TECTONIC STRESS ESTIMATE FOR THE KOYNA EARTHQUAKE OF DECEMBER 11,1967

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SYNOPSIS

An analysis of the strong motion accelerogram of the Koyna earthquake of December 11, 1967 has been carried out to abstract the values of the initial tectonic stress and the effective stress using the acceleration spectrum as well as the peak velocity. The estimate of the effective stress obtained from the former turns out to be 350 bars which is an order of magnitude higher as compared with that obtained using peak velocity. This is, however, considered to be more reliable.

INTRODUCTION

The importance of abstracting parameters of earthquakes which are capable of characterising the nature of strong ground motion is widely realized in earthquake engineering. Recent progress in mathematical modelling of earthquake foci has led to the specification of several parameters which describe various aspects of an earthquake. For example the seismic moment M_o, the average dislocation, the source dimension and the stress drop characterise the static aspects of the faulting. The effective insitu stress available to initiate fault slip governs the dynamics of the faulting and is an extremely relevant parameter to engineering seismology. The near field acceleration is primarily governed by the effective stress (1), a knowledge of which can be used to estimate the maximum possible acceleration in a future earthquake in the area. The determination of effective tectonic stresses has been a difficult task as short period records (accelerograms) carrying this information have been very few. The static parameters have been estimated on a world wide basis from long period seismic wave data as well as from geodetic measurements.

In a recent study Trifunac (2) demonstrated the importance of the seismic moment and the effective stress in engineering seismology by proposing a new rational basis for designing response spectrum curves using these parameters.

The present study gives an analysis of the accelerogram recorded at the Koyna dam in 1967, the estimates of the effective stress operating during the earthquake, the stress drop and the seismic moment.

The earthquake epicenter was estimated to be very close to the dam site. The location parameters are as follows:

O.T. = 22h 51m 17.0s; Latitude = $17^o31.1'$N; Longitude = $73^o43.9'$E;
H = 8 km; M_s = 6.3.

The Earthquake Model

The earthquake source may be represented by a simple circular dislocation in an infinite medium across which traction is suddenly

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lost (Brune (1)). This causes the drop of insitu stress from the initial value of σ_0 prior to the earthquake to σ_f which is the frictional stress opposing the fault slip. The effective stress $\sigma = \sigma_0 - \sigma_f$ gives rise to a shear wave radiating normal to the fault surface (Fig.1) with an initial time function given by

$$\sigma(Z,t) = \sigma H\,(t-Z/\beta) \tag{1}$$

where H(.) is the unit step function, β is the shear wave velocity, t the time and Z the distance from the fault plane (Z=0). An integration of the wave equation gives the shear wave ground motion near the center of an infinite fault as follows

$$V = \frac{\sigma\beta}{\mu} t \tag{2}$$

where μ is the shear modulus and V is the ground displacement. The stress at the fault plane Z = 0 will be given by,

$$\sigma(Z=0) = \mu \frac{\partial V}{\partial Z} \tag{3}$$

and the particle velocity by

$$\dot{V} = \frac{\sigma\beta}{\mu} \tag{4}$$

Equations (2) and (4) also approximate the first motions arising from a finite circular dislocation of radius r near the fault surface until the effects of the boundaries of the dislocation arrive at the point of observation (1). These interference effects cause the particle velocity to drop to zero. The phenomenon is modeled by including an exponential decay factor as follows

$$\dot{V}(Z \approx 0,t) = \frac{\sigma\beta}{\mu} e^{-t/\tau} \tag{5}$$

and

$$V(Z \approx 0,t) = \frac{\sigma\beta\tau}{\mu} (1-e^{-t/\tau}) \tag{6}$$

where τ is of the order of (r/β).

The Fourier amplitude spectrum of the near source shear motion displacement field represented by equation (5) is given by

$$\Omega^S_{NS}(\omega) = \frac{\sigma\beta}{\mu} \cdot \frac{1}{\omega(\omega^2+\tau^{-2})^{1/2}} \tag{7}$$

where ω is the circular frequency. The ideal near source spectral amplitudes $A^S_{NS}(\omega)$ for accelerations may be obtained by multiplying equation (6) by ω^2

$$A^S_{NS}(\omega) = \frac{\sigma\beta}{\mu} \cdot \frac{\omega}{(\omega^2+\tau^{-2})^{1/2}} \tag{8}$$

The term $\omega/(\omega^2+\tau^{-2})^{\frac{1}{2}}$ has been plotted on a log-log scale in Fig. 3 for τ = 2, 1 and 0.2s.

