REVIEW OF SEISMIC ATTENUATION DATA*

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SYNOPSIS

Instrumentally determined measures of anelastic attenuation, which generally lie within a 100 km of the epicenter and which are based primarily upon California data, indicate that (i) peak values of ground acceleration, which predominate at high frequencies, attenuate at approximately the same rate as do peak values of ground velocity, which predominate at intermediate (near 1 Hz) frequencies (ii) the Fourier amplitude spectrum of ground acceleration attenuates approximately linearly with frequency, decreasing with decreasing frequency and (iii) the pseudo-velocity response shows a pronounced minimum at intermediate frequencies. At epicentral distances greater than about 100 km attenuation measures are, for the most part, based upon intensity data and higher-mode surface waves such as the Lg phase.

In a Canadian context both intensity data and higher-mode surface waves attenuate at a much slower rate in the east than in the west. Since the tectonic environment of western Canada is rather similar to that of California, instrumental measures of attenuation in California are applicable to western Canada. The lack of instrumental measures of attenuation in a shield environment, which constitutes much of eastern Canada, requires that the same instrumental data be arbitrarily adopted at present for the east.

RESUME

Les valeurs de l'atténuation anélastique des secousses fortes du sol ont été calculées à partir des enregistrements des instruments situés généralement à moins de 100 km d'un épicentre et principalement à partir des tremblements de terre en Californie. L'accélération au sol atteint son maximum aux hautes fréquences et la vitesse au sol aux fréquences intermédiaires (environ 1 hz). De telles données sur l'atténuation indiquent que i) les valeurs maximales de l'accélération au sol décroissent avec l'augmentation de la distance approximativement au même taux que celles de la vitesse au sol ii) l'amplitude du spectre de Fourier de l'accélération au sol atténue a peu près linéairement avec la réduction de la fréquence et iii) la réponse de la pseudo-vitesse montre un minimum prononcé aux fréquences intermédiaires.

Les valeurs de l'atténuation aux distances supérieures à environ 100 km ont été fondées pour la plupart sur les intensités et sur les ondes superficielles aux modes supérieurs, telles la phase L_g. Dans un contexte canadien, les intensités et les ondes superficielles aux modes supérieurs décroissent avec l'augmentation de la distance à un taux qui est beaucoup plus petit dans l'Est que dans l'Ouest.

Parce que les environnements tectoniques de l'ouest du Canada et de la Californie sont assez semblables, les valeurs de l'atténuation basées sur les données instrumentales de la Californie ont été utilisées pour l'ouest du Canada. Le manque de données instrumentales sur l'atténuation à travers un bouclier, ce que comprend la plupart de l'est du Canada, mène, jusqu'à présent, à l'adoption arbitraire des mêmes données instrumentales pour l'Est.

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INTRODUCTION

Measurements of the attenuation of seismic ground motion with increasing source-to-station (hypocentral) distance depend upon the types and configurations of the seismic instruments and upon the population distribution in the source (epicentral) region. Figure 1 shows the (1977) configuration of the Canadian standard and regional seismograph stations, in conjunction with the year of commencement of operation. One of the primary functions of this network is to detect local earthquakes so that the epicenter and magnitude of these earthquakes can be determined above a threshold level, which generally lies between M3 and M4. This configuration is also suited for the measurement of the attenuation of the fundamental mode surface waves (period range 10-50 s) from intermediate-magnitude ($M \simeq 5$) Canadian earthquakes (e.g. 1, 2) and teleseismic body phases (3, 4, 5). Where the configuration is more closely spaced, such as in the St. Lawrence Valley region the attenuation of higher mode (Lg) surface waves (dominant period close to 1 s) from M4-5 earthquakes can also be measured (e.g. 6).

With respect to the measurement of the attenuation of strong ground vibrations of the types that earthquake engineers are interested in, there are several drawbacks to the configuration shown in Figure 1. The high-gain instruments of the Canadian standard and regional seismograph network tend to saturate in the epicentral region of small to moderate sized earthquakes. In addition the spacing of instruments should be of the order of a few tens of kilometers and not several hundreds of kilometers. In order to ensure that appropriate records of the strong ground vibrations from any earthquake that might occur in heavily populated, seismically active areas of Canada are obtained, appropriate strong motion seismograph networks have been deployed. Figure 2 shows the distribution and number of instruments at each site, of accelerographs in Canada (see 7 for further details). In western Canada the first strong motion instrument was deployed in 1963 and in eastern Canada in 1966. Up to the present time a few strong motion records of local earthquakes have been obtained in western Canada but none in eastern Canada. The larger magnitude earthquakes in these regions have all occurred prior to the deployment of these instruments (e.g. see 8). This necessitates an indirect method of determining attenuation measurements in the near-field of moderate to large earthquakes in both the western and eastern parts of the country. However, any description or measure of seismic attenuation must take into account the fact that, for earthquakes of comparable magnitude in eastern and in western Canada, earthquakes in the east are felt to a much greater epicentral distance than those in the west.

ATTENUATION COEFFICIENTS

Seismologists usually define the amplitude decay of seismic body waves from a causative fault as the product of two factors, an anelastic attenuation term and a geometric spreading factor. In the epicentral region the amplitude of ground motion (AGM) can be written in the following convenient form -

$$AGM = be^{-\alpha R} R^{-B} \qquad \ldots (1)$$

$$= be^{-\frac{\pi f}{QC} R} R^{-B}$$

where b incorporates other parameters such as earthquake magnitude, α is the anelastic attenuation coefficient, R is the hypocentral distance and B is related to the geometric spreading factor. The attenuation coefficient α is dependent upon frequency f, a dimensionless measure of attenuation 1/Q and velocity of energy propagation C. Since 1/Q is essentially independent of frequency over the frequency range of interest (9), α is frequency dependent. This implies that higher frequency waves attenuate more rapidly than do lower frequencies. However the attenuation of strong ground motion is not generally expressed in the form of Eq.1 but in an abridged form, $R^{-\delta}$, where R is hypocentral distance and δ now incorporates geometric spreading and the frequency dependent term. An expression that is being used more often than any other is of the form (10)

$$AGM = b_1 e^{b_2 M} R^{-b_3} \qquad \ldots (2)$$

where the acronym AGM represent amplitude of ground motion, either peak or response spectral values, M is earthquake magnitude, R is hypocentral distance and b_1, b_2 and b_3 are constants that are generally evaluated using regression analysis. The coefficient b_3 is generally referred to as the attenuation coefficient and is frequency dependent because b_3 incorporates implicitly the anelastic attenuation coefficient α in Eq.1 that is frequency dependent. The exponential dependence on M reflects the basic definition of magnitude.

A number of different measures have been used as a means of parameterizing strong vibratory ground motion. They are as follows:

(i) intensity data

(ii) peak values of strong ground motion (acceleration, velocity and displacement)
(iii) Fourier amplitude spectra (FS) of ground acceleration
(iv) Response spectra (either velocity response, SV, or pseudo-velocity response, PSV) at low damping (few % of critical)
(v) Surface waves, both long-period fundamental mode and short-period higher modes.

In general the earthquake engineer or geophysicist requiring attenuation data for a specific project will not have a sufficient number of local measurements of the appropriate parameters listed above. The usual procedure is to select available data from other similar or appropriate tectonic environments, (11).

INTENSITY DATA

Intensity can be regarded as the convolution of the time history of strong ground motion with the delta function time response of the whole range of ground and structures affected (12). Thus intensity depends upon the duration and dominant frequency content of the ground motion, the resonant period of the structure and how close these frequencies are to each other. Intensity is a measure of the combination of human reaction, residual ground deformations and observed property damage caused by strong seismic ground vibrations.

