SITE-SPECIFIC MICROZONATION STUDY IN DELHI METROPOLITAN CITY BY 2-D MODELLING OF SH AND P-SV WAVES

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Site-specific microzonation study in Delhi Metropolitan City by 2-D modelling of SH and P-SV waves

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Abstract

Delhi – the capital of India lies on a severe earthquake hazard threats not only from the local earthquakes but also from Himalayan events just 200-250 km apart. The seismic ground motion in a part of Delhi City is computed with a hybrid technique based on the modal summation and the finite difference scheme for site-specific strong ground motion modelling. Complete realistic SH and P-SV wave seismograms are computed along two geological cross-sections, (1) North-South, from Inter State Bus Terminal (ISBT) to Sewanagar and (2) East-West, from Tilak Bridge to Punjabi Bagh. Two real earthquake sources of July 15, 1720 (MMI=IX, M=7.4) and August 27, 1960 (M=6.0) have been used in modelling. The response spectra ratio (RSR), ie the response spectra computed from the signals synthesized along the laterally varying section normalized by the response spectra computed from the corresponding signals, synthesized for the bedrock reference regional model, have been determined. As expected, the sedimentary cover causes an increase of the signal amplitude particularly in the radial and transverse components. To further check the site-effects, we reversed the source location to the other side of the cross-section and re-computed the site amplifications. There are only a few sites where a large amplification is invariant with respect to the two source locations considered. The RSR ranges between 5 to 10 in the frequency range from 2.8 to 3.7 Hz, for the radial and transverse components of motion along the NS cross-section. Along the EW cross-section RSR varies between 3.5 to 7.5 in the frequency range from 3.5 to 4.1 Hz. The amplification of the vertical component is large at high frequency (> 4 Hz.) whereas it is negligible in lower frequency range.

Introduction

The recent Bhuj earthquake of January 26, 2001 has left thousands dead, hundreds of thousands injured and a much large number destitute. Damage to property apparently runs into billion of Rupees. This was a shocking event that generated untold misery and captured media attention around the world. Several megacities in India, such as Delhi, Mumbai, Kolkata and Guwahati, face severe earthquake hazard. A growing number of large industrial settlements are also located in earthquake-prone areas.

Delhi is a fast growing megacity that influences the economic and industrial development of most of the country. The estimated population of urban Delhi is now
around 12.2 million. An example of the study of site effects and microzonation of a part of metropolitan Delhi city is here presented, based on a detailed modelling along two cross sections: North-South from ISBT to Sewanagar and East-West from Tilak Bridge to Punjabi Bagh. Full synthetic strong motion waveforms have been computed using the hybrid method developed by Fäh et al. (1993a, 1993b). The earthquake source of the July 15, 1720 (MMI=IX, M=7.4) event is considered for the NS cross-section, while the source of the August 27, 1960 (M=6.0) earthquake is adopted for the modeling along the EW cross-section. The site amplification, in terms of response spectra ratio (RSR), has been determined. The computations have been repeated placing the source at both sides of each profile, in order to analyze the variation in the obtained amplification patterns.

**Site-specific strong ground motion modelling**

One of the basic problems associated with the study of seismic zonation/microzonation is to determine the seismic ground motion, at a given site, due to an earthquake with a given magnitude (or moment) and epicentral distance. The ideal solution for such a problem could be to use a wide database of recorded strong motions and to group those accelerograms that have similar source, path and site effects. In practice however, such a database is not available. Actually, the number of recorded signals is relatively low and the installation of local arrays in each zone with a high level of seismicity is too expensive an operation that requires a long time interval to gather statistically significant data sets.

While waiting for data accumulation, a preventive tool is supplied by the realistic modeling, based on computer codes developed from the knowledge of the seismic source and of the propagation of seismic waves associated with the given earthquake scenario. Both the properties and the geometrical configuration of near surface soft soil materials, due to their low density, high compressibility and low strength can influence the amplitude of ground motion. These characteristics can amplify the earthquake induced ground motion, causing, even for relatively low magnitudes, damage (up to collapse) also to structures which are located far from the epicenter.

