DURATION OF STRONG GROUND MOTION

by

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SYNOPSIS

Duration of strong seismic shaking is a sensitive function of wave frequency, amplitude threshold, and Richter magnitude. The magnitude dependence arises from the finite geometry of fault rupture. Frequency dependence enters through the exponential attenuation law for rock; for larger earthquakes (greater fault breakage), duration of higher frequency (> 1 Hz) horizontal waves with amplitudes above 0.05g ground acceleration is unlikely to exceed 35 to 40 sec. Lack of precise definition has led to exaggerated estimates of duration for some design purposes. Filtered records of ground acceleration yield a table for "bracketed duration" as a function of magnitude and source-to-site distance.

INTRODUCTION

The prediction of the duration D (in seconds) of strong seismic shaking is still rather rudimentary even though "duration is possibly the single most important factor in producing excessive damage" (H.M. Engle, in Richter, 1958). In two recent textbooks on earthquake engineering (Wiegel, 1970; Newmark and Rosenblueth, 1971) no explicit treatment of duration as a function of many variables is attempted. Housner's (1965) curve (see Figure 5) for "the strong phase of ground shaking" is essentially a linear law against magnitude M:

$$D = 11\ M - 53. \qquad (1)$$

Esteva and Rosenblueth (1964) define the duration $\underline{s}$ of an "equivalent" ground motion with uniform intensity per unit time (about half D for large M) as

$$\underline{s} = 0.02 \exp\ (0.74\ M) + 0.3r\ , \qquad (2)$$

where r km is the source distance (FS in Figure 5).

These formulae do express the key dependence of D on M which can be inferred at once from the rupture model of earthquakes (e.g. Bolt, 1970) illustrated by the diagram in Figure 5, i.e. M increases with AB. What the formulae lack is a stated threshold of ground acceleration A to define "strong" and a treatment of frequency. Seismic surface waves (Love and Rayleigh type) attenuate (assuming no dispersion) like

$$A = A_0 E/\quad r, \qquad (3)$$

where

$$E = \exp\ (-\pi f\ r/cQ). \qquad (4)$$

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f is frequency (in Hz), c is wave velocity and Q is the mean specific damping constant for the appropriate rocks and soils.

As (4) shows, because high frequency waves attenuate more strongly than low frequency ones, their duration is severely distance limited. Any linear law, such as (1), *overassesses duration for large earthquakes*, at least for 1 Hz and higher frequency waves (e.g. the frequency invariant estimates of Page et al., 1972). The last term of (2) is physically inadmissable for the same reason: as r increases, the amplitudes (and hence, in general, the mean durations above given thresholds of shaking) decrease like (3).

DEFINITION OF DURATION

Two definitions appear useful.

(a) "Duration at a particular frequency is the elapsed time between the first and last acceleration excursions greater than a given level (0.05g, say)." I propose to call this interval the "bracketed duration". It is sometimes measured by cumulatively adding the squared accelerations and adopting the 95 percentile time interval (Husid et al., 1969). Particularly for earthquakes with specially complex multiple sources (e.g. Wyss and Brune, 1967), this definition often leads to a non-physical upper estimate. Spectrograms like Figure 1 (Pacoima, 1971; R. Arms, personal communication) show well the complex amplitude spectrum as a function of time (e.g. Perez, 1973); peak accelerations of 2-3 Hz waves occur at 4 and 8 secs with reduced motion between (see also the quiet interval on the 2 Hz trace of the Olympia record (Figure 2) with unfiltered peak A equal to 0.31g.) For some design and liquefaction analyses the episodes of relatively weak motion may allow some structural recovery and should be excluded.

(b) "Duration at a particular frequency is the total time for which acceleration at that f exceeds a given value." This interval, called "uniform duration" here, may equal the corresponding "bracketed duration" (as on the 2 Hz trace (Figure 3) of the Castaic record ($A>0.05g$), with an unfiltered peak A of 0.39g) or be much less (as on the 1.0 Hz trace). Uniform duration appears to have a greater mechanical significance in some design tests. Circles and triangles plotted in Figure 5 are measured uniform durations from accelerograms.

