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Verification of Seismic Analysis Codes by Means of Test Data

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1 INTRODUCTION

Japan Institute of Nuclear Safety(JINS) of Nuclear Power Engineering Center (NUPEC) has been entrusted to prepare a series of seismic analysis codes called SAN(Seismic Analysis Nuclear) series by Ministry of International Trade and Industry(MITI).

These codes are provided in order to utilize in the safety analysis (cross check) for the safety examination by the government and in the safety verification of nuclear power plant facilities. The codes which are applied for the cross-checking should, in principle, be different from those developed by applicants or industries. From this point of view, those codes have been developed by JINS independently.

In the seismic analyses of nuclear power plants, various codes are necessary in order to evaluate the following items:

i. Earthquake ground motion at a site
ii. Soil-structure interaction
iii. Ground stability
iv. Stresses of building and structure
v. Equipment and piping
vi. Tsunami propagation

JINS started to develop the SAN series in 1980, and 17 codes have been almost completed.

NUPEC has executed a series of experiments (seismic tests) for the verification of those codes and the improvement of seismic safety of buildings and pipings as an entrusted project from MITI, and JINS has been evaluating reliability and effectiveness of the codes using these tests.

This report discusses analytical results using six codes of the SAN series and collation with the test results.

Procedure of the seismic analysis of nuclear power plants using SAN codes are shown in Fig.1.

The six codes which are applied for analyses of soil-structure interaction and stress of structure,are briefly summarized in Table 1, and synopsis of 5 seismic tests which are used for analyses in this reports are shown in Table 2.

2 VERIFICATION OF SAN SERIES CODES BY THE SEISMIC TESTS

(1) SANLUM

a. Verification by "INTERACTION TEST"

Response analysis using SANLUM was carried out for the forced vibration tests AC4 and AC5 (input motion : sine wave) in "INTERACTION TEST". Outline of the tests are shown in Fig.2,and their structure models on the soil (Models A and C) are shown in Fig.3. Analytical models for AC4 and AC5 are shown in Figs. 4 and 5. In the analysis, the soil is modelled by shear and axial springs, and the structures by flexural and shear beam and lumped mass (Lumped Mass Model). Viscous boundaries are assumed for the both sides and bottom of the soil taking into account its semi-infinity.

The analytical results of displacement resonance curve at the top of Model A are compared with the experiments in Fig.6. Every results agree well in the tests AC4 and AC5, and it could be found that existence of the adjacent building in the test AC5 does not affect the results significantly when an excitation direction is parallel with both buildings.

b. Verification by "BASE UPLIFT TEST"

Seismic response analysis with SANLUM (time history response analysis) was carried out for the forced vibration test by shaking table(input motion equivalent to EL CENTRO NS, Maximum acceleration 220 gal) in "BASE UPLIFT TEST". Outline of the test model is shown in Fig.7, and analytical model is shown in Fig.8. In the analytical model, the soil is modelled by rocking and sway springs which have nonlinearity for uplift happened, and structure is modelled by the "Lumped Mass Model".

The analytical and experimental results of natural frequencies, natural modes, time histories of overturning moment and contact ratio, and floor response spectrum at the top of the test model are shown in Figs.9 ~11 respectively. Analyses agree well with the experiments.

(2) SANSSI

Seismic response analysis with SANSSI (frequency response analysis) was carried out for "INTERACTION TEST" where earthquake observation data shown in Table 3 were given. The site layout of structure model is the same as the test AC5 in Fig.2. Analytical model for Model A is shown in Fig.12. The soil is modelled by a 2 dimensional finite element,and the structure is modelled by the "Lumped Mass Model". Energy-transmitting boundary for both sides and viscous boundary for bottom are assumed,respectively,considering the semi-infinity of the soil.

The analytical and observed results of the maximum response acceleration are shown in Fig.13. Though some differences which might be caused by the characteristics of each earthquake appear between both results,their distribution indicates good agreement.

(3) SANSOL

Response analysis using SANSOL was carried out for the forced vibration test BD4 (input motion : sine wave) in "INTERACTION TEST". Outline of the test and the twin structure model on the soil is shown in Fig.14. The analytical model is shown in Fig.15. The soil is modelled by a 3 dimensional thin layered element and the structure is modelled by the "Lumped Mass Model". Viscous boundary at the bottom of the soil is assumed considering the semi-infinity of the soil.

The analytical and experimental results of displacement resonance curve at the evaluated points are shown in Fig.16. Though the analytical amplitudes around the

2nd peak for the smaller structure are a little lower than the experimental results,overall tendency agrees well.

(4) SANSTR

Seismic response analysis(time history response analysis) was carried out using SANSTR for the forced vibration test by shaking table in "FLOOR RESPONSE TEST" (input motion : artificial earthquake wave with the maximum acceleration of 50 gal) with a BWR reactor building model which interacts with soft soil; stiffness of the soil corresponds to a shear wave velosity of 750m/s for a real reactor building. Outline of the test model is shown in Fig.17, and one quarter analytical model of the test model is shown in Fig.18. Walls and slabs are modelled by the shell elements,and base mat and soil are modelled by solid elements,respectively.

