DETERMINATION OF SEISMIC SOURCE PARAMETERS FOR THE 1967 EARTHQUAKE IN KOYNA DAM REGION, INDIA, USING BODY WAVE SPECTRA

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SYNOPSIS

The spectra of teleseismic body wave signals are found to show characteristic features predicted by the Brune earthquake model attesting to tectonic origin of the Koyna Dam earthquake. On the basis of these spectra the seismic moment M_o is found to be 7.76×10^{26} dyne-cm, the source dimension $r(P) = 17.9 \pm 1.2$km and $r(S) = 22.5 \pm 5.8$ km. The stress drop is estimated to be 47 bars and the seismic energy is estimated to be 1.2×10^{20} ergs.

INTRODUCTION

The Koyna earthquake of 1967 ($M_s = 6.3$) has held a special interest to scientists because of its location in the vicinity of a large dam. Several investigations of the focal mechanism of this earthquake have been reported which were based on the classical point source representation of the earthquake foci (1-8). These investigations have supplied the nodal planes which are interpreted in terms of fault plane involved in the earthquake. The dominant finding of these investigations is that the faulting was of strike-slip type. Singh et. al. (8) also studied the spectral structure of surface waves in terms of Ben-Menahem directivity function and derived the fault length. However, there have been opinions that the earthquake could have been due to non-tectonic causes (9-13).

In this paper we analyse the teleseismic body wave spectra to see if the Koyna seismic source can be represented in terms of Brune's model (14) which essentially represents the earthquake source in terms of shear faulting. The model specifies three independent spectral parameters that characterise the far-field body wave displacement spectra. These parameters consist of the long-period body waves spectral levels $\Omega_o^{p,s}$ which are proportional to seismic moment M_o, the corner frequencies ω_p and ω_s which are related to the dimension of the fault and a parameter ε which governs the high frequency ($\omega > \omega_{p,s}$) slope of the displacement spectrum. The parameter ε represents the fractional stress drop in the earthquake.

Theoretical Model

In a 'seminal work' Brune (14) developed a powerful theory describing the nature of seismic spectrum radiated by seismic sources by considering the physical process of energy release. In order to model the transverse elastodynamic radiations from an earthquake fault Brune considered a sudden loss of traction over a circular dislocation surface of radius r. The fault is assumed to be opaque to shear waves during faulting so that energy from one side of the fault does not transmit to the other side. The sudden loss of traction radiates a shear stress wave in a direction normal to the fault plane (Figure 1) whose initial time dependence is given by

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$$\sigma(z,t) = \sigma H(t - z/\beta) \quad (1)$$

where $\sigma = \sigma_0 - \sigma_f$ is the effective stress (stress drop) being the difference between the stress before the earthquake (σ_0) and the frictional stress (σ_f) opposing the fault slip. $H(\cdot)$ is the Heaviside unit step function and β is the shear wave velocity. By integration of the **one dimensional wave** equation we obtain the ground displacement V in the direction of y propagating in Z direction. The stress at Z = 0 is given by

$$\sigma(Z=0) = \mu \frac{\partial V}{\partial Z} \quad (2)$$

where μ is the shear modulus. Then invoking causality condition at Z = 0 we have,

$$V_{NF}(Z=0,t) = \frac{\sigma\beta}{\mu} t \quad (3)$$

This expression represents the initial motions near the fault plane (near field (NF)) that have not been interfered by the effects of edges of the fault plane and diffractions around it. These effects cause the particle velocity to drop and eventually become zero due to interference. This phenomenon is approximately modeled by

$$V_{NF}(Z=0,t) = \frac{\sigma\beta\tau}{\mu}(1-e^{-t/\tau})$$

and

$$\dot{V}_{NF}(Z=0,t) = \frac{\sigma\beta}{\mu} e^{-t/\tau} \quad (4)$$

where $\tau \approx 0\ (r/\beta)$.

