Estimates of source parameters of M 4.9 Kharsali earthquake using waveform modelling

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This paper presents the computation of time series of the 22 July 2007 M 4.9 Kharsali earthquake. It occurred close to the Main Central Thrust (MCT) where seismic gap exists. The main shock and 17 aftershocks were located by closely spaced eleven seismograph stations in a network that involved VSAT based real-time seismic monitoring. The largest aftershock of M 3.5 and other aftershocks occurred within a small volume of 4×4 km horizontal extent and between depths of 10 and 14 km. The values of seismic moment (M_o) determined using P-wave spectra and Brune's model based on f^2 spectral shape ranges from 10^{18} to 10^{23} dyne-cm. The initial aftershocks occurred at greater depth compared to the later aftershocks. The time series of ground motion have been computed for recording sites using geometric ray theory and Green's function approach. The method for computing time series consists in integrating the far-field contributions of Green's function for a number of distributed point source. The generated waveforms have been compared with the observed ones. It has been inferred that the Kharsali earthquake occurred due to a northerly dipping low angle thrust fault at a depth of 14 km taking strike N279°E, dip 14° and rake 117°. There are two regions on the fault surface which have larger slip amplitudes (asperities) and the rupture which has been considered as circular in nature initiated from the asperity at a greater depth shifting gradually upwards. The two asperities cover only 10% of the total area of the causative fault plane. However, detailed seismic imaging of these two asperities can be corroborated with structural heterogeneities associated with causative fault to understand how seismogenesis is influenced by strong or weak structural barriers in the region.

1. Introduction

The Himalaya is the product of collision of Indian and Eurasian plates (Dewey and Bird 1970; Zhao *et al* 1993). At present the Indian plate is underthrusting beneath the Eurasian plate. The elastic strain energy built due to the plate movement is a continuous process which resulted in the occurrence of four great earthquakes in the last one hundred and twenty years in the Indian region (1897 Shilong, 1905 Kangra, 1934 Bihar–Nepal, 1950 Assam) but no great earthquake has occurred in the Garhwal–Kumaun region. This section of Himalayan arc between the ruptured zones of Kangra earthquake and Bihar–Nepal earthquake

has been recognized as seismic gap (figure 1) and it has been interpreted to have accumulated potential slip for generating future great earthquakes (Khattari and Tyagi 1983). On 22 July 2007 a moderate earthquake (M_L 4.9) occurred near Kharsali in this seismic gap region (figure 1) where two moderate earthquakes had occurred in the recent past at an interval of 8 yrs (19 October 1991, Uttarkashi earthquake – M_L 6.5 and 29 March 1999, Chamoli earthquake – M_L 6.6). The 2007 Kharsali earthquake was recorded by recently established VSAT connected eleven station broadband network. Studies have been carried out on the recorded time series data and the modelling results are compared with the synthetic time series.

Keywords. Green's function; near field; Himalaya.

Figure 1. (a) Tectonic map of the region (after Valdiya 1981) showing seismic stations (★) and epicentral locations of moderate earthquakes (■) Kharsali (2007), Chamoli (1999), Uttarkashi (1991) and aftershocks of Kharsali earthquake (○). (b) Four great earthquakes along the Himalayan arc (Richter 1958).

Detailed analysis of time series data recorded during an earthquake helps in understanding the physics of the earthquake source which is quite complicated and cumbersome to work out. The faulting process may be highly inhomogeneous. The distribution of slip over the fault can vary both in magnitude and direction (Mikumo and Miyatake 1987; Wald *et al* 1991). There are regions on the fault where large slip might occur which corresponds to asperities. Some details of this variability of slip distribution over the fault plane can be inferred from modelling of ground motion data.

The earliest and most fundamental synthesis of ground motion was carried out by Keiiti (1968) and Haskell (1969) based on Green's function approach. The response of horizontally layered crustal structure to a double couple point source

has been computed using a number of techniques. The work was further carried out by different researchers using different sets of waveform data (Khattri *et al* 1994; Yu *et al* 1995; Ichinose *et al* 1997; Paul and Pant 2003; Singh and Mittal 2005).

