GEOPHYSICAL ESTIMATES OF SEISMIC SHEAR WAVE MOTION

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SUMMARY

The Brune source model is used as the basis for characterizing far-field seismic shear wave motion. Deriving an expression for the root-mean-square acceleration a_{rms}, and estimating the duration of shear wave motion by the faulting duration, estimates of a_{rms} using a static stress drop $\Delta\sigma$ of 100 bars compare well with observations of a_{rms} calculated from a wide range of California strong motion records. This implies that, for earthquakes in California with $\Delta\sigma$ from 6 to 420 bars, the shear wave motions are most accurately estimated using, for the Brune source model, $\Delta\sigma = 100$ bars.

INTRODUCTION

The specification of high frequency characteristics of seismic ground motion for the design of structures is generally made using rather simple mathematical models. These models often use only earthquake magnitude as the description of the energy source, and usually are calibrated with strong motion records of past earthquakes. The theoretical basis of these models has not changed greatly in recent years, and the catalog of available strong motion records for earthquake magnitudes not yet well documented is growing only slowly.

Estimates of ground motion characteristics using various of these models differ least in the magnitude and distance range where data are abundant. Estimates differ most where extrapolation beyond available data is required, particularly for seismic shaking close to moderate and large magnitude earthquakes. These differences have been well-documented (Donovan, 1974; Idriss, 1978); they depend largely on the mathematical functions assumed and on the particular data set used for calibration. Resolution of these differences by empirically-based methods must necessarily await the collection of strong motion data in the magnitude and distance range of interest.

As an alternative we propose to use the Brune source model for specifying the spectra of far-field shear waves, which dominate the characteristics of high frequency seismic shaking. This model has been demonstrated to be accurate for the 1971 San Fernando earthquake by comparison between estimated shear wave spectra, and spectra calculated from strong motion records (Berrill, 1975; McGuire and Hanks, 1979). In this paper we characterize seismic shear wave motion by the root-mean-square acceleration a_{rms} and duration, and demonstrate the accuracy of the model (under certain assumptions discussed below) for a wide range of earthquake motions. This includes records from the 1971 San Fernando earthquake, from eight other well-recorded earthquakes in California, and from four aftershocks of the 1975 Oroville earthquake.

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THEORETICAL BACKGROUND

The Brune model (1970, 1971) characterizes the energy release causing an earthquake by the seismic moment M_o, the average static stress drop $\Delta\sigma$, and the source dimension r. These are related through:

$$\Delta\sigma = 7M_o/16r^3 \qquad (1)$$

In the presence of anelastic attenuation represented by $\exp(-\pi fR/Q\beta)$, where f is frequency, R is source-to-site distance, Q is quality factor, and β is shear wave velocity, the Fourier spectral amplitudes $\tilde{a}(f)$ at distance R can be estimated by (McGuire and Hanks, 1979):

$$\tilde{a}(f) = (0.85)\frac{\pi M_o f_o^2}{\rho R\beta^3}\exp(-\pi fR/Q\beta)\left(\frac{1}{1+(f_o/f)^2}\right) \qquad (2)$$

In equation (2), is the medium density and f_o is the corner frequency of the source, which for the Brune (1970) model is:

$$f_o = \frac{2.34\beta}{2\pi r} \qquad (3)$$

It is convenient to quantify ground motion in the time domain by the root-mean-square acceleration a_{rms} and by the duration of shear wave motion. The latter quantity can, as a first approximation, be estimated by the faulting duration. Using Parseval's theorem we can estimate a_{rms} from the spectral amplitudes:

$$a_{rms} = (0.85)\ \frac{(2\ \pi)^2}{106}\ \frac{\Delta\sigma}{\rho}\ R^{-3/2}\sqrt{\frac{2Qr}{2.34}} \qquad (4)$$

(McGuire and Hanks, 1979). Note, from equation (1), that $r \propto M^{1/3}$; thus the rms acceleration is only very weakly proportional to earthquake size ($a_{rms} \propto M_o^{1/6}$) but is directly proportional to static stress drop.

It is more convenient to make comparisons of estimates and observations using a_{rms} (eq. 4) rather than $\tilde{a}(f)$ (eq. 2). The former quantity is a single broad-band measure of the amplitude of shear wave motion which is closely correlated with the peak acceleration (Hanks and McGuire, 1980); the latter quantity represents the spectral amplitude at a single frequency and therefore requires comparisons over a range of frequencies. The accuracy of the model can be demonstrated using either quantity (McGuire and Hanks, 1979); we chose a_{rms} here for convenience.

