Dynamic Response of Domes in CANDU 600 MWe Containments

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Summary

CANDU reactors of the 600 MWe type are typically housed in a cylinderical prestressed concrete containment structure; rising from a flat slab and ending in a domed roof. The principal components of this structure are: (a) a circular base slab, (b) a vertical cylinder and (c) a spherical dome cap. A unique feature of a CANDU 600 MWe containment structure is the existence of an inner spherical concrete dome, located below the outer spherical dome, which serves as the bottom of a reservoir for the storage of 560,000 imperial gallons of douzing water. The thickness of the prestressed cylinder wall is approximately doubled between the two domes to create a ring beam. Inside the containment there exists an internal concrete structure which is independent of the containment structure except for support on the base slab. The containment boundary is a fully prestressed concrete structure.

This paper deals with the seismic behaviour of the CANDU 600 MWe containment structure and the effect of its unique features; such as the lower dome and the douzing water on this behaviour. The objective of the study is to evaluate the interaction (coupling) effects between the different components of the structure. The approach taken is to study each component of the structure individually, then an assembly of the different components, and finally the total containment structure. This presentation is limited to the vertical response of the structure under a vertical earthquake only. Axisymmetric finite elements were used in all models. The vertical responses at selected points of the structure were obtained by the response spectrum method as well as the time-history method. It was observed that the response spectrum method over-estimates the vertical response of the domes and under-estimates the vertical responses of the ring girder and the containment cylinder compared to the time-history method.

The effect of the presence of the lower dome and the douzing water on the upper dome response was studied. It was found that the presence of the lower dome and the douzing water in a CANDU 600 MWe decreases slightly the response of the upper dome and is thus beneficial.

Two solution approaches were followed to obtain the domes assembly response; a direct approach where the total containment structure is analyzed; and a substructure approach where the domes assembly was analyzed in isolation of the total structure. Various boundary conditions and input motions were used in the substructure analysis of the domes assembly. The sub-structure approach proved to be a valuable practical solution when implemented properly.

1. Introduction

CANDU reactors of the 600 MWe type are typically housed in a cylinderical prestressed concrete containment structure. The principal components of this structure are: (a) a circular base slab (b) a vertical cylinder and (c) a spherical dome cap. A unique feature of a CANDU 600 MWe containment structure is the existence of an inner spherical concrete dome located below the outer spherical dome which serves as the bottom of a reservoir for the storage of 560,000 imperial gallons of dousing water. The thickness of the prestressed cylinder wall is approximately doubled between the two domes to create a ring girder. Inside the containment there exists an internal concrete structure which is independent of the containment structure except for support on the base slab. Figure 1 shows a cutway for a CANDU 600 MWe Reactor Building. Figure 2 shows a cross section of the prestressed containment structure and the dimensions of the major components.

2. Objective of the Investigation

The objective of the study is to provide an understanding of the dynamic response of a CANDU 600 MWe containment structure with its unique features; mainly the existence of the lower dome and the dousing water. The approach taken here is to study each component of the structure individually, then an assembly of different components, and finally the total containment structure. The nature of interaction between various components is not the same for a vertical ground motion compared to that of a horizontal ground motion. The dominant vertical frequencies of the domes are lower than those of the containment cylinder whereas the dominant horizontal frequencies of the domes are much higher than those of the containment cylinder. This may suggest that in the horizontal direction the upper assembly of domes may ride on the containment cylinder in a rigid manner. Because of this basic difference in the interaction phenomena between the horizontal and the vertical directions; as well as for space limitations; the study is limited to the vertical response of the structure under a vertical Design Basis Earthquake (DBE) only. For space limitation the current presentation will not include the interaction with the soil which can be proven to be beneficial to the response of the domes.

3. Description of Substructures used in the investigation

The substructures used in the investigation are all of the axisymmetric type and are modeled by axisymmetric finite element toriods as shown in Figure 2. The main interest in the current study is the vertical response due to a vertical earthquake motion. The vertical response due to a horizontal earthquake motion is eliminated here for space limitation. All substructures used in this investigation have been analysed utilizing the computer program ANSYS (4).

