CHARACTERISTICS OF STRONG GROUND MOTIONS

By

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ABSTRACT

Three methods, namely probabilistic, Fourier spectra and response spec-
a were used to investigate characteristics of strong ground motions like
rthquakes and underground nuclear explosions. A description is given of
e results obtained with special emphasis on the response spectra method.
e intrinsic relations and properties of five different response spectra
e studied. A peak spectral frequency is defined allowing one to classify
ents as having acceleration spectra of low, medium or high peak spectral
equency type. Apart from the effect of other geophysical parameters a
rrelation is shown to exist between peak spectral frequency and epicentral
stance.

INTRODUCTION

During the last ten years, with the advent of digital computers, a eat amount of knowledge has been gained in the problem of structural res- ise to ground motion excitation. The progress in ground motion character- ation however, has not advanced at the same rate. When studying the dy- nical response of a structure, by the common practice of applying a col- ction of different ground motion accelerations to the dynamical model of e system, it is hard to differentiate those properties of response which are due to the ground motion characteristics from those associated with the particular structure. It has already been recognized that structural modifications are not necessarily beneficial nor detrimental to the dynamical strength of a given structure (1), which depends on the characteristics of the particular ground motion under consideration. These, and other facts, suggest the convenience in trying to isolate ground motion properties from structural characteristics, by choosing certain number of significant geophysical parameters describing the main properties of every particular event. These parameters like peak ground acceleration, epicentral distance, propagation media, event magnitude, focal depth, source mechanism, should be correlated with important structural parameters, like natural frequency for instance, to give some estimate of the potential effect of an event on structures. For a given geographical region, knowing the expectation of the geophysical parameters, it should be possible to predict what type of motion can be expected from natural earthquakes (EQ) or man controlled underground nuclear explosions (UNE).

To establish correlations between geophysical and structural parameters the ground motion acceleration function by itself is not adequate. Its irregularities do not allow one to visualize the factors which are determinant

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in structural response. To this end, transformations of the acceleration function are performed leading to new functions which supposedly represent more clearly those ground motion properties of interest in determining structural response. In previous research (2), three different approaches were used: 1) a probabilistic approach, by means of the power spectral density function, 2) a one to one deterministic approach, using Fourier spectra, and 3) the response (or shock) spectral method, which establishes a many to one transformation.

The probabilistic approach proved to be inadequate since ground motions produced by EQ and UNE are essentially a nonstationary phenomenon, even for dynamical systems having natural periods considerably shorter than the duration of the ground motion. In fact, dispersion of surface waves together with the essentially transient character of source mechanism produce nonstationary ground motions that when recorded do not have the same frequency content as time goes on. As a result, no power spectral density can be defined, since the quotient $|X_T|^2/2\pi T$ do not tend to any limit function. This situation would be completely different if the source mechanism consisted of a sustained action during a certain time interval like, for instance, the passage of a long train with respect to the ground vibrations of a point located near a railroad. Unfortunately, this sustained action is not the case with strong ground motions produced by EQ or UNE.

The Fourier spectra was used because of its direct relation with linear dynamic systems. The Fourier complex transform is the natural spectral representation of the second order linear differential operators resulting from the equations of dynamics when applied to structural models. Results obtained, however, using the Fourier spectral method, were not satisfactory. The sine and cosine Fourier transforms showed high irregularities of the same order as the ground acceleration function, and no correlated characteristics could be found. If one examines the amplitude and phase spectra, the former appears much smoother than the sine or cosine transform, while the latter appears extraordinarly sharp and therefore is practically unusable. Consequently the Fourier spectra are not considered useful for this characterization problem.

Results obtained from the response spectral method will be explained in greater detail, together with the conditions under which they were obtained. Previous investigators (3,4) have introduced and used this method to study mainly EQ characteristics. Other investigators (5) have applied this method to UNE. In the research under consideration (2) five different response spectra as defined subsequently were used to study the properties of both EQ and UNE. With a digital computer, 160 response spectra, each with five different damping ratios, were calculated and graphs were drawn automatically with a digital plotter. Strong motion acceleration records were analyzed for 19 UNE and 10 EQ, which are listed in Table I with some basic data i.e., peak ground acceleration (PGA), epicentral distance (ED), propagation medium, event magnitude, accelerograph instrumental characteristics and version of the ground acceleration digitized data.

Instead of choosing natural period T as the independent variable, as is conventional, the angular frequency $\omega=2\pi/T$ was used. The advantage of this alternative is that the closely spaced oscillations appearing near the origin in the undamped spectra when plotted versus T, do not occur in plots versus ω . The frequency domain selected was $0 \lesssim \omega \lesssim 120$ radians/sec. which is more extensive than the conventional period domain of $0.1 \lesssim T \lesssim 3$ seconds. To extend the frequency domain, special consideration was given to the accelerogram base line error and to the dynamical accelerograph correction. These errors are important in the low and high portions of the frequency domain, respectively; nevertheless, in order not to complicate the main issues of this presentation they will not be considered here.

The principal objectives of the present investigation are 1) to introduce the relations existing between the five response spectra and their main properties, 2) to introudce the definition of peak spectral frequency (PSF) which allows one to classify events according to their frequency content, and 3) to show that, appart from the effect of other geophysical parameters, there exists a clear correlation between PSF and ED. The definition of PSF is based on a 20% damping ration which eliminates the rapid fluctations existing for lower damping ratios. Moreover, the characteristics shown up by those response spectra representing 20% damping, refer to ground motions delivering high energy levels into the structure where it is dissipated in terms of viscous damping. In strong ground motions, the level of energy input into a structure compared to the adequacy of the structure to dissipate such energy constitute one of the main factors of damage. One must recognize, however, that high viscous damping cannot simply take care of the inelastic action developed in structures while strong ground motion occurs. It is a fact that inelastic deformation can reduce considerably the forces and displacements within a structure in a manner quite similar to high viscous damping, but it is also true that no general and clear equivalence has yet been established that allows one to assimilate one effect into the other. However, this fact does not prevent the establishment of important ground motion properties with the 20% damping ratio spectrum, which can be useful in the aseismic design of structures when general trends are being considered.

RESPONSE SPECTRA

To avoid any confusion with other definitions existing in the literature, the definitions for five response spectra will be given in detail. Usually response spectrum is defined as the value of the greatest maximum of the modulus of the output, with respect to a specific input, when the natural period of the system takes on a set of values. This definition is adequate provided the greatest value of the modulus is reached at a point of zero slope. If this is not the case, the greatest value does not constitute a maximum but a least upper bound or supremum (SUP). Since finding the SUP includes checking all zero slope points, it seems more general to define response spectrum as the SUP of the output instead of the greatest maximum.

