Rubber Bearing and Bitumen Infill Support System for Seismic Protection of Nuclear Power Plant Structures

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Summary

Existing methods of earthquake protection of nuclear power plant structures rely, for the most part on structural strengthening to achieve this purpose. During recent years there has been increasing interest in more conventional vibration isolation techniques for protection using springs and dampers. Probably the greatest barrier to development of this system has been the lack of appreciation that rubber and bitumen materials can be designed which are capable of sustaining without damage or instability, the very large translational movements required to isolate the low frequency movement characteristics of earthquakes. The prestressed concrete pressure vessel (PCPV) for the Advanced Gas Cooled Reactor System (AGR) is of cylindrical type. The whole of the reactor primary circuit is contained within the PCPV vault and includes the reactor core and support structures, boilers and gas circulators. The PCPV is essentially free standing on its foundation raft. In order to transmit gravitational and seismic loads between the PCPV and the foundation raft, a support system is used which consists of concentric rings of neoprene pads and a thin annulus of bitumen infill. In order to assess the importance of both stiffness and damping of the PCPV support system on the overall AGR response, detailed parametric studies were carried out using time-history dynamic analysis in conjunction with the modal superposition technique. The effects of both stiffness and damping are compared in terms of the maximum dynamic response (maximum accelerations and maximum relative displacements) and also floor response spectra at various locations on the nuclear island. It is clearly apparent from these investigations that for an appropriate range of structures on the nuclear island (such as the PCPV and its internals), greater reduction in seismic loading can be achieved by proper selection of stiffnesses and damping of the PCPV support system without resorting to strengthening techniques.

1. Introduction

Since the mid 1950's multilaminate steel and rubber bearings were used in supporting bridge decks. Bearings of this type are relatively soft in shear so that the expansion and contraction of the deck imposes only light loads on the supporting piers. This type of bearing construction ensures that the vertical stiffness remains remarkably high and hence there will be a little movement under changing loads. During the 1960's laminated (rubber-steel) bearings were constructed for use as building supports. Their main purpose was to act as an isolation spring from incoming ground bore vibrations. A typical bearing will support a load of about 200 te. Moreover, multilaminate bearings were also used for nuclear power plant applications. The supporting system of the primary circuit of the Advanced Gas Cooled Reactor System (AGR) consists of concentric rings of neoprene pads and a thin annulus of bitumen infill material. An assessment of the effect of both stiffness and damping of such support system on the overall AGR response is the subject matter of this paper.

2. Idealisation

The AGR nuclear island is a complex of many different structural types and containing many different items of plant. The main structural components of the reactor island are taken to be as follows:

Foundation raft
Prestressed concrete pressure vessel (PCPV)
PCPV support system
PCPV internals (gas baffle, graphite core and support structure, boilers and restraint tank)
Reactor building
Charge machine and gantry rails
Fuel handling building complex
Soil media

3. Modelling of the structure

In this paper, we choose cartesian co-ordinates system x, y, z in which to describe the system with the y axis is orientated vertically upwards. Thus the two orthogonal horizontal directions are x and z and we choose the plane of interest in this paper to be x-y plane. The idealisation of the structural components of the AGR nuclear island consists mainly of beam elements with three degrees of freedom per node (two inplane displacements and rotational displacement), lumped masses having both translational and rotary inertia, rigid links and linear-damped-spring-elements. This idealisation is shown in Fig 1. As the main concern of this investigation is the effect of stiffness and damping of the neoprene pads and bitumen infill on the response of the PCPV primary circuit only brief description of these structures will be outlined here.

3.1 Prestressed concrete pressure vessel (PCPV)

The prestressed concrete pressure vessel (PCPV) for the Advanced Gas Cooled Reactor System (AGR) shown in Fig 2 is of cylindrical type. The whole of the reactor primary circuit is contained within the PCPV vault and includes the reactor core and support structures, boilers and gas circulators. The PCPV is essentially free standing on the foundation raft. The weight of the PCPV attachments and vault components is assumed in this paper to be transmitted to the foundation raft by concentric rings of neoprene pads. These pads have high bearing capacity but have very low shear resistance. Consequently, axisymmetric movements of the PCPV can occur relative to the raft due to prestress, pressure and temperature loading without significant restraint from the raft. Horizontal seismic design loads on the PCPV are transmitted to the raft by a shear step around the periphery of the base slab of the vessel. This shear step consists of an annular ring of concrete which is an integral part of the foundation raft. In order that dynamic seismic loads may be transmitted between the shear step and the PCPV and yet relative axisymmetric movements be allowed to take place without significant restraint, a narrow 25 mm infill of bitumen is assumed to be placed between the periphery of the base of the PCPV and the shear step of the foundation raft. The bitumen allows slow rate of deformation such as axisymmetric movements due to prestress, pressure and temperature loadings to take place without significant resistance from the raft or shear step. Under dynamic seismic loading, however, the rate of deformation is high and the bitumen provides high resistance to relative rigid body motion between the PCPV and the raft. The finite element idealisation of the PCPV is defined by nodes 24 to 34 as shown in Fig 1.

3.2 PCPV internals

3.2.1 Gas baffle and diagrid

The gas baffle is a cylindrical pressure vessel with a torispherical head. The knuckle radius, penetrations etc are incorporated in the head or dome, through which the guide tubes for the central rods and fuel stringer pass. The support skirt is effectively a continuation of the gas baffle cylinder anchored deep into the base slab of the PCPV and is cooled at the lower end in order to reduce thermal stresses at the connection with the PCPV liner. Also any seismic loading on the system is transmitted into the PCPV through the support skirt. The idealisation of the gas baffle and diagrid is represented by nodes 29-35-36-37-38-39-40-41 in the idealisation shown in Fig 1.

