TEMPUS PROGRAMME

Lecture Notes:

Measurement and Simulation of Earthquake Vibration

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INTRODUCTION

An earthquake source produces seismic waves that travel in all directions from the source. A train of these waves arrives at a site of observation producing a strong ground motion. When the motion is recorded by an appropriate isntrument, it is called as an earthquake strong motion record. For applications in the field of earthquake engineering the basic characteristics of the strong motions are, Scholl (1968):

a) peak ground: acceleration (PGA), velocity (PGV) and displacement (PGD)
b) time history and duration of the strong motion part
c) spectral characteristics: shape, dominating periods and frequency content

The earthquake Intensity is-still-a very useful tool, since, by this term the engineer can have an indication of the severity of the shaking of the structure exposed to an earthquake of a certain Intensity.

When a structure is stressed beyond its elastic limit the duration of the strong ground shaking directly indicates the degree of expected damage.

The uniformity of the ground motion in relation to its strong motion duration influences the degree of the expected quasi resonance response of the structure.

The information on the occurence of earthquakes are meaningful for the design, when they are related to a specific response of the exposed structures, above a certain level.

Very often information on the earthquake severity is given by the maximum Peak Ground Acceleration (PGA). This is an oversimplification resulting in ambiguities, because we may find at least two-quite reasonable accelerograms-that may have the same PGA and produce much different Intesities.

Instead of the PGA we may use the term Effective PGA, which results after the removal of the high frequency components from the original accelerogram. These components usually do not affect the seismic response of the structures. It is the same, as having passed the original accelerogram through a low pass filter. Practically, the high frequency components may be removed by smoothing the top 15% of the highest peaks of the record.

Actual response spectrum is the envelop of the responses of one DOF oscillators to the given ground motion, for a certain damping ratio.

Smoothed response spectrum results from the actual response spectrum by drawing an overage line of the peaks of the actual response spectrum.

Design response spectrum combines the information of more than one smoothed response spectra and of the desirable response of the structure.

The "Spectrum Intensity" (S.I.) as defined by Housner (1952), is a function of damping ratio ζ:

$$S.I.(\zeta) = \int_{0.1}^{2.5} SV(\zeta,T)\, dT$$

where $SV(\zeta,T)$ is the velocity spectrum corresponding to a period T and damping ratio ζ.

The "Normalized Action" ($\Delta\rho/m_o$) as defined by Carydis (1968), represents the quantity:

$$\frac{\Delta\rho}{m_o} = \int_o^t \left(\int_o^t \ddot{y}(t)dt\right)^2 dt = \int_o^t \dot{y}(t)^2\, dt$$

The "Effective Duration" of the strong motion is the time in which the most part of the energy is released, Carydis (1977). Namely this is calculated from the curve of $\Delta\rho/m_o$, by defining the time in (sec) in which the central 0.9 $(\Delta\rho/m_o)$ has been released.

The "Sharpness" of the response spectrum is the index $(\Delta f)=1/\Delta T$ after Carydis (1977). $\Delta T=T_2-T_1$, where T_2 and T_1 are the natural periods corresponding to values of max $SA/\sqrt{2}$, of the undamped spectrum.

STRONG MOTION MEASUREMENT OF EARTHQUAKES

The Seismometer-Basic Theory

The basic instrument that can measure a vibration is the seismometer. By this term we mean an accelerometer, a velocity meter or displacement meter. The basic principle of the function of the instrument is that of the damped oscillator. Usually the instrument is mounted in a housed frame which is portable, with leveling, attaching and easy positioning possibilities. The output of the instrument is the displacement v(t) of the mass relative to the housing, Clough adn Penzien (1975).

The equation of motion of the mass m of the system is:

$$m\,\ddot{u}(t) + c\,u(t) + K\,u(t) = -m\,\ddot{u}_g(t)$$

If the base motion is harmonic:

$$\ddot{u}_g(t) = \ddot{u}_{go}\sin\bar{\omega}t$$

The dynamic steady-state response of the mass has the amplitude:

$$\delta = \frac{m\,\ddot{u}_{go}}{k}\,D$$

where: D is the dynamic magnification factor given by:

$$D=[1-\beta^2))^2+(2\beta\varsigma)^2]^{-1/2}$$

K is the spring stiffness

$\beta = \bar{\omega}/\omega$

$\bar{\omega}$ is the exciting frequency

ω is the undamped natural frequency of the system

ζ is the damping ratio

Examining the function of D in relation to $\beta=\bar{\omega}/\omega$, for a damping ratio $\zeta=0.7$, one may conclude that D is almost constant for values of $0<B\leqslant0.6$. For exciting frequencies $0<\bar{\omega}\leqslant0.6\omega$ the isntrument gives an output, which is directly related to the input acceleration $\ddot{u}_g(t)$. Thus, we may say that under this frequency $(\bar{\omega}/\omega)$ relation and damping condition the instrument functions as an accelerometer. By increasing the natural frequency of the instrument ω (by increasing the stiffness, or by reducing its mass) to a certain limit (controlled by gain and noise) we may broaden its applicability, since the maximum exciting frequency may be thus increased too.

The input displacement is equal to:

$$u_{go} = \ddot{u}_{go}/\bar{\omega}^2$$

which leads to a dynamic steady-state response of the mass:

$$\delta = \frac{m\, u_{go}\, \bar{\omega}^2}{K} D = \frac{u_{go}}{\omega^2} \beta^2 \omega^2 D = u_{go} \beta^2 D$$

The response function $\beta^2 D$ is presented in the Figure. For $\beta\geqslant1$ and for damping ratio $\zeta=0.5$ the function $\beta^2 D$ is practically constant. Thus, we may say that for input frequencies $\bar{\omega}\geqslant\omega$ and for a damping ratio equal to 0.5, the instrument functions as displacement meter, since the dynamic steady-state response is proportional to the input displacement u_{go}. By reducing the natural frequency of the system (by reducing the stiffness or increasing the mass) we may broaden its applicability.

SOURCE, PROPAGATION PATH AND LOCAL SOIL CONDITIONS

According to geological and seismological observations it is documented that the rupture process of fault segments is repeated in a characteristic manner, Schwartz and Coppersmith (1986).

The linearity of the earth is a valid assumption, since the strains developed during an earthquake are usually small, of the order of 10^{-4} to 10^{-6}. In cases where the deformations are higher and developed in rather small volumes of the earth's mass, as for example in sediments and areas with topographic anomalies, Aki (1985), the non linearity might be closer to the reality. On the other hand, the non linear response occurs in a limited volume of mass, and the rest of the mass is left free to respond linearly.

-After Kanai (1957), for California and Japanese Earthquakes:
In Bed Rock maximum acceleration:

$$\alpha = \frac{5}{\sqrt{T_G}} 10^c \qquad (cm\ s^{-2})$$

Where T_G the fundamental period of the site (S)

$c = 0.61M - P\log R + Q$

M: Richter Magnitude,

R: Hypocentral Distance (km)

$$P = 1.66 + \frac{3.6}{R}, \quad Q = 0.167 - \frac{1.83}{R}$$

After Estava (1969):
On Firm Ground:

$$\alpha = 1230\ e^{0.8M}\ (R+25)^{-2} \quad (cm\ s^{-2})$$

$$\upsilon = 15\ e^{M}\ (R+0.17\ e^{0.59M})^{-1.7} \quad (cm\ s^{-1})$$

while $$\frac{\alpha d}{\upsilon^2} = 1 + \frac{400}{R^{0.6}}$$

R: Hypocentral Distance (Km)

Later, Estava (1970) proposed:

$$\alpha = b_1\ e^{b_2 m}\ (R+25)^{-b_3}$$

R: Hypocentral Distance (km)

and b_1, b_2, b_3 coefficients with similar values, for example, b_3 for rock is 1.65, while for alluvia is 1.32.

Donovan (1972) proposed:

$$\alpha = 1320\ e^{0.58M}\ (R+25)^{-1.52} \quad (cm\ s^{-2})$$

R: in (Km)

accepting that smaller attenuation yields for the eastern North America .

Donovan (1973), including the San Fernando earthquake, working with 678 world earthquake records with $5 \leqslant M \leqslant 8$, proposes:

$$\alpha = 1080\ e^{0.5M}\ (R+25)^{-1.32} \quad (cm\ s^{-2})$$

R: in (Km)

After Orphal and Lahoud (1974):

On any Ground:

$$\alpha = 6.6 \cdot 10^{-2}\ 10^{0.4M}\ R^{-1.39} \qquad (g)$$

$$\upsilon = 7.26 \cdot 10^{-1}\ 10^{0.52M}\ R^{-1.34} \qquad (cm\ s^{-1})$$

$$d = 4.71 \cdot 10^{-2}\ 10^{0.57M}\ R^{-1.18} \qquad (cm)$$

R: Hypocentral Distance (km)

Based on European data Ambraseys (1978) proposes a weaker attenuation law:

$$\alpha = 2.88\ R^{-1.1}\ e^{1.45M}$$

α: maximum ground acceleration $(cm\ s^{-2})$

R: Hypocentral Distance (km)

While for near field sites, Ambraseys (1978) proposes for the mean values:

$$\bar{\alpha} = 1.31\ (\bar{R})^{-0.92}\ e^{1.455\bar{M}}$$

$\bar{\alpha}$: mean value of maximum ground acceleration in $(cm\ s^{-2})$, within the three sets of distances

$\bar{M}$: mean value of magnitude corresponding to the analyzed data within these three sets of distances

$\bar{R}$=5 km (mean value of R<10 km), $\bar{R}$=15 km (mean value of $10 \leqslant R < 19$ km) and $\bar{R}$=25 km (mean value of $20 \leqslant R < 29$ km).

Various researchers like Cloud (1963), Cloud and Perez (1971), Ambraseys (1978) suggest that the maximum ground acceleration is almost independent of the earthquake magnitude, for sites near the focal volume, and it depends on the focal distance only.

Trifunac (1976) proposes the general expression for Western United States:

$$\log_{10}\begin{Bmatrix} \alpha_{max},p \\ \upsilon_{max},p \\ d_{max},p \end{Bmatrix} = M - F(\Delta) - \log_{10}\begin{Bmatrix} \alpha_o(M,p,s,\upsilon) \\ \upsilon_o(M,p,s,\upsilon) \\ d_o(M,p,s,\upsilon) \end{Bmatrix}$$

for epicentral distances $20 \leqslant \Delta \leqslant 350$ km

M: Richter magnitude (M_L)

p: confidence level associated with the values α, υ, d

s: 0 for alluvium deposits

1 for intermediate rock

2 for basement rock

υ: 0 for horizontal component

1 for vertical component

$$F(\Delta) = \begin{cases} \Delta/50 & \text{for } \Delta \leqslant 75 \text{ km} \\ 1.125 + \Delta/200 & \text{for } 75 \leqslant \Delta \leqslant 200 \text{ km} \end{cases}$$

and

$$\log_{10}\begin{Bmatrix} a_0(M,p,s,v) \\ v_0(M,p,s,v) \\ d_0(M,p,s,v) \end{Bmatrix} = \begin{cases} ap+bM+c+ds+ev+fM^2-f(M-M_{max})^2 & \text{for } M \geqq M_{max} \quad (1) \\ ap+bM+c+ds+ev+fM^2 & \text{for } M_{max} \geqq M \geqq M_{min} \quad (2) \\ ap+bM_{min}+c+ds+ev+fM^2_{min} & \text{for } M \leqq M_{min} \quad (3) \end{cases}$$

Function	a	b	c	d	e	f	N Data	M_{min}	M_{max}
$\log_{10}a_0(M,p,s,v)$	−0.898	−1.789	6.217	0.060	0.331	0.186	227	4.80	7.50
$\log_{10}v_0(M,p,s,v)$	−1.087	−2.059	8.357	0.134	0.344	0.201	227	5.12	7.61
$\log_{10}d_0(M,p,s,v)$	−1.288	−2.366	9.717	0.205	0.240	0.226	227	5.24	7.45

* Only the first two digits may be assumed to be significant.

When we have a magnitude M, being $M \leqslant M_{min}$, $M_{min} \leqslant M \leqslant M_{max}$ or $M_{max} \leqslant M$, we must use the appropriate expressions. For example, if M = 5, for accelerations we have to use the (2) equation, for velocities and displacements we have to use the (3) equation, etc.

McGuire (1978) uses the expression:

$$\ell nx = b_1 + b_2 M + b_3 \ell n R + b_4 Y_s$$

Where x: ground motion variable or spectral velocity,

R: Hypocentral distance (Km)

Y_s: site geology indicator, 0: for rock sites, 1: for soil sites

TABLE 3.—Coefficients and Standard Deviations Obtained from Regression Analyses ($\ln x = b_1 + b_2 M + b_3 \ln R + b_4 Y_s$), *after McGuire (1978)*

x (1)	b_1 (2)	b_2 (3)	b_3 (4)	b_4 (5)	$\sigma_{\ln p}$ (6)
a_g	3.40	0.89	−1.17	−0.20	0.62
v_g	−1.00	1.07	−0.96	0.07	0.64
d_g	−2.72	1.00	−0.63	0.12	0.69
PSRV	−1.61	1.16	−0.83	0.31	0.72

Note: a_g = peak ground acceleration; v_g = peak ground velocity; d_g = peak ground displacement; and PSRV = response spectrum velocity (1-sec period, 2-% damping), units used are in centimeters and seconds.

McGuire (1978) concludes that the frequency content υ_g/α_g, d_g/α_g and the response spectra $PSRV/\alpha_g$ ratios depend on earthquake magnitude and hypocentral distance.

McGuire (1977) examined 68 strong-motion records (136 horizontal components) on soft and medium ground, presented on Fig.13.He proposes the general relations:

$$\ell np = C_1 + C_2 M + C_3 \ell n \Delta + C_4 I_s$$

where p: is the peak ground acceleration, velocity or displacement in $cm\,s^{-2}$, $cm\,s^{-1}$ and cm respectively.

Δ: epicentral distance (Km)

I_s: mean site Intensity (M.M.)

while the coefficiensts C_1, C_2, C_3 and C_4 take the values in Tables 1 and 2, and at the last column the standard error is shown.

TABLE 1

REGRESSION COEFFICIENTS FOR SOFT SITES *after McGuire (1977)*

$$\ln p = C_1 + C_2 M + C_3 \ln \Delta + C_4 I_s$$

	C_1	C_2	C_3	C_4	$\sigma_{\ln p}$
ln a_g	.271	x	x	.601	.781
(peak ground acceleration)	2.01	x	-.313	.506	.723
cm/sec²	1.81	.904	-.901	x	.696
ln v_g	-1.51	x	x	.543	.770
(peak ground velocity)	-1.11	x	-.072	.521	.771
cm/sec	-1.58	.997	-.710	x	.715
ln d_g	-1.47	x	x	.415	.791
(peak ground displacement)	-2.35	x	.157	.463	.780
cm	-2.67	.863	-.398	x	.746

TABLE 2

REGRESSION COEFFICIENTS FOR MEDIUM SITES *after McGuire (1977)*

$$\ln p = C_1 + C_2 M + C_3 \ln \Delta + C_4 I_s$$

	C_1	C_2	C_3	C_4	$\sigma_{\ln p}$
ln a_g	-.831	x	x	.851	.753
(peak ground acceleration)	1.45	x	-.359	.680	.703
cm/sec²	1.47	1.01	-.884	x	.619
ln v_g	-4.02	x	x	.952	.751
(peak ground velocity)	-3.61	x	-.064	.923	.758
cm/sec	-3.61	1.37	-.776	x	.605
ln d_g	-4.68	x	x	.899	.664
(peak ground displacement)	-5.75	x	.168	.979	.658
cm	-4.81	1.25	-.509	x	.581

It has been generally accepted that for epicentral distances $\Delta \leqslant 20$ km there is not sufficient data, because it is more seldom to have an instrument close to epicenter, the seismographs go off scale and thus the relations are poorly documented. The lack of data in epicentral regions is more evident for stronger earthquakes.

In the following are presented a few of the existing today expressions combining ground motion parameters with Intensity and distance.

After Kawasumi:

$I = 2M - (0.00183\ R + 2\ell nR) - 0.307$

$\log \alpha = -0.35 + 0.5\ I$

R: Hypoc. Distance (km)

I: Intensity on the Japanese scale

α: average maximum ground acceleration ($cm\ s^{-2}$).

After Estava and Rosenblueth (1964) and Rosenblueth (1964):

$$I = \frac{\log 14\upsilon}{\log 2}$$

I: MM Intensity

υ: maximum ground velocity ($cm\ s^{-1}$).

After Ambraseys (1978), with great scatter:

$\log(\alpha_h) = 0.10 + 0.30\ I$

$\log(\alpha_v) = 0.37 + 0.21\ I$

α_h: maximum ground horizontal acceleration ($cm\ s^{-2}$)

α_v: maximum ground vertical acceleration ($cm\ s^{-2}$)

I : MM Intensity.

After Gutenberg and Richter, in 1942, (Richter(1958)):

$\log \alpha = -0.5 + 0.33\ I$

α: maximum ground acceleration ($cm\ s^{-2}$)

I: MM Intensity.

After Hershberger (1956):

$\log \alpha = -0.90 + 0.43\ I$

After Mercali-Sieberg (1923):

$\log \alpha = -1 + 0.33\ I$

I: Intensity on Mercali-Sieberg scale.

After Neumann (1954) for average epicentral distance of 15 miles and less than 25 miles:

$\log \alpha = -0.041 + 0.308\ I$

After Galanopoulos (1971) for Greek earthquakes:

$\alpha_g = 0.26 - 0.1\ I + 0.01\ I$ in g's units

I: MM Intensity.

After Trifunac and Brady (1975):

$$\log \alpha_h = 0.014 + 0.30\ I$$

$$\log \alpha_\upsilon = -0.18 + 0.30\ I$$

$$\log \upsilon_h = -0.63 + 0.25\ I$$

$$\log \upsilon_\upsilon = -1.10 + 0.28\ I$$

$$\log d_h = -0.53 + 0.19\ I$$

$$\log d_\upsilon = -1.13 + 0.24\ I$$

$\alpha_h, \upsilon_h, d_h$: maximum ground horizontal acceleration ($cm\ s^{-2}$) velocity ($cm\ s^{-1}$) and displacement (cm).

$\alpha_\upsilon, \upsilon_\upsilon, d_\upsilon$: maximum ground vertical acceleration ($cm\ s^{-2}$), velocity ($cm\ s^{-1}$) and displacement (cm).

I: MM Intensity.

McGuire (1976) proposes the relation (see Fig.15):

$$I_s = I_e + 3.08 - 1.34 \ln \Delta \quad \text{for } \Delta \geq 10 \text{ km}$$

$$I_s = I_e \quad \text{for } \Delta < 10 \text{ km}$$

I_s: mean site Intensity (MM)

I_e: epicentral Intensity (MM)

Δ : epicentral distance (km).

Based on Estava and Rosenblueth (1964), Newmark and Rosenblueth (1971) proposed for the duration of a white noise of constant intensity per unit time:

$$S = 0.02\ e^{0.74\ M} + 0.3\ R \quad \text{(sec)}$$

R: Hypoc. Distance (km)

After Donovan (1972) the duration of the strong shaking is:

$$S = 4 + 11(M - 5) \quad \text{(sec)}$$

We have concluded that the information interesting to engineers is contained into the accelerograms and all our work is based on such records, although it is difficult from such records to obtain other information, like the true ground velocity and displacement.

During our efforts for correlation we must have seen that the data is greately scattered. This may be due to the very complicated nature of earthquake ground motion (six degrees of freedom (Fig. 17) for a body resting on the surface of the ground).

Despite these, we register the three components of translational motion only.

The ground motions may be classified into three categories (see also Newmark and Rosenblueth, 1971):

Shock type. This is mainly due to a nearby focus on firm ground, with small duration, like that in Fig.18.

Wave form type. This is mainly due to a distant focus, registered on rather soft soils (Fig.19,20,21).

Irregular wave form type. This is mainly due to a focus at moderate distances, registered on firm ground (Fig.22).

In order to correct the recorded ground motions quite sofisticated procedures have been recently developed (Fig.23,24,25).

We have to unify our procedures in collecting the data, use the same terminology in assigning the ground and we have to impove our knowledge on:

how (transfer function of instrument, kind of instrument, foundation of instrument, the various offsets and orientation of the instrument) **the motion is recorded.**

where (the soil conditions during the earthquake, the depth of the various deposits at the site of the instrument, the effect of the boundary geological conditions, the presence or not of human structures near the instrument) **the motion is recorded.**

when (we do not know how long after the generation of the earthquake at the focus the record is produced in order to correlate it with other records and know the time delay) the motion is recorded.

what (what paths the seismic waves have followed not necessarily by shear waves propagating upwards, and what was the radiation pattern of the energy at the source) **is the recorded motion.**

RESPONSE SPECTRUM

The effect of the earthquake on a structure may be presented by various figures: The response spectrum, the response envelope spectrum and the duration spectrum.

The response spectrum is the most widely used, that presents the envelope of the response of a one degree of freedom oscillator to a given seismic ground motion against the undamped natural period of the oscillator, for various damping.

At each time instant t it is an equilibrium of forces, (Fig.26):

$$P^I_\rho + D_\rho + D^S_\rho = 0 \qquad (1)$$

$$\ddot{\Gamma}_\rho(t) + c_\rho \dot{\gamma}_\rho(t) + K_\rho \gamma_\rho(t) = 0 \quad (2)$$

since:

$$\Gamma_\rho(t) = x_g(t) + \gamma_\rho(t) \text{ or } \ddot{\Gamma}_\rho(t) = \ddot{x}_g(t) + \ddot{\gamma}_\rho(t) \quad (3)$$

$$\ddot{\gamma}_\rho(t)\, m + c_\rho \dot{\gamma}_\rho(t) + K_\rho \gamma_\rho(t) = -\ddot{x}_g(t)\, m \quad (4)$$

or:

$$\ddot{\gamma}_\rho(t) + \frac{c_\rho}{m} \dot{\gamma}_\rho(t) + \frac{K_\rho}{m} \gamma_\rho(t) = -\ddot{x}_g(t) \quad (5)$$

The damping ratio ζ_ρ and the critical damping coefficient $c_{\rho cr}$ are:

$$\zeta_\rho = \frac{c_\rho}{c_{\rho cr}}, \qquad c_{\rho cr} = 2\, m\, \omega_\rho, \qquad \omega_\rho^2 = \frac{K_\rho}{m} \quad (6)$$

eq. (5) is written then:

$$\ddot{\gamma}_\rho(t) + 2\zeta_\rho \omega_\rho \dot{\gamma}_\rho(t) + \omega_\rho^2 \gamma_\rho(t) = -\ddot{x}_g(t) \quad (7)$$

for initial conditions $\gamma_\rho(0) = \dot{\gamma}_\rho(0) = 0$, the Duhamel integral gives:

$$\gamma_\rho(t) = -\frac{1}{\omega_{d\rho}} \int_0^t \ddot{x}_g(\tau)\, e^{-\zeta_\rho \omega_\rho (t-\tau)} \sin \omega_{d\rho}(t-\tau)\, d\tau \quad (8)$$

where:

$$\omega_{d\rho} = \omega_\rho \sqrt{1 - \zeta_\rho^2} \quad (9)$$

The first derivative of $\gamma_\rho(t)$ from eq. (8) is:

$$\dot{\gamma}_\rho(t) = \int_0^t \ddot{x}_g(\tau)\, e^{-\zeta_\rho \omega_\rho (t-\tau)} \left\{ \frac{\zeta_\rho}{\sqrt{1-\zeta_\rho^2}} \sin \omega_{d\rho}(t-\tau) - \right.$$

$$\left. - \cos \omega_{d\rho}(t-\tau) \right\} dt \quad (10)$$

if one replaces in eq. (7) the quantities $\gamma_\rho(t)$ and $\dot{\gamma}_\rho(t)$ from eq. (8) and eq. (10), one may receive:

$$\underbrace{\ddot{\gamma}_\rho(t) + \ddot{x}_g(t)}_{\ddot{\Gamma}_\rho(t)} = \omega_{d\rho} \int_0^t \ddot{x}_g(\tau)\, e^{-\zeta_\rho \omega_\rho (t-\tau)} \left\{ \frac{2\zeta_\rho}{\sqrt{1-\zeta_\rho^2}} \cos \omega_{d\rho}(t-\tau) + \right.$$

$$\left. + \frac{1-2\zeta_\rho^2}{1-\zeta_\rho^2} \sin \omega_{d\rho}(t-\tau) \right\} dt \quad (11)$$

For values of ζ_ρ of about 5%, the coefficient in eq.(10): $\zeta_\rho/\sqrt{1-\zeta_\rho^2}$ is smaller than unit and thus in searching for the maximum absolute value $\max|\dot{\gamma}_\rho(t)|$ we may delete the sinusoidal term, and thus we may write:

$$\max|\dot{\gamma}_\rho(t)| \approx \max\left|\int_o^t \ddot{x}_g(\tau)\, e^{-\zeta_\rho\omega_\rho(t-\tau)} \cos\omega_{d\rho}(t-\tau)d\tau\right| \qquad (12)$$

Similarly, for the maximum absolute value $\max|\ddot{\Gamma}_\rho(t)|$, from eq.(11), the coefficient $2\zeta_\rho/\sqrt{1-\zeta_\rho^2}$ may be deleted, while the coefficient $(1-2\zeta_\rho^2)/(1-\zeta_\rho^2)$ is almost equal to 1. Therefore from eq. (11) one may thus receive:

$$\max|\ddot{\Gamma}_\rho(t)| \approx \omega_{d\rho} \max\left|\int_o^t \ddot{x}_g(\tau)\, e^{-\zeta_\rho\omega_\rho(t-\tau)} \sin\omega_{d\rho}(t-\tau)d\tau\right| \quad (13)$$

From eq. (15) and eq. (20) :

$$\max|\ddot{\Gamma}_\rho(t)| \approx \omega_{d\rho}^2 \max|\gamma_\rho(t)| \qquad (14)$$

If we assume that, independent of time, the values of integrals containing terms of cos or terms of sin have the same maximum , then from eq. (12) one may receive :

$$\max|\dot{\gamma}_\rho(t)| \approx \omega_{d\rho} \cdot \max|\gamma_\rho(t)| \qquad (15)$$

The response may be considered elastic or elastoplastic and the spectra may be given in one tripartite graph.