A summary (see 13) of the seismic vibrations that humans respond to with discomfort and pain ranges from several to several hundred Hz. However the fundamental frequency or sensitive range of frequencies of the whole body ranges from 4-12 Hz. In Canada much of the reported damage to structures from seismic ground vibrations has been generally to one-and two-storey frame or brick buildings, for which the fundamental resonant frequencies are of the order of 10 Hz or more. An empirical measure of the natural period, T (sec) of a structure with N storeys is T=0.1N. Thus most of the reported intensities for Canadian earthquakes can be attributed to felt reports for which the resonant frequencies of the persons or disturbed objects is what we will classify as belonging to the high-frequency range, with a central frequency of, say, 5 Hz.

The dominant frequencies in the seismic waves depend upon the magnitude of the earthquake and the source-to-site distance (14, 15). Smaller earthquakes tend to radiate proportionately more high frequencies. Near the source (within a fault length) high-frequency body waves predominate but with increasing epicentral distance the longer period waves tend to predominate because of anelastic absorption and the geometric spreading factor. At still greater distances surface waves predominate. The higher mode surface waves have frequencies ranging from about 1 Hz to a little over 10 Hz. Fundamental mode surface waves, which have still longer periods (shorter frequencies) are not of interest to most earthquake engineering problems; the exception is for high rises greater than 10 storeys or for other elongated structures for which the natural resonant period is greater than 1s. Although there can be a wide range of frequencies in the seismic signal, in certain regions such as in eastern Canda, the most frequently reported felt sensation (and observed damage) is likely due to a higher mode surface wave (Lg) with a dominant period near 1 Hz, but with an appreciable amount of higher frequencies.

Intensity has been found empirically to be related to the logarithm of ground motion. Some common examples are:

$$\log a = I/3 - 0.5 \qquad (16)$$
$$\log v = -1.14 + 0.30I \qquad (17) \qquad \ldots (3)$$

where ground acceleration a is in units of gals (cm/sec^2), ground velocity v in cm/sec and intensity I in the Modified Mercalli (MM) scale. Suggested revisions to Eq. 3 have been proposed by Davenport (18) and Trifunac and Brady (13). The attenuation coefficient of intensity data can be calculated by using Eq. 3 in conjunction with Eq. 2. For example, from Eq. 2.

$$\log a = \log b_1 + b_2 M \log e - b_3 \log R$$

A substitution of this expression into Eq. 3 yields

$$I/3 - 0.5 = \log b_1 + b_2 M \log e - b_3 \log R$$

or

$$I = 1.5 + 3 \log b_1 + 3b_2 M \log e - 3b_3 \log R \qquad \ldots (4)$$

An equivalent expression can be derived using v in place of a.

An expression similar to Eq. 4 has been used by Evernden et al. (19) and Evernden (20) to evaluate b_3, which Evernden defines as "the term controlling rate of die-off of a" and thus effectively of I. For United States earthquakes studied by Evernden, he computes values for b_3 (his k values of Table 6, p. 1297) that lie between 1 and $1\frac{3}{4}$. For the western United States the values range from $1\frac{1}{2}$ to $1\frac{3}{4}$.
Preliminary results for northeastern United States earthquakes indicate a mean value of 1 (20). Similar calculations are being made for eastern Canada earthquakes (R.J. Wetmiller and P.W. Basham, personal communication, 1978).

Other forms that are often used to express intensity as a function of distance are of the form (e.g. 21, 22, 23, 24, 25).

$$I = I_{max} + a - bR - c \log R \qquad \ldots (5)$$

where I_{max} is the maximum reported intensity in the source region, R is hypocentral distance (with an additive constant in some cases), a, b and c are constants.

A form that is a slight modification to Eq. 5 has been used by Milne and Davenport (26) to evaluate intensity for eastern Canada earthquakes. The quality of the intensity data is such that both representations, i.e. Eq. 4 or 5 are equally appropriate to represent intensity data. However, for the present purposes, it is more convenient to use Eq. 4 because the attenuation coefficient b_3 in Eq. 2 appears explicitly in Eq. 4 but not in Eq. 5. This enables a comparison of the attenuation coefficient as derived from intensity data with those from peak ground motion, Fourier amplitude spectra and response spectra. An example of intensity data for a M4 earthquake in eastern Canada is shown in Figure 3.

PEAK VALUES OF SEISMIC GROUND VIBRATIONS

Most instrumental measures of attenuation have used peak values as a data base. Because peak values can be obtained from accelerograms with relatively minor calculations, in contrast to other values that require a substantial amount of computer time, they also form the largest available data base. Peak values are normally due to constructive interference and consequently are from 20-40% larger than sustained levels of ground motion. Attenuation coefficients of peak values of strong ground motion tend to be frequency dependent, depending upon the specific ground motion parameter that is being analysed. For example Orphal and Lahoud, (27) using primarily San Fernando earthquake data in conjunction with underground nuclear explosion data have derived the following expressions:

$$a\ (g) = 6.6\times10^{-2} e^{0.92M} R^{-1.39}$$

$$v\ (cm/sec) = 7.26\times10^{-1} e^{1.2M} R^{-1.34} \quad \ldots (6)$$

$$d\ (cm) = 4.71\times10^{-2} e^{1.31M} R^{-1.18}$$

where a, v and d are peak ground acceleration, velocity and displacement, respectively and M and R are as defined in Eq. 2. Peak acceleration (a) reaches a maximum at higher frequencies (greater than a few Hz) and is of interest to design engineers because the applied force F = m a where m is the mass of the structure. Peak velocity (v) has a maximum at intermediate frequencies (near 1 Hz) and is of interest to design engineers because kinetic energy $KE = 1/2\ mv^2$. Peak displacement (d) has a maximum at low frequencies (<0.3 Hz) and is only of interest to those design engineers concerned with the strain in extremely large structures.

Since there is general consensus that sustained levels of strong ground motion correlate better with structural damage than peak values do, the attenuation coefficient of sustained levels of ground motion would appear to be more appropriate than that of peak values for earthquake engineers. In the following two sections preliminary statistical measures of the attenuation coefficient of two other physical parameters that may be more relevant to earthquake engineering problems than peak values are described. For certain earthquake engineering problems the maximum value of the area under a half cycle may be more relevant than a peak value, since this has the dimensions of velocity.

Insofar as general building codes are concerned, the question arises "If peak values of strong ground motion are not appropriate, then what are more appropriate parameters to incorporate in a general building code?". Two alternatives may be the Fourier amplitude of ground acceleration (dimensions of velocity) or the velocity response spectra. The former is related to sustained levels of strong ground motion and the latter to the response of structures to strong ground motion. Certainly more than one parameter is required to fully characterize strong ground motion (e.g. 28).

FOURIER AMPLITUDE SPECTRA (FS) OF GROUND ACCELERATION

The Fourier amplitude spectra of ground acceleration is directly related to the seismic signal and consequently seismologists generally analyse FS when they wish to study the special characteristics of the focal mechanism (e.g. 15, 29, 30). However, FS is also related to velocity response spectra, SV, at low levels of damping (c.f. 31), as illustrated in Figure 4. Consequently the (velocity) response of a single-degree-of-freedom oscillator at low damping (few % of critical) can be described from two different viewpoints. Figure 5 illustrates how FS compares with SV spectra. The peaks in the FS spectra occur at those frequencies for which t_{max} is close to t, the total duration of the signal, i.e. $t_{max} \simeq t$. The troughs occur when $t_{max} \ll t$, i.e. t_{max} occurs early in the signal.

