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Study on horizontal and vertical seismic response model of PWR-type reactor building

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ABSTRACT : Implementing a FEM model, the three-dimensional (3-D) vibration properties of a Pressurized Water Reactor (PWR) type reactor building is studied. For design purposes, a 3-D FEM model is not practical for the assembling. Therefore, a simplified lumped mass model is proposed in lieu of the 3-D FEM model. As regards the analytical results, a simplified lumped mass model can be used for the horizontal and vertical simultaneous seismic response analysis design model of the PWR-4Loop type reactor building.

1. INTRODUCTION

In Japan, the vibration models of reactor buildings for horizontal ground motion have been studied and examined through many simulation analyses for forced vibration tests and earthquake observations of actual reactor buildings. However, the vibration models for the horizontal and vertical simultaneous input motion have not been so much studied as the single input motion models.

In this paper, the horizontal and vertical simultaneous seismic response analysis models of a PWR-type reactor building, considering the soil-structure interaction effect, are numerically studied. Primarily a three-dimensional finite element model (3-D FEM) is assembled for realizing dynamic response characteristics. For the design purposes, a 3-D FEM model is not practical for the parametric study. Consequently 3-D and 2-D multi-stick lumped mass models for horizontal and vertical interactive response are assembled. And then these multi-stick lumped mass models are compared with the 3-D FEM model which could be regarded as the reference model.

2. ANALYTICAL CONDITIONS

2.1 *Outline of the Reactor Building and Material Properties*

For this study, a PWR-4Loop type reactor building is drawn up. The PWR-4Loop type reactor building consists of the Prestressed Concrete Containment Vessel (PCCV), Internal Concrete structure (I/C) and Reactor External Building (REB) on the 72.0m×100.0m rectangular foundation and these are structurally isolated from each other. The total weight of the reactor building is about 286,000tf. The plot plan (EL+16.5m) and section (N-S Direction) are shown in Fig. 1. The reactor building is primarily made of reinforced concrete, while the fuel handling building (FHB) in the REB is a steel structure. The reactor building is assumed to be founded on a rock ground surface without embedment.

The material properties of concrete and steel which is used the reactor building are shown in

Table 1. The soil shear wave velocities is Vs=1500 m/s and the other soil conditions are shown in Table 2.

2.2 *Analytical Models*

The reactor building form is almost symmetrical with respect to the N-S axis. The center of geometry and gravity are almost same,consequently the influence of eccentricity is few. Based on this assumption, a half portion of the reactor building is modeled in case of 3-D FEM Model and 3-D Multi Stick Lumped Mass Model.

Consequently the study of the vibration properties (Transfer function to input motion etc.) by the 3-D FEM Model, it is obvious that the vertical response contains the effect of rotational of the foundation and bending of the seismic walls during the horizontal input motion. The effects of the horizontal input motion are notable at the edge of the structure, especially upper floor level. Therefore in case of the 3-D and the 2-D Multi Stick Lumped Mass Model, the effects of the horizontal input motion are evaluated about the Pressurizer wall (PRZ) and the springline level of the PCCV (The level of Polar Crane Girder) for representative points. The following is the outline of the horizontal and vertical simultaneous seismic response analysis models which are surveyed in this paper, as shown in Fig.2 and Table 3.

• 3-D FEM Model

The 3-D FEM Model is a reference model for realizing the vibration characteristics of reactor building. The foundation modeled as solid and shell elements, and the seismic walls, the floor-slabs and roof-slab are modeled by shell elements. Steel beams and columns are modeled as beam elements. The interactive complex soil springs are estimated on the basis of the thin layer element method. And the soil springs are connected with every nodal points of the meshes of the foundation bottom.

• 3-D Multi Stick Lumped Mass Model

The walls of the PCCV and I/C are single stick lumped mass models and the foundation is rigid. The seismic walls in the REB are modeled as five stick models with lumped masses. And the columns and floor slabs are modeled by 3-D beam element and FHB roof slab is modeled by shear springs. The soil stuffiness and damping for sway and rocking motion are evaluated as a constant value on the basis of the vibration admittance theory.

