Seismic status of Delhi megacity

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The seismic status of Delhi, in terms of past history, tectonic setting and soil conditions is reviewed from an engineering point of view. The influence of soft soil deposits in amplifying rock level motion at certain frequencies, which may be detrimental to highrise buildings is highlighted. Seismic microzonation of Delhi city will help engineers in identifying and strengthening structures vulnerable to future earthquakes.

INDIA is among the countries which are most vulnerable to a variety of natural disasters. Perhaps, due to the relatively high frequency of floods, droughts, and cyclones these hazards are managed in a more professional manner. As far as earthquakes are concerned, the level of preparedness among engineers, administrators and property owners needs improvement. As the population of the country is getting agglomerated in the form of urban clusters and cities, the risk of economic and human loss due to seismic hazard is increasing every year. In this article the seismic susceptibility of the city of Delhi is discussed in some detail. The need for investigation and research to evaluate the seismic risk to the city has been highlighted.

Geological setting

Delhi, the capital city of India is bounded by the Indo-Gangetic alluvial plains in the north and in the east, by Thar desert in the west and by Aravalli hill ranges in the south. The terrain of Delhi is flat in general except for a low NNE–SSW trending ridge which is considered an extension of the Aravalli hills of Rajasthan. A computer image of the surface topography of Delhi is presented in Figure 1. The ridge may be said to enter Delhi from the SW. The eastern part of the ridge extends up to Okhla in the south and disappears below Yamuna alluvium in the NE on the right bank of the river. River Yamuna enters Delhi from the north and flows southward with a eastern bend near Okhla. The exposed rocks of Delhi are mainly quartzites with moderate folding. (For a detailed description of the geology of this region see refs 1–4.) What is of interest in a seismic hazard estimation is the depth of sediments over the rock layers. In engineering terminology this is generally referred to as the depth of bedrock below ground level. It is quite well known that[5] tall buildings founded on deep alluvial deposits can be vulnerable to even long-distance earthquakes due to resonance effects. Detailed and accurate information on the depth of bedrock in the Delhi region is not available. GSI reports[6] mention that the bedrock depth is 60 m in the Patel Road area, 15 m in Connaught Place Central Park, 40–50 m near Rajghat and 150 m and beyond in the Yamuna river bed. Similarly, the depth is reported to be 80–100 m in the Aurobindo Marg–Hauz Khas area. Large number of borehole data are available with various construction agencies in Delhi. These are however of varied quality depending on the interest with which these investigations were conducted. As a first effort, nearly 100 borehole data have been compiled at the Central Building Research Institute (CBRI), Roorkee for further work. The bedrock profile as estimated from this data is shown in Figure 2. Admittedly this description is only a first attempt. Most probably the bed rock in the trans-Yamuna region is very deep.

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Seismic history

Delhi and its surroundings should have experienced earthquakes since ancient times. The great epic, *Mahabharatha* mentions about earthquakes[7] during the war at Kurukshetra (Circa 3000 BC?). Sanskrit works, viz. *Brihat Samhita* of Varaha Mihira (5–6 century AD) and *Adbhuta Sagara* of Ballala Sena (10–11 century AD) mention[7] the kingdoms of Kuru, Matsya, Salva, Yaudheya and Trigarta, which include and encircle the present Delhi region, as being susceptible to the severest earthquakes known during their time. However the first eyewitness account of an earthquake in Delhi is of recent origin. It is worthwhile to know about the damages that occurred in Delhi during the earthquake of 15 July 1720, as recorded by Kafi Khan[8].