If y is defined as the relative displacement, a as the ground acceleration, ω as the undamped natural frequency and λ as the damping ratio the equation of motion of a single-degree damped system is

$$\ddot{y} + 2\lambda\omega\dot{y} + \omega^2 y = -a \tag{1}$$

The solution of this equation for homogeneous initial conditions is

$$y = -\frac{1}{\omega'}\int_0^t a(\tau)e^{-\lambda'\omega'(t-\tau)}\sin\omega'(t-\tau)d\tau \qquad (2)$$

where $\omega' = \omega(1-\lambda^2)^{\frac{1}{2}}$, and $\lambda' = \lambda(1-\lambda^2)^{-\frac{1}{2}}$ (3a.b.)

The relative displacement spectrum (RD) is defined by

$$RD(\omega) = \underset{t}{SUP} \mid y(t) \mid \qquad (4)$$

where the SUP is taken with respect to t over the whole semi-infinite time interval $0 \leq t < \infty$. The relative velocity spectrum (RV) is by definition

$$RV(\omega) = \underset{t}{SUP} \mid \dot{y}(t) \mid \qquad (5)$$

$$= \underset{t}{SUP} \mid \int_0^t a(\tau)e^{-\lambda'\omega'(t-\tau)}\left\{\cos\omega'(t-\tau)-\lambda'\sin\omega'(t-\tau)\right\} d\tau \mid \qquad (6)$$

The absolute acceleration spectrum (AA) is defined as

$$AA(\omega) = \underset{t}{SUP} \mid \ddot{y}(t) + a(t) \mid = \underset{t}{SUP} \mid 2\lambda\omega\dot{y}(t) + \omega^2 y(t) \mid \qquad (7)$$

$$= \underset{t}{SUP} \mid \omega'\int_0^t a(\tau)e^{-\lambda'\omega'(t-\tau)}\left\{(1-\lambda'^2)\sin\omega'(t-\tau) + 2\lambda'\cos\omega'(t-\tau)\right\}d\tau \mid \qquad (8)$$

All of the above defined spectra have a clear physical meaning. RD represents the peak value in magnitude of the relative displacement of a single degree system, RV the peak relative velocity, and AA the peak absolute acceleration of the mass of the same system, during the time history of motion. The pseudo relative velocity spectrum (PSRV) is defined as

$$PSRV(\omega) = \omega' \; RD(\omega) \qquad (9)$$

and the pseudo absolute acceleration spectrum (PSAA) by

$$PSAA(\omega) = \omega^2 \; RD(\omega) \qquad (10)$$

PSAA represents the peak value of the elastic spring force per unit of mass in the single degree system. PSRV however, does not have a clear physical meaning in terms of a simple physical quantity.

From the above definitions, asymptotic behavior formulae for spectra can be deduced. If ground motion acceleration $a(t)$, ground velocity $v(t)$ and ground displacement $d(t)$ are zero for $t = 0$, then when $\omega \rightarrow 0$,

$$RD(\omega) = \frac{PSRV(\omega)}{\omega'} = \frac{PSAA(\omega)}{\omega^2} \rightarrow \underset{t}{SUP} \mid d(t) \mid \qquad (11)$$

$$RV(\omega) \rightarrow \sup_t | v(t) | \tag{12}$$

$$\frac{AA(\omega)}{\omega} \rightarrow \sup_t | 2\lambda v(t) + \omega(1 - 2\lambda^2)d(t) | \tag{13}$$

where

$$v(t) = \int_0^t a(\tau)d\tau \tag{14}$$

$$d(t) = \int_0^t v(\tau)d\tau \tag{15}$$

Moreover, since a ground acceleration function satisfies Dirichlet's conditions regarding maximums and minimums and has no discontinuities, it can be shown from the above definitions that when $\omega \rightarrow \infty$,

$$RD(\omega) = \frac{PSRV(\omega)}{\omega^1} = \frac{PSAA(\omega)}{\omega^2} \rightarrow \frac{1}{\omega^2} \sup_t | a(t) | \tag{16}$$

$$RV(\omega) \rightarrow \frac{1}{\omega^2} \sup_t | \dot{a}(t) | \tag{17}$$

$$AA(\omega) \rightarrow \sup_t | a(t) | \tag{18}$$

RELATIONS AND PROPERTIES OF SPECTRA

The intrinsic relations existing between spectra are presented next using as an example Case N°17 of Table I, Aardvark 3773T, which is an UNE. The relations and properties hold in general for all strong ground motions, UNE and EQ, as will be shown subsequently, because they are properties of spectra rather than of the particular acceleration function.

Ground Motion - Fig. 1A represents the ground acceleration which is the basic information for the event obtained from reducing the accelerogram function and is punched in digitized cards. The time duration is restricted to about 4.3 sec. which is considered a proper truncation (2) for this event. No correction whatever has been applied to this function. The PGA has a magnitude of 0.74 g..

Fig. 1B shows the integrated velocity obtained from the function presented in Fig. 1A by performing the integration indicated in Eq. 14. It must be noticed that final velocity is not zero because no base line correction has been applied to the ground acceleration. This fact is immaterial for establishing the main relations and properties of spectra, which is one of the objectives of this paper and besides, when a truncation procedure is used, zero final velocity is not a necessary requirement. The units of ordinates are in seconds so the peak velocity has a magnitude of (0.041)·(386) in/sec.

Acceleration Spectra - Fig. 2A and Fig. 2B show the AA and PSAA spectra. It is interesting to observe that they are very similar. In fact, for zero damping they are identical, by definition, and differ in a small amount for the rest of the damped curves. Table II shows for 20% damping the order of this difference in 4 UNE and 4 EQ as a function of frequency. This Table gives the ratio AA/PSAA. For UNE on the average, AA is 6% greater than PSAA, while for EQ, AA is 7% greater than PSAA. The fact that AA and PSAA have close values, even for 20% damping ratio, reveals that the damping force is out of phase with the elastic force. This can be expected since when the elastic force passes through a maximum or minimum the damping force is zero.

In Fig. 2A and Fig. 2B it can be observed that both AA and PSAA tend to zero when ω does, which agrees with Eqs. (13) and (11), respectively. Also both AA and PSAA tend to PGA = 0.74 g for increasing values of ω as required by Eqs. (18) and (16). This asymptotic behavior is important since it shows a direct correlation between a geophysical parameter PGA and a spectral property. As Eqs. (16) and (18) are independent of damping the asymptotic behavior holds for any curve of spectra. The asymptotic behavior of AA and PSAA for high frequency values agrees with the design criterion required by the Code (6) for stiff structures, like one-story and two-story buildings, which specifies a constant seismic coefficient 'C' and a uniform load distribution over the height.

