DYNAMIC RESPONSE OF NUCLEAR POWER PLANT DUE TO EARTHQUAKE GROUND MOTION AND AIRCRAFT IMPACT

J. V. PARKER, K. M. AHMED, A. S. RANSHI

Water Reactor Division, Nuclear Power Company (Risley) Limited,
Warrington Road, Risley, Warrington, Cheshire WA3 6BZ, United Kingdom

SUMMARY

The reactor primary circuit of a nuclear power station is, in the event of an aircraft crashing onto the facility, protected from direct damage from impacting missiles by the primary containment. The potential for indirect damage does exist however due to vibrations being transmitted through the foundations, the primary circuit components thereby being subjected to base excitations as in the case of ground motion due to earthquakes. This indirect effect of an aircraft crash can be assessed pessimistically by assuming that the aircraft impacts the primary containment directly and horizontally near the top of the structure. Furthermore this pessimism is increased by ignoring the energy absorbed in causing the local damage experienced by the primary containment. This paper examines both the indirect effect of this form of aircraft crash and the effect of earthquake ground motions on the dynamic response of a single reactor nuclear island.

The nuclear island components are idealised using beam elements and rigid elements, the foundation raft being assumed to be rigid. The ground itself is idealised as elastic spring-viscous damper elements. The effect of ground properties on the dynamic response is investigated by varying the ground stiffness and damping over a range defined by the shear wave velocities 500 to 2000 m/sec.

The time-history dynamic response is calculated using modal transformations for

(a) aircraft impact forcing functions corresponding to
  (i) a Boeing 707-320 aircraft at 103 m/sec
  (ii) a Multi Role Combat Aircraft (MRCA) at 215 m/sec
  (iii) as (ii) but with a modified force-time relation
and for
(b) earthquake ground motions corresponding to
  (i) El Centro, May 1940, N-S component
  (ii) Parkfield 5, June 1966, N5W component
  (iii) Temblor, June 1966, S25W component.

The effect of both the aircraft crash and the earthquake on the reactor plant can be compared directly by computing floor response spectra from the time-history response. The precise shape of the forcing function does significantly affect the response and consequently the floor response spectra. Peak floor response accelerations vary by up to 40% in the case of the MRCA and the effect of a variance on the prescribed aircraft impact forcing function should always be considered.

However it is concluded that where nuclear facilities are being designed to ensure a safe shutdown against earthquakes, then provided the primary containment is designed to protect the primary reactor circuit against direct damage from a Multi Role Combat aircraft the reactor plant within the primary containment will have an acceptable response. In the event of a large aircraft such as the Boeing 707 crashing onto the facility, then the design of the reactor plant could be affected depending upon the amount of energy absorbed locally through direct damage.

1. Introduction

Nuclear Power Stations in the U.K. are currently being designed to resist both earthquakes and crashing aircraft. In the event of either of these external hazards, the reactor must have safe shut down capability and any radioactive release must be strictly controlled and limited.

The reactor primary circuit is protected from direct damage from external missiles by the primary containment. However, base excited vibrations will be transmitted in a similar manner to those arising from a seismic disturbance. It is interesting therefore to compare the dynamic response due to an aircraft crash and an earthquake of the components within the primary containment.

The earthquake we are concerned with in any comparison with an aircraft crashing onto the nuclear power station is of course the so called safe shut down earthquake or SSE. We define here the SSE as the most onerous set of free-field ground motions that will be used for safety assessment purposes. Vibrations induced by the aircraft crash are the greatest when it is assumed that impact takes place horizontally at the top of the primary containment building.

The structure chosen for this study is the reactor block for a nuclear power station based on the SGHWR system. The dynamic response of the system is investigated for a range of soil conditions, assumed to be linear elastic and homogeneous, defined by the shear wave velocity ranging from 500 m/sec to 2000 m/sec.