'At this very time, i.e. 22nd of the auspicious month of Ramzan, 1132, A.H. on Friday (17 July 1720 AD), after the expiry of the prohibited time of prayer (zavali), when in most of the mosques of Darul Khilafat (capital, i.e. Delhi) the recitation of Khutba (pre-prayer address) was in progress and people were getting ready for prayer, a horrible earthquake took place. People were afraid of the noise below the ground, the shaking of the walls, and the cracking of the roofs of buildings. During the day and the following night the earth shook with houses, nine or ten times. Though it is well known that the fortification wall and the buildings were destroyed and innumerable people perished both at Shahjahanabad and old Delhi, the writer of this history in order to ascertain the truth mounted on a horse and visited the area with circumspection. He saw with his own eyes that the market road from the Kabuligate in the north up to Lal Darvaza in the south had broken down at several places, and buildings were razed to ground. The battlemented fortification wall near the entrance gate of the Shaharpanah (city wall) was damaged. Three battlements of Fathpuri mosque had also fallen down which killed ten or twelve persons there and many more were wounded. It was noticeable that for one month and ten days afterwards the earth and the buildings trembled four or five times daily and the people got so scared that they did no longer sleep under their roofs. Later on the shocks were reduced but even after that period the earth and buildings vibrated occasionally for the next four or five months and the effects of the earthquake were felt until the arrival of the blessed feet of His Majesty, when the shocks gradually ceased.'

The MM intensity of this earthquake in the felt area, namely old Delhi has been estimated[9] to be XI. The fault which caused this event is yet to be identified. During recent times the most significant event was the shock of 27 August 1960 ($M = 6.0$) having its epicentral tract between Delhi and Gurgaon[10]. On 28 July 1994, an event of magnitude 4.0 was recorded and reported to have caused damage to one of the minarets of Jumma Masjid. Places neighbouring Delhi had also experienced several earthquakes in the historical past. Agra and its environs experienced a severe earthquake on 6 July 1505 (ref. 11).

Tectonic setting

It is seen that the Delhi region has a long seismic history being affected by earthquakes of local origin as well as those of Himalayan origin. Figure 3 shows the locations of epicentres along with the major faults. This figure is based on the tectonic map of the region prepared by Sri-

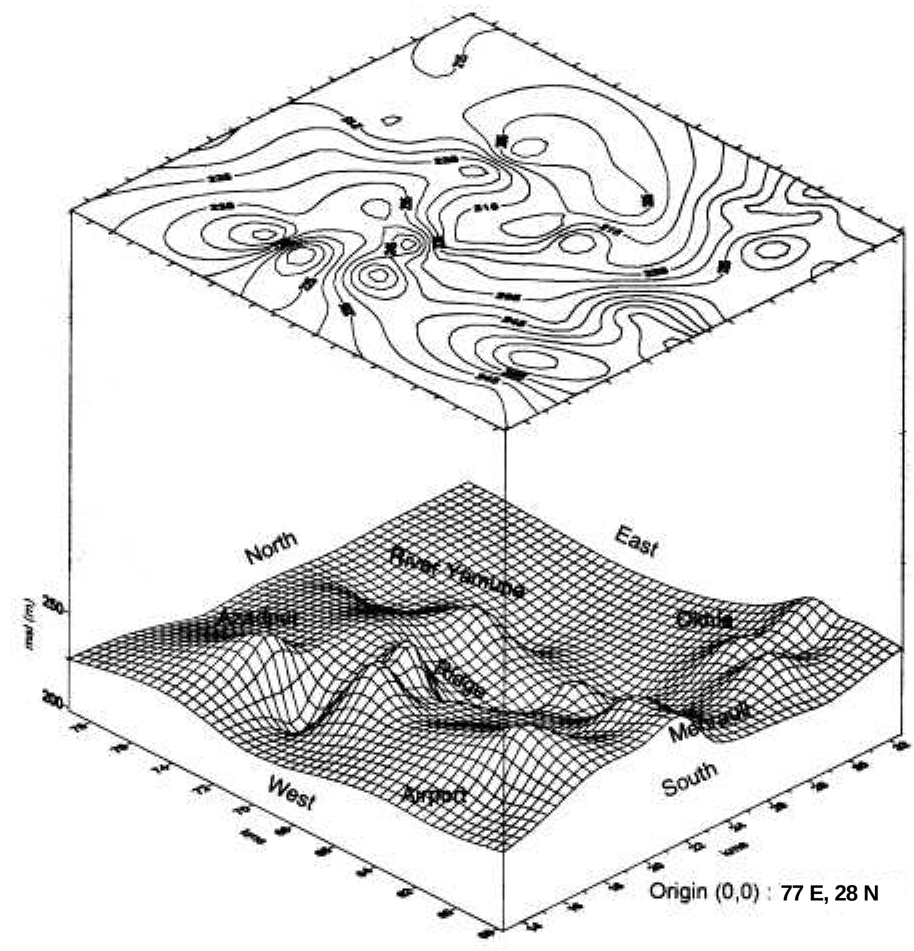

Figure 1. Topography of Delhi.

