Delhi earthquake of 25 November 2007 (M_w 4.1): implications for seismic hazard

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The Delhi earthquake of 25 November 2007 (M_w 4.1) is the best recorded local event ever. Peak ground acceleration (PGA) at seven sites in the epicentral zone ranged between 7 and 118 Gal. An analysis of the earthquake leads to the following conclusions. (1) It occurred at a depth of 30 km and involved strike–slip faulting with some normal component, as against thrust faulting with minor strike–slip component previously reported for the region. (2) Observed PGA of this earthquake is poorly explained by the attenuation relation that has been used in the seismic hazard estimation of the Delhi region. This relation is also inconsistent with data from well-recorded Himalayan arc earthquakes. (3) Recordings from the 2007 earthquake reconfirm that there is a large and variable site effect in Delhi which differs significantly from that estimated from bore-hole penetration test data. These results, together with those from a previous study of two small events in Delhi, and an examination of the seismicity of the region, lead us to conclude that our present knowledge of seismotectonics and seismic hazard of Delhi is fraught with uncertainty, emphasizing an urgent need for improved and enlarged seismic instrumentation.

Keywords: Attenuation relation, Delhi earthquake, peak ground acceleration, seismic hazard, seismotectonics.

DELHI is exposed to large/great thrust earthquakes along the Himalayan arc located at distances exceeding ~250 km, and moderate/large local and regional earthquakes. The current Indian seismic zoning map [IS1893 (Part 1): 2002] defines four zones, i.e. zones II–V. Zone V is exposed to the most severe seismic hazard. Delhi falls in zone IV. The earthquake vulnerability of Delhi has led to numerous recent studies on seismicity[1], site effect and microzonation[2–9], ground-motion prediction[2,10–13], and estimation of seismic hazard of the region[7,14,15].

Unfortunately, the results of many of these studies are poorly constrained by earthquake recordings which are sparse in the region. This is especially true for local and regional earthquakes in and around Delhi. The reason, undoubtedly, is insufficient instrumentation of the region. A 16-element digital telemetered seismic network (DTSN) was established by India Meteorological Department (IMD), New Delhi in 2000–01 (ref. 1). However, this large-aperture network (13 stations in a radius of 200 km from Delhi) has only three stations in Delhi (two of which are located at its periphery). As a consequence, the location accuracy of small-magnitude local earthquakes is expected to be much less than that for the larger ones. Consider, for example, the seismicity of the Delhi region for the period 2001–04 based on recordings of the DTSN. It appears diffused[1]. It is not known whether the scatter is real or is a consequence of location error. Most probably both factors are involved. In the absence of precise locations, it is difficult to associate earthquakes to mapped faults and to assign a percentage to the events which should be considered random.

Shukla *et al.*[1] have used first-motion data recorded on DTSN to determine the focal mechanism of small local and regional earthquakes. They report thrust faulting with minor strike–slip component. The number of first motions used for these small-magnitude earthquakes varies between 6 and 10, and is often difficult to read. Thus, the reported focal mechanisms may not be well-constrained. In a recent study, Bansal *et al.*[9] worked out the focal mechanisms of two small Delhi earthquakes (28 April 2001, M_w 3.4; 18 March 2004, M_w 2.6) which were also well-recorded by the digital strong-motion network (DSMN) operated in the city by the Central Building Research Institute (CBRI), Roorkee. Polarities and waveform modelling of CBRI strong-motion records show that these earthquakes involved normal faulting with large strike–slip component[9]. Well-constrained focal mechanisms of these events differ from that reported by Shukla *et al.*[1]. It follows that the state of stress and the current seismotectonics of the region are not well understood due to lack of good data.

The study by Bansal *et al.*[9] demonstrates that detailed analysis, including waveform modelling, of even a few

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reasonably well-recorded local earthquakes can have a significant impact on our understanding of the seismotectonics and seismic hazard of Delhi. It is in this context that the study of the 25 November 2007 earthquake becomes important as it is the best recorded event in the region so far.

Source characteristics

Location of the earthquake

Figure 1 shows the epicentre of the 2007 earthquake reported by IMD (Table 1). NS component of acceleration at seven sites in and near Delhi are plotted in Figure 2. The (*S–P*) time at these stations was nearly the same, suggesting a relative deep source. This is confirmed from the computed depth of 30 km by IMD, which puts its location in the lower crust. Although the hypocentral distances are about the same, the ground motions are highly variable, reflecting local site effects. The largest acceleration, exceeding 100 Gal, was recorded at Bahadurgarh (BHGR) (Figure 1).

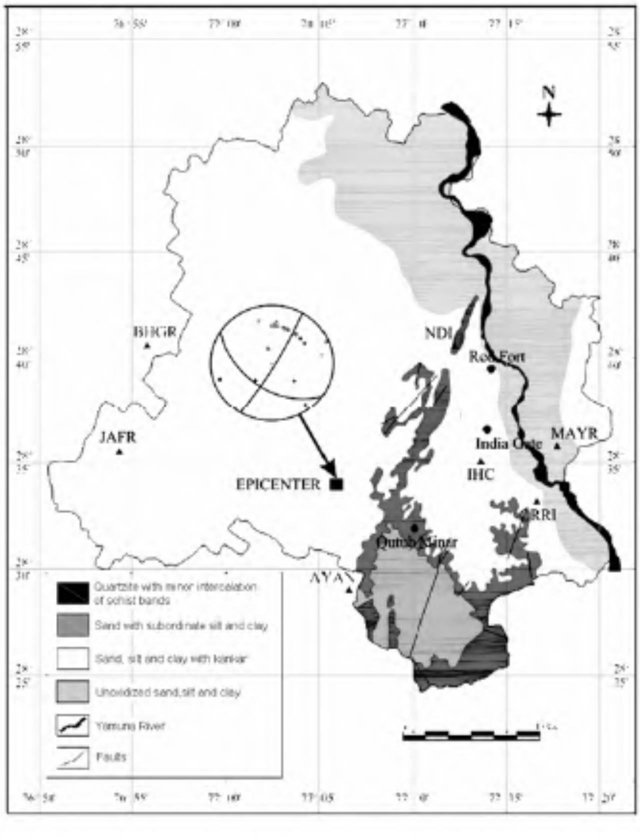

Figure 1. Location of the 25 November 2007 Delhi earthquake and its focal mechanism determined from first-motion data and waveform modelling of NDI displacement traces. Note that one of the nodal planes coincides with the NE–SW orientation of faults and lineaments mapped in the region.