2. Loading

2.1 Earthquake

Two accelerograms have been chosen to describe the SSE. These are:

(a) Parkfield5, June 1966, N5W component

(b) Temblor, June 1966, S25W component

Both these recordings have peak accelerations in excess of 0.5 g. However, for the purpose of this comparative study, we normalise the waves to have a peak acceleration of 0.25 g for horizontal excitation. We also include in the study for comparison purposes, ground motion described by the accelerogram.

(c) El Centro, May 1940, N-S component

also normalised to have a peak acceleration of 0.25 g for horizontal excitation.

2.2 Aircraft crash

Aircraft impact is assumed to take place horizontally against the top part of the primary containment structure. The load-time curves shown in Fig. 1 are chosen to represent the impact reaction force and correspond to the following two aircraft flying at a low level.

(a) Multi Role Combat Aircraft (MRCA) at 215 m/sec.

(b) Boeing 707 - 320 at 103 m/sec.

In the U.K. it is only necessary to consider case (a) for safety assessment purposes. Case (b) has been included in this study purely for comparison purposes.

The load-time curves A and B shown in Fig. 1 represent cases (a) and (b) respectively. The load-time curve C shown in Fig. 1 is included in the study in an attempt to measure the importance of the shape of the load-time curve for case (a).

3. Structural idealisation

The main structural components of the reactor block or nuclear island which we are considering consist of:

reactor primary circuit and support system
primary containment
secondary containment and equipment
foundation raft.

The system, which has two orthogonal vertical planes of symmetry, will have a quasi two-dimensional response in any plane of symmetry in which the system is being excited. A simple finite element idealisation of the structure consisting of beam elements and rigid elements is used as illustrated in Fig. 2. Thus, at each nodal point in the idealised structure, the response is defined by the three components of in-plane displacement; horizontal translation, vertical translation and rotation. Furthermore, for the purpose of this study, we only consider horizontal excitation and consequently the response of any nodal point in our idealisation (Fig. 2) will be zero in the vertical direction.

The foundation raft is considered to be rigid and is therefore idealised as a rigid mass. The ground or soil is idealised in the so called lumped parameter method. Thus the response of the soil is defined entirely by the difference between the three in plane displacements defining the rigid body movements of the raft and the free field ground motion (which is zero in the case of the aircraft impact problem).

The aircraft impact load-time functions (Fig. 1) are applied in the horizontal direction at node 22 of the idealisation (Fig. 2). This will produce the most onerous response of the system. Furthermore we make no allowance for the local effect in which severe local damage will be caused to the primary containment shell and which will absorb much of the energy of the impacting missile. Thus the dynamic response of the idealisation shown in Fig. 2 will overestimate the true response to the aircraft crash.

4. Response calculations

We evaluate the time-history dynamic response of the idealisation illustrated in Fig. 2 to both the earthquake free field ground acceleration-time histories and the aircraft impact load-time curves by modal transformation and superposition. Vibration modes with natural frequencies up to 30 Hz are included in the earthquake response calculations. The inclusion of higher modes was found to have insignificant effect. In the case of the aircraft impact response however, vibration modes with natural frequencies up to 160 Hz are included although it was found that the inclusion of modes higher than 100 Hz had very little effect.

5. Results

Maximum displacements and accelerations at typical positions, nodes 9 and 13 in the primary circuit, node 20 at the top of the secondary containment building, nodes 20 and 21 on the primary containment building are presented in Tables 1 and 2 respectively. These maximum values are obtained from the time-history response to the loadings discussed in Section 2 and for a range of soil conditions.

It is quite clear from Tables 1 and 2 that impact by the MRCA defined by load A, is considerably less onerous than the earthquake with the exception of the primary containment structure which of course is subject to direct impact by the missile. It is also apparent that the shape of the load-time curve representing the impact of the MRCA, comparing the response to load A with that of load C, has almost a trivial influence on the maximum response. By contrast the maximum response to impact by the Boeing 707-320 is considerably more onerous than the earthquake.