DURATION AS A FUNCTION OF FREQUENCY

Nine strong motion records from the U.S. with large recorded horizontal accelerations were passed through a narrow-band Krohn-Hite filter at representative central frequencies (see Figures 2 and 3). For each record the attenuator setting was fixed for all frequencies. The measured durations are shown as dots in Figure 4. The great variability in shaking patterns is exemplified by the San Fernando earthquake which gave at Castaic (Figure 3) the largest motions at 4 Hz early in the shaking while at Pacoima high frequency bursts came towards the end (Bolt, 1972 and Figure 1). This real-time variability is, of course, lost if frequency spectra only are used in analysis.

The values in Figure 4 confirm that, generally, the greatest D (above the modest level $A=0.05g$) occurs in the frequency band $1 < f < 5$ Hz. On the low-frequency side, seismological research indicates that earthquake source mechanisms decrease amplitudes roughly like f. For high frequencies, D is limited by attenuation along the propagation path.

Table 1 gives values of shear (or Love) wave attenuation calculated from (3) taking $Q = 150$, $c = 3$ km/sec. (The amplitude is set, at 5 km from the source, equal to $A_0 \sqrt{5}\, E / \sqrt{r}$, for large Q.) Suppose the site S (Figure 5) is near the end of a fault length AB. The empirical correlation between M and fault rupture length is listed in the first two columns of Table 1. Suppose, to obtain an upper bound, waves of all frequencies are generated at the moving rupture with an amplitude of 1.0g. Then, as the zig-zag line indicates, at each frequency, beyond a certain distance on the slipping fault, SA (=r) is too great for the site S to continue to receive waves with $A > 0.05g$. For example, after the rupture has propagated to 150 km (corresponding to $M = 7.5$) little 1 Hz (or greater) energy above 0.05g will ultimately arrive back at S. In other words, even for the greatest magnitude shocks ($M \geqslant 8.0$) the duration ($A > 0.05g$) at S ($f \geqslant 1$ Hz) would be no longer. The slope of this geometrical maximum is shown as a broken line in Figure 4.

CALIBRATION OF TABLES

Measurements of world-wide strong-motion records were used to fix the curves for D versus M in Figure 5. The curves represent nearly the upper bound so as to include 90 per cent of available data. Many published values (e.g. Donovan, 1972) fix the low magnitude end. Because no similar population is available for large magnitudes, the attenuation values of Table 1 provide the slope for $M > 7.5$, as explained above.

Four points above the curves in Figure 5 need discussion. The Hiroo record (from the 1970 Hidaka Sankei earthquake ($M = 6.8$)) shows an unusually long D of almost monochromatic shaking ($f \approx 5$ Hz) above 0.05g (Omote et al., 1970). In this case, the uniform duration almost equals the bracketed duration and a second energy burst arrives 14 sec from the P onset suggesting a significant multiple dislocation.

The 1906 earthquake value (Lawson, 1908) comes from timed estimates of 40 sec of "severe shaking" felt by the scientists A. McAdie (San Francisco) and A.O. Leuschner (Berkeley). The E-W component of the Ewing seismograph at Lick wrote an almost continuous record. It suggests that motions with periods less than 2 sec had fallen below $A=0.01g$ after 40 sec; smaller fluctuating waves (periods > 3 sec) were recorded for 150 sec or so. Imamura (1925) reproduced the only other record available from the center of a major earthquake. In the 1923 Kwanto shock an E-W seismograph operated at Hongo almost uninterrupted (pendulum period 10 sec, magnification 2). Extreme (discontinuous) oscillations of high frequency ended about 30 sec after the onset of the S waves. Then, for over 2 minutes, the pendulum recorded longer period waves (≈ 5 sec) of smaller A ($\ll 0.05g$), followed by aftershocks.

There is, of course, much evidence that longer period waves than considered in Table 2 and Figure 5 persist for a minute or more at accelerations $A < 0.05g$, because of sharply lower attenuation and surface wave dispersion (e.g. Mooney and Bolt, 1966). Figure 6 demonstrates this property 75 km from the 1969 Santa Rosa shock ($M=5.7$). The unfiltered top trace clipped in the recorders; vertical lines mark 10 sec). At 5 Hz, $D \gtrsim 10$ sec while at 2 sec, $D \gtrsim 70$ sec; however, the ground acceleration is less than 0.01g at all frequencies.