3.1 Upper Dome (UD) and Lower Dome (LD) Behaviour

Although a considerable amount of literature is available on shell vibrations, very little was found with practical value to the CANDU 600 MWe domes. A finite element model of the UD alone was studied. This included four types of boundary conditions at the springing point; fixed; pinned; fixed-sliding horizontally and pinned-sliding horizontally. Frequency results in Table 1 show that the fundamental frequency of the UD alone ranges from 7.46 Hz to 15.14 Hz depending on the chosen boundary conditions. The heavy Ring Girder (RG) which supports the UD places the actual dome's boundary conditions between fixed-sliding and fixed. A similar model was studied for the lower dome (LD) using the same four boundary conditions. The results are displayed in Table 1. From the table it can be observed that the LD is more flexible than the UD. The fundamental frequency for the LD ranges from 7 Hz to 14.93 Hz depending on the boundary conditions. The RG as well as the closed upper dome places the LD boundary conditions between fixed-sliding and fixed.

3.2 Domes Assembly (DA) and Domes Assembly with Water (DA + W) Behaviour

Upper and lower dome models were assembled together through the RG to form the DA model as shown in Figure 2. The same boundary conditions as used for the individual domes were introduced at the bottom of the RG. It can be observed from Table 1 that the three frequencies of the UD below 33 Hz and the three frequencies of the LD below 33 Hz have resulted in 6 coupled frequencies for the DA below 33 Hz, and that the DA has a fundamental frequency between 10.87 Hz and 13.80 Hz, depending on the boundary conditions. The interaction phenomenon between the UD and the LD can be appreciated by comparing the modal quantity '$\Gamma\phi$' (participation factor x mode shape) for node 2 on the UD and node 61 on the LD for the UD, LD and DA models. It was observed in this comparison that the UD actually experienced some reduction in '$\Gamma\phi$' (beneficial interaction) when it was part of the DA. The LD on the other hand experienced some increase in '$\Gamma\phi$'. Thus the domes interaction can be judged to be beneficial for the response of the UD which is a part of the containment boundary. The masses of dousing water (W) were calculated based on tributory volumes and lumped at selected nodes shown in Figure 2. The DA + W was analysed with the same four boundary conditions as discussed before. The first 8 frequencies below 33 Hz are shown in Table 1. The presence of the dousing water mass which is approximately 41% of the concrete mass in DA lowers all frequencies substantially. Figure 3 displays the quantities '$\Gamma\phi$' for nodes 2 and 61 for the cases of DA and DA + W (fixed-sliding boundary conditions) for modes with frequencies below 33 Hz. The addition of masses representing the dousing water has resulted in the phenomenon of 'Breakage of Modes'. The first mode for DA is associated now with the first three modes of the DA + W. To facilitate the comparison, the quantity 'q' ($q = \sqrt{\Sigma(\Gamma\phi)^2}$) which is a measure of acceleration response was calculated for each dome node and for each case. Figure 3 shows that the change in 'q' as a result of adding the water masses is a slight reduction in this acceleration response measure which may prove beneficial.

3.3 Containment Behaviour

The behaviour of the containment structure in the vertical direction is governed by the behaviour of the DA + W and the behaviour of the supporting containment cylinder (C). The fundamental frequency of CANDU 600 MWe C alone is 20.86 Hz [6]. When the total mass of the DA + W was attached as concentrated mass to the top of the C, a frequency of 13.28 Hz was obtained [6]. These two figures represent lower and upper bound estimates for the dominant C mode. The C was modeled with finite elements and the full structure as shown in Figure 2 was analysed. The resulting 10 modes are summarized in Table 1. The introduction of the C into the system (DA + W) involves attempting to inject a new frequency at a particular location. The resulting effect is that frequencies below the new frequency move to the left and frequencies above the new frequency move to the right (Figure 4). The resulting system shows this 'push-right, push-left' phenomenon [2, 3]. To evaluate the effect of the LD and the dousing water on the response of a CANDU 600 MWe containment structure, three independent cases were analysed. Case I - actual structure consisting of DA + W + C; Case II - the same as case I but without water; and Case III - the same as case II but without lower dome. Frequencies obtained for the above three cases are given in Table 1.

4. Evaluation of the Solution Method

The vertical response accelerations at different points, of the three models (Cases I, II and III) were obtained by the response spectrum as well as the time-history methods. In the response spectrum method all modes were combined by the SRSS method. A modal damping value of 3% was assumed for all the resulting modes. The DBE used has a peak vertical ground acceleration of 0.133 g. (2/3 of the peak horizontal ground acceleration). For time-history analysis a spectrum-compatible time-history which is rich in all frequencies has been generated [1]. It can be observed from Table 2 that the response spectrum method leads to higher estimate for the UD and LD responses. On the other hand, the response obtained for the RG as well as the C is lower compared to the time-history results. The response spectrum method results deteriorates near the containment base where the mode shape diminishes to zero at the base. The defficiency of the response at the RG using the response spectrum method can be explained by the fact that some of the contributing modes are interaction modes (e.g. modes 5 and 6 in DA + W + C) and thus are cumulative although not closely-spaced. It appears that such modes should be combined by absolute sum rather than SRSS rule to obtain conservative results.