A more dramatic comparison of the response of the components can be made using the floor response spectra corresponding to the calculated time history response. Such spectra are presented in Fig. 3, 4 and 5 for positions defined by nodes 3, 9 and 21 respectively in the idealisation (Fig. 2). In each of these figures, spectra for 1% and 5% damping are shown as envelopes to the spectra for all the soil conditions and, in the case of the earthquake spectra, for both the Parkfield and Temblor ground motions. These spectra show quite clearly that for the reactor plant, typically represented by nodes 3 and 9 in Fig. 3 and 4 respectively, the effect of impact by the MRCA is less onerous than a modest SSE. Although the response spectra corresponding to the Boeing 707-320 impact are clearly more onerous (Fig. 3 and 4) than those corresponding to the earthquake it is quite likely that if due account were to be taken of the local inelastic impact effect, then the effect on the reactor plant could be shown to be less onerous than the SSE.

In Fig. 5, response spectra are shown for a location,node 21, near the top of the primary containment structure. Here the comparison between the aircraft impact effect and the earthquake is misleading due to the fact that the local impact effects have been ignored.

6. Conclusions

A direct comparison has been made between earthquake induced vibrations and aircraft impact induced vibrations. The calculated response to the aircraft impact is clearly an overestimate since the direct local impact effect which will absorb much of the energy has been ignored. Nevertheless, it is shown that the response of the reactor plant due to the impact of a multi role combat aircraft on the primary containment structure is small compared to the response due to a modest earthquake.

We conclude that where nuclear power stations are being designed to ensure a safe shut down against earthquakes, then provided that the primary containment structure is designed to protect the reactor primary circuit against direct damage from a multi role combat aircraft, it is likely that the reactor plant within the primary containment will have an acceptable response.

TABLE 1

Maximum displacements (mm)

Node	Soil shear wave velocity (m/sec)	Earthquake max acceleration 0.25 g			Aircraft impact		
					MRCA		707
		El-Centro	Parkfield	Temblor	Load A	Load C	Load B
9	500	9.71	7.48	5.76	1.39	1.90	20.19
	800	5.27	5.02	4.55	1.63	1.65	13.25
	1500	2.99	2.61	2.53	0.90	0.92	6.32
	2000	2.84	2.49	2.23	0.83	0.85	5.44
13	500	12.70	9.86	7.77	2.51	2.53	27.38
	800	7.22	6.95	6.30	2.29	2.33	18.78
	1500	4.75	4.11	3.93	1.49	1.53	10.22
	2000	4.62	4.03	3.55	1.37	1.41	9.06
20	500	13.80	10.66	8.04	2.86	2.87	21.89
	800	7.23	6.83	6.23	2.66	2.71	21.63
	1500	3.41	2.89	3.26	1.36	1.39	8.79
	2000	3.46	2.42	2.87	1.15	1.18	7.50
21	500	16.00	12.42	9.78	4.74	4.75	53.81
	800	9.86	9.49	8.18	5.29	5.35	47.90
	1500	8.89	4.65	5.45	5.62	5.71	43.55
	2000	8.93	4.55	4.97	5.77	5.86	44.66
22	500	17.06	13.25	10.47	5.20	5.21	58.91
	800	10.57	10.19	8.81	5.79	5.86	52.93
	1500	9.69	5.05	5.92	6.13	6.24	48.16
	2000	9.75	4.95	5.41	6.29	6.40	49.30

