Influence of source distance on site-effects in Delhi city

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The seismic ground motion along a geological cross-section from Tilak Bridge to Punjabi Bagh in Delhi city has been simulated at every 130 m with a hybrid technique (modal summation and finite differences). We use two earthquake source scenarios: (1) 27 August 1960, $M = 6.0$ at a distance of about 45 km (near source) and (2) a large ($M = 8.0$) earthquake due in the central seismic gap in the Himalayan region, at a distance of about 225 km (far source). We focus on the influence of the seismic source location and focal mechanism on site-response, which, in general, is neglected in traditional site-effect studies. We compare the Response Spectra Ratio (RSR) for frequency up to 3 Hz computed due to far and near sources. We observe 6–7 times higher amplification in the radial component at around 2–2.5 Hz due to the far source as-compared to the near source. However, there is some amplification, of the order 2–3, at lower frequencies (less than 1 Hz) due to the near source, which is missing when the far source is considered. To validate our results, we compare the RSR, obtained from the signals at soft sites, namely CPCB, IHC and CSIR, normalized to the bedrock Ridge site, recorded during Chamoli earthquake of 1999, with that at similar sites theoretically computed along our 2D geological cross-sections.

Keywords: Delhi city, near and far sources, response spectral ratio, site-effects.

ONE of the most important factors influencing the spatial variability of ground motion is the site response. The local amplification, or de-amplification effects can dominate the ground shaking response whenever lateral heterogeneities, such as surface topographical features or soft-sedimentary basins are present in the vicinity of a site. A simple physical explanation for local amplification of ground motion due to soft surface layering, is the trapping of seismic energy due to impedance contrast between the soft surface soils and the underlying bedrock. Moreover, the relatively simple onset of vertical resonances can be transformed into a complex pattern of resonances, strongly dependent on the characteristics of the subsurface topography of the sedimentary deposits. Macroseismic observations made of the destructive events of the twentieth century have clearly shown the strong influence of near-surface geological and topographical conditions on damage distribution. Most anthropic areas (e.g. megacities) are settled in relation to sedimentary basins (e.g. river valleys); therefore a realistic definition of the seismic input that takes into account site response has become one of the most relevant tasks in seismic engineering analysis. Accounting for such site effects in seismic regulations, significant research work has been carried out in the past[1–3]. Most of these researches were based on experimental methods such as Standard Spectral Ratio and Horizontal to Vertical Spectral Ratio, and were carried on after the occurrence of a destructive earthquake as posterior research work. Probabilistic seismic hazard analysis is also questionable and can be misleading for such studies[4]. Being based upon rough assumptions and models (e.g. recurrence and attenuation laws) it cannot take into account, with satisfactory accuracy, some of the most important aspects like rupture process, directivity and site-effects. This is evidenced by a comparison of recent recordings with the values predicted by the probabilistic methods. For example, the GSHAP acceleration values expected for Kobe, Bhuj and Bam earthquakes with a probability of exceedance of 10% in 50 years (return period 475 years) were 0.4, 0.2 and 0.41 g respectively. However, the observed values are found to be 0.7–0.8, 0.6–0.7 and 1 g respectively. Recently, several numerical methods, including finite difference and finite elements, or analytical ones, like modal summation have been employed in order to develop 1D, 2D or 3D prior estimation of ground motion amplification[5–9]. It has always been a matter of discussion whether the site response estimated at a particular site depends only on local geology, geotechnical characteristics or also depends on other factors, e.g. epicentral distance (path-effects), source mechanism and the orientation of focal mechanism. Here, we show that the site-effect cannot be separated from the source and path effect.

Delhi is a city which is under threat of seismic risk not only from the local earthquakes but also from those originating in the Himalayan region (Figure 1). Several groups of researchers are working on seismic hazard and microzonation of Delhi city and a number of research papers[10–14] have been published. Here the question: what is the response at a specific site in the city due to local earthquakes (near source) and to the ones originating from the so-called seismic gap in Central Himalayas? We study the uniqueness of the site-effect by examining the influence of source distance on the variation of ground amplification along a geological cross-section in Delhi city. We show that at some specific sites, the amplification of the far source signal can be 6–7 times larger compared to the one from the near source.

In the last decade, a huge amount of literature has been dedicated to the estimation of site effects, and a practical definition of the site effect, that combines the purposes of the engineering and seismological communities, is proposed by Field[15] 'the unique behaviour of a site, relative to