As mentioned before, the dynamical accelerograph correction is not included in this paper. Table I gives an instrumental period for Aardvark 3773T of T = 0.056 sec. which is ω = 112 radians/sec. falling in the very upper portion of the spectral frequency domain. This confirms that this correction is not of major importance in this case for the acceleration spectra (2).

<u>Velocity Spectra</u> - Fig. 3A and Fig. 3B present RV and PSRV spectra, respectively. For zero damping ratio both spectra show very close values except for frequencies lower than about 4 radians/sec. Below this frequency RV tends to 0.041 g which is the peak ground velocity, whereas PSRV tends to zero. Comparison of the 20% damping ratio curves reveals much greater differences. For increasing values of ω both RV and PSRV tend to zero but at a different rate. This fact agrees with Eqs. (17) and (16), respectively, since the first decreases as ω^{-2} but the last as ω^{-1}. For values of ω approaching zero, RV tends again to the peak ground velocity as required by Eq. (12) and PSRV tends to zero as shown by Eq. (11).

Table III gives the values of the ratio RV/PSRV for 4 UNE and 4 EQ as a function of frequency. Averages are taken between events for every frequency and it is observed that the ratio is a decreasing function of frequency which takes on the value 1 for some frequency ω_1. At this frequency the functions RV and PSRV cross each other. This behavior is illustrated in Fig. 4 for the 20% damping ratio curve which points out that only in the neighborhood of the crossing point does the approximation RV $\cong$ PSRV hold good.

<u>Displacement Spectrum</u> - Fig. 5 presents the RD spectrum. This spectrum is algebraically related to PSAA as shown by Eq. (10). For increasing values of ω, RD tends to zero as ω^{-2}, as shown by Eq. (16), and when ω tends to zero RD tends to the peak ground displacement as shown by Eq. (11). Peak ground displacement is extremely sensitive to base line correction, as well as the RD spectrum near the origin (2). Consequently the RD values for small ω (less than 6 radians/sec.) should be accepted with some reservations.

CLASSIFICATION OF SPECTRA

The purpose in classifying the obtained 160 response spectra is to separate the events that have radically different effects on structures. The main concern was to distinguish the different patterns in the frequency distribution. Ground motions with spectra which peak in the high frequency region have completely different effect on a given population of structures than those which peak at the low frequencies. The first observation, examining the collection of spectra, is that the variability of the frequency distribution is not the same for all five subcollections of spectra. RD shows a lower variability and AA, as well as PSAA, exhibit a higher variability. Since RD decays so rapidly with increasing frequencies it peaks always at the lower frequencies, the range of variation being considerably limited. RV and PSRV exhibit peak frequencies ranging from the low frequencies to about 60 radians/sec. The range of variability of AA and PSAA is the greatest, presenting peak frequencies which vary from 8 radians/sec. to 120 radians/sec.

Because of its great frequency variability AA was selected for classifying ground motion events. Figure 6A, 7A and 8 present the AA spectra of three different ground motions. The first case, Mississippi 1777T, show a clear predominance of low frequencies, the second, Gnome S4R peaks in the middle range and the third, Gnome S2T, exhibits clear predominance of high frequencies. By inspecting closely the different damping ratio curves of Fig. 6A, 7A and Fig. 8, it can be observed that they have different frequency variability. In Fig. 6A the zero damping ratio curve peaks at 22 radians/sec. whereas the 20% damping ratio curve peaks at 8 radians/sec. In Fig. 8 the zero damping ratio curve peaks at 87 radians/sec. while the 20% damping ratio curve peaks at 100 radians/sec. So the range of variability from 22 to 87 radians/sec. in the zero damping curve is extended from 8 to 100 radians/sec. in the 20% damping ratio curve.

At this point is is convenient to give a name to the frequency at which the 20% damping ratio AA spectrum reaches its peak value. It seems natural to refer to its as the peak spectral frequency (PSF) of the event. The importance of this frequency is that it allows one to visualize the type of motion of a particular event. By the knowledge of its value the 20% damping ratio spectrum can be sketched if one knows in addition the value of PGA. In fact, the 20% AA spectrum consist of a monotonically increasing function from zero to the PSF frequency, where its value is about 1.5 times the value of PGA. Then, it decays, practically monotonic, approaching asymptotically the value of PGA.

Consequently, knowledge of the two parameters PGA and PSF for a particular event gives a considerable amount of information refering to its general effects on structures. If the probability expectation of these values were known for a given geographical region, one could contruct a regional probable acceleration spectrum giving a rational basis to the product "AC" prescribed by the Code (6).

In terms of PSF values the UNE of Fig. 6A, 7A and 8 can be referred to as having a low, medium and high PSF. A similar situation occurs with EQ as shown in Fig. 6B and 7B. Nevertheless, no earthquake spectrum was found having a high PSF. Figure 9. illustrates what is considered a low, medium and high PSF spectrum.

CORRELATION PEAK SPECTRAL FREQUENCY WITH EPICENTRAL DISTANCE

In this article the correlations between the spectral parameter PSF and the geophysical parameters of the event are considered. No need to refer to PGA since it is both a spectral as well as a geophysical parameter.

Table I lists the available geophysical parameters for every event. By comparing the values of PSF of each event obtained from the collection of 20% AA spectra with the basic data of Table I, correlations were found with epicentral distances. They are listed in Table IV for UNE and in Table V for EQ. The same correlations are presented graphically in Figs.10A and 10B. Some points do not fit the correlation well. Obviously factors other than distance are involved, as evidenced by the fact that UNE and EQ cannot be placed under the same correlation. The ordinates in Fig. 10A have a scale 8 times smaller than the ordinates in Fig. 10B. It would appear that focal depth, propagation media and energy released, combined with epicentral distance are the crucial factors. Lack of a more complete description of the geophysical parameters do not allow one to obtain better correlations. Nevertheless, epicentral distance by itself shows a predominant trend, namely that for decreasing ED, PSF increases.

The fact that no EQ had a high PSF can be explained now by recognizing that among those earthquakes listed in Table I there is not one having a short epicentral distance. The shortest epicentral distance of 12 Km is for the San Francisco 1957 S80E, which according to its AA spectrum (Fig. 7b) is a medium PSF event. Shorter epicentral distance EQ have occured, as for instance the Agadir, Morocco Earthquake of Feb. 29, 1960 and the Maipo Valley Earthquakes, Chile, Sept. 4, 1958 which produced severe damage to the stiffer structures. An indication of the predominant frequencies that one might expect in these cases can be obtained from Fig. 8.