3.2.2 Core structure and restraint tank

The core is basically an assembly of graphite bricks arranged in eleven horizontal layers. The complete assembly comprises an inner cylinder of moderator graphite surrounded by reflector graphite and covered top and bottom by layers of graphite and steel shielding bricks (referred to as the top and bottom neutron shields). The structure as a whole sits on a mat of steel plates. These plates are in turn carried from the diagrid. Each layer of core is made up from a number of a keyed graphite bricks system which will transmit the maximum seismic loading generated in the layer of the core. The core support system consists of the diagrid core support plates and restraint tank, supported by the diagrid. The restraint tank is a cylindrical vessel of plate thickness of 50 mm. The idealisation of the core and restraint tank is represented in Fig 1 by nodes 37-42-43-44.

3.3 PCPV support system

The PCPV support system is idealised into a linear-spring-dashpot element and represented by element 14 for neoprene pads and element 91 for the bitumen infill in the idealisation shown in Fig 1. The horizontal, vertical and rocking mode stiffnesses of the support system are evaluated using the formulae listed below.

Stiffness constants of the PCPV support system

Vibration mode	Material	Spring constant
Horizontal mode	Bitumen	$\frac{\pi h}{2t} R_B (E + G)$
Vertical mode	Bitumen + Neoprene	$\frac{1}{t} (\pi R^2 E + 2 \pi R_B h G)$
Rocking mode	Bitumen + Neoprene	$\frac{\pi}{t} (E R^3 . \Delta + \pi G R_B^3 h)$

where R_B = mean radius of bitumen annulus, R = mean radius of neoprene pads, t = thickness, h = height of the bitumen, G = shear modulus, E = Young's modulus, Δ = neoprene pads radial thickness

3.4 Modelling of the soil

For embedded structures such as the AGR nuclear island in which the foundations consist of footings and individual rafts and also for known site stratigraphy, the finite element would be the obvious choice for the soil-structure-interaction analysis. However, in this investigation the lumped mass spring dashpot approach is used. This method is acceptable for hard sites with shear wave velocity greater than 1200 m/s or alternatively for homogeneous soil of sufficient depth that can be considered as a half-space. Figure 1 represents a discrete mass model of the AGR island. The foundation raft is assumed to be rigid and thus the response of the soil is defined by the difference between the three rigid body movements of the foundation raft and the free field ground motion. Due to the symmetry of the AGR island, the soil interaction model can be reduced to a two-dimensional system having spring and dashpot in the horizontal direction (K_H, C_H), vertical direction (K_V, C_V) and rocking direction (K_ϕ, C_ϕ). The above parameters were determined on the basis of uniform/linear distribution of pressure on rectangular raft (120 m x 50 m) resting upon homogeneous isotropic and elastic half space. These parameters are listed below.

Spring constants of soil for rectangular footing

Vibration mode	Stiffness	Damping
Horizontal mode	$K_H = \frac{2\pi b \rho V_S^2}{(2-\nu)} B_x$	$C_H = \rho V_S A$
Vertical mode	$K_V = \frac{\pi b \rho V_S^2}{(1-\nu)} B_Z$	$C_V = \rho V_P A$
Rocking mode	$K_\phi = \frac{\pi b^3 \rho V_S^2}{2(1-\nu)} B_\phi$	$C_\phi = \rho V_P I_y$

where $A = 2b \times 2c$ = cross-sectional area of the foundation raft; I_y = second moment of area about y axis; V_S = shear wave velocity; V_P = compression wave velocity, ν = soil Poisson's ratio, ρ = soil density

$$B_x = (2-\nu) \left[\frac{b}{c} (1-\nu) \log \tan \left(\frac{\pi}{4} + \frac{1}{2} \tan^{-1} \frac{c}{b}\right) + \log \tan \left(\frac{\pi}{4} + \frac{1}{2} \tan^{-1} \frac{b}{c}\right) \right]^{-1}$$

$$B_z = 2\left[\frac{b}{c}\log\tan\left(\frac{\pi}{4}+\frac{1}{2}\tan^{-1}\frac{c}{b}\right)+\log\tan\left(\frac{\pi}{4}+\frac{1}{2}\tan^{-1}\frac{b}{c}\right)\right]^{-1}$$

$$B_\phi = 4\left[3\log\tan\left(\frac{\pi}{4}+\frac{1}{2}\tan^{-1}\frac{b}{c}\right)\right]^{-1}$$

