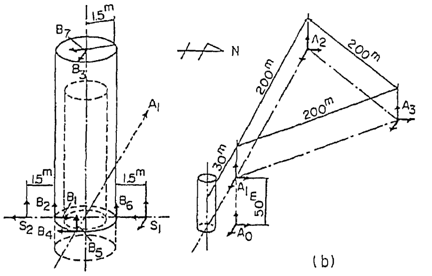


Fig. 5 Seismic instrumentation at Model 2C and seismic array

Computer codes applied First HASSI-4 and later two types of codes, FLUSH-VB and HASSI-2D, were used for simulating the recorded motions of the roof top. The FLUSH-VB is a modified FLUSH code which was attached with viscous dampers at the bottom boundary of near-field soil to incorporate far-field effect, and the HASSI-2D is a two dimensional version of HASSI-4 which was also modified to have far-field impedance expression of plain strain case (Ref. 5).

Material properties used Similarly as mentioned in the forced vibration test case, the strain dependent shear wave velocity and the damping ratio of the soil were assumed respectively as 275 m/s and 0.5 %, based on the estimated maximum

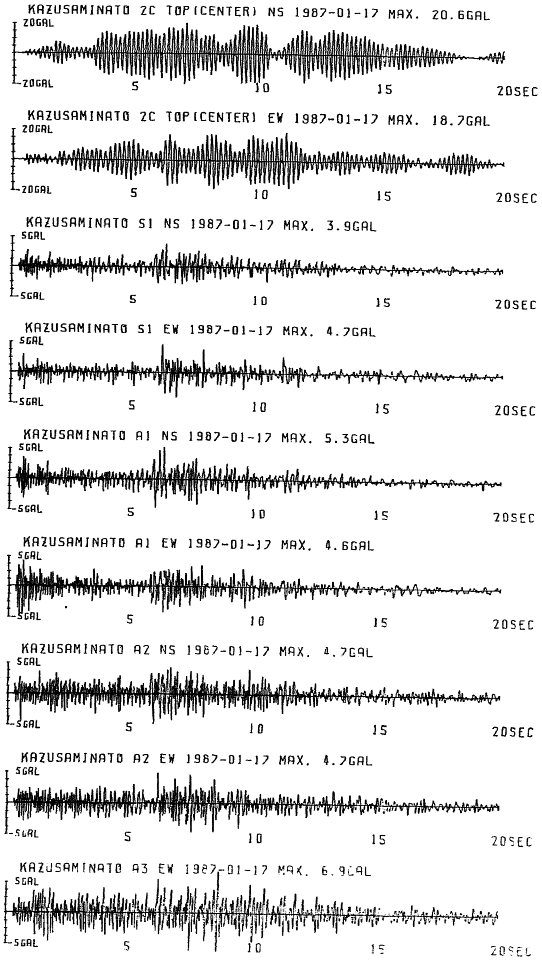


Fig. 6 Observed response of Model 2C and free-field ground motions on Jan. 17, 1987