Because strong ground motion consists of a combination of the direct waves radiated from the source plus a considerable amount of scattered waves, a measure of the attenuation of FS is not, strictly speaking, the measure of the uncontaminated signal radiated from the source. However, it is the closest facsimile that is obtainable. The time domain analog of FS would be sustained levels of ground motion.

Since the attenuation of seismic waves is frequency dependent, the attenuation of FS should show this frequency dependence also. McGuire (30), applying carefully selected data to the model represented by Eq. 2, shows that b_3, the attenuation coefficient is, indeed, frequency dependent. Figure 6 shows this frequency dependence quite clearly. The scatter from a smooth trend is, for the most part, likely due to digitization noise according to McGuire.

VELOCITY RESPONSE SPECTRA (SV_λ)

Sv_λ is the maximum velocity response of a single-degree-of-freedom oscillator with damping λ, expressed as a fraction of critical, that occurs both during and after the passage of a strong earthquake signal. Mathematically SV_λ can be described in either the frequency or in the conjugate time domain. In the frequency domain SV_λ is simply the product of the Fourier transform of the oscillator impulse response with the Fourier amplitude spectra of ground acceleration. In the time domain SV_λ is the convolution of the impulse response of the oscillator with ground acceleration.

Thus $SV_\lambda = \max |\dot{x}(t)|$, $\dot{x}(t) = -\int_0^t \ddot{z}(\tau) e^{-\lambda\omega_n(t-\tau)} \cos \omega_n \sqrt{1-\lambda^2}\,(t-\tau)\,d\tau$

$$+ \frac{\lambda}{\sqrt{1-\lambda^2}} \int_0^t \ddot{z}(\tau) e^{-\lambda\omega_n(t-\tau)} \sin \omega_n \sqrt{1-\lambda^2}\,(t-\tau)\,d\tau \quad \ldots (7)$$

where $\dot{x}(t)$ is the relative velocity response of the oscillator with damping λ (fraction of critical), $\ddot{z}(t)$ is ground acceleration, ω_N the natural resonant (angular frequency of the oscillator, t is time and τ is the dummy variable of integration. Eq. 7 shows that SV_λ depends most strongly upon signal amplitudes at and immediately preceding time t and upon how close the signal periods correspond to the natural period of the oscillator. A negative damping exponential weighting factor that contains λ and ω_N rapidly diminishes the contributions from the earlier part of the time signal.

For an explicit presentation of the time duration of SV_λ at different levels of intensity, a technique such as that proposed by Perez (32) is required. Figure 7 (a) shows how the envelope to SV_λ varies with time and Figure 7 (b), with the number of cycles of a specified response level. Note that the maximum velocity response occurs about 4 sec. before the peak in ground acceleration. This type of presentation is ideally suited for the analysis of structural fatigue.

McGuire (28) has calculated the attenuation of velocity response spectra using a carefully selected data base. The distance dependent term is slightly different from that shown in Eq. 2 in that in place of R, McGuire has used R+25. Figure 6 shows how the attenuation coefficient of the pseudo-velocity response ($PSV_{2\%\lambda}$) oscillator varies with frequency. A comparison between the general trends of the attenuation coefficients between FS and $PSV_{2\%\lambda}$ indicates a significant difference at and slightly below 1 Hz. Whereas the general trend of b_3 for FS has a monotonic decrease with decreasing frequency, the trend for $PSV_{2\%\lambda}$ has a minimum just below 1 Hz. This minimum is likely a distance effect, namely that the seismic signal is becoming progressively more enriched with longer period (higher mode surface) waves. Trifunac (33) has tackled this problem using a different model, namely one that is based upon the definition of local magnitude; consequently Trifunac's model has a far greater number of independent parameters than the simpler model used by McGuire. For most regions where the data base is not large, the expression (Eq. 2) used by McGuire is advantageous because the attenuation coefficient appears explicitly in the formulation.

In the above discussion there has been no distinction made between SV_λ and PSV_λ. The reason for this is as follows. The relative displacement, X(t), of a single-degree-of-freedom oscillator of damping λ and natural angular frequency ω_N, when subjected to a ground acceleration $\ddot{z}$ (t) is

$$x(t) = \frac{-1}{\omega_n \sqrt{1-\lambda^2}} \int_0^t \ddot{z}(\tau) e^{-\lambda\omega_n(t-\tau)} \sin \omega_n \sqrt{1-\lambda^2}\,(t-\tau)\, d\tau \qquad \ldots (8)$$

The maximum value of x(t) is called the relative displacement response SD. The pseudo-(relative) velocity response PSV and the pseudo-(absolute) acceleration response PSA are defined as follows:

$$SD = |x(t)|_{max}$$

$$PSV = \frac{2\pi}{T} SD \qquad \ldots (9)$$

$$PSA = \frac{2\pi}{T} PSV$$

where $T = \frac{2\pi}{\omega_N}$ is the natural period of the oscillator. At low damping PSV $\simeq$ SV (e.g. see 31). Because of Eq. 9, for engineering applications it is convenient to plot PSV vs T on a log-log plot because all three parameters SD, PSV and PSA can be read directly from this plot. Figure 8 shows the PSV curves (on a log-log plot) which correspond to the SV curves in Figure 5. This type of plot is often referred to as a tripartite plot because of Eq. 9.

SURFACE WAVES

The attenuation of the fundamental mode surface (Rayleigh and Love) waves in the period range 10-50 s is generally outside the period range of interest in strong motion seismology. However the period range of some of the higher mode surface waves lies within the range of interest to earthquake engineers. Of particular concern are the higher mode surface waves with periods centered around 1 s and, to a lesser extent 3-12 s. For example, higher mode surface waves generated the peak acceleration recorded at Pacoima Dam due to the San Fernando earthquake of 1971. For eastern Canada earthquakes with $M<5$, the dominant wave at epicentral distances greater than about 100 km is the Lg phase, which consists of undispersed higher mode Love and Rayleigh waves with a dominant period of about 1 s.

Felt sensations and observed structural vibrations and damage are likely due to this wave because the Lg phase predominates over body waves at epicentral distances greater than about 100 km, partly because the geometric spreading factor (B in Eq. 1) is smaller than that for body waves but also because the anelastic attenuation coefficient (α in Eq. 1) is also very small (c.f. 6). This accounts for the observation that the radius of perceptibility of earthquakes occurring in eastern North America can be as much as ten times that for comparable magnitude earthquakes in western North America (34). This observation is also reflected in the attenuation coefficients as derived from intensity data in western and northeastern United States by Evernden (20).

The predominance of an undispersed (Airy phase) over a dispersed surface wave can be seen from the following expressions (35)

$$A_1 = K_1 R^{-\frac{1}{3}} (\sin R)^{-\frac{1}{2}} \exp(-\alpha R)$$

for the Airy (Lg) phase and . . . (10)

$$A_2 = K_2 R^{-\frac{1}{2}} (\sin R)^{-\frac{1}{2}} \exp(-\alpha R)$$

for other phases (e.g. 3-12 sec. fundamental mode), where A_1 and A_2 are amplitudes measured in the time domain, R is hypocentral distance and K_1 and K_2 are constants. The dispersion term is represented by R to some power, -1/3 for the Airy phase and -1/2 for the dispersed wave, the geometric spreading is represented by the $(\sin R)^{-1/2}$ term and the coefficient of anelastic attenuation by α. The Lg phase, which is an Airy phase (with a predominant period near 1 sec. in eastern Canada) has a smaller dispersion term and a smaller anelastic attenuation term than the 3-12 sec. surface wave. Both these factors contribute so that at teleseismic distance the Lg phase tends to predominate over body and other surface waves. For eastern North America α has a value about one-order-of-magnitude less than that for western North America (e.g. see 34, 6).