vastav and Roy[9], who in turn used earlier information available in the literature[3,12]. This region is characterized by several dominant features such as the Delhi–Hardwar ridge, Delhi–Lahore ridge, the Aravalli–Delhi fold, the Sohna fault, the Mathura fault and the Moradabad fault. Verma *et al.*[13] and Chouhan *et al.*[14], who have studied more than 100 events recorded in the region have shown that the epicentres have a pattern of clustering in two belts, namely Rohtak and Delhi. They also opine that the local activity shows a switching between these two places, with Rohtak being more active than the Delhi area. The distribution of the epicentres appears to have a NE-SW trend correlated with the direction of major tectonic features of the region. According to these authors, it is not possible to associate the seismicity of Delhi with any particular tectonic unit. On the other hand, a number of lineaments appear to be active to various degrees[13,14].

It has been already mentioned that Delhi experiences ground vibrations due to Himalayan earthquakes also. The great Kangra earthquake of 1905 reportedly caused damage of intensity MMI = VI in Delhi. The Uttarkashi earthquake of 1991 was felt in the Delhi region. GSI estimated[15] the local MMI intensity as V. The most recent Chamoli earthquake of 29 March 1999 was felt all over the Delhi region. There have been reports of cracks in a few tall buildings located on alluvial deposits in the trans-Yamuna area. This event has been recorded by instruments maintained by the CBRI. The ground acceleration recorded in Delhi city has been of the order of 10 cm/s^2 on soft soil. Three stations on soft soil recorded the event. One such record along with its Fourier transform is shown in Figure 4 *a* and *b*. Stations on hard rock did not record the event at the trigger level of 0.001 *g* acceleration. This implies that the base rock level motions have been amplified by the deep soil deposits to the order of 10 cm/s^2 at the surface level. The narrow band Fourier spectrum indicates strong filtering characteristic of the site which responds mostly near its natural frequency of 1–2 Hz. For engineering evaluation of seismic risk to man-made structures, estimation of the hazard in terms of probable ground acceleration due to future events is essential. Since almost all parameters such as the return periods, magnitudes, epicentral locations, and site characteristics are uncertain or random variables, seismic hazard estimation by its very nature is probabilistic. The so-