5. Effect of the Lower Dome and the Dousing Water

It can be observed from Table 2 that the presence of water slightly decreases the response of the UD. The response of the LD is somewhat unchanged. The same trend has been observed in the DA behaviour under 3.2 before. Floor Response Spectra (FRS) generated for RG (node 43), for case I and II are shown in Figure 5 as curves 'A' and 'B' respectively. It can be observed that the peaks of the FRS for curve 'A' are actually lower than those of curve 'B'; an indication that the existence of the dousing water moderates the equipment responses as well. Comparison of Cases II and III shows that the existence of the LD reduces the response of the UD and has a beneficial effect on the containment boundary. These observations hold whether the analysis is performed by the time-history method or the response spectrum method as shown in Table 2.

6. Substructure Approach

The axisymmetric nature of the full model (case I) does not allow a detailed modelling of any equipment attached to the LD (e.g., dousing frame which is supported from the lower dome and carries the dousing pipes). Also, no further refinement of the DA + W finite element discritization may be possible without substantially increasing the computation cost or endangering the accuracy of the solution; in particular when the foundation soil is included in the full model. It is therefore desirable to analyse the DA + W in isolation from the rest of the structure and the underlying soil. The approach proposed here is to subject an isolated refined model of the DA + W to nodal accelerations (or displacements) obtained from a full model (which may have a less refined DA + W). In this approach the input motion to be applied to the base of the isolated DA + W (bottom of RG) was obtained from two different models and was applied in the form of a response spectrum or a time-history. The objective is to investigate the differences in domes response due to different input-motions. The first input motion considered is the motion obtained for node 43 at the bottom of the RG of Case I. The resulting FRS generated from this motion is shown in Figure 5 as curve 'A'. This Ring Girder motion will be termed motion 'A'. By lumping the total mass of the DA + W at node 43 of the C, a simplified model of the structure was constructed. A second motion for node 43 from this model was obtained and the FRS resulting from it is plotted as curve

'C' in Figure 5. This Ring Girder motion will be termed motion 'C'. Comparing curves 'A' and 'C' shows that the simplified model predicts approximately 50% higher response for the structure. The peak of the FRS of curve 'C' is almost twice that of curve 'A'. The 'Breakage of Modes' which is a characteristic of curves 'A' and 'B' does not appear in curve 'C'. The time-history or the corresponding FRS of motions 'A' and 'C' were used as input to the DA + W using four different boundary conditions as discussed before. The vertical acceleration results of these 16 cases (four boundary conditions and two input motions in two forms) are given in table 2. The tabulated results indicate some differences in responses due to the differences in boundary conditions. The acceleration responses resulting from the single peak nature input motion 'C' are almost double those of input motion 'A'; an indication of the conservatism in this input-motion. Comparison of the response accelerations obtained by the substructure approach for input-motion 'A' to those of the full model using the time-history method shows that the substructure approach can be a valuable practical solution if suitable input motions and boundary conditions are selected.

7. Conclusions

Based on the study presented for the vertical response of CANDU 600 MWe domes to a vertical DBE, the following can be concluded: (a) Domes interaction in the CANDU 600 MWe containment was found to be beneficial for the upper dome response which is part of the containment boundary. (b) The presence of the dousing water and the lower dome in the CANDU 600 MWe containment structure decreases slightly the response of the upper dome. These observations hold true whether the analysis is performed by the time-history or the response spectrum methods. The existence of the dousing water also moderates the equipment response (FRS) as well. (c) The response spectrum method leads to higher estimate for the upper and lower domes responses compared to the time-history method. The response obtained for the ring girder as well as the containment cylinder using this method is lower than that obtained by the time-history method. (d) The substructure approach proposed in the paper to calculate domes response can be a valuable practical solution. Special attention, however, should be given in this approach to the input motions to be used and the sub-structure boundary conditions selected in the analysis.