TABLE 2

Maximum accelerations m/sec^2

Node	Soil shear wave velocity (m/sec)	Earthquake max acceleration 0.25 g = 2.45 m/sec^2			Aircraft impact		
					MRCA		707
		El-Centro	Parkfield	Temblor	Load A	Load C	Load B
9	500	3.49	2.79	2.46	0.83	0.78	5.43
	800	3.54	3.64	3.29	1.45	1.46	10.11
	1500	4.52	4.15	3.69	1.24	1.27	8.07
	2000	4.68	4.40	3.64	1.17	1.20	7.57
13	500	3.97	3.33	2.98	1.08	0.93	6.93
	800	4.13	4.47	4.07	2.35	2.41	16.18
	1500	6.21	5.36	4.84	2.09	2.15	13.29
	2000	6.68	5.86	4.75	1.99	2.05	12.90
20	500	3.80	3.01	2.98	1.24	1.14	7.99
	800	4.16	3.98	4.08	2.29	2.36	14.74
	1500	5.93	4.00	4.45	1.91	1.96	11.77
	2000	6.12	3.70	4.49	1.71	1.76	10.53
21	500	4.15	3.43	3.17	4.84	4.02	20.89
	800	4.58	4.44	3.77	6.27	5.68	31.14
	1500	8.68	4.11	4.78	6.82	6.54	37.68
	2000	9.33	4.46	4.78	7.03	6.82	40.53
22	500	4.32	3.60	3.43	5.89	4.41	24.18
	800	4.99	4.68	4.05	6.28	6.11	35.33
	1500	9.43	4.36	5.15	6.45	6.72	42.09
	2000	10.82	4.77	5.16	6.91	6.91	45.25

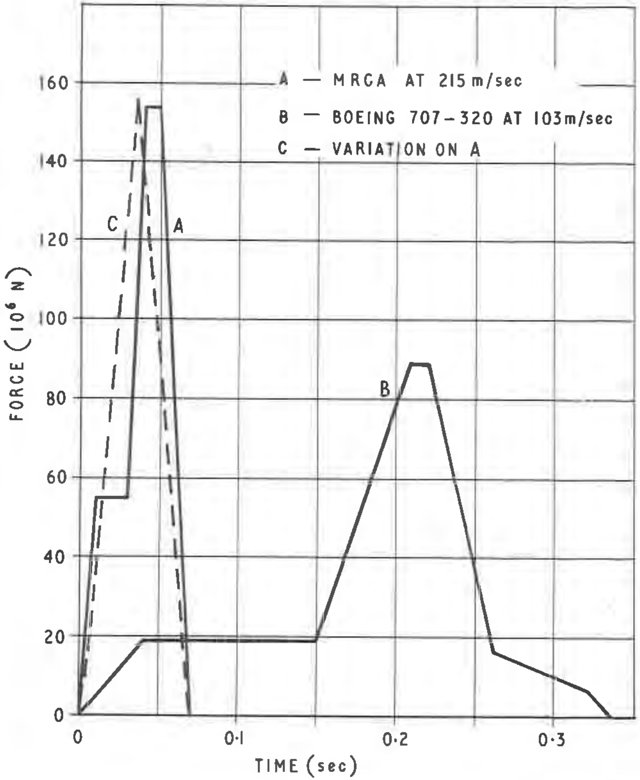


Fig. 1 Aircraft impact loading

ELEMENT DEFINITIONS

4-1	SOIL
1-2-3	FOUNDATION RAFT
3-6-7-8-9-10-11-12-13	PRIMARY CIRCUIT AND SUPPORTING STRUCTURES
8-9-14	
3-12	
3-21-22	PRIMARY CONTAINMENT AND POLAR CRANE
3-15-16-17-18-19-20	SECONDARY CONTAINMENT BUILDING