CONCLUSIONS

The principal conclusions which can be drawn from this investigation are listed as follows:

1. Using frequency as obcissa avoids the accumulation of oscillations near the origin that occur when spectra are plotted versus period and, thus, usually gives smoother curves.

2. Absolute and pseudo absolute acceleration spectra are identical for zero damping ratio, and for other damping ratios are quite similar along the whole frequency range. This characteristic makes it practically immaterial which one is used in estimating loads or deformations.

3. Relative and pseudo-relative spectra present clearly a different character. The approximation RV $\cong$ PSRV which is valid for zero damping above a certain frequency, say 4 radians/sec., can be considerably in error for higher damping ratios.

4. Classification of response spectra leads one to the conclusion that there are primarily, two parameters controlling the 20% absolute acceleration spectrum; i.e., peak spectral frequency and peak ground acceleration. The first parameter controls the frequency distribution and the later controls the

intensities. Knowledge of the probabilistic expectation of these parameters, for a given geographical region, would allow one to construct a regional probable spectrum.

5. A correlation exists between peak spectral frequency and epicentral distance, however, other factors like focal depth, propagation medium and event magnitude would appear to influence this correlation.

6. It would be desirable to elucidate the effect of other geophysical parameters on the peak spectral frequency - epicentral distance correlation, since it would allow one to construct regional probable spectra directly from the knowledge of the expectation of the geophysical parameters.

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TABLE I

ANALYZED RECORDS

Case No.	Event	Peak Acc. (%g)	Epic. Dist. (km)	Medium Sor.	Medium Rec.	Magn. (*)	Ins. T (sec)	Char. ε	Vrs	
1	Gnome 2T	.74	1.6	S	A	3.1	.061	10	L	Underground Nuclear Explosions
2	" 3T	.23	3.2	S	A	3.1	.112	10	"	
3	" 4R	.05	6.5	S	A	3.1	.140	7	"	
4	" 4T	.02	6.5	S	A	3.1	.141	7	"	
5	" 6T	.03	1.6	S	A	3.1	.059	9	"	
6	" 7T	.16	3.2	S	A	3.1	.111	10	"	
7	Dannyboy D5R	.09	1.2	B	B	.4	.070	8	"	
8	" D8R	.03	2.1	B	B	.4	.110	8	"	
9	Mississippi 1777T	.05	8.9	T	A	-	.111	9	P	
10	" 8228T	.04	6.1	T	A	-	.056	12	"	
11	" 7245R	.45	2.0	T	A	-	.030	10	"	
12	" 9537R	.98	1.0	T	A	-	.017	13	"	
13	" 4074T	.25	3.1	T	A	-	.039	8	"	
14	" 4074R	.30	3.1	T	A	-	.040	7	"	
15	Hard Hat 1091T	.52	1.2	G	L	5.	.034	9	"	
16	" 4496T	.29	6.3	G	A	5.	.146	9	"	
17	Aardvark 3773T	.74	1.1	A	A	37.	.056	15	"	
18	" 1437T	.05	7.5	A	A	37.	.101	13	"	
19	Sedan R3	.15	1.1	A	A	110.	.017	5	L	
20	Taft 52 N21E	.18	64	-	-	7.7	.081	8	B	Earthquakes
21	" "	.18	64	-	-	7.7	.081	8	H	
22	" "	.18	64	-	-	7.7	.081	8	V	
23	" "	.18	64	-	-	7.7	.081	8	C	
24	El Centro 40 NS	.32	48	-	-	6.7	.099	8	B	
25	" 40 EW	.23	48	-	-	6.7	.100	7	B	
26	" 34 NS	.26	54	-	-	6.5	.098	8	B	
27	Olympia 49 N80E	.32	72	-	-	7.1	.080	9	B	
28	S. F. 57 S80E	.13	12	-	-	5.3	.078	10	V	
29	Ferndale 41 S45E	.12	32	-	-	6.6	.099	10	V	

<u>Tabulation Versions</u>:
- L - Lawrence Radiation Lab.
- P - Planetary Sciences Inc.
- B - Berg
- C - Clough
- H - Hudson
- V - Veletsos

<u>Medium Characterization</u>:
- A - Alluvium
- S - Salt
- B - Basalt
- L - Limestone
- G - Granite
- T - Wether Tuff

(*) Magnitude in kilotons for blasts, in Richter magnitude for earthquakes.

TABLE II

RATIO OF ABSOLUTE ACCELERATION TO PSEUDO ABSOLUTE ACCELERATION
(λ = 20% of critical)

Case No.	Event	ω = 6 (T = 1.05)	ω = 10 (T = 1.63)	ω = 20 (T = 0.31)	ω = 40 (T = 0.16)
9	Mississippi 1777T	1.08	1.06	1.04	1.00
10	Mississippi 8228T	1.20	1.10	1.04	1.01
16	Hard Hat 4496T	1.05	1.07	1.03	1.01
18	Aardvark 1437T	1.12	1.08	1.04	1.02
	Average	1.11	1.08	1.04	1.01
24	El Centro 40 NS	1.09	1.10	1.04	1.06
25	El Centro 40 EW	1.09	1.09	1.03	1.09
26	El Centro 34 NS	1.11	1.07	1.01	1.02
27	Olympia 49 N80E	1.08	1.19	1.05	1.03
	Average	1.09	1.11	1.03	1.05

TABLE III

RATIO OF RELATIVE VELOCITY TO PSEUDO RELATIVE VELOCITY
(λ = 20% of critical)

Case No.	Event	ω = 6 (T = 1.05)	ω = 10 (T = 0.63)	ω = 20 (T = 0.31)	ω = 40 (T=0.16)
9	Mississippi 1777T	1.10	0.82	0.90	0.41
10	Mississippi 8228T	1.25	0.97	0.75	0.63
16	Hard Hat 4496T	1.71	1.05	0.79	0.83
18	Aardvark 1437T	1.05	1.09	0.66	0.50
	Average	1.28	0.98	0.77	0.59
24	El Centro 40 NS	1.27	1.19	1.02	0.77
25	El Centro 40 EW	1.96	1.11	0.72	0.87
26	El Centro 34 NS	1.70	1.05	0.70	0.56
27	Olympia 49 N80E	1.54	1.16	0.69	0.89
	Average	1.62	1.13	0.78	0.77