Source Parameters

The Koyna dam earthquake was recorded on a three component accelerograph placed within the dam. The recordings may have been influenced by the response of the monolith and this effect has been neglected. The present analysis has been carried out for the horizontal component accelerogram which was oriented along the dam axis. The recorded particle acceleration is shown in Fig. 4. The corresponding particle velocity and displacement determined by numerical integration (3) are also shown in the same figure.

The hypocenter of the Koyna earthquake was located near the dam at a depth of about 8 km. Although there was no accompanying surface fracture, the fault edge may have been even closer to the surface and the expressions (4) and (7) from near source theory may be used to a first approximation to determine the effective stress operating during the earthquake. The transmission properties of the crust are neglected and the free surface amplification has been accounted for by a division by 2. We assume a value of 3×10^{11} dynes/cm^2 for μ and 4.0 km/s for β for the source region. The peak velocity recorded on the horizontal component is 24 cm/s (3). Using equation (4) we estimate σ to get

$$\sigma = \sigma_0 - \sigma_f = \dot{V}_{max.} \frac{\mu}{\beta} \approx 9 \text{ bars} \qquad (9)$$

Averaging the particle velocity over the process time one obtains the following relation between the average value of $\dot{V}$ and the effective stress (4)

$$\bar{\dot{V}} = \left(1 - \frac{1}{e}\right) \frac{\sigma\beta}{\mu} = 0.63 \frac{\sigma\beta}{\mu} \qquad (10)$$

The average particle velocity $\bar{\dot{V}}$ may be estimated using the average final dislocation $\bar{V}$ over the fault and the rise time (RT) which is the time required for the completion of dislocation at a point.

$$\bar{\dot{V}} = \bar{V}/RT \qquad (11)$$

The average dislocation may be estimated from long period seismic data using (5)

$$\bar{V} = \frac{M_0}{\mu\pi r^2}$$

Taking (M_0) = 7.76×10^{26} dynes-cm and (r) $\approx$ 20 km estimated by Khattri et. al. (6) we get $\bar{V}$ = 202 cm.

The estimation of rise time is more problematic and Kanamori (7) has devised a procedure of matching synthetic seismograms to estimate both $\bar{V}$ and RT by comparison with the corresponding observed time histories. Here we approximate it by 2 $(r/\beta) \approx$ 11s. Thus we have $\bar{\dot{V}}$ = 18.4 cm/s. This gives the following estimate of the effective tectonic stress.

$$\sigma \approx 21 \text{ bars} \qquad (12)$$

Another estimate of σ is obtained by fitting the theoretical spectrum given by equation (7) to the observed spectrum. The spectrum of the observed accelerogram is shown in Fig. 5. The wave propagation effects have been neglected and the effect of the free surface is assumed to amplify the ground acceleration by a factor of 2. The response of the dam monolith is also neglected. Since the accelerograph transfer function is essentially flat in the frequency range of interest, no correction for this is required. The observed spectrum shows an expected fall off at high frequencies. The fall off at the lower frequency and may in part be due to the interference of crustal reflections and also the effect of the radiation from a finite moving source which degrades the amplitudes by a factor of $\omega = 2\pi/T$ for periods long compared to the radiation time from the source. In the present case $T \sim 6s$ and the predicted effect seems to be significant for $\omega < 3$. The theoretical acceleration spectra were fitted to the observed one. The theoretical curve for $\tau \sim 0.2$ has a satisfactory fit to the observed spectrum for a value of log ($\sigma\beta/\mu$) of about 2.7. We thus deduce that

$$\sigma \approx 350 \text{ bars}$$

This value is one order of magnitude higher than that obtained in expressions (9) and (12), the significance of which is discussed below.

There is no direct information available for the displacement on the fault as no surface trace was seen. However, if the previous estimate for $\bar{V}$ can be used the stress drop $\Delta\sigma$ is given by (8)

$$\Delta\sigma = \frac{\mu\bar{V}}{\gamma} \cdot \frac{7\pi}{16} \approx 42 \text{ bars} \qquad (13)$$

DISCUSSION AND CONCLUSIONS

The estimates of the effective stress obtained here vary over a wide range. The estimate of 350 bars obtained using the acceleration spectra reflects the high acceleration recorded. It may be noted that the reported accelerations (3) during the Koyna earthquake are one of the highest ever recorded with a peak value of 0.63g. The near source recordings of ground motion have an advantage over teleseismic recordings as the former are relatively unaffected by inelastic attenuation which filters out the high frequency energy at teleseismic distances. Also, the effects of geometrical divergence are largely absent.

