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SEISMIC DESIGN MODEL OF EMBEDDED STRUCTURES

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SUMMARY

This paper describes a practical earthquake response analysis method for embedded structures. The analysis method described here is the sway-rocking model, and this model uses the soil springs for evaluation of the dynamic soil-structure interaction, which is very important for the earthquake response analysis. Presented is the rational method for the evaluation of the soil springs and input motions into resulting analysis model on the basis of earthquake observations and forced vibration test results of embedded structures.

INTRODUCTION

The dynamic characteristics of structure with the high rigidity such as nuclear reactor buildings are influenced strongly by the dynamic soil-structure interaction (SSI). As the SSI for embedded structures are induced not only through the bottom area but also through the embedded wall parts of the structure, the influence of the SSI for this type of structure becomes still remarkable. Until now, the earthquake response analysis for embedded reactor buildings in Japan has been executed by the lattice model or the sway-rocking model. The earthquake response analysis at the time of practical design requires response analyses for extremely large cases with various changes for the soil constants and the building data, so that an analysis model with a short calculation time is required. From this point of view, the sway-rocking model is better than the lattice model, but as the SSI is evaluated via the soil springs in the case of the sway-rocking model, sufficient attention must be paid to the evaluation of the soil springs.

In this paper, a rational and practical modellization method for the sway-rocking model as an earthquake response analysis method for embedded structures is proposed on the basis of the results of forced vibration tests and earthquake observations.

FORCED VIBRATION TEST RESULTS

The forced vibration test results used in this research are the results of the reactor buildings of Plant I and Plant II as shown in Fig.1. Plant I has a total weight of 520,000 tons and an embedding depth of 45m, while Plant II has a total weight of 210,000 tons and an embedding depth of 17m. Plant I has the deepest embedding depth of all reactor buildings in Japan. The forced vibration tests were executed by setting an excitor on the refuelling floor (Plant I: GL+12.7m, Plant II: GL+38.5m) and applying sinusoidal excitation force in the direction of the two horizontal axes (NS direction: Parallel to the turbine building, EW direction: At a right angle to the turbine building). Fig.2 shows the resonance curves at the refuelling floor in the excitation directions. The followings can be understood from test results. (1) In comparison with the resonance curves of the Plant II, that of the Plant I with its deep embedding shows no clear resonance peak, and it can be seen that the damping is increased by the embedding. (2) A difference between the resonance curves in accordance with excitation direction can be recognized slightly for Plant II with its shallow embedding depth, but it may be disregarded for practical application. The following investigations are limited to the results in direction parallel to turbine building. (3) The dotted lines in Fig.2 show the analysis results when the embedding is disregarded. For both plants, the analysis results with disregarded embedding show resonance curves differing considerably from the test results, and it can be seen that the embedding effect must be evaluated properly.

ANALYSIS MODELS

Until now, a large number of methods have been proposed for analysis of the dynamic characteristics of embedded structure. This paper executes comparative investigations of the forced vibration test results with those of following four analysis models A to D. Model A: In this model, the soil springs K_H (swaying spring) and K_R (rocking spring) at the bottom area of the structure and the soil springs K_u (horizontal spring) and K_ϕ (rotational spring) at the embedded part of the side walls are calculated individually. The base spring assumes the base level at the ground surface, and calculation is executed with application of the dynamic ground compliance of Kobori[1] or the vibration admittance theory of Tajimi[2], while the theory of Novak[3] is applied for calculation of the side spring. The resulting analysis model is shown in Fig.3. Model B: This model applies only for the plant I. This plant is embedded into the firm rock underneath, and the soil spring for this part is calculated by the boundary elements method as the base spring. The other side springs are the same as for the model A. Model C: The thin layered element method developed by Tajimi[4] is applied for this model. Model D: The axis-symmetric finite element method is used for this model. The energy dispersion from the analysis boundary of the finite soil to the outside is evaluated with addition of viscous damping at the analysis boundary.

COMPARATIVE INVESTIGATIONS

Resonance curves Modelling the building into a lumped mass system, the resonance curves are calculated by four Models. Fig.4 shows the comparison of resonance curves at refuelling floor. As for Plant I, its main feature in which the resonance curve has no peak is expressed well by Model A to D. The analytical results of Plant II by Model A, C and D show good conformity to test results.