With the available geological, geophysical, seismological and seismotectonic data, we can compute realistic seismograms from the first principals of physics (e.g. Panza, Radulian and Trifu, Editors, 2000; Field, E.H. and the SCEC Phase III
Working Group, 2000). Fäh et al. (1993a, 1993b) developed a hybrid method that combines the modal summation technique (Panza, 1985; Panza and Suhadolc, 1987; Florsch et al., 1991; Panza et al., 2001) with finite differences (Virieux, 1984; 1986; Levander, 1988), exploiting both methods to their best. In the framework of the UNESCO-IUGS-IGCP Project 414 “Realistic Modelling of Seismic Input for Megacities and Large Urban Areas” (Panza et al., 1999a), this hybrid approach has been successfully applied, for the purpose of the deterministic seismic microzoning, in several urban areas: Beijing (Sun et al., 1998), Benevento (Fäh and Suhadolc, 1995; Marrara and Suhadolc, 1998), Bucharest (Moldoveanu and Panza, 1999; Moldoveanu et al., 2000), Catania (Romanelli et al., 1998a, 1998b), Mexico City (Fäh et al., 1994), Rome (Fäh et al., 1993b, Fäh and Panza, 1994), Naples (Nunziata et al., 1995, 2000), Santiago de Cuba (Alvarez et al., 2001) and Delhi (Parvez et al., 2002).

With this approach, source, path and site effects are all taken into account and a detailed study of the wavefield that propagates at large distances from the epicentre is possible. Several techniques have been proposed to empirically estimate the site effects using observations. As pointed out by Panza et al. (2001), those techniques supply reliable information about the site response to non-interfering seismic phases, but they are not adequate in most real cases when the seismic sequel is formed by several interfering waves. Romanelli and Vaccari (1999) and Lokmer et al. (2001) demonstrated that the focal mechanism can play an important role in the local amplification of seismic ground motion, sometimes masking the effects of the local structure itself. Given the complexity of the problem of site response estimation, the realistic modelling of ground motion can be considered the main way to be followed in the assessment of the hazard. This can be done considering several scenario earthquakes and taking envelopes of averages and of upper extremes of the parameters describing the hazard itself, extracted from the synthetic signals, that can be calibrated against the available records, if any.

Geological Background and Seismicity of Delhi

Delhi is located at the northern end of the Aravalli mountains and it is almost fully surrounded by Gangetic alluvium. An extension of the Aravalli Hills enters Delhi region from the South, spreads out into a rocky table-land and runs in a north-easterly direction across the Delhi State (Sett, 1964). The conspicuous longitudinal ridge, trending NNE-SSW runs from the West of the capital city and terminates on the
right bank of the Yamuna on the north (Figure 1). The greatest part of Delhi lies in the alluvium, but the small hills and ridges in and around New Delhi consist of Alwar quartzites. Delhi area is occupied by quartzites interbedded with mica schist belonging to the Delhi Super Group, unconformably overlain by unconsolidated Quaternary to recent sediments. The quartzites are gray to brownish gray, massive to thinly bedded and structurally form a coaxially refolded regional antiform plunging towards southwest. The major planar structure strikes NE-SW with steep southeasterly dips. These quartzites occur in the central and southern part of the area while the Quaternary sediments comprising older and newer alluvium cover the rest of the area (Figure 1). The older alluvium comprises silt, clay with minor lenticular fine sand and kankar beds. The newer alluvium mainly consists of unoxidised sands, silt and clay occurring in the older and active flood plains of Yamuna river. The thickness of the alluvium, both on the eastern and western side of the ridge, is variable, but it is generally larger to the West of the ridge (GSI, 1997).

Delhi and its surroundings are seismically active. Earthquakes of magnitude from 3 to 7.4 have observed in and around Delhi during the past 3 centuries. Figure 2 shows the epicentres of some moderate and large earthquakes, which occurred in Delhi region, as well as the events which occurred in the Himalayan region, along the Main Boundary Thrusts (MBT) and Main Central Thrusts (MCT), that have been felt in Delhi. The Himalayan thrust zone, just 200-250 km North of the megacity, has been identified as a significant seismic gap in the Central Himalayas (Khattri, 1987; Bilham et al., 2001), thus it can be presently considered one of the most hazardous areas of the world. Delhi is therefore quite vulnerable to Himalayan earthquakes and its burgeoning population and industrial works face increasing risk from seismic hazard.

**Input Parameters**

The input data, necessary for the ground motion simulation with the hybrid approach, consist of the laterally heterogeneous local model, the regional bedrock model and the earthquake source model.