As regards the effects of the horizontal input motion, the vertical response due to rotational of the foundation and bending of the seismic walls is evaluated simplistically in consideration of the eccentricity distance from the rotational center. The base of the PRZ wall is connected to the same level mass point of the S/G wall by the 11.4m length of rigid beam element. And the evaluation points of the PCCV are connected to the same level mass point of the PCCV by the $\pm$22.8m length of rigid beam element.

• 2-D Multi Stick Lumped Mass Model

The PCCV and I/C are much the same as 3-D Multi Stick Lumped Mass Model and the foundation is rigid. The the seismic walls in the REB are modeled as three stick models with lumped masses. The sticks are two-dimensional beam element and the floor slabs are modeled by the axial springs and the shear springs. The soil interactive springs are the same as 3-D Multi Stick Lumped Mass Model.

2.3 *Seismic Ground Motion*

The input horizontal and vertical input ground motion are an artificial waves with the phase angle sets of the EL Centro observed accelerogram, and those are simulated so as to fit the target spectra. The vertical target spectrum is generated by the horizontal design response spectrum with the magnitude of 7.0 and epicentral distance of 20 km, but the control point values of the vertical target spectrum depend on the transfer coefficient to the horizontal design response spectrum.

The input horizontal and vertical acceleration time histories and those acceleration response spectra with 5% damping are shown in Fig. 2. The horizontal maximum acceleration is 267.4 gal and vertical maximum acceleration is 172.1 gal.

3. ANALYTICAL RESULTS

3.1 *Modal Analysis*

Table 4 shows the comparison of the typical natural frequencies and periods of each analysis model on condition that degree-of freedom (DOF) at the foundation bottom is fixed. The horizontal and vertical natural frequencies and periods of the 3-D FEM Model are almost the same as the Multi Stick Lumped Mass Models.

Fig. 4 shows the typical mode shapes of the 3-D FEM Model on condition that the DOF at the foundation bottom is fixed. The first mode is the natural frequency of FHB in the horizontal direction at 2.39Hz and the second mod is the natural frequency in the center of the FHB roof in the vertical direction at 4.66Hz. The natural frequency of the PCCV in the horizontal direction is 3.24Hz. The natural frequencies of the I/C in the horizontal direction are 7.87Hz and 10.63Hz.

3.2 *Transfer Function*

By way of example, the acceleration transfer functions of typical points at PCCV to horizontal and vertical excitation in the 3-D FEM Model (Soil-structure interaction model) are shown in Fig.5. Regarding the horizontal acceleration transfer functions to horizontal excitation (Ih⇒Ah), the PCCV has a peak value at about 4.8Hz. And there are the same peaks at the springline level points in the vertical transfer functions (Ih⇒Av),the peak values are the influence of the horizontal excitation.

3.3 *Maximum Acceleration Value*

Table 5 shows the comparison of the maximum response accelerations at the principal points of each analysis model. The vertical acceleration of the PCCV in the Multi Stick Lumped Mass Models are larger than those in the 3-D FEM Model but the horizontal accelerations are almost the same as each models.

As regards the result of I/C, the horizontal accelerations of the PRZ wall in the 3-D FEM Model are larger than those in the Multi Stick Lumped Mass Models, and the horizontal accelerations of the S/G wall in the 3-D FEM Model are smaller those in the Multi Stick Lumped Mass Models. But the vertical accelerations of the PRZ and S/G wall are almost the same as each model. The horizontal and vertical accelerations in the roof of FHB and on the center of foundation are in good agreement among each model.

3.4 *Floor Response Spectrum*

The comparison of acceleration response floor response spectra (FRS) between lumped mass models and 3-D FEM model are shown in Fig.6 through Fig.9. Fig.6 shows the comparison at the top of PCCV and Fig.7 shows the springline level of the PCCV. The peak value of vertical FRS at the top of PCCV in the Multi Stick Lumped Mass Models are little larger than that of the 3-D FEM model, but the horizontal FRS are in good agreement each other.. The horizontal and vertical FRS at the springline level of the PCCV in the Multi Stick Lumped Mass Models are in good agreement with the FRS of 3-D FEM model. It is surmised that the peak at about 0.21 second of the vertical FRS is due to the rocking motion which is caused by the horizontal motion. Because the natural period of the first horizontal mode of PCCV is about 0.21 second (4.7Hz).