Soil springs Correlation analyses are conducted between soil springs derived from the forced vibration test results and those by the above-mentioned Models. After calculating the overturning inertia moment and horizontal inertia force of the whole building from the observed records and adding these to the terms due to the excitation force, total moment Mo. and horizontal force Fo at the bottom center are estimated. Dividing Mo and Fo respectively by rocking angle ϕ_0 and horizontal displacement Uo at the bottom center, rocking and swaying spring values are obtained. As the values of these springs are equal to the combination values of the base springs with the side springs, the springs obtained by aboveprocedure are termed combined soil springs. In the analysis Model, the combined soil springs are calculated under the assumption that the embedded part of building is rigid and its vibration mode is prescribed by ϕ_0 and Uo as shown in Fig.5. Fig.6 to Fig.9 show the comparison of the combined soil springs, comparing tests with results obtained by the four analysis Models and a Model neglecting the side soil springs in Model A. The followings are pointed out from these comparisons. (1) Plant I (Fig.6, Fig.7): As for the real part of combined swaying soil spring $K_H^{(c)}$, four analysis Model results are slightly over the test ones, while the imaginary parts are well evaluated. The real parts of the combined soil springs $K_R^{(c)}$ by Model B, C and D conform well to the test results in the lower frequency range, while the result A is somewhat lower. The imaginary part is somewhat underestimated by all models, particularly Model C. (2) Plant II (Fig.8, Fig.9): As for the real part of $K_H^{(c)}$, Model A, C and D show good agreement with tests, while the imaginary part is somewhat underestimated. The imaginary part of $K_R^{(c)}$ is well accounted for, but there is some discrepancy in real part. (3) Model neglecting the side soil springs leads the lower imaginary part of all springs than the test results.

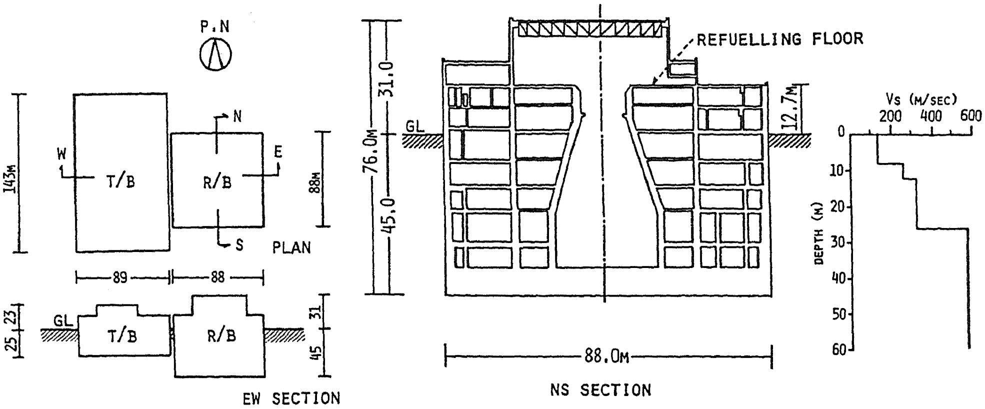
Comparative investigations show that four analysis Models A to D have the proper dynamic characteristics in practical application. Judging the computation time, Model A is superior to the other Models. More simplified and practical Model is a model in which rotational side soil springs $K\phi$ are excluded in Model A as shown in Fig.10. Fig.11 shows the resonance curve of Plant A calculated by this model. Model without rotational springs provides the resonance curve which has lower damping, but this degree of damping decrease is negligible in the practical design.

Earthquake observations Simplified substructure method[5] is applied to seismic response analysis of Model A without rotational springs, namely 1) calculating the seismic response of ground due to design basis earthquake by one-dimensional shear wave propagation theory (such as computer code: SHAKE), 2) applying the calculated ground motions to all springs and also applying the total shear force of ground at base level to bottom springs. The outline of input motions is shown in Fig.10. Fig.12 depicts the seismometers installation position (GO, R1, 2, 3) of two plants. Considering the earthquake records at GO as design basis earthquake, the response of Plants are calculated by the above-mentioned procedure and the comparison of maximum response accelerations are shown in Fig.12. These results lead the conclusion that analysis model and its input motions procedure are proper.