The generation of synthetic seismograms helps in estimating several critical parameters, such as location of a point of initiation of rupture, rupture velocity, rise time and distribution of slip amplitude on the fault, which are considered rigorously during analysis.

In the present work, the generation of synthetic seismograms in the near field is based on dislocation moving over a fault plane. Nature of rupture propagation over the fault plane, radiation pattern effects, presence of free surface layering in the earth between the source and free surface and effect of finite moving source are some

of the key fault features considered for waveform generation.

2. Geology and tectonics of the region

Sandwiched between the Main Boundary Thrust (MBT) in the south and Main Central Thrust (MCT) in the north, the Garhwal–Kumaun Hills are structurally very complex and ecologically sensitive. Geologically the rocks in this region constitute the southeastern terminus of the Krol belt (Auden 1934; Heim and Gansser 1939; Valdiya 1988). The Krol belt in Garhwal–Kumaun Hills comprises the Jaunsar and Krol group in an ascending order of succession. The Nagthar formation made up of thick succession of Quartzarenite associated with penecontemporaneous mafic lava flows constitutes the lowermost litho unit in the area. There are two major sets of active northward dipping thrusts MCT and MBT. Along these thrusts, slabs of the subducting Indian plate have piled southward. These thrusts form the boundaries of geological subprovinces having characteristic geology and physiography (Gansser 1964). Along the MCT, the crystallines of the Higher Himalaya (Precambrian) are overthrust southward and have overridden the metasedimentary formations (Paleozoic) of the lesser Himalaya. These formations of Lesser Himalaya have overridden the mollasic Shiwalik (Cenozoic) sedimentary formations of the outer Himalaya along the MBT. The formations just to the north of MBT are highly folded and thrust.

The slopes of the region are steep. The disposition of various discontinuities including bedding and cleavages and joints with respect to the slope is such that the slopes lie in a critical state and even minor changes in the topographic configuration either by man or natural processes may trigger mass movement leading to disastrous consequences. The creep of slopes during rains is one such example. It is significant to note that the region has a past history of major catastrophe and a vast area is covered with debris fans of old landslides that are still in the process of stabilization. Therefore even a small magnitude may cause great damage to life and property. The area is characterized by high seismicity. Figure 1 shows the tectonic setup of the region. Genesis of earthquakes in this region may be attributed to the strain generated by the convergence of the Indian and the Eurasian plate.

The Indian plate is moving at a rate of 5 cm/yr relative to the Eurasian plate in a northeasterly direction (Yu *et al* 1995). The highest seismic activity is confined to a narrow zone which follows the Himalayan trend and lies south of surface trace

of the MCT. The foci of most of the earthquakes in this zone lie in the upper 20 km of the crust (Ni and Barazangi 1984). The fault plane solutions are mostly of thrust type with the P-axis normal to the trend of the Himalayan arc. One of the nodal planes in most of the fault plane solutions is shallow dipping towards the northeast, which is confirmable with conformity with the surface geological evidence for thrusting (Yu *et al* 1995).

Seismic studies based on microearthquake recording using local networks have also shown that belt of local seismicity lies to the south of the MCT in a local region. The composite fault plane solutions based on these microearthquake studies show thrust as well as strike slip mechanism (Khatti 1992a, 1992b).

3. Data and instrumentation

Recently, Wadia Institute of Himalayan Geology (WIHG), Dehradun, India has established a total of eleven broadband seismic stations (Dehradun, Tapovan, Adibadri, Gaurikund, Ghuttu, Deoban, Kotdwar, Chakrata and Kharsali in Uttaranchal and Nahan and Kotkhai in Himachal Pradesh) in the NW Himalaya region which have been connected through VSAT telemetry network. This network acquires the seismic data in continuous real mode at Central Recording Station, Dehradun. The upgraded VSAT linked seismic network is equipped with broadband seismometers (Trillium 240) and Taurus digital data acquisition system. The ground velocity data are recorded in broad frequency band at the rate of 100 sps.

