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High Frequency Cut-Off of Observed Earthquake Spectrum and Source Parameters of Local Earthquakes in Himachal Himalaya

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Abstract: ***A dataset of 20 local earthquakes (3.4≤Mw≤5.2) occurred in the Himachal Himalaya recorded by Indian nation strong motion instrumentation network have been analyzed to infer the characteristics of high frequency attenuation of observed earthquake spectrum and source parameters of earthquakes of this region. In this study Brune's earthquake source model (Brune, 1970) that yield a fall-off of 2 beyond corner frequency has been considered to estimate the source parameters namely seismic moment, source radius and stress drop of earthquakes. High frequency attenuation of earthquake source spectrum have been modelled with two high-cut fall off functions - κ factor presented by Anderson and Hough (1984) and another arbitrary high-cut filter (Boore,1983; Wen and Chen, 2012) that fits well for frequencies greater than f_{max}. The seismic moment for these earthquakes vary between $4.2x10^{13}$ Nm and $2.3x10^{16}$ Nm and their moment magnitudes ranges from 3.4 to 5.2. The source radii of these events lie in the range 226 m to 511 m. The stress drops for these earthquakes vary from 0.2 MPa to 13.3 MPa and found in agreement with the other region of Himalaya as well as for other tectonically active regions of the world. Both functions f_{max} and κ accounting this high frequency attenuation seems to represent the same phenomenon. The results obtained in this study infer that source process is the prime controlling factor for this attenuation of earthquake spectrum at high frequencies. The data used in the present study is of 20 earthquakes, which were recorded on different sites. Data sets of earthquakes having large magnitude range (3.0≤M≤8.0) and recorded on stations having different geological site conditions will obviously help this effect to confirm properly.***

Keywords: Brune source model, high-cut frequency (f_{max}), kappa (κ), strong motion, Himachal Himalaya.

1. Introduction

Engineering designs of critical structures demand knowledge of high-frequency ground motion radiating from large and strong earthquakes. The description of an earthquake spectrum plays an important role in ground-motion prediction. A suitable representation of the earthquake-induced ground acceleration, for engineering purposes, is furnished in Fourier spectral models. The shape and amplitude of the Fourier amplitude spectrum of strong ground acceleration is recognized as useful for various applications to earthquake engineering (McGuire, 1978). This acceleration spectrum also contains fundamental information about physical processes at the earthquake source and wave propagation in the crust of the earth. Yet at high frequencies, we still do not have a satisfactory model for the shape of the acceleration spectrum. According to ω^2earthquake source model (e.g., Brune, 1970; 1971) the acceleration spectrum grows with a slope of two till corner frequency, which is related to dimension of the earthquake source (radius as considered by Brune, 1970) and beyond this corner frequency the spectrum has flat or constant shape having slope zero. Hanks (1982) observed that acceleration spectrum again decay at high frequencies and named 'f_{max}' from where spectrum shows decay.

In order to simulate strong ground motion using stochastic model Boore (1983) used a Butterworth high-cut filter that fits well for frequencies greater than f_{max} in observed acceleration spectrum as

$$\frac{1}{\sqrt{1+\left(\frac{f}{f_{max}}\right)^{N}}}$$

where N is order of filter.

Later Anderson and Hough (1984) modelled this high frequency diminution as an exponential function

$$e^{-\pi f \kappa}$$

where κ represents decay in the spectrum and interpreted that it is because of near surface crustal effects that absorb high frequencies of the spectrum.

This high frequency diminution is still a matter of active debate as to whether this high frequency diminution observed in the spectrum of an earthquake reflects the source characteristics or is on account of attenuation due to subsurface geological characteristics below the recording site (e.g., Hanks, 1982; Papageorgia and Aki, 1983a,b; Campillo, 1983; Anderson and Hough, 1984; Anderson, 1986, 1991; Faccioli, 1986; Aki, 1987; Papageorgiou, 1988; Fujiwara and Irikura, 1991; Yokoi and Irikura, 1991; Kinoshita, 1992; Morikawa and Sasatani, 2000; Tsai and Chen, 2000;Tsurugi et al., 2000, 2008;Purvance and Anderson, 2003; Kumar et al., 2012, 2013a,b,c; 2014).

In the present study, 20 local earthquakes (3.4≤Mw≤5.2) occurred in the Himachal Himalaya recorded by Indian nation strong motion instrumentation network (Kumar et al., 2012, Mittal et al., 2012) have been analyzed to infer the characteristics of high frequency attenuation of observed earthquake spectrum and source parameters of earthquakes of this region. The software EQK_SRC_PARA (Kumar et al., 2012) has been used to estimate earthquake spectral and source parameters.

2. Seismotectonics of the Study Region

With in the framework of new global tectonics the Himalayan is considered to be the result of continent-continent collision of the Indian and Eurasian plates (e.g. Le Fort, 1975; Seeber et al., 1981; Khattri 1987). The Himalaya is divided into four major tectonic and physiographic belts from south to north namely the Outer Himalaya (Siwalik), the Lesser Himalaya, the Great Himalaya and the Tethyan Himalaya or Tibat Himalaya (Himadri). The Himalaya can be subdivided into seven geographical sectors from West to East, Kashmir Himalaya, Himachal Himalaya, Kumaun, Nepal, Sikkim, Bhutan and Arunachal Himalaya.