The effective stress of 9 bars obtained using the peak ground velocity is considered to be an underestimate as the point of observation was not at the fault surface and the interference effects from the perimeter of the fault would tend to reduce the peak ground velocity considerably. We therefore conclude that the value of σ estimated from the accelerogram spectra is more reliable and the effective stress is of the order of hundreds of bars rather than tens of bars, since the estimated stress drop $\Delta\sigma$ of 42 bars is an order of magnitude less than the effective stress, only a partial stress drop has probably occurred in the Koyna earthquake. It therefore follows that the initial tectonic stress σ_0 in the Koyna area was of the order of several hundred bars. Guha et.al. (9) have estimated σ_0 to be 140 bars whereas Balakrishna and Gowd (10) found a value of 2000 bars. The estimates given in this investigation should be considered as first order approximations using simplified theoretical models. The seismic moment $\langle M_0 \rangle$ determined from long period seismic data turns and to be 7.8×10^{26} dyne-cm (6). The above value of $\langle M_0 \rangle$ together with that of $\sigma \approx 350$ bars are considered sufficiently reliable to be of use in scaling the response spectra curves.

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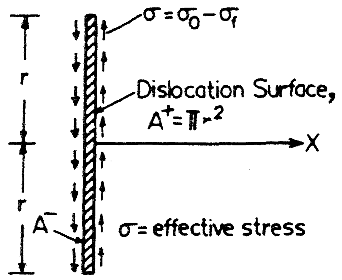

Fig.1 Dislocation model proposed by Brune (1970) to model S - wave spectra.

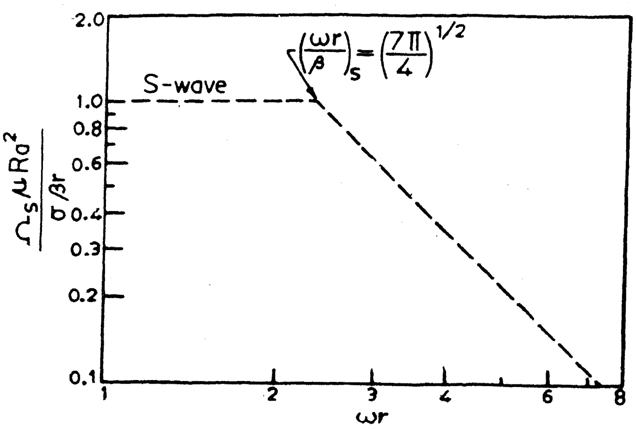

Fig.2 Comparison of spectral asymptotes for far-field S - wave displacement spectra.