The long period vibrations, taken with the aftershocks, add to the human propensity to exaggerate the duration of shaking. (Humans can feel $A \gtrsim 0.001g$). Some people in the 1964 Alaska earthquake reported feeling motions for 150 sec (Kachadoorian and Plafker, 1967). The only close "instrumental" record in 1964 is the tape recording of a radio announcer's reaction near Anchorage (Pate, 1965). Many replayings of this remarkable felt record convince me that the audible background noise and voice response ("...has not stopped shaking yet") are consistent with cessation ($A > 0.01g$) of high frequency shaking after 45 sec.

CONCLUSIONS

Durations of higher frequency shaking do not significantly increase above magnitude 7.5 for $A > 0.05g$ and above magnitude 7 for $A > 0.10g$. Bracketed durations ($f > 1$ Hz) within 25 km of the fault rupture are not likely to exceed the following values (see Figure 5) for $A > 0.05g$ and $A > 0.10g$, respectively:

$$D = 17.5 \tanh (M-6.5) + 19.0, \tag{5}$$

and

$$D = 7.5 \tanh (M-6.0) + 7.5. \tag{6}$$

Table 2 gives D as a function of magnitude and distance from the source (Δ km). It was constructed using (5), Table 1 applied to the fault rupture model of earthquake genesis, and spectrally filtered records such as Figures 2 and 3. The observational scatter indicates that the chance of exceeding the tabulated values by 20 per cent or more is about 1 in 10.

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TABLE 1 Ground Acceleration Attenuation Tables

M	r (km)	1/√r	Function of Frequency									
			8 Hz		5 Hz		2 Hz		1 Hz		0.5 Hz	
			E	A/A_o	E	A/A_o	E	A/A_o	E	A/A_o	E	A/A_o
	5	0.447	.756	.756	.840	.840	.933	.933	.966	.966	.983	.983
5.5	10	0.316	.572	.405	.705	.499	.870	.615	.933	.660	.966	.682
6.0	20	0.224	.327	.163	.498	.251	.756	.378	.870	.436	.933	.468
6.5	30	0.183	.187	.076	.351	.143	.658	.268	.811	.331	.900	.369
6-3/4	50	0.141	.061	.019	.175	.056	.498	.157	.705	.221	.840	.264
7.0	70	0.120			.086	.022	.376	.101	.613	.166	.783	.210
7-1/4	100	0.100					.248	.056	.498	.112	.705	.159
7.5	150	0.081					.123	.022	.351	.065	.592	.107
8.0	250	0.063							.175	.025	.418	.058

TABLE 2 Bracketed Duration (sec) (Acc ≥ 0.05g; freq ≥ 2 Hz)

Mag / Δ	5.5	6.0	6.5	7.0	7.5	8.0	8.5
10	8	12	19	26	31	34	35
25	4	9	15	24	28	30	32
50	2	3	10	22	26	28	29
75	1	1	5	10	14	16	17
100	0	0	1	4	5	6	7
125	0	0	1	2	2	3	3
150	0	0	0	1	2	2	3
175	0	0	0	0	1	2	2
200	0	0	0	0	0	1	2