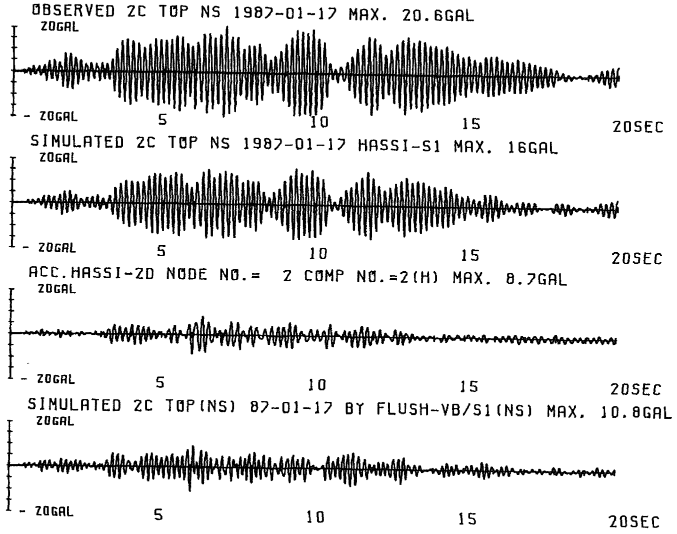


Fig. 7(a) Comparison of the observed and simulated response motion of Model 2C

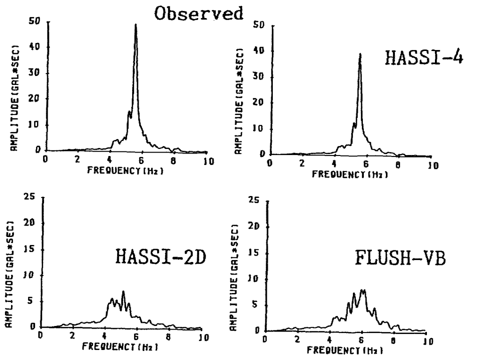
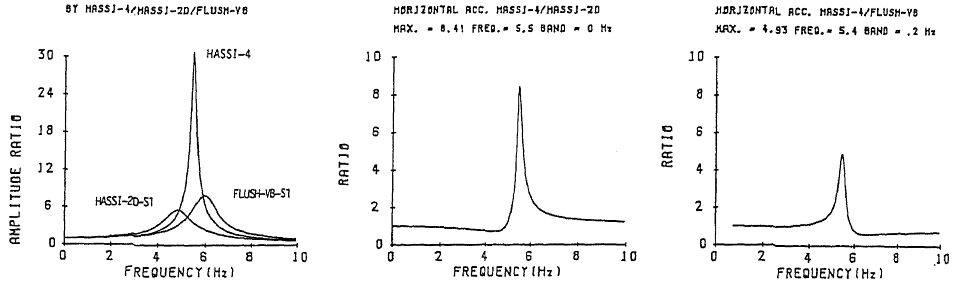


Fig. 7(b) Comparison of simulation results on Fourier spectra (NS components) shear strain near the ground surface just close to the wall of the model 2C. The material damping of the structure was set as 0.5 %. In case of FLUSH-VB, the previous strain dependent shear modulus and damping ratio curve in Fig. 2 were applied and automatic convergence function was utilized. As for the HASSI-2D code, the same material properties used for the case of HASSI-4 were assigned.

Results The observed and calculated horizontal NS components of the roof top motions for the corresponding input ground motion of S1 by using the above three codes are shown in Fig. 7(a). The Fourier spectra of these observed and the calculated motions are shown in Fig. 7(b). From these figures, it is evident that each calculated motion excluding the one by HASSI-4 differed much from the recorded motion on both time history and Fourier spectrum. The characteristics of the results obtained by these two-dimensional codes are well compared with three-dimensional code on the transfer functions shown in Figure 8.



(a) Comparison between three codes

(b) Ratio; HASSI-4 vs. HASSI-2D

(c) Ratio; HASSI-4 vs. FLUSH

Fig. 8 *Comparison of* absolute acceleration transfer functions of the roof top motions by HASSI-4, HASSI-2D, and FLUSH-VB

DISCUSSION

As having been already pointed out by Luco and Hadjian (Ref. 1) and Wolf (Ref. 6), these two-dimensional codes cause a small shift of the primary frequency and significant over-damping to the system response as clearly shown in Fig. 8. The frequency shift is not so significant but the over-damping is very serious because it leads to a serious underestimate of response of the structure. The maximum over-damping by FLUSH-VB and HASSI-2D in this case were accounted respectively as 8.4 and 4.9 times relative to the response by HASSI-4.