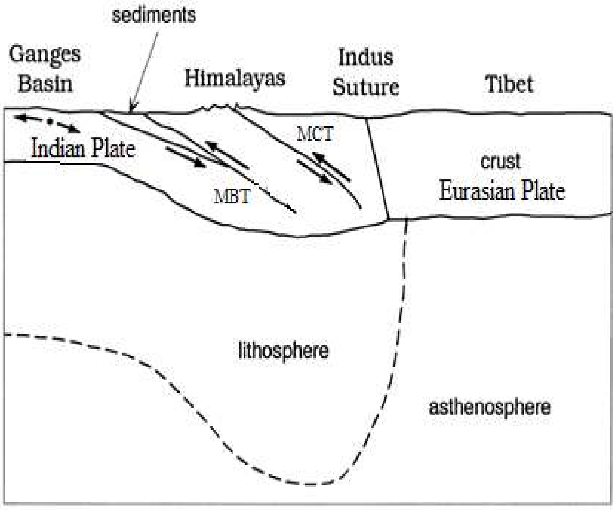


Figure 1. Schematic description of Indian plate and Eurasian plate along with prominent tectonic features like MCT, MBT and Indus Suture Zone along the Himalaya (After Molnar, 1984).

The Indus–Tsangpo Suture Zone (ITSZ) is the northern boundary of the Indian plate. The Tethyan Himalaya and the Great Himalaya are divided by Trans-Himardi fault. Main Central Thrust (MCT) is a tectonic contact between Great Himalaya and Lesser Himalaya whereas the Main Boundary Thrust (MBT) separates the Lesser Himalaya from the Outer Himalaya (Siwaliks). Himalaya Frontal Thrust (HFT) separates Outer Himalayas from the Indo-Genetic Plains as shown in Figure 1. Within the above broad tectonic framework, the Himachal Himalaya lies in the NW portion of Himalaya. This region is marked by the presence of two major tectonic features, the MCT and the MBT and several other local tectonic features such as the Drang Thrust, the JawalaMukhi Thrust and the Brasar Thrust. Besides these tectonic features, some nappe window and lineaments are also present around the dam site as shown in Figure 3. The MBT marks the northern boundary of the Siwalik belt and separates sub-Himalayan from the Lesser Himalayan. The Main Frontal Thrust (MFT) has its surface manifestations only at a few places and marks the southern limit of the Frontal Belt. The belt between the MBT and MFT is traversed by several subsidiary thrusts some of which have considerable spatial extent viz. JawalaMukhi Thrust and Drang Thrust. Evidences of neotectonic activity have been documented at several places along the MBT and in Western parts of the JawalaMukhi Thrust (Srikanita and Bhargava, 1998).

Himachal Himalaya is highly seismically active and lies in seismic zone V (IS: 1893-(Part l) 2002: General Provisions and Buildings). Many moderate to large sized earthquakes, have occurred in this region. The prominent earthquakes occurred around the study area during last more than 100 years are (i) the Kangra earthquake of 4th April 1905 (Mag.=8.0), (ii) the Chamba earthquake of 22ndJune 1945 (Mag.=6.5), (iii) the Kinnaur earthquake of 19thJanuary 1975 (Mag.=6.2), (iv) the Dharamshala earthquake of 26th April 1986 (Mag.=5.5).

3. Data Set

Indian nation strong motion instrumentation network has been in operation by Department of Earthquake Engineering, Indian Institute of Technology Roorkee (funded by Ministry of Earth Sciences, Govt. of India). In this network 300 strong motion accelerographs (Figure 2) in North and NE India covering seismic zones V, IV and some thickly populated cities of seismic zone III have been in operation. Under this project, strong motion stations have been installed in the states of Himachal Pradesh, Punjab, Haryana, Rajasthan, Uttarakhand, Uttar Pradesh, Bihar, Sikkim, West Bengal, Andman and Nicobar, Meghalaya, Arunachal Pradesh, Mizoram and Assam. This network comprised of GSR-18 (Geosig, model GSR-18 sampling rate 200 Hz) digital instruments with best possible communication facilities to network these instruments.