The propagation effects in the far field are modelled by including a factor (r/R) exp(-at) in which 1/R represents the geometrical divergence, R being the distance. The exponential term takes into account the inelastic attenuation and the effects of the radiation from the boundaries of the fault. Further, the radiation pattern for the classical double couple point source has to be included. We thus have the following expression for the far field (FF) displacement

$$V_{FF}(Z=R,t') = \frac{r}{R}\frac{\sigma\beta}{\mu} t' e^{-at'} R^s_{\theta\phi} \quad (5)$$

where $t' = t - R/\beta$,

and

$$R^s_{\theta\phi} = (0, \cos 2\theta \sin\phi, \cos\theta\cos\phi) \quad (6)$$

when referred to spherical polar coordinates having the conventional relation to cartesian frame with the fault plane Z = 0 and slip in the Y direction. The Fourier transform of equation (5) representing the spectrum of the far field radiation is given by

$$\Omega^s_{FF}(\omega) = \frac{r}{R}\frac{\sigma\beta}{\mu} R^s_{\theta\phi} / (\omega^2 + \omega_s^2) \quad (7)$$

here

$$\omega_s = \left(\frac{7\pi}{4}\right)^{\frac{1}{2}} \frac{\beta}{r} \quad (8)$$

s defined as the corner frequency in the spectrum and is obtained y considering the asymptotic value of as 0 and comparing t with the static dislocation field (15).

The parameter ε is defined by

$$\varepsilon = (\sigma_0 - \sigma_1)/(\sigma_0 - \sigma_f) \tag{9}$$

which gives the fractional stress drop. In this relation σ_0 is the average stress in the plane of the fault surface before earthquake faulting, σ_1 is the average shear stress in the plane of the fault surface after the earthquake and σ_f is the frictional stress on the fault surface which opposes fault slip. The stress drop is complete when $\sigma_1 = \sigma_f$ and $\varepsilon = 1$ and the above development deals with this case.

The simplified stress time history taken above may be modified to take into account the case of partial stress drop of ε (final stress $\sigma_1 > \sigma_f$) by applying a reverse stress $(1 - \varepsilon)$ after a short time interval t_d. The Fourier spectrum in this case is modified by a function $F(\varepsilon)$ given by

$$F(\varepsilon) = \left| 1 - (1-\varepsilon)\, e^{-i\omega t_d} \right| \tag{10}$$

The P - wave displacement spectra is obtained by considering the tangential stress σ in terms of a pair of orthogonal dipoles oriented at $\pi/4$ with the direction of σ and with magnitude $\sigma/\sqrt{2}$ (Figure 2). The uniform stress $\sigma/\sqrt{2}$ applied at $Z' = 0$ sends a one dimensional pulse given by (16)

$$\sigma(Z', t) = \frac{\sigma}{\sqrt{2}}\, H(t - Z'/\alpha) \tag{11}$$

where α is the P - wave velocity, other symbols being as before. The stress $\sigma_{Z'Z'}$ is given by

$$\sigma_{Z'Z'} = (\lambda + 2\mu)\, \frac{\partial W'}{\partial Z'} \tag{12}$$

The displacement W' at $Z' = 0$ is as follows

$$W'_{NF}(Z' = 0, t) = \left(\frac{\sigma\alpha}{\sqrt{2}\mu}\right) t \tag{13}$$

where it is assumed that $\lambda = \mu$. Following the same procedure as in the case of shear waves the far field spectrum of P - waves is obtained to be

$$\Omega^{P}_{FF}(\omega) = \left(\frac{r}{R}\right)\left(\frac{\sigma\alpha}{\sqrt{2}\mu}\right) R^{P}_{\theta\phi} \Big/ (\omega^2 + \omega_p^2) \tag{14}$$

where the P - wave corner frequency ω_p is

$$\omega_p = \left(\frac{7\pi}{4\sqrt{2}}\right)^{\frac{1}{2}} \frac{\alpha}{r} \tag{15}$$

and the point source radiation pattern factor $R_{\theta\phi}$ is

$$R_{\theta\phi} = \sin 2\theta \sin \phi \tag{16}$$

The P - wave spectra is also modified by $F(\varepsilon)$ when there is a partial stress drop ε

The ideal asymptotic amplitudes of the for field P and S wave spectra for the case of complete stress drop ($\varepsilon = 1$) are displayed in Figure 3. We note that for a Poisson solid the following relationship hold

$$\lim_{\omega \to 0} \frac{\Omega^S(\omega)}{\Omega^P(\omega)} = 3\sqrt{3}$$

$$\lim_{\omega \to \infty} \frac{\Omega^S(\omega)}{\Omega^P(\omega)} = \sqrt{6} \qquad (17)$$