TABLE IV
CORRELATION FREQUENCY - EPICENTRAL DISTANCE
UNDERGROUND NUCLEAR EXPLOSIONS

Case No.	Event	Peak Spect. Frequency (rad/sec)	Epic. Dist. (km)
15	Hard Hat 1091T	120	1.2
1	Gnome 2T	100	1.2
12	Mississippi 9537R	87	1.0
5	Gnome 6T	80	1.6
11	Mississippi 7245R	80	2.0
6	Gnome 7T	70	3.2
13	Mississippi 4074T	66	3.1
2	Gnome 3T	63	3.2
17	Aardvark 3773T	58	1.1
7	Dannyboy D5R	49	1.2
4	Gnome 4T	48	6.5
16	Hard Hat 4496T	45	6.3
3	Gnome 4R	45	6.5
19	Sedan R3	33	1.1
8	Dannyboy D8R	15	2.1
14	Mississippi 4074R	13	3.1
10	Mississippi 8228T	13	6.1
18	Aardvark 1437T	13	7.5
9	Mississippi 1777T	8	8.9

TABLE V
CORRELATION FREQUENCY - EPICENTRAL DISTANCE
EARTHQUAKES

Case No.	Event	Peak Spect. Frequency (rad/sec)	Epic. Dist. (km)
28	San Francisco 57 S80E	54	12
29	Ferndale 41 S45E	26	33
23	Taft 52 N21E	19	64
27	Olympia 49 NE	18	72
24	El Centro 40 NS	14	48
25	El Centro 40 EW	13	48
26	El Centro 34 NS	12	54