Fig.8 shows the FRS at the top and bottom of PRZ wall and Fig.9 shows the FRS at the top and bottom of S/G wall. The horizontal and vertical FRS at the top and bottom of the PRZ wall in the Multi Stick Lumped Mass Models are in good agreement with the FRS of 3-D FEM model. It is surmised that the peak at about 0.13 second of the vertical FRS is due to the rocking motion which is caused by the horizontal motion. The natural period of the first horizontal mode of I/C is about 0.13 second (7.7Hz). The horizontal and vertical FRS at the top and bottom of the S/G wall in the Multi Stick Lumped Mass Models are larger than that of the 3-D FEM model in the higher frequency range (<0.02 second), but the shape of FRS are in good agreement each other.

4. CONCLUSIONS

Horizontal and vertical simultaneous seismic response models of PWR 4-loop reactor building were numerically studied by comparing dynamic characteristics of lumped mass models to that of 3-D FEM model. As a result of the comparison, it was found that even most simplified 2-D multi-stick lumped mass model can reasonably represent the dynamic characteristics of the reactor building. Therefore 2-D multi-stick lumped mass model is considered to be the rational horizontal and vertical simultaneous seismic response model for primary design purpose.

ACKNOWLEDGMENT

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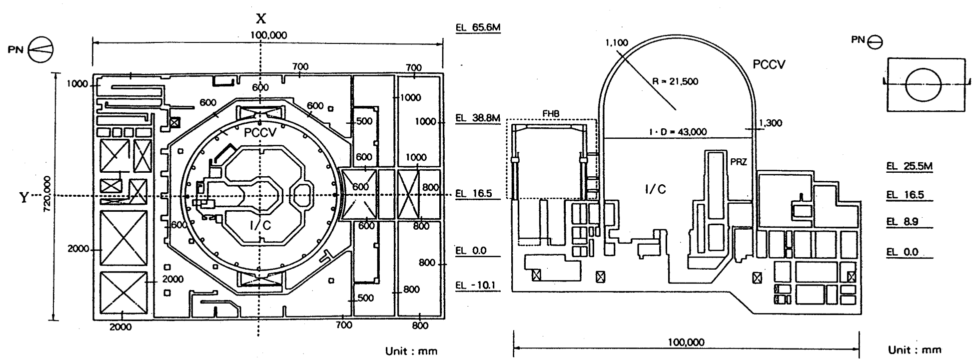


(a) PLAN (EL+16.5m)　　(b) SECTION (N-S Direction)

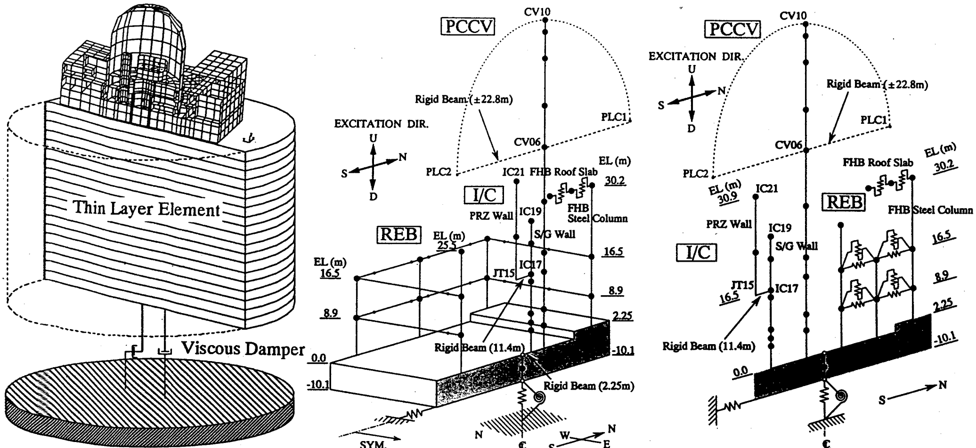
Fig.1 Plan and Cross Section of PWR-4Loop Type Reactor Building