The analytical and experimental results of the maximum response accelerations along the elevations of the center of shield wall(S/W),inner box wall(I/W) and outer box wall (O/W) are shown in Fig.19. They agree well with each other.

(5) SANSHL

Response analysis(spectrum modal analysis) was carried out with SANSHL for the forced vibration test by shaking table(input motion: artificial earthquake wave with the maximum acceleration of 600gal) in "CONTAINMENT VESSEL TEST". Outline of the test model is shown in Fig.20. The axisymmetric analytical model is shown in Fig.21. The lumped mass and shell element are applied.

The analytical and experimental results of natural frequencies and natural modes(oval mode) and the distribution of the maximum response acceleration are shown in Figs.22~24. Their analytical and experimental results showed good agreement to each other. Though the distribution of the maximum acceleration looks to be a little different in the area which is affected by ovalling, overall tendency indicates good agreement.

(6) SANREF

Static nonlinear analysis was carried out with SANREF for the static lateral load test of BWR and PWR reactor building models in "RESTORING FORCE CHARACTERISTIC TEST". BWR and PWR reactor building models are shown in Figs.25 and 27. One half analytical models for those test models are shown in Figs.26 and 28. Multi-layered shell element is applied in the analytical model. An assumed stress-strain relation of concrete based on the plastic theory is shown in Fig.29.

The analytical and experimental results of load-deflection curves are shown in Fig. 30 for BWR and Fig.31 for PWR. Those results agree well in both models.

3 CONCLUSION

The seismic response analyses,response analyses for the forced vibration tests and static nonlinear analyses were performed by use of 6 SAN series codes on 5 seismic tests, and the analytical and test results were compared with each other for each case.

Both the results agreed well in every cases,and the reliability and effectiveness of the above mentioned codes have been verified.

4 ACKNOWLEDGEMENT

The authors wish to express their gratitude to a Committee on Seismic Safety in JINS for their cooperation and valuable suggestions.

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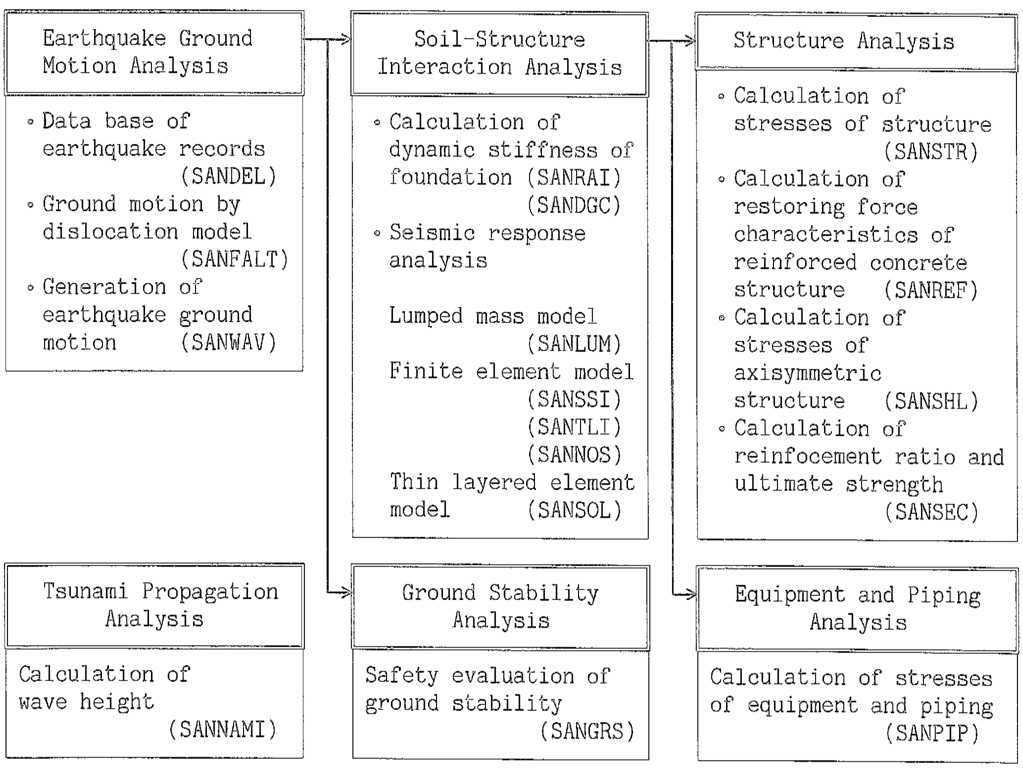


Note : Names of SAN-Series codes are shown in parentheses.