Focal mechanism

We determined the focal mechanism of the earthquake from first-motion data and inversion of the displacement waveforms at NDI (Ridge Observatory; Figure 3). The first-motion data were used to restrict the range of parameters to explore in the inversion. The inversion assumes that the events may be approximated by a point-source shear dislocation in an infinite space. Synthetic seismograms include near- and intermediate-field contributions[16]. The theory predicts simple unipolar *P* and *S* displacement pulses. The effect of free surface is approximately taken into account by multiplying the infinite-space synthetics by two. This approximation is acceptable if the epicentral distance Δ is smaller than the depth *H*.

The focal mechanism thus obtained (nodal plane 1: $\varphi = 31°$, $\delta = 86°$, $\lambda = -35°$; nodal plane 2: $\varphi = 124°$, $\delta = 55°$, $\lambda = -175°$) is plotted in Figure 1. This mechanism is similar to those of two other small earthquakes in the area which have been previously studied in some detail[9]: 28 April 2001, $H = 15$ km, M_w 3.4; 18 March 2004, $H = 8$ km, M_w 2.6. All three events reveal strike–slip faulting with some normal component. One of the nodal planes of these earthquakes is consistent with the NE–SW orientation of the faults and lineaments mapped in the region[17]. These relatively well-constrained mechanisms differ from the results of Shukla *et al.*[1], who reported thrust faulting with minor strike–slip component in the region. The focal mechanism solutions obtained from a combination of *P*-wave polarities and waveform inver-

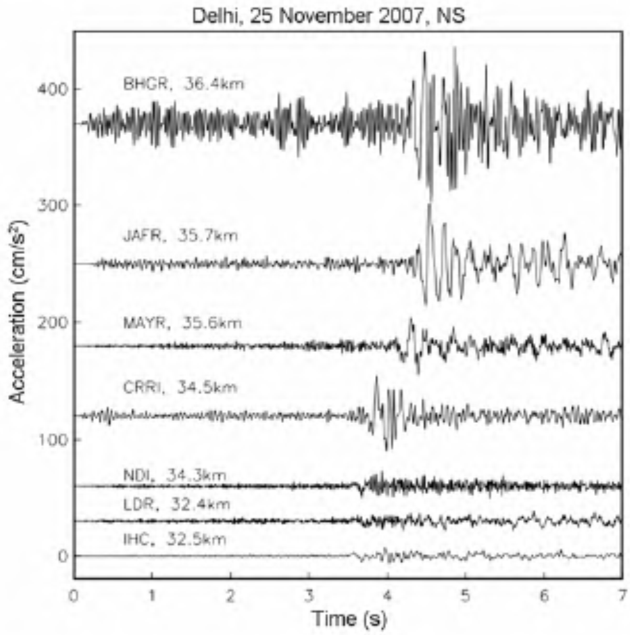

Figure 2. NS component of accelerograms recorded at seven sites in and near Delhi. Note similar (*S–P*) times and large variability of the ground motion. The number following each station code is the hypocentral distance.

Table 1. Earthquakes, their locations and some relevant parameters used in computing peak ground acceleration via random vibration theory

Earthquake	Latitude (°N)	Longitude (°E)	Depth (km)	M_0 (N-m)	$\Delta\sigma$(MPa)	β(km/s)	ρ(g/cm^3)
19 October 1991	30.75	78.86	12	1.8×10^{19}	10*	3.5	2.85
28 March 1999	30.41	79.42	21	7.7×10^{18}	10*	3.5	2.85
22 July 2007	30.91	78.30	26	1.37×10^{16}	46	3.5	2.85
25 November 2007	28.57	77.10	30	1.9×10^{15}	13	4.2	3.2
15 June 2008	29.45	81.10	13	3.93×10^{15}	3.4	3.5	2.85

#In all cases the source follows Brune ω^2 model; $Q = 253f^{0.8}$; cut-off frequency, f_m = 35 Hz and effective duration, $T_d = 1/f_c + 0.05R$, where R is in kilometres. Geometrical spreading is taken as $1/R$ for $R \leq 100$ km and $(1/R)^{1/2}$ at larger distances.
*Value of $\Delta\sigma$ has been assumed.

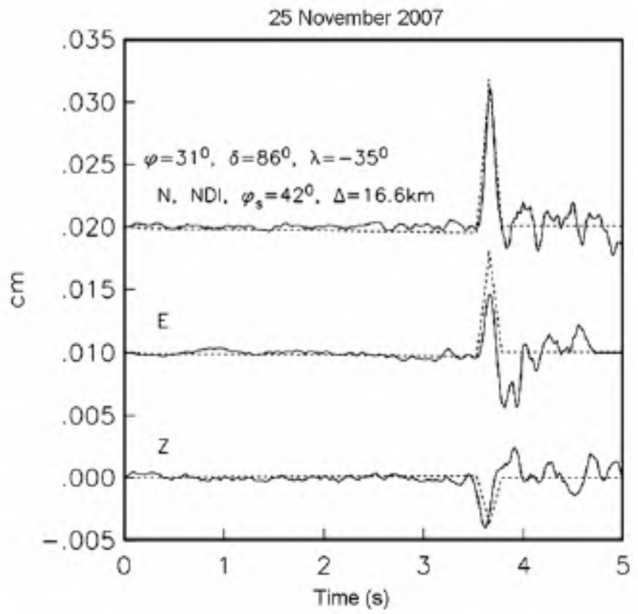

Figure 3. Observed (continuous curves) and synthetic (dashed curves) displacements at NDI (Ridge Observatory) during the 2007 earthquake. Synthetic displacements correspond to a focal mechanism of strike $\varphi = 31°$, dip $\delta = 86°$ and rake $\lambda = -35°$ shown in Figure 1.