In the present work, the high quality digital data of VSAT linked broadband stations (figure 1) has been processed to obtain both kinematic and dynamic source parameters of Kharsali earthquake and its aftershock activity.

4. Methodology – synthetic seismogram

The methodology to compute the synthetic accelerograms is based on a dislocation moving over a fault plane using Green's function approach (Aki and Richards 1980). First, the source is characterized which extends over a finite area (the fault plane) and over a finite amount of time. The rupture process produces dislocations over the fault which varies both in direction and magnitude. The displacement produced by such a realistic source model can be synthesized from a far field radiation using a point double couple source. Although in the near field of a large earthquake, the dimensions of the source cannot be ignored but in the present work, the fault area is divided into a

number of subfaults which can be approximated as point source with area much smaller than the distance to the observation point. Under such assumption, ground motion can be computed using far field radiation from a point double couple source. The radiation pattern has been expressed in terms of fault parameters slip (u), rake (λ), strike of the fault (φ_s), dip (δ) and take off angle (i_0). Following are the formulation used for evaluating displacement (Keiiti and Richards 1980):

$$\mathbf{u}^P(\mathbf{x}, t) = (M_o R^P / 4\pi\rho\alpha^3 r) f(t - r/\alpha) \mathbf{e}_p, \quad (1)$$

$$\mathbf{u}^{SV}(\mathbf{x}, t) = (M_o R^{SV} / 4\pi\rho\beta^3 r) f(t - r/\beta) \mathbf{e}_s, \quad (2)$$

$$\mathbf{u}^{SH}(\mathbf{x}, t) = (M_o R^{SH} / 4\pi\rho\beta^3 r) f(t - r/\beta) \mathbf{e}_t, \quad (3)$$

where $\mathbf{e}_p$, $\mathbf{e}_s$, $\mathbf{e}_t$ are unit vectors in the direction of particle motion in the P-, SV- and SH-wave, respectively. $\mathbf{u}^P(\mathbf{x}, t)$, $\mathbf{u}^{SV}(\mathbf{x}, t)$ and $\mathbf{u}^{SH}(\mathbf{x}, t)$ are displacement due to P-, SV- and SH-wave, respectively. α and β are the P- and S-wave velocity, respectively, r is hypocentral distance, ρ is density of medium, $f(t - r/\alpha)$ is source time function for P-wave, $f(t - r/\beta)$ is source time function for S-wave, M_o is seismic moment, R^P , R^{SV} and R^{SH} are the radiation pattern term for P-, SV- and SH-waves, respectively.

The formulations for radiation pattern terms used in the present work are:

$$\begin{aligned} R^P = & \cos \lambda \sin \delta \sin^2 i_0 \sin 2(\phi - \phi_s) \\ & + \sin \lambda \cos 2\delta \sin 2i_0 \sin(\phi - \phi_s) \\ & + \sin \lambda \sin 2\delta [\cos^2 i_0 - \sin^2 i_0 \sin^2(\phi - \phi_s)] \\ & - \cos \lambda \cos \delta \sin 2i_0 \cos(\phi - \phi_s), \end{aligned} \quad (4)$$

$$\begin{aligned} R^{SV} = & +1/2(\cos \lambda \sin \delta \sin 2i_0) \sin 2(\phi - \phi_s) \\ & + \sin \lambda \cos 2\delta \cos 2i_0 \sin(\phi - \phi_s) \\ & - 1/2 \sin \lambda \sin 2\delta \sin 2i_0 [1 + \sin^2(\phi - \phi_s)] \\ & - \cos \lambda \cos \delta \cos 2i_0 \cos(\phi - \phi_s), \end{aligned} \quad (5)$$

$$\begin{aligned} R^{SH} = & \cos \lambda \sin \delta \sin i_0 \cos 2(\phi - \phi_s) \\ & + \sin \lambda \cos 2\delta \cos i_0 \cos 2(\phi - \phi_s) \\ & - 1/2 \sin \lambda \sin 2\delta \sin i_0 \sin 2(\phi - \phi_s) \\ & + \cos \lambda \cos \delta \cos i_0 \sin(\phi - \phi_s), \end{aligned} \quad (6)$$