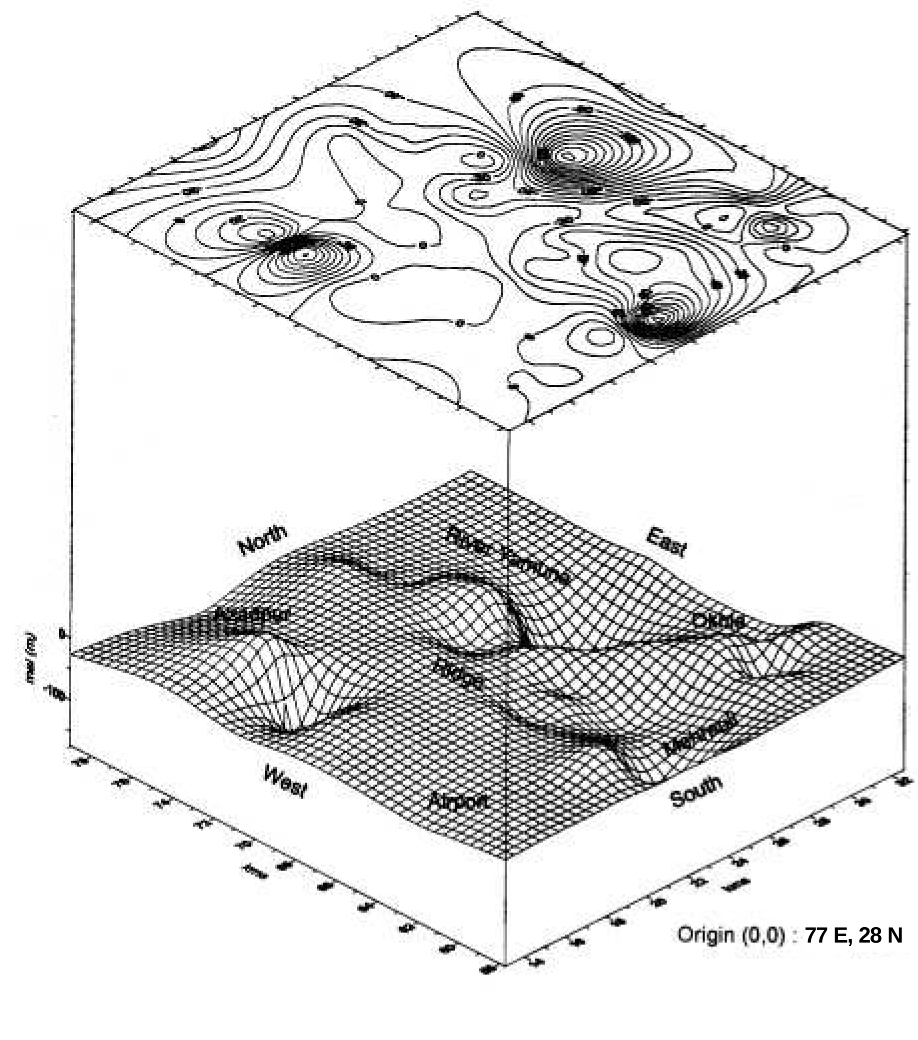

Figure 2. Approximate depth of bedrock below ground level in Delhi.

called deterministic hazard estimation methods are currently out of vogue in this field. It is not the purpose of this paper to compare and contrast probabilistic and deterministic approaches to hazard estimation. However, it is worth mentioning that the former approach needs detailed data; it is complex but objective and rational. The latter approach overlooks or ignores the details of the phenomenon; it depends only on a few easily available data and hence with subjective empirical techniques or investigations arrives at unique numbers, which gives a false sense of precision to lay users who are prone to treat probabilities as imprecise due to their own inexposure to scientific language. Rigorous quantification of seismic hazard in detail for the Delhi region has not been carried out so far. Chouhan[12] estimated the focal depth of earthquakes around Delhi to be about 8 km. His frequency–magnitude analysis lead to the conclusion that the maximum size of an earthquake that may occur in this region would be 7.6. The work of Srivastav and Roy[9] indicates that in a period of 50 years a magnitude 6 earthquake is almost certain and that there is 80% probability of a 7 magnitude event visiting the region. Khattri[16] has carried out an exercise estimating the seismic hazard for the northern region of the country.

