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Comprehensive evaluation of verification tests for seismic analysis codes. Part 1 : outline of study

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ABSTRACT: The Nuclear Power Engineering Corporation of Japan has conducted a systematic directed research program since 1980 to assist with the earthquake resistant design process for nuclear power plants. These are on Soil Structure Interaction, Embedment Effect, Basemat Uplift, Restoring Force Characteristics Tests etc.. Beginning in 1992, we have comprehensively compiled and reviewed the results of these test programs and their applicability to nuclear power plant seismic design. The papers from part 1 to part 7 present an outline and comprehensive results of this review and evaluation program.

1. INTRODUCTION

Earthquake resistant design is a critical part of the safety design of structures in Japan, where damaging earthquakes are frequent. In such design, both the behavior of the structure and the soil-structure interaction (SSI) must be analyzed. It is necessary to verify that the structural system possesses the required safety factors against the established seismic demand. Design of nuclear reactor structures necessitates a higher level of safety and therefore demands a higher level of analysis than ordinary structures. This more detailed analysis in turn requires a thorough background of research to verify and define the various analysis assumption and design parameters.

With the above background, the Nuclear Power Engineering Corporation of Japan has conducted a systematic directed research program since 1980 to assist with the earthquake resistant design process for nuclear power plants. The main research programs are Model Tests on Dynamic Soil Structure Interaction, Tests on Embedment Effect of Reactor Buildings, Basemat Uplift Tests of Reactor Buildings, Experimental Evaluation of Floor Response, Restoring Force Characteristics Tests of Reactor Buildings, and Seismic Behavior Tests of Reactor Buildings.

Numerous important result have been obtained from the above test programs. However, the obtained results have not necessarily been categorized in an ordinary manner. Beginning in 1992, we have comprehensively compiled and reviewed the results of these test programs and evaluated their applicability to nuclear power plant seismic design. Fig.1 shows the process of applicability evaluation of the test results for seismic design of reactor buildings. The papers from Part 1 to Part 7 present an outline and results of this review and evaluation program.

2. RE-EVALUATION OF TEST RESULTS

Detailed review and comparison of other state-of-the-practice of respective experimental test results were performed to clarify the status of the respective test results and to evaluate the applicability of the simulation analysis methods from the view point of current plant design. Followings are reviewed test programs.

Model Tests on Dynamic Soil Structure Interaction, 1980-1986: Vibration tests by exciter and earthquake observations were performed using 5 kinds of models conducted in a field representing BWR and PWR. In the tests, soil structure interaction relating the relationship between soil spring and basemat size, effects of soil layered, soil contact pressure distributions at basemat bottom were confirmed. The simulation analyses were performed using S-R model based on a 3-Dimensional wave propergation theory, 2-D FEM model including out of plane viscous boundary and lattice model.

Tests on Embedment Effect of Reactor Buildings, 1986-1995: Vibration tests by exciter and earthquake observations were performed using 4 models constructed in a field representing BWR and PWR in the parameter of embedment depth and soil stiffness. To supplement the field tests, laboratory tests using silicon rubber soil models also were performed. In the tests, soil structure interaction with embedment and soil contact pressures at basemat bottom and side wall were confirmed. The simulation analyses were performed using axisymmetric FEM model and S-R model.

Basemat Uplift Tests of Reactor Buildings, 1981-1987: Basemat uplift tests for structure model on a silicon rubber soil model were performed using shaking table and for concrete block in a field using exciter. In the tests, overturning moment and rotational angle relationships, soil stiffness and basemat contact ratio relationships, soil damping and basemat contact ratio relationships, dynamic response of structure with basemat uplift, amplification in high frequency region by basemat uplift and vertical amplification induced by basemat uplift were confirmed. The simulation analyses were performed using S-R model and 2-D FEM model. Simulation analysis using Green's functional principle in time domain is introduced as a detail model from the state-of-the-practice in the re-evaluation process.