where ϕ is the azimuth. To obtain the ground motion in a finite medium the above formulations are modified for free surface effect as follows:

$$\mathbf{u}^P = u_H^P \cos \phi \mathbf{e}_1 + u_H^P \sin \phi \mathbf{e}_2 + u_3^P \mathbf{e}_3, \quad (7)$$

$$\mathbf{u}^{SV} = u_H^{SV} \cos \varphi \mathbf{e}_1 + u_H^{SV} \sin \phi \mathbf{e}_2 + u_3^{SV} \mathbf{e}_3, \quad (8)$$

$$\mathbf{u}^{SH} = -C \sin \phi + C \cos \phi, \quad (9)$$

where C is the amplitude of the SH waves in an infinite medium. For a moving source the effect of rupture propagation has been taken. The delay time (τ) taken to move the radiation point from one subfault to another is evaluated and the final expression for far field displacement due to a finite moving source is given by:

$$\begin{aligned} u(\mathbf{x}, t) = & (M_o R^P / 4\pi\rho\alpha^3 r \tau_\alpha \{f[t - (r_o/\alpha)] \\ & - f[t - (r_o/\alpha) - \tau_\alpha]\}) \\ & + (M_o R^{SV} / 4\pi\rho\alpha^3 r \tau_\beta \{f[t - (r_o/\beta)] \\ & - f[t - (r_o/\beta) - \tau_\beta]\}) \\ & + (M_o R^{SH} / 4\pi\rho\alpha^3 r \tau_\beta \{f[t - (r_o/\beta)] \\ & - f[t - (r_o/\beta) - \tau_\beta]\}), \end{aligned} \quad (10)$$

where M_o , R^{SH} , R^{SV} , R^P , ρ , α , r , τ_α are the seismic moment, radiation pattern due to SH, SV and P wave, density of the medium, P wave velocity, hypocentral distance and delay time taken by P wave, respectively. The wave field given by this equation is then corrected for free surface effect using equations (7–9). It has been found that location of point of initiation of rupture, rupture velocity, rise time and distribution of slip amplitude on the fault are the most critical parameters in generation of synthetic seismograms.

5. Computation of synthetic waveform

For the purpose of simulation, a source model has been specified which includes spatio-temporal parameters of earthquake focus, fault geometry, slip distribution over the fault plane and source time function. The fault plane chosen for modelling of ground motion is assumed to be buried in a homogenous half space.

The velocity model considered is the two layered P-velocity model derived from the local earthquake

surveys (Khattari 1992a) with P wave velocity of 5.2 km/s in the first layer and 6.0 km/s in the second layer with the density of half space 2.7 g/cm^3 . These velocities correspond to a material with Poisson's ratio of 0.25 which signifies that half space is made up of well consolidated rocks. The source time function used in the present work is the ramp function with rounded shoulders (Ben-Menahem and Singh 1981):

$$F(t) = \begin{cases} 0, & t \leq 0 \\ (t/T_o)/\omega_o t, & 0 \leq t \leq T_o \\ 1, & t \geq T_o \end{cases} \quad (11)$$

where T_o is the rise time and $\omega_o = 2\pi/T_o$. This function is continuous everywhere and is easily differentiable. The above form is chosen to model slip as a function of time at a point on the fault. For generating synthetic seismograms in the near field geometry, the size of the source, i.e., the fault plane is carefully specified. The fault is considered to be made of a number of subfaults each of size $1 \times 1 \text{ km}$.

The variation in slip amount in each subfault is estimated from the amplitude variation in the observed time series coupled with the rupture propagation model on the fault. The observed time series gives the variation of amplitude with time. The location and number of grids contributing to the corresponding amplitude depends on rupture propagation model. The rupture propagation model used in the present study consists of rupture starting from a single point (i.e., the hypocenter) and then spreading all over the fault in the form of circular rupture fronts for both P and S-waves. The equal time contours (isochrones) are drawn at an interval of one second. The contours join all those points on the fault plain from which the total travel time of P (or S) wave is the same. This total travel time consists of time of rupture propagation from hypocenter to a point on the fault at the velocity of rupture propagation v_r and the time taken at the P (or S) wave velocity from that point on the fault to the recording station. All subfaults through which the contours pass contribute to waveform on the synthetic time series at the same instant of time.