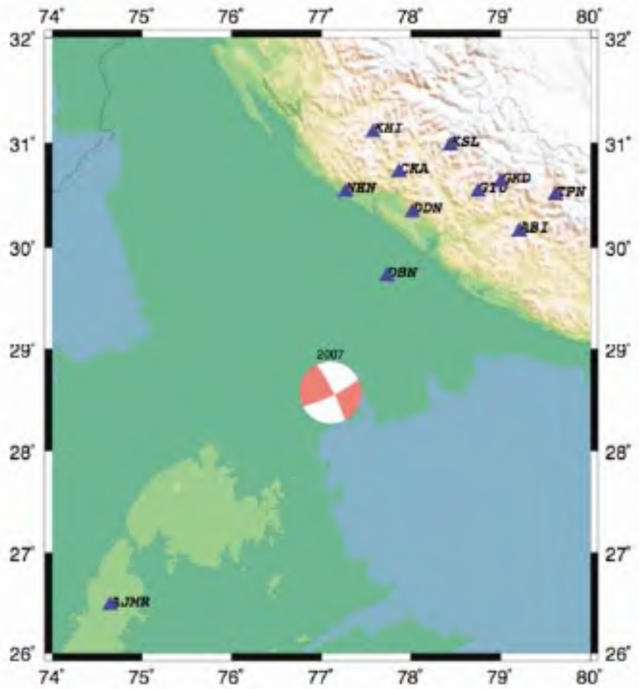

Figure 4. Stations at regional distances considered in regional moment tensor inversion. Stations KHI, CKA, ABI and AJMR were finally used in the inversion. The focal mechanism is centred at the epicentre of the earthquake.

sion are expected to be better constrained than those obtained from P-wave polarities alone.

Regional moment tensor

To further check the focal mechanism of the earthquake, we performed a regional moment tensor inversion following a procedure described by Randall *et al.*[18]. Seismograms recorded by the broadband network of Wadia Institute of Himalayan Geology (WIHG), Dehradun (stations to the north of the epicentre in Figure 4) and AJMR (IMD station located to the south) were band-pass filtered (15–30 s). Synthetic seismograms were generated with the reflectivity code[19] corresponding to the crustal structure of the Indian Shield[20]. The depth was fixed at 30 km. Signal-to-noise ratio was low at long periods for this relatively small earthquake. Figure 5 shows observed and synthetic seismograms as well as the best double-couple focal mechanism ($\varphi = 64°$, $\delta = 81°$, $\lambda = 7°$). This mechanism violates some first motions and differs somewhat from the one shown in Figure 1. Nevertheless, it confirms a predominantly strike–slip nature of the faulting.

Source spectrum

We used S-wave recording at the hard site of NDI (Ridge Observatory) to estimate the source spectrum, corner frequency and Brune stress drop[21]. Here we provide a brief description of the method; the details are described elsewhere[22].

The Fourier acceleration spectral amplitude of the intense part of the ground motion at a station may be written as:

$$A(f,R) = Cf^2\dot{M}_0(f)G(R)e^{-\pi fR/\beta Q(f)}, \quad (1)$$

where

$$C = FPR_{\theta\varphi}(2\pi)^2/(4\pi\rho\beta^3). \quad (2)$$

In the above equations, $\dot{M}_0(f)$ is the moment rate spectrum so that $\dot{M}_0(f) \rightarrow M_0$ as $f \rightarrow 0$, R is the hypocentral distance, $R_{\theta\phi}$ the average radiation pattern (0.55), F the free surface amplification (2.0), P takes into account the partitioning of energy in the two horizontal components ($1/\sqrt{2}$), β the shear-wave velocity at the source (taken as 4.2 km/s for this earthquake), ρ the density in the focal region (taken here as 3.2 g/cm^3) and $Q(f)$ is the quality factor which includes both anelastic absorption and scattering. The geometrical spreading term, $G(R)$, in eq. (1) was taken as $1/R$. We rewrite eq. (1) as:

$$\log[A(f,R)] = \log C + \log[G(R)] + \log[f^2\dot{M}_0(f)] - 1.36fR/\beta Q(f). \quad (3)$$

We used $Q(f) = 253f^{0.80}$ previously estimated for the Himalayan arc[23]. This Q was also found satisfactory for paths from central Himalaya to Delhi[23]. Equation (3) was solved in the least-square sense to obtain $\log[f^2\dot{M}_0(f)]$. The source displacement and acceleration spectra are illustrated in Figure 6. The spectra are well-fitted by an ω^2-source model with $M_0 = 1.9 \times 10^{15}$ N-m (M_w 4.1) and a corner frequency of 3.92 Hz. The stress drop, $\Delta\sigma$, computed using the Brune model[21] is 13 MPa. For comparison, the estimated $\Delta\sigma$ for the earthquakes of 2001 and 2004 was 3.4 and 10 MPa respectively[9].

Site effect

Ideally, site effect should be estimated by simultaneous recording of earthquakes at a reference site and the site of interest, and computing spectral ratios. This ratio is often called the standard spectral ratio (SSR) in the literature. For Delhi, NDI (Ridge Observatory) provides a convenient reference site. If ground motion at NDI is known (either recorded or predicted), then it can be computed at other localities with known SSRs through the application of random vibration theory. Unfortunately, published SSRs using earthquake recordings are available only at a few sites in Delhi[2,5,9]. [Earthquake recordings are available at some more sites which are currently being processed (Kamal and H. Mittal, pers commun., 2008).]

