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Source Parameters of Some Significant Earthquakes near Koyna Dam, India

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Abstract—Seismic moment, stress drop, source radius, and fault dislocation have been determined for nineteen significant earthquakes in the Konya area, India using displacement spectra of shear waves computed from strong-motion accelerograph records. Though the stress-drop shows a definite increasing trend with the seismic moment, its correlations with source radius and corner frequency indicate that a constant stress drop of 170 bars represents a good mean value to describe the source mechanism of the Koyna dam earthquakes. An empirical relationship also has been established between magnitude and seismic moment.

Key words: Koyna dam, accelerogram, source parameters, moment, stress-drop, corner frequency.

Introduction

The Koyna reservoir, India, provides one of the four major examples of induced seismicity in the world where earthquakes of magnitude greater than 6.0 were experienced after filling of the reservoir (GUHA and PATIL, 1990). Before impoundment of the Koyna reservoir there was no recorded evidence of any seismic activity in the reservoir area. However, with the filling of the reservoir in 1963, reports of very small earthquakes began to be prevalent in the vicinity of the dam. On September 13, 1967, five significant earthquakes ($M_L = 4.0$ to 5.6) occurred in the reservoir area; shortly followed by the main earthquake of magnitude 6.5 on December 10, 1967. Since then, the seismic activity in the Koyna reservoir area has been continuing at a relatively lower level with an occasional spurt in the activity, producing earthquakes of magnitude reaching 5.0 (GUHA *et al.*, 1974; PADALE *et al.*, 1983).

Several strong-motion accelerograms have been recorded in the Koyna area from earthquakes ranging in magnitude from 3.2 to 6.5. But the majority of these are recorded at various locations in the dam and are thus influenced by the response of the dam. However, a set of 25 accelerograms recorded in the free-field or at the

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foundation gallery of the dam from 19 significant earthquakes, has been used to compute the source parameters in the present study. The accelerograms have been digitized and processed to apply the instrument and base-line corrections (GUPTA and JOSHI, 1989), and then employed to compute the displacement spectra of the shear waves. These spectra are corrected for the free-surface amplification and the anelastic attenuation for the whole path to obtain accurate values of the low-frequency spectral amplitude, corner-frequency and the high-frequency roll-off. These values are used in BRUNE's (1970) dislocation model to evaluate the seismic moment, effective stress drop, source radius, and the fault dislocation for all 19 earthquakes.

The geology of the Koyna area, as described in the report of the Committee of Experts (1968), is characterized by basaltic rock of lava flows during the late Cretaceous to Eocene interval. These are locally known as Deccan Trap formations. The volcanics in the dam area are disposed almost horizontally with a very gentle eastward dip of about 1°. The thickness of the surface layer of basalt at the Koyna dam site is about 1.2 km. Underneath the Deccan volcanics lies the great peninsular shield of India, which is a Pre-Cambrian stable land mass. Thus no seismic activity was expected or was known to have occurred in the Koyna area. However, as mentioned before, after impounding the reservoir in 1963, significant local activity was exhibited, which is thought to be of an induced nature.

Several studies (e.g., MARION and LONG, 1980; HUTCHENSON and TALWANI, 1980; FLETCHER, 1982) have investigated the spectral characteristics and source parameters of reservoir-induced earthquakes *vis-à-vis* natural earthquakes of the same region. MARION and LONG (1980) have found that reservoir-induced earthquakes are characterized by smaller stress-drops and faster decay of high frequency spectral amplitudes. But, in the case of Koyna earthquakes no definite discriminant characteristic could be identified for the reservoir-induced nature of the earthquakes.

Theoretical Relations

According to BRUNE's (1970) source model, the displacement Fourier spectrum of far-field (large distances and long wavelengths relative to source dimension) shear waves can be idealized by a constant amplitude, Ω_0, up to a certain frequency f_c, known as the corner-frequency, and rolls off after that as $f^{-\gamma}$, where $\gamma \approx 2.0$ (HASKELL, 1964; AKI, 1967; HANKS, 1979). Thus the far-field displacement spectrum can be written as

$$\Omega(f) = \Omega_0 \frac{1}{1 + (f/f_c)^2}. \quad (1)$$

The low frequency spectral level, Ω_0, in cm-sec and the seismic moment, M_0, in dyne-cm are related as follows (KEILIS-BOROK, 1960; HASKELL, 1964; BRUNE, 1970)

$$M_0 = \frac{4\pi\rho R\beta^3}{R_{\theta\phi}}\Omega_0 \tag{2}$$

where β is the shear-wave velocity in cm/sec and ρ the density in gm/cm^3 of the earth's crust, R is the hypocentral distance in cm and $R_{\theta\phi}$ is the radiation pattern of the shear-waves.