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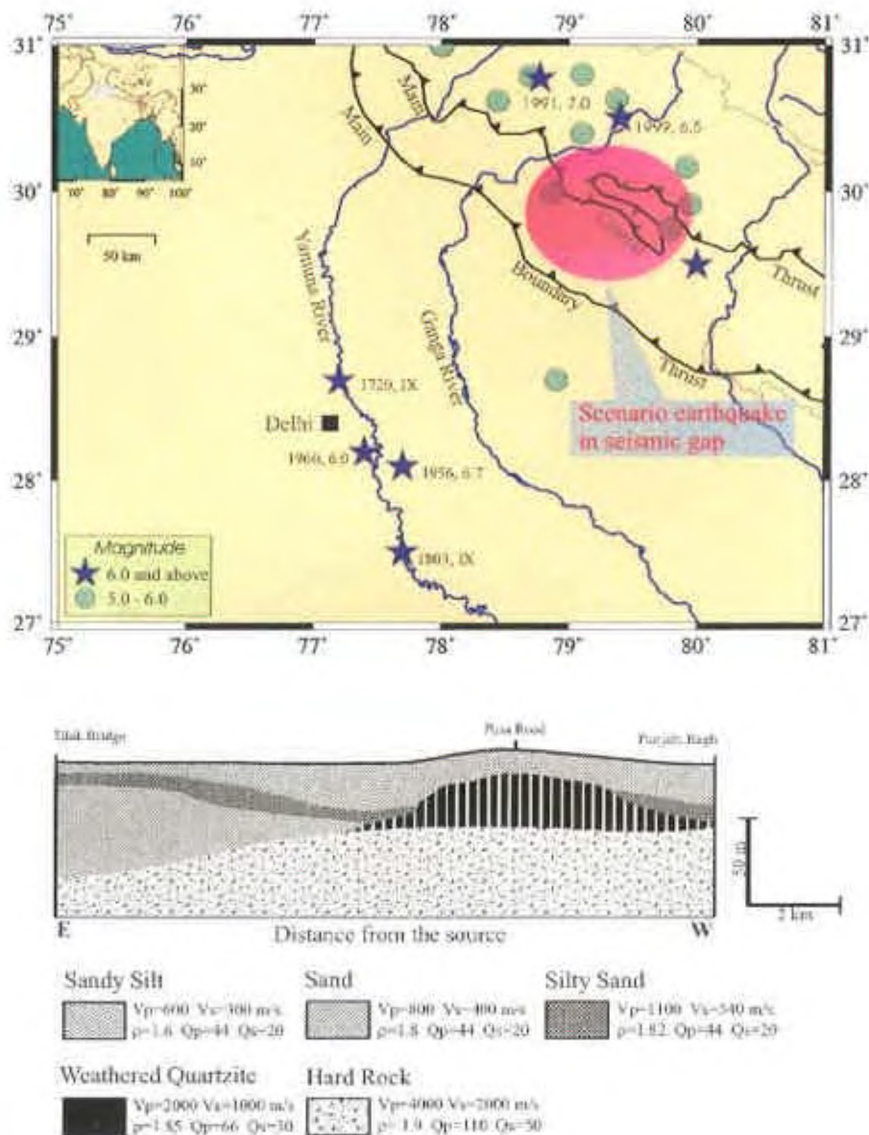
Figure 1. Regional map of Delhi and its surrounding areas with epicentres of earthquakes that occurred in the region, along with soil properties of the cross-section from Tilak Bridge to Punjabi Bagh used in the simulation.

other sites, that persists given all (or most) of the potential sources of earthquake ground motion in the region'. Such a definition implicitly reveals the difficulties connected with the correct site response estimation, i.e. identification of the different ingredients involved in the resulting ground motion signal: source, path (including the presence of lateral heterogeneities), and local soil effect, including its possible nonlinear behaviour. The nonlinear effects will not be treated in the following; we just mention that the assumption of linearity between stress and strain can be no longer valid for accelerations larger than 0.1–0.3 g, quite important values from the seismic engineering point of view. In fact, due to nonlinearity the actual shear wave velocity decreases with increasing stress, and hysteresis leads to energy loss at any deformation cycle. As a con-

sequence, the resonance of surficial layers can be shifted to lower frequencies, and this can lead to a lower amplification of ground motion at higher frequencies.

The experimental approach to estimation of site response is based on the measure of ground motion at different sites. This implies the recording with a network of instruments of multiple seismic sources. If a network of I sites has recorded J events, the amplitude spectrum O of the jth event recorded at the ith site is usually represented as[3]:

$$O_{ij}(\omega) = E_j(\omega).P_{ij}(\omega).S_i(\omega), \tag{1}$$

where E is the source term, P is the path term, and S is the site-effect term. Most traditional techniques for the estimation of the S term are based on the computation of

the ratio between the spectrum of the signal (or a portion of it) at the sedimentary site and the spectrum of a reference signal, preferably recorded at a nearby bedrock site[16]. The most frequently used techniques for the empirical estimation of site effects based on eq. (1), supply reliable information about the site response to non-interfering seismic phases or to single modes of vibration; they are not always adequate in most real cases when the seismic sequel is formed by several interfering waves or equivalently by several modes. In fact, in the far field (and point source) approximation, i.e. in the mathematically simplest possible situation, the kth component of seismic ground displacement is given by:

$$u_k(t) = \sum_{ij} M_{ij}(t) * G_{ki,j}(t), \qquad (2)$$

where $*$ means convolution, G is the Green's function that represents the medium response and M_{ij} are moment tensor rate functions that represent the source properties[17,18]. If they are considered to be independent in the description of the source, the above equation is linear (it corresponds to a mechanism generally varying with time). However, if we constrain their independence and ask for a constant mechanism (even an unconstrained one, i.e. the full moment tensor), i.e. if we impose the constraint:

$$M_{ij}(t) = M_{ij}.m(t), \qquad (3)$$

the problem becomes nonlinear because of the product $M_{ij}. m(t)$ (both M_{ij} and $m(t)$ are model parameters controlling source properties). Thus, the problem in the time domain is nonlinear even without the double-couple constraint (an additional nonlinearity here), usually assumed for seismic sources. In the frequency domain it may seem simpler because the convolution in eq. (2) is converted to pure multiplication and the equation is solved for each frequency separately. Within linearity we get $M_{ij}(\omega)$, but to split the source time function and the mechanism again a nonlinear constraint is needed, so the advantage of the frequency domain is fictitious. In general, the nonlinearity deriving from the double-couple constraint derives from the fact that the double-couple constraint imposes a nonlinear combination of the components of the moment tensor, namely zero value of its determinant.

An alternative to the questionable empirical approach to site response estimation is based on computer codes, developed from the detailed knowledge of the seismic source process and the propagation of seismic waves[8,9]. This approach allows us to use the source and path effects both on the site response and can simulate the complete ground motion associated with a given earthquake scenario. In such a way, using available geological and geotechnical information, a low-cost parametric analysis can be performed.