The 2007 earthquake permits estimation of SSR at three new sites: BHGR, Mayur Bihar (MAYR), and Jaffarabad (JAFR) (Figure 1). Figure 7 illustrates the SSRs at these sites and, for comparison purposes, at six other sites in Delhi. We note that the SSRs exceed 10 at most soft sites and the amplification is fairly broadband.

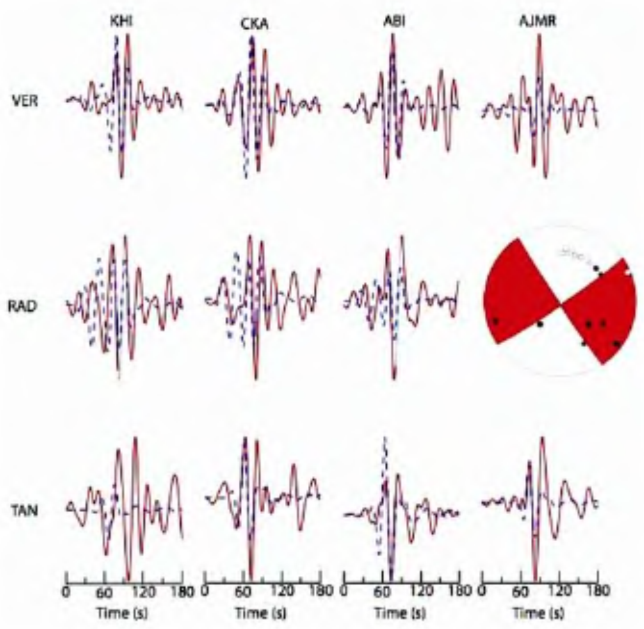

Figure 5. Observed (continuous red line) and synthetic (dashed blue line) seismograms corresponding to the regional moment tensor solution. The focal mechanism corresponding to the best double-couple solution is also shown.

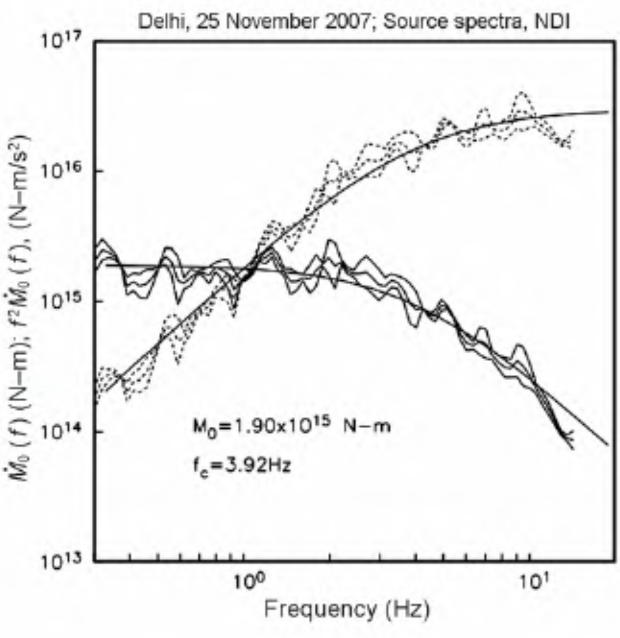

Figure 6. Source displacement (continuous curves) and acceleration spectra (dashed curves), $\dot{M}_0(f)$ and $f^2\dot{M}_0(f)$, of the 2007 earthquake, retrieved from the recording at NDI, a hard site. Median and ± 1 standard deviation curves are shown. The spectra are reasonably well-fitted by a ω^2-source model with seismic moment $M_0 = 1.9 \times 10^{15}$ N-m (M_w 4.1) and a corner frequency of 3.92 Hz.