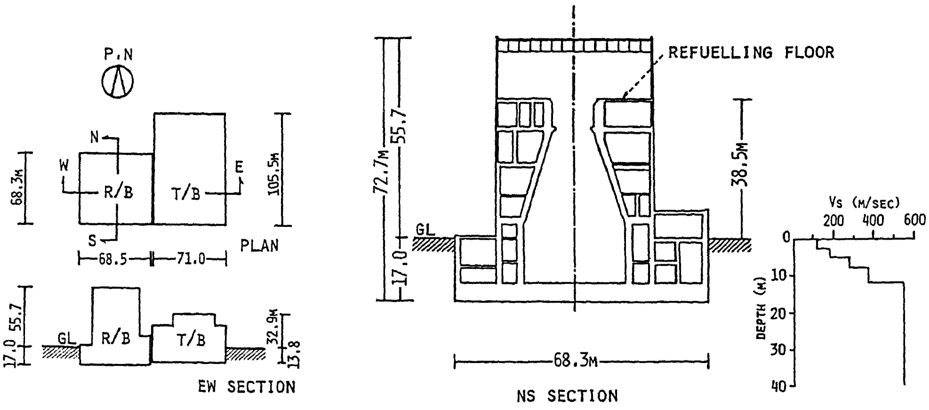
CONCLUSION

The seismic design models for embedded structures are discussed from the practical viewpoint. As the result of this investigation, the analytical Model shown in Fig.10 is proposed. This Model is constituted under the analytical assumptions and lacks the mathematical rigorous aspects. However, the results obtained by this model indicate good agreements with the forced vibration tests and the earthquake observation results. Lastly, it is projected that several nuclear reactor buildings with deep embedment will be constructed in Japan. Seismic designs for two of the buildings have already been excuted by the proposed Model.

Finally, this work is a part of the joint study which has been carried out by Tokyo Electric Power Co., Inc., The Hokkaido Electric Power Co., Inc., Tohoku Electric Power Co., Inc., The Chubu Electric Power Co., Inc., Hokuriku Electric Power Co., Inc., The Kansai Electric Power Co., Inc., Chugoku Electric Power Co., Inc., The Shikoku Electric Power Co., Inc., The Kyushu Electric Power Co., Inc. and The Japan Atomic Power Co., Inc..



PLANT I



PLANT II

Fig.1 Embedded Structures

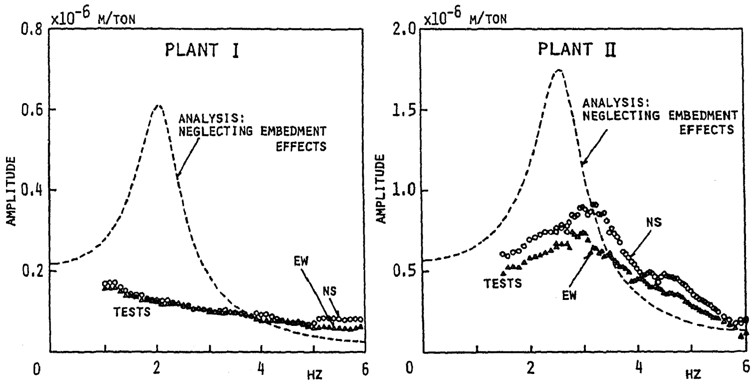


Fig.2 Resonance Curves at Refuelling Floor

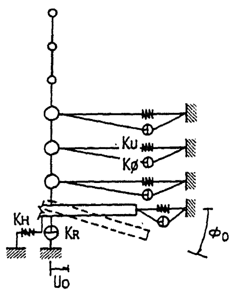
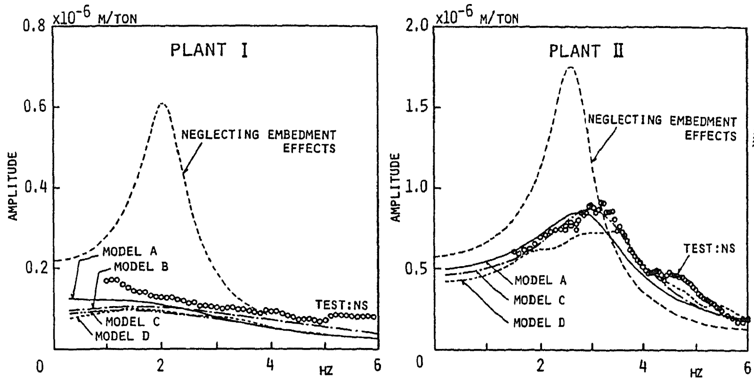