COMPARISON OF ATTENUATION COEFFICIENTS

For a first-approximation review of the attenuation coefficients of North America, it is convenient to partition North America into two parts, an eastern part (east of the Rocky Mountains) and a western part. Furthermore, because of the frequency dependence of the attenuation coefficient, three frequency ranges will be considered, namely a high-frequency range centered around 5 Hz, an intermediate range centered around 1 Hz and a low-range centered around 0.2 Hz. At high frequencies ground acceleration reaches a maximum, at intermediate frequencies, ground velocity and at low frequencies, ground displacement (e.g. see Figure 8).

It is not difficult to partition peak ground motion, FS and PSV into frequency compartments but it is inherently difficult to partition intensity the same way. The reason is that intensity is generally reported at epicentral distances that tend to cover a much greater range than that for the other three. As a consequence the longer period (higher mode surface waves) tend to predominate where most intensities are reported. Consequently the question arises "Is the attenuation coefficient as derived from intensity data representative of the longer period (about 1 sec.) surface waves or of the shorter period human reactions and reports of property damages?".

Tables 1 and 2 summarize some pertinent attenuation data for North America. Since there is this dichotomy in thought concerning intensity data, the latter is included in both the high- and intermediate-frequency sections. An argument that may support the viewpoint that intensity relates to intermediate period (near 1 sec.) surface waves is that the attenuation coefficient for intensity is about the same as that for surface waves (e.g. 20, 34) for both western and eastern North America. However, since we feel that intensity is a convolution process, namely a human reaction or structural response, and that there were few (if any) structures in Canada that have a natural resonant frequency as low as 1 Hz where most intensity reports were obtained, we tend to favour the viewpoint, in a Canadian context, that intensity is the analogue of PSV (or SV) at high frequencies. An argument to support this viewpoint is that in Table 1 where the attenuation coefficient for intensity correlates with that for PSV in the high-frequency range but not at intermediate frequencies, where the difference is very pronounced. The parameter that shows a monotonic decrease in the attenuation coefficient with decreasing frequency is FS. Peak values show a negligible decrease from high to intermediate frequencies but a significant decrease at low frequencies. PSV values show this pronounced minimum at intermediate frequencies that was described and explained previously.

Figure 9 summarizes these general trends for western North America. The data base for P, FS and PSV are basically the same carefully selected data set as is the model used to calculate these attenuation coefficients (see 28, 30). However the data base and models used to calculate the attenuation coefficients for I are different (e.g. see 19, 20). The fact that the attenuation coefficient for FS is less than that for P over the entire spectrum of frequencies shown, reinforces our viewpoint that constructive interference is more prevalent near the epicenter than at greater distances.

Insofar as a Canadian context is concerned, the empirical measures of attenuation shown in Tables 1 and 2 show the necessity of partitioning Canada into an eastern and western section. Furthermore, in each section there should be two epicentral distance ranges: 0 - 100 km where body waves predominate; >100 km where (higher-mode) surface waves tend to predominate. In addition the pronounced minimum in $PSV_{2\%\lambda}$ near 1 Hz (28) indicates further subdivision into two frequency ranges: an intermediate frequency range (centered around 1 Hz) for high rises and other elongated structures for which the natural resonant frequency is close to 1 Hz; a high frequency range (centered around 5 Hz, say) for one to two storey buildings and other structures with high natural resonant frequencies. Since the tectonic environment for western Canada is rather similar to that of California, instrumental measures of attenuation in the latter are appropriate for the former. The lack of instrumental data in eastern Canada leaves no alternative at present but to adopt the same instrumental data results for the east. Intensity data complements surface wave data at distances greater than 100 km in both eastern and western Canada. An appropriate model for a country as extensive as Canada is that represented by Eq. 2, i.e. Kanai's (10) empirical model, with the focal depth fixed at approximately mid-crustal depth. This would lead to more internally consistent empirical measures of attenuation than those shown in Tables 1 and 2, which are based on different models.

The statistically significant variation with frequency in the attenuation of PSV at low damping and FS (see Fig. 6) indicates the inadequacy of a single-parameter seismic zoning map. A companion paper in this volume (36) describes how attenuation coefficients fit into the framework of seismic zoning mapping in Canada.

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TABLE 1

Seismic Attenuation Coefficients

for Western North America

	Reference
5 Hz (acceleration a maximum)	
Peak a(g) = 0.48 exp (0.64M)(R + 25)$^{-1.30}$,	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(28)
FS (cm/sec) = 1.42 exp (1.01) $R^{-1.11}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(30)
$PSV_{2\%\lambda}$(cm/sec) = 81.3 exp (0.53M) (R + 25)$^{-1.29}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(28)
I (MM) varies from $R^{-1\frac{1}{2}}$ to $R^{-1\frac{3}{4}}$	
M = intermediate to large, R = epic to 500 km	(20)
1 Hz (velocity a maximum)	
Peak v(cm/sec) = 5.64 exp (0.92M) (R + 25)$^{-1.20}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(28)
FS (cm/sec) = 0.29 exp (1.12M) $R^{-0.89}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(30)
$PSV_{2\%\lambda}$ (cm/sec) = 1.09 exp (0.88M) (R + 25)$^{-0.59}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(28)
I (MM) varies from $R^{-1\frac{1}{2}}$ to $R^{-1\frac{3}{4}}$	(20)
Higher mode surface waves (Rg and Lg) waves in the range	
$R^{-1.2}$ to $R^{-1.66}$, $R \simeq 10-120$ km	(34)

TABLE 1 (CONT'D)