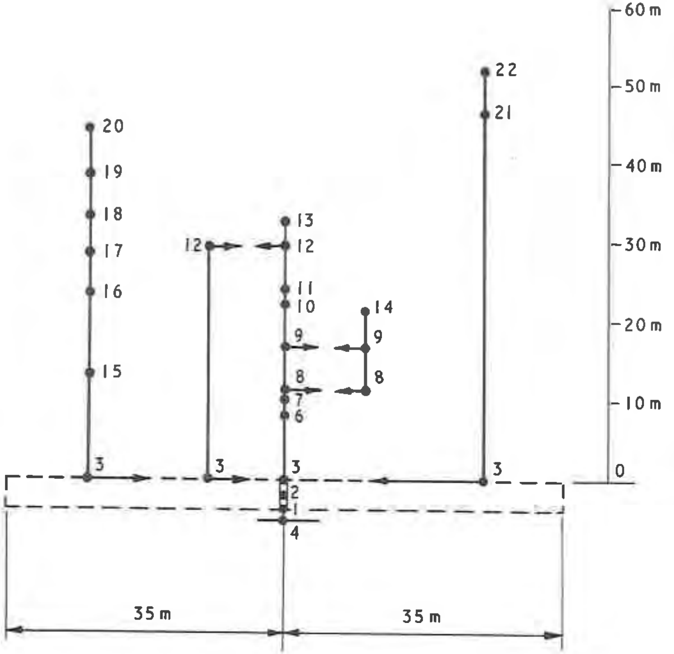
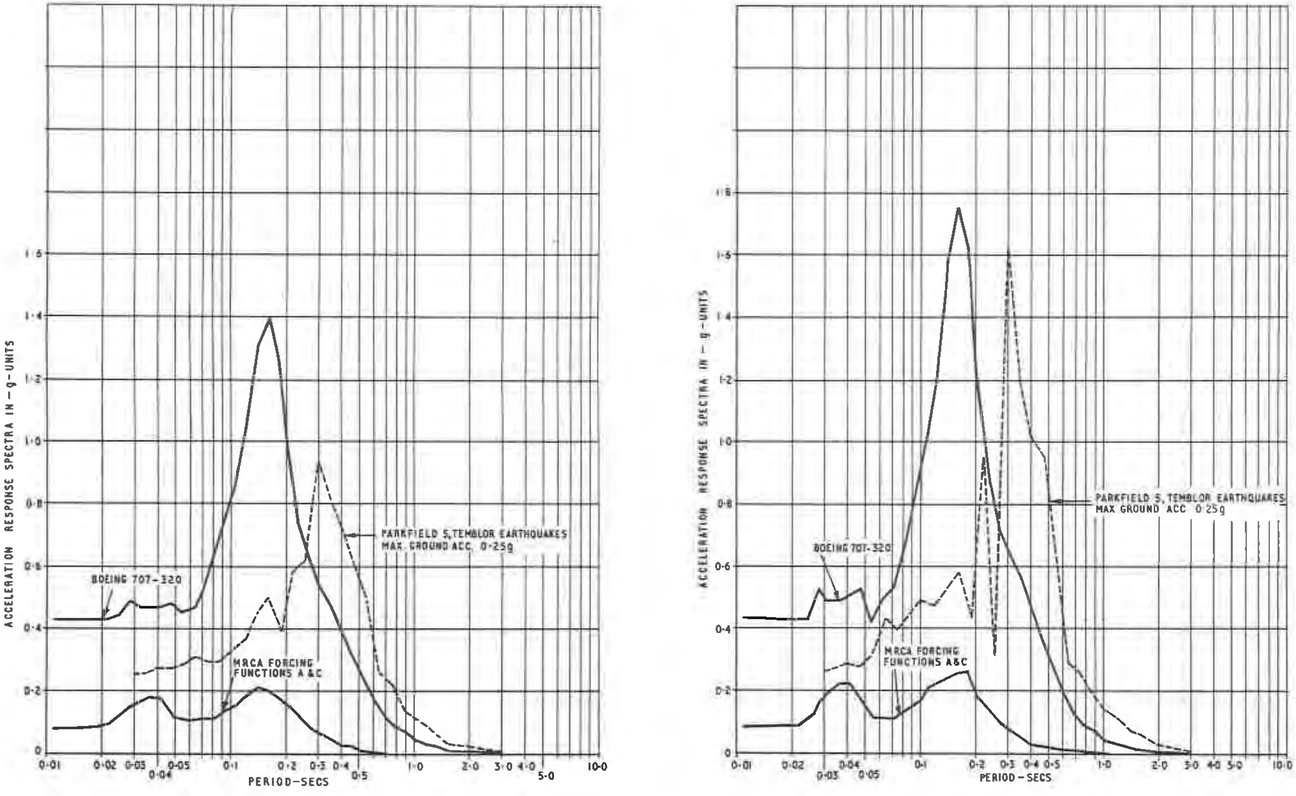