**2-D Cross-Sections**

As discussed earlier, the aim of the present study is to define the site-effects due to the presence of sub-surface material above the bedrock. Figure 3 shows the
local soft soil above the bedrock for two representative geological cross-sections in Delhi City (from Iyengar, 2000). The NS cross-section runs from ISBT to Sewanagar and the EW cross-section from Tilak Bridge to Punjabibagh. These profiles, initially available up to 30-35 m of depth, have been further extended down, to approximate the bedrock depth level, using Iyengar (2000) data. The details of the material properties of these cross-sections are also shown in figure 3. The S-wave velocity ($V_s$) and density ($\rho$) are adopted from the range given by Iyengar (2000) and, to be conservative, we have assumed P-wave velocity, $V_p = 2V_s$. The Quality factor ($Q_p$ and $Q_s$) values for the different soils are taken from standard compilations. The regional bedrock structure (figure 3) is taken from the structural polygon no. 3 of Parvez et al., (2001).

**Earthquake Source**

Many earthquakes occurred in and around Delhi city since ancient time. For the modeling, we choose the events of July 15, 1720 (MMI=IX, $M=7.4$) and August 27, 1960 (MMI=VII, $M=6.0$). The 1720 event has been used as seismic source in the modelling for the NS cross section, with an epicentral distance of 10 kms from the nearest site in the local model. The epicentre (28.7 N, 77.20 E) and magnitude ($M=7.4$) of this event are taken from the Global Seismic Hazard Assessment Program (GSHAP) catalogue. This event was very devastating and damaging. Iyengar (2000) reports that people were scared by the noise below the ground, the shaking of the walls, and the cracking of the roofs of buildings, and that nine or ten strong aftershocks occurred during the day and the following night. Most of the damages occurred within a relatively narrow area running in the north-south direction. There are reports describing that the market road from the Kabul gate, to the North, up to Lal Darwaza, to the South, had broken down at several places, and buildings were razed to ground.

During recent times, the most significant event was the shock of August 27, 1960, having its epicentral tracts about 45 km from Delhi, towards Gurgaon. The probable cause of this event was a slip fracture in the weak brittle zone beneath the alluvium or along the contact of the alluvium with the Aravalli mountains. Nath et al. (1968) report that 100 people were injured and 2 died during this quake. The area in which the shock was felt extended up to Kanpur, to the southeast and to Jaipur, to the
southwest. However, the damage was confined to parts of Delhi and Gurgaon cities. This event is assumed in our modelling along the EW cross-section.

For the definition of the focal mechanisms to be adopted in the simulations, given that no fault plane solution is available in the literature for both events, we considered the earthquake of October 10, 1956 which took place near Moradabad about 150 km East of Delhi. The focal mechanism of this event was obtained by Molnar et al. (1973) and shows a normal faulting. The depth of the source is assumed to be 8 km for both events.

**Numerical Modelling of Seismic Ground Motion:**
The hybrid method used couples two computational techniques that permit the solution of the equation of motion in a laterally varying anelastic medium with no limitations for the source-receiver distance.

The seismic wavefield is computed in the 1-D part of the structural model (“regional” bedrock model, where the source is located) with the modal summation method and it is introduced in the laterally heterogeneous local model and numerically propagated in it with the finite difference method. Preliminarily to any computation, the soundness of the boundary conditions applied to the borders of the local model and the correct specification of the anelasticity has to be tested. The testing procedure is based on the comparison between the synthetic seismograms computed, at the same sites of the “regional” bedrock model, both using the hybrid and the modal summation methods. The choice of the input parameters describing the boundary conditions and the anelasticity of the model is considered acceptable if the peak amplitudes of the numerically computed signals do not differ by more than 5% from those computed by mode summation.

**Results along the NS cross-section**
The synthetic seismograms (SH- and P-SV-waves) have been computed with the hybrid method for an array of 100 sites regularly spaced, every 100 meters, along the NS cross section. The source modeling the event of July 15, 1720 has been placed in turn 10 km to the North and to the South of the profile, in order to analyze the ground motion amplifications obtained for waves travelling in the two opposite directions. Figure 4 shows the three-component synthetic strong motion accelerograms computed for the “northern source”, whereas the similar
accelerograms, computed for the “southern source”, are shown in figure 5. These figures clearly define the trend of the amplification effects and well reflect the geometry of the cross section models, used in the computations. Peak acceleration (AMAX) of 1.6 g is estimated in the transverse component at 10.2 km of epicentral distance from the source in figure 4, whereas a similar value is seen in figure 5 at a distance of 11 km from the source. This is a quite large value and represents a severe seismic hazard, as it can be expected in the epicentral area of an event of magnitude 7.4. We believe that the peak values within 10 km of epicentral distance is saturated for a large event in terms of damage/ground motion like what is observed at the epicenter. Such high values of AMAX are in agreement with the reports of the damage caused by the 1720 earthquake (Iyengar, 2000). The radial components of ground motion exhibit peak values in the range from 0.41 to 0.59 g, and the vertical components reaches similar peak amplitudes, in the range from 0.42 to 0.43 g.