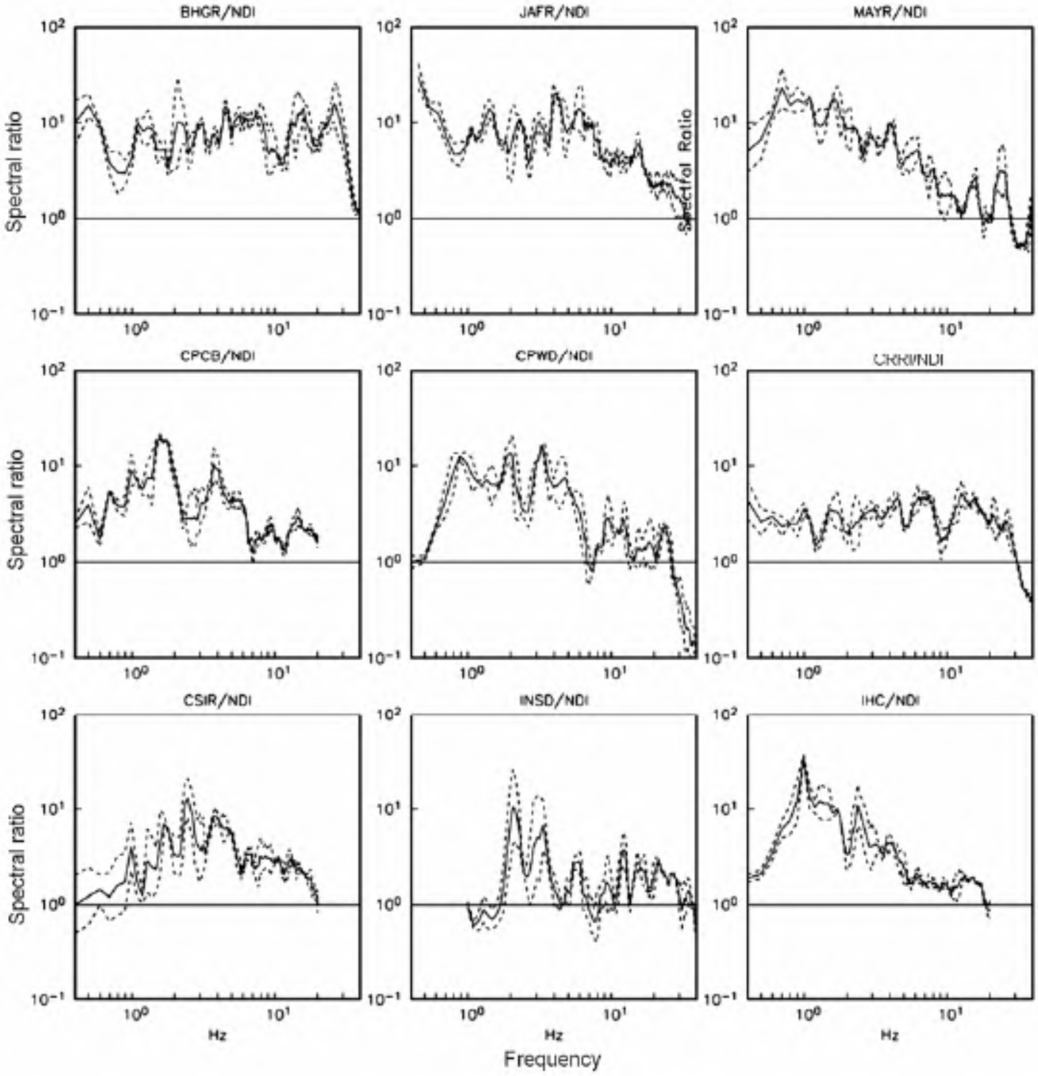

Figure 7. Examples of site effect in Delhi as estimated from spectral ratio (ratio of *S*-wave spectrum at the site of interest to the corresponding spectrum at the reference hard site of NDI) using earthquake recordings. Continuous and dashed lines indicate mean and ± 1 standard deviation curves. Standard spectral ratios in the top three frames correspond to new sites.

At BHGR the SSR exceeds 10 even in the high-frequency range of 10–25 Hz. Very high PGA of service during the 2007 earthquake at this site, 118 Gal on one of the horizontal components, is a consequence of the large site amplification at high frequencies.

Microtremors studies[4], shear-wave velocity inferred from bore-hole penetration data[7] and numerical methods[6] have also been used to estimate site effect in Delhi. Large differences in the estimated site effect obtained from these methods and those estimated from spectral ratios of earthquake recordings are often observed. As mentioned above, the earthquake recordings reveal SSRs exceeding 10 at soft sites in Delhi (Figure 7). The amplifications estimated from bore-hole penetration data, however, are less than about 3 at the natural frequency of the site, which varies between 0.5 and 6.0 Hz (ref. 7). It follows that the results from methods other than SSR need extensive validation before being used in practical applications.

Attenuation of PGA

The 2007 Delhi earthquake was recorded not only in the near-source region, but also by two arrays at farther distances: the broadband seismographic array operated by WIHG to the NE of Delhi (Figure 4) and a temporary linear array, oriented NS along ~80°E, crossing the Indo-Gangetic plains. The latter array was being operated by the National Geophysical Research Institute (NGRI), Hyderabad to study amplification of seismic waves in the Ganga basin. Figure 8 shows PGA on the two horizontal components as a function of hypocentral distance *R*. Here the dot indicates hard site, whereas the open circle represents soft site. As expected, PGAs at soft sites are greater than those at hard sites.

For seismic hazard estimation of Delhi, Iyengar and Ghosh[7] derived a ground-motion prediction equation (GMPE). This equation is based on strong-motion data from earthquakes in the Himalayan arc. A subset of these data was previously used by Sharma[10] to derive an attenuation relation for PGA. Figure 8 shows PGA for M_w 4.1 earthquake computed from the GMPE of Iyengar and Ghosh. It is clear that the equation greatly overestimates the PGAs of the 2007 event, especially for $R > 100$ km. Figure 8 suggests that this GMPE may not be adequate for events occurring in the Delhi region.

It is of interest to investigate whether the equation of Iyengar and Ghosh[7] reliably predicts PGA in the Delhi region from earthquakes originating in the Himalayas. Figure 9 illustrates PGAs from the Himalayan arc earthquakes of Uttarkashi (19 October 1991; M_w 6.8) and Chamoli (28 March 1999; M_w 6.5). Strong-motion data of the Chamoli earthquake shown in Figure 9 have been augmented with recordings from broadband seismographs at larger distances[2,24]. We have also added PGA at NDI in Delhi from a moderate earthquake with its epicentre near Chamoli (14 December 2005, M_w 5.1). Figure 9 includes predicted curves for magnitude 5, 6 and 7 earthquakes. We note that much of the data from Uttarakashi and Chamoli earthquakes are poorly fitted by the GMPE[7]. The equation grossly overestimates the observed data recorded at NDI and broadband data at distances > 200 km. It predicts PGAs at NDI from $M5$ and $M6.5$ earthquakes in the Chamoli region, which are about ten times greater than the observed values.

Further check of the GMPE is provided by data from two recent Himalayan earthquakes: Khursali earthquake of 22 July 2007 (30.91°N, 78.30°E; $H = 26$ km), and Pithorgarh earthquake of 15 June 2008 (29.45°N, 81.10°E; $H = 13$ km). Source spectra of these two events, estimated using the procedure outlined above, are given in Figure 10. The estimated seismic moments and stress drops of these earthquakes are listed in Table 1. Figure 11 shows a plot of PGA as a function of R. It also gives the attenuation curves for $M4$ and $M5$ earthquakes based on the equation of Iyengar and Ghosh[7]. It is at once clear that the data and predictions bare little resemblance with each other. This is particularly true for the 2008 Pithorgarh earthquake.