Fig.1 Seismic Analysis Flow of Nuclear Power Plants and SAN Series Codes

Table 1 Synopsis of 6 Codes

Code Name	Outline of Codes
① SANLUM Lumped Mass Model Analysis Code	Seismic response analysis code concerned with the soil-structure interaction by lumped mass model. Structural nonlinearity can be considered.
② SANSSI Soil-Structure Interaction Analysis Code	Two-dimensional finite element code for the soil-structure interaction analysis. Semi-infinity of soil can be considered by viscous and energy-transmitting boundaries.
③ SANSOL Layered Soil Structure Interaction Analysis Code	Thin layered element code for the soil-structure interaction analysis of structure embedded in three-dimensional layered soil medium.
④ SANSTR General Structure Analysis Code	Three-dimensional linear static and dynamic analysis code by finite element for calculating stress and deformation, etc. of strutures.
⑤ SANSHL Axisymmetric Structural Analysis Code	Code for static analysis and dynamic response analysis of axisymmetric structure such as containment vessel. It is also applicable to heat conduction and creep problems of concrete.
⑥ SANREF Restoring Force Characteristics Analysis Code	Static non-linear finite element code to evaluate the restoring force characteristics and ultimate strength of reinforced concrete structures.

Table 2 Synopsis of Seismic Tests

Seismic Tests	Outline of Seismic Tests	Applied Code
(a) INTERACTION TEST Model Test on Dynamic Interaction between Reactor Building and Soil	Test model was set on real soil. Forced vibration test by vibration exciter and natural earthquake observation were carried out. The purpose of the test is to evaluate the dynamic interaction between soil and reactor building and between adjacent buildings. 1),2),3)	SANLUM SANSSI SANSOL
(b) BASE UPLIFT TEST Model Test on Base Mat Uplift of Reactor Building	Forced vibration test of the test model for soil and structure by shaking table, forced vibration test by vibration exciter and static load test of concrete block on real soil were carried out. The purpose of the test is to investigate the uplift phenomenon of base mat of reactor building in case of earthquake. 4)	SANLUM
(c) FLOOR RESPONSE TEST Model Test on Development of Floor Response Spectra	Forced vibration test by shaking table was carried out for BWR and PWR reactor building models which interact with soil. The purpose of test is to investigate the influences of local vibration of building(in-plane vibration of slab and out-of-plane vibration of wall) and out-of-plane vibration of base mat on the floor response spectra and of soil rigidity.	SANSTR
(d) CONTAINMENT VESSEL TEST Seismic Proving Test for Reactor Containment Vessel	Forced vibration test by shaking table and leak rate test were carried out for PWR reactor containment vessel(steel) in order to prove the seismic safety and air tightness after vibration.	SANSHL
(e) RESTORING FORCE CHARACTERISTIC TEST Model Test for Evaluation of Restoring Force Characteristics of Reactor Building	Static lateral load test was carried out for small, partial and total models of reactor building of BWR and PWR. The purpose of the test is to investigate nonlinear behavior of reactor buildings under large scale seismic force. 5)	SANREF

Note: Reference number in the middle column are the same with numbers in page 4.

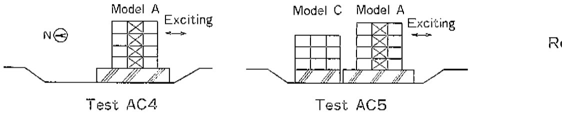


Fig.2 Outline of Tests AC4 and AC5 (Test (a))

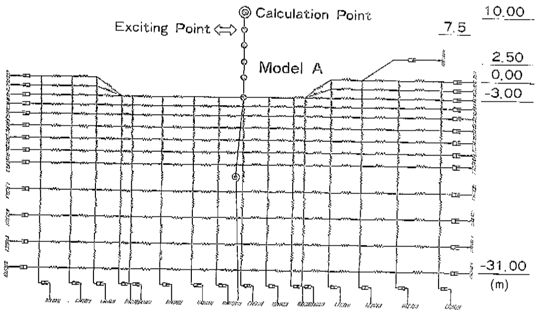


Fig.4 Analytical Model AC4(SANLUM)

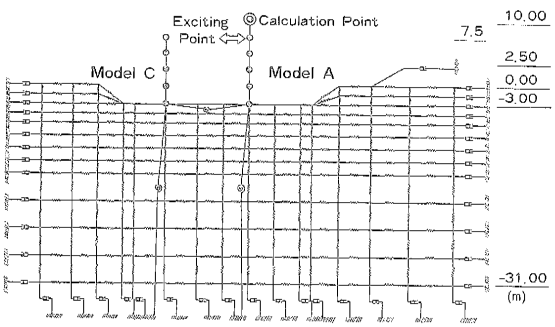


Fig.5 Analytical Model AC5(SANLUM)