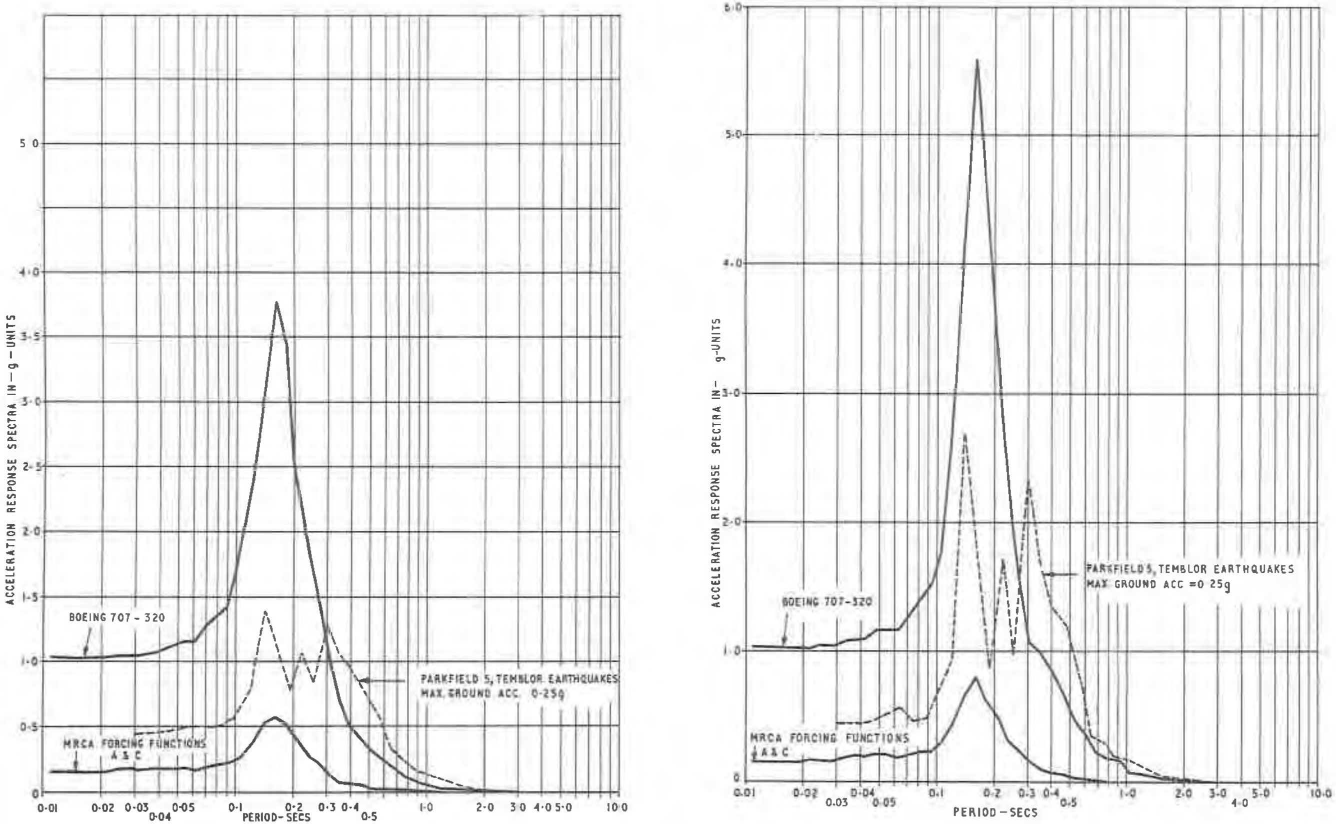
Fig. 2 Structural idealisation of a reactor block