RESULTS

Figure 1 shows a_{rms} calculated from strong motion records obtained during the 1971 San Fernando earthquake, determined by identifying the initial shear wave arrival on each record and using a duration equal to the faulting duration of 10 sec. Because of the strong azimuthal dependence exhibited by accelerograms (and damage) for this earthquake, only records obtained at southern azimuths (between 130° and 200°) are shown in Figure 1. For comparison, the estimates using eq. 4 are shown, corresponding to $\Delta\sigma$ = 50 bars and 100 bars, $R_{\theta\phi}$ (which accounts for radiation pattern) equal to unity (rather than 0.6 as has been subsumed in the constant 0.85 of equation (4), $r = 11.9$ km, $\rho = 2.8$ g/cm^3, and $Q = 300$. The model estimate shows a distance-dependence ($R^{-3/2}$) which is in reasonable agreement with observed data. The estimate using $\Delta\sigma = 50$ bars, which is a typical static stress drop reported for this earthquake, lies below the data; the estimate using $\Delta\sigma = 100$ bars is in better agreement with observations.

In fact, the ground motions during most California earthquakes indicate that an average stress drop of about 100 bars is appropriate for characterizing the source, at least when approximated by the Brune model. This is evident in Figure 2 which shows estimated a_{rms} versus a_{rms} calculated from 51 strong motion accelerograms during eight California earthquakes (1933 Long Beach, 1940 Imperial Valley, 1952 Kern County, 1954 Wheeler Ridge, 1957 San Francisco, 1966 Parkfield, 1968 Borrego Mt., 1970 Lytle Creek).

In Figure 2a, estimates of a_{rms} were made using, in eq. 4, the stress drop associated with each event (as reported by Thatcher and Hanks, 1973), which ranged from 6 to 60 bars. In determining the record observations of a_{rms} for each earthquake, the average seismic moment reported in the literature was used, along with $\Delta\sigma$, to calculate the source dimension (eq. 1), estimate the source corner frequency (eq. 3), and determine a faulting duration T_d as the inverse of the corner frequency, which is a valid approximation for typical rupture velocities. The shear arrivals were then identified on each record and a_{rms} calculated for the succeeding T_d seconds. The estimates of a_{rms} were obtained by eq. (4), using $\Delta\sigma$ as reported in the literature and appropriate values of the other parameters. More details are given in Hanks and McGuire (1980). The comparison indicates virtually no correlation between estimated and observed values of a_{rms}.

Figure 2b shows a similar comparison in which $\Delta\sigma = 100$ bars has been used to estimate a_{rms} or all records. Observed values of a_{rms} have been recalculated using a faulting duration T_d appropiate for this $\Delta\sigma$. The agreement in this comparison is much better than in Figure 2a. The residual uncertainty in observed a_{rms} given the estimate) can be characterized by a standard deviation of $\ln a_{rms}$ of 0.6 which is comparable to residual uncertainty in peak accelerations estimated by empirical attenuation functions.

Figure 3a shows a comparison for four aftershocks of the 1975 Oroville earthquake. In estimating a_{rms} we have used values of $\Delta\sigma$ (ranging from 60 to 420 bars) shown in the figure which were determined for each aftershock from the recorded accelerograms following the method described by Fletcher et al (1979). There is no general agreement between estimated and observed a_{rms} for these stress drops. Figure 3b, on the other hand, shows better agreement when a_{rms} has been estimated using $\Delta\sigma = 100$ bars. (For the observed values in Figure 3b, we have used the same a_{rms} as in Figure 3a, rather than recalculate these values based on a new faulting duration. The difference is not expected to be large.).

These results imply that for moderate earthquakes in California, high stress drops ($\Delta\sigma \doteq 100$ bars) associated with the initial rupture and with the deeper parts of the rupture surface are generally and primarily responsible for the character of high frequency ground motion. Such a high stress drop phenomenon has been shown to be associated with the 1971 San Fernando earthquake (Hanks, 1974) and apparently is common for moderate earthquakes in California. The results from the small magnitude Oroville aftershocks, with calculated stress drops generally greater than 100 bars, are more difficult to interpret; these results remain unexplained at this time.