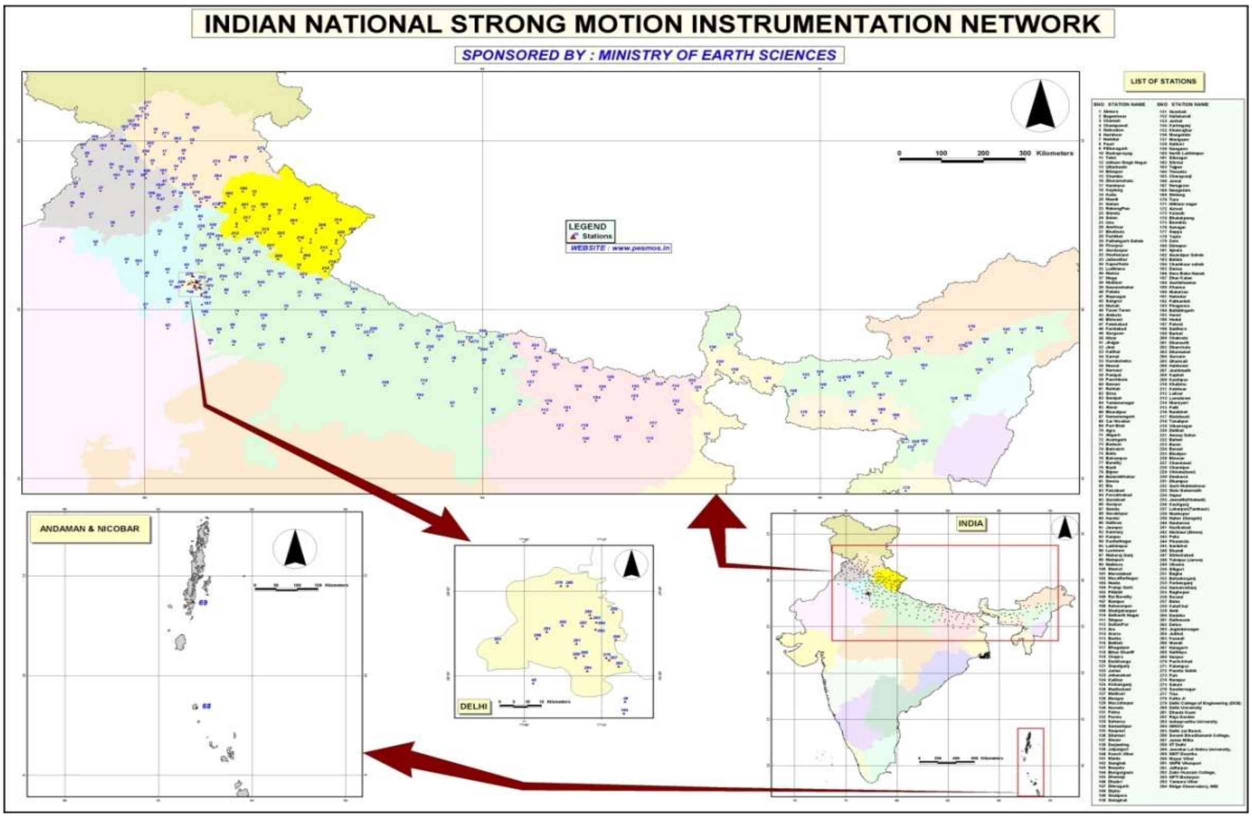


Figure 2: Indian nation strong motion instrumentation network (Kumar et al., 2012).

Out of 300, 31 instruments have been installed in Himachal Pradesh to closely monitor the seismic activity in Himachal Himalayas (Kumar et. al., 2012). A dataset of 20 local earthquakes (3.4≤Mw≤5.2) occurred in the Himachal Himalaya have been used in this study (Figure 3).

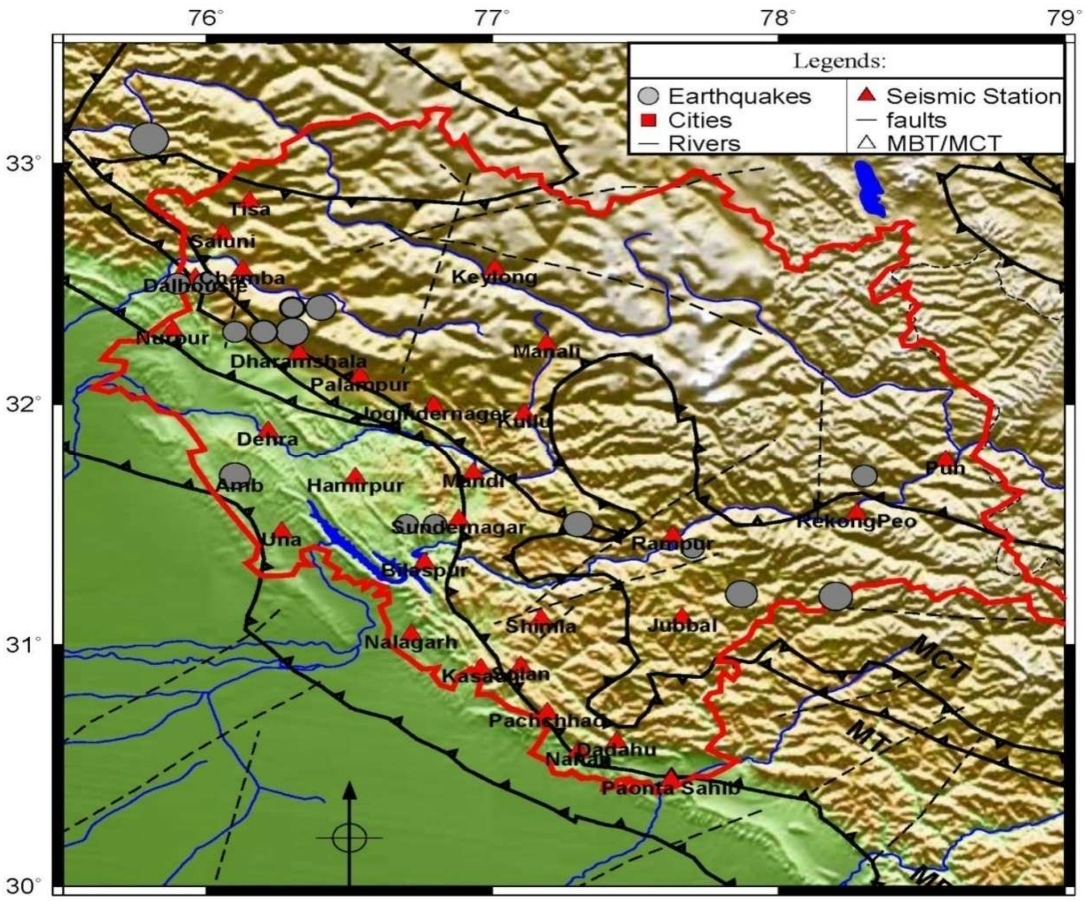


Figure 3: Map showing strong motion network in Himachal Pradesh (red coloursolid triangles) and epicenters of recorded events (grey colour solid circles).Tectonics after GSI (2000).