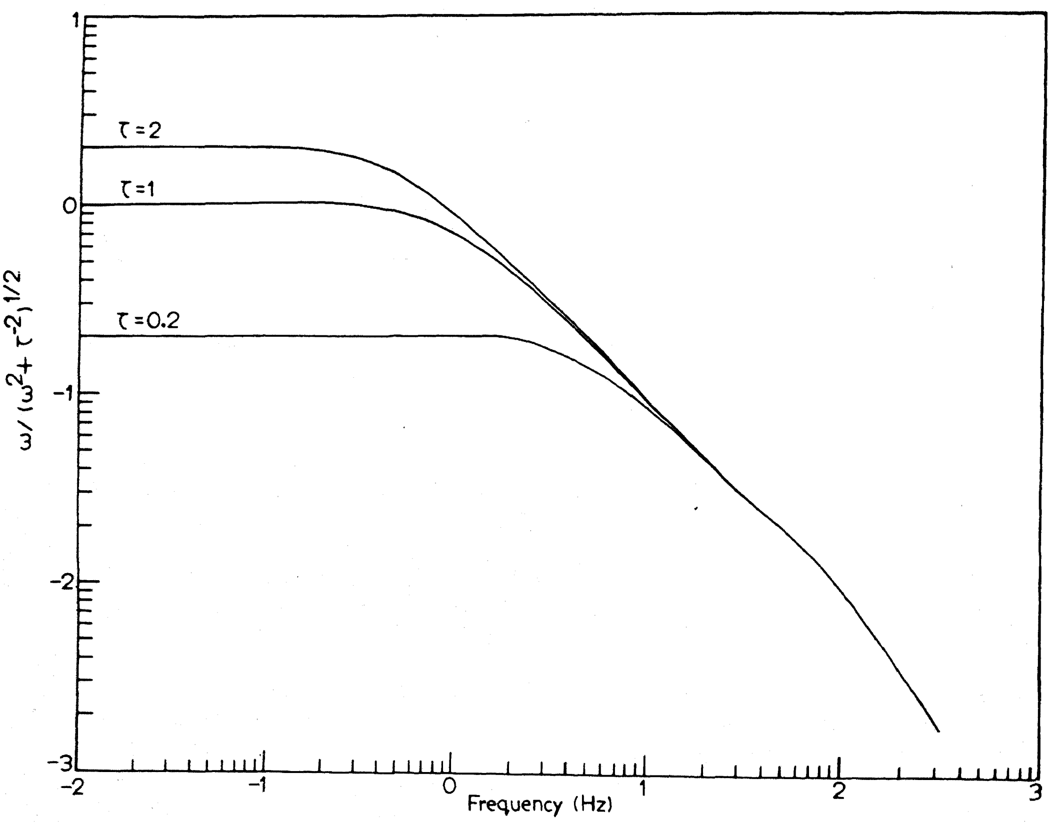

FIG.3_Near field S-wave acceleration spectral density curves.

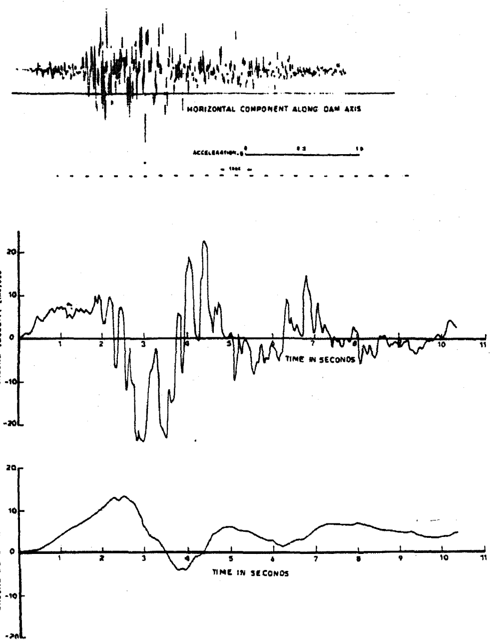

FIG.4_Ground acceleration, velocity and displacement for longitudinal component (3)

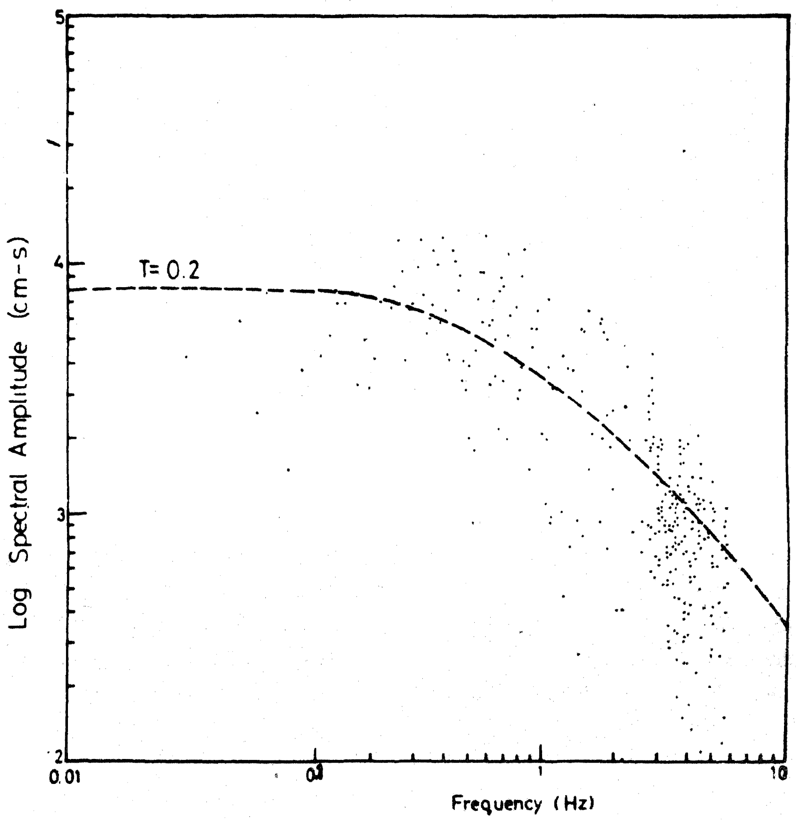

FIG.5_ Fourier amplitude spectra of Koyna longitudinal accelerogram.