4. Analysis method and results

In this paper we evaluate the time-history dynamic response of the idealisation shown in Fig 1 to the earthquake free field ground acceleration-time history by modal transformation and superposition technique using NNC in-house computer program MODAN for the excitation in the x-direction, the idealisation of the simple model of the AGR nuclear island in the x-y plane is used. Since the modal participation factors of the symmetric modes of vibration were very small and also the eigenvectors corresponding to the vertical displacement ω of the fuel handling building complex were extremely small ($<10^{-15}$), it was decided to consider half of the model as shown in Fig 1 and to restrain this model along the central line in the y-direction but it was free to displace in the x-direction and rotate about the z-direction. For the half-model idealisation shown in Fig 1, from the subsequent modes of vibration, vibration modes with natural frequencies up to 36 Hz for hard soil (V_S = 2000 m/s) are included in the earthquake response calculations. The inclusion of higher modes of vibration was found to have insignificant effect. The lumped parameter model shown in Fig 1 was excited by the modified Temblor wave in the horizontal direction and both stiffness and damping values were varied from those original values (K_o = original stiffness, C_o = original damping). The results thus obtained are shown in Tables I and II and also in Fig 3 to 6. It is clear from this investigation that both stiffness and damping have dramatic effect on the response of the primary circuit. Increasing damping values by up to twenty times of the original damping ($C = 20\ C_o$), both relative displacements, peak accelerations and also floor response accelerations may be reduced by up to 40%. Similar effect is produced due to the increase in the PCPV support stiffness except that in this case the response of the core increases in the region $K = 10\ K_o$. The effect of stiffness and damping on other structures such as the reactor building and the fuel handling building complex is of minor importance. It is also of interest to note that the relative displacements of the reactor building which is normally connected by pipes, cables and other mechanical equipments to other structures on the AGR island are relatively unchanged by increasing the PCPV support stiffness and damping. The results thus indicate that for an appropriate range of structures on the nuclear island (particularly for the PCPV and its internals), greater seismic loading reduction can be achieved by the proper selection of bitumen infill and neoprene pad stiffnesses and dampings without restoring to strengthening techniques.

Acknowledgement

The permission of the National Nuclear Corporation Limited to present this paper is acknowledged.

TABLE I

MAXIMUM HORIZONTAL DISPLACEMENT AND ACCELERATION RESPONSE OF THE SIMPLE MODEL OF THE AGR ISLAND, HORIZONTAL EXCITATION x-DIRECTION, TYPE II PCPV SUPPORT SYSTEM, V_s = 2000 m/s

Effect of damping

Position	Node No.	Earthquake acceleration = 0.1 g							
		C_o		5 x C_o		10 x C_o		20 x C_o	
		Disp. (mm)	Acc (m/s^2)	Disp (mm)	Acc (m/s^2)	Disp (mm)	Acc (m/s^2)	Disp (mm)	Acc (m/s^2)
Reactor building									
-9.0 m	46	-0.1191	1.030	-0.1129	1.024	-0.1098	1.021	-0.1054	1.016
0.0 m	47	-0.3211	1.149	-0.3066	1.139	-0.2996	1.133	-0.2901	1.124
6.0 m	48	-0.4495	1.203	-0.4292	1.190	-0.4195	1.182	-0.4071	1.172
26.3 m	49	-1.457	1.745	-1.405	1.711	-1.378	1.693	-1.340	1.670
37.4 m	50	-1.679	1.909	-1.618	1.935	-1.585	1.927	-1.545	1.909
64.4 m	51	-3.753	2.822	-3.747	2.825	-3.737	2.825	-3.723	2.830
PCPV									
-8.975 m	25	-0.1212	1.033	-0.09761	1.001	-0.08819	0.9957	-0.07567	0.9922
-8.0 m	26	-0.1745	1.057	-0.1346	1.031	-0.1199	1.004	-0.0996	0.9977
-7.35 m	27	-0.2281	1.084	-0.1728	1.028	-0.1530	1.012	-0.1252	1.003
-4.5 m	28	-0.4323	1.182	-0.3173	1.079	-0.2769	1.046	-0.2197	1.022
0.15 m	29	-0.7925	1.351	-0.5718	1.166	-0.4938	1.111	-0.3856	1.061
4.57 m	30	-1.227	1.554	-0.8784	1.270	-0.7550	1.187	-0.5869	1.113
21.87 m	31	-3.002	2.319	-2.119	1.655	-1.805	1.471	-1.380	1.304
27.39 m	32	-3.510	2.529	-2.473	1.761	-2.104	1.550	-1.618	1.357
34.9 m	33	-4.207	2.814	-2.958	1.913	-2.513	1.662	-1.930	1.429
Gas baffle									
2.925 m	36	-1.323	1.640	-0.9442	1.335	-0.8068	1.233	-0.6261	1.133
4.57 m	38	-1.485	1.722	-1.058	1.381	-0.9026	1.263	-0.6996	1.153
9.522 m	39	-1.997	2.039	-1.418	1.586	-1.206	1.427	-0.9295	1.257
16.25 m	40	-2.694	2.463	-1.906	1.858	-1.618	1.650	-1.240	1.423
Restraint tank and core									
6.015 m	42	-2.047	2.069	-1.441	1.591	-1.220	1.425	-0.9418	1.251
11.415 m	43	-3.559	2.693	-2.439	1.846	-2.051	1.597	-1.588	1.360
16.045 m	44	-4.641	3.140	-3.137	2.008	-2.649	1.647	-2.069	1.349
Foundation raft									
-12.13 m	2	-0.02668	0.9912	-0.02351	0.9882	0.02204	0.9873	-0.01982	0.9867
Central block									
-9.0 m	4	-0.1858	1.032	-0.1907	1.036	-0.1842	1.030	-0.1711	1.019
-4.5 m	5	-0.4918	1.152	-0.5140	1.174	-0.4969	1.161	-0.4706	1.132
0.0 m	6	-0.8908	1.306	-0.9379	1.354	-0.9066	1.329	-0.8582	1.275
8.5 m	7	-1.699	1.664	-1.801	1.741	-1.740	1.678	-1.643	1.561
17.9 m	8	-2.750	2.103	-2.927	2.234	-2.824	2.127	-2.666	1.931
26.3 m	9	-3.709	2.487	-3.956	2.667	-3.816	2.533	-3.603	2.283
32.0 m	10	-4.340	2.737	-4.633	2.950	-4.468	2.812	-4.220	2.525
Fuel services block									
-9.0 m	11	-0.1740	1.027	-0.1781	1.030	-0.1719	1.025	-0.1624	1.016
-4.5 m	12	-0.4884	1.151	-0.5103	1.173	-0.4934	1.159	-0.4673	1.131
0.0 m	13	-0.8865	1.304	-0.9333	1.352	-0.9022	1.327	-0.8511	1.271
8.5 m	14	-1.703	1.666	-1.805	1.744	-1.744	1.681	-1.647	1.562
17.9 m	15	-2.752	2.105	-2.929	2.236	-2.827	2.129	-2.669	1.934
26.3 m	16	-3.709	2.487	-3.957	2.667	-3.816	2.533	-3.603	2.283
32.0 m	17	-4.345	2.739	-4.639	2.955	-4.474	2.817	-4.226	2.529
37.4 m	18	-5.116	3.098	-5.470	3.436	-5.273	3.275	-4.993	2.975