In light of the scatter evident in Figures 2b and 3b, it is important to put in perspective the more detailed models available (e.g. Boore and Zoback, 1974; Heaton and Helmberger, 1979) to predict seismic ground motion, which require more detailed descriptions of source properties (e.g., the location, direction, and velocity of rupture). These models are quite accurate for estimating recorded earthquake motions and are useful for understanding past seismic events; they are not appropriate for predicting motion during future earthquakes because the specific characteristics of faulting cannot be anticipated. The effects of these and other unknown characteristics on ground shaking are revealed in our comparisons as scatter in observed values of spectral amplitudes and a_{rms} from the predicted values. This uncertainty in predicting ground shaking characteristics will remain until more specific source properties for future earthquakes can be predicted.

CONCLUSIONS

The Brune source model provides accurate estimates of seismic shear wave characteristics in the far-field, as measured by the root-mean-square acceleration, if a static stress drop $\Delta\sigma$ of 100 bars is used rather than a value calculated for the entire rupture surface. This holds for a wide range of earthquakes recorded in California, with $\Delta\sigma$ from 6 to 420 bars. These results imply that a one-parameter source model is sufficient to estimate rms accelerations: designation of the seismic moment, and use of $\Delta\sigma = 100$ bars, completely characterizes the seismic source. This conclusion is particularly surprising for the Oroville data, because the source parameters were estimated from the recorded accelerations (long period displacement spectral level, corner frequency, and shear wave pulse shape), but $\Delta\sigma = 100$ bars is more accurate for estimating a_{rms}. This theory allows estimation of shear wave characteristics with some confidence for earthquakes not yet well documented with strong motion data, if the proper source and crustal characteristics are specified. This is possible because the proposed method has been developed essentially independently of strong motion data; these data are used for verification, not calibration.

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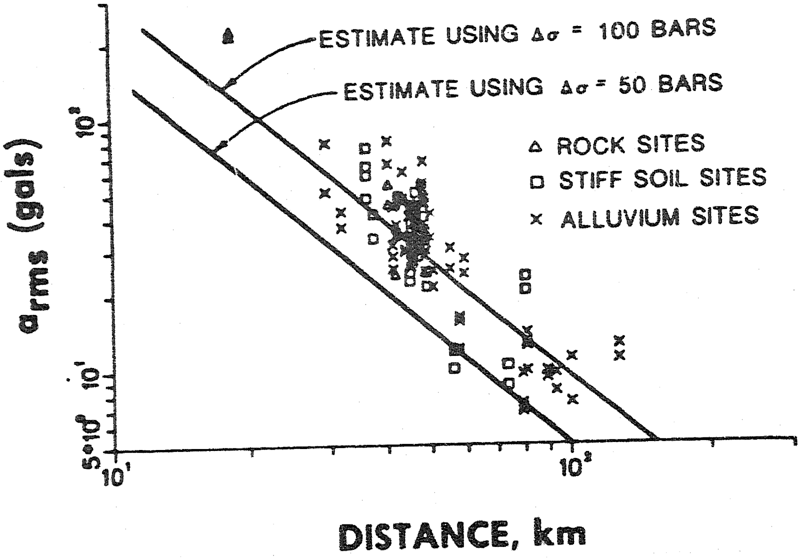

FIGURE 1: Observed a_{rms} during the 1971 San Fernando earthquake at sites south of the epicenter, plotted versus distance, and estimate using $\Delta\sigma = 50$ bars and $\Delta\sigma = 100$ bars.

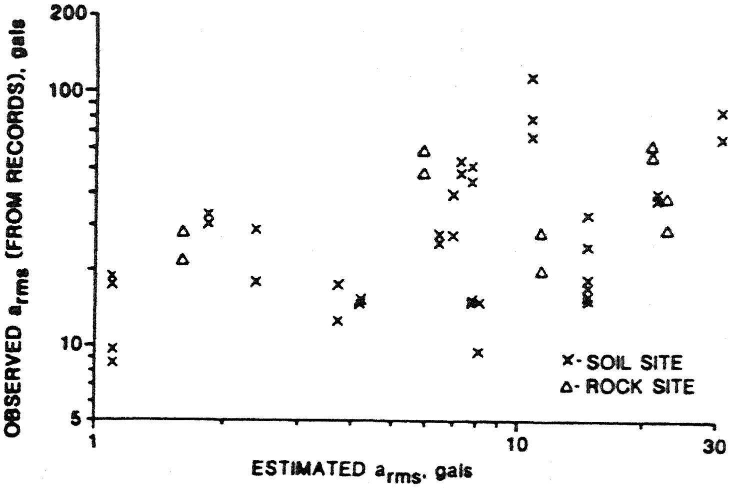

FIGURE 2a: Observed a_{rms} from strong motion record during eight California earthquakes, versus a_{rms} estimated using $\Delta\sigma$ reported in literature.