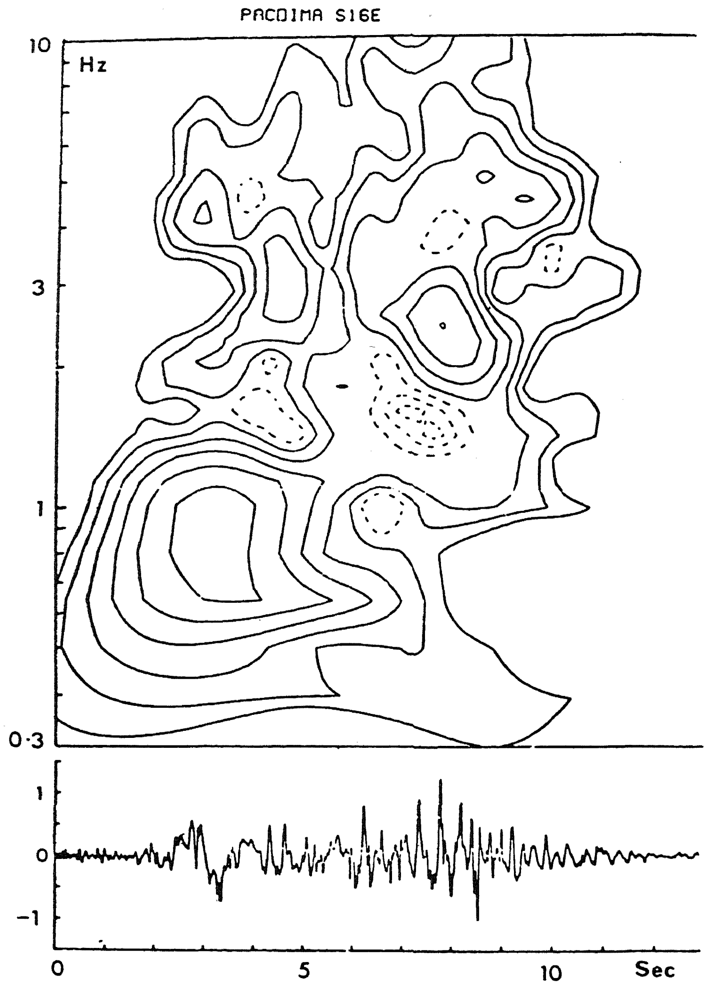

FIG 1

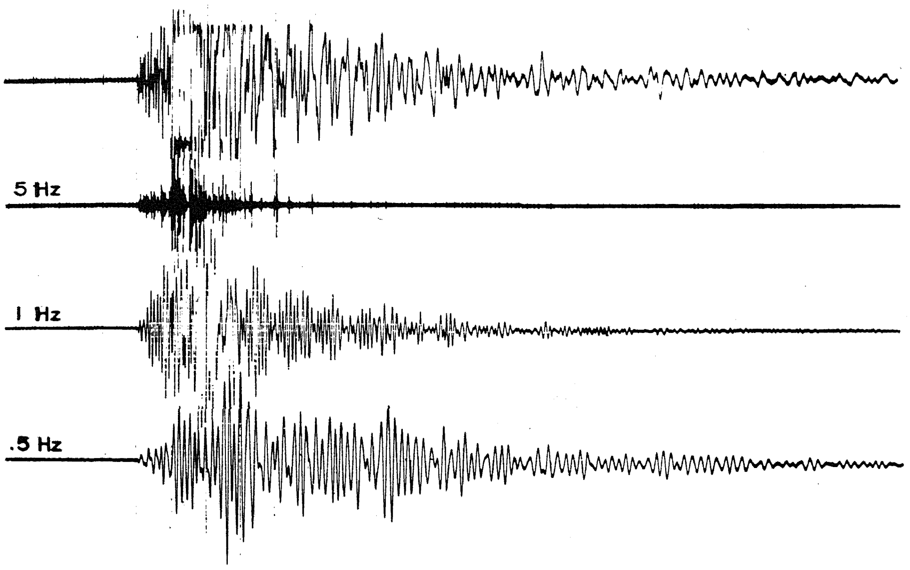

FIG 6. BERKELEY

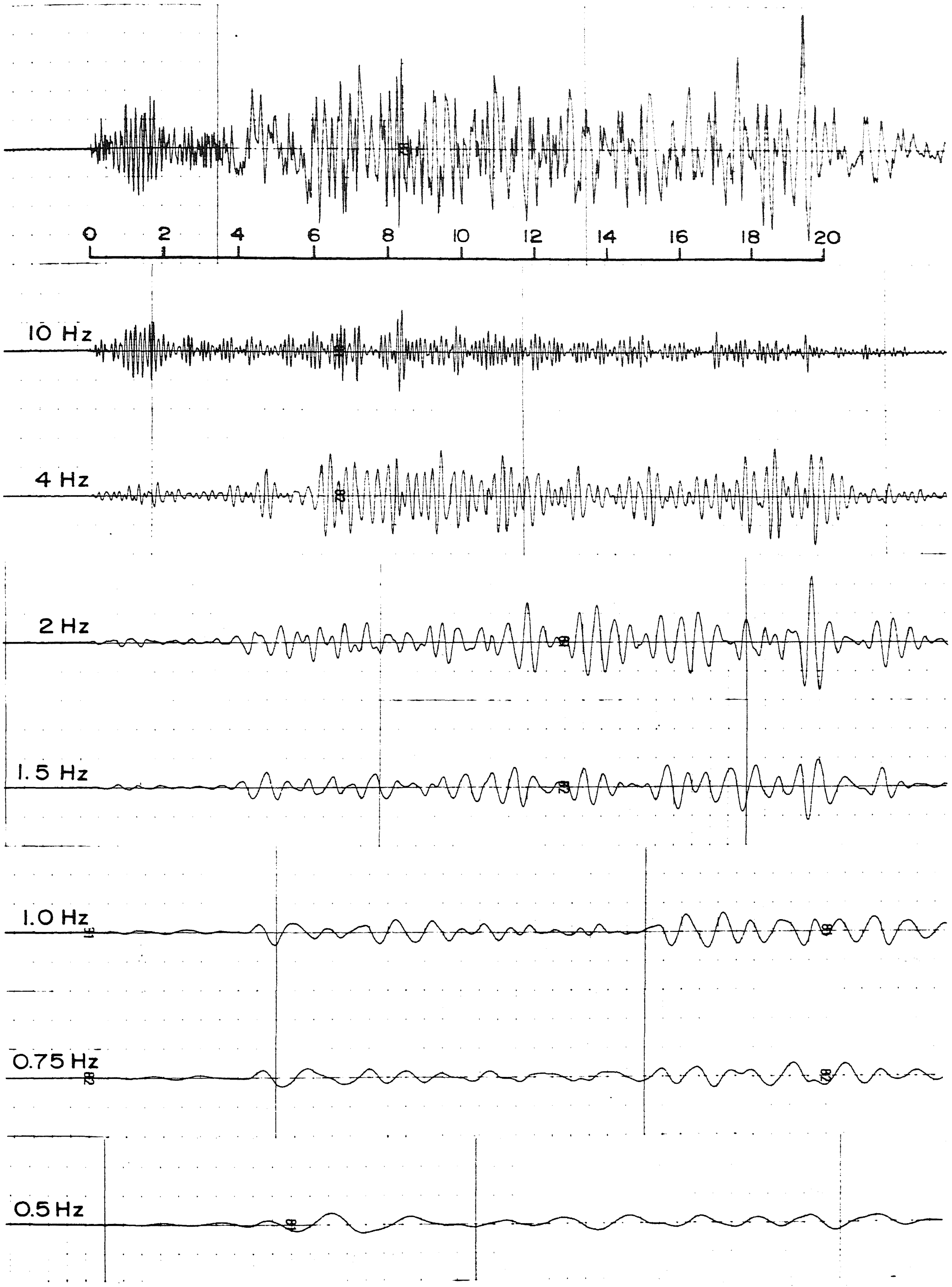

FIG 2