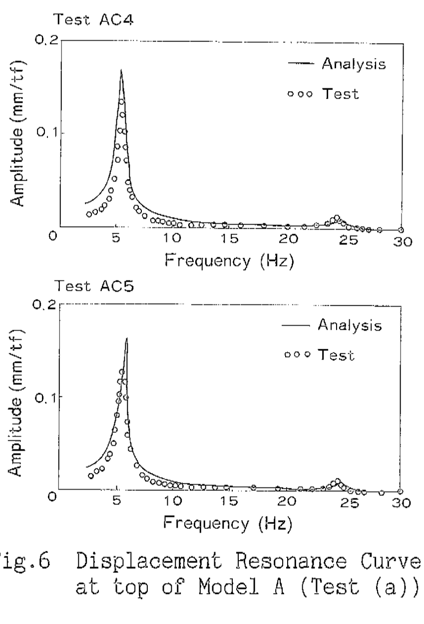


Fig.6 Displacement Resonance Curve at top of Model A (Test (a))

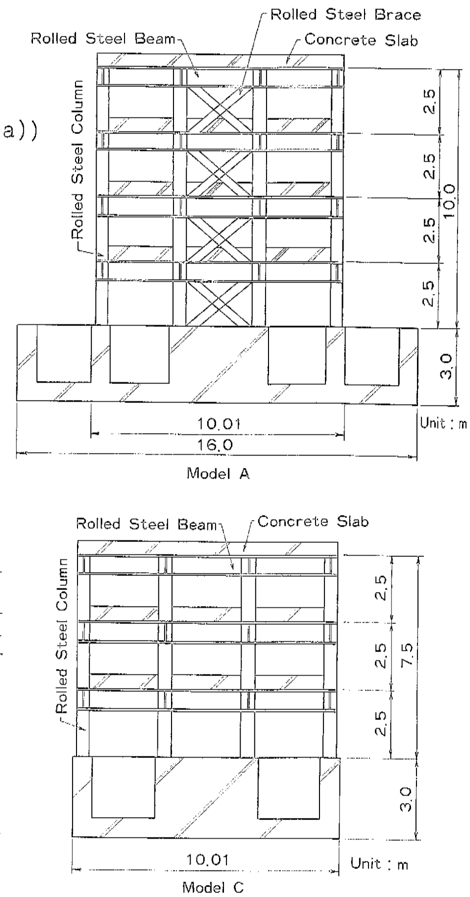


Fig.3 Test Models A and C (Test (a))

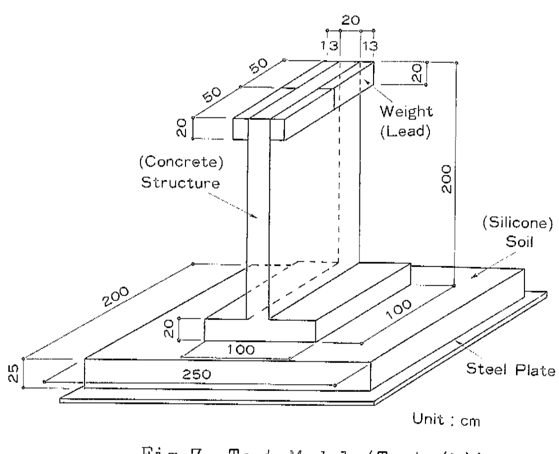


Fig.7 Test Model (Test (b))

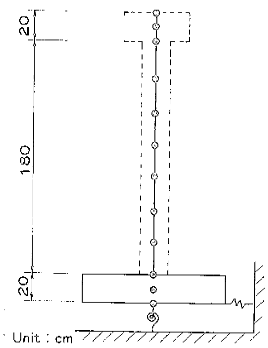


Fig.8 Analytical Model of Test (b) (SANLUM)

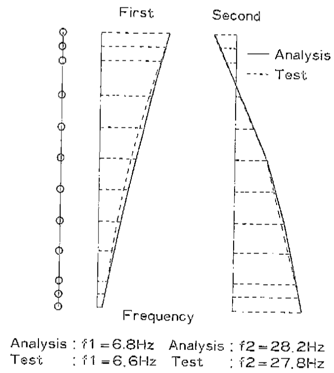


Fig.9 Natural Frequency and Natural Mode (Test (b))

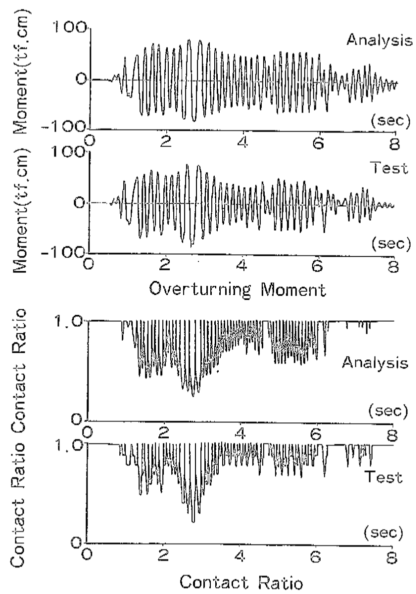


Fig.10 Overturning Moment and Contact Ratio (Test (b))