Seismic Attenuation Coefficients

For Western North America

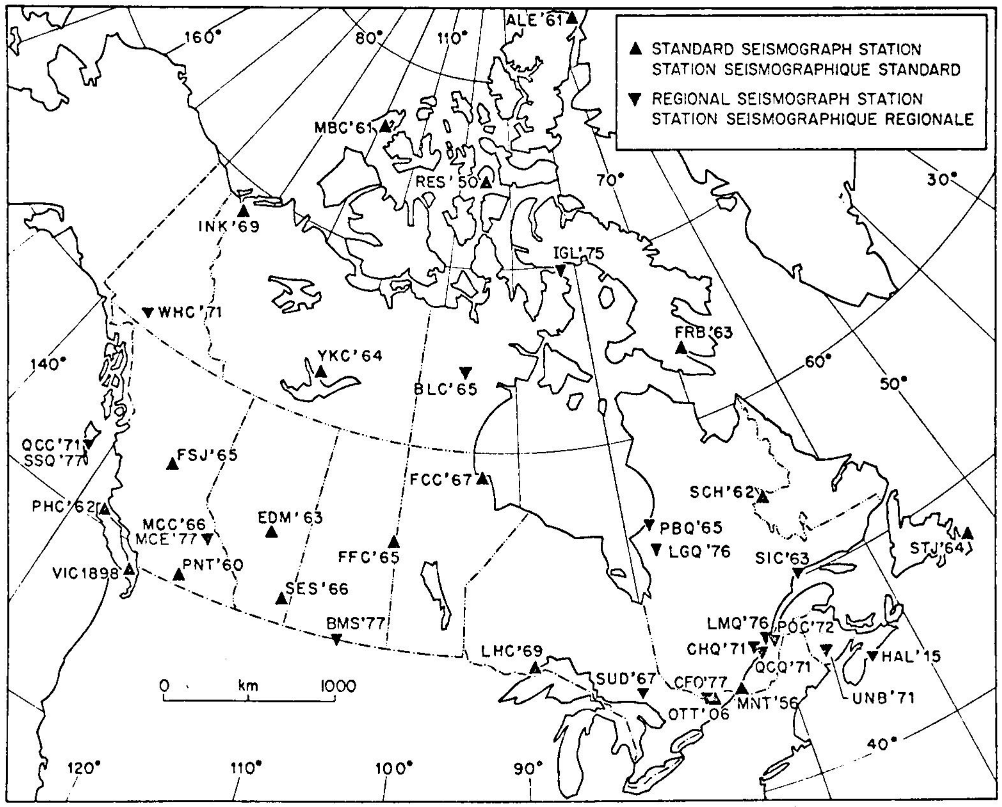
	Reference
0.2 Hz (displacement a maximum)	
Peak $d(cm) = 0.39 \exp(1.00M)(R + 25)^{-0.89}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(28)
$FS\ (cm/sec) = 0.03 \exp(1.20M)\ R^{-0.61}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(30)
$PSV_{2\%\lambda}(cm/sec) = 0.19 \exp(1.30M)\ (R + 25)^{-0.93}$	
$M = 5\frac{1}{3} - 7\frac{1}{2}$, R = 10-130 km	(28)
I (MM) varies from $R^{-1\frac{1}{2}}$ to $R^{-1\frac{3}{4}}$	(20)
Higher mode surface wave varies in the range $R^{-1.2}$	
to $R^{-1.66}$, $R \simeq 10-120$ km	(34)
Fundamental mode surface wave varies as $R^{-1.66}$	
(20 sec period), $R = 20^{\circ} - 120^{\circ}$	(34)

TABLE 2

Seismic Attenuation Coefficients

for Eastern North America

	Reference
5 Hz	
I (MM) varies as R^{-1}	
M (intermediate to large); R = epic to 500 km	(20)
1Hz	
Higher mode surface wave (Lg) varies as $R^{-0.90}$	
M (intermediate); R = 50-450 km	(34)
Lg varies as $R^{-1.66}$	
M (intermediate); R = 450-3000 km	(34)
I (MM) varies as R^{-1}	
M (intermediate to large); R = epic to 500 km	(20)
0.2 Hz	
Higher mode surface wave varies as $R^{-1.66}$	
M (intermediate); R = 50-450 km	(34)
I (MM) varies as R^{-1}	
M (intermediate to large); R = epic to 500 km	(20)



CANADIAN STANDARD AND REGIONAL SEISMOGRAPH STATIONS 1977

Figure 1 Canadian Standard and Regional Seismograph Stations 1977.

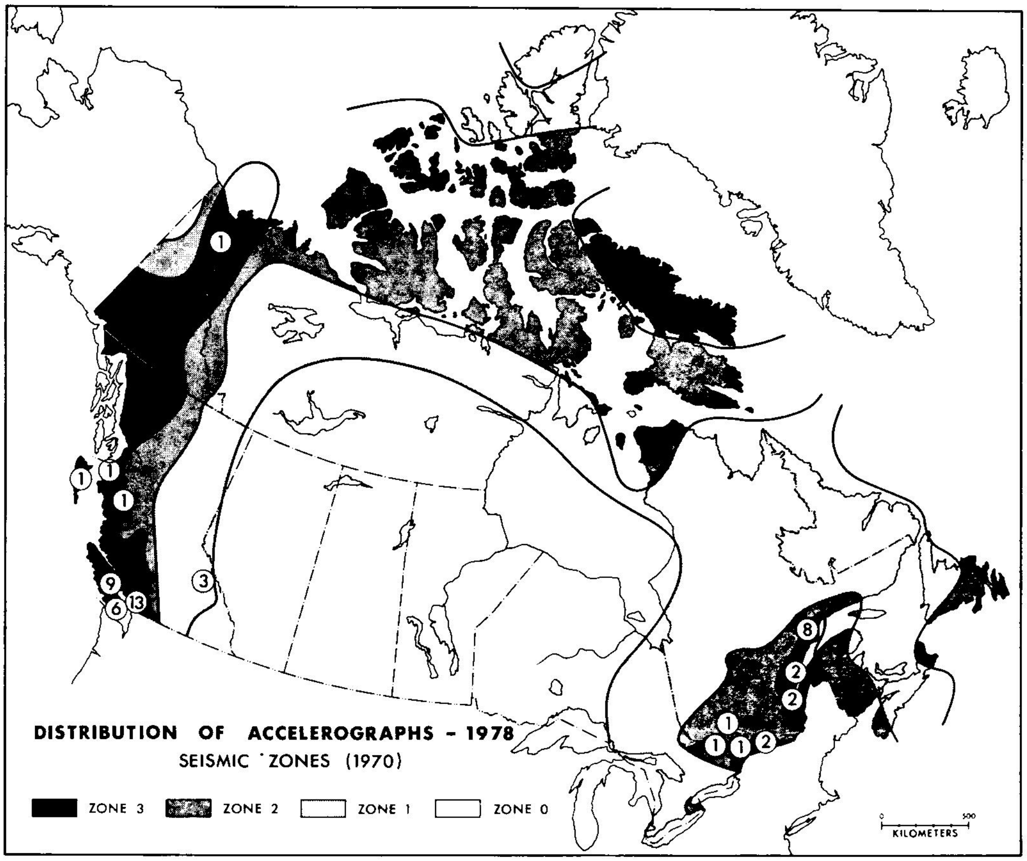


Figure 2 Distribution of Accelerographs (1978) and Seismic Zones (1970) (from Rogers, personal communication, 1979). The darker the shading the greater the expected ground acceleration with a 0.01 probability of exceedence per annum (see 8).