The presentation on a tripartite graph uses the approximate relations (14),(15), assuming that the displacement response spectrum is the initial (Fig. 28), from which the other result. With that procedure we obtain smooth response spectra which are very useful for design purposes , since we reduce the effect of a wrong estimation, or of an accidental change of the natural frequency of the structures. The pseudo velocity and pseudo acceleration response spectra resulting from eqs (14) and (15) diverge from the exact values either in the region of the long periods, (Fig.30 for the relative velocity response spectrum) or in the region of short periods, (Fig. 31 for the total acceleration response spectrum).

Housner (1959) proposes the smooth average spectra for various earthquakes and various epicentral distances (Fig. 32,33,34). In order to estimate an average or an envelope response spectrum the nonlinearity of the seismic response of the ground and the influence of many other parameters must be taken into account, (Trifunac and Anderson 1977, and 1978). In Fig. 35 the envelope acceleration response spectrum for Greek earthquakes is presented, which results directly from the various calculated acceleration response spectra and without any other consideration. The spectra have been simply normalized to maximum ground acceleration equal to 1g.

Simple spectrum amplification factors are given by Newmark and Hall (1973) shown in the 2 and 6 columns of the following table, for the Acceleration and Velocity response spectrum. For a level of probability of not been exceeded 84.1%, the values are shown in the 3 and 7 columns after Hall and Newmark (1980). In the 4 and 5 columns the values are shown for peak ground acceleration 250 $cm\,s^{-2}$ and 500 $cm\,s^{-2}$ respectively, while in 8 and 9 columns the values are shown for peak ground velocity 20 $cm\,s^{-1}$

SPECTRUM AMPLIFICATION FACTORS								
ζ%	Acceleration				Velocity			
	N & H (1973)	H&N (1980) 84.1%	P.C. a=250 $cm\,s^{-2}$	P.C. a=500 $cm\,s^{-2}$	N & H (1973)	H&N (1980) 84.1%	P.C. v = 20 $cm\,s^{-1}$	P.C. v = 60 $cm\,s^{-1}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0	6.4		6.9	5.59	4.0		4.9	3.86
2	4.3	3.66	3.52	3.05	2.8	2.92	3.35	3.04
5	2.6	2.71	2.78	2.58	1.9	2.30	2.45	2.32
10	1.5	1.99	2.18	2.09	1.3	1.84	1.97	1.97
20	1.2	1.26	1.73	1.7	1.1	1.37	1.49	1.55

and 60 $cm\,s^{-1}$, after Carydis (1977) for Greek records. In the same work the acceleration and the velocity spectrum amplification factors are given as a function of damping ratio and the maximum ground acceleration or ground velocity respectively (Fig. 36,37).

The effect of the different site conditions and epicentral distances on the acceleration spectrum is studied by Seed, Ugas and Lysmer (1974) (Fig. 38,39,40).Similar figures are presented by Hayashi (1971) for records in Japan (Fig. 41). These properties are reflected into the modern codes.

Lessons learned from the study of Strong Ground Motions and their effects, see also School (1986)

1) The free-field ground motion is influenced by the charactristics of the source and the travel path. The characteristics of the local ground conditions modify the strong motion.

2) Depending on the characteristics of the source, the travel path and the location of the site relative to the source, the variations in the ground motion due to the effects of local soil conditions may overshadow the source effects, or the source effects may overshadow the effect of local soil conditions.

3) For periods of the strong ground motion higher than 0.3 sec, a local amplification of the shaking (PGV and PGD) may occur at a site which is located towards the direction of the fault-rupture due to the directivity of the wave front along the rupture. In this case the propagation along the rupture should be in a rather unilateral coherent manner, Singh (1985).

4) The attenuation characteristics of the strong motion vary from one region to the other and depend on the focal mechanism and the tectonic-geologic and morphologic conditions along the paths.

5) Near field strong ground motions contain a long-period pulse which corresponds to the "fling" along the fault. This long period pulse is usually unidirectional as compared to long-period oscillations with repeated large amplitudes in soft soil conditions.

6) Strong motion amplitudes are substantially lower at the base of large structures than in the free field. This is most pronounced for the high frequency part of the motion.

7) Even small earthquakes can produce high accelerations. These high accelerations, usually expressed in short period waveforms, may not be damaging. There are observations according to which a small shallow earthquake of M=4.2 caused the collapse of a multistorey block of flats and extended damages to other buildings in close distance.

8) Peak ground acceleration may not indicate the damaging potential of the earthquake ground motion near the epicenter. According to Hanks and Johnson (1976), this parameter, in close distances from the source (10 to 20 km), has little relation with the earthquake Magnitude and the observed Intensity.

9) According to Singh (1985), ratios of peak vertical to horizontal acceleration can significantly exceed the value of 2/3 for the epicentral region (within a distance of 15 km from the epicenter of earthquakes with Magnitude equal or greater than 6).

10) At the epicentral region the amplitudes, velocities and accelerations of the high frequency strong motion part of the ground movement are rather independent of local geologic and soil conditions. Exceptions might be at sites with shallow soil deposits, or at sites of anomalous topography, steep slopes and on ridge crests where important amplification may occur. On the other hand, low frequency motions have lower amplitudes, velocities and accelerations on rock than on soil, according to Seed et al.(1976), Hays (1980), Singh (1985). Also, in the epicentral region it is difficult to tell any predominant direction of the strong ground motion.

11) The strong ground motion can not be characterized by a single only parameter. A complete description requires specification of the amplitudes, uniformity, duration, frequency content, energy content, the interelation of

the motion along the three axes and the whole nature of the ground motion.

12) Near field records indicate that high accelerations are possible in soil sites as well as in rock sites. The little energy that these single pulses contain, and when they have a high frequency content, usually do not effect the response of common structures.

13) According to observations along the depth (h) of soil deposits, frequencies of the order of $f=u_s/4h$ (u_s=shear wave velocity of the soil, h=depth from the surface) will be missing from the strong motion due to surface reflection effects.

Generation of artificial earthquake time histories

There are various methods according to which earthquake time histories may be developed. There are analytical, numerical and hybrid procedures. The use of an artificial earthquake record helps to better understand the interelation betweeen the response of a structure and the earthquake excitation, mainly when a non linear response of the structure is anticipated. Thus, it is quite feasible to study the response of a structure for a family of earthquake records which might have among them some common characteristics and differ to a set of parameters. This procedure of analysis of structures might be indispensable when the input motion presents considerable uncertainties.

A very good example for the use of the artificial accelerogram is given by Housner and Jennings (1982): "A much better method of describing the ground motion simply would be to compare it to a known accelerogram, such as recorded in Taft, California in 1952, or to a synthesized accelerogram. The description could thus be phrased as: 1.5 times as intens as Taft 1952, with a duration of strong motion shaking 1.2 times as long and with similar frequencies of motion".

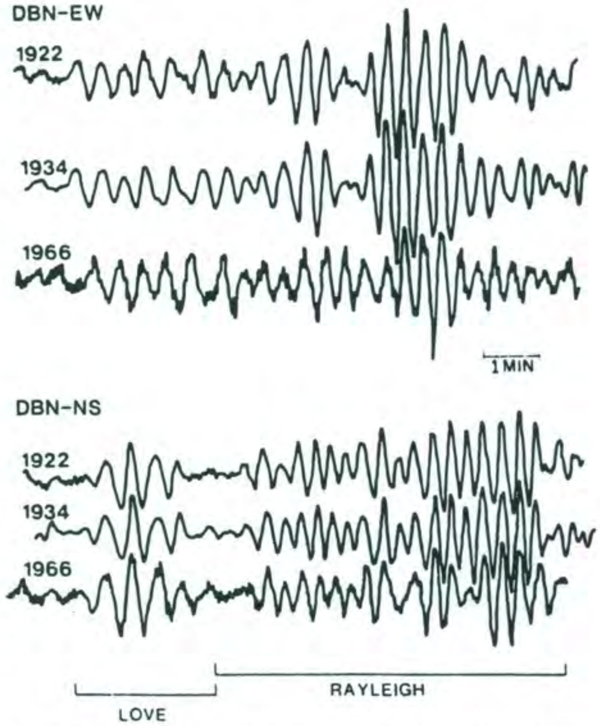
Research on generation of artificial earthquake time histories goes as back as 1960 by Bycroft (1960), Tajimi (1960), and later by Housner and Jennings (1964), Tsai

(1969), Campillo and Bouchon (1985), Papageorgiou and Aki (1981), and many others. Today, we are using computer packages for the generation of artificial earthquake time histories, as for example the ones by Tilliouine et al (1984), by Gasparini (1975), by Spudich (1985), by Preumont (1980) and others.

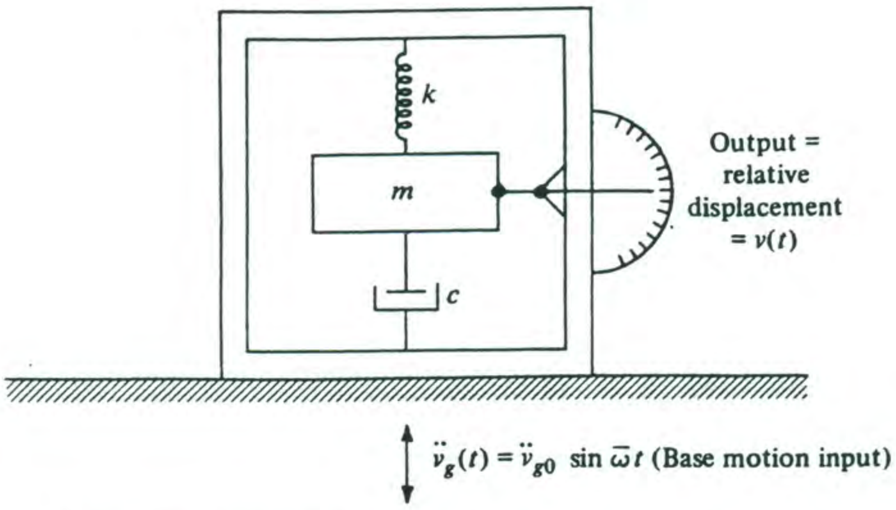
The methods may be divided into three groups, Wakabayashi (1986):

o By composing harmonic waves with different amplitude and phase angles
o By white noise excitation of one degree of freedom system and production a response spectrum
o By composing a time history from various pulses randomly (or not) along the time axis. The same is achieved when the source of pulses is being moved along the rupture.

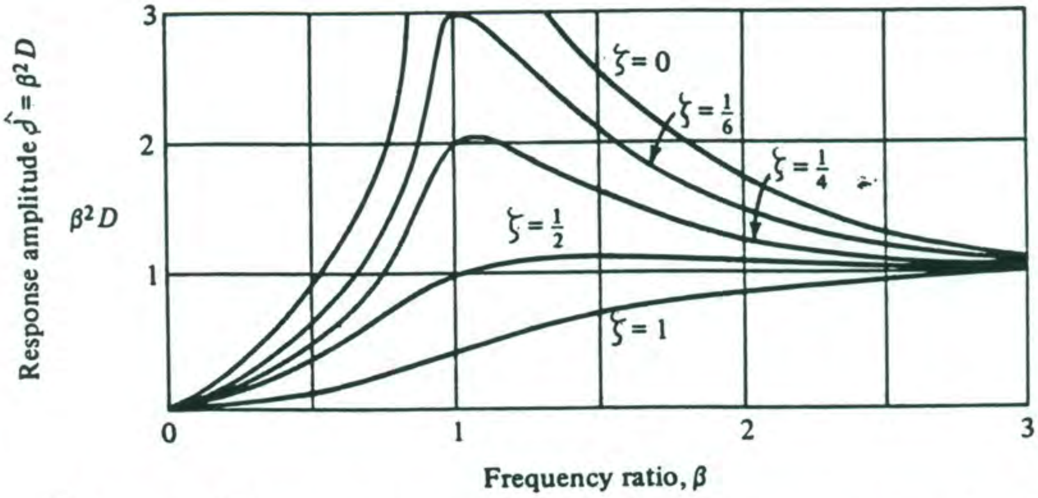
The most often used is the first method. The acceleration response spectrum is the product of a function with initially given power spectral characteristics and a function—as envelope—that expresses the amplitude change in time. The resulting artificial ground motion may be further modified so that its response spectrum fits better to the given smoothed response spectrum curve.



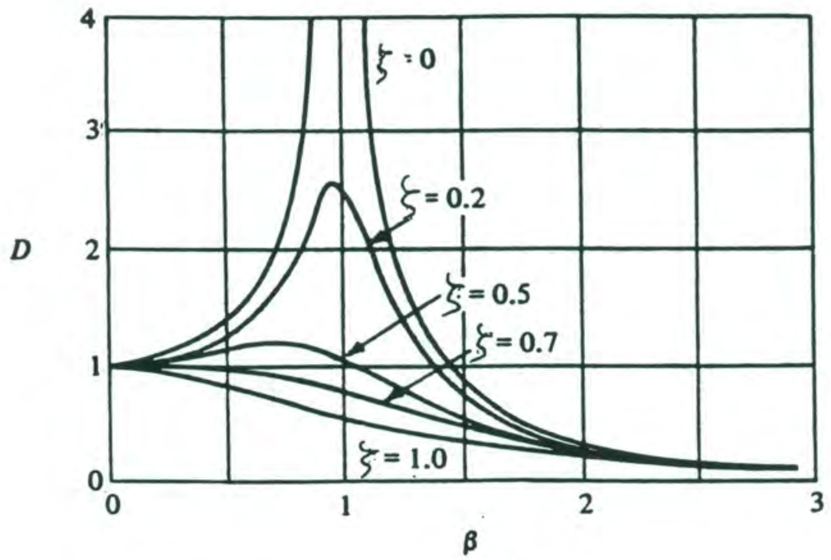
Seismograms of the three Parkfield, California earthquakes in 1922, 1934, and 1966 showing the similarity of waveforms for all three earthquakes recorded at DeBilt, Netherlands (DBN). During the past decade, studies of these earthquakes and the geology of the "Parkfield" segment of the San Andreas fault indicate a 95 percent probability that an earthquake of about magnitude 6 will occur between 1986 and 1993 (from Bakun and McEvilly, 1984), in Scholl and King (1985)



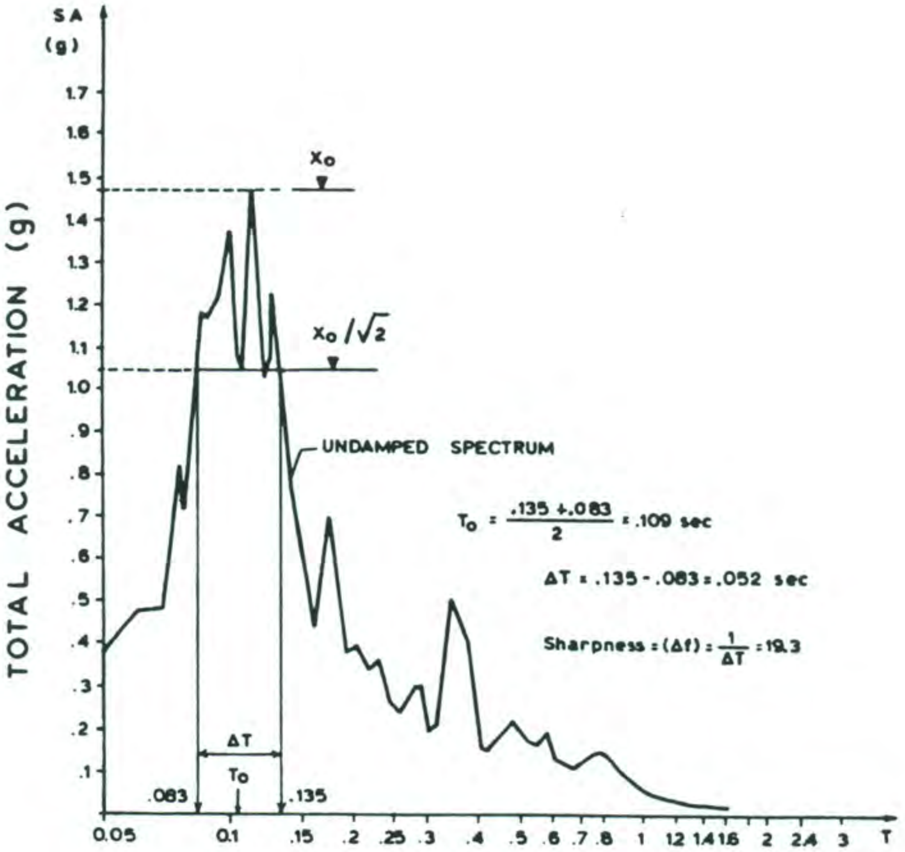
Schematic diagram of a typical seismometer, *after Clough and Penzien (1985)*



Response of seismometer to harmonic base displacement, *Clough and Penzien (1975)*



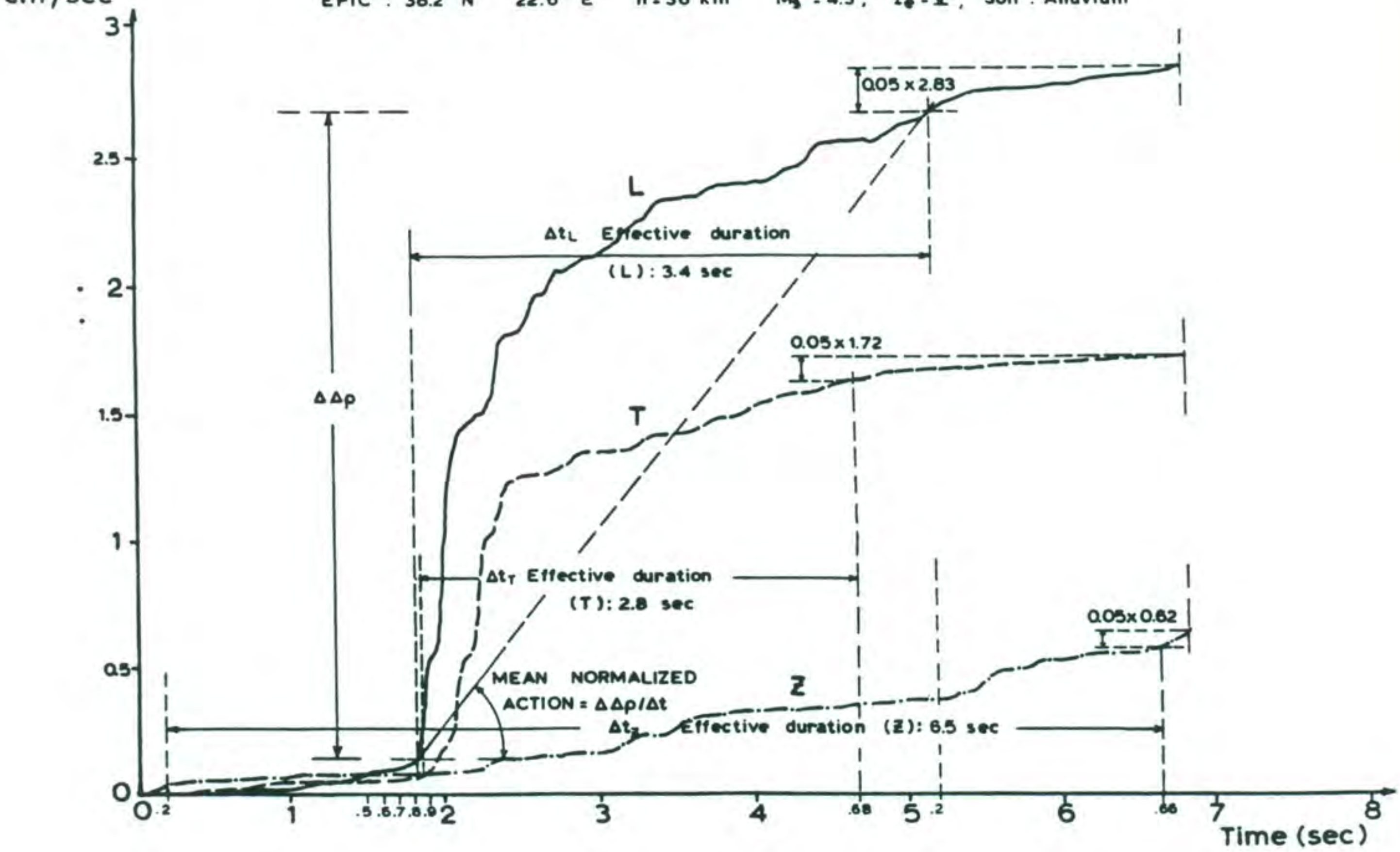
Variation of dynamic magnification factor with damping and frequency, *after Clough and Penzien (1985)*



NORMALIZED ACTION

XYLOKASTRON EARTHQUAKE MAY 13, 1975 Δ = 15 km

EPIC : 38.2° N 22.6° E h = 36 km M_s = 4.3, I_e = V°, Soil : Alluvium



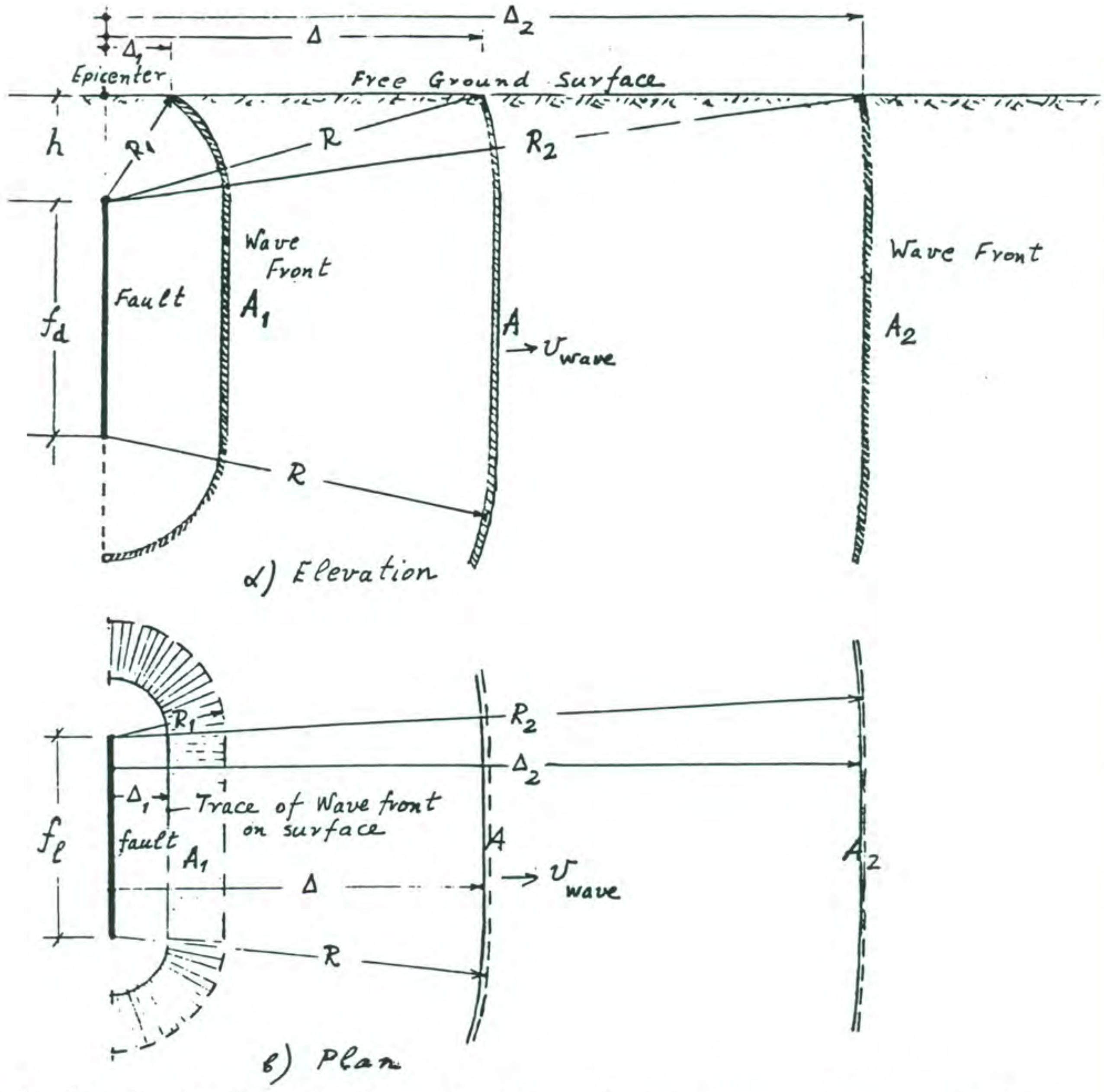


Fig. 2 Vertical Fault. Presentation of the wave front in elevation and plan, after Schnabel and Seed (1973).