Experimental Evaluation of Floor Response, 1984-1987: Dynamic response tests of reactor building models in scale 1:50 on silicon rubber soil models representing BWR and PWR respectedly were performed using large shaking table. The behavior confirmed in the tests, response of structure including floors flexibility and basemat flexibility were evaluated analytically by simulation analyses using 3-D FEM model.

Restoring Force Characteristics Tests of Reactor Buildings, 1980-1984: The static cyclic load tests were performed for partial structure models, total structure models representing BWR and PWR respectively to confirm the restoring force characteristics of RC shear walls of reactor buildings and scale effect test models to investigate the influences for the restoring force characteristics obtained by tests when applying actual buildings. The relationships between load and displacement, area of hysteresis lopes, deformation modes, strain of reinforcing bars were confirmed in the tests.

Seismic Behavior Tests of Reactor Buildings, 1986-1995: In this project, three kinds of tests were performed that are restoring force characteristics in dynamic response, strength and stiffness of shear walls with openings and air leakage through cracks in shear walls. Dynamic restoring force characteristics were confirmed by the tests of RC shear wall models, to study about relationship between the shear strain velocity and shear strength, damping coefficient by the forced static deformation or shaking table and restoring force characteristics by earthquake input motion. The strength and stiffness of shear walls with openings were studied to establish the evaluation method of it with many small openings by the forced static cyclic loading test of RC walls with the parameter of openings rate, array, shape and location, etc.. The air leakage through cracks in shear walls were studied to established the evaluation method using experienced maximum shear strength or using experienced maximum shear strain by the tests through single crack and through several random cracks.

3. APPLICABILITY STUDY OF TEST RESULTS

3.1 Modeling of the test results

The modeling for the applicability study of the test results were derived through interpretation analyses of test results to actual plant conditions using the simulation analysis methods of the test results. The analysis methods confirmed in the simulation analyses of the test results were categorized into two advanced models as a detail model and a quasi-detail model to study the applicability for actual plant design in comparison with the conventional design model.
The detail model is the model which takes into account the most details of the modeling for each behavior of the experimental tests. The quasi-detail model is the rational model which avoid unnecessary complication of the model within the acceptable limit of the accuracy.
·Soil structure interaction: The modeling of the soil structure interaction behavior including embedment (See Fig.2) were derived from the simulation analyses of "Tests on Embedment Effect of Reactor Buildings" and "Model Tests on Dynamic Soil Structure Interaction". The detail model is used frequency dependent matrix springs based on the axial symmetry FEM model and the quasi-detail model is used frequency dependent soil springs and considered rotational springs corresponding lateral notch force along the side wall surface. The paper of Part 2 present the modeling detail of the soil structure interaction of reactor buildings.
·Basemat Uplift: The modeling of the basemat uplift behavior (See Fig.3) was derived from the simulation analysis of "Basemat Uplift Tests of Reactor Buildings". The detail model is used Green's functional principle in time domain. The quasi-detail model takes into account vertical movement induced by the basemat uplift by a spring model.
·Floors and basemat flexibility:The modeling of the deformation behavior for flexibility of floors and basemat were selected from "Experimental Evaluation of Floor Response, 1984-1987". The detail model take into account both the flexibility of floors and basemat. The quasi-detail model takes into account the flexibility of the floors only and the basemat was considered rigid. The paper of Part 3 present the modeling detail of the basemat uplift and floors and basemat flexibility.
·Restoring force characteristics: The modeling of the restoring force characteristics of reactor buildings (See Fig.4) were derived from "Restoring Force Characteristics Tests of Reactor Building" and "Seismic Behavior Tests of Reactor Buildings". The detail model and quasi-detail model are used the skeleton curve including the dynamic effects related to the shear strain rate. The papers of Part 4 and Part 5 present the modeling detail of the restoring force characteristics of reactor buildings.
·Strength and stiffness of shear walls with openings: The evaluation methods of strength and stiffness of shear walls with openings were derived from the test results of seismic shear walls with small openings in the "Seismic Behavior Tests of Reactor Building". The influence of openings on restoring force characteristics is expressed by the multiplying the reduction factor obtained by the effective strut method to initial stiffness and each turning point force in the skeleton curve. The paper of Part 6 present the detail of evaluation method of strength and stiffness of shear wall with many small openings.
·Air leakage through residual cracks: The negative pressure inside of the building of BWR and at the annuls zone of PWR should be maintained under control even in the case that S1 design earthquake occurs after LOCA.
In order to estimate air leakage through residual cracks in RC shear walls, two kind of evaluation methods for extra air flow through residual cracks around openings in RC shear walls were proposed adding to the previously proposed estimation formulas for without openings.
The evaluation methods for extra air flow through residual shear cracks around openings in RC