The corner frequencies $\omega_{P,S}$ are determined by the intersection of the flat and sloping asymptotes. The ratio of the two characteristic frequencies is given by

$$\frac{\omega_P}{\omega_S} = \frac{\alpha}{\beta}$$

Data Analysis

The long period seismograms at eight stations for P-waves and five stations for S-waves were Fourier analysed. The seismograms were taken from the WWSSN network. FFT algorithm (17) was used for the evaluation of spectra. The signal time gate analysed ranged from ~17s to 50s for P - waves and ~ 40s to 140s for S - waves. The time signals were sampled at interval of 0.55s which corresponds to Nyquist frequency of 0.9Hz. It is considered that for long-period signals there would be no appreciable energy beyond this frequency and aliasing effects would be negligible. The computed spectra were corrected for instrumental response using the theoretical expression for critically damped seismograph (18). The propagation effects consisting of geometrical divergence and anelastic loss were compensated according to a procedure outlined by Teng and Ben-Menahem (19). No correction for either source or receiver crust was made for the crustal structures are not known to sufficient accuracy. The spectra are shown in Figure 5. The focal mechanism solution (4) is also shown. Among the thirteen P - wave spectra those of HKC(Z), AAE(Z), SHI(NS,EW), TAB(Z) and KEV(Z), permit a good estimation of the asymptotes. In the other spectra the picture is not as clear and the estimates may be less reliable.

For five (AAE, TAU, VAL, MUN, IST) of the six shear wave spectra analysed here the asymptotes are well determined. However, as pointed out by Hanks and Wyss (21), the (0) level can in general be estimated to a factor of 2 from spectral measurements.

Estimate of moment M_0

The moment M_0 is related to long period level of displacement spectrum by (15)

$$M_0^{P,S} = \frac{\Omega^{P,S}(0)}{R_{\theta\phi}^{P,S}} \, 4\pi\rho R\,(\alpha,\beta)^3 \qquad (19)$$

A summary of the aymptotic estimates of $\Omega^{P,S}(0)$ made on the spectra at various stations have been given in Table 1. These spectra have to be corrected for the point source radiation pattern . This term is sensitive for stations near the nodal planes and small errors in the orientation of the fault plane cause a very rapid variation in the amplitudes. Moreover, the $R_{\theta\phi}$ term controls only the amplitude of the first half cycle (20,21) and spectral analysis is carried over a time window which spans several cycles of the signal. The estimates of $\Omega(0)$ in such cases would be too large. We have been guided by the experience of Hanks and Wyss (21) in omitting those estimates of $\Omega(0)$ from calculation of moment for which $R_{\theta\phi} < 0.05$. The fault plane solution by Khattri (4) has been used for calculating $R_{\theta\phi}$ term. A correction for the free surface and crustal effect has been applied by dividing $\Omega(0)$ estimates by 2.5 (22). The errors arising due to inclusion of other phases like pP, sS in the time signal has been neglected which are likely to overestimate the spectral levels. The average value of $M_o = 7.7 \times 10^{26}$ dyne-cm which compares well with the value of 1.7×10^{26} dyne-cm obtained from an analysis of surface waves (8).

Estimates of Seismic Energy

The application of Parseval's theorem to a volume integration of Kinetic energy density gives the energy E_s in the form of S - waves as

$$E_s = I_s R^2 \rho \beta \frac{1}{2\pi} \int_0^{\infty} |\Omega(\omega).\omega|^2 . d\omega$$

where ρ is the density, and $I = 24\pi/15$ is a term which results from the integration of S - wave radiation pattern about the source (23). The corresponding result for P waves shows that $E_p << E_s$ (23). The estimates of energy obtained in this way are listed in Table 1. The average value of $E_s = .124 \times 10^{21}$ ergs which is in good agreement with the value estimated by Singh et. al. (8) and also predicted by energy magnitude relation for body waves (24).

Corner Frequencies and Source Dimension

As noted in the earlier section the corner frequencies are related to the source dimension r through equations (8) and (15). The knee in spectra are quite clear and the estimates are reliable. The corner frequency for S - waves are lower than for P waves, a result predicted from theoretical considerations (25,26) and demonstrated in the case of a large number of earthquakes (26). The average dimension $r(P) = 17.9 \pm 1.2$km and $R(S) = 22.5 \pm 5.8$km have been obtained. The ratio $r(S)/r(P) \simeq 1.4$. This feature may be explained by considering that the source radiates a large fraction of energy simultaneously and it radiates for a time small compared with the time for seismic waves to traverse the source (26). The values of r(P) and r(S) are listed in Table 1.

Stress Drop

Assuming the source to have a circular geometry the stress drop may be estimated using the relation (14)

$$\sigma = \frac{7}{16} \frac{M_o}{r^3}$$

which gives an average value of 47.0 bars for all the determinations.