The source radius, r, in cm of an equivalent circular source (fault) is related to the corner frequency, f_c, in Hz as follows (BRUNE, 1970)

$$r = \frac{2.34\beta}{2\pi f_c}. \tag{3}$$

The stress-drop, $\Delta\sigma$, in bars is related to M_0 and r by the relation

$$\Delta\sigma = \frac{7M_0}{16r^3} \times 10^{-6}. \tag{4}$$

The effective stress in Brune's model refers to the difference between the applied and the frictional stress opposing the rupture.

The fault dislocation, u, in cm is given in terms of M_0 and r by the following relation

$$u = \frac{M_0}{\pi\rho\beta^2 r^2}. \tag{5}$$

From eqs. (3) and (4), the corner frequency in Hz can be related to the stress drop in bars and the moment in dyne-cm as follows

$$f_c = 49\beta(\Delta\sigma/M_0)^{1/3}. \tag{6}$$

In view of eqs. (2) and (6), the spectra of different earthquakes are controlled by only two source parameters; viz., the seismic moment and the effective stress drop.

Computation of Source Parameters

To compute the source parameters using eqs. (2) through (5), resultant spectra of the two horizontal components of 25 accelerograms recorded from 19 different earthquakes (Table 1) have been used. These accelerograms have been recorded at five different stations. Three of the stations are located in the foundation gallery of the dam, which is a concrete monolith founded on good quality basaltic rock of Deccan Trap formations. One station is located 100 m downstream on the right

Table 1

Source parameters of the Koyna Dam earthquakes computed from accelerograph records

Sr #	Rec #	MAG (M_L)	D (km)	Ω_0 (10^{-2} cm-sec)	f_c (Hz)	γ	M_0 (10^{22} dyne-cm)	r (m)	$\Delta\sigma$ (bar)	u (cm)
01	04	3.5	14.4	0.2738	4.88	2.33	0.472	267.1	108.4	6.1
02	05	6.5	17.0	421.69	0.52	1.85	858.32	2506.7	238.4	126.8
03	06	3.8	20.2	0.7079	4.87	2.17	1.712	267.7	390.6	22.2
04	08	4.7	19.2	0.9363	4.57	2.47	2.152	285.2	405.0	24.6
05	09	4.6	19.0	0.8536	4.10	2.32	1.942	317.6	265.2	17.8
06	10	3.8	25.0	0.2585	6.62	1.96	0.774	196.9	443.0	18.5
07	11	4.1	16.5	0.3548	5.21	2.02	0.701	250.1	195.9	10.4
08	12	4.1	5.8	0.4732	4.87	3.16	0.330	267.7	74.9	4.3
09	13	3.7	10.4	0.6978	3.78	2.83	0.872	344.3	93.5	6.8
10	14	5.0	21.2	0.9306	3.53	1.72	2.362	369.8	204.4	16.1
11	15	5.0	21.2	0.9716	3.46	1.90	2.466	376.7	201.8	16.1
12	16	4.1	4.3	0.8659	4.20	3.18	0.446	310.8	64.9	4.3
13	17	4.1	4.3	0.6780	4.57	2.68	0.349	284.9	66.0	4.0
14	18	3.6	18.3	0.3705	4.05	1.89	0.812	321.9	106.5	7.3
15	46	5.2	8.8	1.8836	4.99	3.37	1.985	261.2	487.1	27.0
16	47	5.2	8.8	4.2169	3.23	2.94	4.443	403.6	295.8	25.3
17	48	5.2	8.8	1.7782	3.63	2.23	1.874	358.8	177.5	13.5
18	49	4.7	3.2	1.7782	4.32	3.20	0.681	301.5	108.7	6.9
19	23	4.4	9.5	0.6309	3.92	1.94	0.718	332.2	85.6	6.0
20	26	4.4	17.0	1.0000	3.75	2.19	2.035	347.6	212.0	15.6
21	27	4.2	9.5	0.4532	3.92	2.07	0.514	332.2	61.4	4.3
22	36	4.3	18.5	0.9716	3.38	1.98	2.152	385.6	164.1	13.4
23	37	4.3	18.5	0.9440	4.47	2.51	2.091	291.2	370.4	22.8
24	38	4.7	22.5	1.5848	2.96	1.84	4.269	440.4	218.7	20.4
25	39	4.9	18.8	0.5233	4.07	1.98	1.177	320.5	156.4	10.7