To compute very broadband synthetic seismograms, we use the hybrid method, that combines the modal summation technique[5,8,19,20] with finite differences[21–23], exploiting both the methods to their best. First, the wave equation is 'analytically' solved with the modal summation technique in the 1D part of the structural model ('regional' model), where the source is located. The obtained time series of the regional model is the result of the influence of the regional path, consisting of a set of flat parallel, homogeneous and anelastic layers, on the wavefield generated by the source. The seismic wavefield is then introduced in the 2D part of the structural model and numerically propagated within it with the finite difference method. With this approach, source, path and site-effects are all taken into account and a detailed study of the wavefield that propagates at long distances from the epicentre is possible.

We used a geological cross-section in Delhi city from Tilak Bridge in the east to Panjabi Bagh in the west[10–12]. Details of the material properties along the cross-section are shown in Figure 1. The S-wave veloctiy (V_s) and density (ρ) are adopted from the range given by Iyengar[10]. As we deal with quite low velocities, we considered it appropriate to choose $V_p = 2V_s$, according to Vuan et al.[24]. The quality factor (Q_p and Q_s) values for different soils are taken from standard compilations. The regional bedrock structure is taken from Parvez et al.[25].

During recent times, the most significant event near Delhi was the shock of 27 August 1960, with epicentre at 45 km towards Gurgaon. Nath et al.[26] studied this event in detail and reported that 100 people were injured and two died during the quake. We adopt the location of this event to define the near source used to calculate the site-effect along the cross-section. Further, Delhi city is also under threat from the Himalayan earthquakes, sitting just 225–250 km from Delhi towards northeast in Central Himalayas. This has been identified as a seismic gap with significant strain accumulation capable of a big earthquake[27,28]. Therefore, we assume a great earthquake at 225 km in Central Himalaya as a far source for this study and we compute the site-effects due to this source along the same cross-section. We also try to see the site effects upon reducing the distance of the far source on an incremental basis of 50 km. For the definition of the focal mechanism, we consider the earthquake of 10 October 1956, which took place near Moradabad about 150 km east of Delhi. The focal mechanism of this event was obtained by Molnar et al.[29] and shows normal faulting. For the Himalayan source we adopt thrust faulting, because majority of the earthquakes are of the thrust-type in Central Himalayas.

The synthetic seismograms (SH and P-SV waves) have been computed with the hybrid method for an array of 100 sites regularly spaced every 130 m, along the profile. Two sets of synthetics have been obtained by (a) assuming the sites are underlain by regional 1D velocity model (bedrock model) and (b) by placing the sites on top of the laterally heterogeneous velocity model embedded in the bedrock. Figure 2 shows the three-component synthetic strong
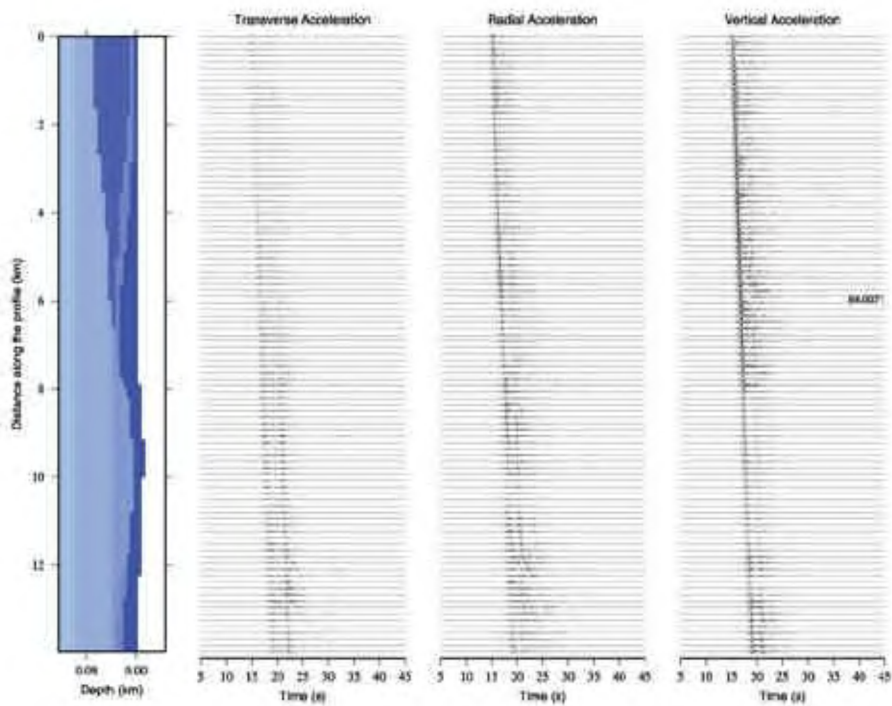
Figure 2. Geological cross-section and corresponding synthetic strong motion records computed when the source is at 45 km (near source). The maximum amplitude value in cm/s^2 is also indicated.
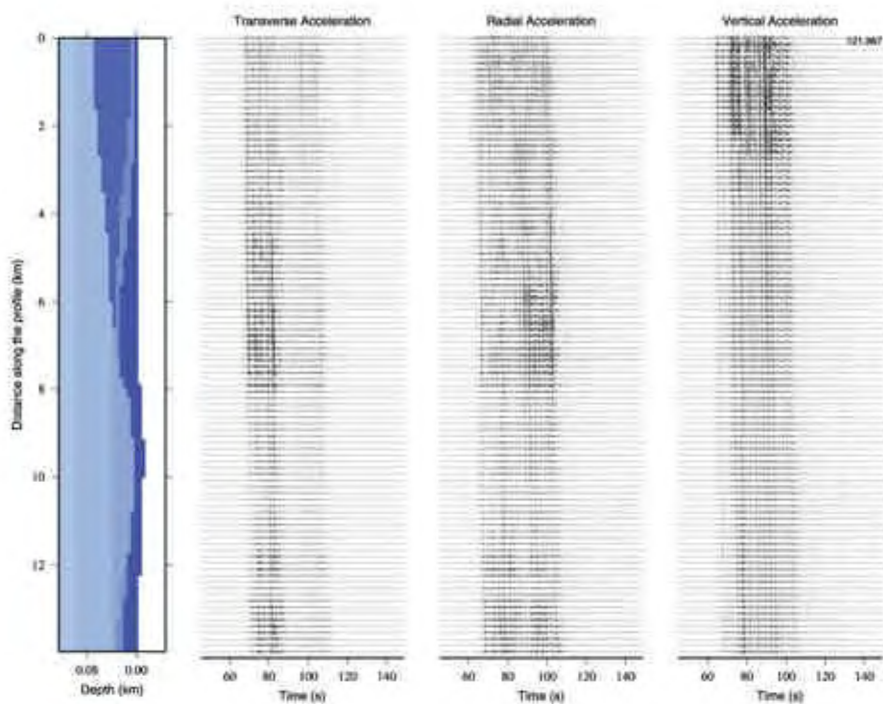