The slight difference in amplitude of pulse shape is also contributed by the each subfault on a given contour by virtue of different geometric attenuation, radiation pattern contribution and free surface effect. The direction of slip vector is kept constant in each subfault.

The coordinates of epicenter and station location are available in terms of their latitudes and longitudes. These were converted into Cartesian

co-ordinates x_1 and x_2 with epicenter as origin, x_1 positive towards north and x_2 positive towards east. The third coordinate x_3 is taken positive downward. All the stations are considered to be situated on the same elevation as the epicenter (above sea level) and the difference between the station elevations were ignored. Following formulae given by Lee and Stewart (1981) were used to obtain coordinates of stations on x_1 - x_2 planes:

$$x_1 = 60A(\lambda - \lambda_o), \quad (12)$$

$$x_2 = 60B(\phi - \phi_o), \quad (13)$$

where λ and ϕ are the longitude and latitude of the station and λ_o and ϕ_o are the longitude and latitude of the epicenter in the equations, respectively. The values for A and B in these equations are obtained as follows:

$$A = 1.8553654 + 0.0062792 \sin^2 \Phi + 0.0000319 \sin^4 \Phi, \quad (14)$$

$$B = 1.8428071 + 0.0187098 \sin^2 \Phi + 0.0001583 \sin^4 \Phi, \quad (15)$$

where $\Phi = 1/2(\phi + \phi_o)$.

In this study, a local (i.e., fault based) coordinate system (y_1, y_2, y_3) was chosen in the following manner. The focus which lies on the footwall side of the fault is chosen as the origin. A line on the fault plane parallel to strike of the fault is chosen as the y_1 -axis with y_2 -axis in the up dip direction and perpendicular to the y_1 -axis. The y_3 -axis is chosen perpendicular to the fault plane and penetrating the hanging wall. Figure 2 shows the local co-ordinate systems on a fault with ϕ_s as strike angle and δ as the angle of dip. The tangent to the seismic ray makes an angle i_o at the focus. The line joining the origin to the recording station makes an angle of ϕ with the x_1 -axis.

6. Spectral analysis and source parameters

The source model relates the corner frequency and low frequency asymptote to source dimension and seismic moment (Brune 1970). Observations of spectra consistent with Brune's theory have been reported for large earthquakes (Hanks and Wyss 1972; Wyss and Hanks 1972; Ichinose *et al* 1997) in

Figure 2. Local and global co-ordinates co-ordinate systems on a fault (ϕ_s : strike angle, δ : angle of dip, λ : slip angle, O(E): epicenter, i_o : take off angle, ϕ azimuth. Y_1 , Y_2 and Y_3 are local co-ordinates and X_1 , X_2 and X_3 are global co-ordinates.

addition to micro-earthquakes (Douglas and Ryall 1972; Kumar *et al* 2006) thus covering a very wide range of computed values for source parameters based on the theory.

A time window of 4 s (sampling rate 100 samples per second) was applied from the start of P wave to compute P-wave spectra. This has been done to exclude S-wave effects. After conversion of velocity to displacement in the Fourier domain, the spectral parameters, i.e., f_c and Ω_o are estimated. The physical parameters, i.e., seismic moments and stress drops, were then computed from the spectral analysis of the recorded data using Brune's model (Kellis-Borok 1959; Brune 1970; Sharma and Wason 1994). The formulations used for the purpose were as follows:

$$M_o = 4\pi\rho v^3 D \Omega_o / R \quad (16)$$

$$r = 2.34v / 2\pi f_c \quad (17)$$

$$\Delta\sigma = 7M_o / 16r^3 \quad (18)$$

where, M_o , ρ , v , r , f_c , $\Delta\sigma$, D , Ω_o and R denote seismic moment, density, velocity, source radius, corner frequency, stress drop, epicentral distance, spectral amplitude and radiation pattern, respectively. The above formulations are widely used to compute the source parameters. The radiation pattern R was approximately taken to be 85% (Prochazkova 1980). M_o was taken as the average of seismic moments computed from different recording stations for the event. The estimated values for the seismic moments and the stress drops are given in table 1.