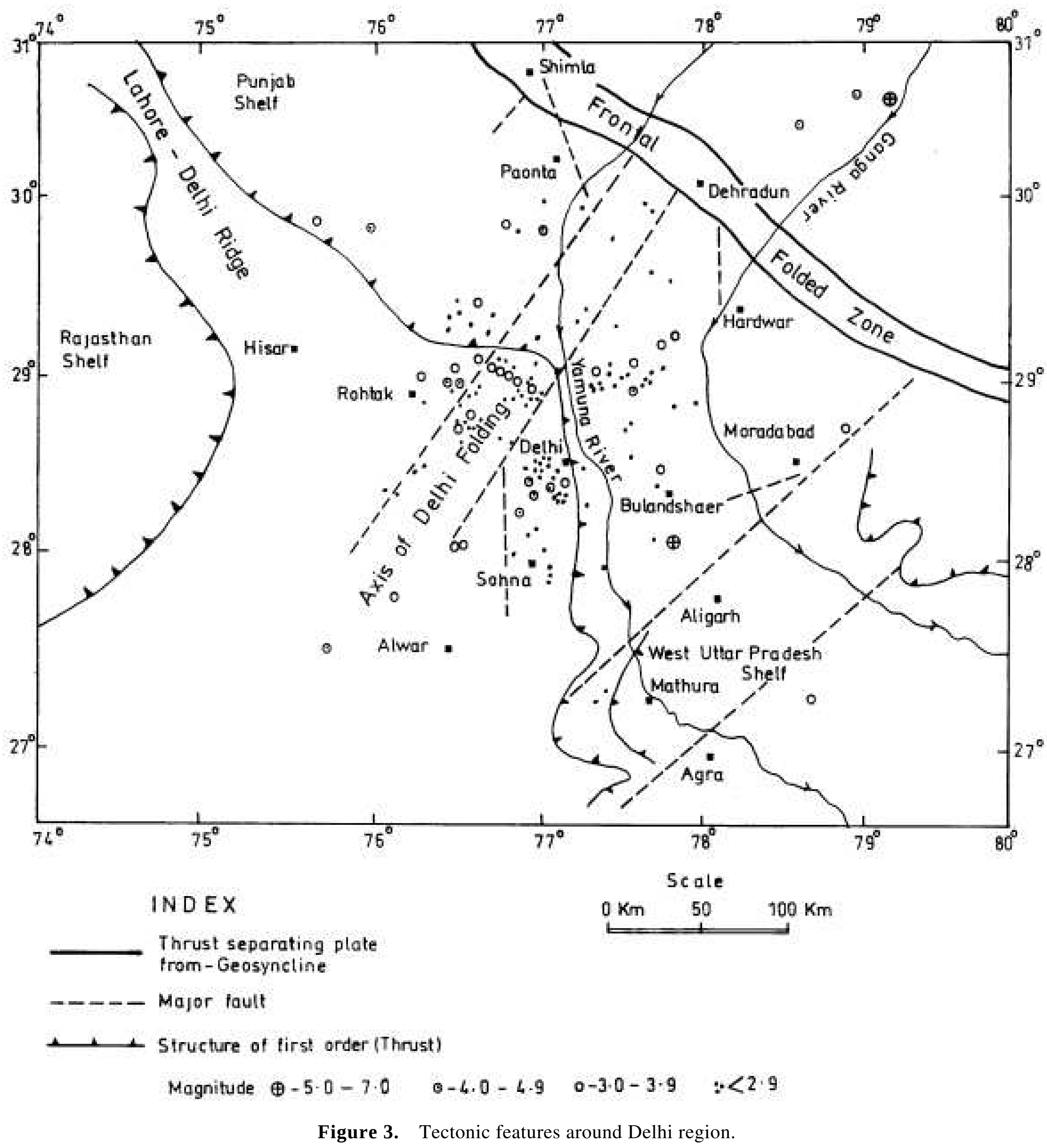

Figure 3. Tectonic features around Delhi region.

According to this study in a fifty-year window of 1983–2033, the peak ground accelerations around Delhi would be 0.2 *g* with 10% probability of excedance. Delhi and its environs have not yet experienced this level of ground vibration in the above time period. Even if these estimates need further refinement they indicate the nature of events expected for Delhi city.