4. Methodology

The time histories are rotated about azimuth to obtain SH-component of ground motion and corrected to account path effects. The frequency dependent attenuation, $70f^{1.23}$ (estimated from coda waves) and average shear wave velocity (3.3 km/s) estimated for the crust below Bilaspur region of Himachal Lesser Himalaya have been considered. In this study Brune's source model (Brune, 1970; 1971) that yields a fall-off of 2 beyond corner frequency is considered. The observed acceleration spectrum has the following mathematical form:

$$A(R,f) = \frac{C\,\omega^2\Omega_0}{1+(\frac{f}{f_c})^2} \qquad (1)$$

Similarly for displacement spectrum

$$D(R,f) = \frac{C\,\Omega_0}{1+(\frac{f}{f_c})^2} \qquad (2)$$

Hanks (1982) observed that acceleration spectrum diminishes beyond after certain frequency and named it as f_{max}. This high frequency diminution is still controversial about its relationship whether it is because of earthquake source or subsurface geological characteristics below the recording site. In order to model this high-cut frequency and its slope following two functions have been adopted for analysis.

An arbitrary high-cut filter (Boore, 1983; Wen and Chen, 2012) has been used to estimate f_{max} and slope of the spectrum above f_{max} in observed acceleration spectrum.

$$P(f) = \frac{1}{1+(\frac{f}{f_{max}})^p} \qquad (3)$$

Another type of high frequency attenuation parameter κ presented by Anderson and Hough (1984) has been used:

$$P(f) = e^{-\pi f \kappa} \qquad (4)$$

The software EQK_SRC_PARA (Kumar et al., 2012) modified to model high frequency attenuation of earthquake source spectrum with above two high-cut fall off functions - κ factor presented by Anderson and Hough (1984) and another arbitrary high-cut filter (Boore, 1983; Wen and Chen, 2012) that fits well for frequencies greater than f_{max} has been used to estimate the spectral and source parameters. Following Kellis-Borok, (1959) the seismic moment is estimated from the value of Ω0 as:

$$\text{Seismic Moment, } M_o = \frac{4\pi\rho\beta^3 R\Omega_0}{R_{\theta\varphi}.S_a} \qquad (5)$$

Here ρ is the average density (2.67 g/cm3), β is shear wave velocity in the source zone (3.3 km/sec), R is the hypocentral distance that accounts for geometrical spreading, $R_{\theta\phi}$ is the average radiation pattern (0.63), S_a is free surface amplification (2).

The moment magnitude has been estimated following Hanks and Kanamori (1979) as:

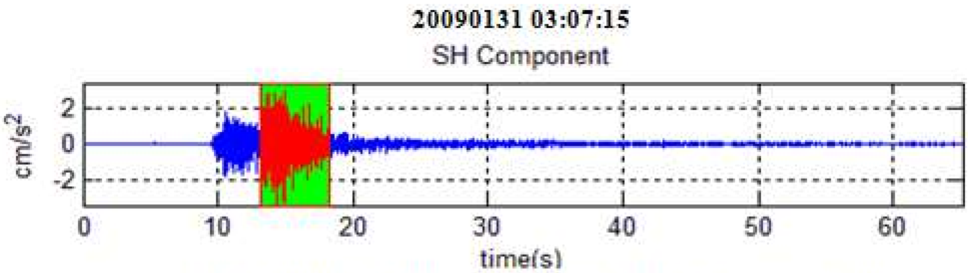
$$\text{Moment magnitude, } M_W = \frac{2}{3}\log(M_o) - 10.7 \qquad (6)$$

The source radius and stress drop are estimated following Brune (1970, 1971) as:

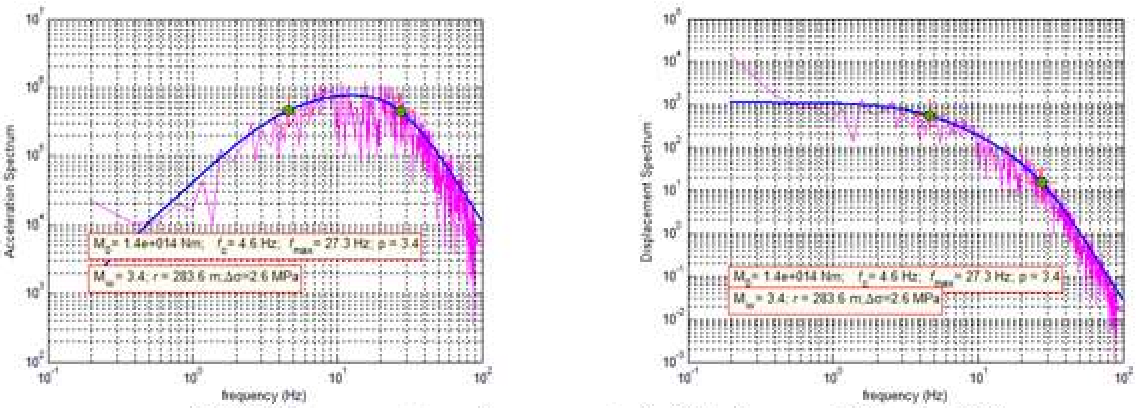
$$\text{The source radius, } r = \frac{2.34\beta}{2\pi f_c} \qquad (7)$$