Table 1. Hypocentral and source parameters of the main shock and aftershocks obtained from P-wave displacement spectra using Brune's circular model.

Sl. no.	Date	Time	Latitude	Longitude	Depth	M_L	Seismic moment (M_o) Nm	Source radius (r) m	Stress drop ($\Delta\sigma$) bars
1	7/22/2007	23:02:13.3	30.90	78.31	14	4.9	4.16×10^{16}	2110	41.5
2	7/22/2007	23:05:51.2	30.94	78.35	10.8	2.3	6.6×10^{14}	540	18.3
3	7/22/2007	23:07:50.6	30.83	78.32	8.9	2.0	2.2×10^{14}	673	3.2
4	7/22/2007	23:09:26.3	30.93	78.23	10.1	1.9	2.9×10^{14}	474	12.2
5	7/22/2007	23:12:08.4	30.91	78.31	11.2	1.8	2.4×10^{14}	510	7.9
6	7/22/2007	23:12:50.5	30.94	78.27	10.2	2.0	3.2×10^{14}	492	9.8
7	7/22/2007	23:25:16.8	30.81	78.29	10.1	2.2	1.5×10^{14}	596	3.1
8	7/22/2007	23:38:52.6	30.91	78.31	4.9	2.3	2.2×10^{13}	465	1
9	7/22/2007	23:45:07.1	30.84	78.27	11.9	2.3	6.6×10^{13}	588	1.5
10	7/22/2007	23:57:53.6	30.87	78.27	11.8	2.2	8.0×10^{14}	494	29.7
11	7/22/2007	05:39:17.9	30.89	78.29	10.3	2.4	2.3×10^{14}	352	7.6
12	7/22/2007	06:33:20.3	30.86	78.25	9.2	2.2	1.7×10^{14}	460	6
13	7/23/2007	05:39:17.0	30.89	78.32	10	2.2	7.6×10^{13}	381	10.7
14	7/23/2007	06:33:20.8	30.89	78.27	8.6	2.0	2.4×10^{14}	459	3.5
15	7/23/2007	07:57:05.4	30.91	78.30	8.8	2.3	6.5×10^{13}	430	2.5
16	7/23/2007	08:00:00.3	30.88	78.30	7.8	2.3	7.12×10^{13}	501	1
17	7/23/2007	09:08:08.1	30.91	78.32	9.9	2.3	1.7×10^{13}	434	7.03
18	7/23/2007	20:19:59.5	30.85	78.26	9.8	1.2	7.5×10^{13}	366	23.4

Figure 3. Variation of stress drop for the main shock and well located aftershocks.

7. Results and discussion

The present work is based on analyses of the data recorded by broadband seismograph stations consisted of a total of 11-telemetered Trillium 240s seismometers. In principle, it is possible to use empirical Green functions to separate fault and auxiliary plane and to estimate parameters of the extended source, slip and source time (rise time) of main and aftershock. The aftershocks are very close to the main shock. The spectral analysis has not been performed because it is more important and feasible for aftershocks. The seismograms are processed in full frequency band which is a very difficult task. The inversion of many source parameters like strike, dip, rake, rise time, rupture velocity and even the slip distribution are obtained by applying forward modelling using geometric ray method for full band seismograms. In the different stages of the computation of synthetic accelerograms at the time of performing waveform modelling are taken into account of several parameters, such as location of the point of rupture initiation or focus, rupture velocity, rise time and distribution of slip amplitude on the fault plane. These are the most critical parameters which dictate the generation of synthetic seismograms. The degree of matching between the observed and synthetic seismogram depends on accurate selection of these parameters.