bank and another one about 300 m away from the right bank along the dam axis. Both of these stations are located directly on basaltic rock in the free-field.

Due to small hypocentral distances, the Koyna accelerograms are dominated by shear body waves. Thus, after deleting the P-wave portions, those have been used to compute the displacement spectra of shear waves to obtain the values of low-frequency spectral level, Ω_0, and corner frequency, f_c. The displacement spectra have been obtained simply by dividing the acceleration spectra by $(2\pi f)^2$. To obtain accurate values of Ω_0 and f_c, the Fourier spectra are first corrected for the free-surface amplification and the anelastic attenuation along the travel path. These are defined combinedly by the factor: $FS \exp(-\pi f R/\beta Q)$, where FS is the amplification due to free surface and the exponential term accounts for the whole path attenuation. Quantity Q is known as the quality factor. Following several past studies (TRIFUNAC, 1972; THATCHER and HANKS, 1973) the value of FS has been taken equal to 2.0. Consistent with the attenuation of peak ground acceleration in the Koyna area (GUPTA *et al.*, 1991), a constant value of 300 has been used for Q in the present study.

In addition to the above, HANKS (1982) noted that beyond a certain maximum frequency, f_{max}, the acceleration spectra exhibit rapid decay; much faster than that predicted by the Q term. BOORE (1983) used a Butterworth filter and ANDERSON