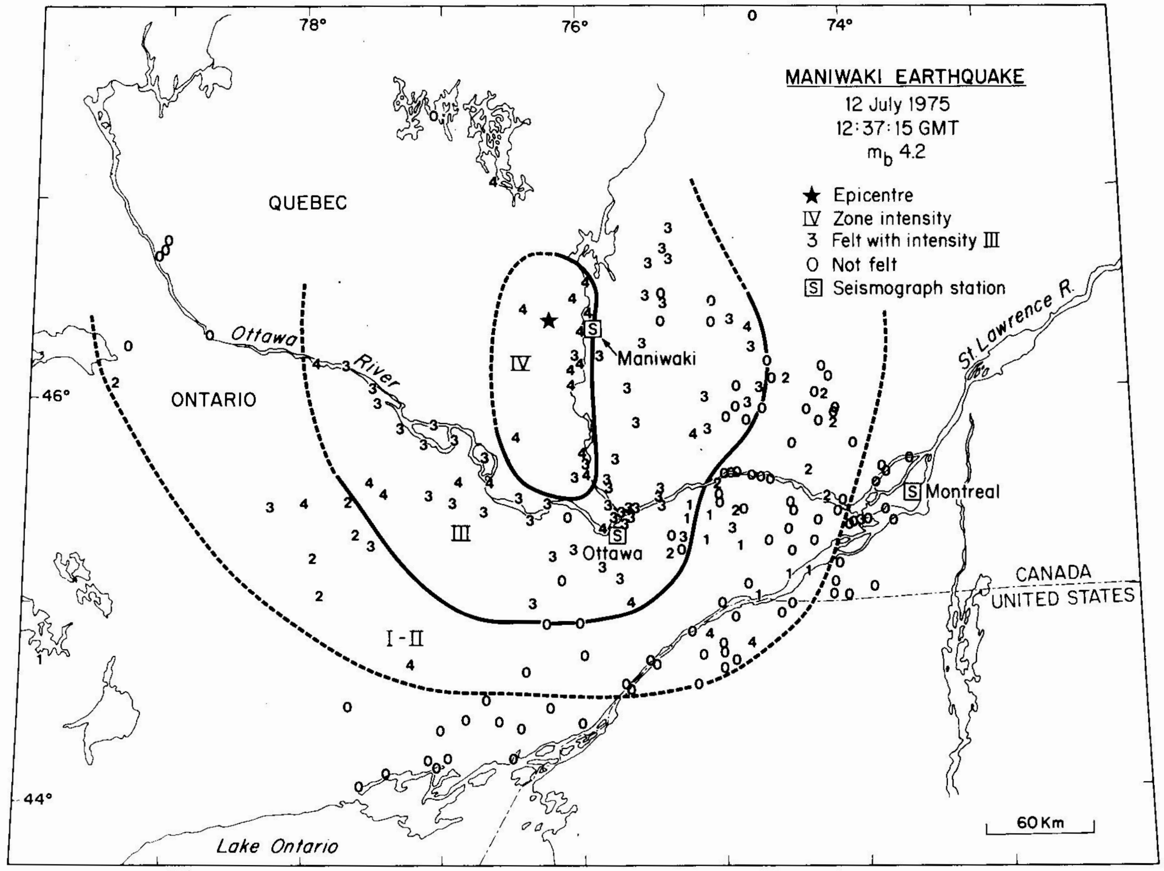


Figure 3 An example of intensity (MM) data in epicentral region of Maniwaki (1975), Quebec, earthquake (from 6).

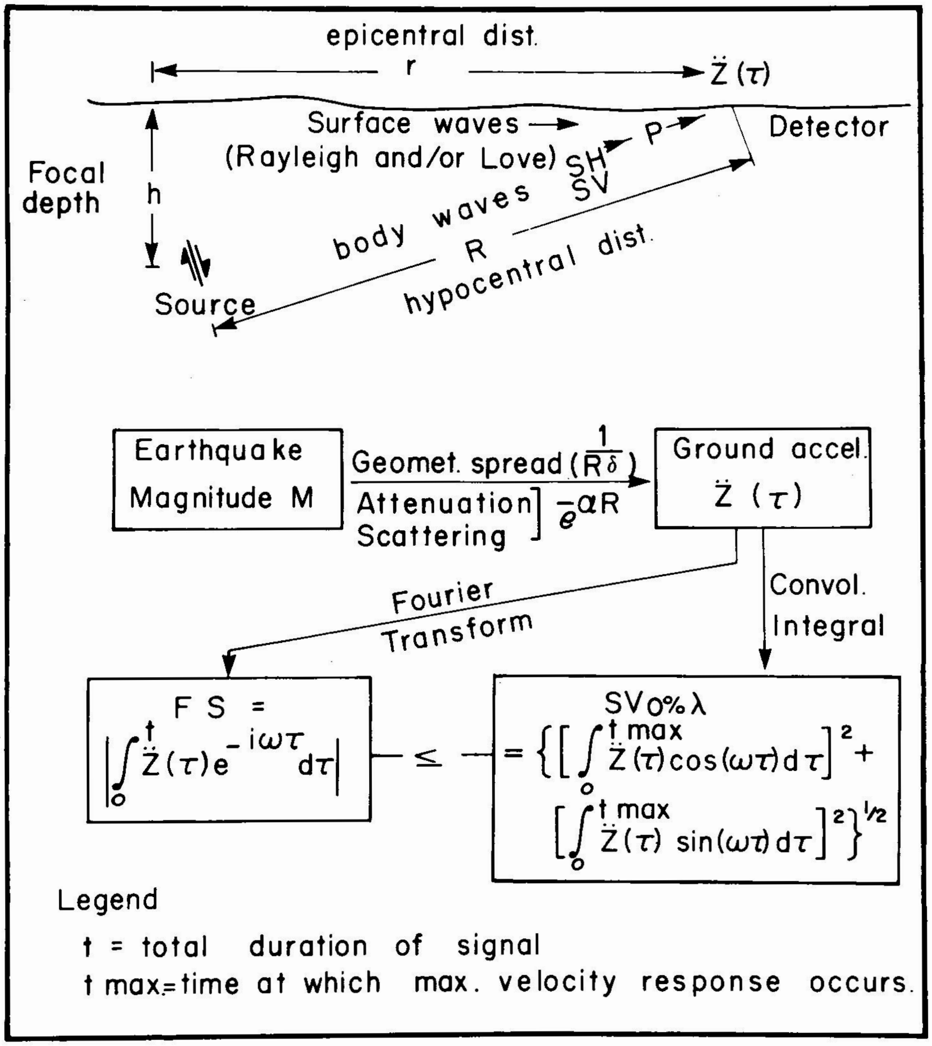


Figure 4 Relation between Fourier amplitude spectra (FS) of ground acceleration and relative velocity response (SV) at 0% of critical damping (λ) (from 12).

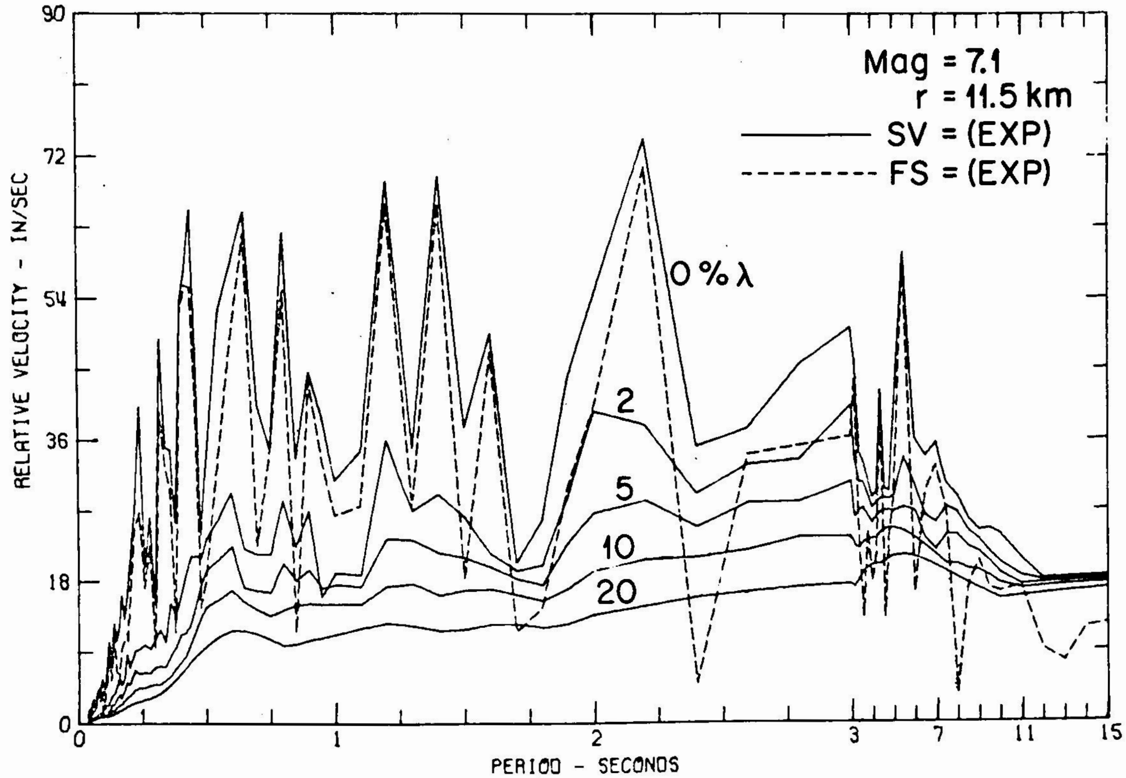


Figure 5 Velocity response spectra (SV) at five levels of damping and Fourier amplitude spectra (FS) of ground acceleration recorded at epicentral distance r = 11.5 km for the Imperial Valley, California, earthquake of May 18, 1940 (from 11).