Fig.3 Analytical Model (MODEL A)



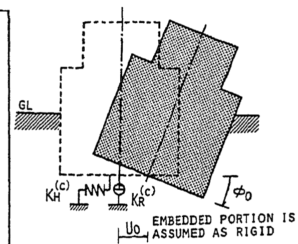


Fig.5 Combined Soil Springs

Fig.4 Resonance Curves at Refuelling Floor

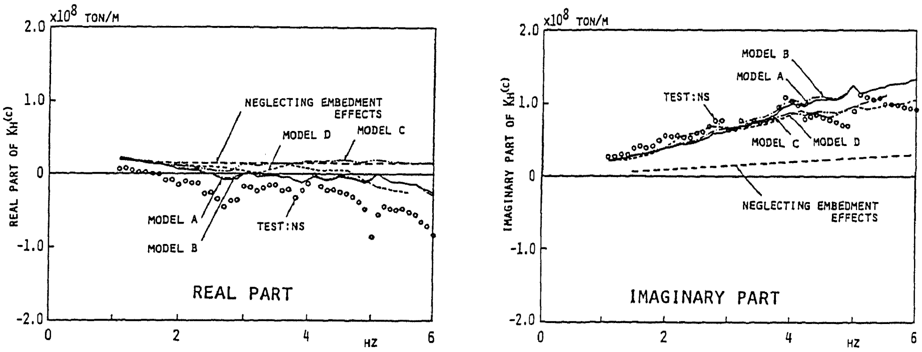


Fig.6 Combined Swaying Soil Spring (PLANT I)

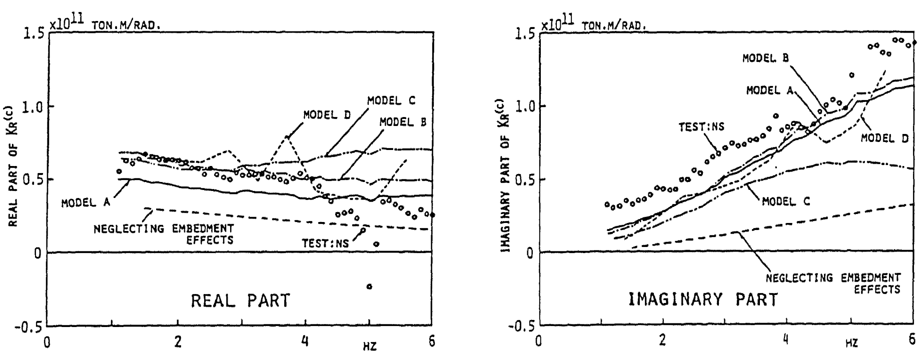


Fig.7 Combined Rocking Soil Spring (PLANT I)

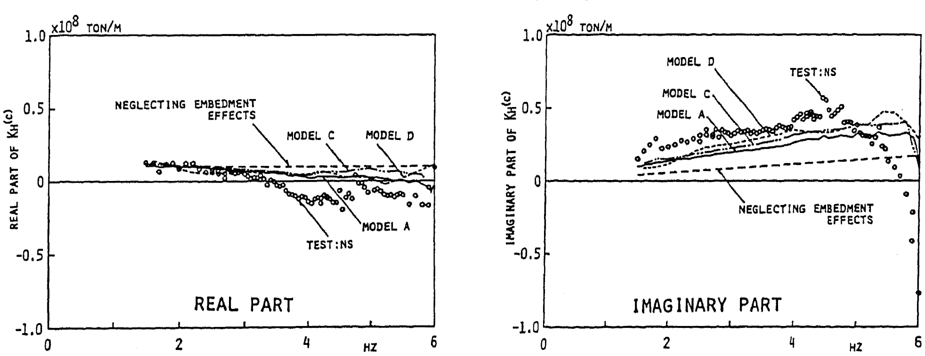


Fig.8 Combined Swaying Soil Spring (PLANT II)