Recently, Sharma *et al.*[11] have obtained GMPEs based on merged data from the Himalayan and Zagros regions. In these equations, the distance metric is the distance to the surface projection of the rupture, i.e. the Joyner–Boore distance, R_{JB}, which enters the GMPEs as $\log[(R_{JB}^2 + 15^2)^{1/2}]$. As the distance metric in Iyengar and Ghosh[7] is the hypocentral distance, R, the predictions of PGAs from the two studies are not directly comparable. However, for shallow ($H \sim 15$ km), moderate earthquakes ($M_w < 7$), the distance $(R_{JB}^2 + 15^2)^{1/2}$ roughly equals R if

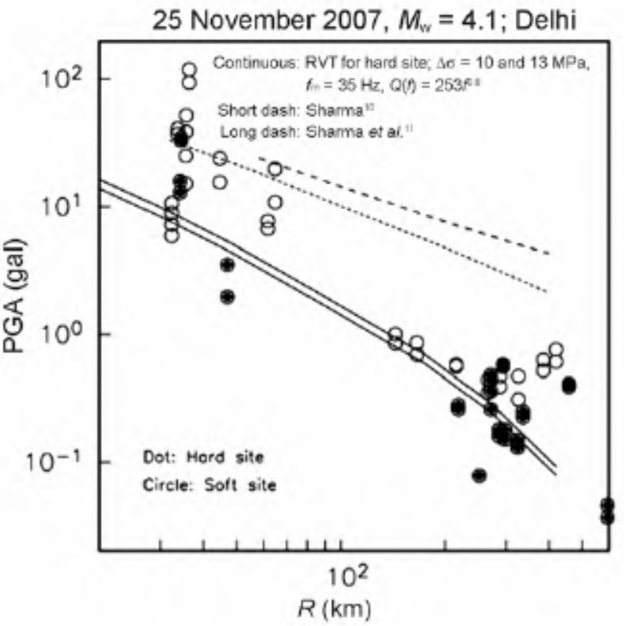

Figure 8. Peak ground acceleration (PGA) as a function of hypocentral distance R for the 2007 Delhi earthquake (M_w 4.1). Dots and open circles indicate hard and soft sites respectively. The predicted PGA for M_w 4.1 earthquake (dashed curve) from an attenuation relation given by Sharma[10] (short dashed curve) and Sharma *et al.*[11] is also shown. Continuous curves give predicted PGAs for M_w 4.1 based on random vibration theory (RVT) ω^2-source model, stress drop of 10 and 13 MPa, a cut-off frequency of 35 Hz and $Q = 253f^{0.8}$.

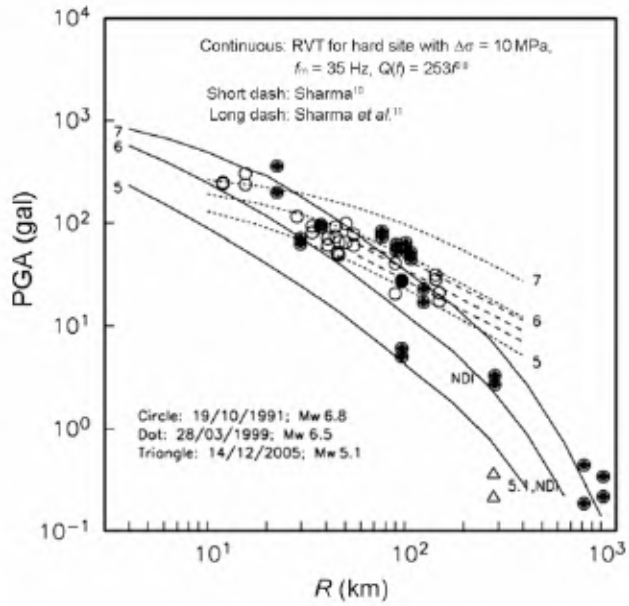

Figure 9. PGA during Uttarkashi (M_w 6.8) and Chamoli (M_w 6.5) earthquakes. Also shown is PGA at NDI for an earthquake near Chamoli (M_w 5.1). Predicted PGA curves for magnitudes 5, 6 and 7 earthquakes based on the attenuation relation of Iyengar and Ghosh[7] (short dashes) and Sharma *et al.*[11] (long dashes) are shown. Continuous curves illustrate attenuation relation based on RVT, ω^2-source model and stress drop of 10 MPa.