A. Geometric Attenuation (after Schnabel and Seed 1973):

particle motion: $y = d\cos(\omega t)$ $\dot{y} = -v\sin(\omega t) = -d\omega\sin(\omega t)$

$\ddot{y} = -a\cos(\omega t) = -v\omega\cos(\omega t) = -d\omega^2\cos(\omega t)$

the energy in the time unit:

$$E = \frac{1}{2} m\,(\max\dot{y})^2 = \frac{1}{2} m\, v^2 = \frac{1}{2} m \left(\frac{a}{\omega}\right)^2$$

Volume $= V = A\cdot v_{wave}$, $m = V\cdot\rho = A\cdot v_{wave}\cdot\rho$

$$E = \frac{1}{2}\left(\frac{a}{\omega}\right)^2 A\cdot v_{wave}\cdot\rho$$

max acceleration $a = \omega\sqrt{\dfrac{E}{A\cdot v_w\cdot\rho}}$

$$\frac{a_1}{a_2} = \frac{\omega_1}{\omega_2}\sqrt{\frac{A_2}{A_1}} \quad , A = f_e\cdot f_d + \pi R\cdot f_d + \pi R f_e + 2\pi R^2 , \; R = \sqrt{D^2+h}$$

$$\frac{a_0}{a} = \frac{\omega_0}{\omega}\sqrt{\frac{A}{A_0}} = \frac{\omega_0}{\omega}\sqrt{\frac{f_e f_d + \pi R f_d + \pi R f_e + 2\pi R^2}{f_e f_d}}$$

$$a = a_0\,\frac{\omega}{\omega_0}\sqrt{\frac{f_e f_d}{f_e f_d + \pi R(f_d + f_e) + 2\pi R^2}}$$

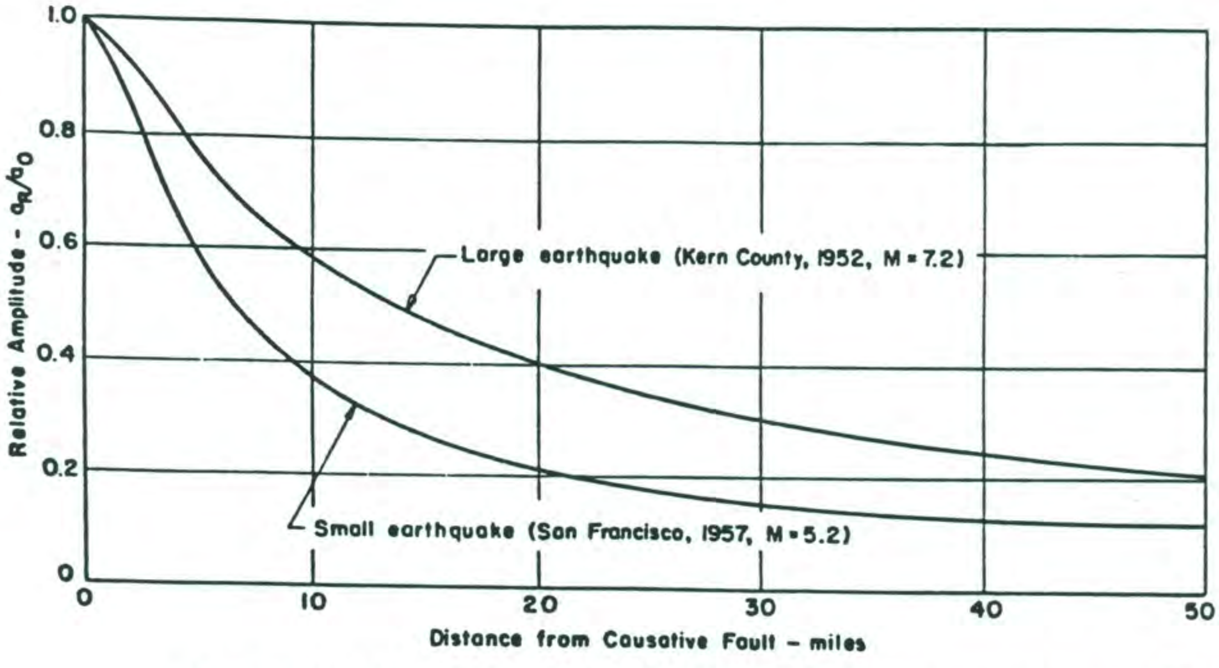


Fig. 3 EFFECT OF GEOMETRIC ATTENUATION ON MAXIMUM ACCELERATION, after SCHNABEL & SEED (1973)

B. Attenuation due to ABSORBTION:

For a constant v_{wave} : $R = v_{wave}\cdot t$

The amplitude $d = e^{-\xi\omega t}(A\sin\omega_D t + B\cos\omega_D t)$ is the product of the sinusoidal terms $(A\sin\omega_D t + B\cos\omega_D t)$ and the exponential term $e^{-\xi\omega t}$. The maximum values are given from the envelope $e^{-\xi\omega t}$, Thus:

The acceleration: $a = a_0 e^{-\xi\omega t} = a_0 e^{-\xi\omega\frac{R}{v_{wave}}}$

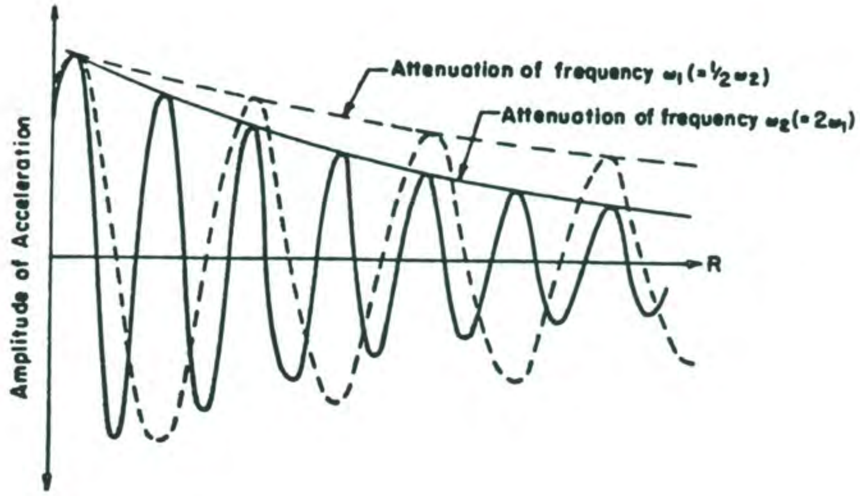


Fig. 4 ATTENUATION DUE TO ABSORBTION, after SCHNABEL & SEED (1973)

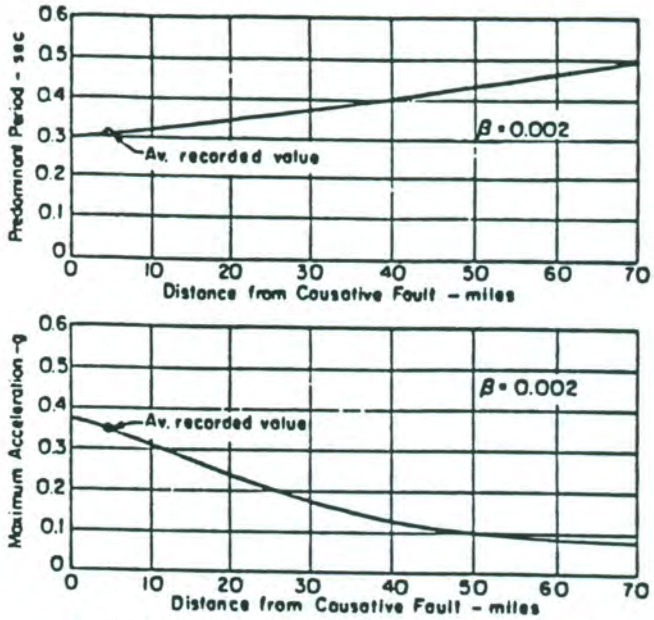


Fig. 5 EFFECT OF ABSORBTION ON MAXIMUM ACCELERATION AND PREDOMINANT PERIOD (Temblor, Parkfield 1966, M=5.6), after SCHNABEL & SEED (1973)

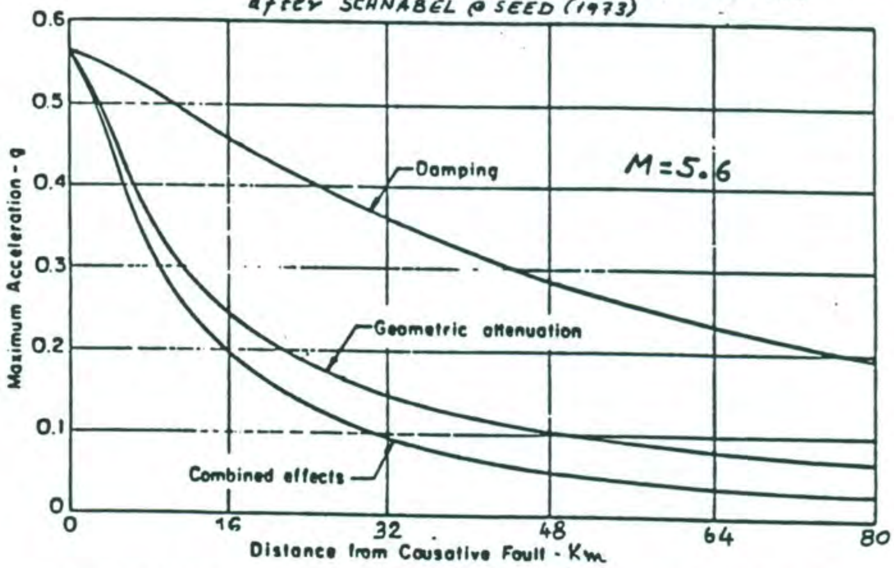


Fig. 6 COMPUTED EFFECTS OF GEOMETRIC ATTENUATION AND DAMPING ON MAXIMUM ACCELERATIONS IN PARKFIELD EARTHQUAKE OF 1966, after SCHNABEL & SEED (1973)

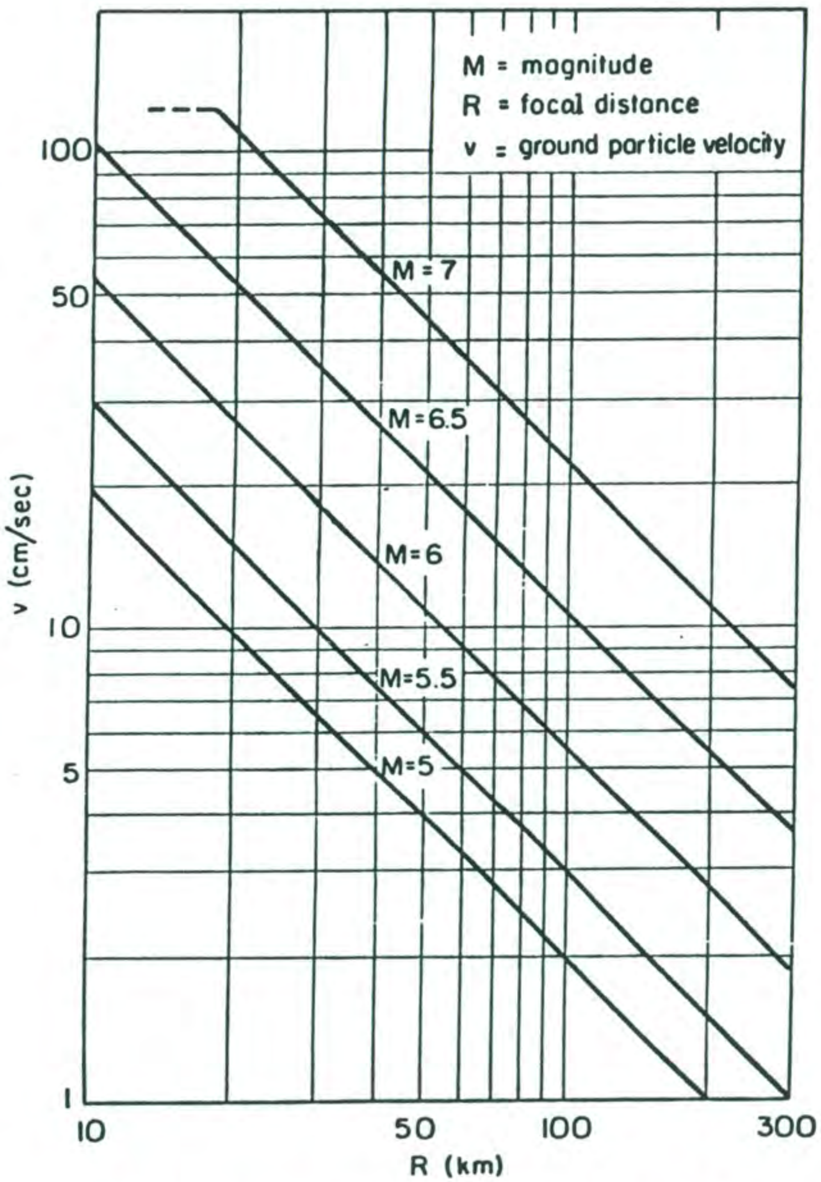


Fig. 7 MAXIMUM PROBABLE GROUND VELOCITIES (after Ambraseys, 1973)

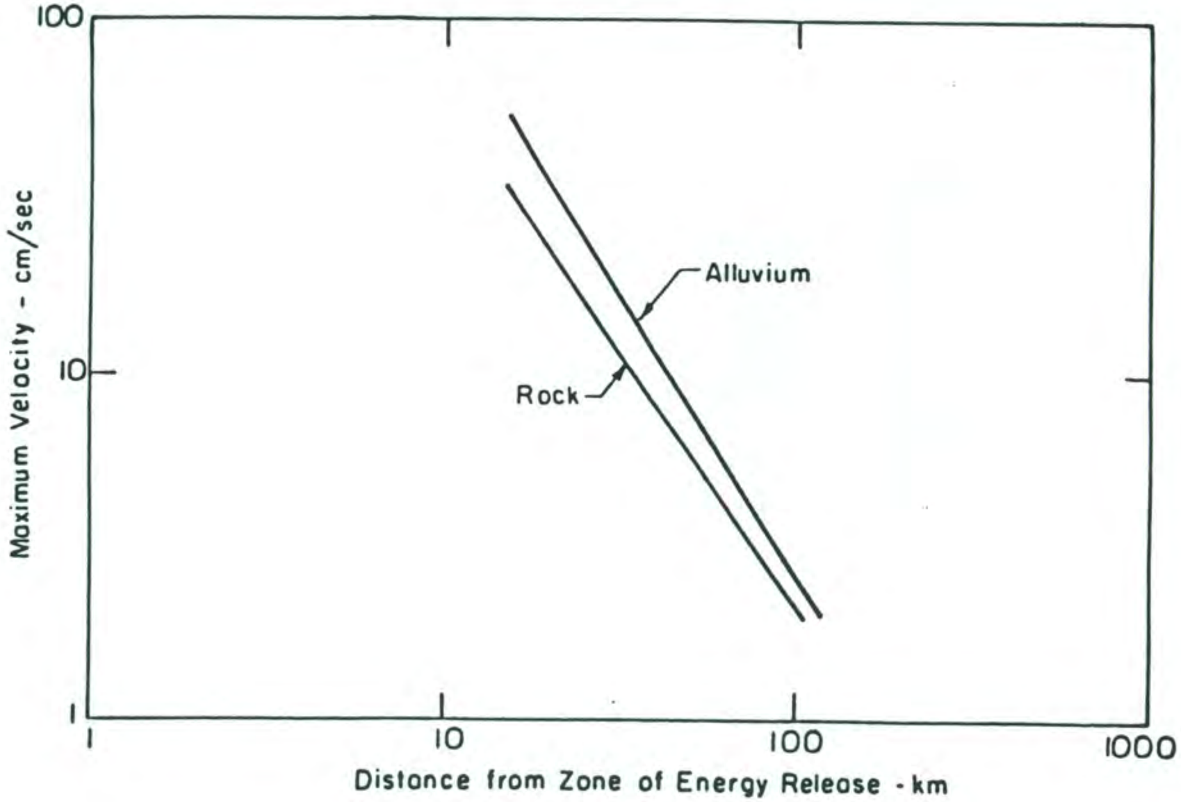


Fig. 8 INFLUENCE OF LOCAL SOIL CONDITIONS ON MAXIMUM GROUND VELOCITIES FOR MAGNITUDE 6½ EARTHQUAKES (after Seed, Murata, Lysmer, Idriss, 1975)

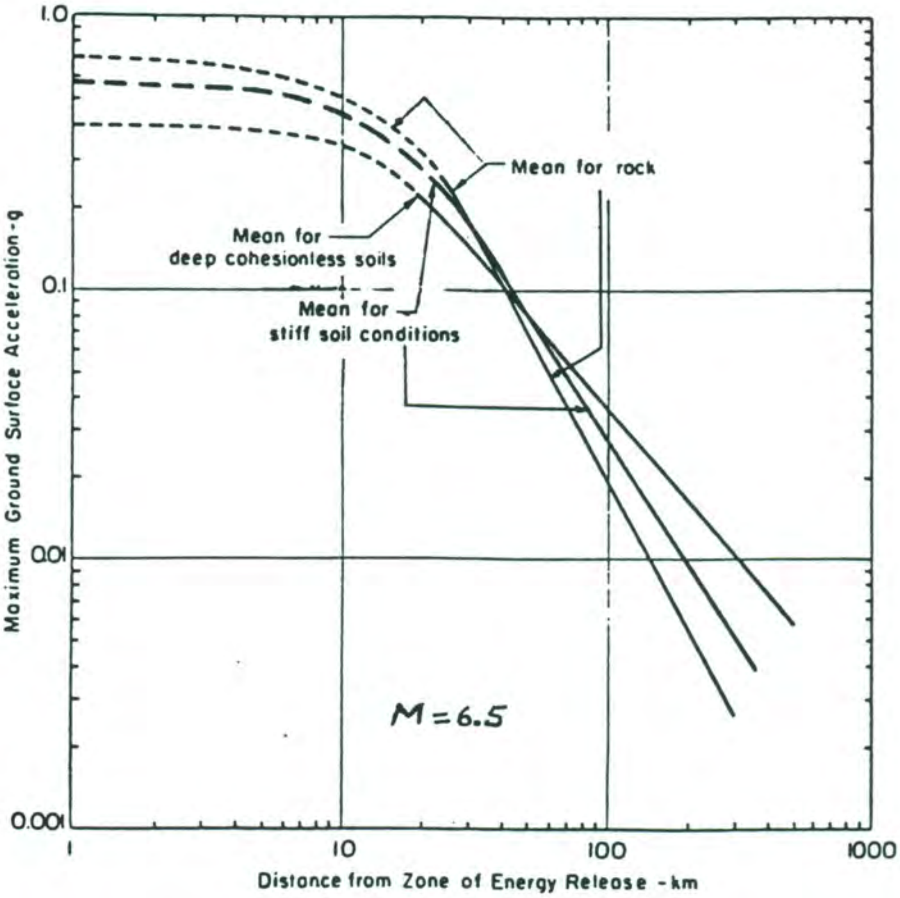


Fig. 9 COMPARISON OF MAXIMUM GROUND SURFACE ACCELERATIONS FOR ROCK ~~STIFF SOIL CONDITIONS~~ AND DEEP COHESIONLESS SOIL CONDITIONS (Seed, Muraka, Lysmer, Idriss, 1975)

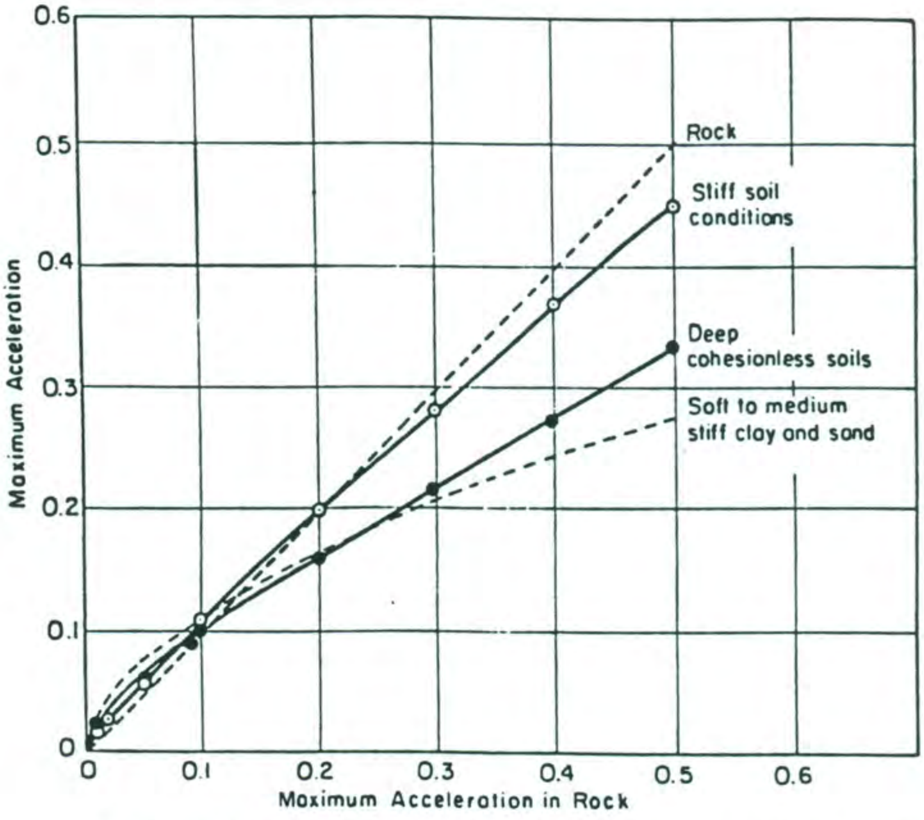


Fig.10 APPROXIMATE RELATIONSHIPS BETWEEN MAXIMUM ACCELERATIONS ON ROCK AND OTHER LOCAL SITE CONDITIONS (Seed, Muraka, Lysmer, Idriss, 1975)

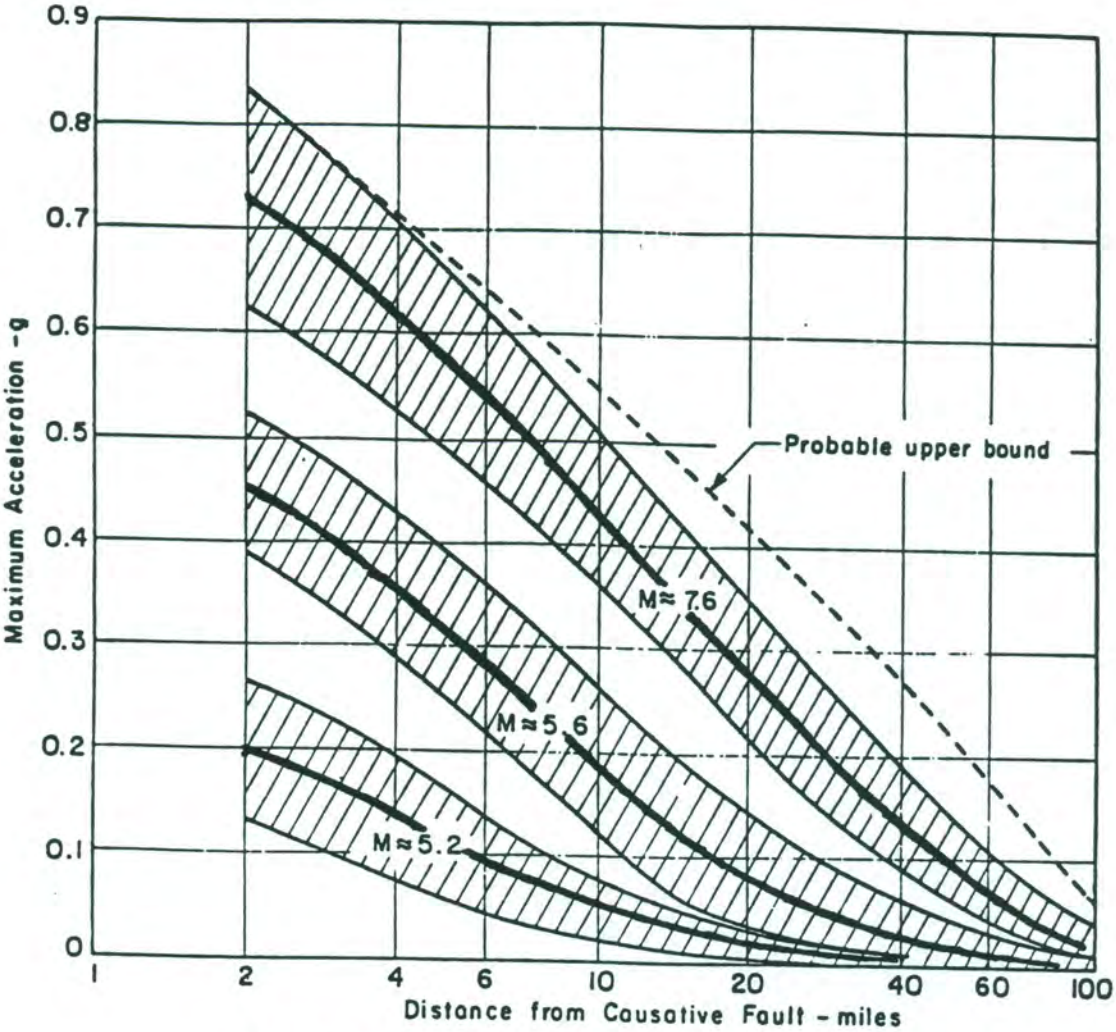


Fig.11 RANGES OF MAXIMUM ACCELERATIONS IN ROCK, *after* SCHNABEL & SEED (1973)