(a) NODE 3, $\eta = 0{\cdot}05$

(b) NODE 3, $\eta = 0{\cdot}01$

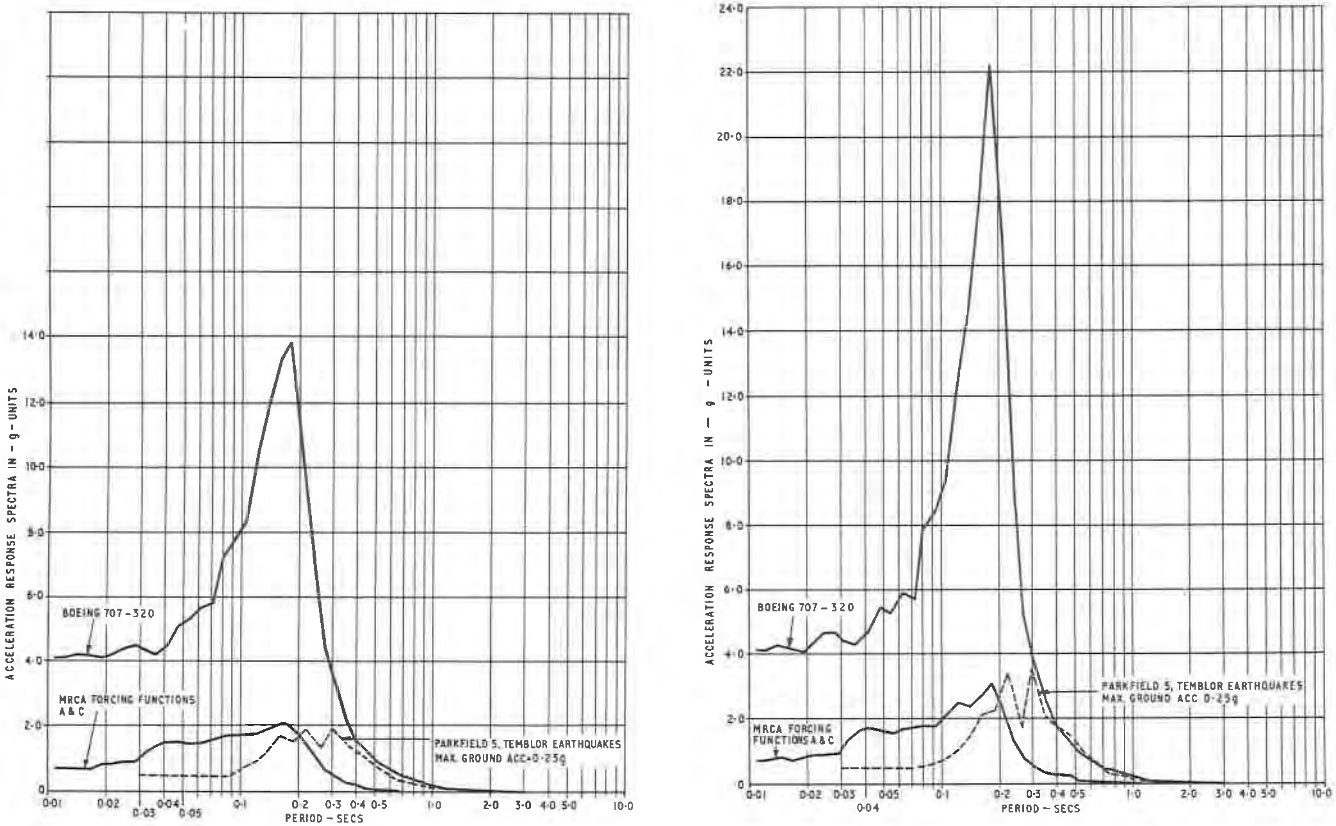
Fig. 3 Floor response spectra, node 3



(a) NODE 9, $\eta = 0{\cdot}05$

(b) NODE 9, $\eta = 0{\cdot}01$

Fig. 4 Floor response spectra, node 9



(a) NODE 21, $\eta = 0{\cdot}05$

(b) NODE 21, $\eta = 0{\cdot}01$

Fig. 5 Floor response spectra, node 21