7.1 Source parameters from spectral studies

The seismic moment of the main shock determined from the displacement spectra is 4.16×10^{16} Nm with source radius of 1.76 km. The seismic moment of the aftershocks vary from 1.7×10^{13} Nm to 6.6×10^{14} Nm (table 1) with the variation of source radii from 0.35 to 0.54 km. The stress drop obtained for the main event using spectral analysis of Brune's circular model is 41.6 bar that is close

Table 2. Other source parameters of Kharsali earthquake of 22 July 2007 obtained by waveform modelling.

Sl. no.	Parameter	Value
1	Length of the fault	10 km
2	Width of the fault	6 km
3	Dip of the fault	14°
4	Strike of the fault	N279°
5	Rise time	0.28 s
6	Rupture velocity	1.7 km/s
7	Slip angle	117°
8	Rupture model	Circular rupture
9	Average slip	57 cm
10	Maximum slip	97 cm

to the specified value of 30 bar for the interplate region of Himalayan tectonics. The stress drop obtained for the aftershocks varies from 1 to 30 bar (table 1 and figure 3). The calculated stress drops in the region are low, which can be understood with the partial stress drop model (Brune 1970; Brune *et al* 1986). These earthquakes arise as a consequence of strain accumulation due to the adjustments undergoing in the region. The low value of stress drops at shallow depths indicates that the constituent rock mass of the region cannot withstand large amount of accumulated strain energy. Figure 3 shows the variation of stress drop for the main shock and well located aftershocks. The early aftershocks occurring at greater depth near and below the main shock have caused higher stress drop in comparison to the later aftershocks occurring at shallow depth in the northwest side. It may be explained in terms of consolidation of lithological setup. The formation at greater depth has more stress accumulating strength with decrease in brittle strength and increase in the ductility. Therefore, the earthquakes of higher magnitude are expected to occur at greater depth in the Himalaya region, the similar facts has also been given by Ni and Barzangi (1984).

Figure 4. Station Tapovan E-W component seismograms: (a) observed, (b) synthetic seismogram, and (c) superimposed seismograms (40 s each).

Figure 5. Station Tapovan N-S component seismograms: (a) observed, (b) synthetic seismogram, and (c) superimposed seismograms (40 s each).

7.2 Source parameters from waveform modelling

The seismograms have been synthesized at all the eleven sites. The locations of these sites along with the epicenter of the earthquake have been shown in figure 1. The source parameters given in table 2 are

obtained on the basis of comparison of synthetic seismograms with the observed ones. Figures 4, 5 and 6 show the comparison of seismograms for seismic station Tapovan for the ground motions in E-W, N-S and vertical directions, respectively and figures 7 and 8 show the comparison of P- and S wave spectra for Tapovan station, respectively.

Figure 6. Station Tapovan vertical component seismograms: (a) observed, (b) synthetic seismogram, and (c) superimposed seismograms (40 s each).

These source parameters arrived at in this study were obtained after numerous numerical simulations. It has been found that slip distribution plays an important role in synthesizing waveforms. The distribution of slip (Wald *et al* 1991) over the fault can vary both in amount and direction. There are regions on the fault where large slip might occur which corresponds to asperities. Regions of small slip are found to be close to regions of aftershock activity. Some details of this variability of slip distribution over the fault plane for the Kharsali earthquake is shown in figure 9. The distribution of slip amount on the fault plane show two regions having large concentration of high slip amplitude. The centers of these regions lie at times 2.34 s and 3.74 s after the initiation of rupture. The point of rupture initiation (i.e., the focus) lies at a depth of 10 km from the surface of the earth and is situated at a point on the fault plane lying at a distance of 7 km in the strike direction and 2 km in the up-dip direction.

A close examination of comparison of observed and synthetic seismograms match fairly for seven stations (Kotkhai, Chakrata, Gaurikund, Tapovan, Nahan, Adibadri and Ghuttu). The match is observed to be the best at Tapovan recording station. A good number of peaks lie close to each other. On comparing source parameters of the Kharsali earthquake with the source parameters of *M* 6.5, 1991 Uttarkashi earthquake (Yu *et al* 1995) and Chamoli earthquake (Joshi 2003) it can be said that the region continues to exhibit low

angle thrust mechanism rupture sources occurring at mid-crust depth.