Table 1 Material Properties of Building

	PCCV	I/C,REB (RC) Foundation	REB (Steel)
Young's Modulus (10^5kgf/cm^2)	3.15	2.57	21.00
Shear Modulus (10^5kgf/cm^2)	1.35	1.10	8.10
Compressive Strength (kgf/cm^2)	450	300	—
Damping Factor	0.03	0.03	0.02

Table 2 Material Properties of Soil

Shear Wave Velocity Vs(m/s)	1500
Unit Weight (t/m^3)	2.3
Poisson's Ratio	0.38
Shear Module(10^5t/m^2)	5.28

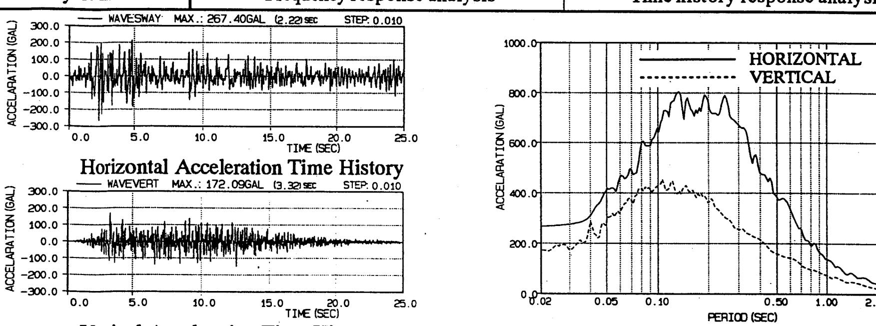


(a) 3-D FEM model (b) 3-D multi stick lumped mass model (c) 2-D multi stick lumped mass model

Fig.2 Horizontal and Vertical Simultaneous Seismic Response Analysis Models

Table 3 Outline of the Analytical Model Conditions

	3-D FEM model	3-D multi stick lumped mass model	2-D multi stick lumped mass model
Extent of the modeling	1/2 portion of the building		Whole building
Interaction spring	Interactive complex soil springs connected with every nodal points of the foundation (Thin layer element method)	Constant sway and rocking springs based on the wave propagation theory (Vibration admittance)	
Analysis method	Frequency response analysis	Time history response analysis	



Horizontal Acceleration Time History

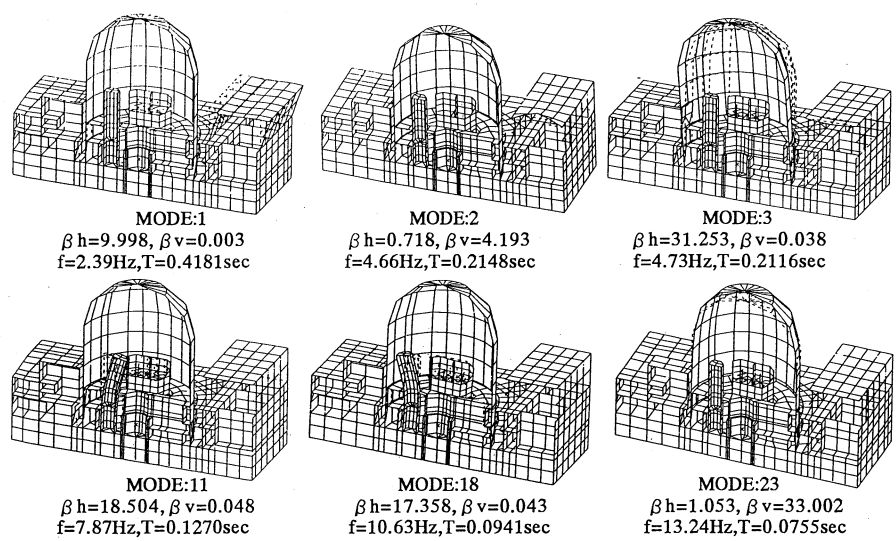
Vertical Acceleration Time History

Acceleration response spectra (h=0.05)