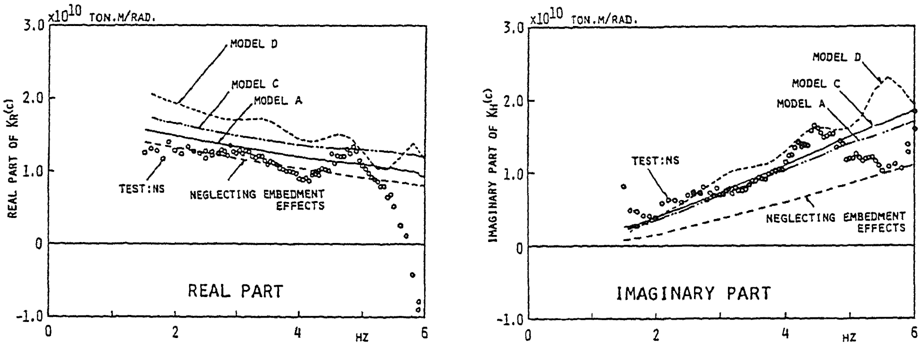


Fig.9 Combined Rocking Soil Spring (PLANT II)

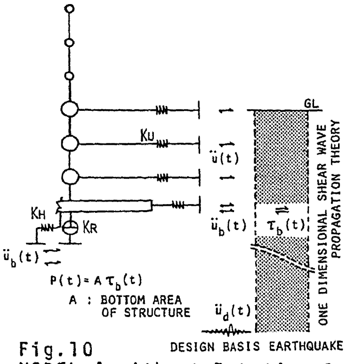


Fig.10
MODEL A without Rotational Side Soil Springs and its Input Motions

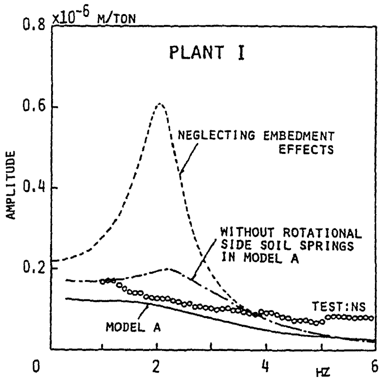


Fig.11 Resonance curves at Refuelling Floor

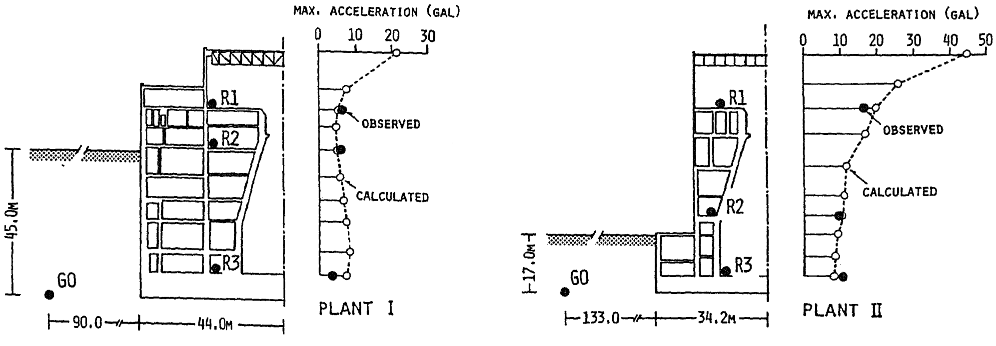


Fig.12 Earthquake Observations

REFERENCES

1. Thomson, W. T. and Kobori T., "Dynamic Compliance of Rectangular Foundations on an Elastic Half-Space", Journal of Applied Mechanics, vol. 30, (1963)
2. Tajimi, H., "Dissipation Dampings of Vibrational Systems on the Elastic Ground", Proceedings of the Seventh Japan National Congress for Applied Mechanics, (1958)
3. Novak, M., Nogami, T. and Aboul-Ella, F., "Dynamic Soil Reactions for Plane Strain Case", ASCE, EM4, (1978)
4. Tajimi, H., "A Contribution to Theoretical Prediction of Dynamic Stiffness of Surface Foundations", Proceedings of 7WCEE, (1980)
5. Tanaka, H., Motohashi, S., Motosaka, M., Kamata, M. and Kanda, M., "Study on a Simplified Dynamic Model of Reactor Building Taking Account of Embedded Effects", Proceedings of Annual Meeting of AIJ, (1985), (in Japanese)