The slip distribution over the fault indicates that the area of the fault which contributes to the large amplitudes of recorded seismograms is a small fraction of the total area. On this portion of the fault the slip amplitudes are high. These regions of the fault have been termed as asperities. Most of the seismic wave energy takes place from such asperities. The complexity of observed seismograms depends on the size and number of such asperities.

A contour map of the slip distribution over the fault shows two asperities (figure 9). These asperities occurred at 2.44 s and 3.78 s from the initiation of rupture. The two asperities are nearly contiguous. The larger asperity at 3.78 s lies to the west of the hypocenter and contributes larger amplitudes in the recorded seismograms. The largest value of slip is 97 cm and the average slip is 57 cm. The total area of the fault plane is 60 km² of which the smaller asperity covers 2 km² and the larger asperity covers 6 km². The rest of the 52 km² does not contribute much to the radiated energy. The two asperities on the fault plane occupy those regions in which the slip amplitude is more than 25 cm. The rupture front takes about 2.92 s to cover this asperity which is also found to be the duration of those portions of the recorded seismograms where amplitudes are high, especially at those stations which are nearer to the epicenter like Kharsali and Gaurikund.

Figure 7. Comparison of P wave spectrum for Tapovan station of components. **(a)** East-west (EW), **(b)** north-south (NS), and **(c)** vertical (V).

Our study helps proper characterization of source using waveform modelling of the Kharsali earthquake (M 4.9) because of better constraints on location of rupture initiation, rupture velocity, rise time and distribution of slip amplitude on the fault. Estimates of source parameters and their analyses support the idea that it is structural heterogeneity which can initiate the brittle failures since earthquake generating processes are closely associated with nature and extent of asperities that cover only a part of the total area of the causative fault plane (10%) in the present study. However,

detailed seismic imaging of these two asperities can be corroborated with structural heterogeneities associated with causative fault to understand how seismogenesis is influenced by strong or weak structural barriers in the region (Mishra and Zhao 2004; Mishra *et al* 2008; Kumar *et al* 2009).

7.3 Relevance of the study

Four great earthquakes M 8.7, 8.6, 8.4 and 8.7 have occurred in the Himalaya region in India at different parts in the last two hundred years period

Figure 8. Comparison of S wave spectrum for Tapovan station of components. (a) East-west (EW), (b) north-south (NS), and (c) vertical (V).

(Richter 1958). In these earthquakes, the Kangra Earthquake (*M* 8.6) of 1905, occurred in western Himalaya and its meizoseismal area was reported to be extended into Garhwal Himalaya the region to the east of 1905 Kangra earthquake and west of 1934 Bihar earthquake (*M* 8.4) have been recognized as 700 km long seismic gap (Bilham and Gaur 2000). So far this region has recorded any large earthquake and from long back being treated

as potential site of its occurrence. Therefore, the recent earthquake recorded by high dynamic range digital broadband seismographs is a critical evaluation to elaborate the ongoing earthquake processes in this region. We have obtained detailed information using observed and theoretical approach which is helpful for evaluating source processes which would be useful for developing seismotectonic model. This is a step towards seismic risk

Figure 9. Slip distribution model for Kharsali earthquake. Depth contours in km at intervals of 20 km.

mitigation in the region due to a possible great magnitude earthquake. This is a strong motivation for investing the ongoing seismicity and earthquake source process in the Garhwal Himalaya.

Further, there are number of perennial rivers originating from Garhwal Himalaya offering vast potential for irrigation and generation of hydro-electric power. Multipurpose river valley schemes have been conceived for the region. Some of them have been completed and many are in progress. The power generation at 260m high earth and rock fill Tehri Dam on the Bhagirathi river is operational now.

The present work is a step towards seismic risk mitigation in the region due to a possible great magnitude earthquake. This is a strong motivation for investing the ongoing seismicity and earthquake source process in the Garhwal Himalaya.

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