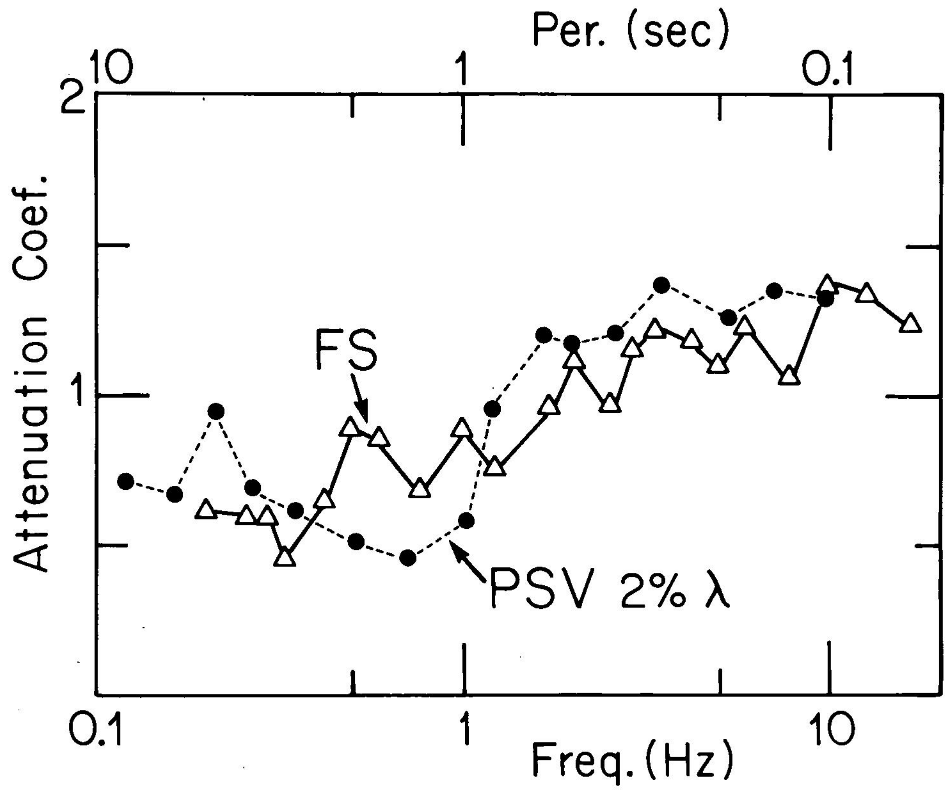


Figure 6 Attenuation coefficient (b_3 in Eq. 2) for FS and $PSV_{2\%\lambda}$ versus frequency (or period) for predominantly California earthquakes (from 28, 30).

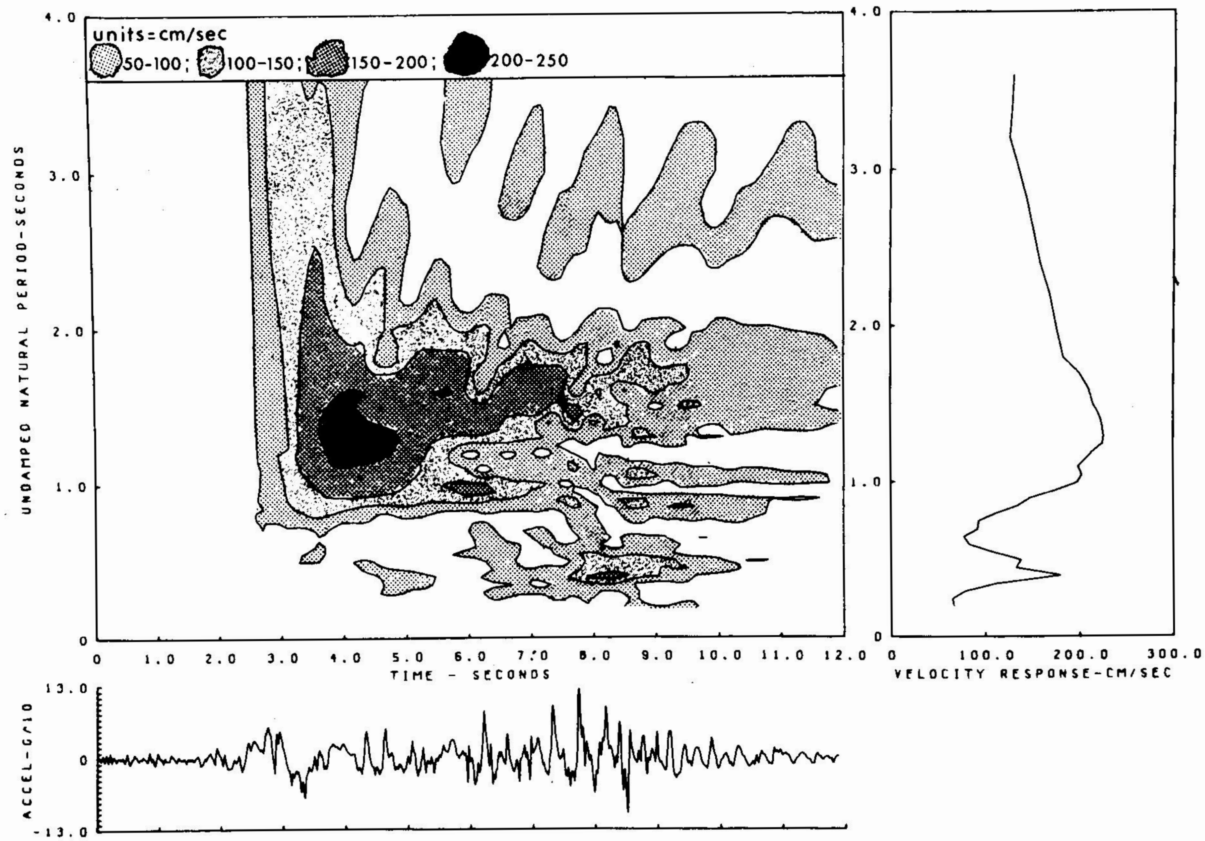


Figure 7(a) Velocity response envelope as a function of time for the Pacoima Dam, San Fernando, earthquake of 1971 (from 32).