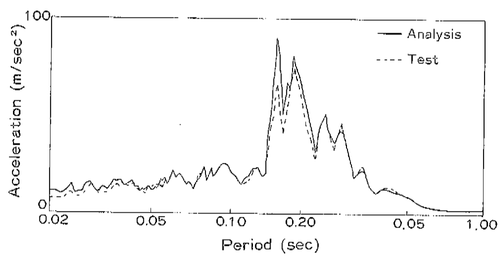


Fig.11 Floor Response Spectrum at top of Model (Test (b))

Table 3 Outline of Earthquakes (Test (a))

No.	Date	Origin Time (JST)	M	D (km)	X (km)	Δ (km)	Amax (gal)
1	Mar. 29, 1985	1:07	6.5	164	327	322	12.2
2	Aug. 12, 1985	12:49	6.4	52	97	82	49.6
3	Oct. 4, 1985	21:25	6.1	78	203	189	7.5

M : Magnitude D : Depth X : Hypocentral Distance Δ : Epicentral Distance
Amax : Maximum Acceleration of Free Surface Ground Motion(Horizontal Direction)

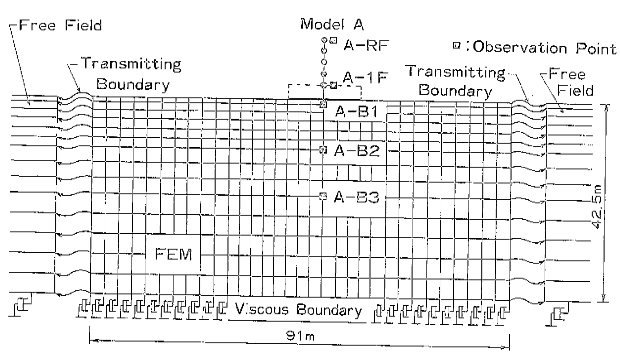


Fig.12 Analytical Model of Model A (SANSSI)

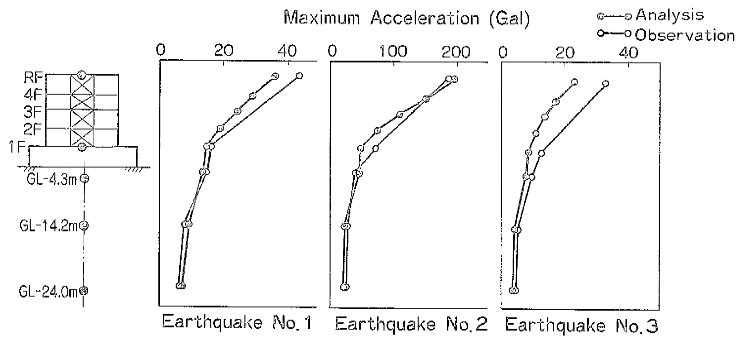


Fig.13 Distribution of Maximum Response Acceleration
(Earthquake Observation in Test (a))

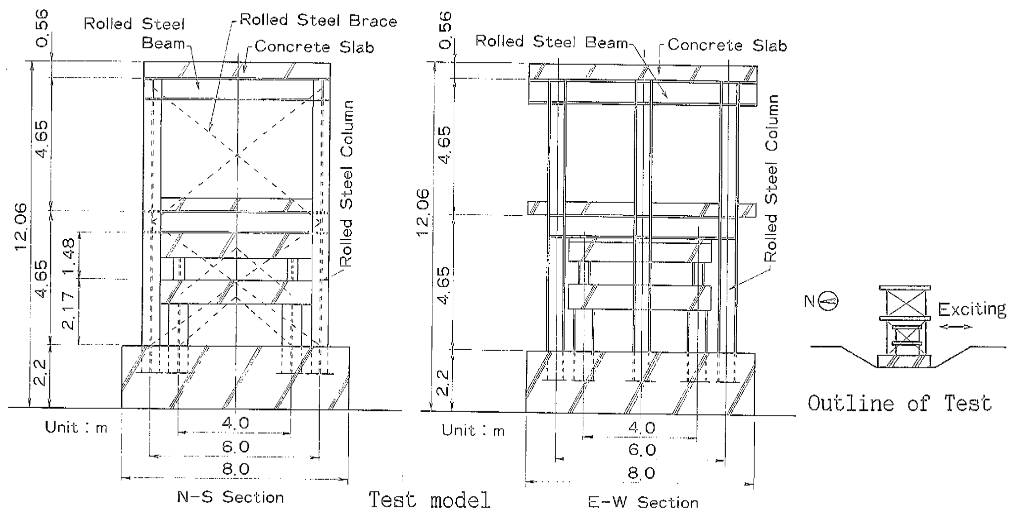


Fig.14 Outline of Test BD4 and Test Model (Test (a))