Fig.3 Input Ground Motion

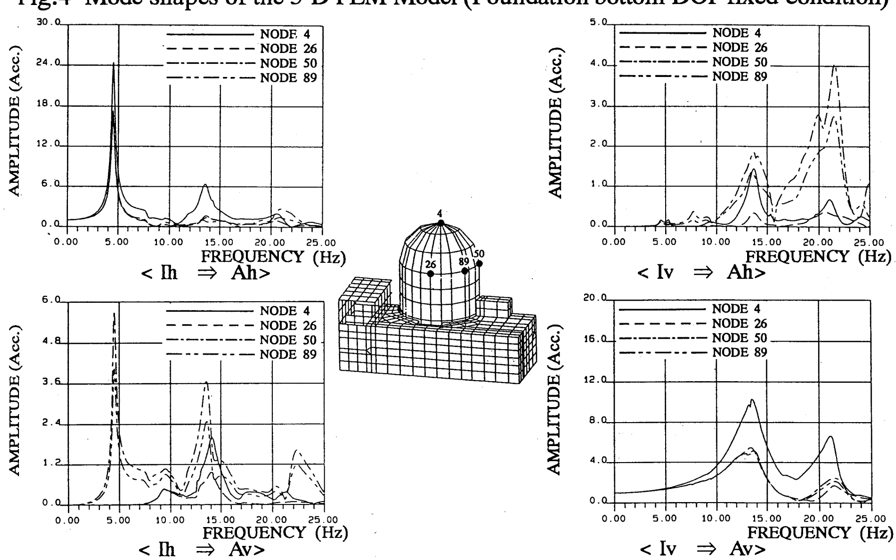
Table 4 Fundamental Natural Frequency and Period (Foundation bottom DOF fixed condition)

3-D FEM			3-D multi stick lumped mass			2-D multi stick lumped mass			Remarks
No.	f(Hz)	T(sec)	No.	f(Hz)	T(sec)	No.	f(Hz)	T(sec)	
1	2.392	0.4181	1	2.375	0.4211	1	2.375	0.4210	FHB (Horizontal)
2	4.655	0.2148							Roof Center of FHB (Vertical)
3	4.727	0.2116	2	4.691	0.2132	2	4.689	0.2133	PCCV (Horizontal)
4	5.274	0.1896	3	5.122	0.1952	3	5.123	0.1952	Roof Edge of FHB (Vertical)
11	7.874	0.1270	4	8.194	0.1220	4	8.194	0.1220	I/C (Horizontal)
18	10.63	0.0941							I/C (Horizontal)
23	13.24	0.0755	10	13.82	0.0724	9	13.82	0.0724	PCCV (Vertical)



(βh: Horizontal Participation Factor, βv: Vertical Participation Factor, f: Frequency, T: Period)

Fig.4 Mode shapes of the 3-D FEM Model (Foundation bottom DOF fixed condition)

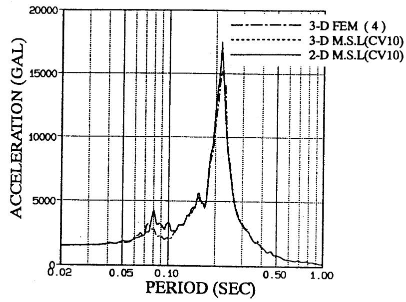


(Ih :Horizontal Input Motion Iv :Vertical Input Motion, Ah :Horizontal Amplitude, Av :Vertical Amplitude)

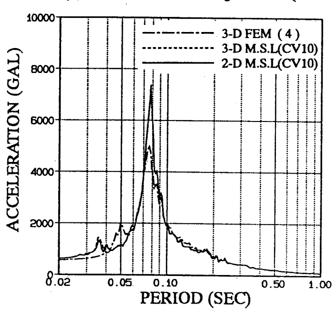
Fig.5 Acceleration Transfer Functions at PCCV to the Input Motion for the 3-D FEM Model

Table 5 Maximum Response Acceleration (Vs=1500m/sec)