References

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(2) T.S. Aziz and C.G. Duff, 'Decoupling Criteria for Seismic Analysis of Nuclear Power Plant Systems' ASME Paper 78 PVP-27, Proceedings of the ASME/CSME PV&P Conference, Montreal, Canada, June 25-29, 1978.

(3) T.S. Aziz and C.G. Duff, 'Mass Coupling Effects in the Dynamic Analysis of Nuclear Power Plants', ASME Paper 78 PVP-28, Proceedings of the ASME/CSME PV&P Conference, Montreal, Canada, June 25-29, 1978.

(4) ANSYS User Information Manual, Revision 3, Swanson Analysis Systems Inc.

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(6) R.D. Blevins, 'Formulas for Natural Frequency and Mode Shape', Van Nostrand Reinhold Company, 1979.

Table 1 Frequencies of Models analysed in the Study (Hz)

Model	Boundary Conditions	Modes 1	2	3	4	5	6	7	8	9	10
UD	F	15.14	19.26	26.33							
	P	14.24	18.49	20.01							
	F-S	10.46	16.10	25.77							
	P-S	7.46	14.26	20.01							
LD	F	14.93	19.47	29.30							
	P	13.71	19.75	24.23							
	F-S	8.65	15.61	25.07							
	P-S	7.00	14.40	22.20							
DA	F	13.80	14.89	17.21	19.37	26.13	29.11				
	P	12.63	14.86	16.76	19.23	26.10	28.81				
	F-S	11.79	14.51	16.30	18.11	25.70	28.47				
	P-S	10.87	12.76	15.98	16.86	25.09	27.36				
DA+W	F	10.13	12.24	13.52	14.56	19.18	23.01	29.02	36.56		
	P	10.02	12.08	12.24	14.51	19.00	22.90	28.55	34.17		
	F-S	8.41	11.94	13.04	14.41	17.99	22.87	28.91	23.36		
	P-S	7.29	11.65	12.16	14.33	16.14	22.52	28.35	29.98		
DA+W+C	F*	8.35	11.61	12.17	14.06	15.83	19.13	23.08	27.74	28.96	29.36
DA+C	F*	11.09	14.10	15.46	17.40	18.43	25.86	27.70	27.92	29.48	32.87
UD+RG+C	F*	11.68	15.50	18.01	25.07	27.82	29.23	29.99	36.27	39.57	43.04

UD = Upper Dome
LD = Lower Dome
RG = Ring Girder
DA = Domes Assembly
W = Water
C = Containment Cylinder

F = Fixed
P = Pinned
F-s = Fixed-Sliding
P-S = Pinned-Sliding

*Fixed at the bottom of C

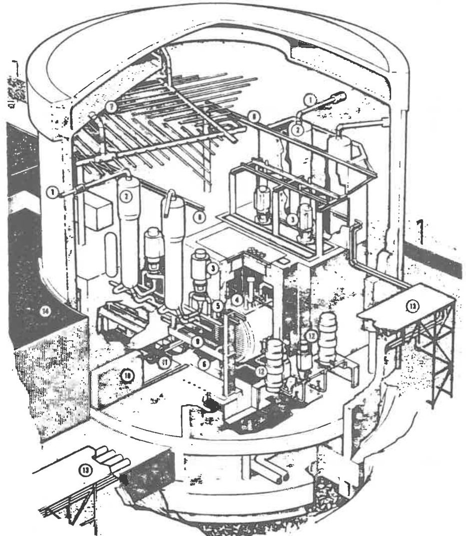
Table 2 Comparison between the Direct and the Substructure Approachs
Vertical Acceleration due to Vertical DBE (g)