$$\text{The stress drop, } \Delta\sigma = \frac{7M_o}{16r^3} \qquad (8)$$

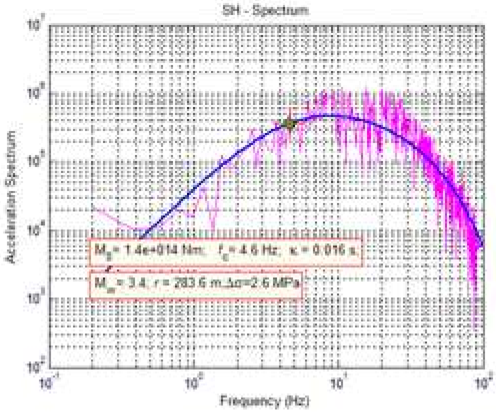
A typical example of an earthquake (Mw 3.5) occurred 31st January 2009 has been shown in Figure 4. The estimated acceleration and displacement spectra along with modeled source model (Brune, 1970) along with high-frequency decay functions are also shown in Figure as a solid blue line. The hypocenter parameters have been adopted as reported by Indian Meteorological Department (IMD). The hypocenter parameters and estimated values of spectral and source parameters for these earthquakes are given in Table 1.



a) Arbitrary high-cut filter "f_{max}" (Boore, 1983; Wen and Chen, 2012)



b) High frequency attenuation parameter "κ" (Anderson and Hough, 1984)



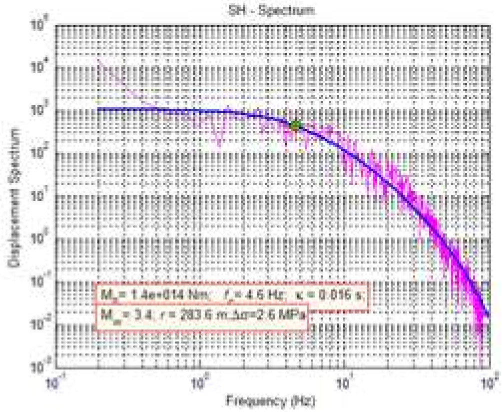


Table 1: Hypocenter parameters of local earthquakes occurred in Himachal Himalaya along with estimated spectral parameters and source parameters.

Sr. No	*DATE*	*Time*	*Lat. (ºN)*	*Long (ºE)*	*Depth (Km)*	*Mag.*	f_c *(Hz)*	f_{max} *(Hz)*	*p*	*κ*	M_0 *(Nm)*	*R (m)*	*Δσ (MPa)*
1	20061210	08:19:29	31.5	76.7	33	3.5	3.1	16.9	2.3	0.014	1.7E+14	419.0	1.3
2	20071004	05:14:15	32.5	76	10	3.8	2.7	27.3	3.4	0.014	2.60E+14	476.7	1.1
3	20081021	15:09:06	31.5	77.3	10	4.5	3.3	16	2.6	0.016	3.20E+15	393.0	13.2
4	20090109	12:40:18	31.7	78.3	16	3.8	5.7	13.8	1.9	0.015	9.10E+13	230.6	3.2
5	20090131	03:07:15	32.5	75.9	10	3.7	4.6	27.3	3.4	0.016	1.40E+14	283.6	2.6
6	20090717	11:07:47	32.3	76.1	10	3.7	2.9	13.1	2.7	0.021	9.10E+13	327.2	1.1
7	20100314	06:53:21	31.7	76.1	29	4.6	3.8	14.7	2.6	0.019	5.80E+14	343.3	6.2
8	20100528	07:25:06	31.21	77.871	43	4.8	3.7	8.8	2.7	0.023	5.30E+13	348.8	0.6
9	20100813	17:11:07	31.4	77.7	6	3.4	5.3	18.4	2.5	0.016	1.90E+14	245.7	5.7
10	20111026	16:17:32	31.5	76.8	5	3.5	3.9	11	3.2	0.021	3.00E+14	337.8	3.5
11	20120813	20:32:59	34.8	73.7	30	5.2	2.8	15.7	2.0	0.056	4.20E+13	471.9	0.2
12	20121002	03:45:28	32.4	76.4	10	4.5	3.7	20.9	3.3	0.016	3.10E+14	348.8	3.2
13	20121002	08:34:52	32.3	76.3	10	4.9	3.2	11.2	3.0	0.028	2.30E+16	402.5	13.3
14	20121003	10:04:34	32.4	76.3	5	3.8	3.8	33.6	3.3	0.008	5.10E+14	343.3	5.5
15	20121003	10:49:28	32.4	76.3	10	3.6	3.6	20.2	2.5	0.015	9.40E+14	360.0	8.8
16	20121003	17:48:28	32.4	76.3	10	3.4	5.3	18.4	2.5	0.016	1.90E+14	245.7	5.7
17	20121106	12:21:12	32.3	76.2	5	4.1	5.8	24.9	2.2	0.009	2.90E+14	226.3	11.1
18	20121111	20:23:12	32.3	76.2	5	4.0	3.0	14	2.5	0.025	1.20E+15	427.8	6.9
19	20130604	17:34:44	32.7	76.7	10	4.8	3.8	19.3	2.2	0.015	4.50E+15	338.7	10.2
20	20130605	22:04:00	32.8	76.3	10	4.5	2.6	12.3	2.4	0.020	1.00E+15	511.0	3.3