Figure 3. Same as Figure 2 but for the source at 225 km (far source).

motion accelerograms computed for the near source placed at 45 km from the profile. Similarly, Figure 3 shows the three-component accelerations when the source is placed at 225 km in the Central Himalayas. For each site along the profile, we calculate the response spectra ratio (RSR), i.e. the response spectra (5% damping) computed from signals synthesized along the local model normalized by the response spectra (5% damping) computed from the
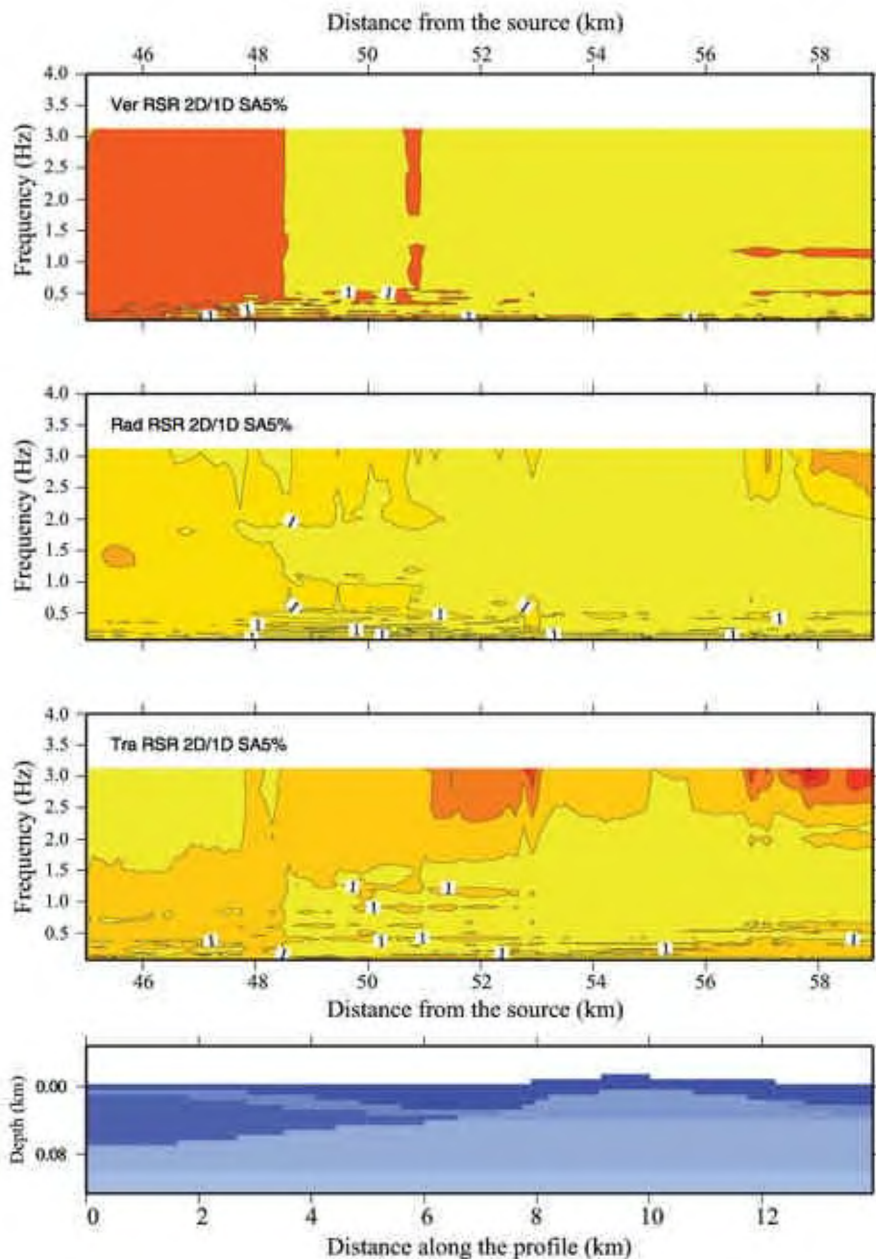
Figure 4. 2D model and corresponding plot of the response spectra (5% damping) ratio (RSR) versus frequency for the near source.

corresponding (same epicentral distance) signals synthesized for the regional bedrock model. On account of hardware limits, the simulation has been performed up to a maximum frequency of 5 Hz for the near source and 3 Hz for the far source. Since we are interested in a comparative analysis, we estimate the RSR to 3 Hz for both the sources. We used normal faulting for the near source and thrust-type for the far source, which is commonly observed in the Central Himalayas. In order to see the effect of focal mechanism for both the sources, we use normal and thrust-type of faulting in both cases. We observe that the

results are stable with respect to variation in the orientation of the fault.