TABLE II

MAXIMUM HORIZONTAL DISPLACEMENT AND ACCELERATION RESPONSE OF THE SIMPLE MODEL OF THE AGR ISLAND, HORIZONTAL EXCITATION, V_s = 2000 m/s, $\eta_{\text{PCPV SUPPORT}}$ = 0.072

Effect of the PCPV support stiffness

Position	Node No.	Earthquake Acceleration = 0.1 g							
		K_o		$5 \times K_o$		$10 \times K_o$		$20 \times K_o$	
		Disp (mm)	Acc (m/s^2)	Disp (mm)	Acc (m/s^2)	Disp (mm)	Acc (m/s^2)	Disp (mm)	Acc (m/s^2)
Reactor building									
-9.0 m	46	-0.1191	1.030	-0.1197	1.032	-0.1192	1.030	-0.1188	1.029
0.0 m	47	-0.3211	1.149	-0.3174	1.153	-0.3165	1.151	-0.3161	1.149
6.0 m	48	-0.4495	1.203	0.4406	1.208	-0.4392	1.207	-0.4399	1.204
26.3 m	49	-1.457	1.745	1.476	1.770	-1.508	1.831	-1.509	1.847
37.4 m	50	-1.679	1.909	-1.758	2.118	-1.798	2.182	-1.799	2.188
64.4 m	51	-3.753	2.822	-3.808	2.963	-3.858	3.027	-3.861	3.031
PCPV -8.975 m	25	-0.1212	1.033	-0.03929	0.9977	-0.03275	0.9943	-0.02925	0.9921
-8.0 m	26	-0.1745	1.057	-0.04747	1.001	-0.03769	0.9959	-0.03257	0.9930
-7.35 m	27	-0.2281	1.084	-0.06444	1.007	-0.05204	1.001	-0.04513	0.9962
-4.5 m	28	-0.4323	1.182	-0.1188	1.027	-0.09740	1.051	-0.08370	1.005
0.15 m	29	-0.7925	1.351	-0.2252	1.065	-0.1883	1.041	-0.1639	1.021
4.57 m	30	-1.227	1.554	-0.3817	1.121	-0.3323	1.081	-0.2932	1.043
21.87 m	31	-3.002	2.319	-1.014	1.368	-0.9228	1.403	-0.8233	1.339
27.39 m	32	-3.510	2.529	-1.182	1.596	-1.075	1.514	-0.9580	1.439
34.9 m	33	-4.207	2.814	-1.430	1.961	-1.285	1.679	-1.144	1.579
Gas baffle									
2.925 m	36	-1.323	1.640	-0.5506	1.293	-0.4948	1.253	-0.4641	1.230
4.57 m	38	-1.485	1.722	-0.6187	1.333	-0.5569	1.289	-0.5218	1.264
9.522 m	39	-1.997	2.039	-0.8476	1.469	-0.7716	1.414	-0.7236	1.384
16.25 m	40	-2.694	2.463	-1.168	-1.737	-1.064	1.633	-0.9987	1.590
Restraint tank and core									
6.015 m	42	-2.047	2.069	-1.144	1.649	-1.072	1.606	-1.029	1.584
11.415 m	43	-3.559	2.693	2.708	-3.396	2.601	-3.310	2.479	-3.139
16.045 m	44	-4.641	3.140	3.850	-4.721	3.719	-4.672	3.541	-4.437
Foundation raft									
-12.13 m	2	-0.02668	0.9912	-0.02250	0.9903	-0.02193	0.9898	-0.02156	0.9892
Central block									
-9.0 m	4	-0.1858	1.032	-0.1851	1.035	-0.1841	1.034	-0.1837	1.033
-4.5 m	5	-0.4918	1.152	-0.5008	1.167	-0.4994	1.166	-0.4987	1.165
0.0 m	6	-0.8908	1.306	-0.9144	1.337	-0.9126	1.337	-0.9117	1.336
8.5 m	7	-1.699	1.664	-1.756	1.713	-1.754	1.713	-1.753	1.712
17.9 m	8	-2.750	2.103	-2.855	2.190	-2.853	2.191	-2.852	2.192
26.3 m	9	-3.709	2.487	-3.859	2.607	-3.857	2.610	-3.855	2.611
32.0 m	10	-4.340	2.737	-4.519	2.880	-4.517	2.885	-4.515	2.886
Fuel services block									
-9.0 m	11	-0.1740	1.027	-0.1727	1.029	-0.1717	1.028	-0.1713	1.027
-4.5 m	12	-0.4884	1.151	-0.4972	1.165	-0.4958	1.165	-0.4951	1.163
0.0 m	13	-0.8865	1.304	-0.9099	1.335	-0.9081	1.335	-0.9072	1.334
8.5 m	14	-1.703	1.666	-1.760	1.716	-1.758	1.715	-1.757	1.715
17.9 m	15	-2.752	2.105	-2.858	2.191	-2.856	2.193	-2.854	2.193
26.3 m	16	-3.709	2.487	-3.860	2.607	-3.857	2.611	-3.856	2.612
32.0 m	17	-4.345	2.739	-4.525	2.882	-4.523	2.887	-4.521	2.888
37.4 m	18	-5.116	3.098	-5.335	3.328	-5.333	3.333	-5.332	3.337