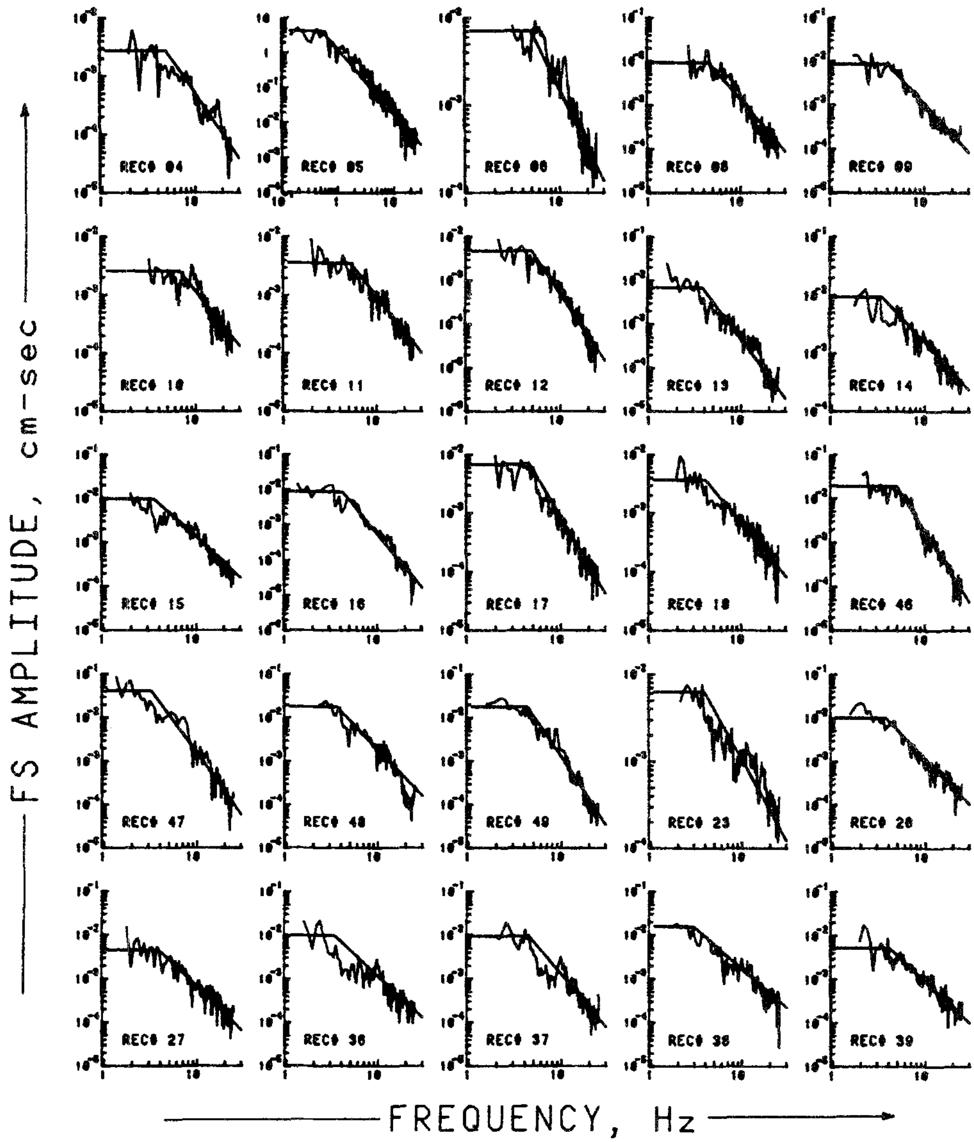

Figure 1
Resultant Fourier spectra of shear waves along with the two asymptotic lines to define the spectral parameters Ω_0, f_c and γ for all the 25 accelerograms used in this study.

and HOUGH (1984) an exponential filter to model the f_{max} phenomenon. But this effect is not seen to be very prominent in the case of Koyna accelerograms, and hence no correction has been applied on this account in this paper. Further, the path and site effects may influence the high-frequency spectral amplitudes and hence the corner frequencies determined directly from the Fourier spectra may not represent the true source property (FRANKEL and WENNERBERG, 1989; CASTRO *et al.*, 1990; SINGH *et al.*, 1989). To eliminate these recording effects, many investigators (BAKUN and BUFE, 1975; GLASSMOYER and BORCHERDT, 1990; CHAEL, 1987) have employed the spectral ratio approach, which is equivalent to the deconvolution technique using small events as Green's function (MORI and FRANKEL, 1990). But, as the recording site condition for all the accelerograms used in this study is very good quality hard rock and the geology of the Koyna area is quite homogeneous without any top thin layer of low-velocity, no high-frequency contamination is apparent in the Fourier spectra. Thus the correction applied for anelastic attenuation using Q value as above is considered to be adequate for obtaining reasonably accurate values of the corner frequencies.

To define the low-frequency level Ω_0 and the high-frequency roll-off $f^{-\gamma}$, two asymptotic lines are fitted by observation to the resultant spectra of two horizontal components of the accelerograms. Figure 1 presents the resultant spectra along with the two asymptotic lines fitted to all the 25 accelerograms used in this study. In some cases, the fitting of these two lines cannot be considered as unambiguous. Several different possibilities were tried in these cases and those from which the estimates of source parameters were assessed to be the best are retained. In addition to spectral parameters Ω_0 and f_c obtained as above, it is also necessary to know the values of shear-wave velocity β, density ρ and the radiation pattern $R_{\theta\phi}$, to compute various source parameters of the Koyna earthquakes. For the crustal structure of the Koyna area (DUBE, 1986), average values of β and ρ for the range of focal depths of interest can be taken equal to 3.5 km/sec and 2.8 gm/cm^3, respectively. The radiation pattern $R_{\theta\phi}$ is used to account for the effect of fault orientation with respect to the recording site and depends on the azimuth θ and the take-off angle ϕ (BEN MENAHEM *et al.*, 1965). However, in the present study, $R_{\theta\phi}$ has been taken equal to 0.63, which is the r.m.s. value of the double-couple radiation pattern (THATCHER and HANKS, 1973; BOORE, 1983). Using these values of β, ρ and $R_{\theta\phi}$, and the values of spectral parameters Ω_0 and f_c, source parameters M_0, $\Delta\sigma$, r and u have been computed.