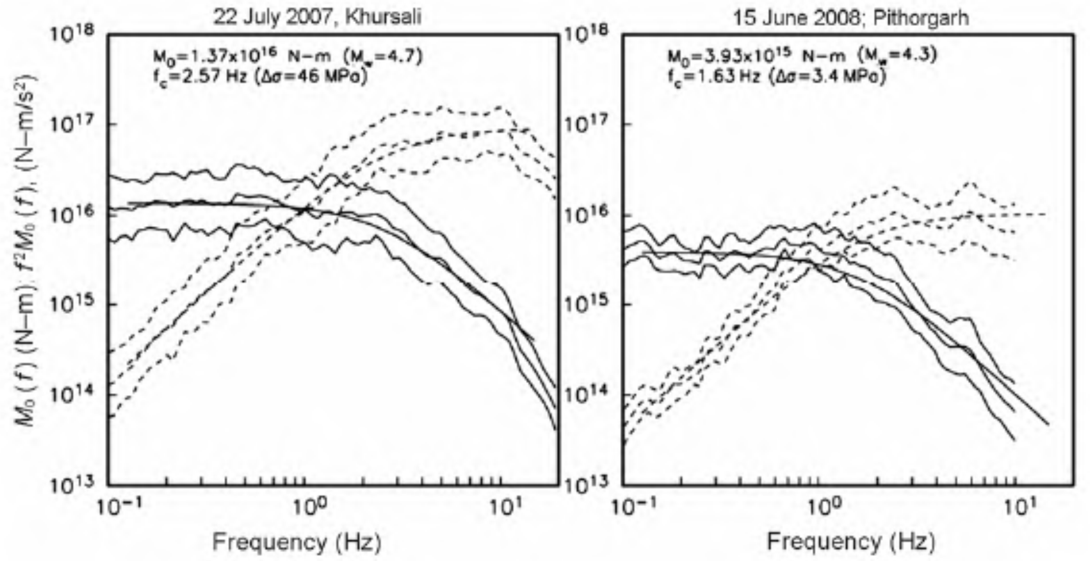

Figure 10. Source displacement (continuous curves) and acceleration spectra (dashed curves), $\dot{M}_0(f)$ and $f^2\dot{M}_0(f)$, of Khursali (left) and Pithorgarh (right) earthquakes. Data from seven ($54 < R < 136$ km) and five ($185 < R < 421$ km) stations were used for the two earthquakes. Median and ± 1 standard deviation curves are shown. The spectra are reasonably well-fitted by ω^2-source model with $M_0 = 1.37 \times 10^{15}$ N-m (M_w 4.7) and $f_c = 2.57$ Hz for the Khursali earthquake, and $M_0 = 3.93 \times 10^{15}$ N-m (M_w 4.3) and $f_c = 1.63$ Hz for the Pithorgarh earthquake.

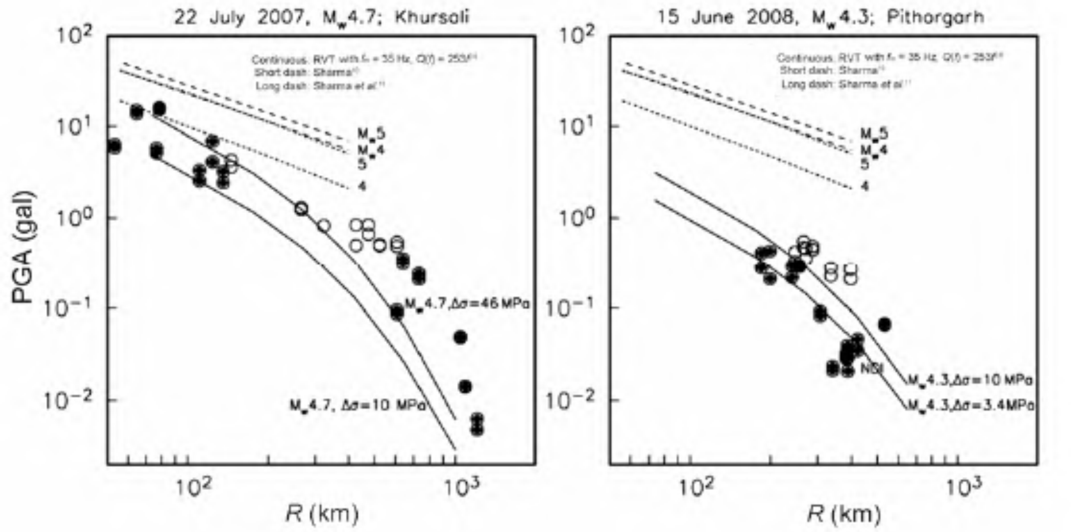

Figure 11. PGA during Khursali (M_w 4.7; left) and Pithorgarh (M_w 4.3; right). Predicted PGA curves for magnitude 4 and 5 earthquakes based on the attenuation relation of Sharma[10] (short dashes) and Sharma *et al.*[11] earthquakes (long dashes) are shown. Continuous curves illustrate attenuation relations using RVT, assuming ω^2-source model, and stress drops of 46 and 10 MPa for the Khursali earthquake, and 3.4 and 10 MPa for the Pithorgarh earthquake.

the epicentral distance, Δ, is greater than $\sim 3H$. In Figures 8, 9 and 11, the predictions from the new equations are given for $50 < R < 300$ km. We note that the dependence of PGA on M_w in the new GMPEs is unusually small and the predictions are no better than the previous relation[7].

Thus Figures 8, 9 and 11 cast serious doubts on the ability of these GMPEs to accurately predict PGAs at hard sites in Delhi from local, regional and Himalayan-arc earthquakes.

There are several possible reasons for the inadequacy of these GMPEs. Iyengar and Ghosh[7] do not clearly mention the data used in their analysis, but they probably included recordings of earthquakes in the magnitude range 5.5–6.8, at distances of less than about 300 km. The earthquakes and all of the recording sites were most probably located in the Himalayan arc. Almost certainly no data from Delhi were included in the analysis. We note that the thick Indo-Gangetic basin sediments separate the Himalayas from Delhi. Thus, extrapolation of the GMPE of Iyengar and Ghosh[7] to predict PGA from an M_w 4.1 earthquake in Delhi up to a distance of 600 km (Figure 8) is unfair. Yet, in as much as the equation has been used in the estimation of seismic hazard in Delhi from local and regional events[7], comparison of predicted and observed PGA at short distances is justified. Although the magnitudes of Khursali and Pithorgarh earthquakes (M_w 4.7 and 4.3 respectively) are also outside the range of the data used in deriving the GMPE, the difference in predicted and observed PGA is alarmingly large. Data from Uttarkashi (M_w 6.8) and Chamoli (M_w 6.5) earthquakes are reasonably well-fitted up to a distance of about 150 km. This is to be expected since these events were most probably included in deriving the equation. Yet, the predicted PGAs at NDI in Delhi at a distance of 300 km are an order of magnitude greater than the observed values. We think that this large difference is not due to the presence of thick basin sediments between the Himalayas and Delhi. This is supported by Chamoli data which show that a continuous attenuation curve can fit data at $R < 150$ km and the data at NDI equally well (Figure 9). (Note that there was no instrument to record the Uttarkashi earthquake at NDI.) This is also confirmed by the recording at NDI of the Pithorgarh earthquake (Figure 11, right). (The Khursali earthquake was not recorded at NDI due to instrument malfunction.). The discussion above is also valid for the new GMPE of Sharma *et al.*[11] (see Figures 8, 9 and 11), which is based on data in the magnitude range 5.2–6.8 at distances ≤ 200 km.