5. Results and Discussions

The earthquake source parameters viz., seismic moment, source radius and stress drop have been estimated for almost all seismically active regions of the world. The well-known earthquake source model also called Brune's source model (1970) have been used in thousands of studies. The low frequency spectral level of displacement spectra defines seismic moment of an earthquake, and the corner frequency defines the radius of fault as assumed by Brune (1970) that small earthquakes can be represented as circular fault. Hanks (1982) observed that acceleration spectrum diminishes beyond after certain frequency and named it as f_{max}. This high frequency diminution is still a matter of active debate as to whether this high frequency diminution observed in the spectrum of an earthquake reflects the source characteristics or is on account of attenuation due to subsurface geological characteristics below the recording site (e.g., Hanks, 1982; Papageorgia and Aki, 1983a,b; Campillo, 1983; Anderson and Hough, 1984; Anderson, 1986, 1991; Faccioli, 1986; Aki, 1987; Papageorgiou, 1988; Fujiwara and Irikura, 1991; Yokoi and Irikura, 1991; Kinoshita, 1992; Morikawa and Sasatani, 2000; Tsai and Chen, 2000;Tsurugi et al., 2000, 2008;Purvance and Anderson, 2003; Kumar et al., 2012, 2013a,b,c; 2014).

In this study both factors that accounts for attenuation of earthquake spectrum at high frequency have been estimated. An arbitrary high-cut filter (Boore, 1983; Wen and Chen, 2012) to estimate "f_{max}" and slope of the spectrum above $f_{max.}$ Papageorgia and Aki (1983a,b) inferred this factor due to source process and cohesive zone between ruptured and un-ruptured portion of rupturing fault attenuates high frequency portion of the spectrum. The other attenuation parameter "κ" presented by Anderson and Hough (1984), they interpreted that near surface attenuation causes the high frequency decay.

The obtained spectral parameters namely seismic moment, corner frequency (f_c), high-cut frequency (f_{max}), slope of acceleration spectrum above f_{max} and near surface attenuation factor (κ) have been analyzed and interpreted.

Figure 5 presents the plot of seismic moment with the factors accounting this high frequency diminution, viz. kappa (κ) plotted as 1/κ; f_{max} and slope (p) of spectrum for frequencies above f_{max}. All these factors have almost similar trends with seismic moment inferring that these factors account the same phenomenon whether it is source process or near surface attenuation. Kumar et al. (2012; 2013a,b,c; 2014) studies the dependence of f_{max} has been studied on the basis of comparative dependency of f_c and f_{max} and found that source process is the main factor for this attenuation and is independent of distance and focal depth of earthquakes as well as recording site conditions.

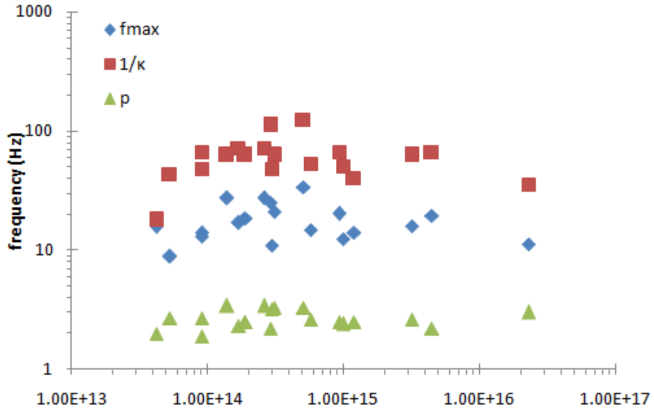


Figure 5: Plot of seismic moment vs factors accounting high frequency diminution.

The plot in Figure 6 showing the relationship of f_{max} with κ. The following have been estimated between these factors:

$$\kappa = -0.0005\, f_{\max} + 0.0258$$

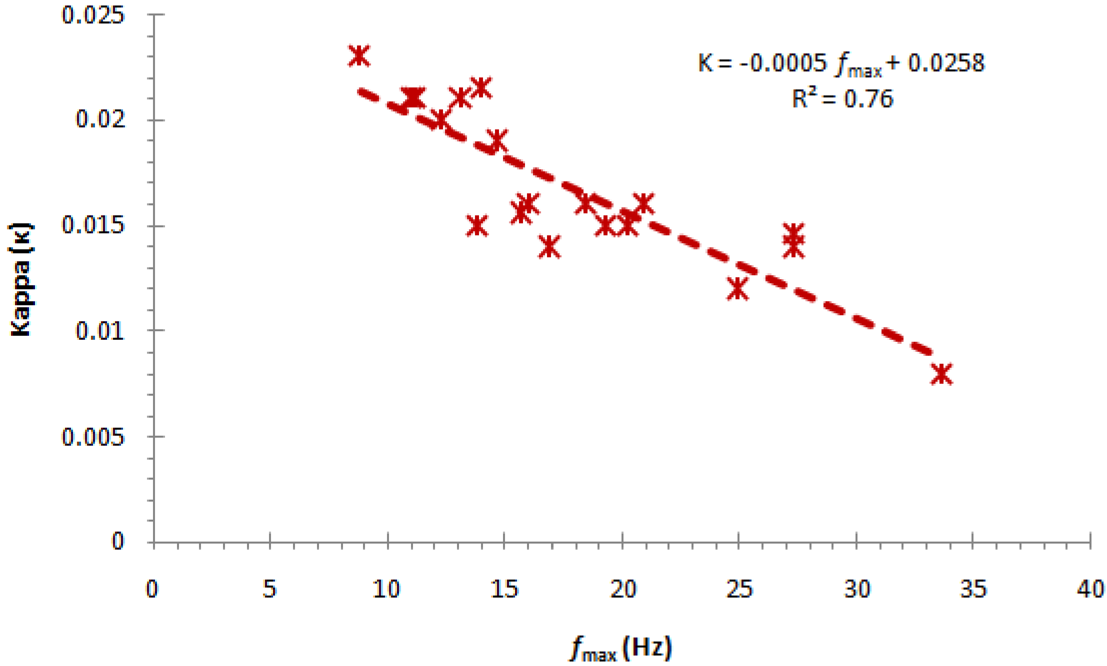


Figure 6: Plot showing the relationship of f_{max} with κ.

Havskov and Ottemöller (1999) as given in 'qspec' manual define the high-cut frequency f_κ as "the frequency where the spectral level reached 0.5 (acceleration spectrum) as a result of the effect of near surface attenuation" and estimated it as

$$e^{-\pi\kappa f_\kappa} = 0.5$$

$$=> f_\kappa = \frac{0.223}{\kappa}$$

The relationship of both high-cut frequencies f_{max} and f_κ with seismic moment (Figure 7) shows they are almost similar. A little difference in the estimated f_{max} from spectrum and f_κ calculated from κ may be due to the difference of obtaining these values during processing with different functions.A linear relationship (Figure 8) has been obtained between f_{max} and f_κ as given below:

$$f_\kappa = 0.54\, f_{\max} + 4.4981$$

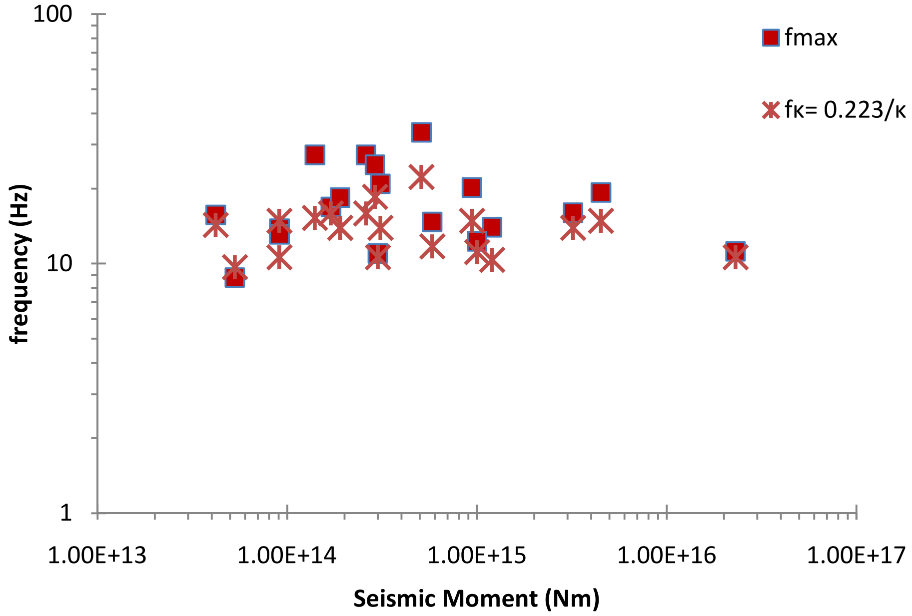


Figure 7: Plot showing the relationship of f_{max} and f_κ with seismic moment.

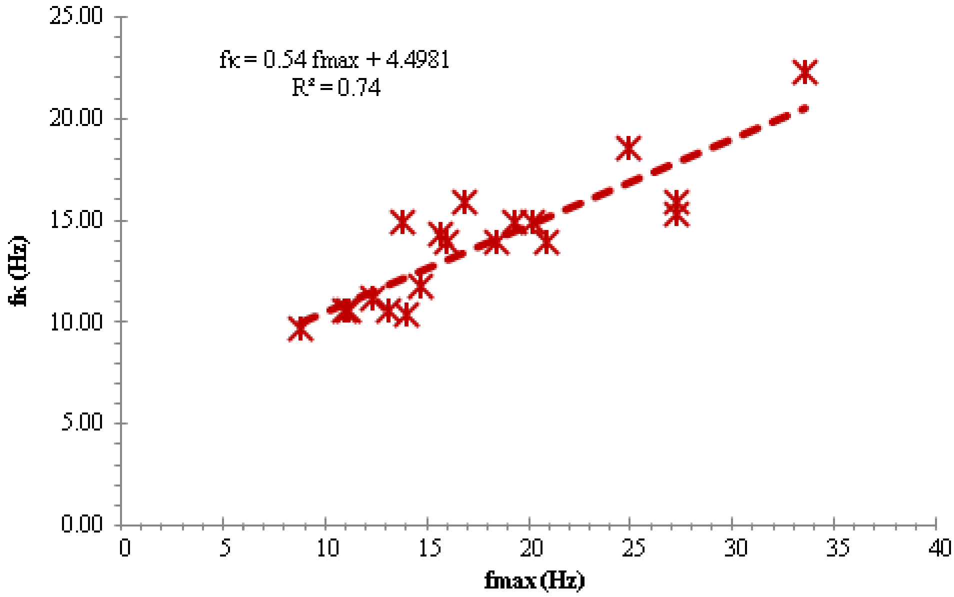


Figure 8: Plot showing the relationship between f_{max} and f_κ.