shear walls were derived from "Seismic Behavior Tests of Reactor Buildings".
The detail of the two methods were presented in the paper of Part 7: evaluation method of air leakage through cracks in RC shear walls with openings.

3.2 Applicability study by plant equivalent models

Regarding the models of the soil structure interaction behavior including embedment effects, the basemat uplift behavior and the restoring force characteristics, the applicability for actual plant design were studied individually by seismic response analysis of plant equivalent model considering various actual reactor building conditions as shown in Fig.5. The spectrums of input ground motion are shown in Fig.6.
For the applicability study of the model of the soil structure interaction behavior including embedment effects, seismic response analyses of plant equivalent models of BWR and PWR were performed with the parameter of embedment depth and soil stiffness. The analysis results were evaluated by comparison with the "Tests on Embedment Effect of Reactor Buildings" and comparison with the observed seismic records at actual plants. The seismic response analysis results of plant equivalent models to evaluate the soil structure interaction behavior including embedment effects using three type models that are detail model, quasi-detail model and conventional design model showed almost same response characteristics among the three type models.
For the applicability study of the model of the basemat uplift behavior, seismic response analyses of plant equivalent model of PWR were performed by large earthquake input motions to cause uplift of the basemat contact ratios around 75%, 65% and 50% with the parameter of soil stiffness and soil reaction pressure distribution forms. The analysis results were evaluated by comparison with the "Basemat Uplift Tests of Reactor Buildings". The results of the seismic response analyses of plant equivalent model showed that the detail model evaluate little bit larger uplift than quasi-detail model and conventional design model.
For the applicability study of the model of the restoring force characteristics, seismic response analyses of plant equivalent model were performed with the various plant conditions. The analysis results were evaluated by comparison with the "Restoring Force Characteristics Tests of Reactor Buildings" and "Seismic Behavior Tests of Reactor Buildings".
The response results of the detail model and quasi-detail model which considered the effect of dynamic shear strain rate for the restoring force characteristics were shown the tendency of increasing stress response and decreasing deformation response than the conventional design model.

4. OVERALL EVALUATION

For the overall evaluation of applicability of the soil structure interaction behavior including embedment effects, the basemat uplift behavior and the restoring force characteristics, a integrated analysis model was proposed (See Fig.7) to evaluate simultaneously these phenomenons in the seismic response analysis of plant equivalent models of BWR and PWR. The quasi-detail model of the respective test results were selected to the integrated analysis model considering the analytical applicability lamitation for the nonlinear analysis in time domain. The seismic response analysis of the integrated analysis model were performed with the several conditions of soil stiffness and embedment depth increasing earthquake input motions into three steps in order to see the behavior change by the increasing nonlinearity of shear walls and basemat uplift with embedment. The response analysis results in becoming larger input motion showed that the increasing rate of the maximum acceleration response of structure was swung owing the response amplification by the growing basemat uplift and the response deamplification by the growing structural nonlinearity. Embedment effects showed not always reduce the

structural response but increased it in deep embedment case than shallow embedment case. One of the analysis results is shown in Fig.8.
These results showed us that the structural response in a large input motion causing structural nonlinearity and basemat uplift become difficult to evaluate the response qualitatively by the complex influences of the structural nonlinearity, basemat uplift and embedment effects.
The integrated analysis model in order to apply for the estimation of ultimate seismic resistance conditions therefore is required further study to improve the evaluation methods of these influences more realistically in accordance with verification tests.