		3-D FEM		3-D multi stick lumped mass		2-D multi stick lumped mass	
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
PCCV	Top	1495	562	1528	626	1533	622
	Springline Level	884-967	349-595	890	706,604	891	709,608
I/C	Top of PRZ Wall	2629-2659	310-471	2169	430	2168	459
	Top of S/G Wall	762-923	260-335	1449	254	1456	254
	O/F Level	424-620	242-265	808	205	821	204
REB Roof of FHB		669-679	666-1339	633	866	633	867
Center of Foundation		300	221	334	198	335	198



(a) Horizontal component (h=2.0%)



(b) Vertical component (h=2.0%)

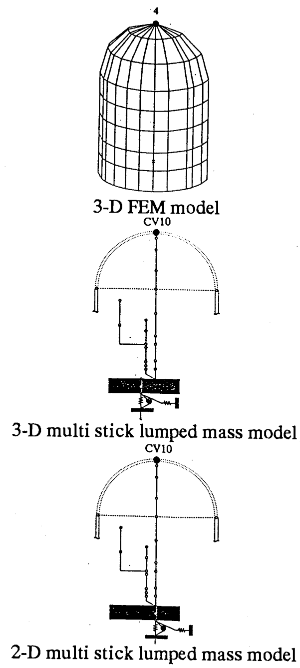
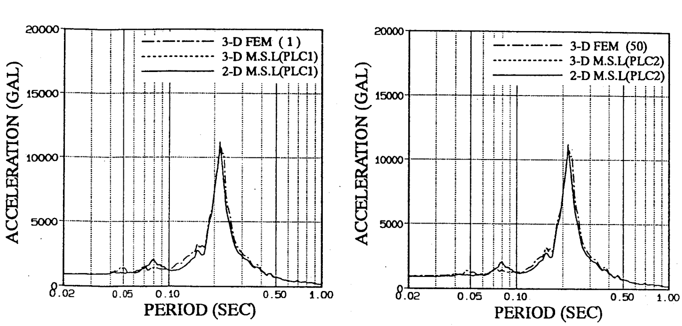
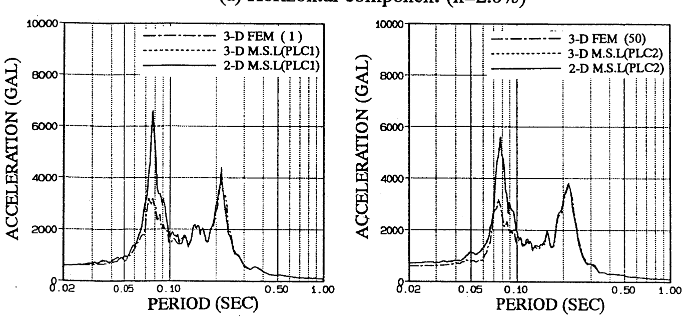


Fig. 6 Acceleration Floor Response Spectra (Top of PCCV)



(a) Horizontal component (h=2.0%)



(b) Vertical component (h=2.0%)

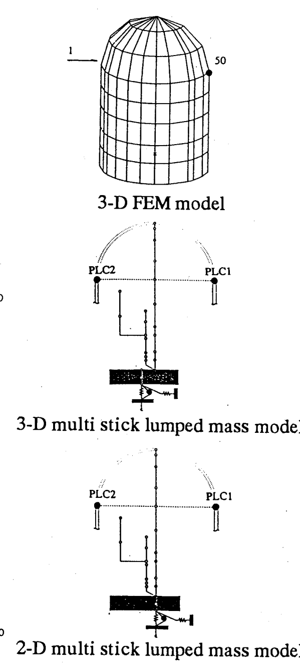


Fig.7 Acceleration Floor Response Spectra (Springline of PCCV)