Results

Table 1 gives the results on source parameters computed as described above along with the values of spectral parameters Ω_0, f_c and γ. The seismic moment for the main earthquake of 10 December, 1967 with magnitude 6.5 is found to be

858.32×10^{22} dyne-cm, whereas for remaining earthquakes with magnitudes between 3.5 and 5.2 it ranges from 3.3×10^{21} to 4.443×10^{22} dyne-cm. The computed stress drop varies from 61.4 to 487.1 bars, with the majority of earthquakes registering a stress drop of between 100 and 300 bars. The source radius and the fault dislocation for the main earthquake are 2.5 km and 1.12 m, respectively; whereas for other earthquakes their values range from 196.9 to 440.4 m and 3.5 to 21.2 cm, respectively.

Figures 2(a) and (b) show respectively the plots of $\log r$ and $\log f_c$ versus $\log M_0$. The theoretical relations defined by eqs. (4) and (6) are plotted in these figures for several values of stress-drop, $\Delta\sigma$, along with the computed results. The least-squares regression equations fitted to the data are also plotted in the figures and are given below,

$$\log M_0 = 14.48 + 3.04 \log r \tag{7}$$

$$\log M_0 = 23.97 - 3.04 \log f_c. \tag{8}$$

In these equations, M_0 is in dyne-cm, r is in meters and f_c is in Hz. The mean regression relation in Figure 2(a) corresponds to a stress drop of 161.4 bars and

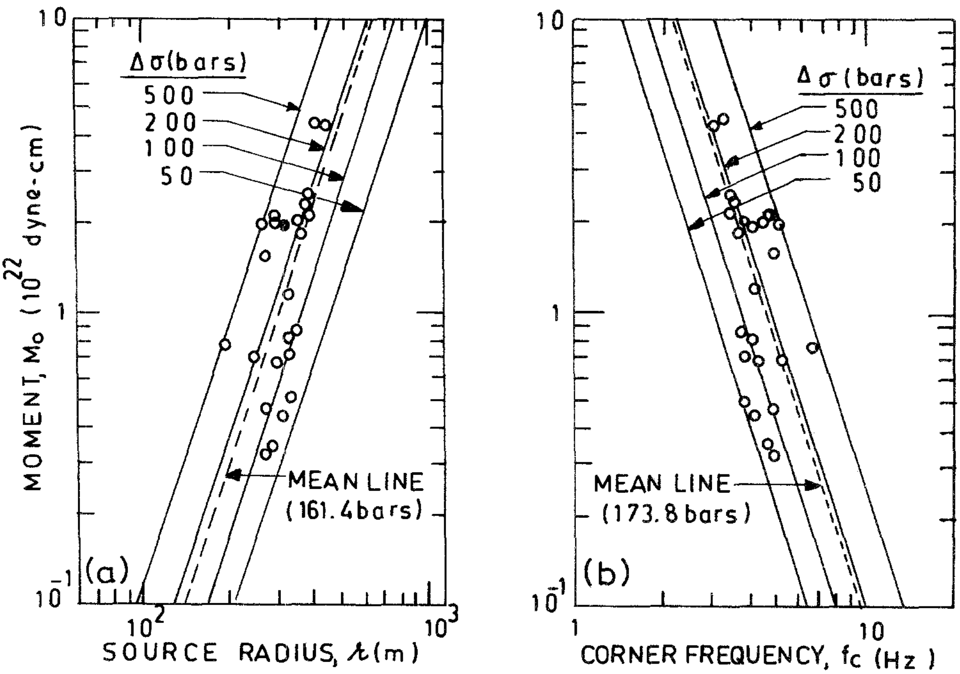

Figure 2

Plots of seismic moment M_0 versus (a) source radius r and (b) corner frequency f_c. Continuous lines show the theoretical relations for several values of stress-drop $\Delta\sigma$, and the least-squares fit to the data are shown by the dashed lines.

that in Figure 2(b) corresponds to a stress drop of 173.8 bars. Also, the least square lines in Figures 2(a) and 2(b) are parallel to the theoretical lines with different stress drops and thus describe the trend of the computed source parameters very well. Hence it is concluded that the source of Koyna earthquakes can be characterized by a mean stress-drop of about 160 to 175 bars. A stress drop of 170 bars can be considered as a good representative value.