Discussion and Conclusions

The most notable finding of the present investigation is the excellent match of the far field body wave spectra with those predicted by Brune model. This may be taken to mean that the Koyna Dam earthquake was the result of the release of tectonic shear stresses in the earth. The various seismic parameters (M_o, E_s, r and σ) estimated here agree fairly well with those determined by other workers (8). The present data, however, did not permit an estimation of the fractional stress drop parameter ε which has been assumed to be 1.

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TABLE - 1

P and S Wave Spectral Data, Koyna Earthquake, 1967

Station	Phase	Component	Az (deg)	$R_{\theta\phi}$	$R^{SH}_{\theta\phi}$	$R^{SV}_{\theta\phi}$	Ω_0 $\times 10^5$ cm-sec	ω_c	r km	M_0 $\times 10^{26}$ dyne-cm	E_s $\times 10^{21}$ ergs
AAE	P	Z	260.8	.165	.628	.020	190	.56	24.6	16.3	-
AAE	P	NS	260.8	.165	.628	.020	10	1.0	13.8	.86	-
DAV	P	Z	94.8	-.124	.144	-.445	180	.76	18.2	20.7	-
HKC	P	Z	75.9	-.100	.350	-.212	164	.55	25.1	23.3	-
IST	P	Z	311.1	-.035	.186	-.422	27	1.2	11.5	10.9	-
JER	P	EW	299.7	-.022	.342	-.421	26	.71	19.4	16.6	-
JER	P	Z	299.7	-.022	.342	-.421	50	.67	20.6	32.0	-
KEV	P	Z	342.9	-.177	-.071	-.225	25	.8	17.2	2.01	-
SHI	P	EW	306.0	-.097	.216	-.510	7	.74	18.6	1.02	-
SHI	P	NS	306.0	-.097	.216	-.510	11	.90	15.3	1.61	-
TAB	P	Z	316.2	-.067	.083	-.444	30	.76	18.2	6.32	-
TAB	P	NS	316.2	-.067	.083	-.444	19	.93	14.8	4.0	-
TAB	P	EW	316.2	-.067	.083	-.444	16	.90	15.3	3.4	-
AAE	S	NS	260.8	.166	.656	-.006	150	.60	15.8	.62	.04
IST	S	NS	311.1	-.052	.170	-.446	230	.33	28.7	3.7	.16
MUN	S	EW	140.2	-.045	-.556	-.403	96	.62	15.3	.59	.28
MUN	S	NS	140.2	-.045	-.556	-.403	86	.40	23.7	.42	.04
TAU	S	NS	135.2	-.011	-.461	-.377	150	.33	28.7	.89	.07
VAL	S	NS	319.9	-.015	.117	-.358	160	.42	22.6	3.8	.16

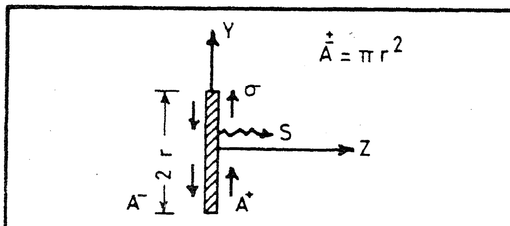

FIG.1_Dislocation model for S waves.