The mechanism of the above over-damping was tested by simulating the recorded motions on a stick model with soil springs (SMSS: rocking and translational springs) and a single degree of freedom model (SDOF). To these models, the static soil springs of circular disc were attached to the base mass. The calculated results are shown in Fig. 9. First the soil properties used for HASSI-4 were also used for SMSS and the fit to the recorded motion was very poor. Then, this was improved by raising the shear wave velocity to 420 m/sec and assuming modal damping of 2.1 % as the sum of radiation and material damping. In case of SDOF, by the combination of the shear wave velocity and damping ratio of 340 m/sec and 2.0 %, a fairly good fit was obtained. These equivalent modal damping ratios of 2.0 *to 2.1 % in these models are comparable with the previous working damping* ratio in these two-dimensional codes, if we should take the ratios of peaks shown in Fig. 8(a).

CONCLUSIONS

The three-dimensional soil-structure interaction analysis code, HASSI-4, gave us good fit to the recorded response of a model structure for both representative field vibration test result and earthquake response records. On the other hand, the typical two-dimensional codes not only modulated the characteristic frequency but also generated significantly excessive damping, resulting into serious underestimate of the structural response. The excessive damping working in the two-dimensional codes which may be estimated from theoretical analysis was confirmed by the so-called simple classical models. These facts clearly account for the needs to treat the soil-structure interaction phenomena of three-dimensional structures as three-dimensional.

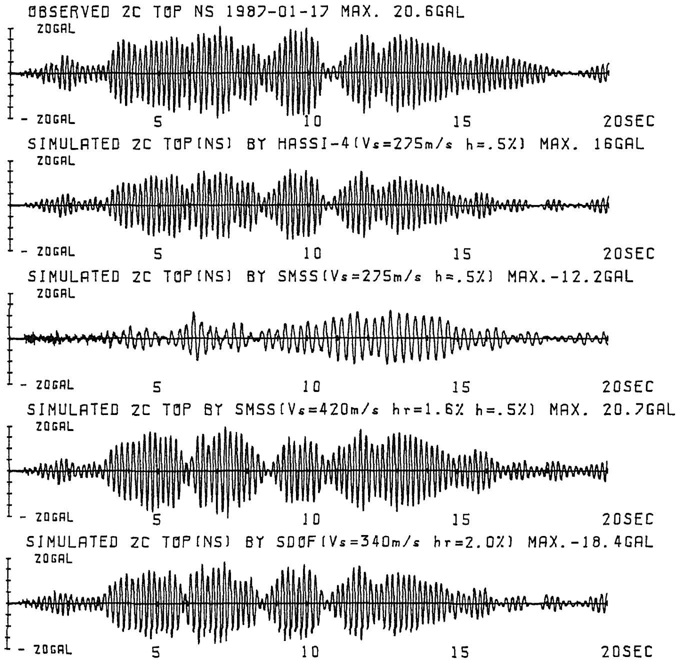


Fig. 9 Simulation by classical models; From upper to lower, the observed motion, the simulated motions by HASSI-4, SMSS, SMSS, and SDOF

REFERENCES

(1) Luco, J. E. and A. H. Hadjian, Two-Dimensional Approximations to the Three-Dimensional Soil-Structure Interaction Problem, Nuclear Engineering and Design 31, (1974).

(2) Gupta, S. and J. Penzien. Hybrid Modeling of Soil-Structure Interaction for Embedded Structures. Proc. 6th. SMiRT, (1981).

(3) Katayama, I and others, Experimental Validation of Soil-Structure Interaction Analysis, Invited Paper at US-Korea Seminar on Critical Engineering Systems, Seoul, Korea, May 11-15, (1987).

(4) Niwa, A., I. Katayama, T. Ohsumi, Y. Kubo, H. Nakase, and J. Penzien. 1987. Verification of Hybrid Analysis Concept of Soil-Foundation Interaction by Field Vibration Tests (1) - Experimental Phase. 9th SMiRT, (1987).

(5) Tzong, T. J. and J. Penzien. Hybrid Modeling of Soil-Structure Interaction in Layered Media. Report No. UCB/EERC-83/22, UCB, (1983).

(6) Wolf, John P., Dynamic Soil-Interaction, Chapter 7, 7.4.2 Two-Dimensional versus Three-Dimensional Modeling, Prentice-Hall, (1985).