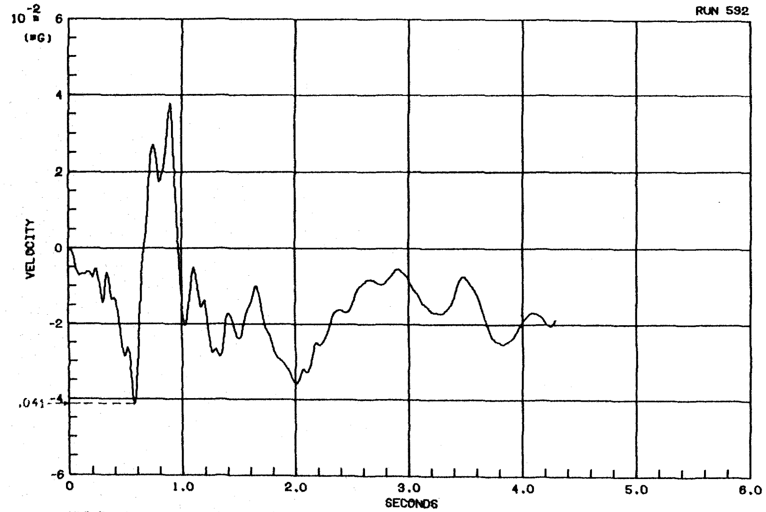

FIG. 1B. AARDVARK 3773 - TRANSVERSE

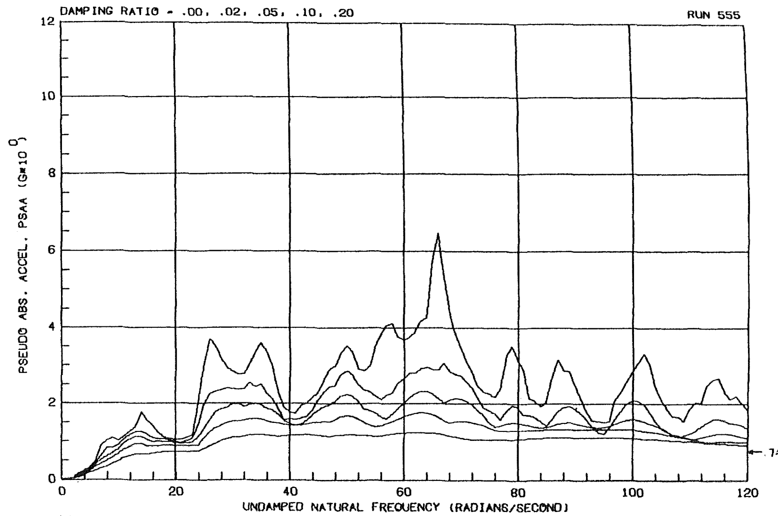

FIG. 2B AARDVARK 3773 - TRANSVERSE

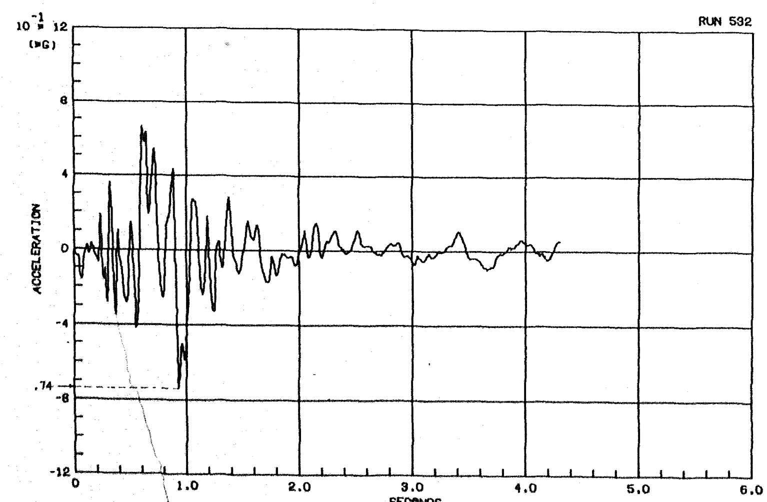

FIG. 1A. AARDVARK 3773 - TRANSVERSE

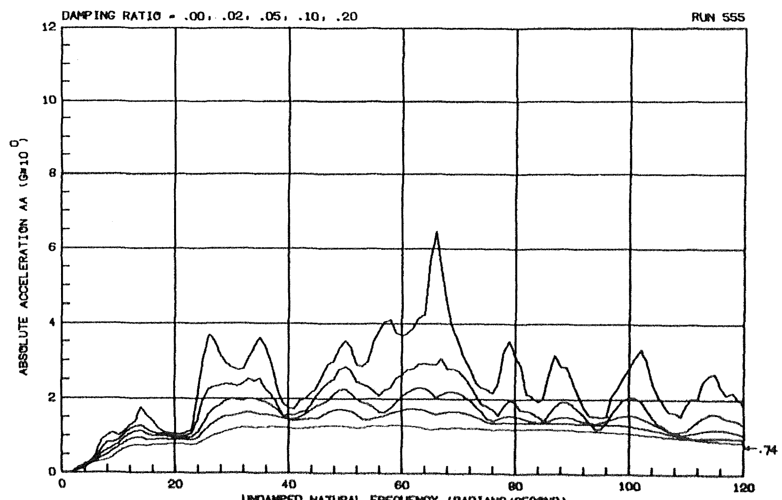

FIG. 2A. AARDVARK 3773 - TRANSVERSE

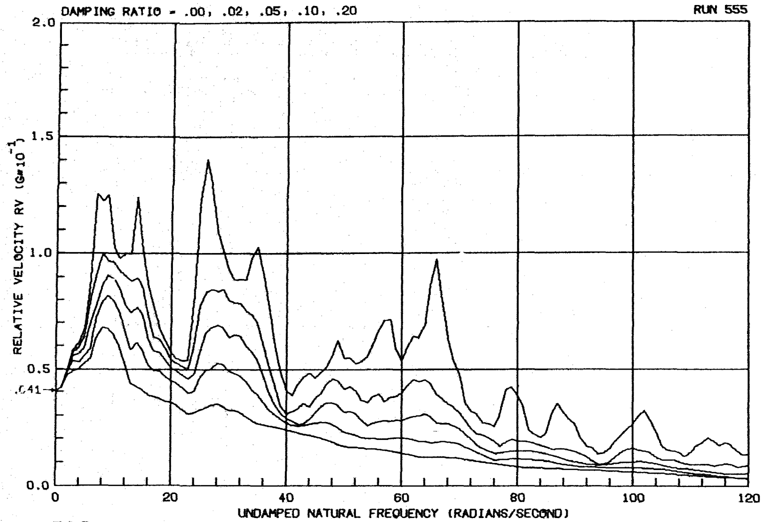

FIG. 3A. AARDVARK 3773 - TRANSVERSE

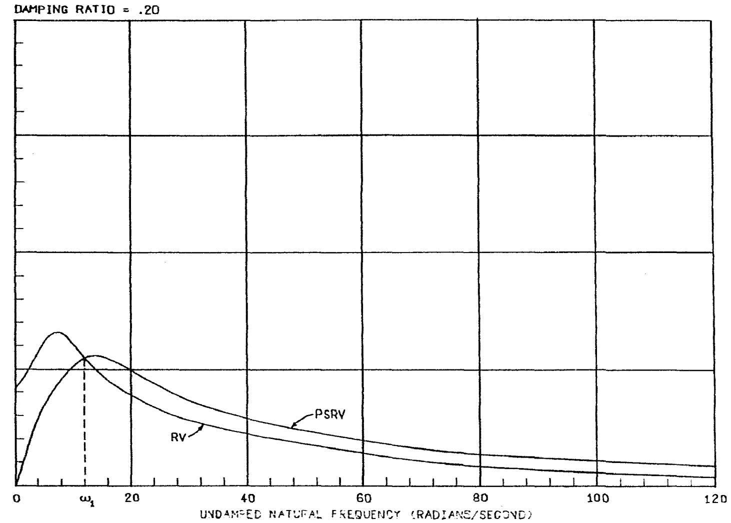

FIG. 4. VELOCITY SPECTRA

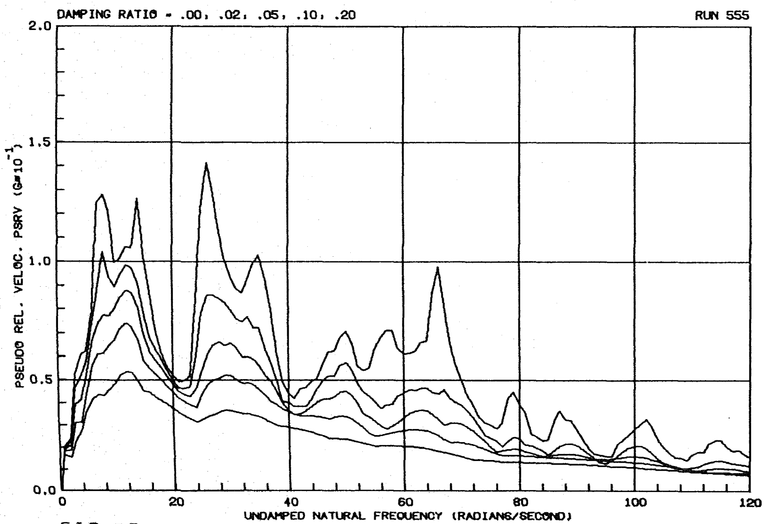

FIG. 3B. AARDVARK 3773 - TRANSVERSE

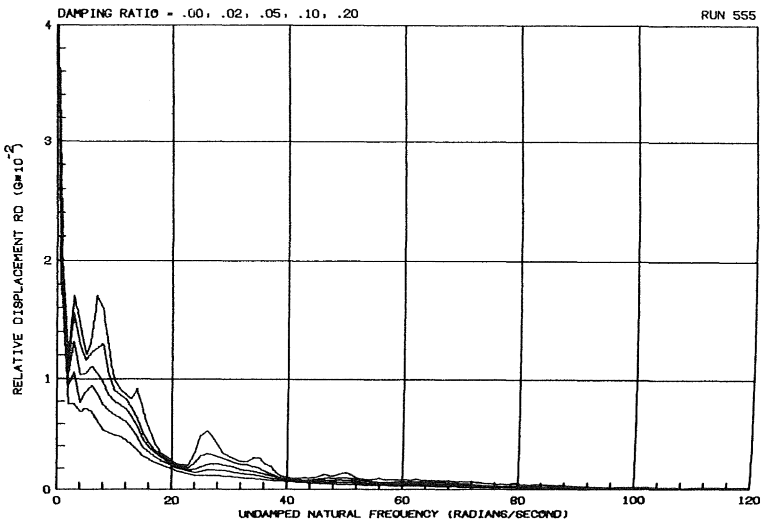

FIG. 5. AARDVARK 3773 - TRANSVERSE

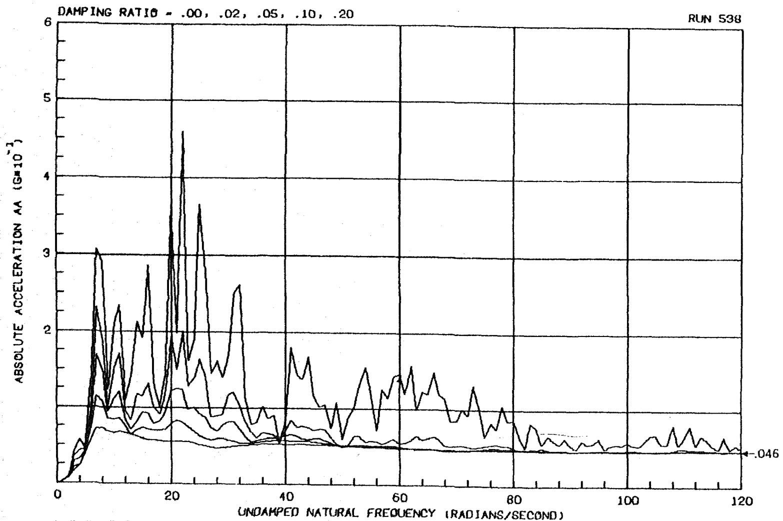

FIG. 6A. MISSISSIPPI 1777 - TRANSVERSE

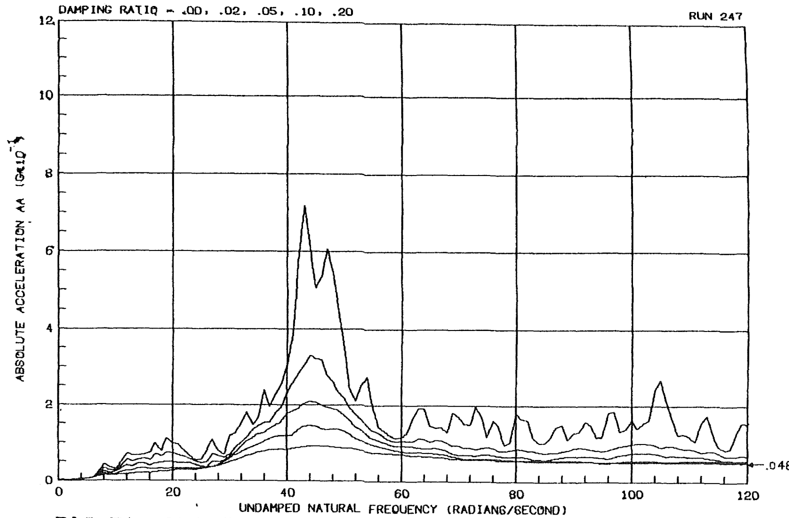

FIG. 7A. GNØME 10 DEC 1961 - S4 RADIAL

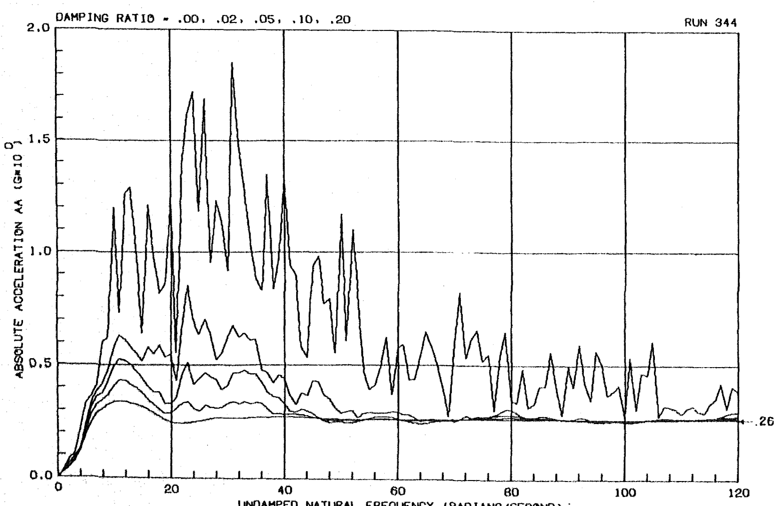

FIG. 6B. EL CENTRØ EARTHQUAKE 30 DEC 1934 - NS

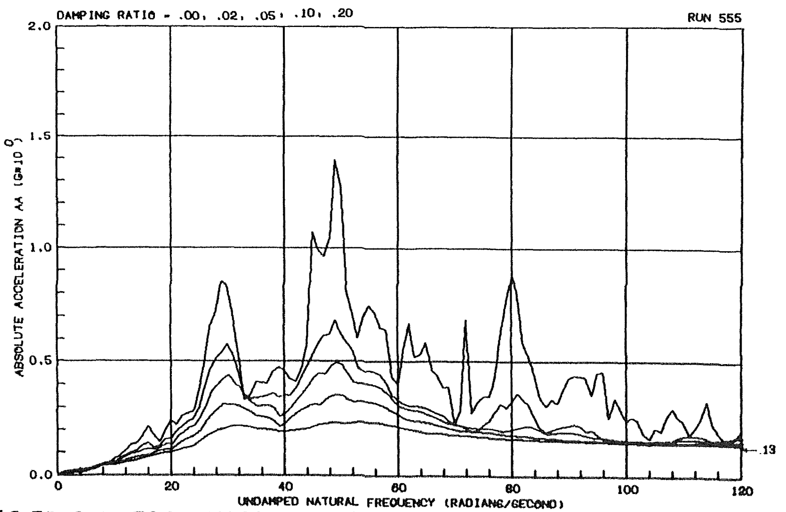

FIG. 7B. SAN FCØ. MARCH 1957 - GØLDEN GATE PARK S80E

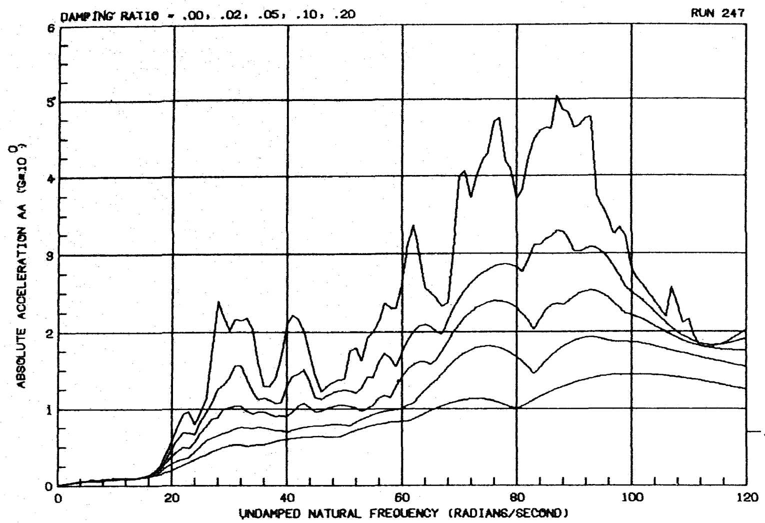

FIG. 8. GNØME 10 DEC 1961 - S2 TRANSVERSE

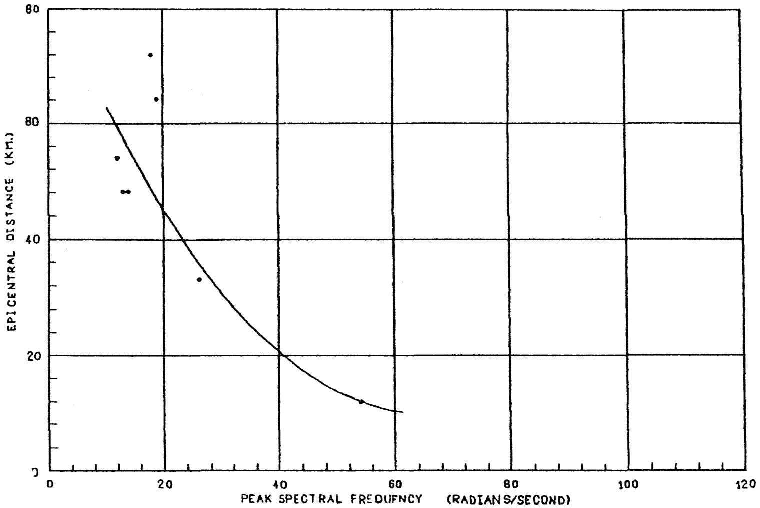

FIG. 10A. CORRELATION FOR EQ.

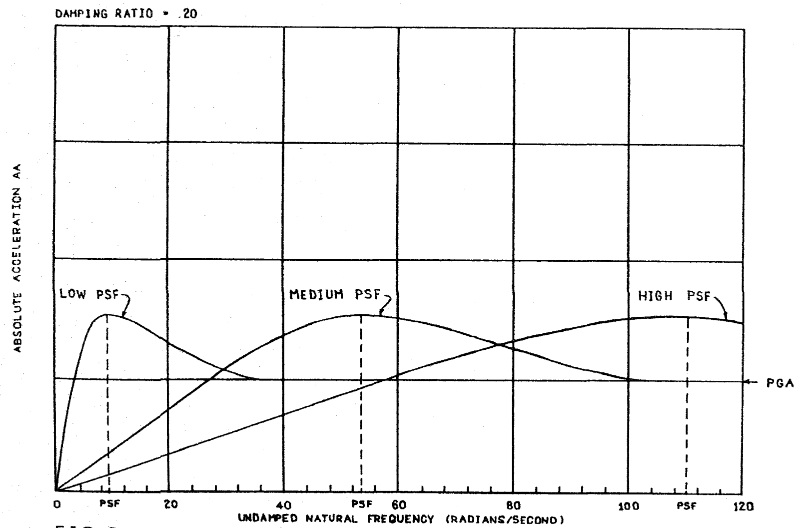

FIG. 9. CLASSES OF SPECTRA

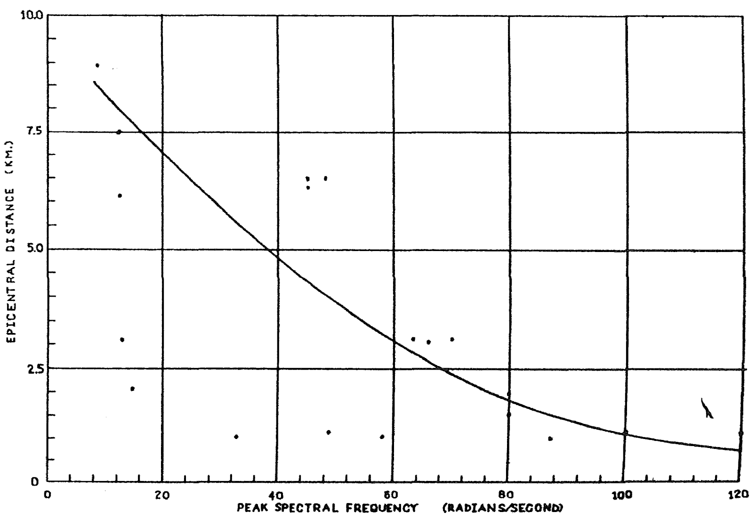

FIG. 10B. CORRELATION FOR UNE.

CHARACTERISTICS OF STRONG GROUND MOTIONS

BY V.A. JENSCHKE, R.W. CLOUGH, J. PENZIEN

COMMENT BY: N.M. NEWMARK - U.S.A.