The response spectra ratio (RSR), i.e. the response spectra computed from the signals synthesized along the local model normalized by the response spectra computed from the corresponding (same epicentral distance) signals synthesized for the regional bedrock model, is another parameter relevant for earthquake engineering purposes. The distribution of RSR as a function of frequency and epicentral distance along the profile, up to a maximum frequency of 5 Hz is shown for the three components in figure 6 (northern source) and in figure 7 (southern source). For each component of motion, the numbers in parenthesis identify the maximum amplification. In order, the distance from the source in km, the frequency in Hz and the value of RSR are given. A 5% damping of the response spectra is considered since reinforced concrete buildings are already or will be built in the area. There are sites, where the amplifications are relevant in all the three components, even if the maximum amplifications are always found in the horizontal components. If we compare figures 6 and 7, we see that the direction of propagation of the waves influences the pattern of amplification significantly. We can notice a shift both in the frequency and the location of the peaks. For instance, if we look at the position of the absolute maximum, found in the radial component for the southern source, we see that for the northern source we have an amplification around 3 instead of about 10. Large differences can be seen in the patterns of the vertical component as well. Almost no amplification is observed for the southern source in the region where the largest amplification of almost 4 is obtained with the northern source. Such differences could
not be predicted by the widely used convolutive approaches, most of which are based on the treatment of vertically propagating wavefield s.

**Results along EW cross-section**

Synthetic seismograms (SH and P-SV waves) have been computed for an array of 100 receivers regularly spaced every 140 meters using the source model corresponding to the event of August 27, 1960. At first we placed the source to the East of the cross-section, where the 1960 event actually occurred. Then we moved the source to the West of the cross-section and recomputed the synthetic seismograms to see if and how the amplification pattern changes. Figure 8 shows the three-component synthetic seismograms when the source is to the East of the cross-section whereas the similar seismograms are shown in figure 9 for the source placed to the West of the cross-section. As in the case of the NS profile, the geometry of the cross section clearly influences the waveforms, for both propagation directions. Here, the largest acceleration (AMAX) is seen in the vertical component rather than in the horizontal components. For instance, 0.06 g is seen at 48.7 km from the source in figure 8, and 0.07 g is seen in figure 9 at the distance of 45.5 km from the source. The peak acceleration in the radial component is around 0.05 g and in transverse component is less than 0.025 g.

The distribution of RSR versus frequency and epicentral distance along the profile, up to a maximum frequency of 5 Hz is shown for the three components in figures 10 (eastern source) and 11 (western source). The maximum amplification is obtained for the transverse components: less than 8 in figure 10 and almost 6 in figure 11 at a frequency of 3.9 and 3.7 Hz, respectively. The radial components have almost the same amplification in both cases whereas the vertical component shows amplification around 4 at frequencies higher than 4.5 and 4.9 Hz, respectively. If we compare figures 10 and 11, they look almost alike. Contrary to the case of the NS profile, even if we reverse the propagation direction, the response spectra ratio along several parts of the EW profile is practically the same for all the three components. Part of the explanation could be searched in the larger epicentral distance adopted for the EW profile (45 km instead of 10 km). The local amplifications, seen along the two profiles, tell us that, in general the local intensity (MCS) increments can be as large as two units, with respect to the average value, observed in the whole urban area (Panza et al., 1999b)
Discussion and Conclusions

Delhi represents a typical example of a megacity, which is under severe seismic threats not only from the local earthquakes but also from the Himalayan earthquakes, located just 200-250 km from the city. The city has already suffered serious damages in the past because of the degraded conditions of the historical built environment, and because of severe local site amplification. In the present scenario, the high density of population and the kind of built environment increase the vulnerability of many parts of this megacity. Such vulnerability may be reduced through the retrofitting of ancient buildings and monuments and through the design of reinforced concrete structures that are able to better resist the high amplitudes of the seismic ground motion. Sound anti-seismic construction requires the knowledge of seismic site response, both in terms of peak ground acceleration and response spectral ratio.