Similar to several past studies (NUTTLI, 1983; MULLER and CRANSWICK, 1985) the moment versus stress-drop plot of Figure 3 shows a definite increasing trend of stress drop with increasing moment. Assuming that stress-drop values greater than 300 bars may not be very reliable, the following regression equation has been obtained between stress drop $\Delta\sigma$ in bars and seismic moment M_0 in dyne-cm, using the stress-drop data at ≤ 300 bars to describe this increasing trend,

$$\Delta\sigma = 176.72 \log M_0 - 3744.7 \pm 35.0. \tag{9}$$

But the large earthquakes, such as the main earthquake of magnitude 6.5, do not agree with this increasing trend, and are perhaps characterized by a much slower rate of increase or by a constant stress drop. Therefore, consistent with the

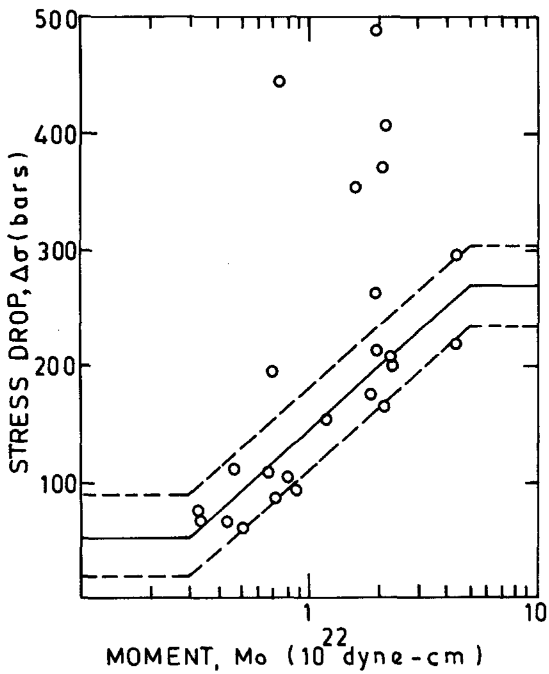

Figure 3
Correlation of stress drop $\Delta\sigma$ with the seismic moment M_0. The middle continuous curve represents the mean trend of data with $\Delta\sigma \leqslant 300$ bars, and the two dashed curves represent ± 1 standard deviation values.

available data it is suggested that the relation of eq. (9) should be used only for the range: $0.3 \times 10^{22} < M_0 < 5.0 \times 10^{22}$. For values of M_0 smaller or greater than this range, constant stress drops obtained respectively for the lower and the upper limits of M_0 are proposed to be used. Further, from the plot of Figure 4 it is seen that though the data are scattered very widely, there is a general increasing trend of stress drop with increase in focal depth. Thus the Koyna earthquakes with deeper focal depths are characterized by higher stress drops and higher seismic moments. However, the implication of these observations in relation to the reservoir-induced nature of the Koyna earthquakes is not very clear.

From the results in Table 1, the trend of the Koyna earthquakes is found to be described by the following regression relation between M_0 in dyne-cm and the local magnitude M_L

$$\log M_0 = 1.018 M_L + 17.597 \pm 0.361. \qquad (10)$$

Because the available data for the Koyna area are dominated by earthquakes with magnitudes below 5.0, the low value of the coefficient of M_L, obtained in eq. (10) is quite consistent with the findings of HANKS and BOORE (1984), who have established that both in theory and practice the $\log M_0$–M_L plot is characterized by a continuously increasing slope with increase in M_L. KANAMORI and ANDERSON (1975) have also explained on a theoretical basis that for the above magnitude range, $\log M_0 \sim M_L$, which is the case in eq. (10). The relation of eq. (10) is thus applicable only up to about magnitude 5.0.