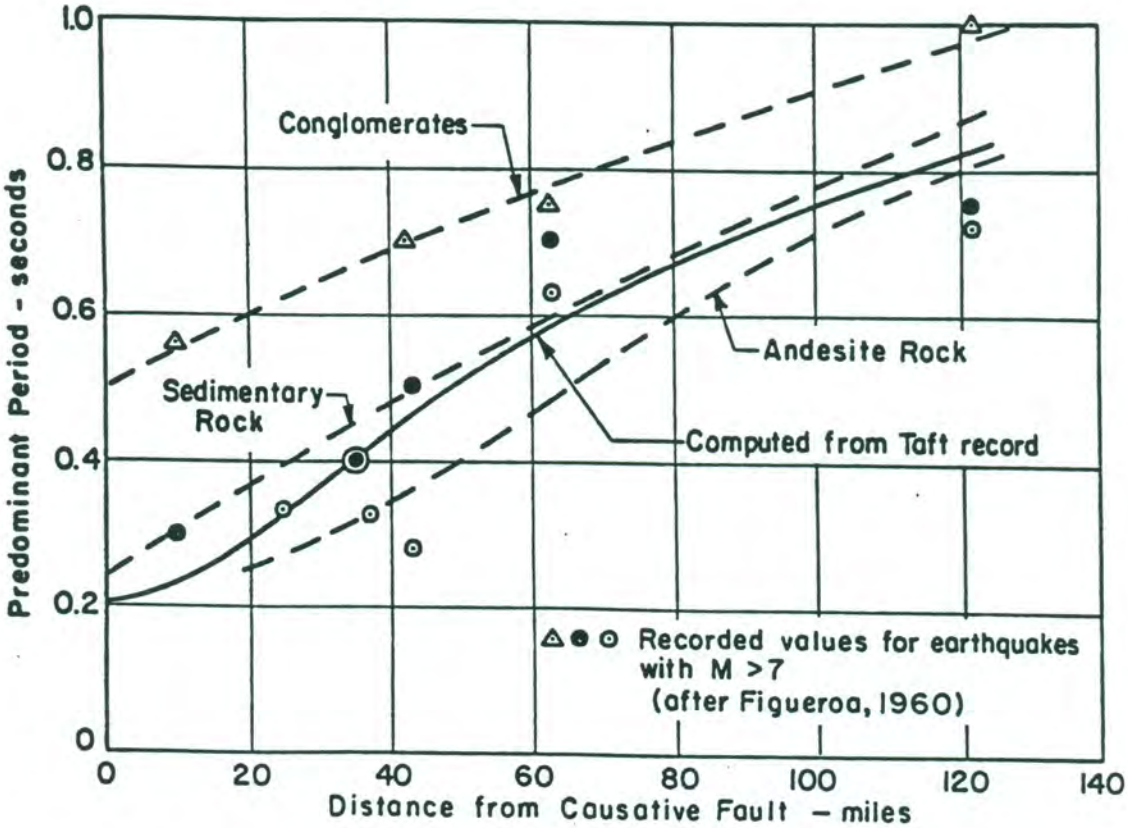


Fig. 12 CHANGES IN PREDOMINANT PERIOD IN ROCK MOTIONS, *after* SCHNABEL & SEED (1973)

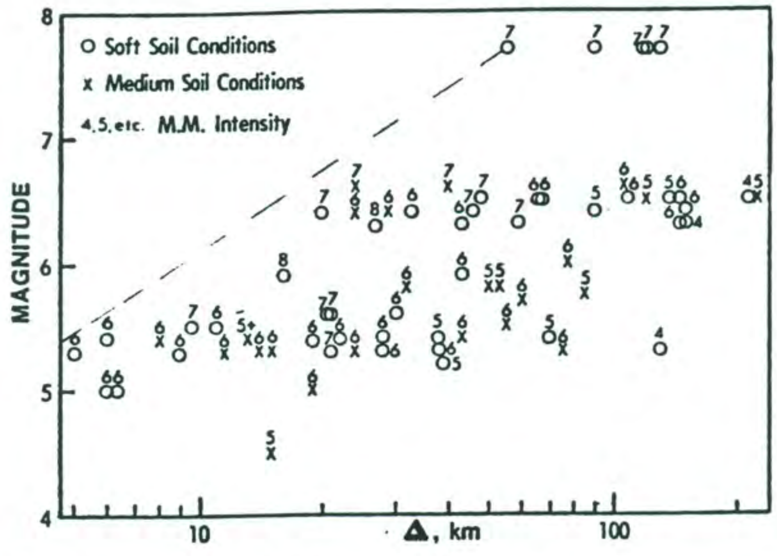


Fig. 13 MAGNITUDE, DISTANCE, INTENSITY, AND SOIL CONDITIONS OF RECORDS, after McGUIRE (1977)

R.F. (1)	F.M. (2)	M.C. (3)	M.C.S. (4)	M.S. (5)	M.M. (6)	J.S. (7)	A.S. U.S.S.R. (8)	MSK (9)
II	I II	II	II	I	I	0	II	II
III	III	III	III	II III	II III	I	III	III
IV	IV	IV	IV	IV	IV	II	IV	IV
V		V	V	V	V	III	V	V
VI VII	V VI	VI	VI	VI	VI	IV	VI	VI
VIII	VII	VII	VII	VII	VII		VII	VII
IX	VIII IX	VIII	VIII	VIII	VIII IX	V	VIII	VIII
		IX	IX	IX	X		IX	IX
X	X	X	X	X		VI	X	X
	XI	XI	XI	XI	XI	VII	XI	XI
	XII	XII	XII	XII	XII		XII	XII

where:

R.F. = Rossi-Forel (1883)
F.M. = Forel-Mercalli (1904)
M.C. = Mercalli-Cancani (1904)
M.C.S. = Mercalli-Cancani-Sieberg (1923)
M.S. = Mercalli-Sieberg (1923)
M.M. = Modified Mercalli (1931, 1956)
J.S. = Japanese Scale (1949)
A.S. U.S.S.R. = Academy of Sciences USSR (1952)
M.S.K. = Medvedev-Sponheuer-Kárník (1964)

Fig. 14 Relation among various Macroseismic Intensity Scales

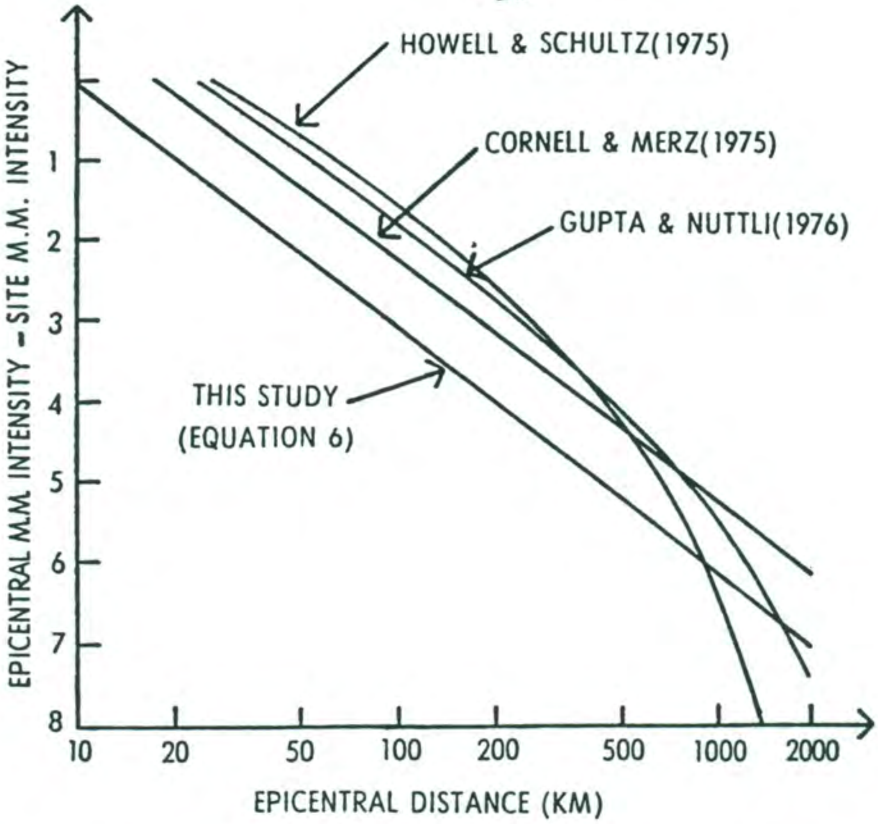


Fig. 15 Epicentral M.M. intensity minus site M.M. intensity, as a function of epicentral distance; several reported relations for the central and eastern U.S., and the relation used in this study, *after McGUIRE (1976)*

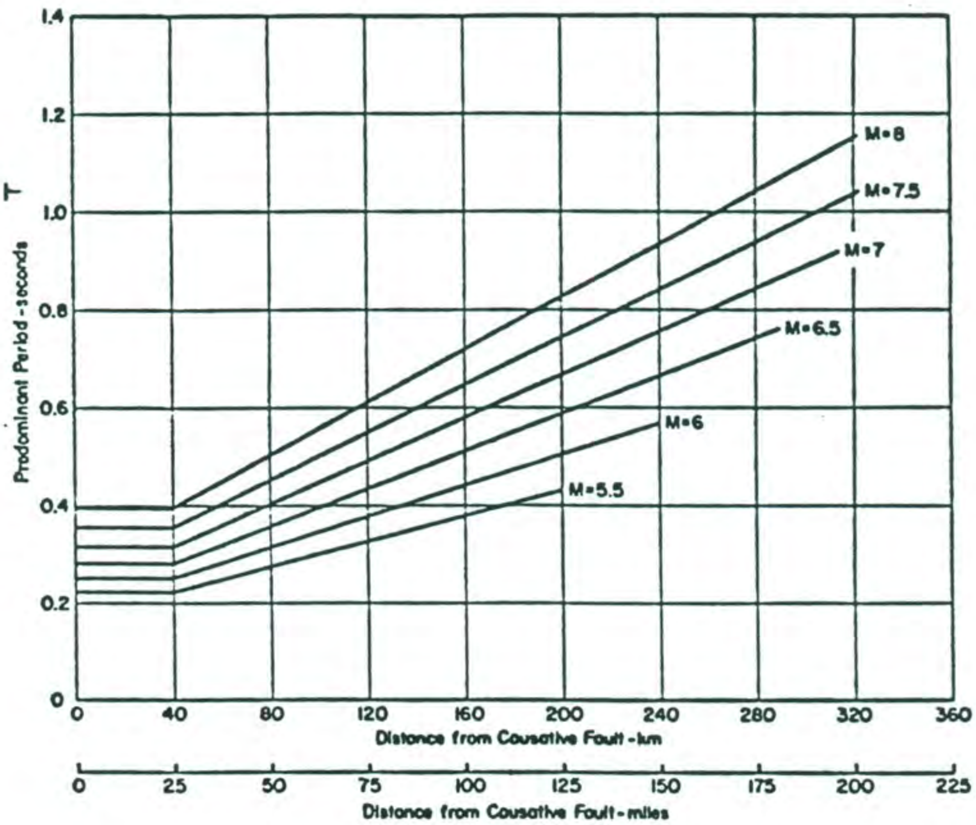


FIG.*16* PREDOMINANT PERIODS FOR MAXIMUM ACCELERATIONS IN ROCK, *(Seed, Idriss and Kiefer 1969)*

Predominant Periods for Granite and Epicentral Distance D < 50 km

M :	1-2	2-3	3.5-5.5	6-6.5	7.6
T (sec) :	0.1	0.2	0.25	0.3	0.5

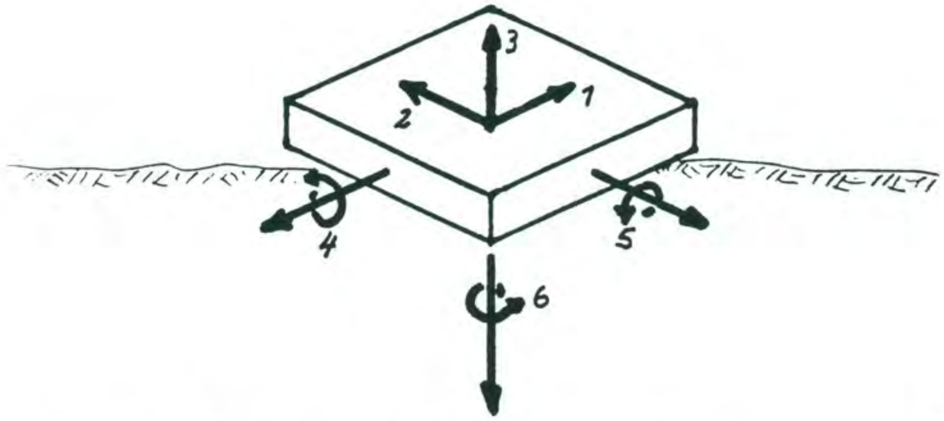
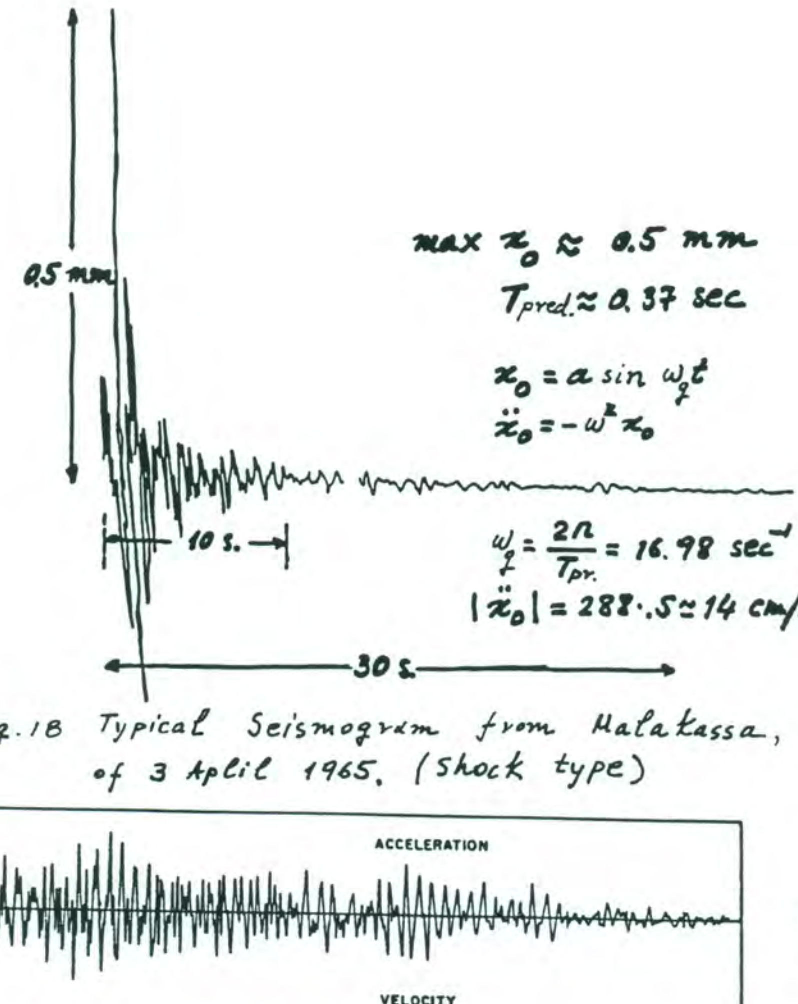


Fig. 17 A body standing on the free surface of the ground experiences during an earthquake all 6 degrees of freedom.



$$\max x_0 \approx 0.5\ mm$$
$$T_{pred.} \approx 0.37\ sec$$
$$x_0 = a \sin \omega_q t$$
$$\ddot{x}_0 = -\omega^2 x_0$$
$$\omega_q = \frac{2\pi}{T_{pr.}} = 16.98\ sec^{-1}$$
$$|\ddot{x}_0| = 288 \cdot .5 \simeq 14\ cm/sec^2$$

Fig. 18 Typical Seismogram from Malakassa, 30 km N of Athens, of 3 Aplil 1965. (Shock type)

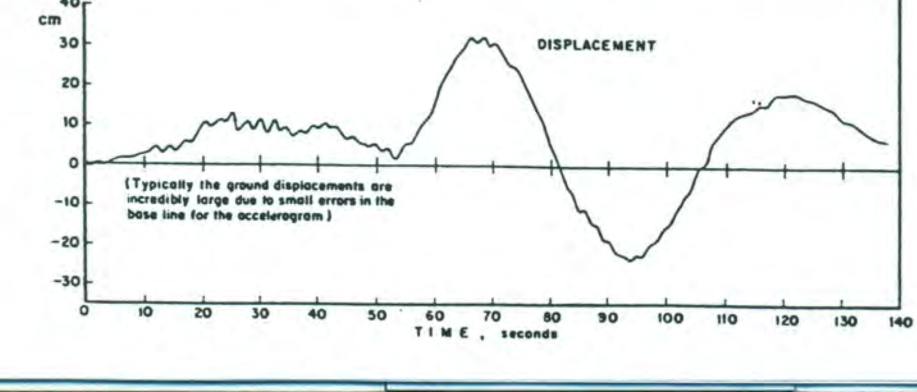


Fig. 19. Mexico City Earthquake of July 6, 1964, NS component, after Rosenblueth (1966). (Wave form type)

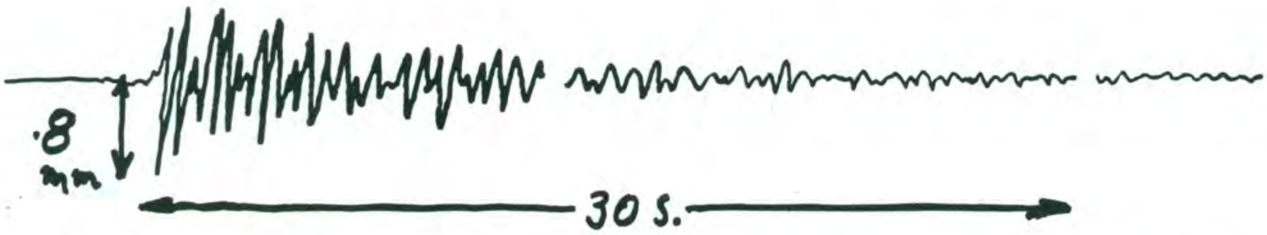


Fig. 20 Epidaurus earthquake, July 4 1968, $M_S = 5$, max $x_g =$ $= .8$ mm, $\omega_g = \frac{2\pi}{T_{pr}} = 7.85\ s^{-1}$, max $\ddot{x}_g = 49\ cm\ s^{-2}$ (Wave form type).

Fig. 21. St. Eustratius earthquake, November 20, 1968, $M = 4$, $H = 45$ Km, (Wave form type)

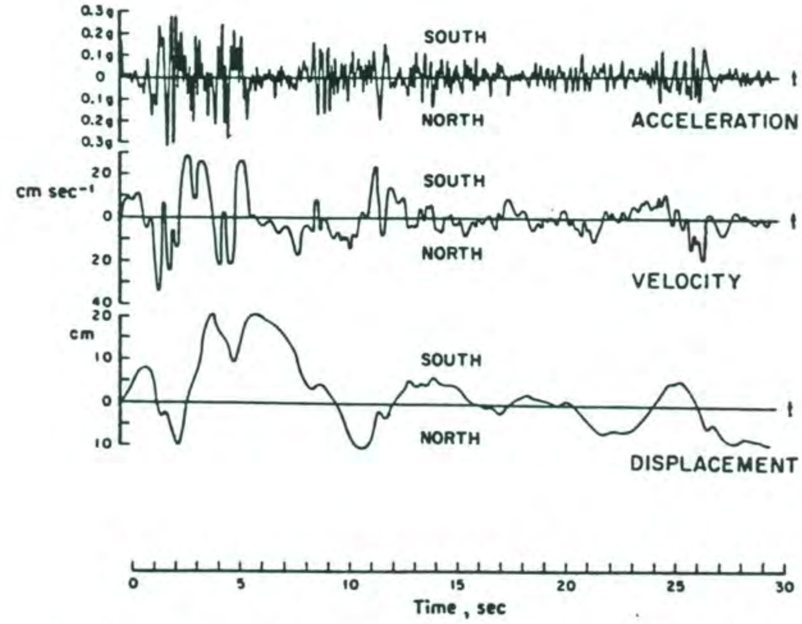


Fig. 22. El Centro, California Earthquake, May 18, 1940, NS component, after Blume, Newmark and Corning (1961), (Irregular wave form type).

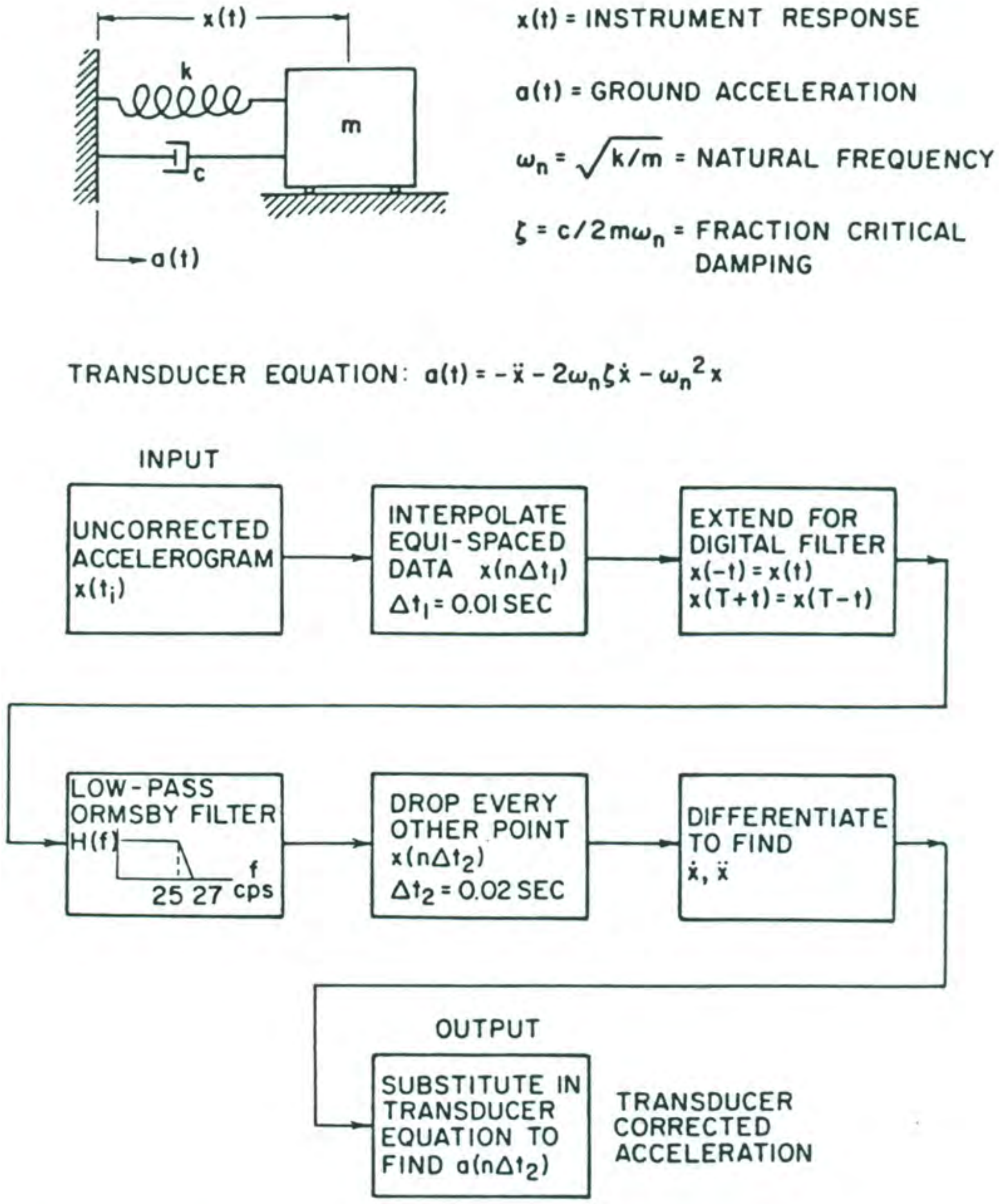


Fig. 23 Transducer Corrections for Strong Motion Accelerographs, after Hudson (1979)

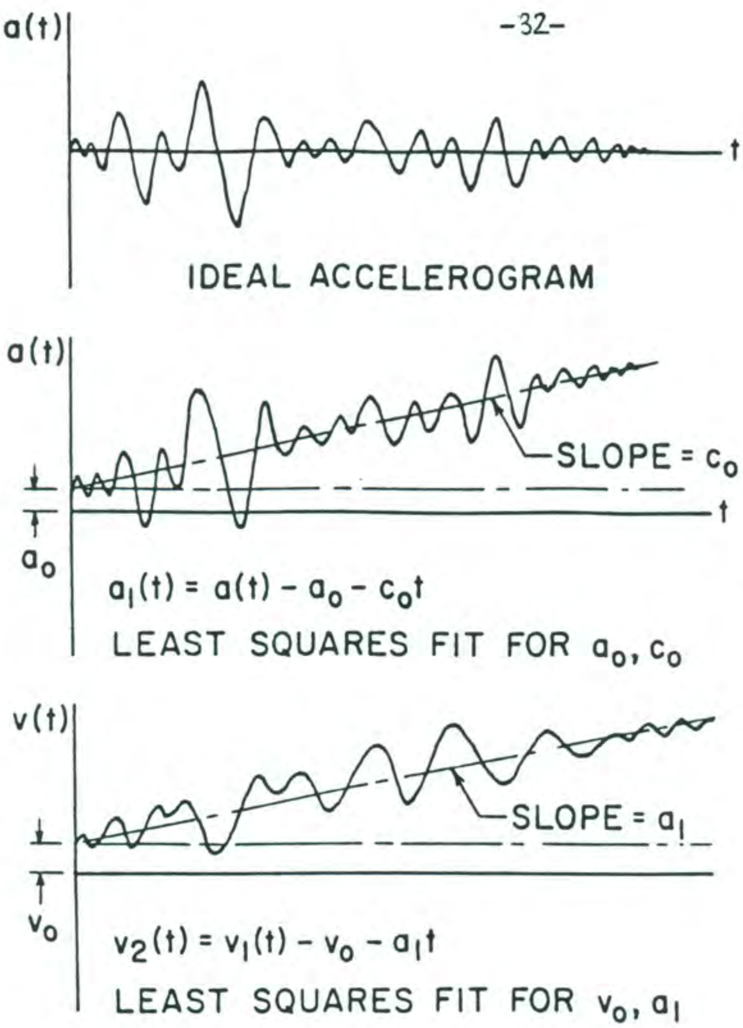


Fig. 24 Correction for Linear Trends by Least Squares Adjustment, after Hudson (1979)