The estimated values of seismic moment for these earthquakes varybetween 4.2×10^{13} Nmand2.3×10^{16}Nmand their moment magnitudes ranges from3.4 to 5.2. The source radii of these events lie in the range 226 m to 511 m.

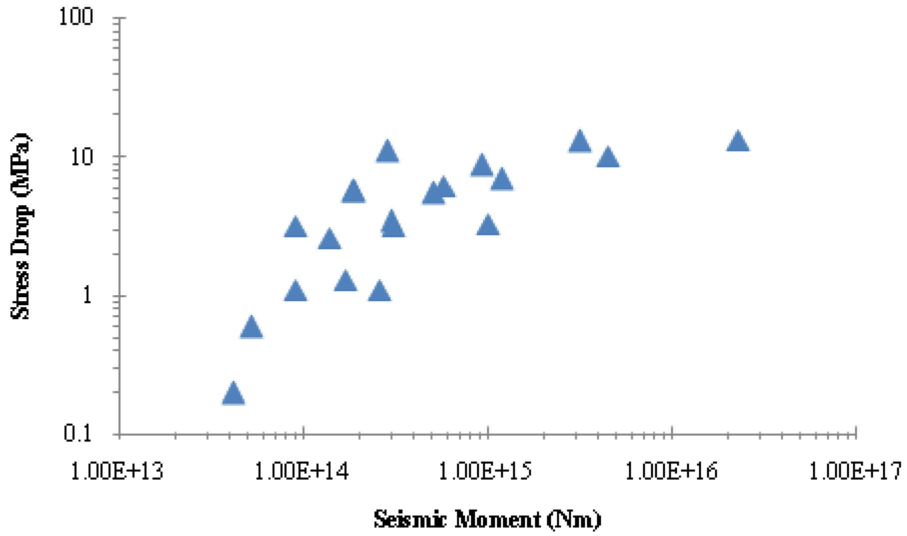


Figure 9: Plot showing the estimated stress dropsvs. seismic moments.

The obtained stress drops vary from 0.2 MPa to 13.3 MPa. The plot in Figure 9 shows the stress drops for earthquakes with different seismic moments and found in agreement with the other region of Himalaya as well as for other tectonically active regions of the world. The average stress drop observed for Himalayan earthquakes is about 58 bars by Kumar et al. (2008) and about 60 bars as reported by Kumar (2011). The stress drop shows increasing trend with seismic moment for low magnitudes and becomes almost constant for higher magnitude events, this observation has been reported in various studies (e.g., *Sharma and Wason, 1994; Wason and Sharma, 2000; Paul et al., 2007; Paul and Kumar, 2010; Kumar et.al., 2006; 2012; 2013a, b, c; 2014; Borkar et al., 2013; Sivaram et al., 2013; Paidi et al., 2013, Parshad et al., 2014; Sen et al., 2014).*

6. Conclusions

High frequency attenuation and source parameters have been studied from 20 earthquakes recorded by strong motion network deployed in Himachal Himalaya. The seismic moment for these earthquakes vary between 4.2×10^{13} Nm and 2.3×10^{16} Nm and their moment magnitudes ranges from 3.4 to 5.2. The source radii of these events lie in the range 226 m to 511 m. The stress drops for these earthquakes vary from 0.2 MPa to 13.3 MPa and found in agreement with the other region of Himalaya as well as for other tectonically active regions of the world. Both considered functions f_{max} and κ accounting high frequency attenuation seems to represent the same phenomenon. The results obtained in this study infer that source process is the prime controlling factor for this attenuation of observed earthquake spectrum at high frequencies. The data used in the present study is of 20 earthquakes which were recorded on different sites. Data sets of earthquakes having large magnitude range ($3.0 \leq M \leq 8.0$) and recorded on stations having different geological site conditions will obviously help this effect to confirm properly.

7. Future Scope

Engineering designs of critical structures demand knowledge of high-frequency ground motion radiating from large and strong earthquakes. The description of an earthquake spectrum plays an important role in ground-motion prediction. According to ω^2 earthquake source model (e.g., Brune, 1970; 1971) the acceleration spectrum grows with a slope of two till corner frequency, which is related to dimension of the earthquake source (radius as considered by Brune, 1970) and beyond this corner frequency the spectrum has flat or constant shape having slope zero. Hanks (1982) observed that acceleration spectrum again decay at high frequencies and named 'f_{max}' from where spectrum shows decay. Yet at high frequencies, we still do not have a satisfactory model for the shape of the acceleration spectrum and the exact knowledge about its origin; whether earthquake source or near surface attenuation. Present study found that both models; f_{max} and κ are equivalent and represent the same phenomenon and source process is the prime controlling factor for this high frequency cut-off of observed earthquake spectrum. Data sets of earthquakes having large magnitude range ($3.0 \leq M \leq 8.0$) and recorded on stations having different geological site conditions will obviously help this effect to confirm properly.

8. Acknowledgment

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