Paucity of data from the Himalayan earthquakes as well as events in the Delhi region suggests that the random vibration theory (RVT), in conjunction with reasonable source model, geometric spreading and anelastic attenuation may provide a more reliable estimation of ground-motion parameters[25,26]. RVT has previously been used for ground motion estimation in India[2,23]. Figures 8, 9 and 11 show the RVT predictions. For Delhi, Khursali and Pithorgarh earthquakes we have estimated $\Delta\sigma$ in this study (Table 1). The figures show predictions based on these stress drops. As the stress drop of future, postulated earthquakes will not be known a priori, we also give predictions based on a generic $\Delta\sigma$ of 10 MPa. For Uttakashi and Chamoli earthquakes, only the generic stress drop has been used. All other parameters required in the RVT calculations are given in Table 1.

As seen in Figure 8, the predicted curve agrees well with the observed data on hard sites for the Delhi earthquake. The same is true for the Uttarkashi and Chamoli earthquakes (Figure 9), where the stress drop has been arbitrarily chosen as 10 MPa and an approximate finite source model[27] has been used. Observed PGA of the Pithorgarh earthquake is well-fitted by the predicted curve with $\Delta\sigma = 3.4$ MPa. The predicted curve for the Khursali earthquake poorly approximates the observed PGA, especially at $R > 500$ km. We note that hard sites at these distances are located in the Indian shield. Q used in RVT calculation is inadequate for paths to these stations. Even in this case, the predicted RVT provides a much better approximation to the observed data than the currently available GMPEs. The fit with generic $\Delta\sigma$ of 10 MPa is obviously bad for the Khursali and Pithorgarh earthquakes (Figure 11), but it is still much better than those based on GMPEs.

Discussion and conclusion

Focal mechanism of the 2007 earthquake and two previously studied small earthquakes[9] suggests that the earthquakes in the Delhi region are associated with strike–slip faulting with some normal component, as against thrust faulting with minor strike–slip component reported previously by other workers[1]. NE azimuth of one of the fault planes coincides with mapped orientation of the lineaments and faults in the region[17]. Delhi is bounded by two major strike–slip faults, namely the Mahendragarh–Dehradun Subsurface Fault (MDSSF) and Great Boundary Fault (GBF). There is diffused seismicity in the vicinity of the MDSSF[1]. Quite possibly, these events also have a focal mechanism similar to that of the 2007 earthquake.

Available GMPEs for the region are not consistent with the observed PGAs during the reasonably well-recorded 2007 Delhi event. These equations are also inconsistent with data from the Himalayan-arc earthquakes recorded in Delhi and at broadband seismographs at longer distances. For example, predicted PGAs in Delhi from M_w 5.0 and M_w 6.5 earthquakes in the Chamoli region are about ten times greater that the observed ones. We find that application of RVT, assuming an ω^2-source model with a generic stress drop of 10 MPa and other reasonable parameters listed in Table 1, predicts much better the observed PGAs. In view of the paucity of strong-motion data in the region, the GMPEs developed using RVT are recommended in the seismic hazard estimation.

The estimation of site effect in Delhi using the SSR technique is available only in few localities. These site effects significantly differ from those computed from shear-wave profiles inferred from bore-hole penetration tests. Furthermore, the site effects inferred from microtremor studies and theoretical works need to be validated rigorously. It follows that much needs to be done to understand the site effect in Delhi.

Seismicity in and around Delhi for the period 2001–04 appears diffused[1]. It is unknown whether the scatter is real or is a consequence of less accurate locations. Most probably both factors are involved. In the absence of precise locations, it is difficult to associate events to mapped faults. For the same reason, the percentage of events which should be considered random is not known.

A matter of concern is the difference in the seismicity rate in Delhi and the surrounding region (excluding the

Himalayan arc), reported by Iyengar and Ghosh[7] and Shukla *et al.*[1]. The area covered in the former study is about 2×10^5 km^2, whereas it is 4×10^4 km^2 in the latter work. The normalized seismicity rate (per year per unit area) in the former study is ten times smaller than that in the latter. One possibility is that the seismicity is in fact higher in the smaller area than in the larger area. It is also possible that the earthquake catalogue used by Iyengar and Ghosh[7] is incomplete. In any case, it is critically important to address and resolve this issue.

In summary, it is felt that much needs to be done to improve our knowledge of seismicity, present seismotectonics, attenuation relation and site effect in Delhi, without which the estimation of seismic hazard in the city would remain fraught with uncertainty. As shown above, detailed analysis of even a few reasonably well-recorded earthquakes can lead to significant improvement in our knowledge. This can only be accomplished by a denser network of seismic instrumentation. The recently completed 20-station strong-motion network in Delhi by IIT-Roorkee (IIT-R) and the upcoming broadband network of IMD for Delhi region should prove useful.

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ACKNOWLEDGEMENTS. Data used in this study were obtained under projects funded by the Ministry of Earth Sciences and Department of Science and Technology, Government of India to IMD, WIHG, IIT-R and CBRI. The research was partly funded by CONACyT, Mexico and DST, India under the Indo-Mexican Cooperation Programme in Science and Technology. We thank R. Dharmaraju and A. Iglesias for help in preparing some figures. A part of this paper, in its preliminary version, was presented by the first author at the 29th ISET Annual Lecture at IIT-Roorkee in March 2009. An extended abstract of the lecture is included in *ISET Journal of Earthquake Technology*, 2009, vol. 46.

Revised 5 January 2010; accepted 2 September 2010