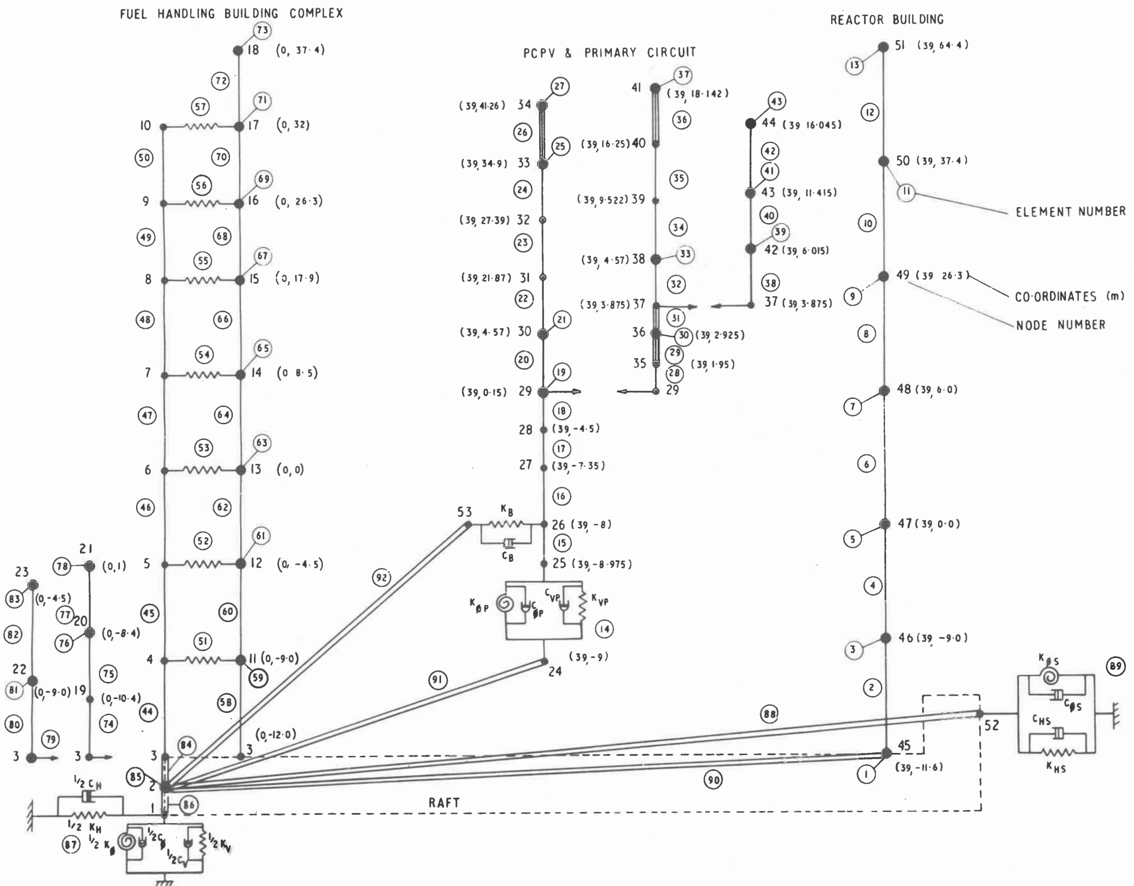


FIG 1

SIMPLE MODEL OF THE AGR ISLAND FOR MODAN COMPUTER CODE

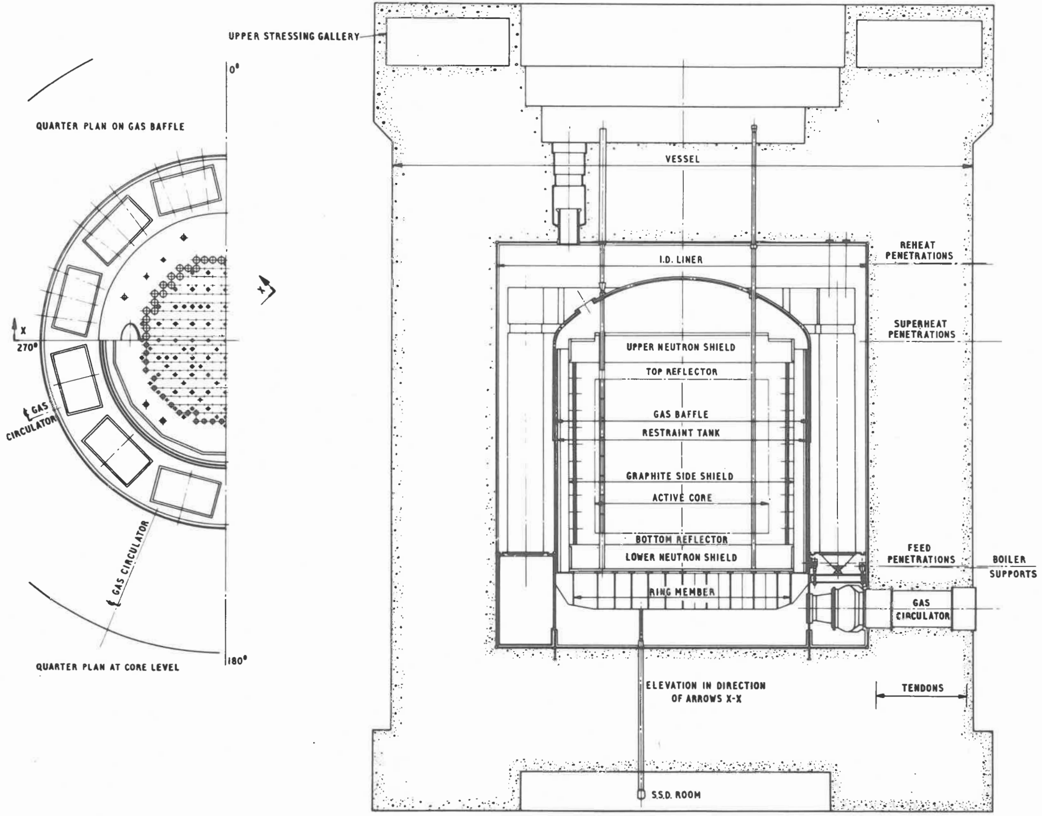


FIG 2 THE PRESTRESSED CONCRETE