Soil conditions in Delhi

All other parameters such as magnitude and distance remaining the same, local soil conditions dramatically modify the amplitude and frequency content of ground motions. The effect of soil conditions in modifying the damage to buildings of the same type is well-recognized by engineers. Two typical subsoil cross-sections of Delhi in the E-W and N-S directions as estimated by Rao[17] are shown in Figure 5. Wherever there are deep deposits of alluvium, tall buildings at such locations are likely to experience amplification of ground motion as the seismic waves pass through the intervening medium. The risk to a building depends on the level of ground motion at the foundation integrated with the strength properties or vulnerability of the building. An understanding of how much and at what frequencies the base rock motion gets amplified is essential for proper risk evaluation. A standard approach of representing this property of a soil deposit is through its frequency response function. This is defined as the ratio of the steady state surface amplitude to the amplitude of the bedrock motion, which is taken to be sinusoidal as a function of frequency. In Figures 6–8 amplification results are presented for different sites in Delhi for three soil damping values. The soil profile is based on the actual borehole data up to the depth indicated. Below this depth, the soil is assumed to be a rock half-space. The standard software SHAKE has been used in arriving at these results. It may be mentioned here that this software treats soil deposits as viscoelastic layered media, overlying a uniform half space subjected to vertically propagating shear waves. At Delhi maximum amplification is observed in the frequency band of 1–2 Hz which would be in the range of the first natural frequency of the soil deposit itself. Multistorey apartment buildings are likely to have their first natural frequency in the same range and hence are prone to experience relatively higher levels of seismic forces in comparison with shorter buildings. The results shown in Figure 6–8 are to be taken as indicative of the effects of alluvial soil deposits. Depending on the depth of the deposit the amplification pattern would change. For a better study of soil amplification in Delhi one needs the ground motion data simultaneously recorded on hard rock and soft soil sites. Such type of data are yet to be obtained. Tentatively it may

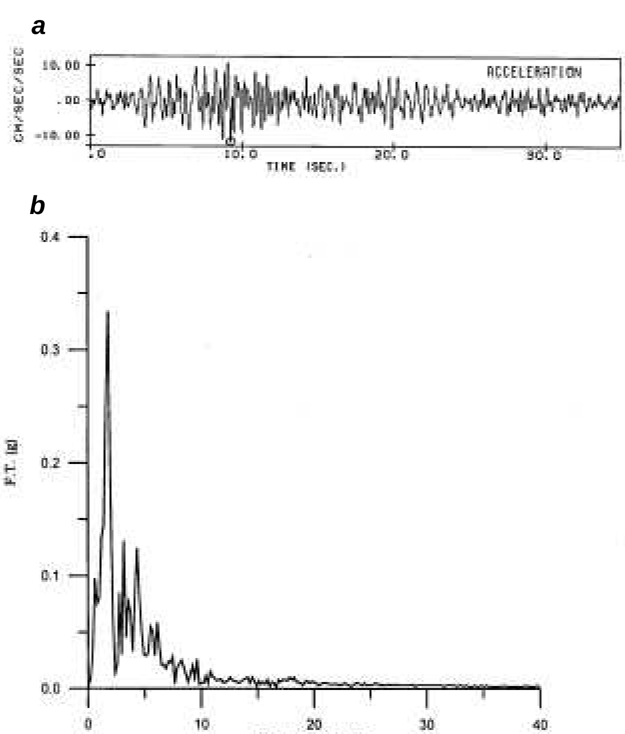

Figure 4. ***a***. Accelerogram (N-S Component) of Chamoli earthquake (29-03-99, 00:35:00) recorded at CPCB, New Delhi. ***b***. Fourier transform of Chamoli earthquake accelerogram at CPCB, New Delhi.