The three-component simulated strong ground motion for the near source is shown in Figure 2. The seismograms are scaled corresponding to the event of 27 August 1960 which was of magnitude 6.0. Figure 2 clearly defines the trend of the amplification effects and reflects well the geometry of the cross-section models used in the computation. Peak acceleration (AMAX), 0.06 g is seen in the vertical component rather than in the horizontal components. The amplitudes in the other component are normalized to
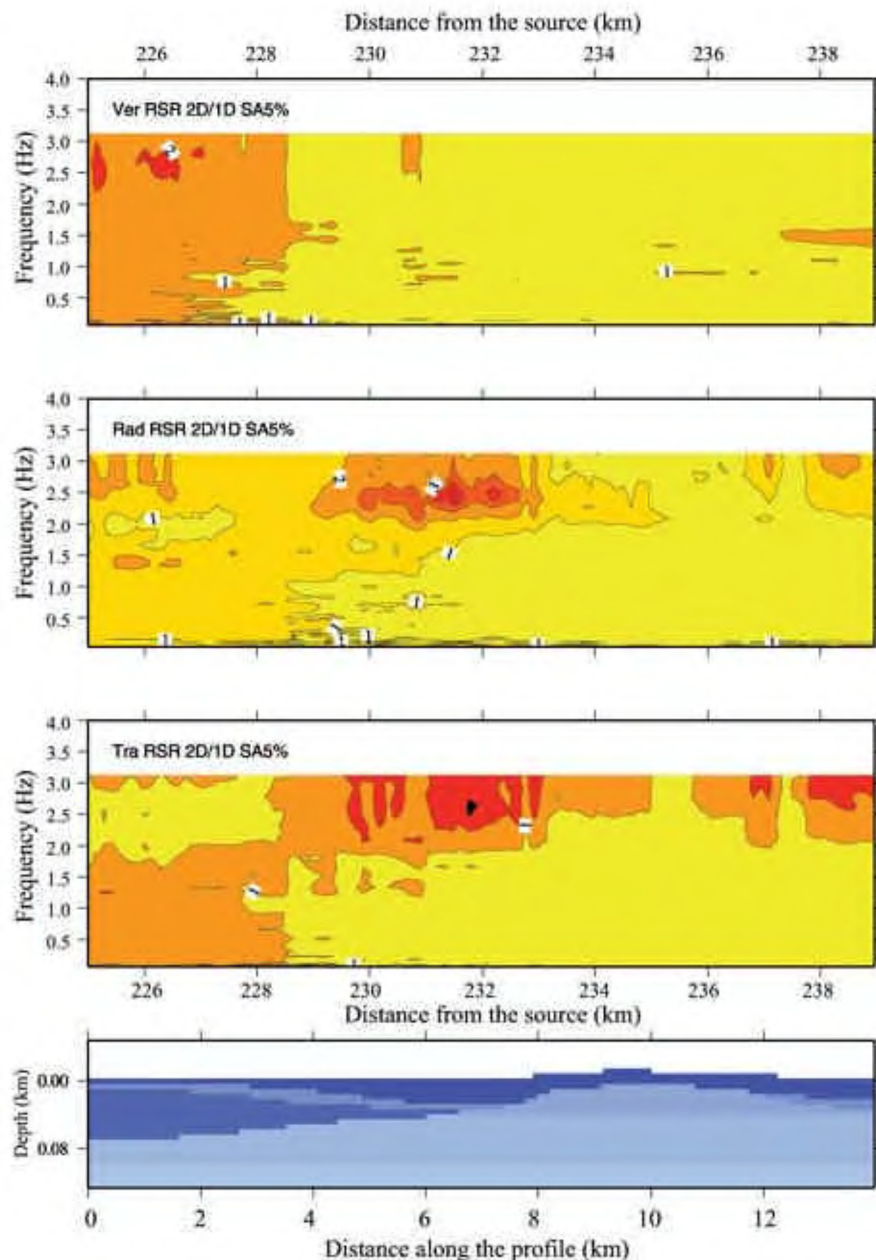
Figure 5. 2D model and corresponding plot of the RSR (5% damping) versus frequency for the far source.

the maximum. Figure 3 shows similar results when the source is chosen at a distance of 225 km, placed in the seismic gap of Central Himalayas. The signals here are scaled to an earthquake of magnitude 8.0. Taking the source distance into account, the duration of the signal has been much larger compared to the near source. In this case, we estimate the peak acceleration as 0.12 g in the vertical component.