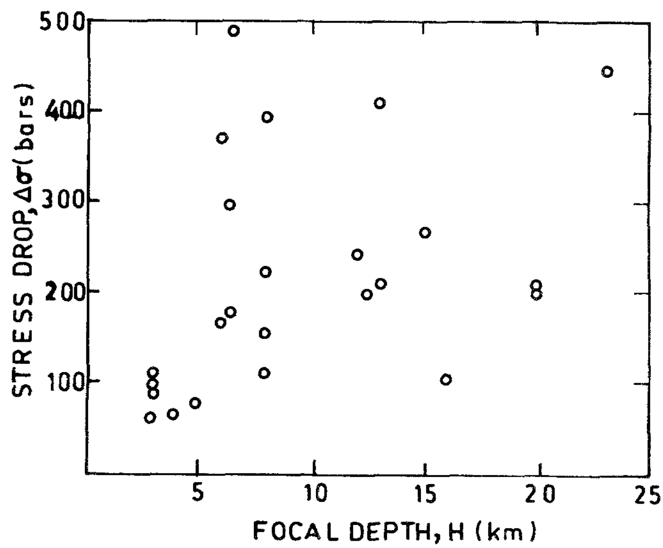

Figure 4
Plot of stress drop $\Delta\sigma$, versus focal depth H.

Conclusions

Theoretical expressions based on BRUNE's (1970) simple dislocation model have been used to compute the source parameters of nineteen significant earthquakes in the Koyna dam area. Though the computed values of stress drop show an increasing trend with an increase in seismic moment, it is found that the average behavior of the observed spectra can be described by a constant stress drop of 170 bars. Also, the observed spectra corrected for whole-path attenuation do not significantly violate the ω-squared law. The moment-magnitude data display very wide scattering and the mean regression equation fitted between them is characterized by a large standard deviation. No spectral or source characteristics could be identified in this study which may be ascribed to the reservoir-induced nature of the Koyna earthquakes.

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REFERENCES

AKI, K. (1967), *Scaling Law of Seismic Spectrum*, J. Geophys. Res. *72*, 1217–1231.

ANDERSON, J. G., and HOUGH, S. (1984), *A Model for the Shape of the Fourier Amplitude Spectrum of Acceleration at High Frequencies*, Bull. Seismol. Soc. Am. *74*, 1969–1994.

BAKUN, W. H., and BUFE, C. G. (1975), *Shear-wave Attenuation along the San Andreas Fault-zone in Central California*, Bull. Seismol. Soc. Am. *65*, 439–459.

BEN-MENAHEM, A., SMITH, S. W., and TONY, T. L. (1965), *A Procedure for Source Studies from Spectrum of Long-period Seismic Body Waves*, Bull. Seismol. Soc. Am. *55*, 203–205.

BOORE, D. M. (1983), *Stochastic Simulation of High-frequency Ground Motions Based on Seismological Models of the Radiated Spectra*, Bull. Seismol. Soc. Am. *73*, 1865–1894.

BRUNE, J. N. (1970), *Tectonic Stress and Spectra of Seismic Shear Waves from Earthquakes*, J. Geophys. Res. *75*, 4997–5009.

CASTRO, R. R., ANDERSON, J. G., and SINGH, S. K. (1990), *Site Response, Attenuation and Source Spectra of S-waves along the Guerrero, Mexico, Subduction Zone*, Bull. Seismol. Soc. Am. *80*, 1481–1503.

CHAEL, E. P. (1987), *Spectral Scaling of Earthquakes in the Miramichi Region of New Brunswick*, Bull. Seismol. Soc. Am. *77*, 347–365.

DUBE, R. K. (1986), *Relocation of the Koyna Earthquakes with a New Velocity Model*, Bull. Seismol. Soc. Am. *76*, 395–407.

FLETCHER, J. B. (1982), *A Comparison between the Tectonic Stress Measured in situ and Stress Parameters from Induced Seismicity at Monticello Reservoir, South Carolina*, Geophys. Res. *87*, 6931–6944.

FRANKEL, A., and WENNERBERG, L. (1989), *Microearthquake Spectra from the Anza, California Seismic Network: Site Response and Source Scaling*, Bull. Seismol. Soc. Am. *79*, 581–609.

GLASSMOYER, G., and BORCHERDT, R. D. (1990), *Source Parameters and Effects of Bandwidth and Local Geology on High-frequency Ground Motions Observed for Aftershocks of the Northeastern Ohio Earthquake of 31 January 1986*, Bull. Seismol. Soc. Am. *80*, 889–912.

GUHA, S. K., and PATIL, D. N. (1990), *Large Water-reservoir-related Induced Seismicity*, Geriand Beiträge zur Geophysik *99*, 265–288.