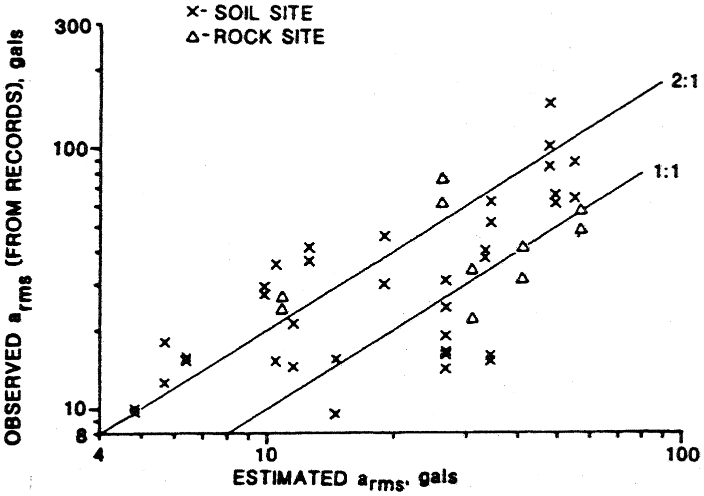

FIGURE 2b: Observed a_{rms} from strong motion records during eight California earthquakes, versus a_{rms} estimated using $\Delta\sigma$ = 100 bars.

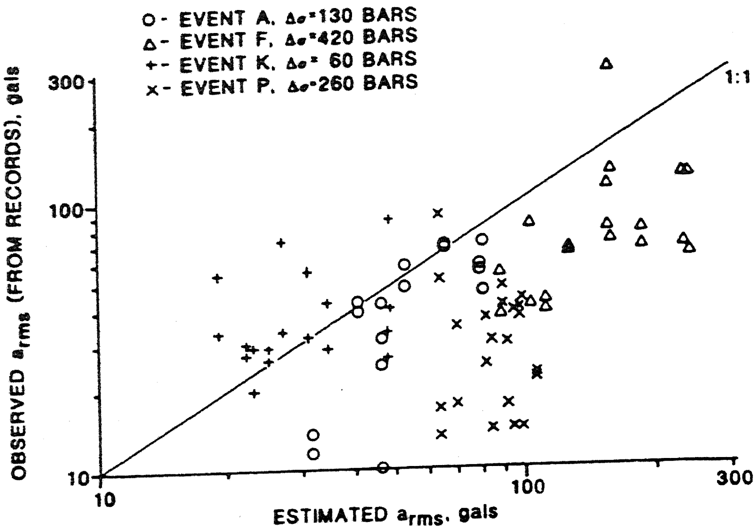

FIGURE 3a: a_{rms} observed during four Oroville aftershocks, versus a_{rms} estimated using Δσ shown.

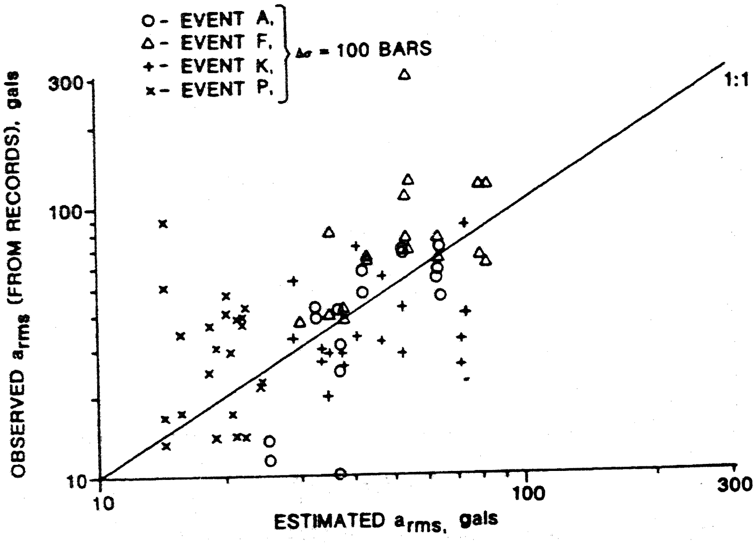

FIGURE 3b: a_{rms} observed during four Oroville aftershocks, versus a_{rms} estimated using Δσ = 100 bars.