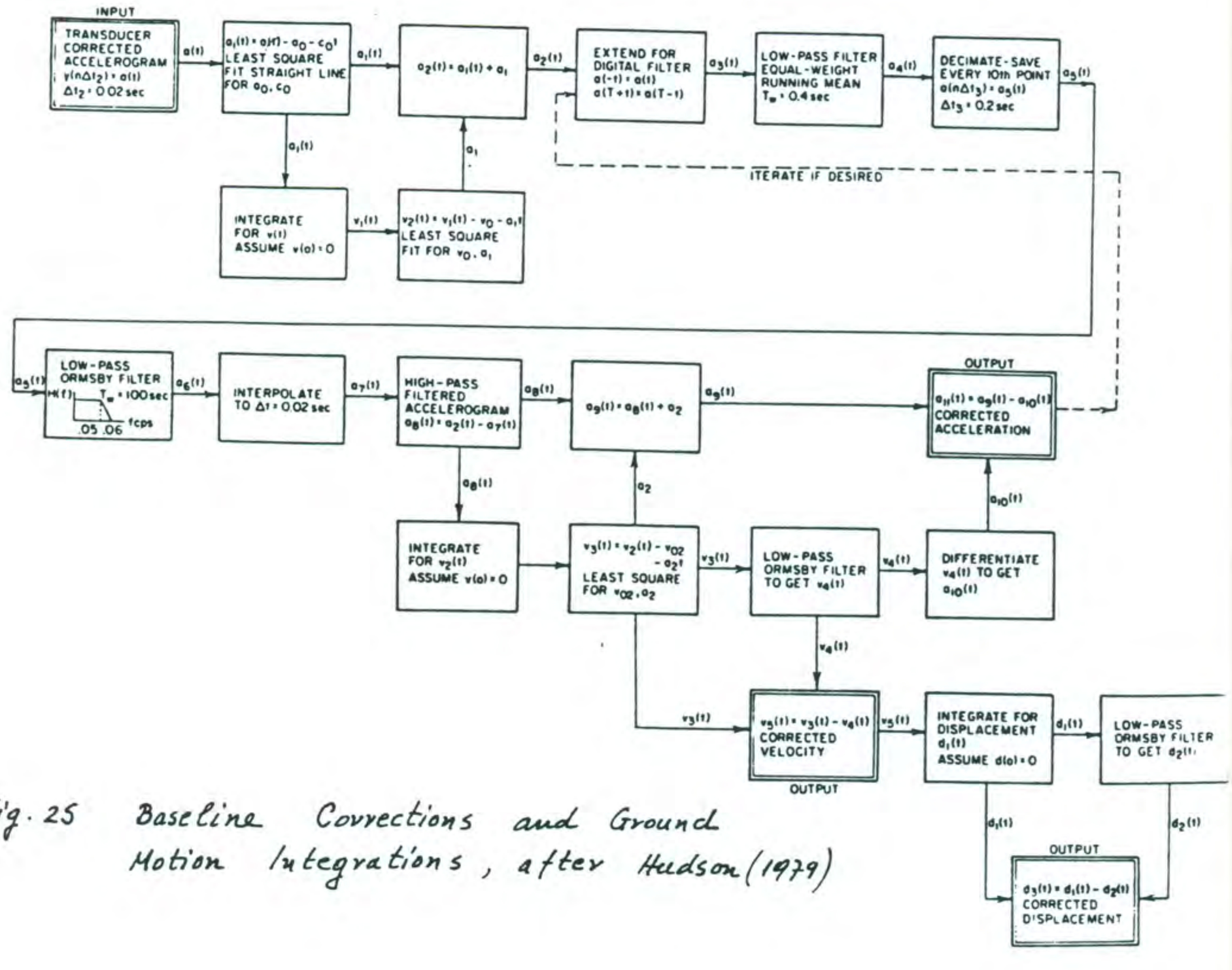


Fig. 25 Baseline Corrections and Ground Motion Integrations, after Hudson (1979)

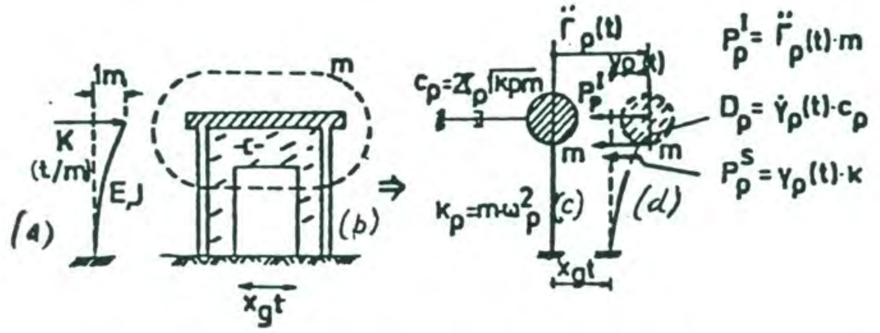


Fig. 26 The one degree of freedom system under seismic excitation.

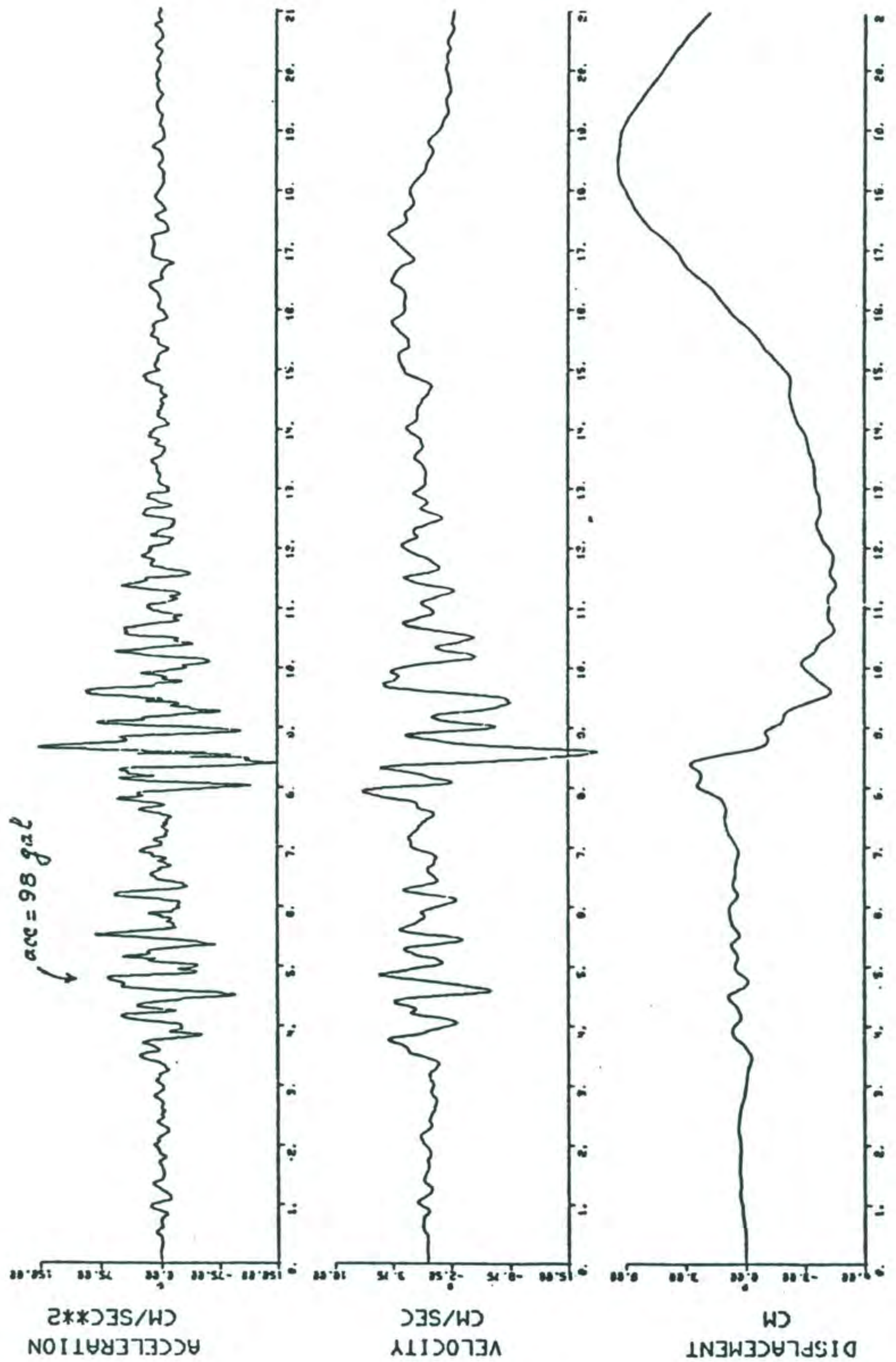


Fig. 27 GROUND ACCELERATION-VELOCITY-DISPLACEMENT
THESSALONIKI LONG. JUN 20, 1978 23H 03M 25S
EPIC (NOA) [40°... N, 23°... E
D=20 KM. MS= 6.5 IE=VIII+ SOIL=SOFT ALLUVIUM
ACCEL=+151.4 CM/SEC**2 VELOC= 18.2 CM/SEC DSPL=+6.4 CM

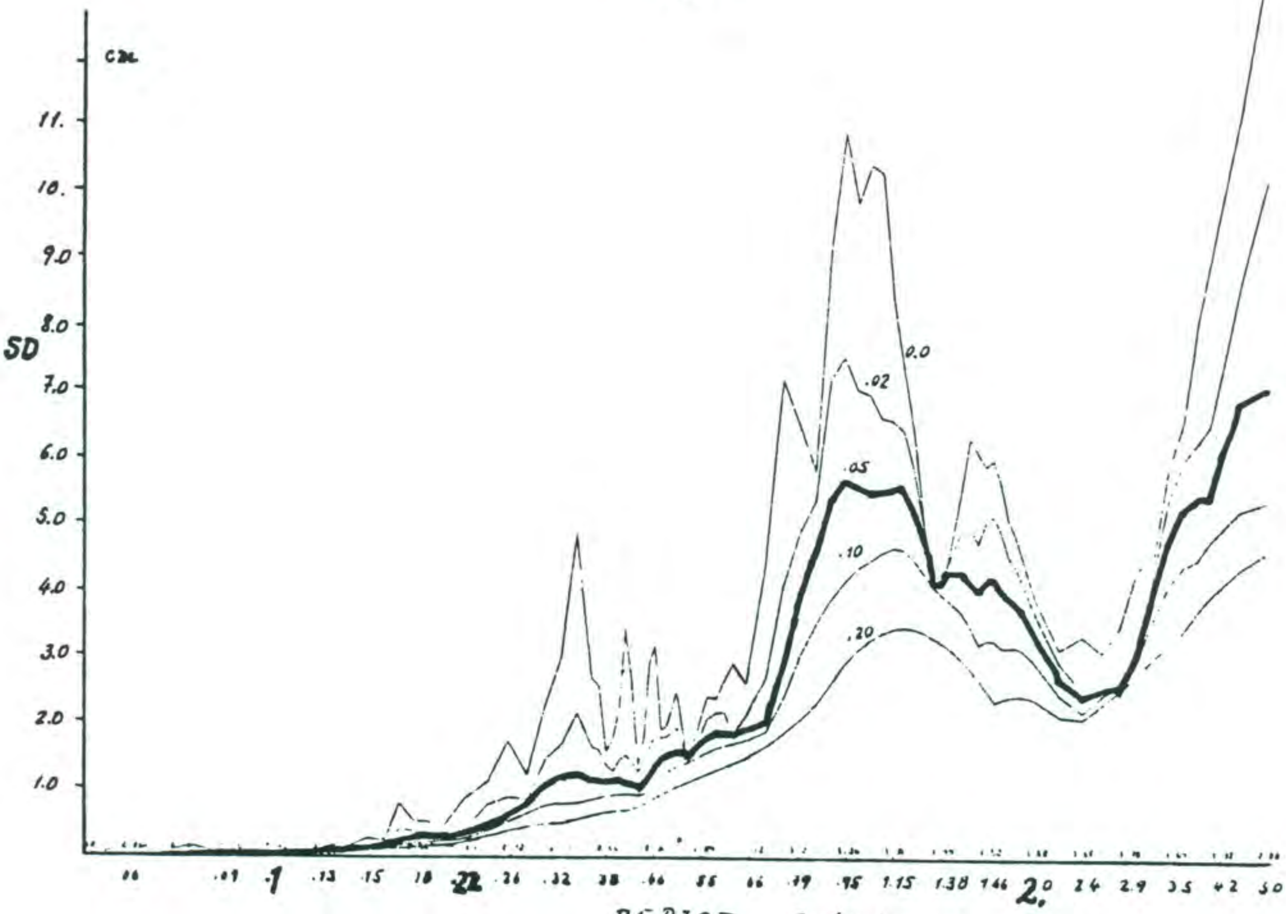
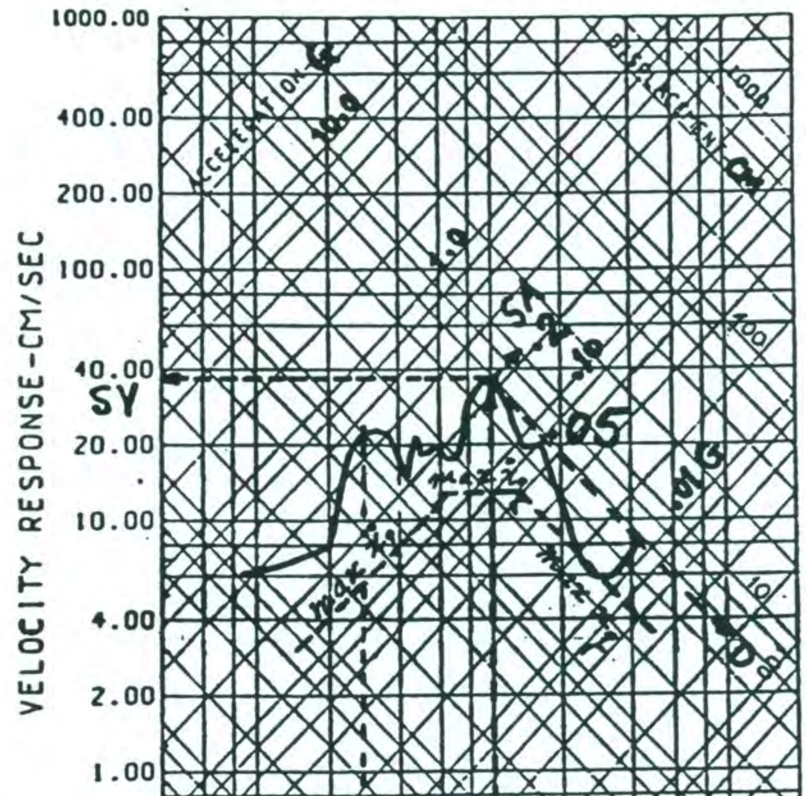


Fig. 28 Displacement response spectrum (LONG), Thessaloniki earthquake, June 20, 1978 Basement "CITY" Hotel.

Fig. 29 Response Spectrum of Thessaloniki Earthquake June 20, 1978, (LONG)
$M_S = 6.5$
Basement "CITY" Hotel.

The heavy line of the 5% displacement response spectrum is used.



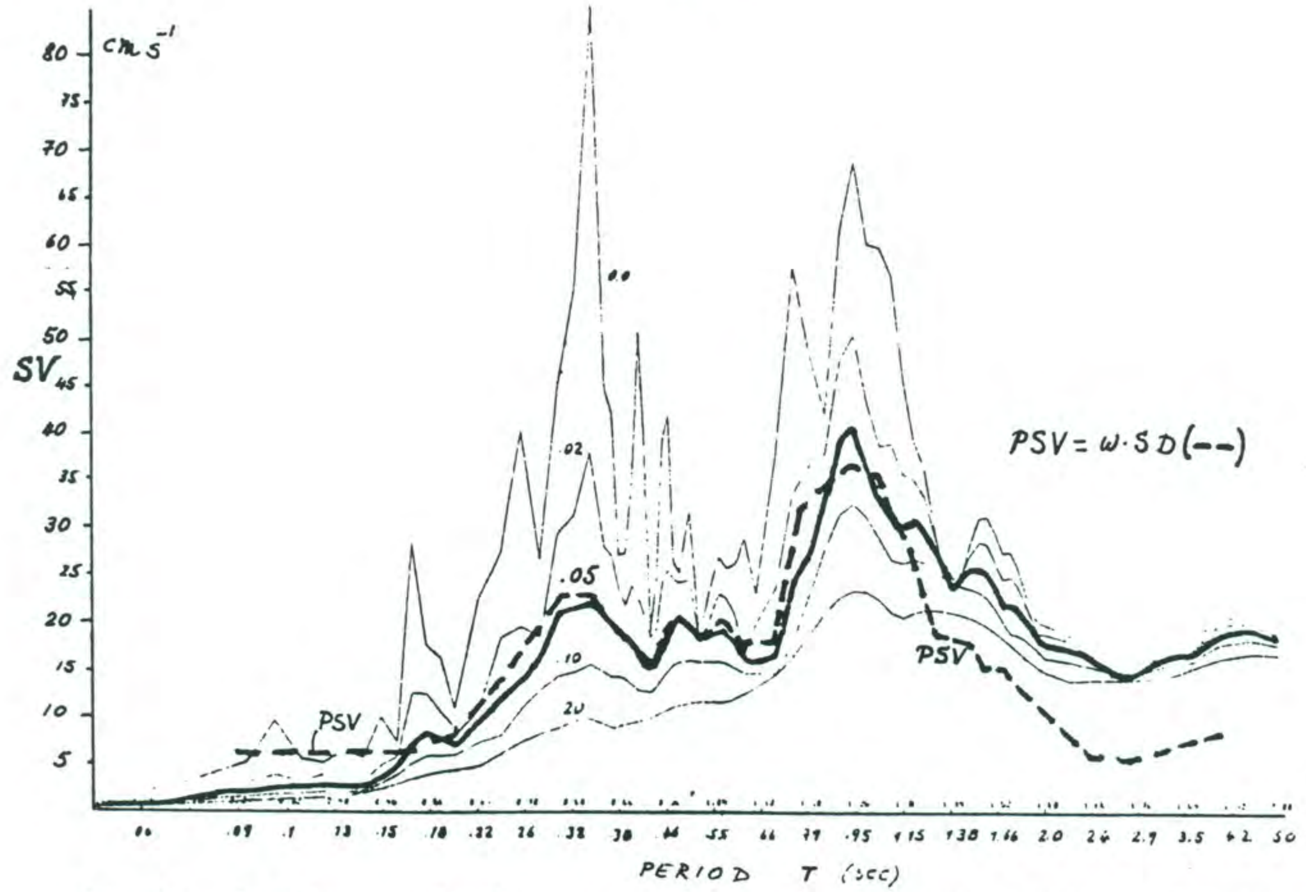


Fig. 30 Relative velocity response spectrum (LONG), Thessaloniki earthq. June 20, 1978, and PSV for 5% damping. (--).

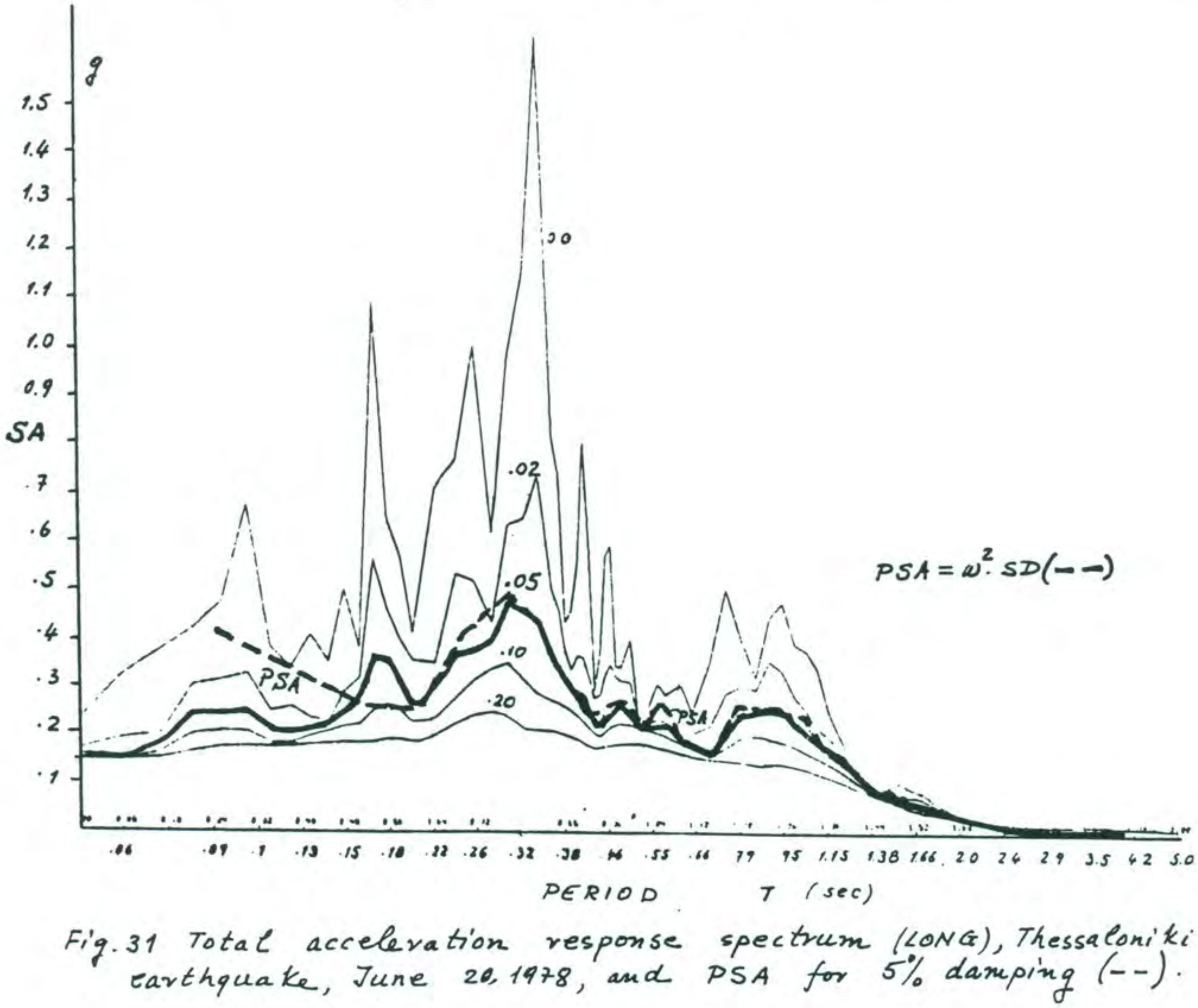
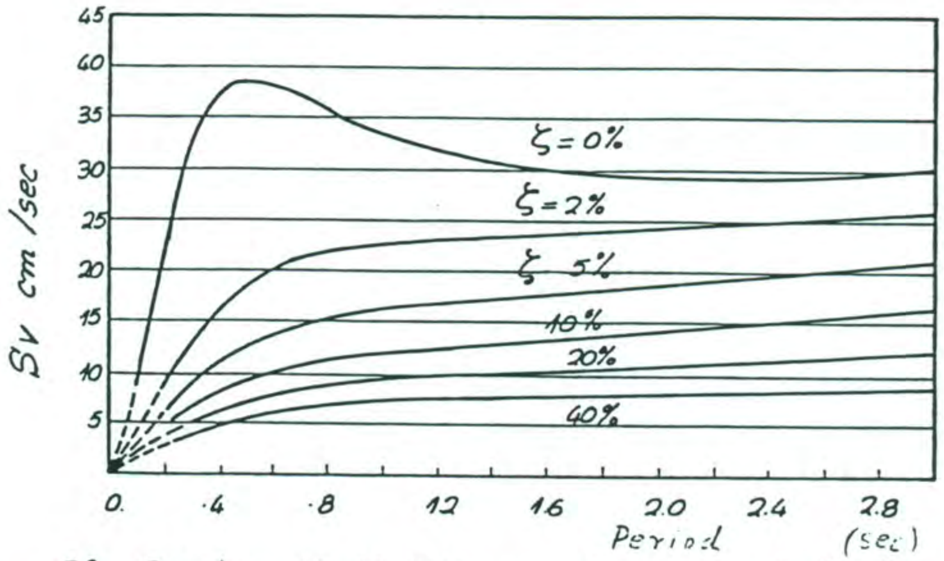


Fig. 31 Total acceleration response spectrum (LONG), Thessaloniki earthquake, June 20, 1978, and PSA for 5% damping (--).