COMPONENT	APPROACH	DIRECT APPROACH (FULL MODEL)						SUBSTRUCTURE APPROACH (UPPER ASSEMBLY)															
	INPUT MOTION	Ground Motion (1)						Ring Girder Motion = A (2)								Ring Girder Motion = C (2)							
	MODEL	DA+W+C		DA+C		UD+RG+C		DA+W								DA+W							
	BOUNDARY CONDITIONS	Fixed at the bottom of C						F		P		F-S		P-S		F		P		F-S		P-S	
	SOLUTION METHOD	RS	TH	RS	TH	RS	TH	RS	TH	RS	TH	RS	TH	RS	TH	RS	TH	RS	TH	RS	TH	RS	TH
UD	Node 2	1.12	.79	1.18	.84	1.71	1.06	1.10	.92	.89	.77	.75	.78	.93	.85	3.00	2.72	1.74	1.88	1.94	2.02	2.0	1.92
	Node 6	.88	.67	1.01	.71	1.34	.81	.86	.78	.62	.63	.61	.69	.75	.67	2.60	2.49	1.35	1.64	1.71	1.83	1.69	1.65
	Node 12	.51	.51	.66	.54	.74	.55	.42	.54	.30	.41	.43	.49	.39	.39	1.36	1.70	.68	.90	1.11	1.23	.97	.92
	Node 24	.17	.22	.17	.21	.19	.20	.04*	.21	.06*	.21	.05*	.22	.17*	.24	.01*	.29	.10*	.35	.06*	.30	.18*	.36
RG	Node 32	.14	.20	.18	.21	.17	.20	.02*	.21	.02*	.21	.02*	.20	.06*	.23	.08*	.32	.04*	.25	.04*	.27	.06*	.27
	Node 43	.14	.20	.17	.21	.17	.20	.02*	.20	0.02*	.20	.02*	.20	.06*	.20	.08*	.27	.04*	.27	.04*	.27	.06*	.27
LD	Node 61	1.10	.80	1.10	.84	--	--	.92	.96	1.10	.96	1.02	.94	1.11	1.17	1.56	1.49	2.04	1.70	1.56	1.25	1.46	1.84
	Node 66	1.08	.85	1.06	.81	--	--	.79	.83	.96	.85	1.08	.97	1.10	1.13	1.48	1.38	1.87	1.61	1.48	1.23	1.38	1.69
	Node 72	.51	.42	.49	.38	--	--	.48	.46	.56	.52	.38	.49	.60	.56	.57	.51	.73	.53	.58	.53	.62	.61
	Node 47	.16	.21	.16	.20	--	--	.02	.21	.04*	.21	.02*	.21	.13*	.22	.06*	.27	.07	.32	.04*	.27	.14*	.32
C	Node 474	.14	.20	.16	.20	.16	.19																
	Node 324	.03*	.14	.03*	.13	.03*	.14																

RS = Response Spectrum
TH = Time History

*Response Spectrum method is deficient near support points. This can be rectified by the Residual Term Method (5).

(1) Ground Motion in the form of Response Spectrum or Time-History is applied to the bottom of C.
(2) Ring Girder Motion in the form of Response Spectrum or Time-History is applied to the bottom of the RG (Node 43) Floor Response Sprectrum for Motions A and C are shown in Figure (5).



1. MAIN STEAM SUPPLY PIPING
2. BOILERS
3. MAIN PRIMARY SYSTEM PUMPS
4. CALANDRIA ASSEMBLY
5. FEEDERS
6. FUEL CHANNEL ASSEMBLY
7. DOUSING WATER SUPPLY
8. CRANE RAILS
9. FUELLING MACHINE
10. FUELLING MACHINE DOOR
11. CATENARY
12. MODERATOR CIRCULATION SYSTEM
13. PIPE BRIDGE
14. SERVICE BUILDING