5. CONCLUSION

In the comprehensive evaluation of the verification tests for seismic analysis codes which have been conducted in a systematic directed research program since 1980 to assist with the earthquake resistant design process for nuclear power plants, the results of these test programs and their applicability to nuclear power plant seismic design were compiled and reviewed and following outcomes were derived consequently,
(1) The results of seismic response analyses of plant equivalent model of BWR and PWR using the evaluation methods of the test results were compiled to the data base of benchmark case for the improvement of the seismic analysis codes of NUPEC.
(2) The new evaluation methods were proposed for the evaluation of restoring force characteristics including dynamic effects of skeleton curves, evaluation of strength and stiffness of RC shear walls with many small openings, and evaluation of air leakage through cracks in RC shear walls with openings.
(3) The proposal of the integrated analysis model for overall seismic response analysis in larger input motions and the requirement of seismic verification tests for further improvement of the model .

ACKNOWLEDGMENT

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REFERENCES

1. Odajima, M., et al. 1987. Analytical Study on Model Tests of Soil-structure Interaction. Conf. 9th SMiRT, KI:311-316
2. Endoh, A., et al. 1988. Model Tests for Evaluation of the Seismic Behavior of Reactor Buildings (Part 1: Overall View of Model Tests). Annual Meeting of Architectural Institute of Japan, (in Japanese): 2609-2610
3. Iguchi, M., et al. 1989. Model Test on Interaction of Reactor Building and Soil (Part 1: Cross Interaction Tests). Conf. 10th SMiRT, KI: 211-216
4. Hangai, Y., et al. 1989. Model Test of Base Mat Uplift of Nuclear Reactor Building (Part 1: Laboratory Test). Conf. 10th SMiRT, KI: 169-174
5. Kobayasi, T., et al. 1991. Forced Vibration Test on Large Scale Model on Soft Rock Site (Embedment Effect Tests on Soil-structure Interaction). Conf. 11th SMiRT, KO6/4: 129-134
6. NUREG/CR-6241. 1994. Technical Guidelines for Aseismic Design of Nuclear Power Plants, Translation JEAG 4601-1987