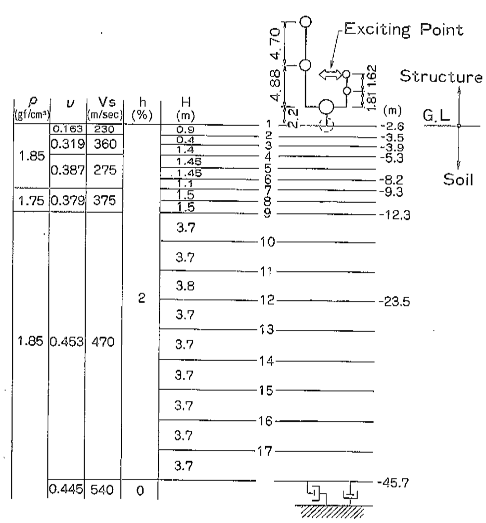


Fig.15 Analytical Model BD4(SANSOL)

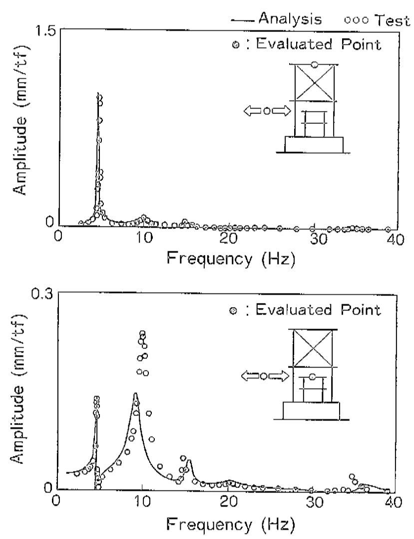


Fig.16 Displacement Resonance
Curve of Test BD4

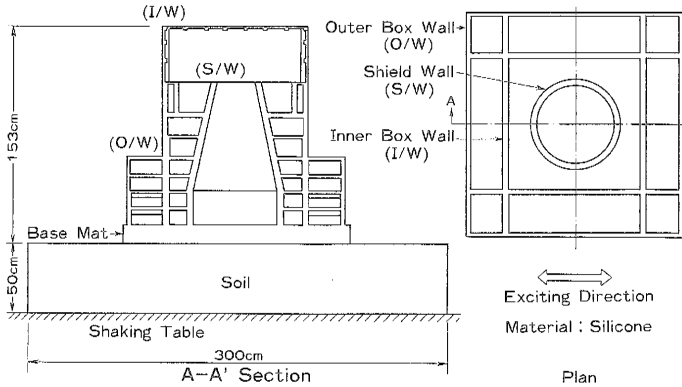


Fig.17 Test Model of BWR Reactor Building (Test (c))

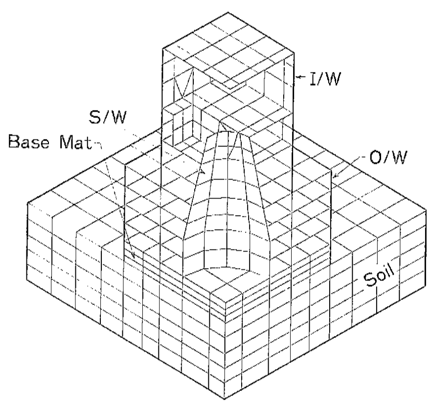


Fig.18 Analytical Model of BWR Reactor Building Model (SANSTR)

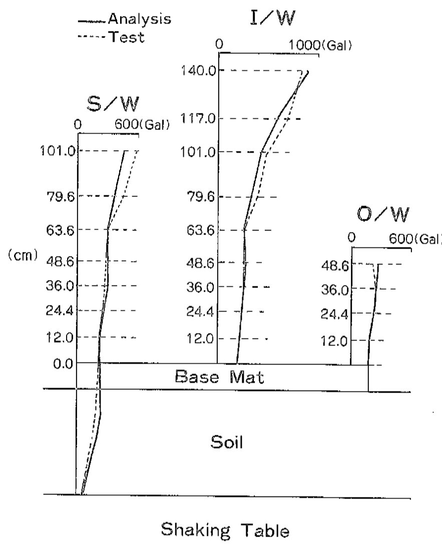
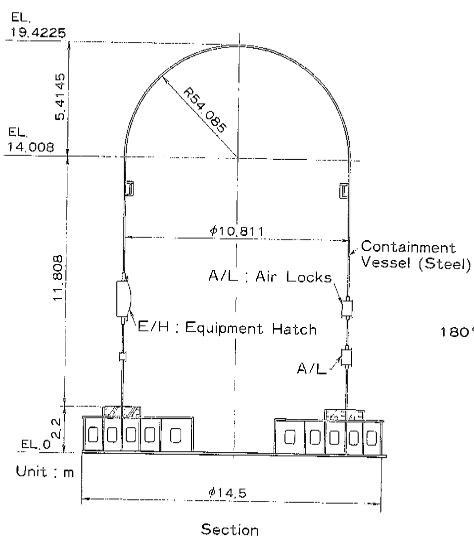