PRESSURE VESSEL (PCPV) AND ITS PRIMARY CIRCUIT

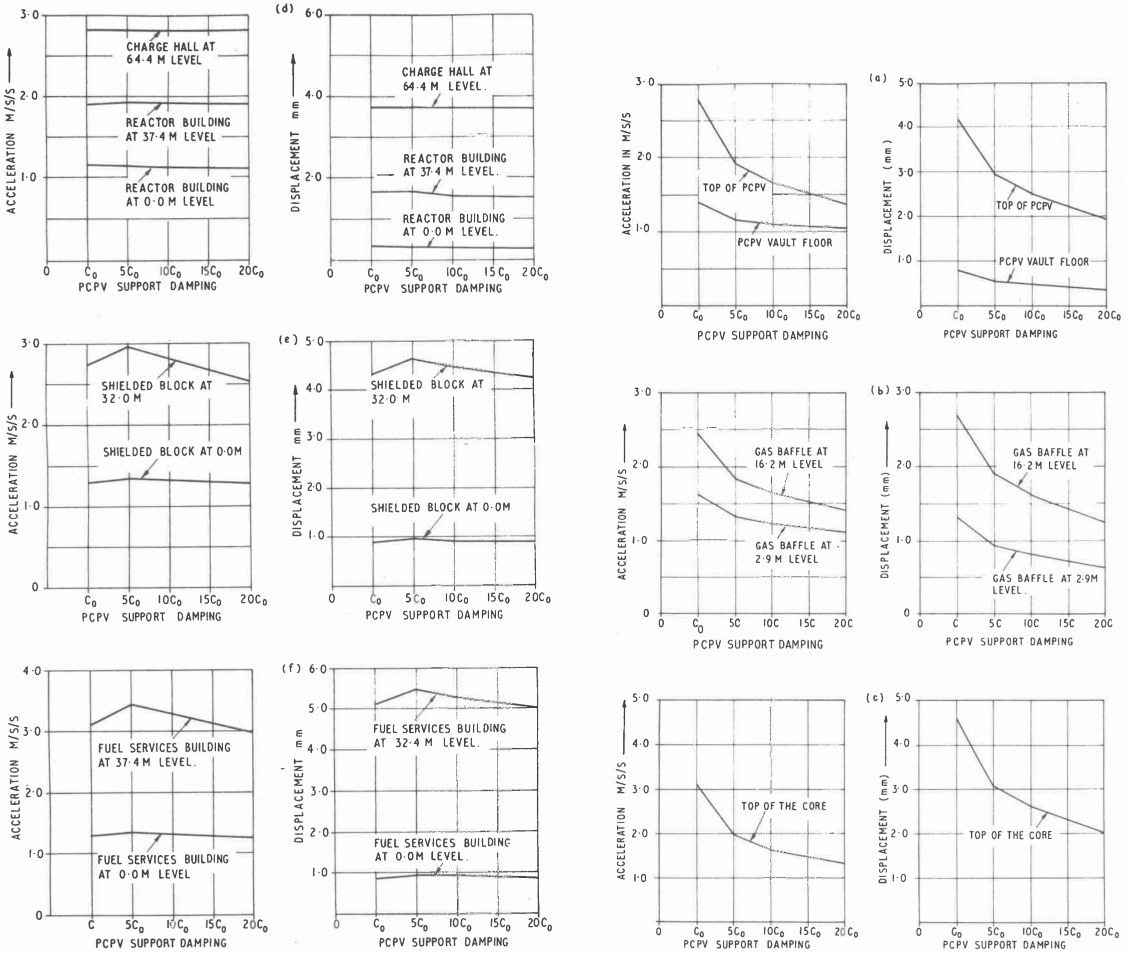


FIG 3 EFFECT OF PCPV SUPPORT DAMPING ON THE OVERALL AGR RESPONSE

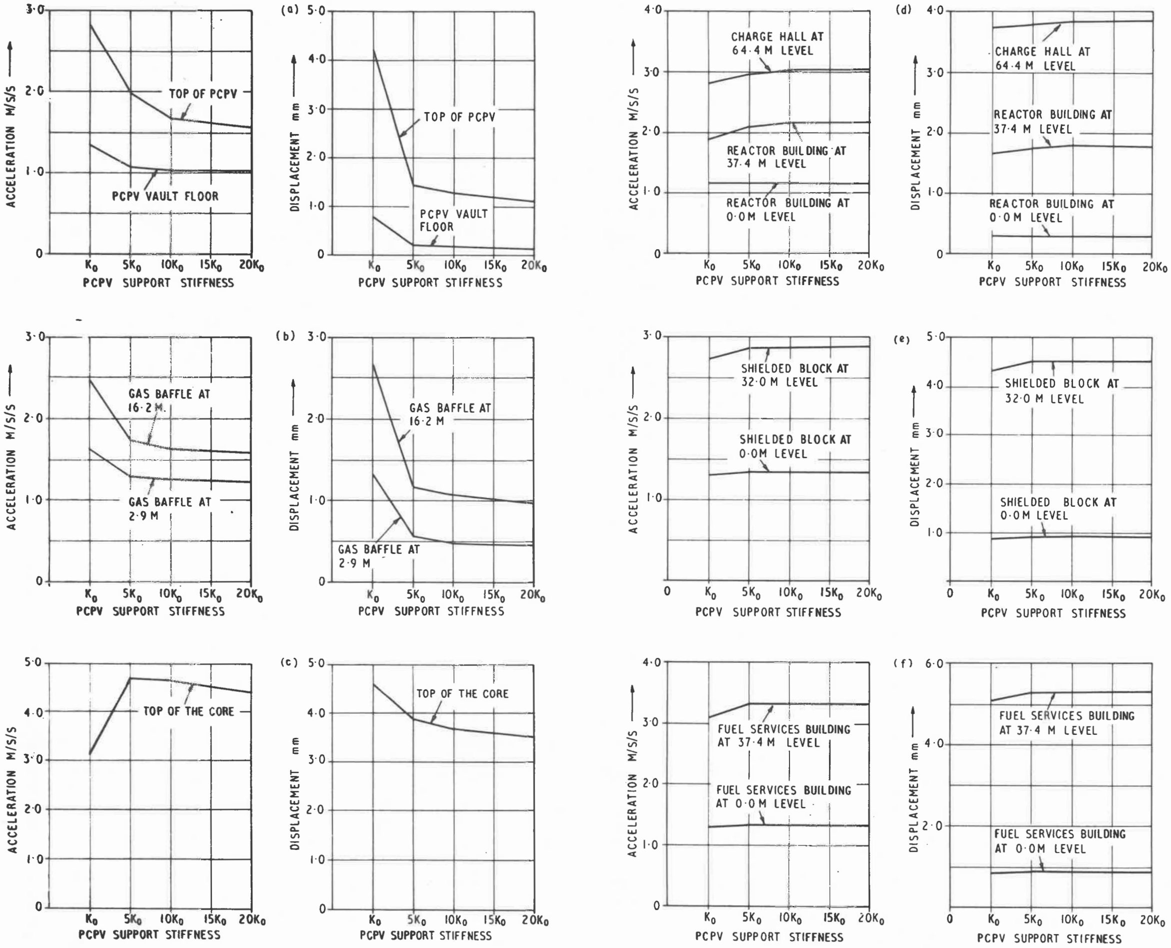