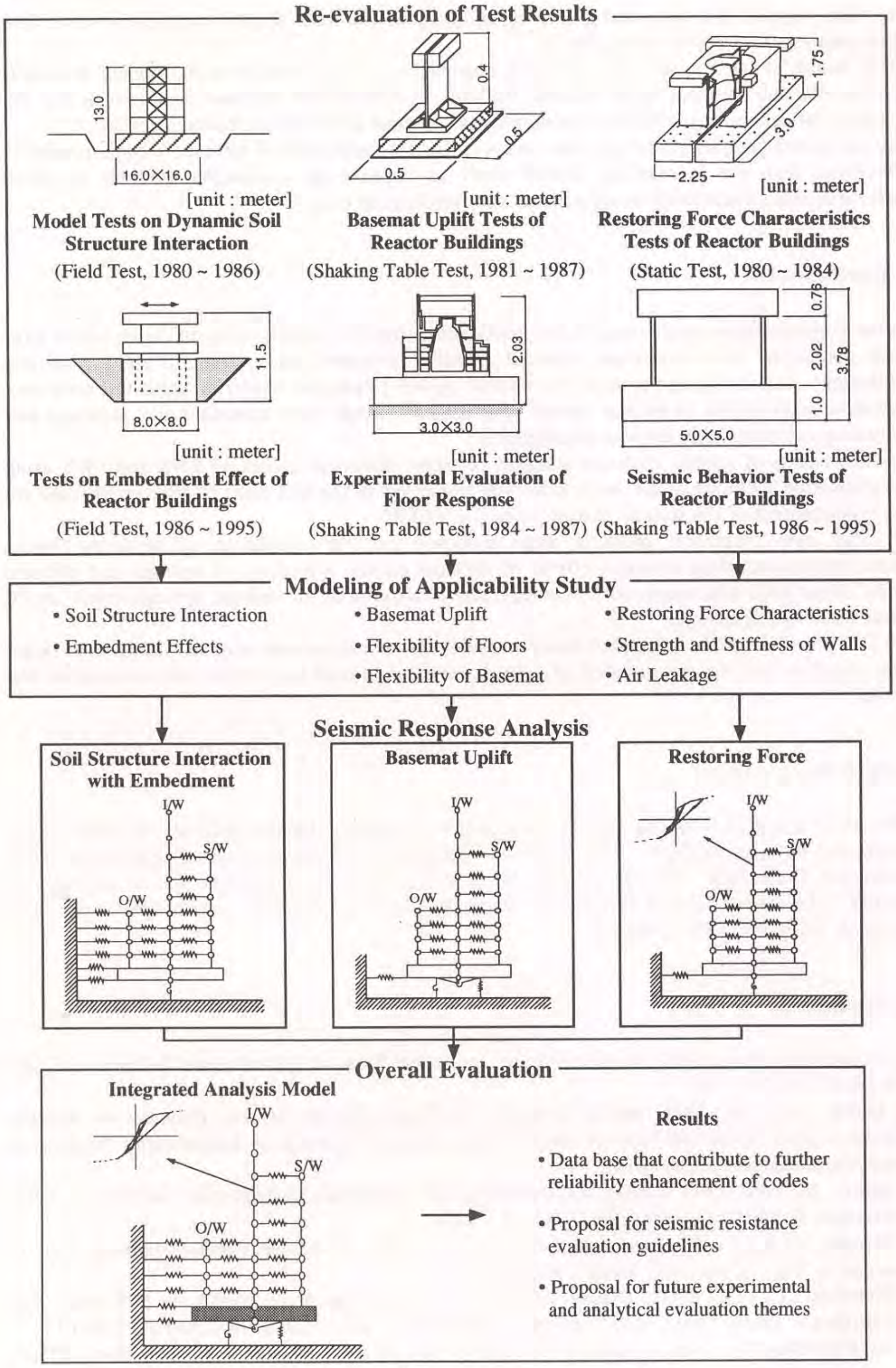


Fig. 1 Process of Comprehensive Evaluation

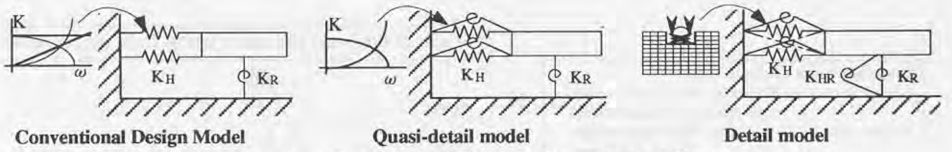


Fig. 2 Soil Structure Interaction Models Considering Embedment

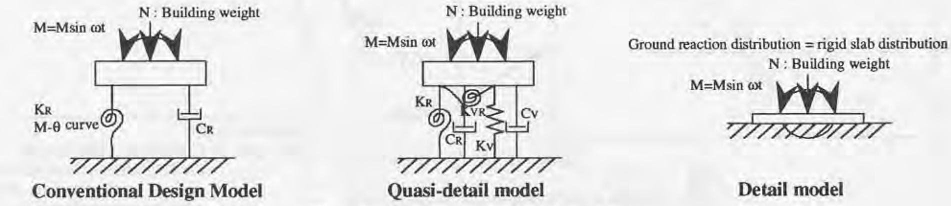
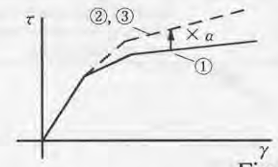