The distribution of RSR versus frequency and epicentral distance along the profile of Tilak Bridge to Punjabi Bagh, for the near source, is shown for all the three components in Figure 4. Maximum amplification is around 3–4 times for the transverse component at a frequency close

to 3 Hz, for epicentral distance around 53 km. There is also some amplification towards the end of the profile in the same component. For the radial component, RSR is fairly close to 1 and 2 and for the vertical component RSR is around 1. In Figure 5, which shows RSR due to the far source, we see a drastic change in the amplification pattern for the same sites. In this case, the transverse component has, for frequencies above 2 Hz, a similar pattern of amplification as in Figure 2, but in the radial component, for an epicentral distance of 231–232 km, we get amplification of the order of 5–6 at about 2.5 Hz. This phenomenon is not seen in the case of the near source. The RSR for the vertical component is around 1 and 2, as for the near source
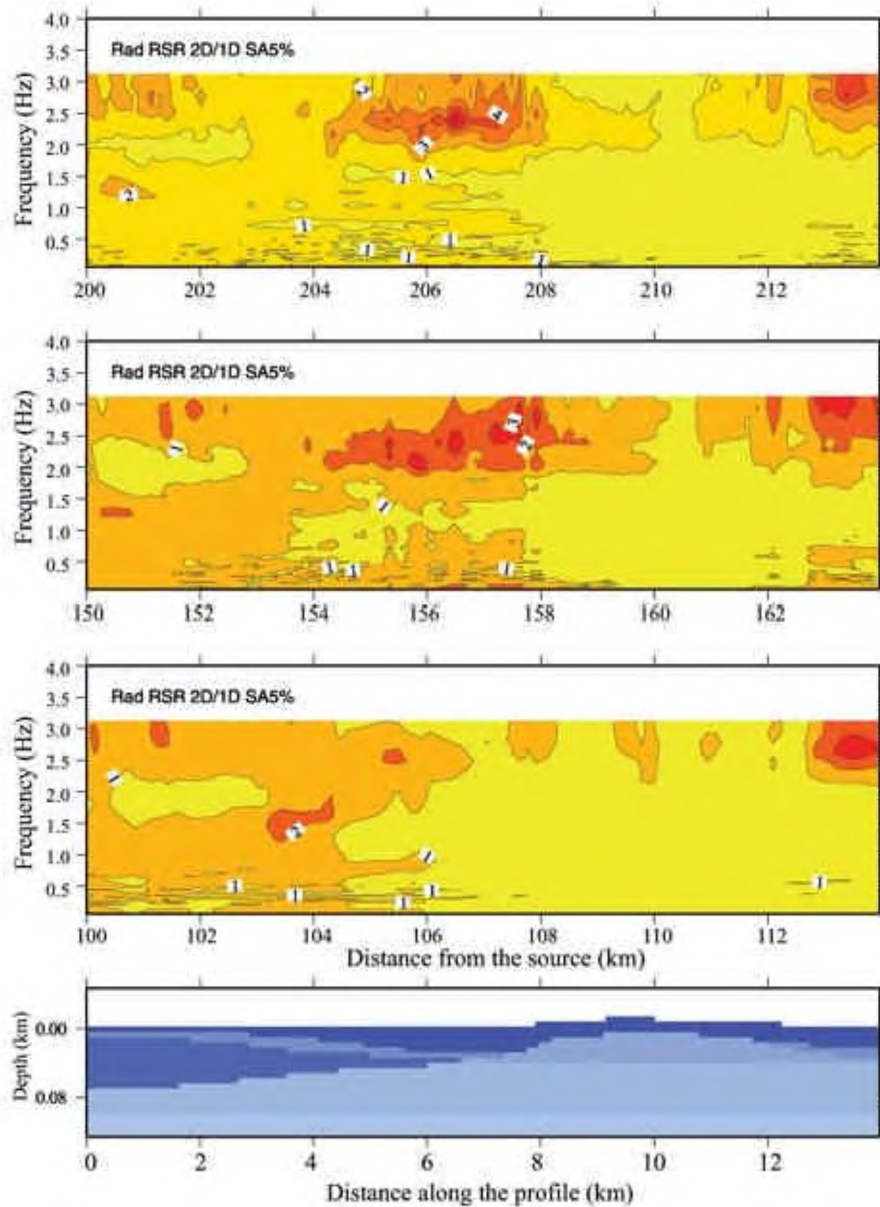
Figure 6. 2D model and corresponding plot of the RSR (5% damping) for radial component versus frequency for sources at 100, 150 and 200 km.

case. The main factor giving rise to these differences is the variability of the seismic wavefield generating source used for the simulation. Our major finding is that signals from the far source can be amplified up to 6–7 times at places where the near source signals do not show any amplification. Such differences could not be predicted by the widely used convolutive methods based on the vertical incidence of the wave field. To get a clear idea of the influence of the source, we also performed computations at epicentral distances of 100, 150 and 200 km and checked the variation in the amplification pattern for the radial component. Figure 6 shows the RSR for radial component only at 100, 150 and 200 km of source distance. We found that from 150 on to 225 km the amplification pattern is

quite similar. Hence it is stable independent of the source distance, and therefore amplification can also be considered a 'property' of the medium. This is contrary to what we can see at shorter distances, given that the amplification patterns are quite different at 45, 100 and 150 km. Hence at distances below 150 km we cannot identify the effects purely due to site: the site is the same, but a change in the source leads to a change in the amplification patterns. It is true that 3D effects may dominate near the source, but even our 2D modelling can explain the change in amplification pattern, not explainable with convolutive approaches.