Fig.19 Distribution of Maximum Response Acceleration (Test (c))



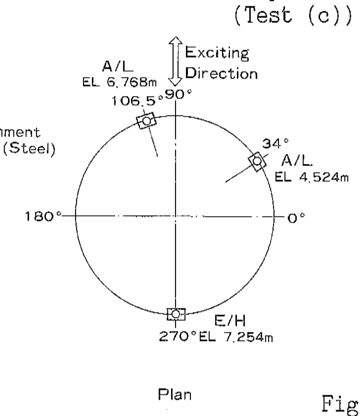


Fig.20 Test Model of PWR Containment Vessel(Test (d))

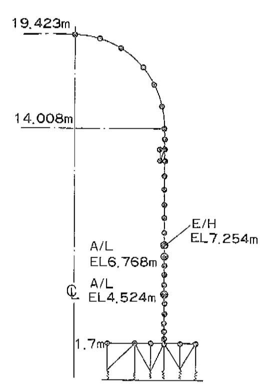


Fig.21 Analytical Model of Test (d) (SANSHL)

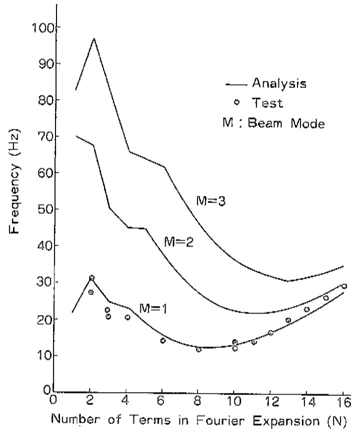


Fig.22 Natural Frequency (Test (d))

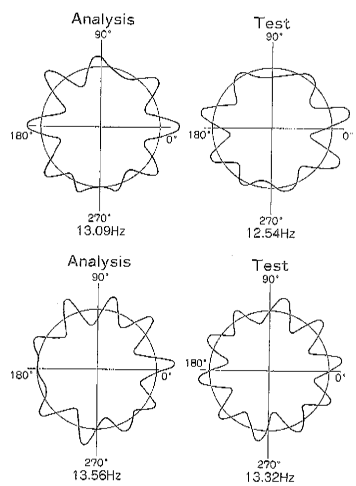


Fig.23 Oval Modes (Test (d))

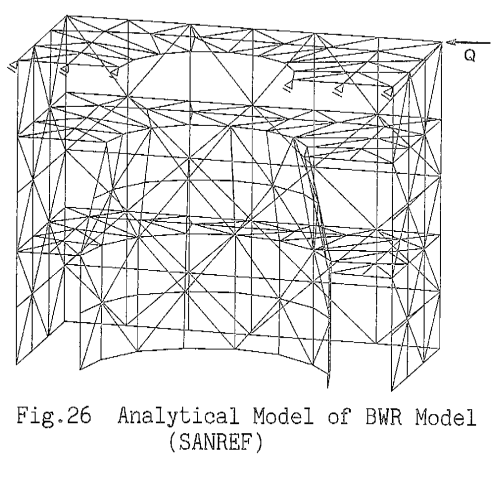


Fig.26 Analytical Model of BWR Model (SANREF)

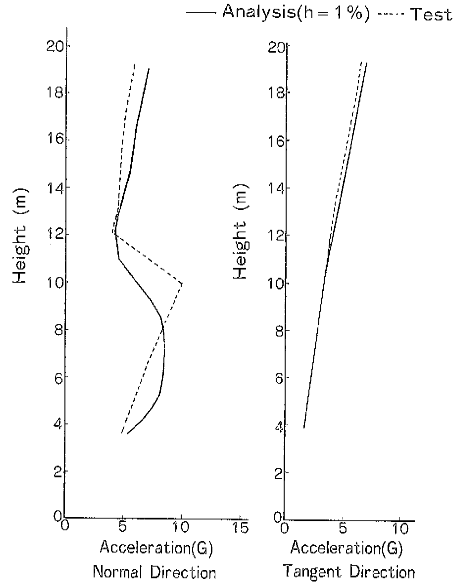


Fig.24 Distribution of Maximum Response Acceleration (Test (d))

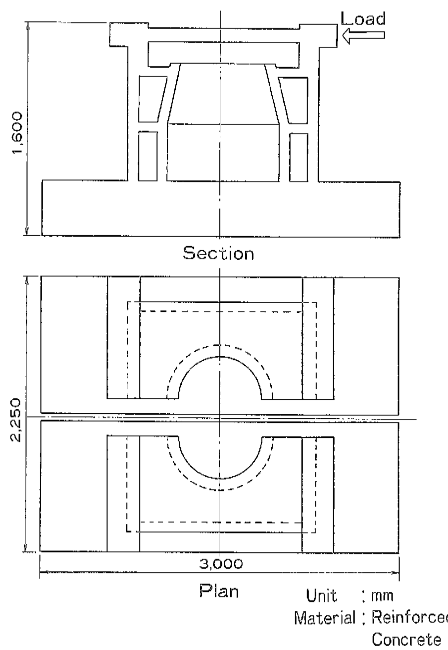


Fig.25 Test Model of BWR Reactor Building (Test (e))