Fig. 3 Basemat Uplift Models



① Conventional Design Model : derived from static tests

② Quasi-detail model : ①× α , considering one α through analysis

③ Detail model : ①× α , considering every steps different α

α : Coefficients of dynamic effects

Fig. 4 Restoring Force Characteristics

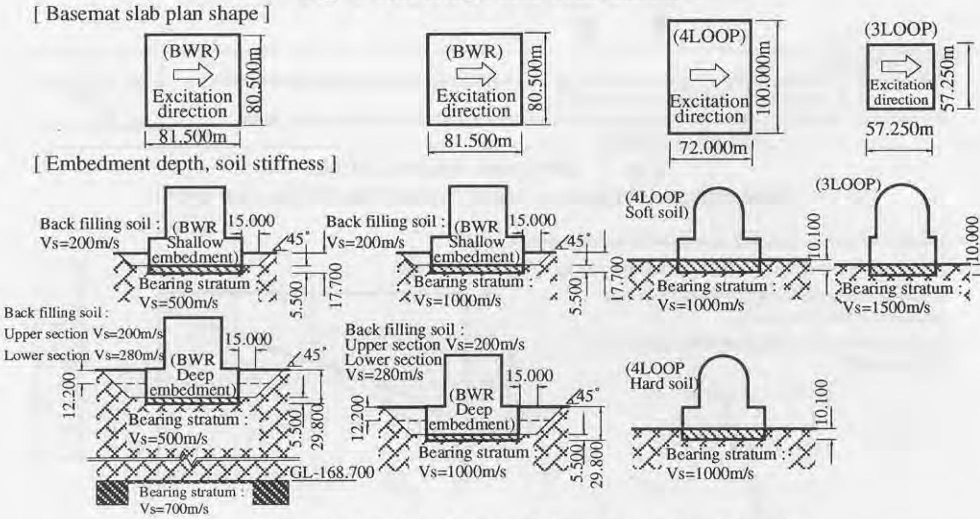


Fig. 5 Siting Conditions of Plant Equivalent Models