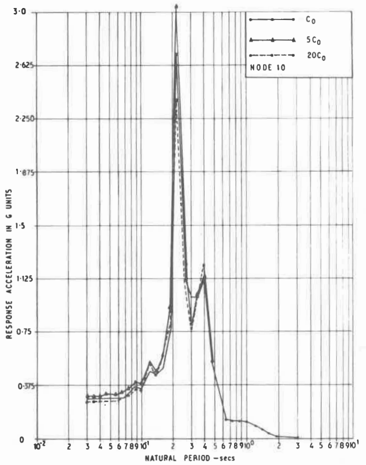
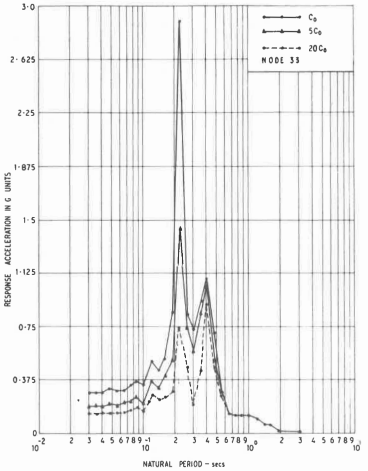
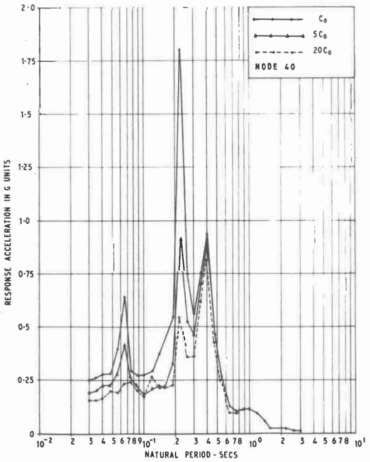
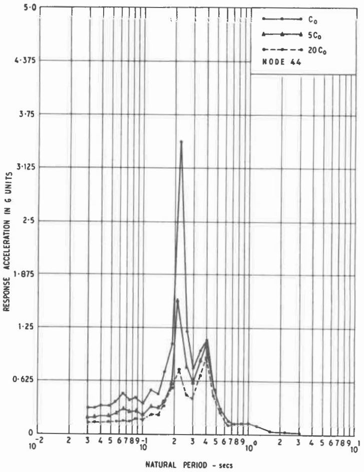