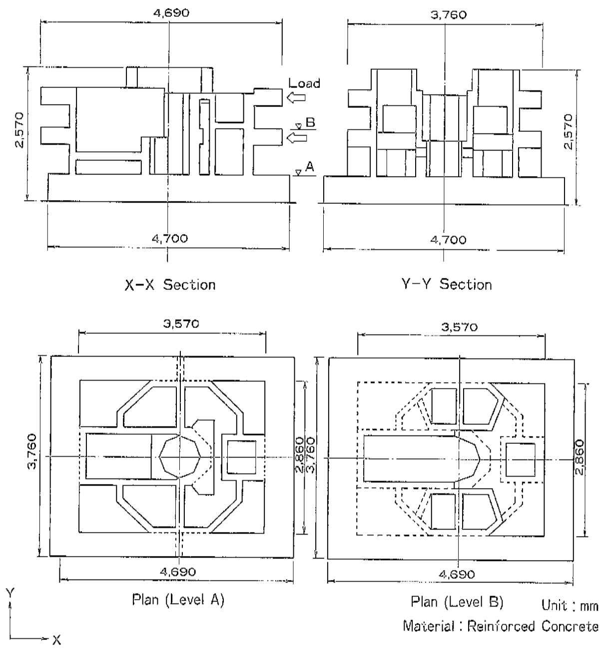


Fig.27 Test Model of PWR Reactor Building (Test (e))

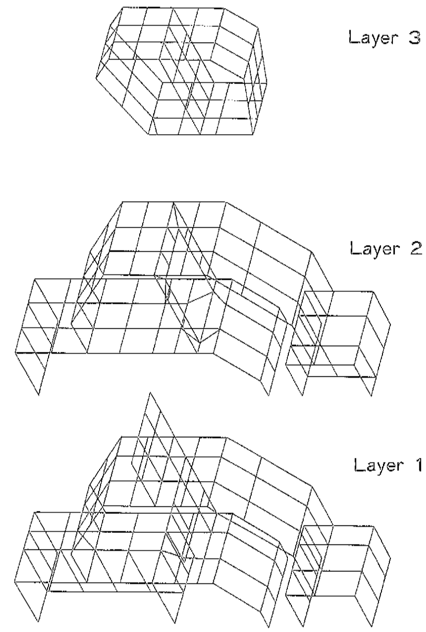


Fig.28 Analytical Model of PWR Model (SANREF)

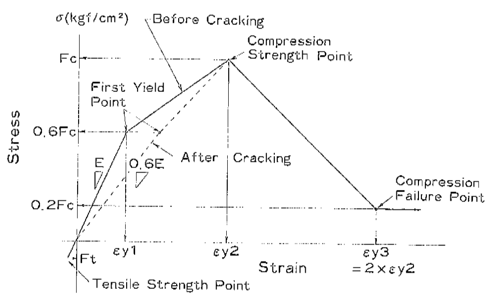


Fig.29 Stress-Strain Relation of Concrete

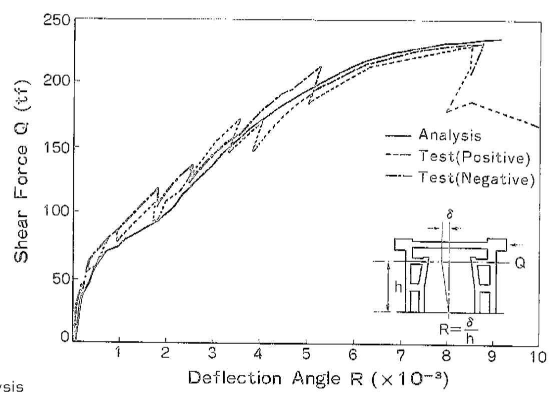


Fig.30 Load-Deflection Curve of BWR Model

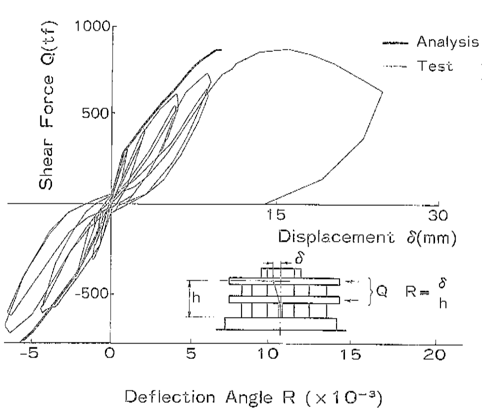


Fig.31 Load-Deflection Curve of PWR Model