El Centro 18 . V. 1940 = 2.7 ✱ spectral Values
El Centro 30. XV. 1940 = 1.9 ✱ —»—
Olympia 13. IV. 1949 = 1.9 ✱ —»—
Taft 21. VII. 1952 = 1.6 ✱ —»—
Vernon 10. III. 1933 = 1.5 ✱ —»—

Fig. 32 Average Velocity Spectrum Curves (Housner 1959)

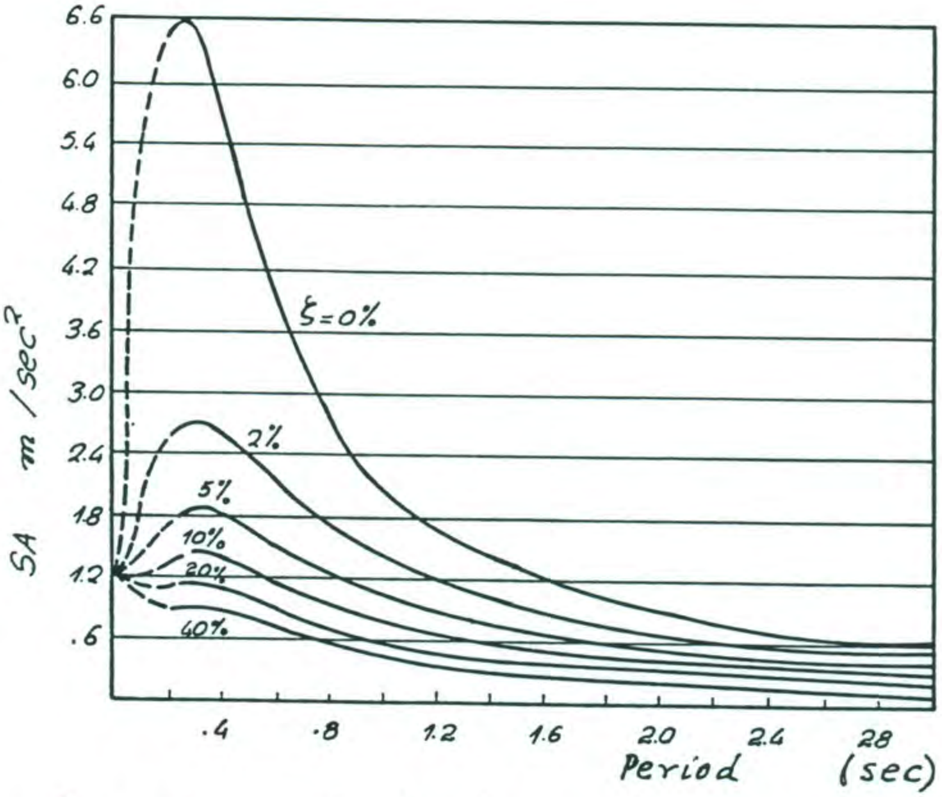
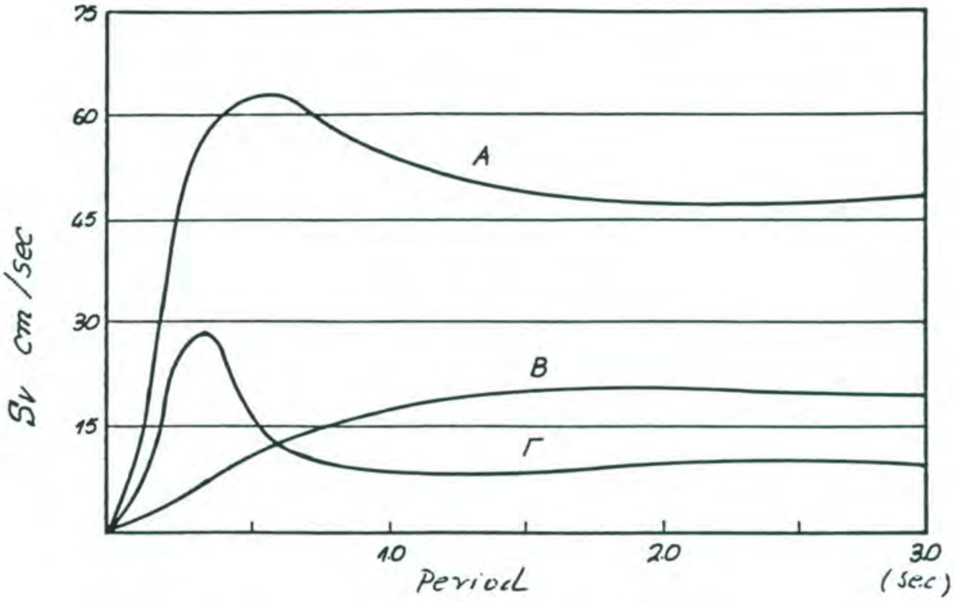


Fig. 33 Average Acceleration Spectrum Curves (Housner 1959)



A : 40 km From Center of Large Shock

B: 120 km From Center of Large Shock

Γ: 20 km From Center of Small Shock

Fig. 34 Undamped Velocity Spectra, after Housner (1959)

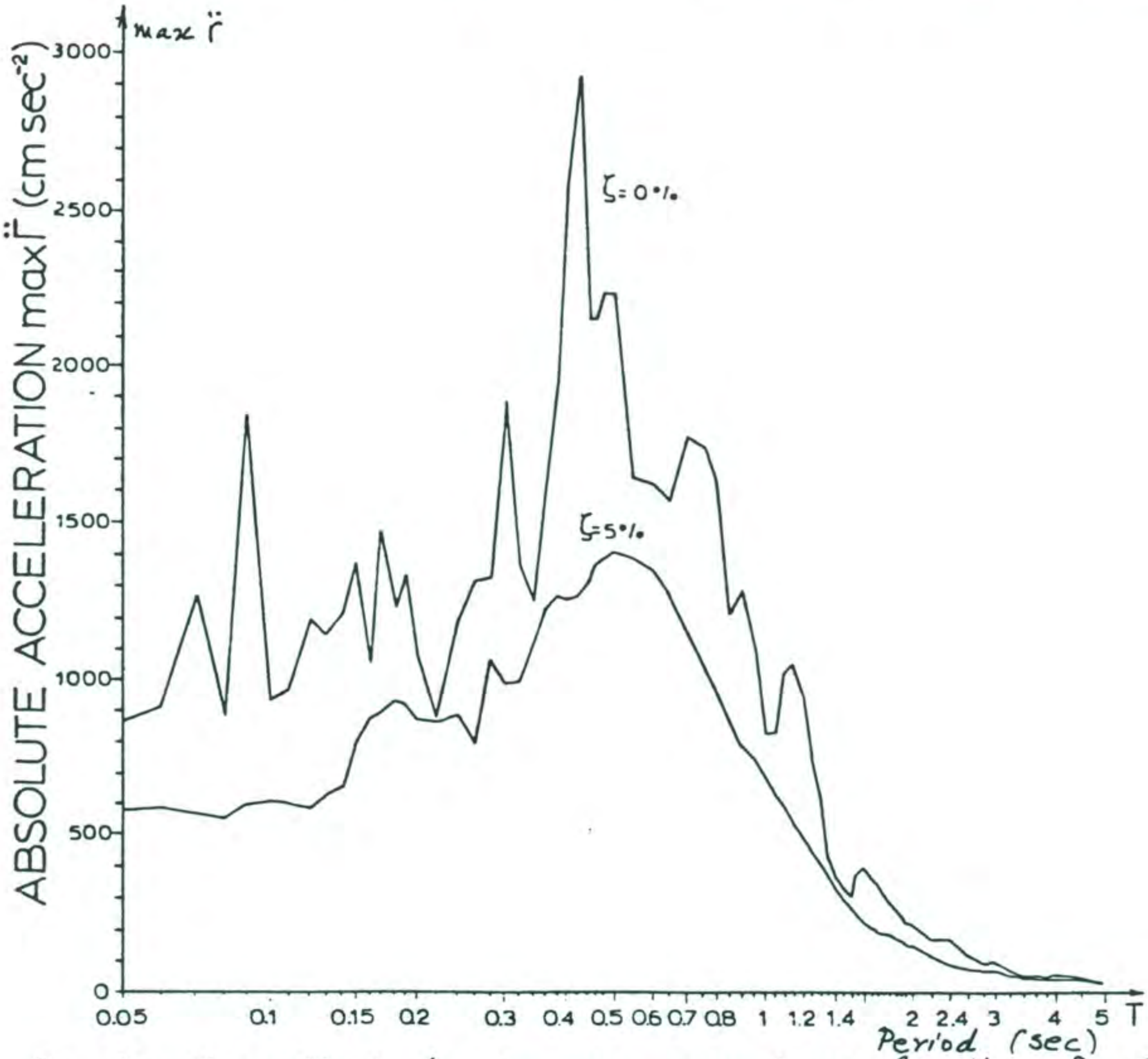


Fig. 35 Normalized to 1g max ground acceleration Envelope Response Spectrum for Greek Earthquakes, 1972÷1975

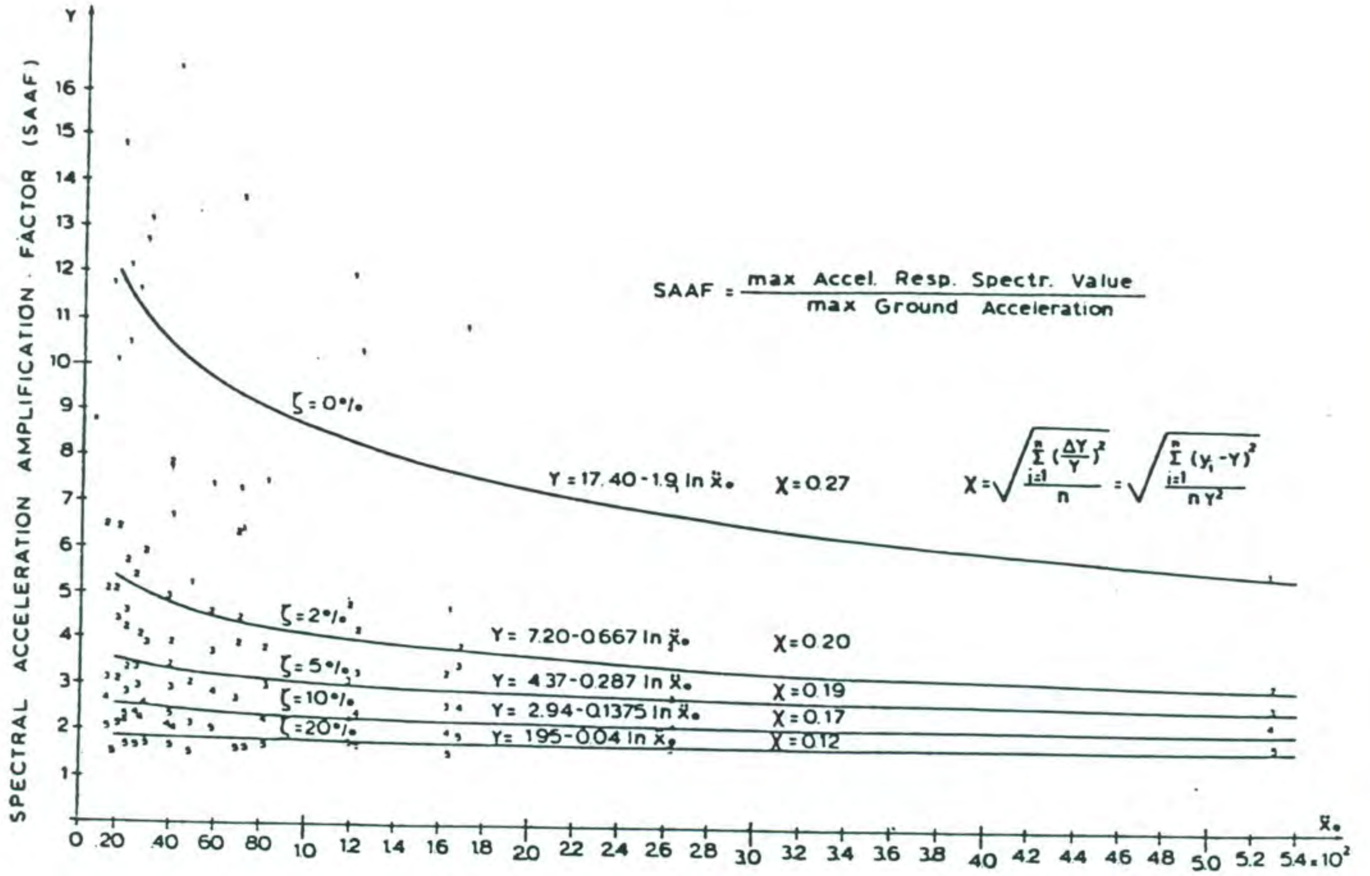


Fig. 36 Spectral Acceleration Amplification Factors vs the respective maximum ground acceleration, for Greek records, after Carydis (1977)

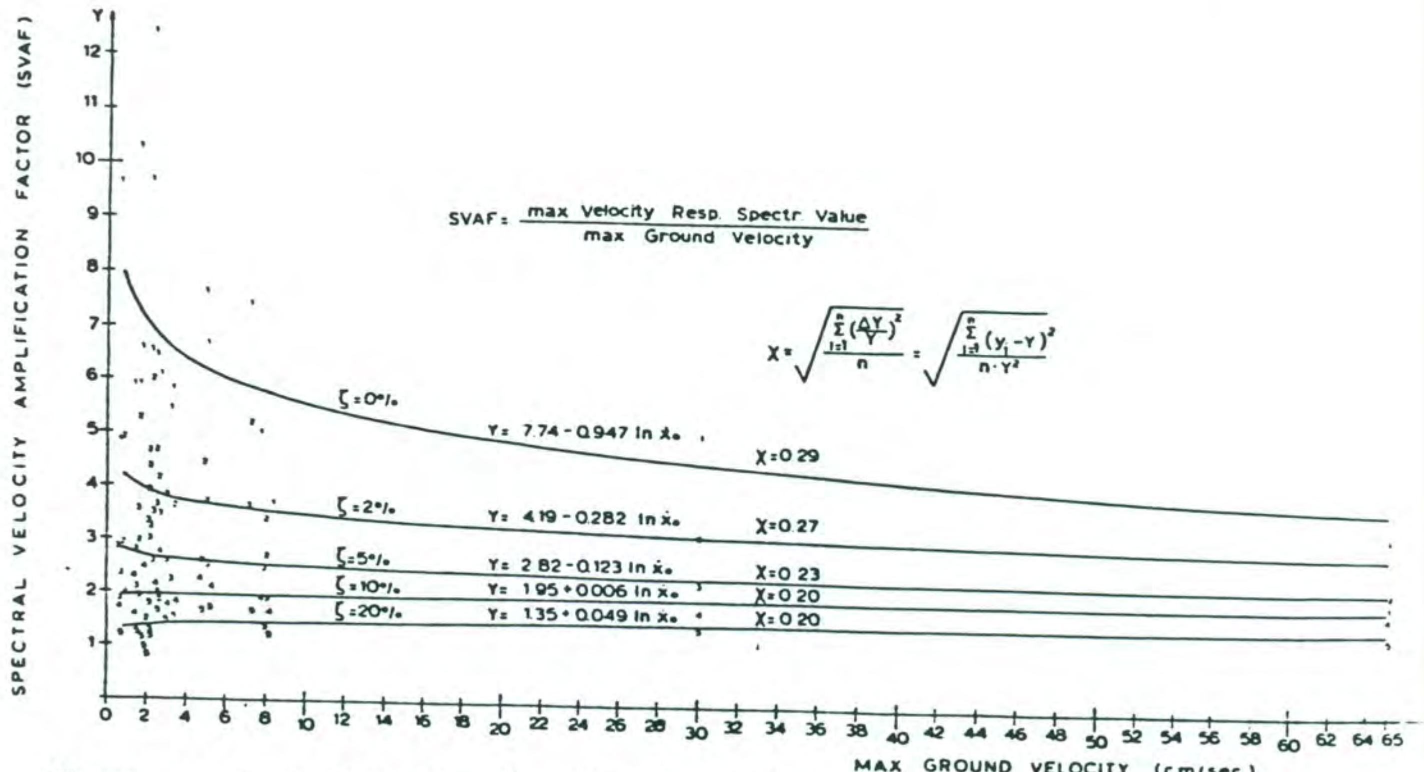


Fig. 37 Spectral Velocity Amplification Factors vs the respective maximum ground velocity, for Greek records, after Carydis (1977).

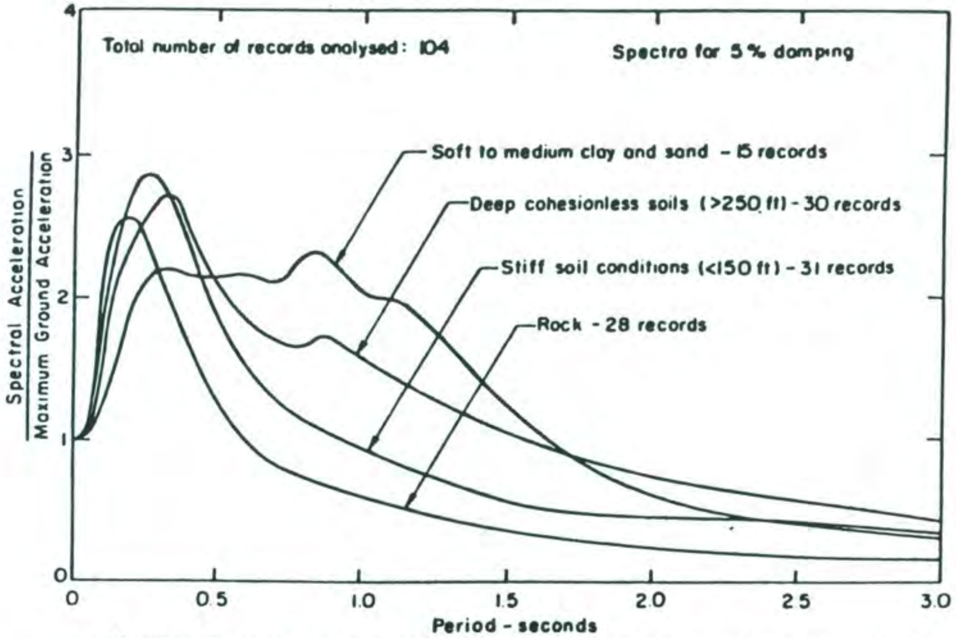


Fig. 38 AVERAGE ACCELERATION SPECTRA FOR DIFFERENT SITE CONDITIONS (after Seed, Ugas, Lysmer 1974)

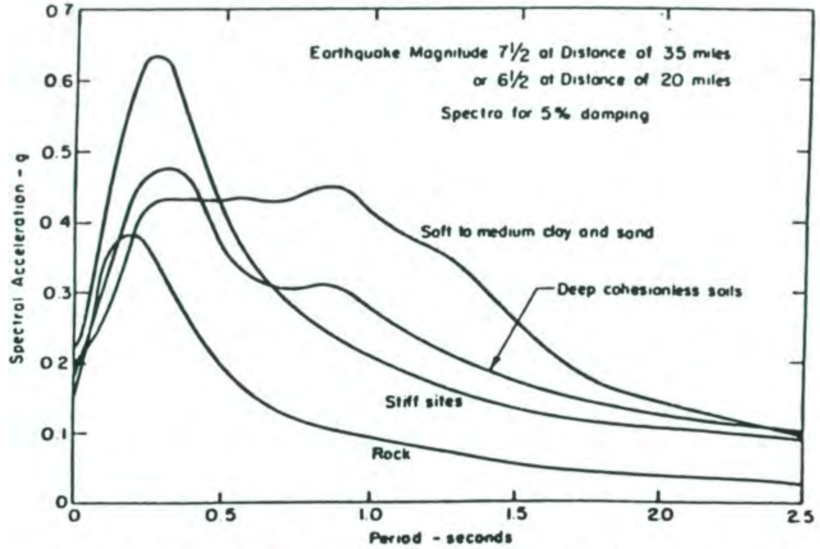


Fig. 40 ANTICIPATED MEAN SPECTRA FOR MAGNITUDE 6½ EARTHQUAKE AT DISTANCE OF 20 MILES (after Seed, Ugas, Lysmer 1974)

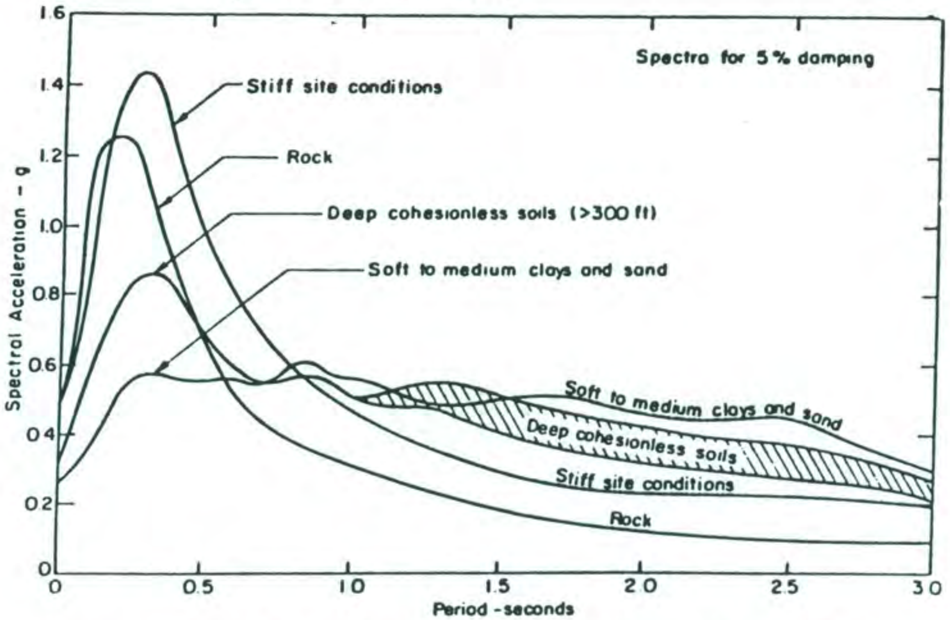


Fig. 39 ANTICIPATED MEAN SPECTRA FOR MAGNITUDE 6½ EARTHQUAKE AT DISTANCE OF 5 MILES (after Seed, Ugas, Lysmer 1974)

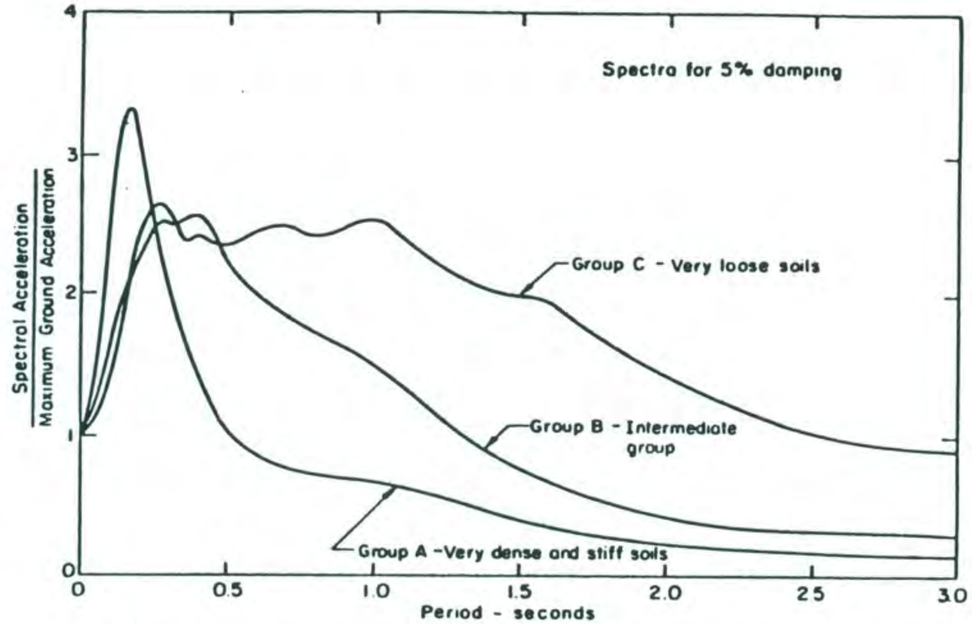


Fig. 41 AVERAGE ACCELERATION RESPONSE SPECTRA FOR EARTHQUAKE RECORDS IN JAPAN (after [illegible]