The *Mw* 6.5 Chamoli earthquake (Central Himalaya) was recorded in Delhi city. The accelerograms were recorded on three soft sites, namely CSIR, Rafi Marg; IHC, Lodhi
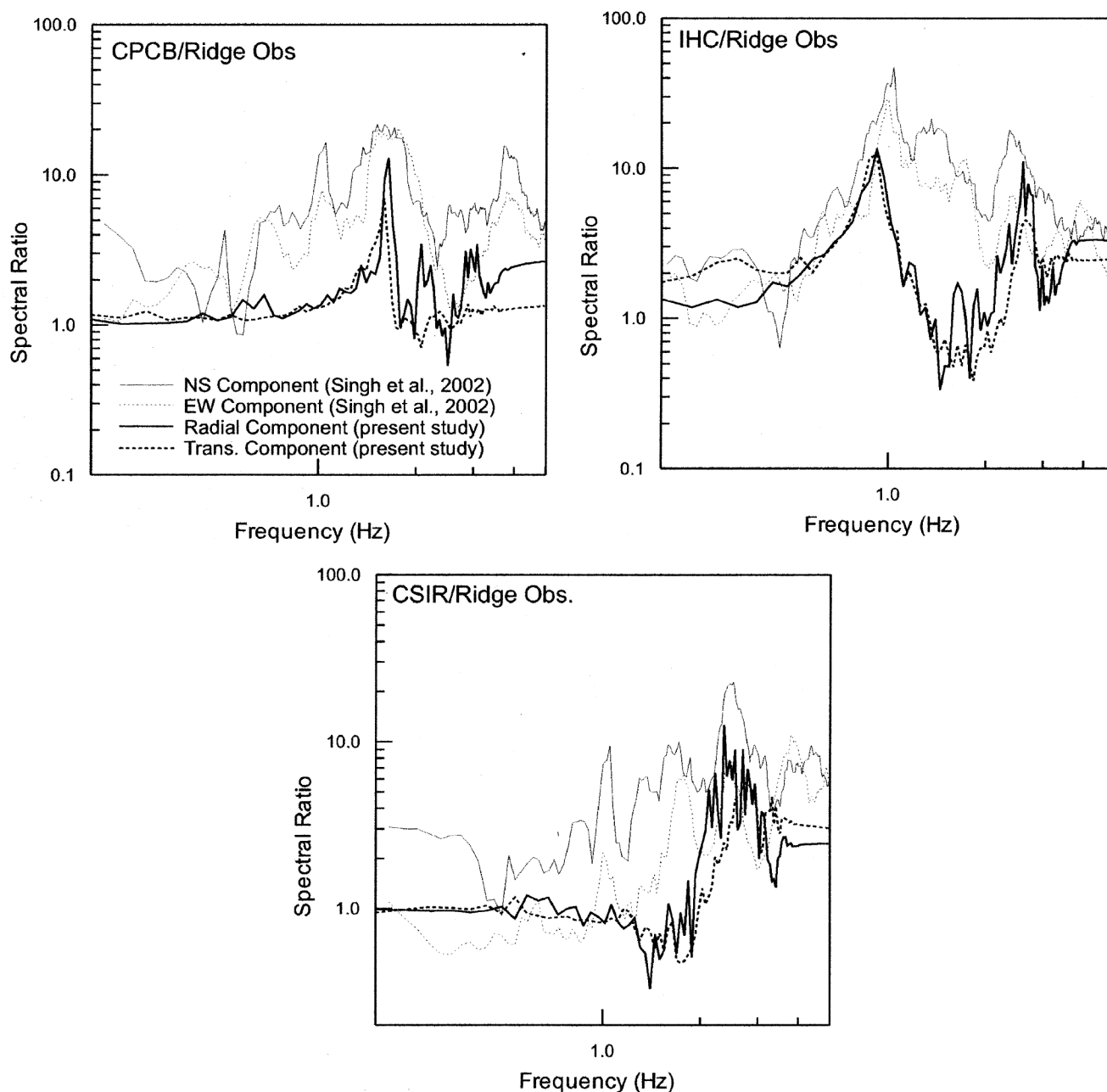
Figure 7. Comparison of synthetic spectral ratio (no damping) with observed data at CPCB, IHC and CSIR stations in Delhi city.

Road, and CPCB, Arjun Nagar. The same event was also recorded on a rocky site (Ridge Observatory), which is located on top of quartzites of Alwar series. Singh et al.[30] have analysed these accelerograms and estimated the spectral ratios of soft sites with respect to the hard site of Ridge Observatory. Figure 7 shows the spectral ratios obtained by Singh et al.[30] for CPCB, IHC and CSIR with respect to the Ridge Observatory site. The figure indicates also that the amplification of seismic waves at 'soft' sites of Delhi may reach a factor of 15–20 at frequencies between 1–2 Hz. We have selected similar soft sites along our profile, namely site nos 45, 51 and 56 lying at 6–7 km

from the origin of the profile. From the synthetic signals of these sites, for the bedrock model and the laterally heterogeneous one, the response spectral ratios have been computed without applying any damping factor and are plotted in Figure 4 with bold lines. In terms of frequency distribution, our results agree well with the observed spectral ratio. We underestimate the maximum amplification by 10–20%, which may be considered acceptable not only because of the error affecting Mw estimates, but also given that, when considering damage observations, to have a jump of one class in the macroseismic intensity an amplification of 2 (that is 100%) is required.

The findings of the present study show that the source plays an important role in the site response estimation, which varies mainly with the source distance. We observe at the same site amplification of the order of 6–7 for a far source (distance about 225 km) and in contrast we do not obtain any amplification for a near source (distance about 45 km). Therefore, for a detailed microzonation study, source, path and site, all effects need to be taken into account. The ground response at a given location must be examined for various earthquake scenarios, with varying hypocentral distance, focal mechanism, azimuth and magnitude, compatible with the characteristics of the active faults in the surrounding areas. This kind of investigation is made possible only by the massive use of synthetic modelling, and the ideal situation is when the modelling can be calibrated, as in our case, against some pertinent observations.