FIGURE 1 REACTOR BUILDING CUTAWAY

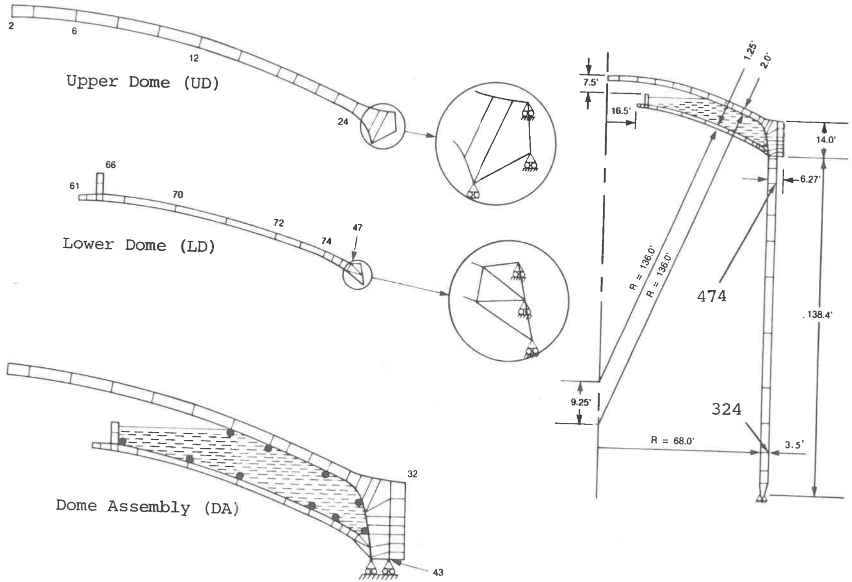


FIGURE 2 600 MW e FINITE ELEMENT MODELS

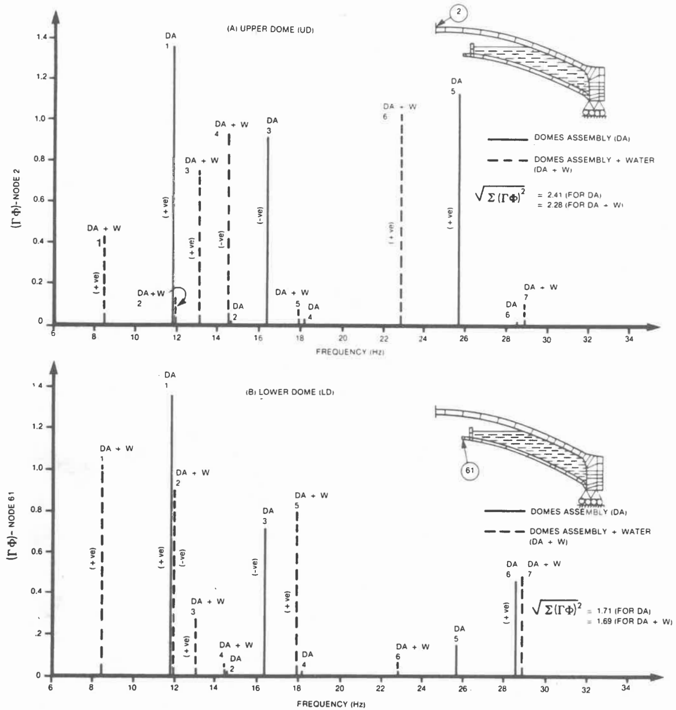


FIGURE 3 EFFECT OF WATER ON UPPER AND LOWER DOME BEHAVIOUR

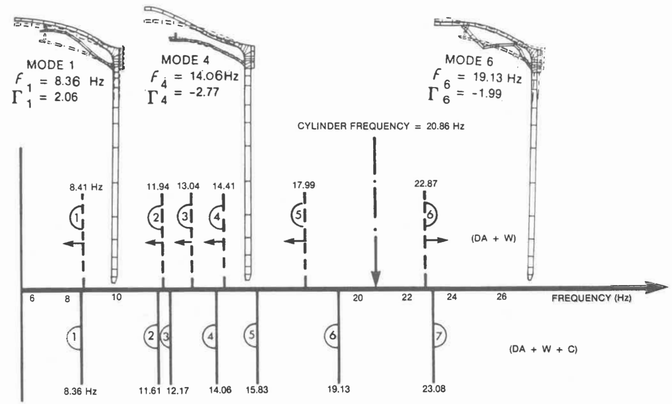


FIGURE 4 INTERACTION BETWEEN (DA + W) AND CONTAINMENT CYLINDER (C)

DA = DOME ASSEMBLY = 13,725. kips
W = WATER = 5,600. kips
C = CONTAINMENT CYLINDER = 30,684. kips

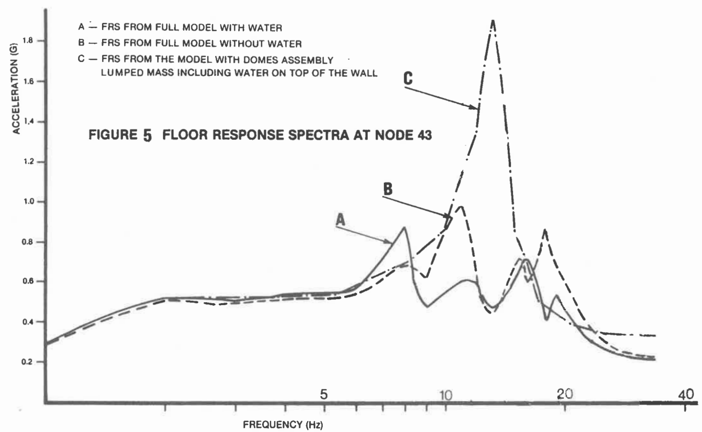


FIGURE 5 FLOOR RESPONSE SPECTRA AT NODE 43