I should like to raise some questions regarding the interpretation of response spectrum values determined from the various input ground motions considered. As a result of studies made under my direction at the University of Illinois, we have been able to develop general rules for the construction of response spectra from the general characteristics of the ground motion. For almost any type of motion including those arising from nuclear blasts, or from earthquakes, if one has values of the maximum ground displacement, the maximum ground velocity and the maximum ground acceleration, one can construct reasonably accurate values of the response spectrum by noting that the response spectrum can be related to the sort of trapezoidal plot that these ground motion values produce on a tripartite logarithmic spectrum plot (in which one plots frequency on a logarithmic scale along the base, pseudo relative velocity on a logarithmic scale as ordinates, and relative displacement and pseudo absolute acceleration on logarithmic scales on lines sloping upward at 45° from right to left and from left to right, respectively).

For very low frequencies, the response spectrum plotted in this way approaches the maximum ground displacement line. This arises from the fact that for very low frequencies the mass of the oscillator can be considered to be very large and the spring very soft; hence the maximum relative displacement in the spring is precisely equal to the ground displacement.

For very high frequencies, unless the accelerations involve discontinuities, which in general they do not under earthquake conditions, the maximum pseudo acceleration response approaches the maximum ground acceleration. In other words, the oscillator acts like an accelerometer. However, for intermediate frequencies, the response spectrum is characterized reasonably well by bounds consisting of lines parallel to the ground displacement, the ground velocity, and the ground acceleration, each with amplification factors, which are successively larger as one goes from displacement to velocity to acceleration. These amplification factors are, for moderate amounts of damping in the range of 5 to 10 percent critical, roughly only slightly greater than 1 for displacement, about 1.5 for velocity and about 2 for acceleration. As the damping becomes less, all of these amplification factors increase.

In general the logarithmic plot I have described brings out in clearer detail than the arithmetic plot described by the authors the various physical phenomena encountered in dynamic response problems.

QUESTION BY: J.A. BROOKS - PAPUA - NEW GUINEA

Do the authors have any information at all on the likely effect of change of focal depth on the position of the peak spectral frequency at any epicentral distance?

REPLY BY: J. PENZIEN

No, there was insufficient data to make this correlation.