1. Aki, K., Local site effects on ground motion. In *Earthquake Engineering and Soil Dynamics II – Recent Advances in Ground Motion Evaluation* (ed. Von Thun, J. L.), Geotechnical Special Publication No. 20, Am. Soc. Civil Eng, New York, 1988, pp. 103–155.
2. Bard, P. Y., Effects of surface geology on seismic motion: Recent results and remaining issues. In Proc. 10th ECEE (ed. Duma), Balkema, Rotterdam, 1995, pp. 305–323.
3. Field, E. H. and Jacob, K., A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent. *Bull. Seismol. Soc. Am.*, 1995, **85**, 1127–1143.
4. Castanos, H. and Lomnitz, C., PSHA: is it science? *Eng. Geol.*, 2002, **66**, 315–317.
5. Panza, G. F. and Suhadolc, P., Complete strong motion synthetics. In *Seismic Strong Motion Synthetics, Computational Techniques 4* (ed. Bolt, B. A.), Academic Press, Orlando, 1987, pp. 153–204.
6. Fäh, D., Suhadolc, P., St. Müller and Panza, G. F., A hybrid method for the estimation of ground motion in sedimentary basin: Quantitative modeling for Mexico City. *Bull. Seismol. Soc. Am.*, 1994, **84**, 383–399.
7. Furumura, T. and Takenaka, H., 2.5-D modeling of elastic waves using the pseudospectral method. *Geophys. Res. Lett.*, 1996, **25**, 785–788.
8. Panza, G. F., Romanelli, F. and Vaccari, F., Seismic wave propagation in laterally heterogeneous anelastic media: theory and application to seismic zonation. *Advances in Geophysics* (eds Dmowska, R. and Saltzman, B.), Academic Press, San Diego, USA, 2001, pp. 1–95.
9. Field, E. H. and the SCEC Phase III Working Group, Accounting for site effects in probabilistic seismic hazard analyses of Southern California: overview of the SCEC Phase III report. *Bull. Seismol. Soc. Am.*, 2000, **90**, S1–S31.
10. Iyengar, R. N., Seismic status of Delhi megacity. *Curr. Sci.*, 2000, **78**, 568–574.
11. Parvez, I. A., Panza, G. F., Gusev, A. A. and Vaccari, F., Strong-motion amplitudes in Himalayas and a pilot study for the deterministic first-order microzonation in a part of Delhi city. *Curr. Sci.*, 2002, **82**, 158–166.
12. Parvez, I. A., Vaccari, F. and Panza, G. F., Site-specific microzonation study in Delhi metropolitan city by 2-D modelling of SH and P-SV waves. *Pure Appl. Geophys.*, 2004, **161**, 1165–1184.
13. Mukhopadhyay, S., Pandey, Y., Dharmaraju, R., Chauhan, P. K. S., Singh, P. and Dev, A., Seismic microzonation of Delhi for ground-shaking site effects. *Curr. Sci.*, 2002, **82**, 877–881.
14. Iyengar, R. N. and Ghosh, S., Microzonation of earthquake hazard in Greater Delhi area. *Curr. Sci.*, 2004, **87**, 1193–1202.
15. Field, E. H., Spectral amplification in a sediment-filled valley exhibiting clear basin-edge-induced waves. *Bull Seismol. Soc. Am.*, 1996, **86**, 991–1005.
16. Bard, P.-Y., Local effects on strong ground motion: basic physical phenomena and estimation methods for microzoning studies. In Proceedings of the Advanced Study Course on Seismic Risk SERINA – Seismic Risk: An Integrated Seismological, Geotechnical and Structural Approach, Thessaloniki, Greece, 21–27 September 1997, pp. 229–299.
17. Sileny, J. and Panza, G. F., Inversion of seismograms to determine simultaneously the moment tensor components and source time function for a point source buried in a horizontally layered medium. *Stud. Geophys. Geod.*, 1991, **35**, 166–183.
18. Sileny, J., Panza, G. F. and Campus, P., Waveform inversion for point source moment tensor retrieval with variable hypocentral depth and structural model. *Geophys. J. Int.*, 1992, **109**, 259–274.
19. Panza, G. F., Synthetic seismograms: The Rayleigh waves modal summation. *J. Geophys.*, 1985, **58**, 125–145.
20. Florsch, N., Fäh, D., Suhadolc, P. and Panza, G. F., Complete synthetic seismograms for high-frequency multimode SH-waves. *Pure Appl. Geophs.*, 1991, **136**, 529–560.
21. Virieux, J., SH-wave propagation in heterogeneous media: velocity-stress finite-difference method. *Geophysics*, 1984, **49**, 1933–1957.
22. Virieux, J., P-SV wave propagation in heterogeneous media: velocity-stress finite-difference method. *Geophysics*, 1986, **51**, 889–901.
23. Levander, A. R., Fourth-order finite-difference P-SV seismograms. *Geophysics*, 1988, **53**, 1425–1436.
24. Vuan, A., Tilahun, M., Costa, G. and Panza, G. F., Inversion for shear wave velocity in sediments and estimation of near-surface anelastic parameters. *Ethiop. J. Sci.*, 1998, **21**, 157–170.
25. Parvez, I. A., Vaccari, F. and Panza, G. F., A deterministic seismic hazard map of India and adjacent areas. *Geophys. J. Int.*, 2003, **155**, 489–508.
26. Nath, M., Narain, K. and Srivastava, J. P., The Delhi earthquake of 27th August 1960. *Rec. Geol. Surv. India*, 1968, **98**, 367–382.
27. Khattri, K. N., Great earthquakes, seismicity gaps and potential for earthquakes disaster along the Himalayan plate boundary. *Tectonophysics*, 1987, **138**, 79–92.
28. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.
29. Molnar, P., Fitch, T. J. and Wu, F. T., Fault plane solutions of shallow earthquakes and contemporary tectonics of Asia. *Earth Planet. Sci. Lett.*, 1973, **16**, 101–112.
30. Singh, S. K., Mohanty, W. K., Bansal, B. K. and Roonwal, G. S., Ground motion in Delhi from future large/great earthquakes in the central seismic gap of the Himalayan arc. *Bull. Seismol. Soc. Am.*, 2002, **92**, 555–569.