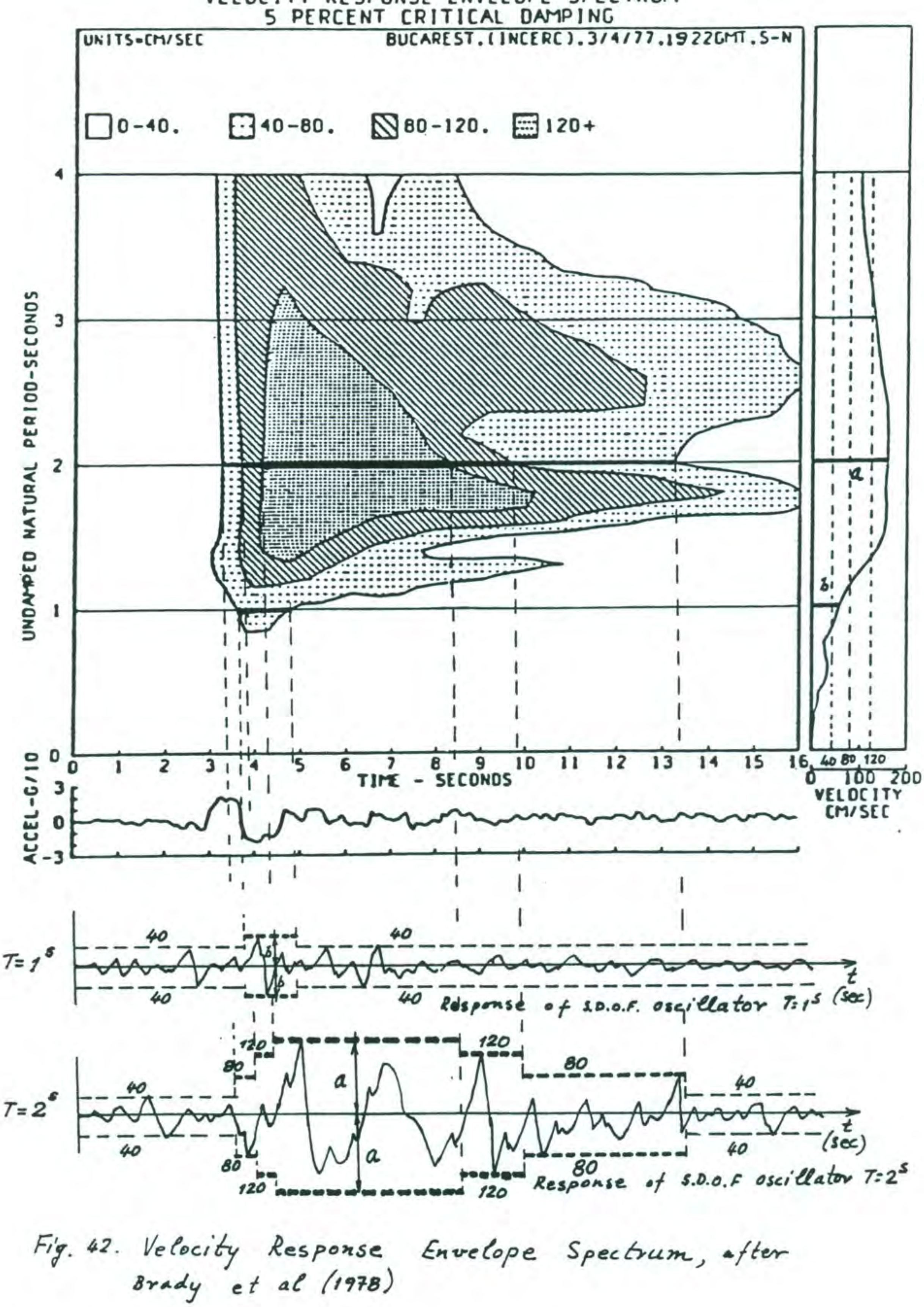


Fig. 42. Velocity Response Envelope Spectrum, after Brady et al (1978)

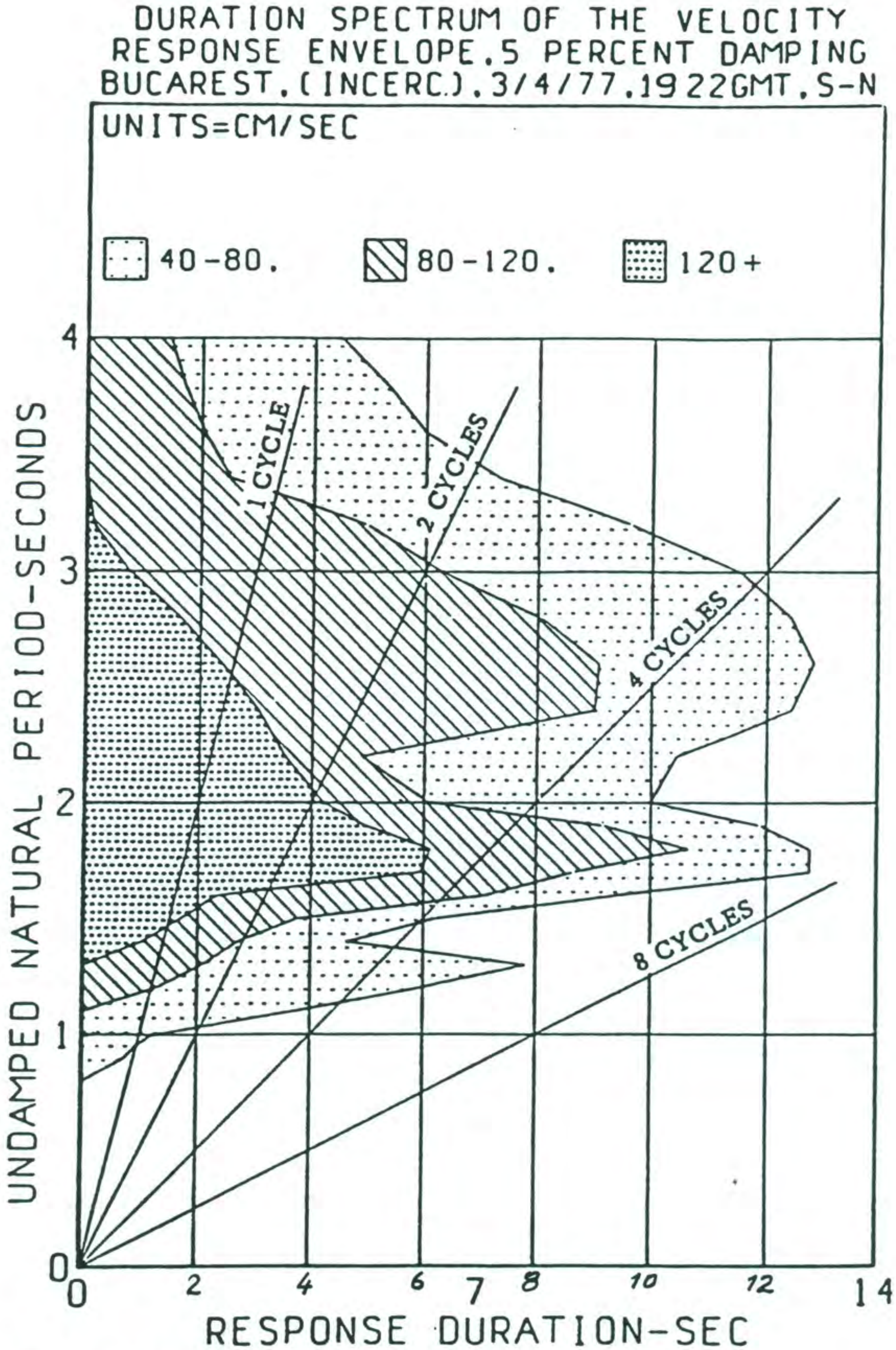


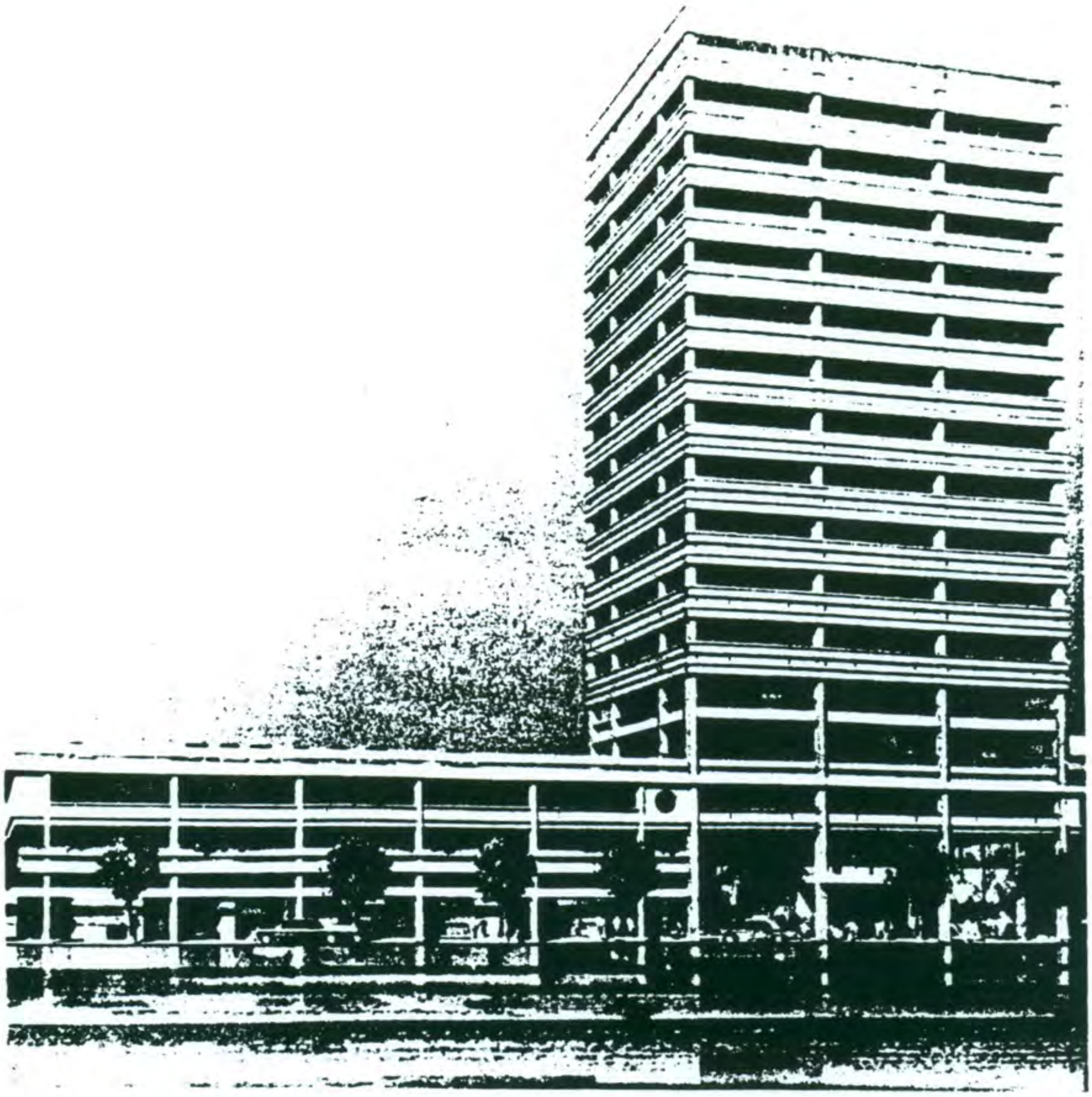
Fig. 43 Duration Spectrum of the Velocity Response Envelope, after Brady et al (1978).

The value of the recorded building vibrations

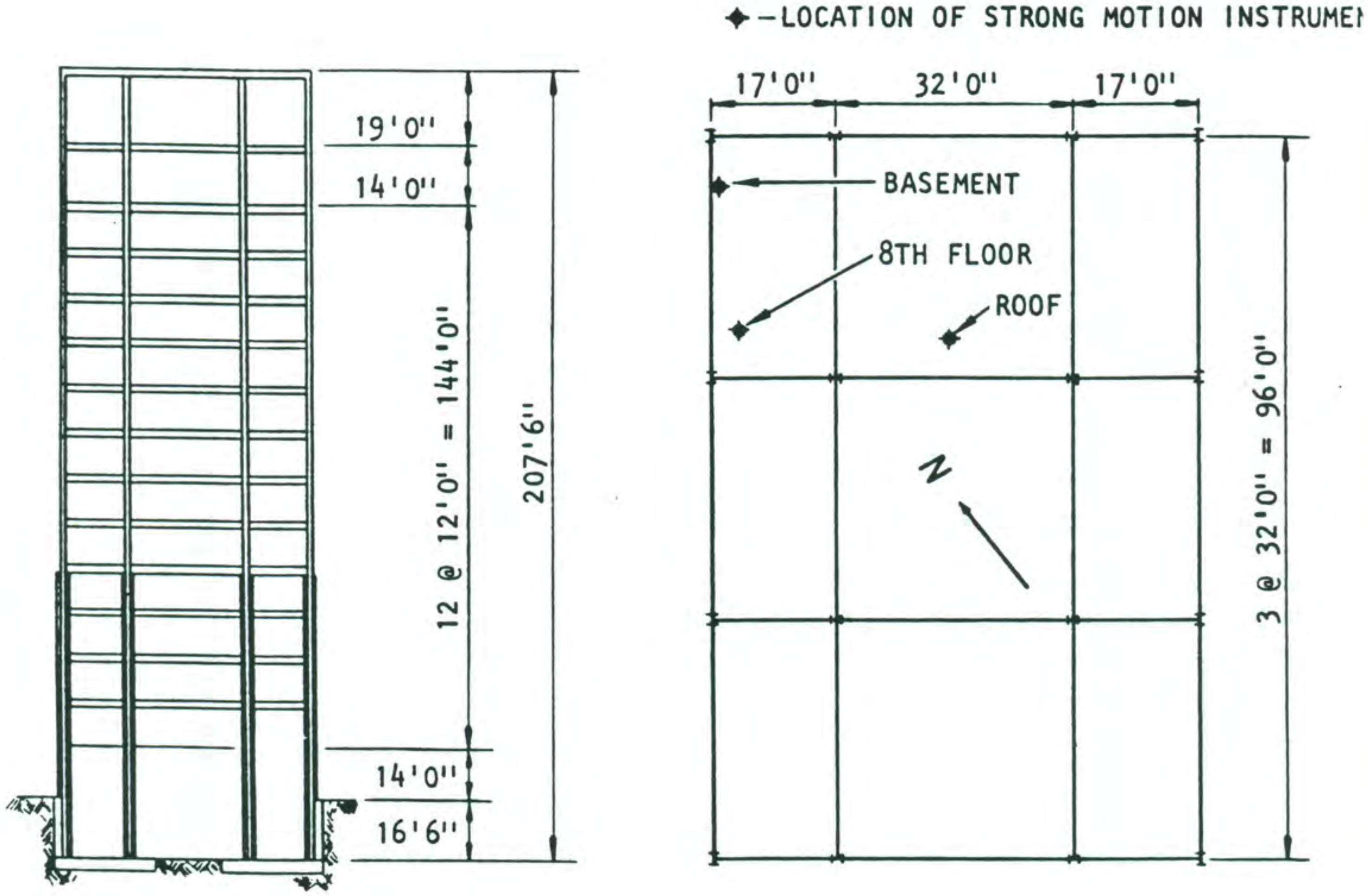
Two examples are presented from Housner (1982):

1) 15-story steel frame building, with nonstructural damage due to San Fernando Earthquake of 1971

2) Imperial Cunty Services Building a 6-story renforced concrete structure that was severely damaged after the 1979 Ken County Earthquake. Are teh first records in abuilding that suffered major structural damage.



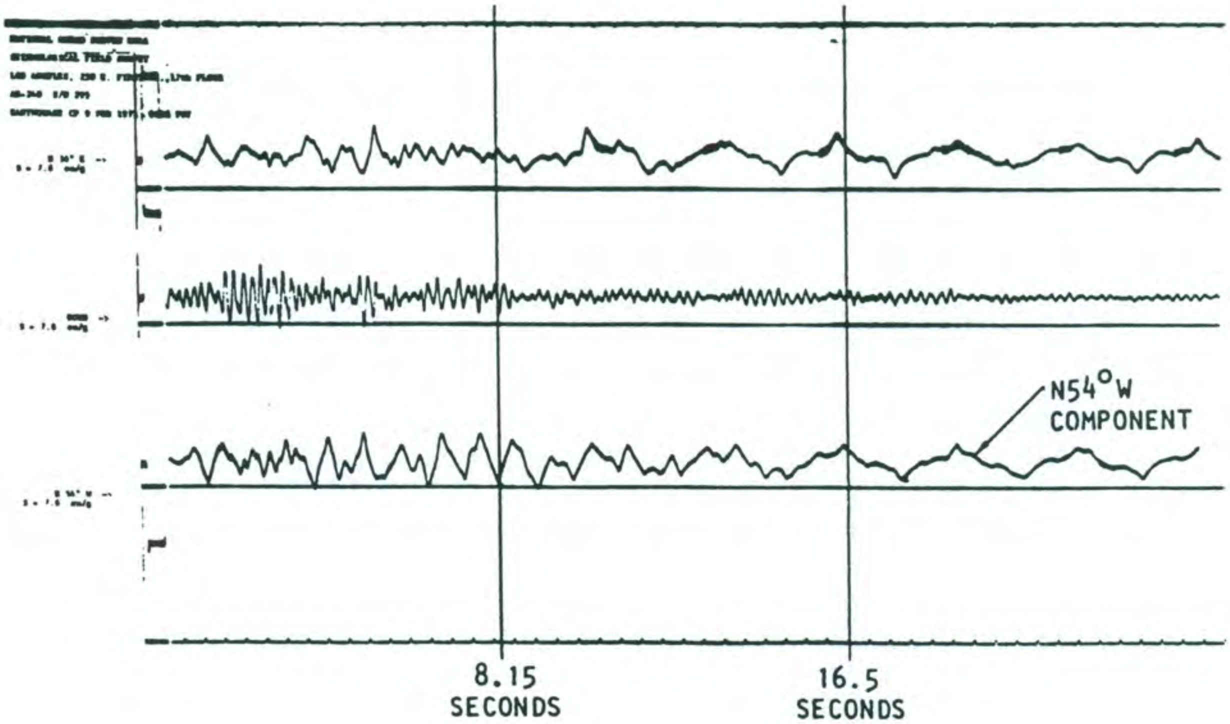
. The Kajima International Building in downtown Los Angeles. This steel-framed structure was strongly shaken during the San Fernando earthquake (Feb. 9, 1971). The basement, 8th floor and roof motions were recorded by strong-motion accelerographs.



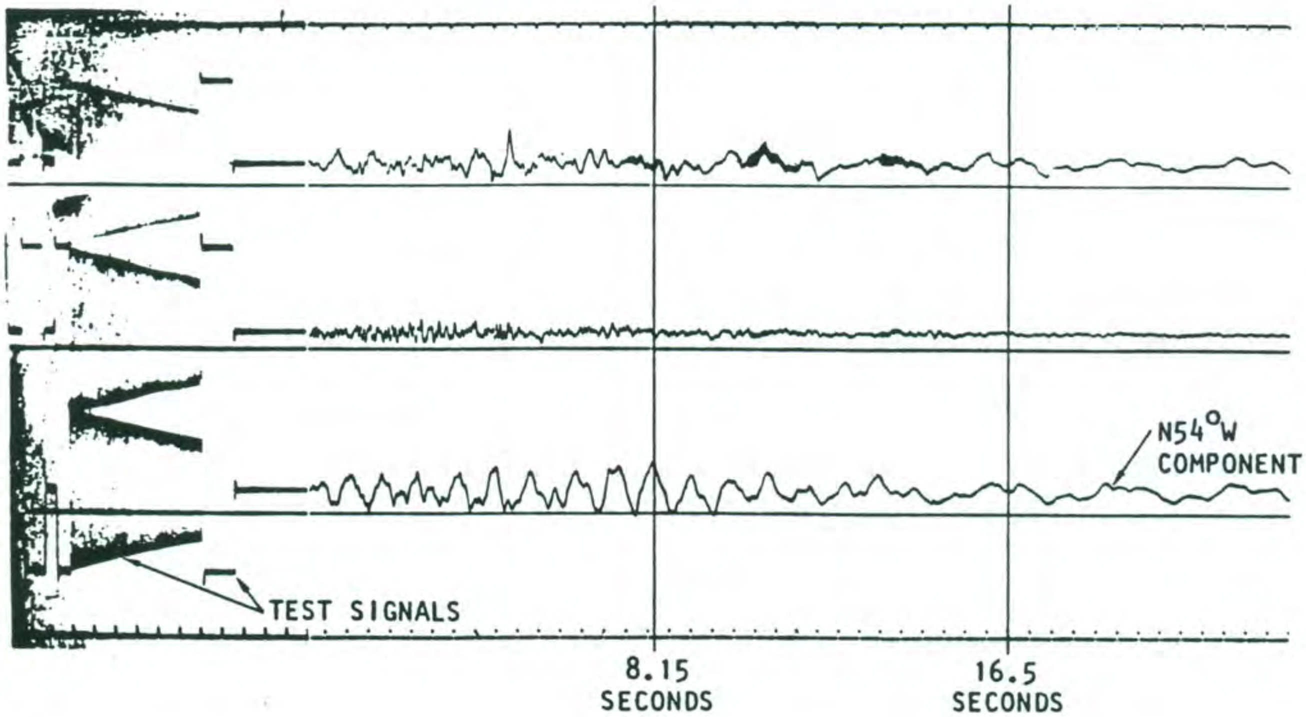
(a) *Profile*

(b) *Plan view*

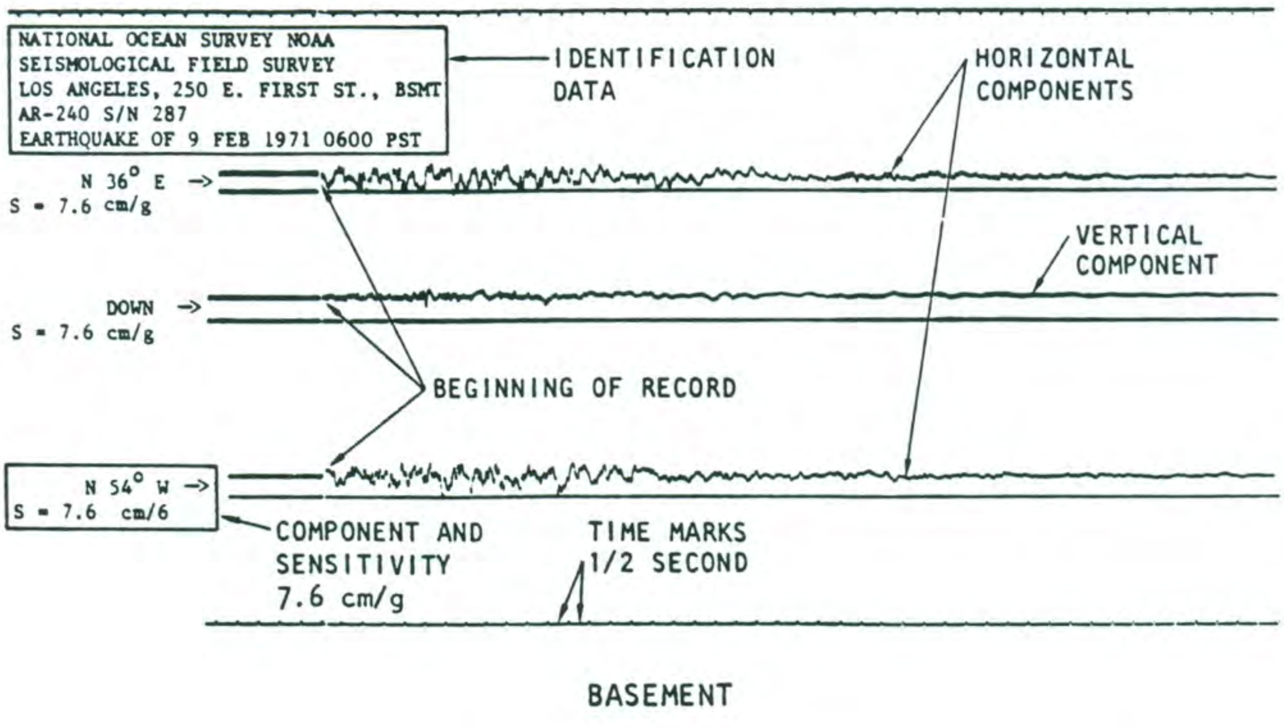
Structural configuration of the Kajima International Building. Earthquake motions are resisted by four frames in each direction. The locations of the accelerometers are indicated in the plan view.



ROOF

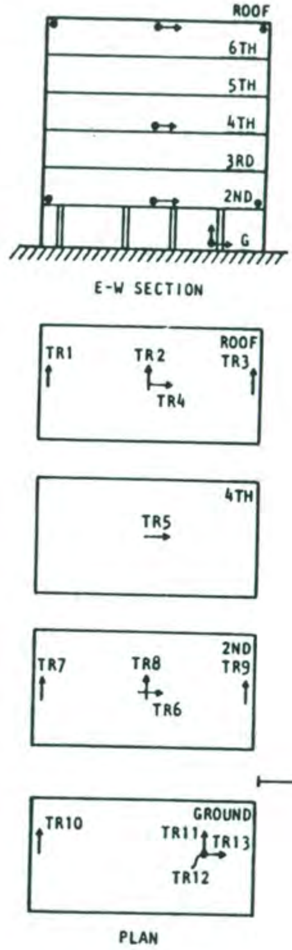


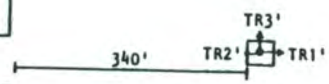
8TH FLOOR



BASEMENT

Records from the Kajima International Building during the San Fernando earthquake (Feb. 9, 1971). At time $t = 16.5$ sec, the fundamental mode is large, whereas the second mode dominates the response at $t = 8.15$ sec.