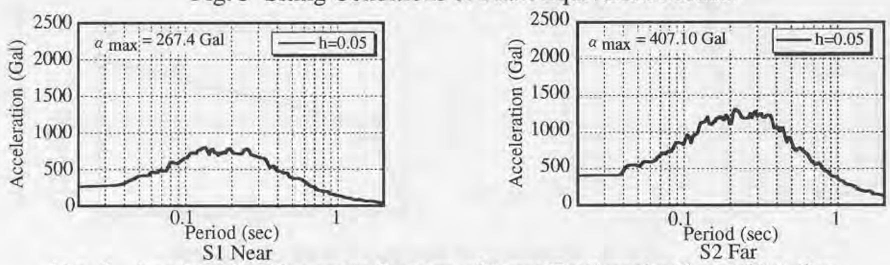


Fig. 6 Acceleration Response Spectra of Input Earthquake Ground Motion

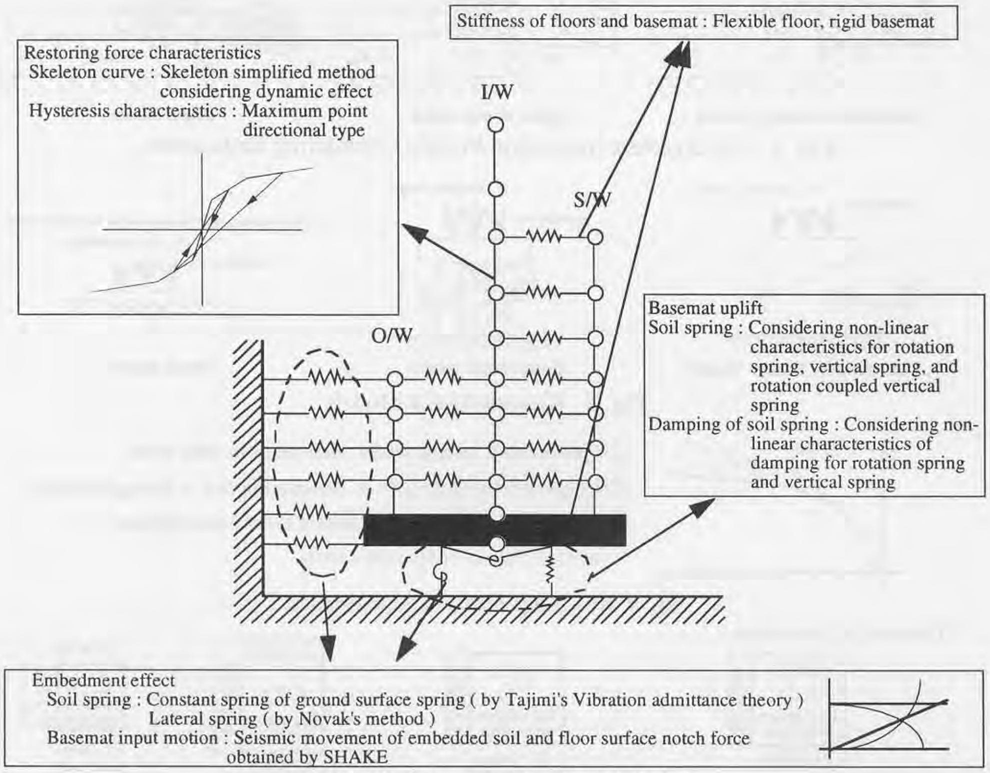


Fig. 7 Integrated Analysis Model
(Considering building non-linear • embedment • basemat uplift)

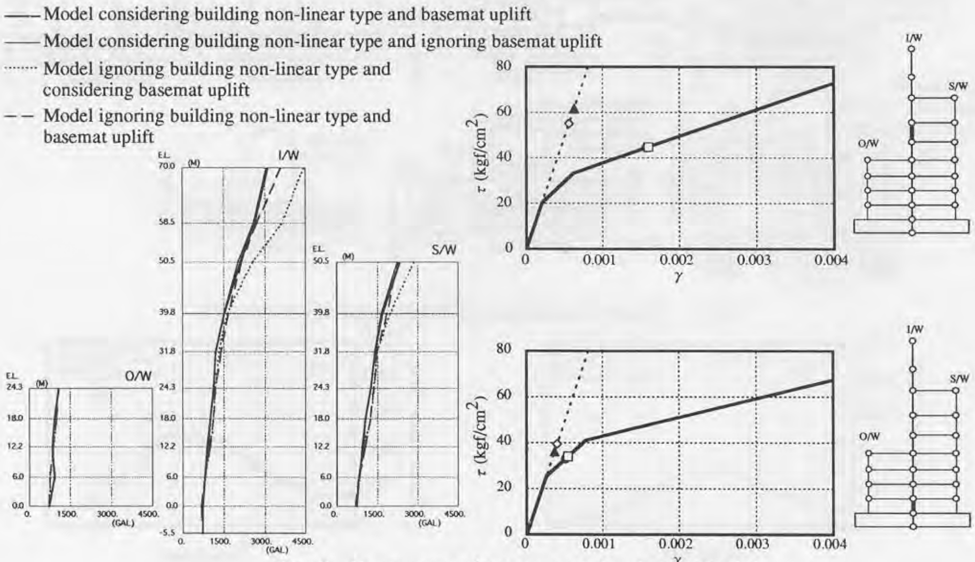


Fig. 8 Response of integrated Analysis Model
(BWR, Vs=1000m/s, Shallow embedment, PGA=814.2Gal)