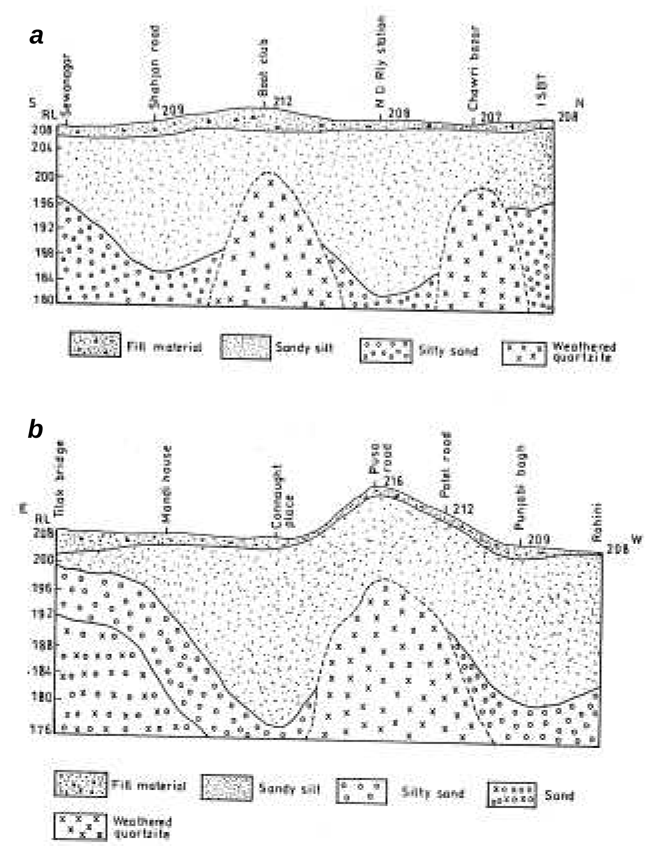

Figure 5. Sub soil profile (***a***) along N-S corridor and (***b***) along E-W corridor.

be said that hard rock sites are expected to carry base motion as it is, with its energy more evenly distributed, with a shift towards the higher frequency range of 5–10 Hz. Soft soil sites filter the high frequencies and exhibit surface motion with energy predominantly in the frequency range of 0–5 Hz.

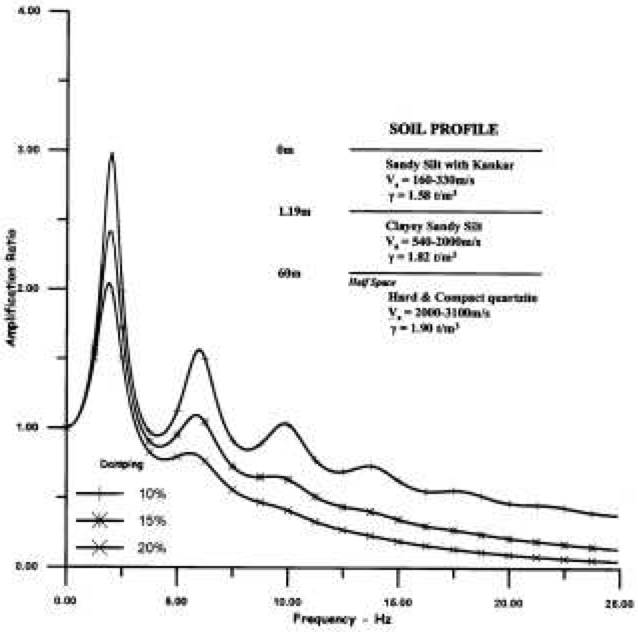

Figure 6. Amplification ratio at Rafi Marg, New Delhi.

Discussion

The recent spate of earthquakes in the country has highlighted the level of seismic hazard and the vulnerability of built-up regions in India for damage. The prevalent seismic zoning map of India according to the Bureau of India Standards (IS:1893–1984) divides the country into five zones (I–V) in the increasing order of seismic hazard. This approach of deterministically fixing the seismicity of macro-regions has been proved wrong by the Khillari earthquake of 30 September 1993 which occurred in a region identified as zone I and hence of least hazard according to the above map. Delhi city and the surrounding region are well known to be seismically active. Thus, instead of being satisfied with a broad macro-zoning concept of Delhi being in zone IV, it will be prudent to delineate the hazard and the resulting risk at the city level. This calls for a multidisciplinary effort on the part of scientists and engineers to create a seismic hazard map on the scale of city sectors or blocks. Such a map would discriminate between soft soil and hard rock sites, and would incorporate the depth of the soil deposit as a parameter in hazard estimation. To understand the damages caused to buildings on a large scale due to foundation failure, regions of soil susceptible for compaction and liquefaction have to be identified. Further, building damage depends on the strength of the structure which in turn is a function of parameters such as the materials used, design details, quality of construction and age.