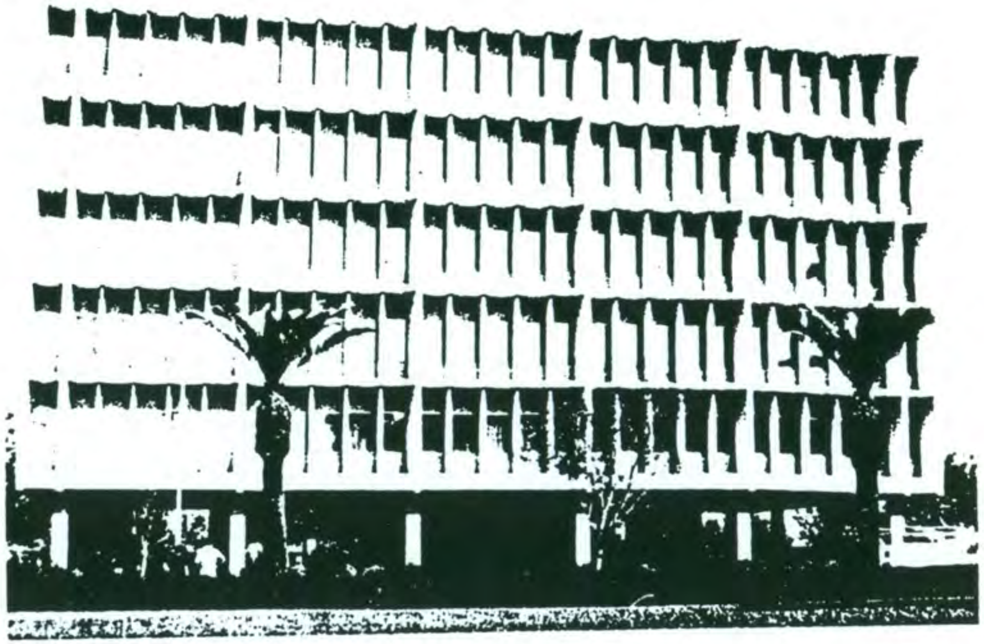




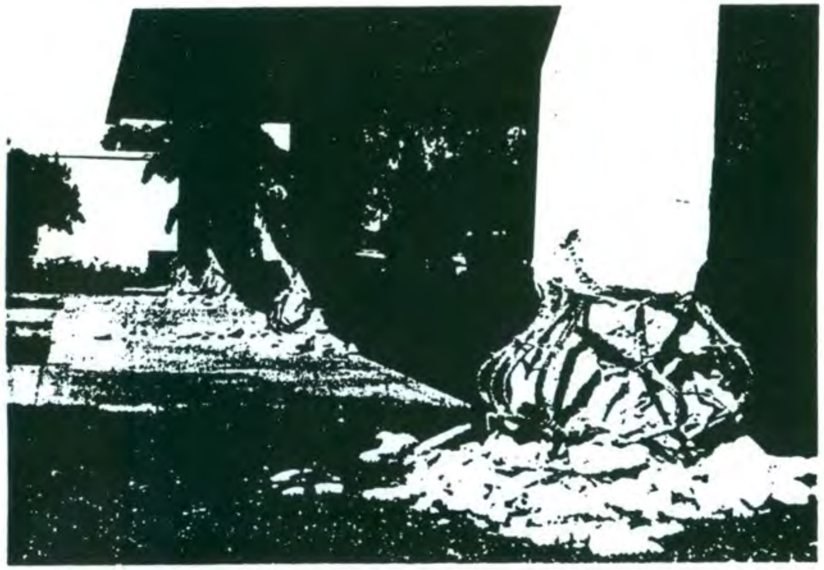
	Max. Acc cm/s^2
TR1	531.34
TR2	- 551.56
TR3	- 569.38
TR4	- 443.90
TR5	258.21
TR6	- 268.54
TR7	355.80
TR8	307.44
TR9	- 310.00
TR10	330.57
TR11	284.03
TR12	- 174.26
TR13	- 324.96

TR1'	231.44
TR2'	230.90
TR3'	209.02

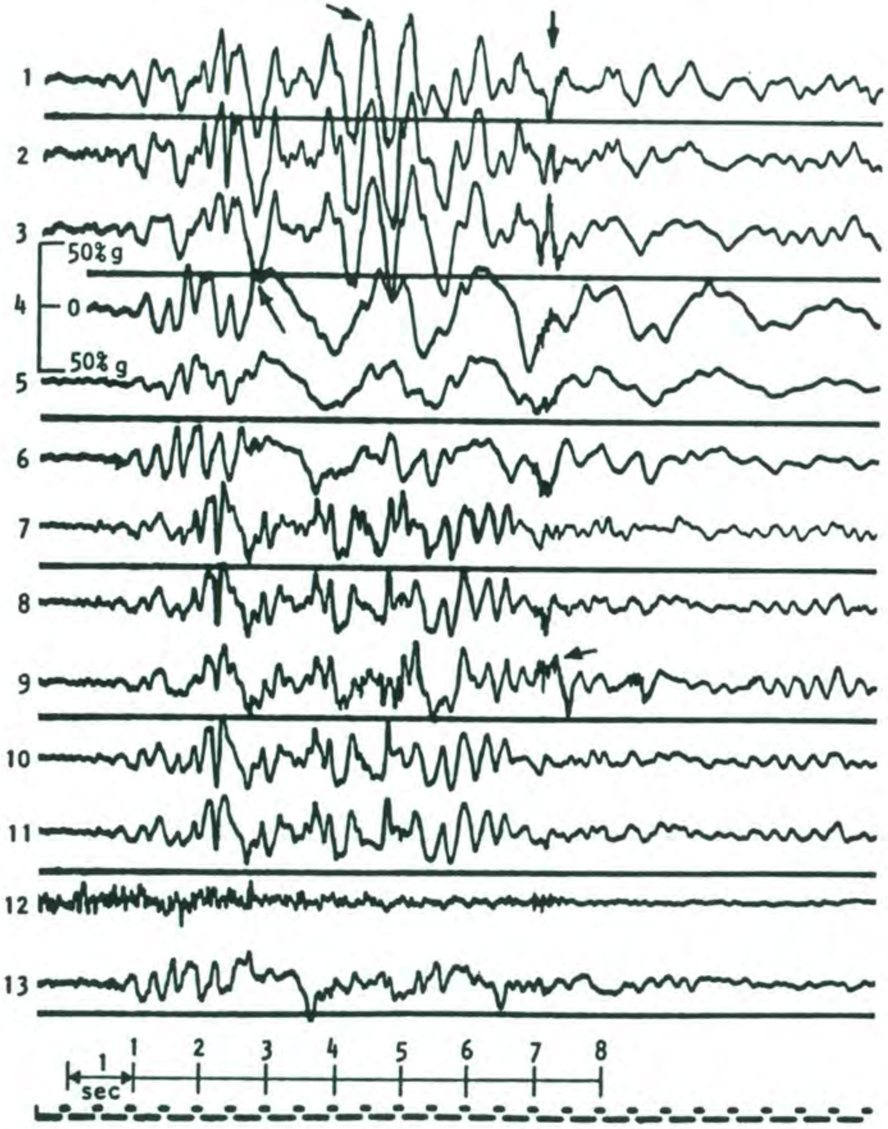
Accelerograms obtained from the Imperial County Services Building during the earthquake of October 15, 1979. The insert shows the location of the traces, which are arranged in descending numerical order. The free-field records are not shown. The insert also shows the peak accelerations from the traces. Time and amplitude scales have been added to the record, as well as four arrows indicating points discussed in the test. The records were obtained under the program operated by the California Office of Strong Motion Studies, Division of Mines and Geology.



The Imperial County Services Building, looking north, photographed the day after the October 15, 1979 earthquake. At this distance, the only visible damage was the sagging of the easternmost bay on the right side of the photograph.



Failed line of columns at the east end of the Imperial County Services Building. The upper photo shows all four columns as seen looking south. The lower photograph is of the most heavily damaged column on the southeast corner of the building. The failure of the columns occurred at the juncture between closely spaced ties below grade and the widely-spaced ties seen in the photographs. The photographs were taken the day after the earthquake.



Some Characteristics of Digital Strong-Motion Accelerographs

In the attached table some characteristics of several digital data acquisition systems for recording strong motions are presented, see Borcherdt et al (1984).

Instruments on Buildings

We may divide the instruments on buildings in three categories as exposed by Hart, Rojahn and Yao (1980):

Category A: Ground Level Instrument In or Near Building
In this category on a single triaxial strong-motion isntrument records the earthquake motion; it is located at ground level in or near the building under study.

Category B: Code-type Instrumentation
In this category there are three triaxial instruments in the building located in the basement, near mid-height, and near the top. Such instrumentation is employed bythe City of Los Angeles and other muncipalities that adopted the strong-motion instrumentation provision of the Uniform Building Code (ICBO, 1979).

Category C: Remote Accelerometer/Central Recording Instrumentation.
In this category the building is instrumented with a multi-channel accelerograph system consisting of remotely placed accelerometers connected by cable to system contains 13 accelerometers but in rare instances may contain as few as 6 or as many as 26. This type of instrumentation is currently being employed in the structural instrumentation

programs of the U.S.Geological Survey, the University of California at Los Angeles, and the California Division of Mines and Geology (Rojahn and Ragsdale, 1978). Most of these systems have been installed in accordance with the placement guidelines of Rojahn and Matthiesen (1977).

In 1959 the city of Los Angeles eased height limitations on new buildings. In response to concern over the safety of high-rise buildigns in a seismically active area, the City Council adopted a code provision in 1965 requiring the installation of three strong-motion accelerographs in new high-rise buildings.

Other jurisdictions subsequently adopted isntrumentation requirements when the 1967 edition of the Uniform Building Code included strong-motion accelerograph requirements in Article 2314 of the Appendix. This code provision, similar to that adopted by the city of Los Angeles, required not only installation but maitenance ofthe accelerographs

Earthquake Recording Instrumantations from UBC 1976 ED

Sec.2312(1). 1.General. In Seismic Zones No 3 and No 4 every building over six stories in height with an aggregate floor area of 60,000 square feet or more, and every building over 10 stories in height regardless of floor area, shall be provided with not less than three approved recording accelerographs.

2. Location. The instruments shall be located in the basement, midportion, and near the top of the building. Each instrument shall be located to that access is maintained at all times and is unobstructed by room contents. A sign stating "Maintain Clear Access to This Instrument" shall be posted in a conspicuous location.

3. **Maintenance.** Maintenance and service of the instruments shall be provided by the owner of the building subject to the approval of the Building Official. Data produced by the instruments shall be made available to the Building Official upon his request.

4. **Instrumentation of existing buildings.** All owners of existing structures selected by the jurisdiction authorities shall proviede accessible space for the installation of appropriate earthqukae recording instruments. Location of said instruments shall be determined by the jurisdiction authorities. The jurisdiction authorities shall make arrangements to provide, maintain and service the instruments. Data shall be the property of the jurisdiction, but copies of individual records shall be made available to the public upon request and the payment of an appropriate fee.

Table : Some Characteristics of Several Digital Data-Acquisition Systems Capable of Recording Strong-Motion Data

DESIGN FEATURES 1.

Company/ Model No.	Nature (hardwired logic, microprocessors, etc)	Chassis (designated slots, modular, card complement, buss concept, etc)	Display	Controls: switches	Controls: keyboard	Dialup interrogation capability, parameters: reviewed	Dialup interrogation capability, parameters: controlled	Pre-programmable start, stop, enable times
Kinemetrics PDR-1	Hardwired (CMOS 4000 series logic)	Card cage with plug-ins	LCD, event number	Selectable filters each channel, key switch w/cal, & reset, sample rate STA/LTA, ratio/difference	No	No	No	-
PDR-2	2 RCA-1802	4 large PC boards	9 digit LED status	Lock switch	Two	Yes	Yes	Yes
DSA-1/-3	Hardwired (CMOS 4000 series logic)	Designated slots	none	Key switch w/cal	No	No	No	No
Sprengnether DR100 EX	Hardwired 1 RCA-1802 μp	Designated slots, wire wrapped	LED	Power, clock, trigger test, record parameters.	No, optional on pre-programmer	No	No	Optional, 31 set points
DR200	4 RCA-1802 μp -	Modular, PC backplane	32 character, LCD alpha-numeric	Power, pre-amp gain	All others reviewed/ set	Yes	Yes	Yes
Teledyne-Geotech MCR-600	5 RCA-1802 μp	7 cards, 8 slots (opt. RS232 card)	6 digit	Power, gain, filters	Yes	Yes	Yes	Yes, 5 start-stop intervals
A-700	Intel 8031	3 modules, cabled	Sep. unit	Power, trigger, record parameters	No	Planned	Planned	-
Terra Technology DCA-300	Hardwired/μp	Modular	LED	Clock set, trigger	No	No	No	-
DCA-302	Hardwired/μp	Designated slot	LED	Gain, display controls, time, trigger & clock controls	No	No	No	-
DCA-310	Hardwired/μp	Designated slot	LED	Display control, trigger, time & clock	No	No	No	-
DCA-333	Hardwired/μp	Single board	LCD	Trigger, time sync, clock set	No	No	No	-
USGS-Developed GEOS	IM6100 μp	Modular, PC cards, 100 pin bus	32 character - alphanumeric LED	Power, time source select, monitor select	20 key, numeric & function	Planned	Planned	Yes
Woods Hole Geophysical Inst. DASY-1	NSC 800	5100 bus, 8 slots	LED event no. ext. terminal	Power terminate	Ext. terminal	Planned	Planned	256 setups

(continued)

Table , (continued)

2.

SIGNAL CONDITIONING

Company/ Model No.	Amplification (gains, steps)	Noise level referred to input	Anti-alias filter (types, corners)	Sensor types	Number of inputs
Kinemetrics					
PDR-1	Pre-amp gain of 1 (50 optional), gain-range of 1, 4, 16, 64	40 µV pk-pk	2 pole standard (option of additional 3 pole) selectable 2.5, 12.5, 25, 50 Hz	Seismometers, FBA, others	3
PDR-2	Pre-amp gain of 1, gain range of 1, 2, 4, 8, 16, 32, 64, 128	<50µV pk-pk	2-pole, 7 freqs.	Seismometers, FBA	1-3 (6 optional)
DSA-1/-3	None	1.2 mV pk-pk	2-pole, 50 Hz	FBA included, internal to DSA-1 external to DSA-3	3 (DSA-1) 12 (DSA-3)
Sprengnether					
DR100 EX	0-120 dB 6 dB steps	<0.1 µV rms	5-pole, 50 or 25 Hz std (others optional)	Seismometers, FBA	1-3
DR-200	Pre-amp 0-60 dB, 20 dB steps, gain-range of 1, 4, 16, 64	<0.03 µV rms	7-pole, plug-in, 0.25-200 Hz, (10 freqs.) any 4 provided	Seismometers, FBA, others	1-4
Teledyne-Geotech					
MCR-600	60-120 dB, 6 dB steps	0.2 µV rms, 0.2-13Hz	4-pole, 8 freqs.	Seismometers FBA, other	1-3
A-700	0.5-5g full scale	~1 LSB	2-pole, 68 Hz (200 sps); 2 sample ave. for 100 sps.	FBA internal	3
Terra Technology					
DCA-300	Pre-amp gain of 1 (others optional)	-	1-pole standard, 30, 45, 70 Hz (5 pole optional)	Seismometers, FBA	12
DCS-302	1, 5, 25, 100 with AGC; also fixed gain of 1, 10, 100	-	5-pole, 30, 50, 70, Hz	Seismometers, FBA	1-3
DCS-310	1, 5, 25, 100 fixed	-	None	Seismometers, FBA	1-3
DCA-333	-	-	5-pole, 30 Hz	FBA (included)	3
USGS-Developed					
GEOS	0-60 dB, 6 dB steps	<0.1 µV rms	7-pole, Corner freqs. CPU selectable	Seismometers, FBA, others	1-6
Woods Hole Geophysical Inst.					
DASY-1	Pre-amp 0-42 dB, 6 dB steps, gain-range 6-60 dB, 6 dB steps	~1µV	8-pole, 1/4 sample rate	Seismometers, FBA others	4 (1-12 optional)

(continued)

Table , (continued)

3.

		ADC						
Company/ Model No.	Dynamic range (including gain-ranging)	Resolution (number of bits	LSB at ADC input (full scale)	Sample rates (sps) Internal Control maximum	minimum	External input	Pre-event Memory (total samples) Standard	Optional
Kinemetrics								
PDR-1	108 dB gain-ranged	72 dB (12 bit)	19.8 μv	200	100	no	512	1024
PDR-2	114 dB gain-ranged	72 dB (12 bit)	1.2 mv (2.5 V) (9.53 μV ref to input)	500	1.01×10^{-3}	yes	3K	6K
DSA-1/-3	72 dB	72 dB (12 bit)	1.2 mV	200	200	no	0	512 or 1024
Sprengnether								
DR100EX	72 dB	72 dB (12 bit)	4.8 mV (10 V)	600	25	no	551-1675 (dep. on smp. rate)	3350
DR-200	108 dB, instantaneous floating point	72 dB (12 bit)	38 μV (5 V)	800	1	yes	200 to 4K selectable	-
Teledyne-Geotech								
MCR-600	72 dB	72 dB (12 bit)	2.4 mV (10V)	600	1	yes	864	-
A-700	72 dB	72 dB (12 bit)	1.25 mV (2.50)	200	100	no	200-2000	-
Terra Technology								
DCS-300	72 dB	72 dB (12 bit)	2.4 mV (5 V)	600	50	no	192	15,360
DCA-302	112 dB gain-ranged	72 dB (12 bit)	2.4 mV (5 V)	600	50	no	192	15,360
DCA-310	72 dB	72 dB (12 bit)	2.4 mV (5 V)	600	50	no	192	15,360
DCA-333	72 dB	72 dB (12 bit)	1.2 mV (2.5 V)	600	50	no	300	1200
USGS-Developed								
GEOS	96 dB	96 dB (16 bit)	305 μV (10 V)	1200	0.293	yes	4096	8192
Woods Hole Geophysical Inst.								
DASY-1	126 dB instantaneous floating point	72 dB (12 bit)	2.5 mV (5 V)	2048 (4 chan)	64	yes	4096	32K

(continued)

Table , (continued)

4.

Company/ Model No.	TCXO specifications: temperature stability	TCXO specifications: for temperature range	short term stability (constant temp)	aging rate	TIMING SYSTEM: Synchronizing slew rate	Time record	Clock synchronization methods	Automatic clock correction
Kinemetrics								
PDR-1	$\pm 3x10^{-7}$	0-50°C	$\pm 1x10^{-8}$ (24 hrs)	$5x10^{-7}$/yr	-	Code on tape-with data	External using TDC-1,2 and WWV receiver	Optional auto radio reception
PDR-2	$3x10^{-7}$	0-50°C	$\pm 1x10^{-8}$ (24 hrs)	$4x10^{-8}$/mo	None	Time recorded to 1 msec resol. in each record header	Manual from keyboard semi-auto to WWV etc. (opt. GOES auto satellite RCVR)	Yes
DSA-1/-3	0.1001% @ 25°C (sample clk)	-	-	-		-	-	Optional auto radio reception
	(optional TC Gen.) $\pm 1x10^{-5}$	0-50°C	-	$3x10^{-6}$/yr	None	Multiplexed w/ data	To ext time tick e.g. WWV	None
	$\pm 3x10^{-7}$	"	$\pm 1x10^{-8}$(24 hrs)	$5x10^{-7}$/yr	"	" "	" "	"
Sprengnether								
DR100EX	$\pm 1x10^{-6}$	0-50°C	$\pm 1x10^{-9}$(sec)	$5x10^{-7}$/yr	±20 msec/ sec	BCD in header/ tailer	Sync. or slew	Optional auto radio reception
DR-200	STD $\pm 1x10^{-7}$ optional $\pm 5x10^{-7}$)	0-50°C optional -20°C to 70°C	$\pm 1x10^{-9}$(sec)	$5x10^{-7}$/yr	±10 msec/ sec	Coded in header each block	Sync. or slew	Yes
Teledyne-Geotech								
MCR-600	$\pm 1x10^{-6}$	0-55°C	$\pm 3x10^{-9}$(sec)	$1x10^{-6}$/yr	5 msec/ sec	BCD in header	Slew & auto synch, manual slew and synch	Operator initiated auto synch
A-700	$\pm 1x10^{-6}$	0-55°C	$\pm 3x10^{-9}$(sec)	$1x10^{-6}$/yr	none	In header	Ext start	None
Terra Technology								
DCA-300	$\pm 5x10^{-6}$	0-50°C	$\pm 1x10^{-7}$(sec)	$5x10^{-6}$/yr	3.3 ms/sec	BCD each sample	-	-
DCS-302	$\pm 5x10^{-7}$	-25-50°C	$\pm 1x10^{-9}$(sec)	$5x10^{-7}$/yr	3.3 ms/sec	BCD each sample	WWVB/WWV	-
DCA-310	$\pm 5x10^{-6}$	0-50°C	$\pm 1x10^{-7}$(sec)	$5x10^{-6}$/yr	3.3 ms/sec	BCD each sample	WWV/WWVB	-
DCA-333	$\pm 5x10^{-6}$	0-50°C	$\pm 1x10^{-6}$(sec)	$5x10^{-6}$/yr	3.3 ms/sec	BCD each sample	-	-
USGS-Developed								
GEOS	$\pm 1x10^{-6}$	-20-70°C	$\pm 1x10^{-9}$(sec)	$5x10^{-7}$/yr	None	In data header	Internal WWVB, external to any standard, manual via keyboard	Yes, correction in data header & in program clock record
Woods Hole Geophysical Inst.								
DASY-1	$\pm 1x10^{-7}$	0-50°C	$\pm 1x10^{-9}$(sec)	$5x10^{-7}$/yr	None	In header and tape directory	Ext start	none

(continued)

Table, (continued)

5.

RECORDER

Company/ Model No.	Tape form/ length	Write mode (continuous, blocked, etc.)	Density/coding	Tracks	Transport	Data samples per tape	Recording time @ 200 sps x 3 ch (600 sps total)
Kinemetrics PDR-1	Cassette/282'	Continuous, frame sync every 64 samples	1280 bpi, phase encoded	4	Kinemetrics	790 K	22.5 min
PDR-2	Cassette/282'	Blocked - 3072 samples & parity	1667 bpi, phase-encoded	4	Kinemetrics	922 K	25.6 min
DSA-1/-3	Cassette/282'	Continuous , frame sync every 64 samples	1280 bpi, phase-encoded	4	Kinemetrics	790 K	20 min
Sprengnether DR100EX	Cassette/300'/450'	Continuous	800 bpi, NRZ	4	Phi-Deck	440 K (300') 660 K (450')	12 min (300') 18 min (450')
DR-200	Cassette/300'/450'	Blocked, 2000 samples	1600 bpi, phase-encoded	4	Phi-Deck	1.2×10^6(300') 1.8×10^6(450')	35 min (300') 53 min (450')
Teledyne-Geotech MCR-600	Cassette	Blocked, 1296 samples	800 bpi ANSI-ECMA	2	MFE	234 K	6.5 min (300')
A-700	Cmos RAM	-	-	-	-	648 K	18 min
Terra Technology DCA-300	Cassette	Continuous	1200 bpi, NRZI	2	VM	252 K	7 min
DCS-302	Cassette	Continuous	1200 bpi, NRZI	2	VM	252 K	7 min
DCS-310	Cassette	Continuous	1200 bpi, NRZI	2	VM	252 K	7 min
DCA-333	Cassette	Continuous	1200 bpi, NRZI	2	VM	252 K	7 min
USGS-Developed GEOS	Cartridge/300'/450'/600'	ANSI standard blocked, 1024 bytes (512 samples)	1600 bpi, phase encoded (6400 bpi planned)	4 (1 track, serpentined)	Kennedy 631	1.25×10^6(300') 1.9×10^6(450') ($23\text{-}67 \times 10^6$ planned)	35 min (300') 52 min (450')
Woods-Hole Geophysical Inst DASY-1	Cartridge	Blocked, 8K bytes (4K samples)	1600 bpi, phase encoded (6400 bpi possible)	4 (1 track serpentined)	Digidata	$\sim 10^6$ ($\sim 10^7$ at 6400 bpi planned)	~1 hr (450') (4 hrs at 6400 bpi planned)

(continued)

Table 7 (continued)

6\. DETECTION ALGORITHM

Company/ Model No.	Type	Number of Channels
Kinemetrics		
PDR-1	Analog STA/LTA ratio or difference	1
PDR-2	Digital STA/LTA or difference	all (1-6)
DSA-1/-3	Analog, threshold	1
Sprengnether		
DR100EX	Analog STA/LTA, optional digital threshold	1 STA/LTA 3 threshold
DR-200	Digital STA/LTA or threshold	1 to 4
Teledyne-Geotech		
MCR-600	Selectable, STA/LTA or SSCR (4 stage freq-power detector)	1,2 or 3
A-700	Threshold	3
Terra Technology		
DCA-300	Energy, level or peak	3
DCS-302	Digital STA/LTA, energy	3
DCA-310	Energy , level or peak	3
DCA-333	Digital level	3
USGS-Developed		
GEOS	General: STA/LTA ratio; teleseismic: comparative ratios for 2 freq. bands	1 (1-6 possible)
Woods Hole Geophysical Inst.		
DASY-1	Digital STA/LTA	4 (<500 sps) 1 (>500 sps)

(continued)

Table, (continued)

7.

POWER PHYSICAL

Company/ Model No.	Voltage	Current (600 sps, quiescent)	Operating temperature	Weight (lbs) incl. internal batteries	Dimensions (inches)
Kinemetrics					
PDR-1	± 12 VDC	~ 35 ma	0°-70°C std. -20°C-70°C optional	30	14x18x9 approx
PDR-2	± 12 VDC	100 ma	0-50°C	54	26x14.25x8.75
DSA-1/-3	± 12 VDC	~ 30 ma (with PEM) ~ 200 μa (no PEM)	0-70°C	43	10x17x8.5 (DSA-3 rackmounted, depends on no. chan)
Sprengnether					
DR100EX	+ 12 VDC	36 ma	0-70°C	28	15.5x9.5x10.5
DR-200	+ 12 VDC	60 ma	-20-65°C	30	optional cases
Teledyne-Geotech					
MCR-600	± 12 VDC	100 ma	0-60°C	36	8.5x12x19.6
A-700	± 12 VDC	60 ma, 120 ma, ext batt	-20-60°C	44	9x11x13
Terra Technology					
DCA-300	± 12 VDC	100 ma	32-120°F	25	19x14x16
DCS-302	± 12 VDC	50 ma	-20-55°C	12	14x8x10
DCA-310	± 12 VDC	50 ma	-20-55°C	12	14x8x10
DCA-333	+ 12-15 VDC	60 ma	-23-60°C	22	12x12x6
USGS-Developed					
GEOS	24 VDC	40 ma	-20-60°C	47	9x13.75x20.5
Woods Hole Geophysical Inst.					
DASY-1	+ 12 VDC	40 ma	0-50°C	30	10x13x19

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