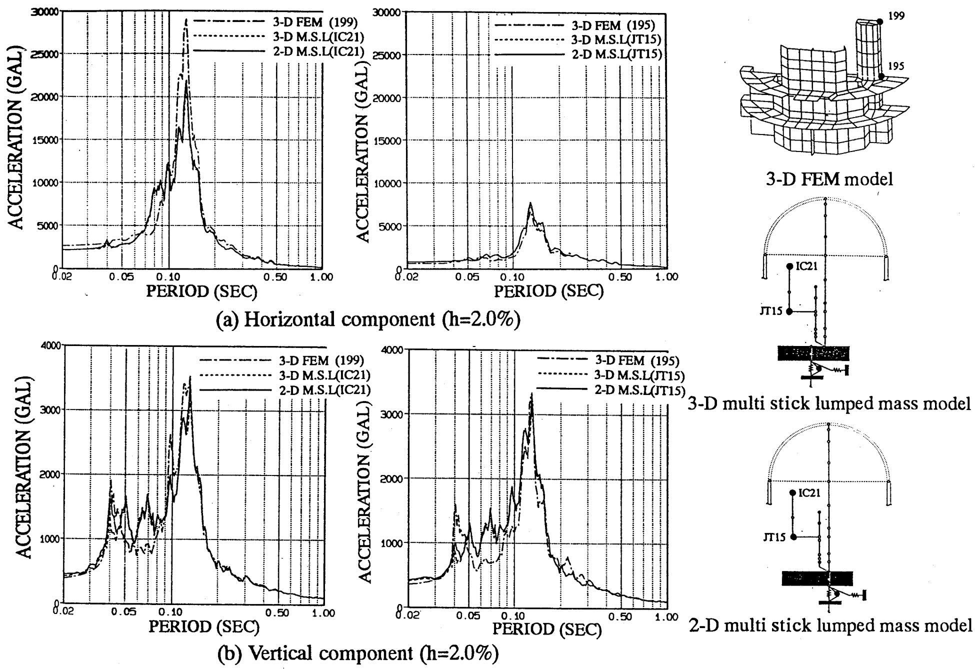


Fig.8 Acceleration Floor Response Spectra (Pressurizer Concrete Wall)

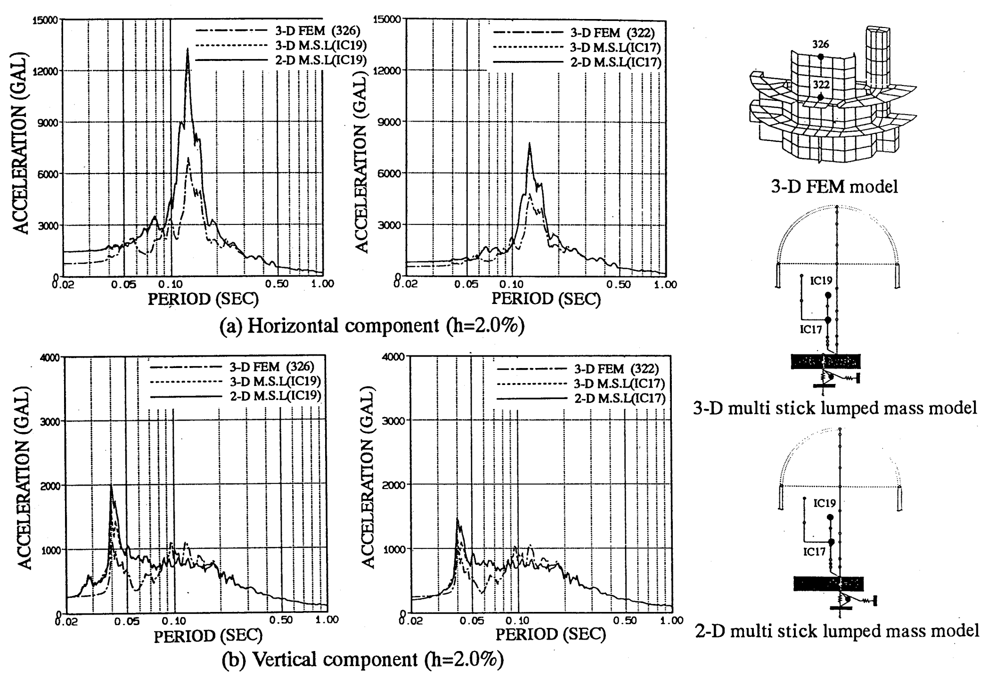


Fig.9 Acceleration Floor Response Spectra (Steam Generator Concrete Wall)