Conclusion

The level of safety of a city during an earthquake depends on a variety of factors including geology, topography, sub-

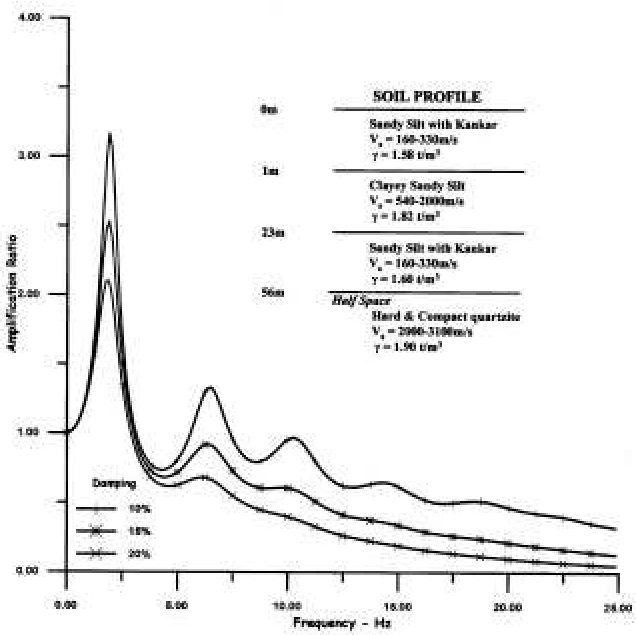

Figure 7. Amplification ratio at Lodhi Road, New Delhi.

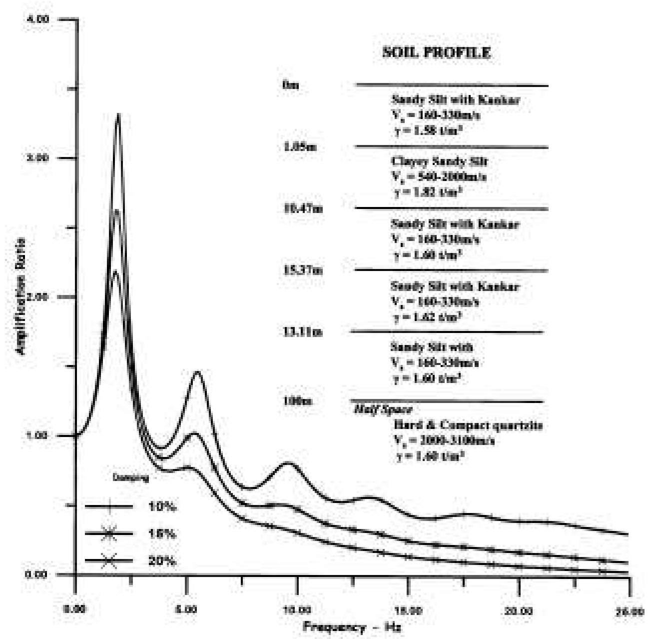

Figure 8. Amplification ratio at Arjun Nagar, New Delhi.

soil conditions, building morphology, communication network, and societal awareness. In the present paper the level of knowledge of seismic status for the city of Delhi has been reviewed from an engineering point of view. It is seen that the presently available information is rather sparse. The situation urgently calls for investigations to map the subsoil profile of Delhi. Apart from amplifying rock level seismic motion to induce higher forces on buildings, granular soils may get compacted and saturated loose sand can liquefy, leading to settlement and tilting of buildings. Delhi city encompasses an area of nearly 500 km^2, with varied soil conditions. The building types in terms of their engineering properties, social functions and vulnerability are also quite varied. Detailed investigations of the seismic hazard and its integration with the vulnerability of the built environment to evaluate the risk distribution are yet to be undertaken. Preparation of microzonation maps of Delhi city for seismic risk is foreseen to be the first step in minimizing economic damage and social disruption in the event of an earthquake. This work will help in identifying a fail-safe corridor for the city, which will remain serviceable after a major earthquake.

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ACKNOWLEDGEMENTS. Thanks are due to Dr J. M. Siddiqui, Aligarh Muslim University, for translation of ref. 8. Thanks are also due to Sri Y. Pandey, Sri Dharmaraju and Sri B. Venkateswarlu for help with the manuscript.

Received 12 August 1999; revised accepted 31 December 1999