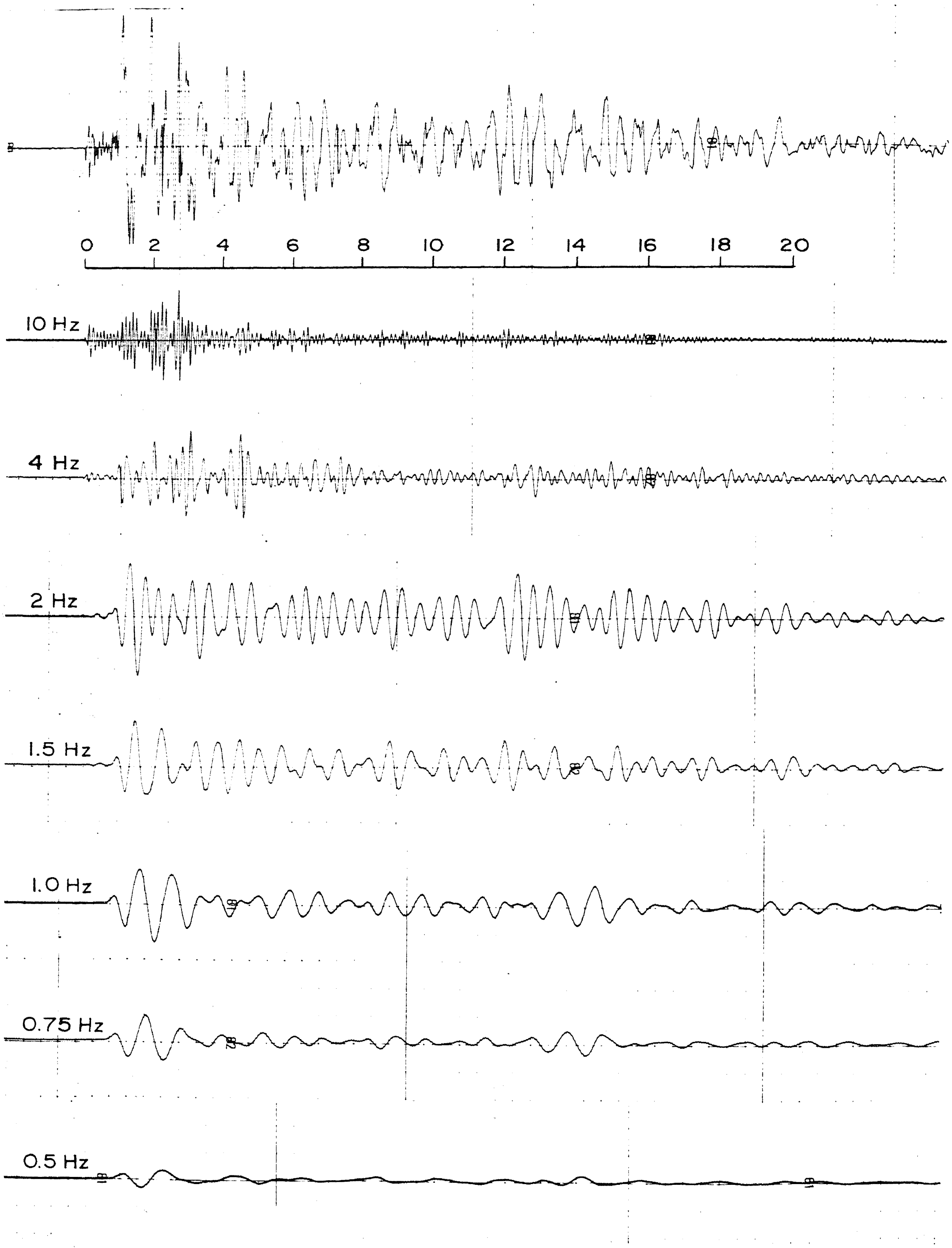

FIG 3

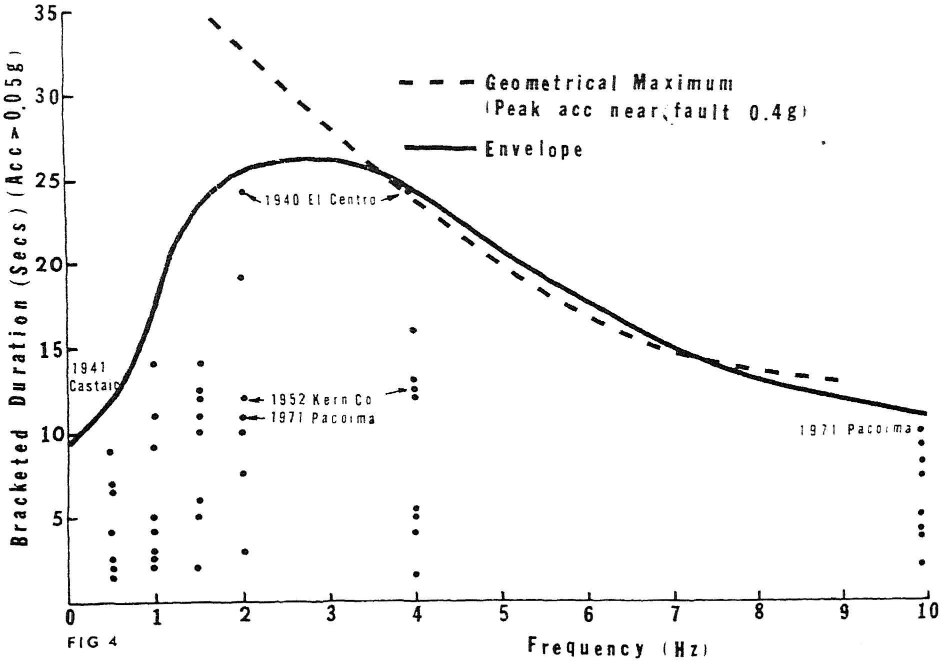
Bracketed Duration (Secs) (Acc > 0.05g)
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
Frequency (Hz)
Geometrical Maximum
(Peak acc near fault 0.4g)
Envelope
1940 El Centro
1941 Castaic
1952 Kern Co
1971 Pacoima
1971 Pacoima