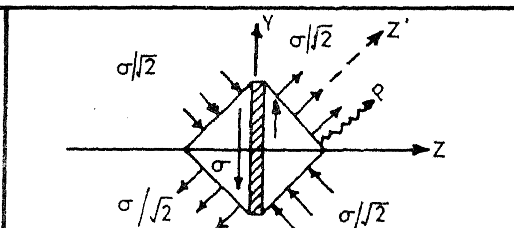

FIG.2_ Dislocation model for P waves

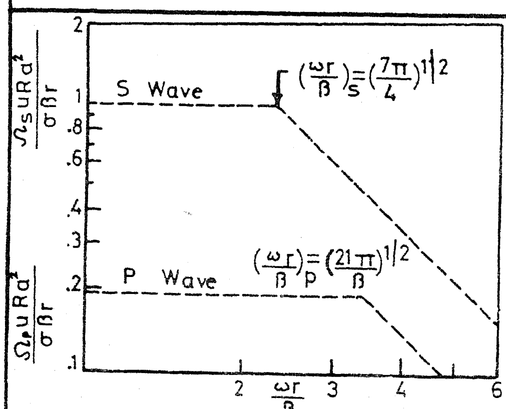

FIG.3_The far field body wave displacement spectra for $\epsilon = 1$

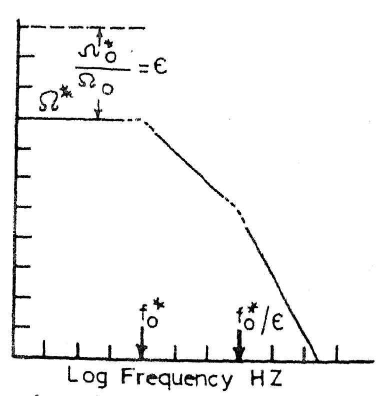

FIG.4_The far field shear displacement spectra for $\epsilon < 1$

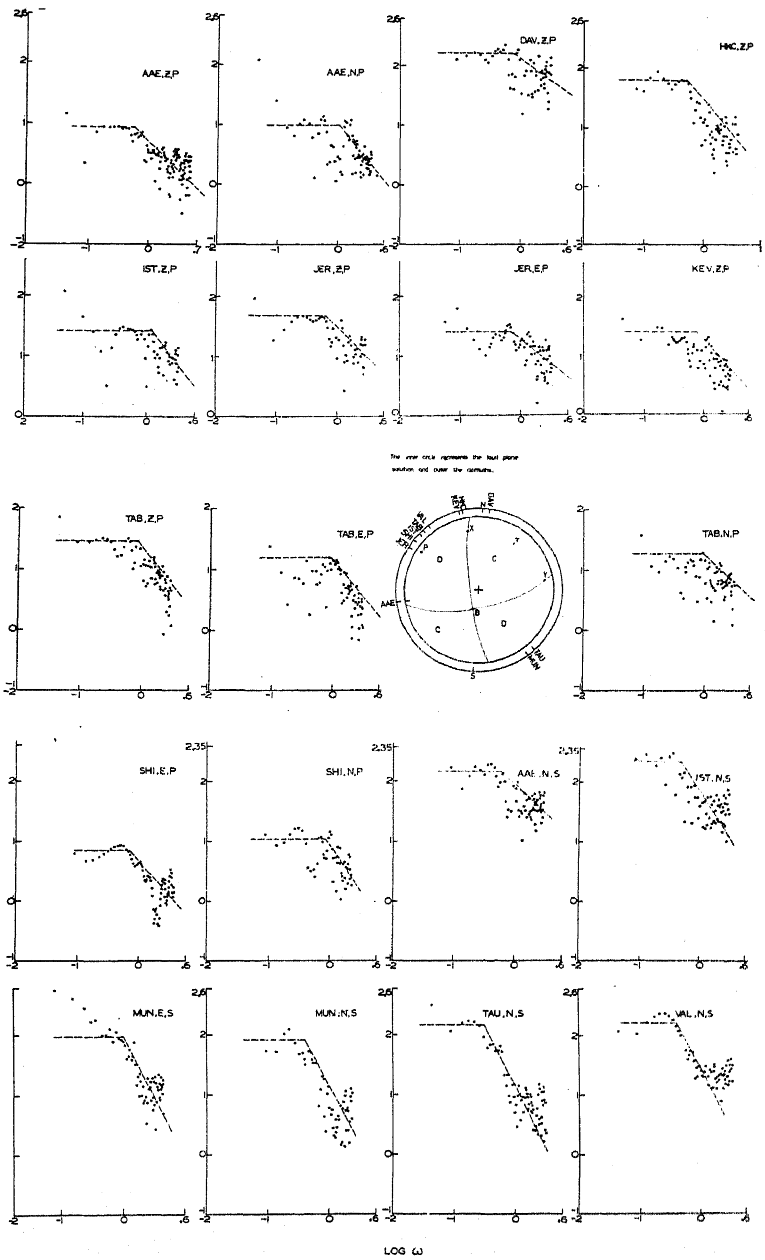

FIG. 5_ FOURIER SPECTRA OF P-AND S-WAVES

DISCUSSION

J.B. Berrill (Australia)

Has a comparison been made between your instrumentally determined seismic moment and estimate of M_o from fault effect?

Author's Closure

In response to the discussion on our paper by J.B. Berrill, we would like to reply as follows:

The Koyna earthquake was not accompanied by surface faulting. The moment M_o obtained by us is based on the analysis of body waves recorded instrumentally. The value obtained is in fair agreement with that obtained by Singh and others from an analysis of the surface waves.