GUHA, S. K., GOSAVI, P. D., NAND, K., PADALE, J. G., and MARWADI, S. C. (1974), *Koyna Earthquakes (October, 1963 to December 1973)*, Report, Central Water and Power Research Station, Khadakwasla, Pune, India, 344 pp.

GUPTA, I. D., and JOSHI, R. G. (1989), *Advancement in the Methods of Strong Motion Accelerogram Analysis at CWPRS, Pune, India*, Proc. Silver Jubilee Symp. of Indian Soc. Earthq. Tech., University of Roorkee, Roorkee, India, Feb. 25–26, 1989, II, 13–20.

GUPTA, I. D., RAMBABU, V., and JOSHI, R. G. (1991), *Attenuation of Peak Acceleration, Velocity and Displacement at Small Distances in Koyna Dam Region, India*, 1st International Conf. on Seismology and Earthq. Engrg., Tehran, Iran, May 27–29, 1991, 307–316.

HANKS, T. C. (1979), *b-Values and Seismic Source Models: Implication for Tectonic Stress Variations along Active Crustal Fault Zones and the Estimation of High-frequency Strong Ground Motion*, J. Geophys. Res. *84*, 2235–2242.

HANKS, T. C. (1982), f_{max}, Bull. Seismol. Soc. Am. *72*, 1867–1879.

HANKS, T. C., and BOORE, D. M. (1984), *Moment-magnitude Relations in Theory and Practice*, J. Geophys. Res. *89*, 6229–6235.

HASKELL, N. (1964), *Total Energy and Energy Spectral Density of Elastic Wave Radiation from Propagating Faults*, Bull. Seismol. Soc. Am. *54*, 1811–1841.

HUTCHENSON, K. D., and TALWANI, P. (1980), *Source Properties of Earthquakes near Monticello Reservoir*, Earthquake Notes *51*, 21.

KANAMORI, H., and ANDERSON, D. L. (1975), *Theoretical Basis of Some Empirical Relations in Seismology*, Bull. Seismol. Soc. Am. *65*, 1973–1095.

KEILIS-BOROK, V. I. (1960), *Investigation of the Mechanism of Earthquakes*, Sov. Res. Geophys. *4* (English translation), 201 pp. American Geophys. U. Consultants Bureau, New York.

Koyna Earthquake, December 11, 1967. Report of the Committee of Experts. Vol. I, New Delhi, April 1968.

MARION, G. E., and LONG, L. T. (1980), *Microearthquake Spectra in the Southeastern U.S.*, Bull. Seismol. Soc. Am. *70*, 1037–1054.

MORI, J., and FRANKEL, A. (1990), *Source Parameters for Small Events Associated with the 1986 North Palm Springs, California, Earthquake, Determined Using Empirical Green Function*, Bull. Seismol. Soc. Am. *80*, 278–295.

MUELLER, C. S., and CRANSWICK, E. (1985), *Source Parameters from Locally Recorded Aftershocks of the 9 January 1982 Miramichi, New Brunswick, Earthquake*, Bull. Seismol. Soc. Am. *75*, 337–360.

NUTTLI, O. W. (1983), *Average Seismic Source Parameter Relation for Mid-plate Earthquakes*, Bull. Seismol. Soc. Am. *73*, 519–535.

PADALE, J. G., KULKARNI, U. A., KULKARNI, R. C., and PATIL, S. S. (1983), *Koyna Earthquakes (1984 to 1981), Vol. II*, Report, Central Water and Power Research Station, Khadakwasla, Pune, India, 409 pp.

SINGH, S. K., ORDAZ, M., ANDERSON, J. G., RODRIGKEZ, M., QUAAS, R., MENA, E., OTTAVIANI, M., and ALMORA, D. (1989), *Analysis of Near-source Strong-motion Recordings along the Mexican Subduction Zone*, Bull. Seismol. Soc. Am. *79*, 1697–1717.

THATCHER, W., and HANKS, T. C. (1973), *Source Parameters of Southern California Earthquake*, J. Geophys. Res. *78*, 8547–8576.

TRIFUNAC, M. D. (1972), *Stress Estimates for San Fernando, California Earthquake of February 9, 1971: Main Event and Thirteen Aftershocks*, Bull. Seismol. Soc. Am. *62*, 721–750.

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