FIG 4

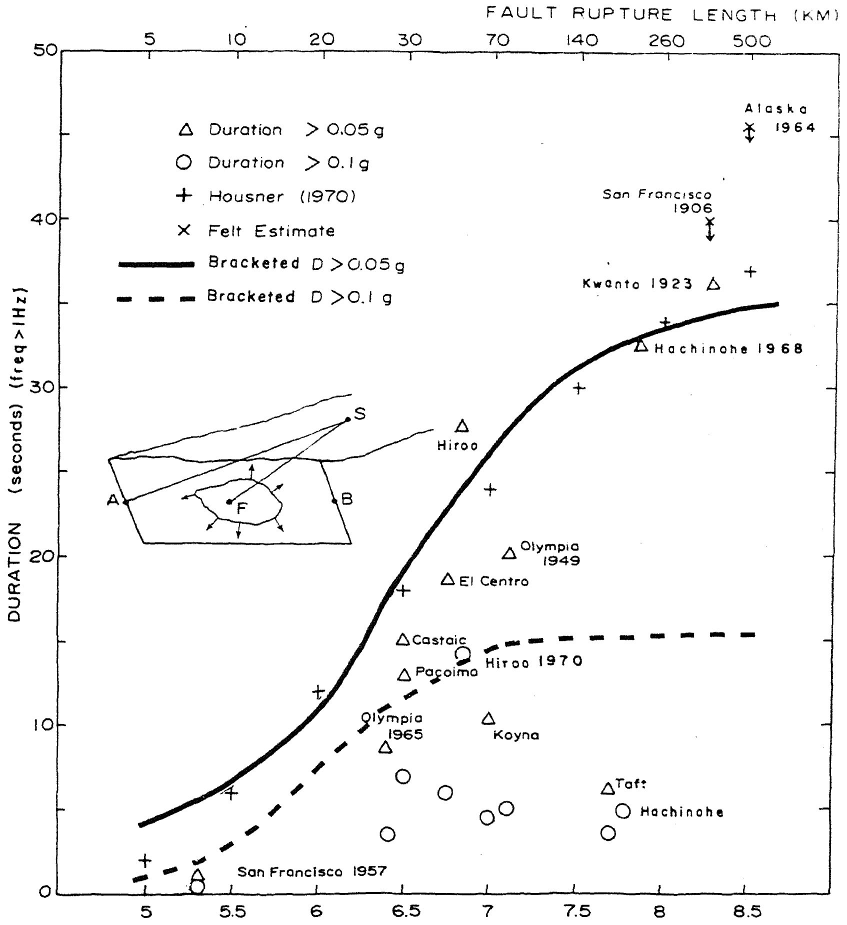
FAULT RUPTURE LENGTH (KM)
5
10
20
30
70
140
260
500
DURATION (seconds) (freq > 1Hz)
50
40
30
20
10
0
5
5.5
6
6.5
7
7.5
8
8.5
MAGNITUDE
△ Duration > 0.05 g
○ Duration > 0.1 g
+ Housner (1970)
× Felt Estimate
Bracketed D > 0.05 g
Bracketed D > 0.1 g
Alaska 1964
San Francisco 1906
Kwanto 1923
Hachinohe 1968
Hiroo
Olympia 1949
El Centro
Castaic
Pacoima
Hiroo 1970
Olympia 1965
Koyna
Taft
Hachinohe
San Francisco 1957
S
A
B
F

FIG 5