FIG 4 EFFECT OF PCPV SUPPORT STIFFNESS ON THE OVERALL AGR RESPONSE









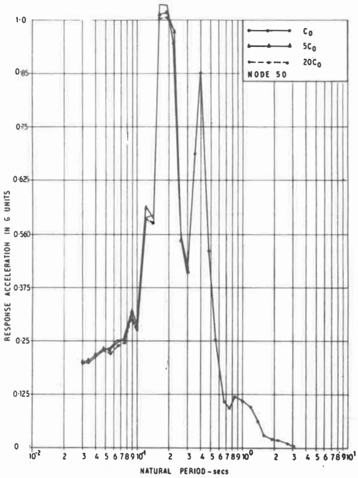


FIG 5

EFFECT OF PCPV SUPPORT DAMPING ON THE FLOOR RESPONSE SPECTRA AT VARIOUS LEVELS ON THE AGR ISLAND

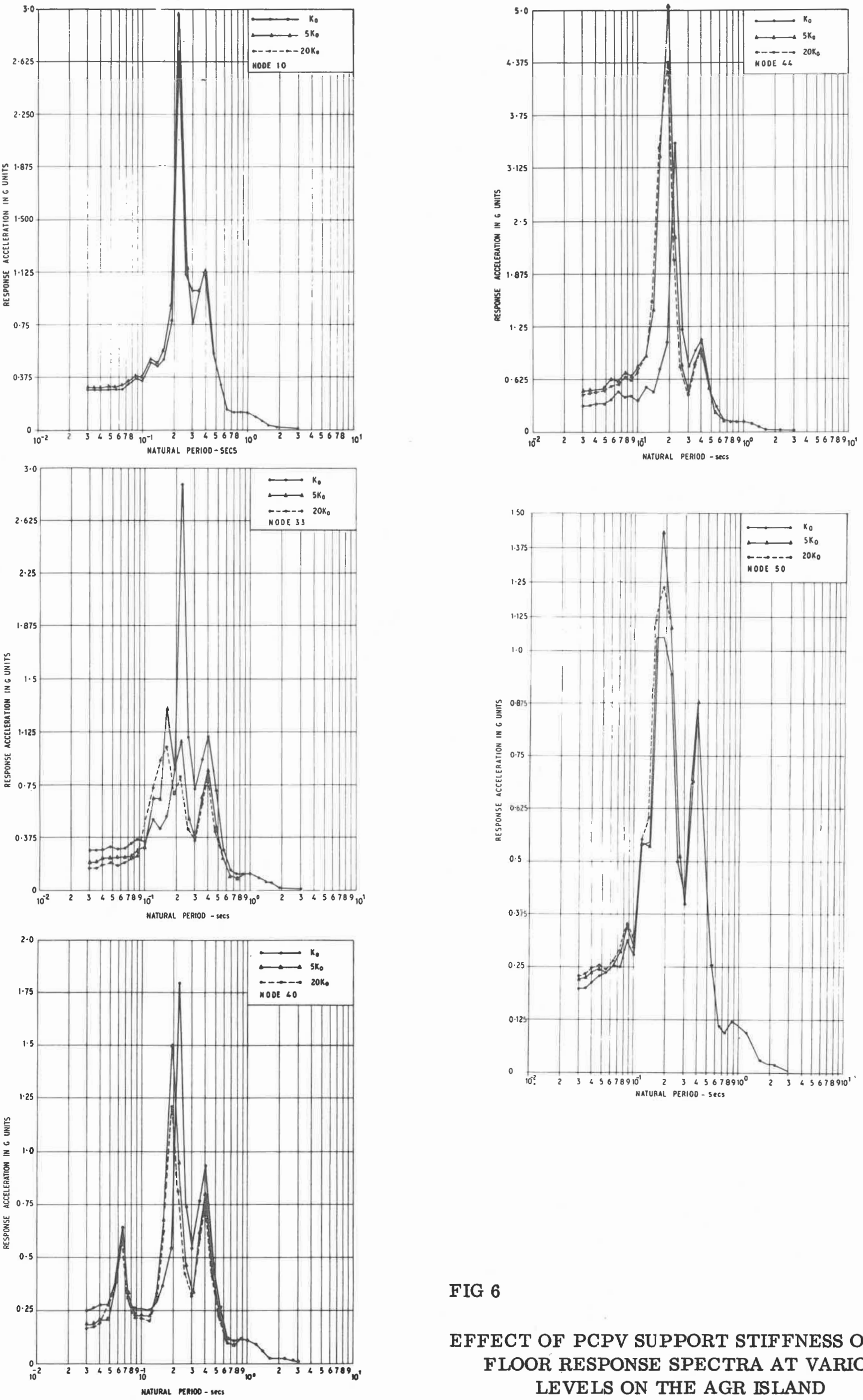


FIG 6

EFFECT OF PCPV SUPPORT STIFFNESS ON THE FLOOR RESPONSE SPECTRA AT VARIOUS LEVELS ON THE AGR ISLAND