The present paper illustrates the simulation of the ground motion along two cross-section located in Delhi City. Realistic SH- and P-SV- wave seismograms are computed twice: (i) placing the source at a given distance from one side of the profile and (ii) placing the same source to the other side of the profile, keeping the distance unchanged. The ground motion modelling of complete SH- and P-SV-waves and the response spectra ratio (RSR) show that the laterally heterogeneous shallow soil deposits, composed of sandy silt and silty sand materials, are responsible for a large increase in site amplification of the horizontal components of motion. These amplification effects of the sediments peak in the frequency range from 2.8 to 3.7 Hz (NS cross-section) or from 3.5 to 4.1 Hz (EW cross-section) for the horizontal components, while the vertical component is amplified at higher frequencies (up to 4.7 Hz in the case of NS cross-section, and 4.9 Hz for the EW cross-section). The peak spectral amplifications, for the transverse and radial components, reach similar values and, in general, they are larger than those for the vertical component of motion. In our opinion, a correct definition of the response spectrum of the studied area should be based on the average or, better, on the maximum spectral amplifications computed along the profiles. Maximum spectral amplifications of the transverse and radial components, computed with a 5% response spectral damping, range between more than 3 to about 10 in the frequency range from 2.8 to 4.1 Hz.

Given a certain earthquake scenario, and an appropriate structural model, based on detailed geological, geophysical and geotechnical data, it is possible to
realistically evaluate the local amplification in the frequency range of interest for civil engineering, and to obtain valuable parameters for the realistic microzonation. This is possible by applying numerical modelling that takes into account source, propagation and local site effects, without having to resort to convolutive methods. This is the first detailed study done for Delhi City based on ground motion modelling, in terms of both the peak ground acceleration and the spectral amplification carried out along two profiles. Parvez et al., (2002) have shown just one example computed along the NS cross-section. The results of this study can readily be applied to site-specific design spectra based on average or maximum amplification and should strictly be followed on revising the building codes. Such building codes must not only allow but encourage on demand the use of such site-specific design procedures on soft-soils, in order to protect buildings during earthquakes comparable to those we have considered in the modelling.

Although this is a good starting point for the microzonation of Delhi, many more cross-sections will be required to cover the whole city, and an attempt is currently going on in such a direction. One of the important aspects of the future study will be to model the site-effects, due to the sub-surface soil of Delhi City, as caused by an expected great earthquake in the Central Himalayas.

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References


Figure Captions

Figure 1. Generalized geological map of Delhi area and the locations of the cross-sections used in the present study for the numerical modelling (modified after GSI, 1997).

Figure 2. The regional map of Delhi and surrounding areas with the epicentres of the earthquakes occurred in the region.

Figure 3. The soil properties of the NS cross-section from ISBT to Sewanagar and the EW cross-section from Tilak Bridge to Punjabi Bagh. The original model (Iyengar, 2000) gives S-wave velocity ($V_s$) and density ($\rho$); to be conservative we have assumed $V_p = 2V_s$. The Q values for the different soils are taken from standard compilations. The regional bedrock model is also shown.

Figure 4. The NS cross-section and corresponding synthetic strong motion records computed when the source is to the North of the cross-section.

Figure 5. Same as figure 4 but for the source to the South of the cross-section.

Figure 6. The NS cross-section and the corresponding plot of response spectra ratio (RSR) versus frequency, when the source is to the North of the cross-section. The numbers in brackets represent in order the distance in km, frequency in Hz and value of the peak RSR, where maximum amplification is found.

Figure 7. Same as figure 6 but for the source to the South of the cross-section. The maximum RSR, of about 10, is obtained in the radial component and it is shown by the black contour (this is the only component where RSR exceeds the upper limit of the legend of RSR).

Figure 8. The EW cross-section and corresponding synthetic strong motion records computed when the source is to the East of the cross-section.

Figure 9. Same as figure 8 but for the source to the West of the cross-section.

Figure 10. Same as figure 6 for EW cross section when the source is to the East of the cross-section.

Figure 11. Same as figure 6 for EW cross section when the source is to the West of the cross-section.
Figure 2
Figure 6