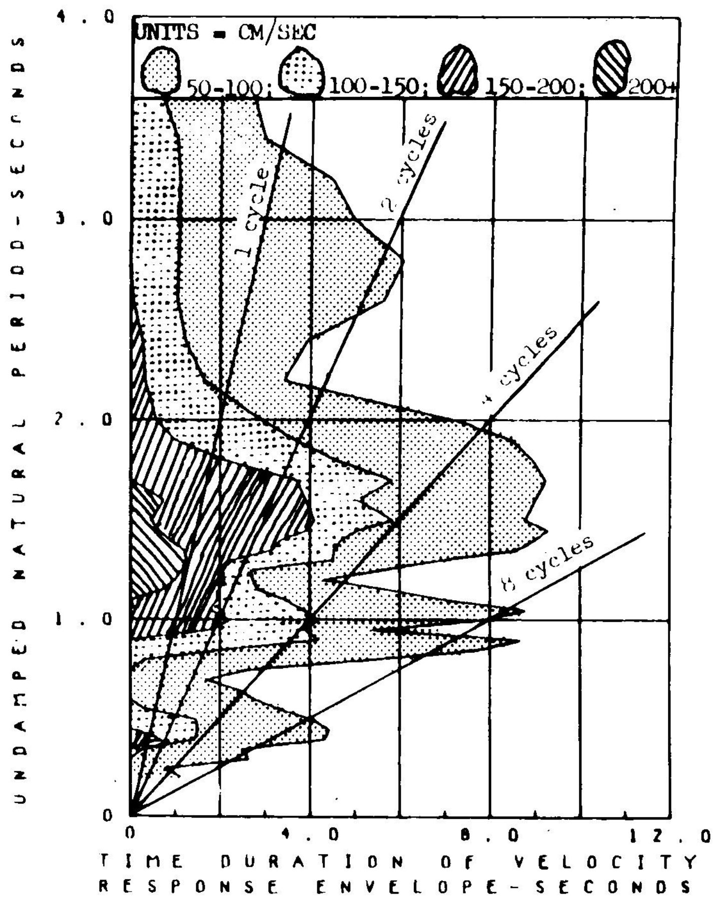


Figure 7(b) Duration of velocity response envelope (from 32).

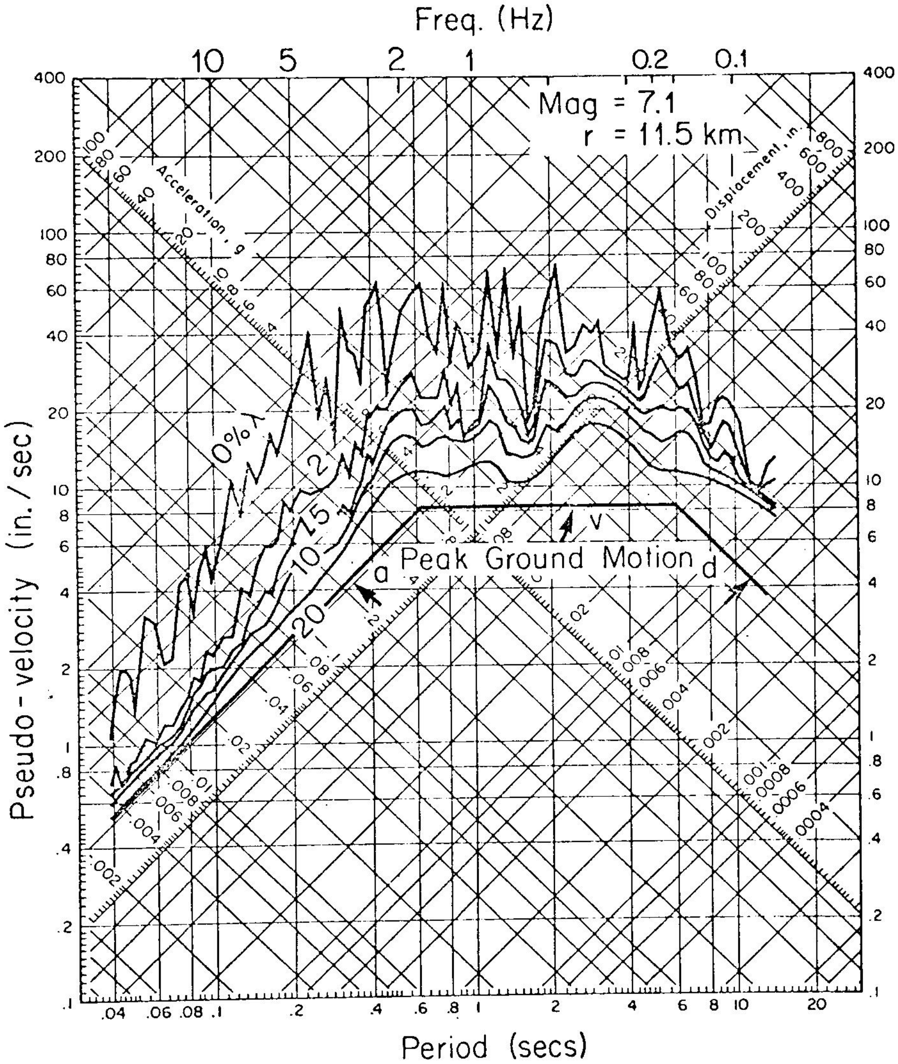


Figure 8 Pseudo-velocity response for Imperial Valley earthquake of May 14, 1940 (from 11). Peak ground acceleration (a), velocity (v) and displacement (d) are represented by smoothed (linear) line segments (from 11).

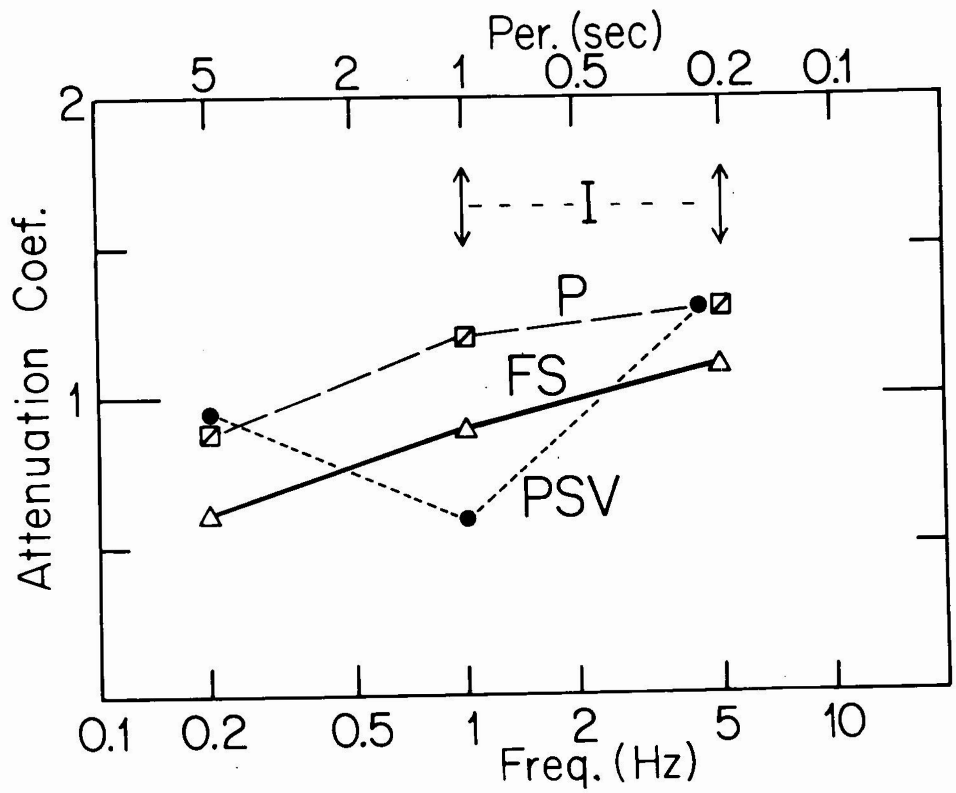


Figure 9 Attenuation coefficient (b_3 in Eq. 2) for Intensity (I), peak ground motion (P), Fourier amplitude spectra (FS) and pseudo-velocity response at 2%λ versus frequency or period (from 28, 30, 20).