Deterministic Seismic Microzonation of the NCT-Delhi (India) and Earthquake Engineering Implications

Luxman Kumar
Indian Institute of Technology Roorkee
J. P. Narayan (jp.narayan@eq.iitr.ac.in)
Indian Institute of Technology Roorkee

Research Article

Keywords: Finite-fault stochastic ground motion simulation, dynamic corner frequency, seismic microzonation of Delhi, local site effects

Posted Date: June 1st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-499148/v1

DETERMINISTIC SEISMIC MICROZONATION OF THE NCT-DELHI (INDIA) AND EARTHQUAKE ENGINEERING IMPLICATIONS

Luxman Kumar and J.P. Narayan

Department of Earthquake Engineering, Indian Institute of Technology Roorkee, India

e-mail: kumarluxman90@gmail.com; jp.narayan@eq.iitr.ac.in

ABSTRACT

A deterministic seismic microzonation of the NCT Delhi (The capital of INDIA) and its earthquake engineering implications is presented in this paper. The NCT Delhi with population density around 21,000/sq. Km has experienced several severe earthquake shakings in the past due to earthquake occurrences in its vicinity and in the Great Himalaya. The exposed central quartzite ridge, Badarpur-Okhala hillocks and River-Yamuna are responsible for the very large spatial variation of sediment thickness (10 m to more than 300 m) in the NCT Delhi. The dynamic properties of sediment layers over the quartzite basement at 158 sites, well distributed in the NCT Delhi, are considered for seismic microzonation. First, we have finalised the maximum credible earthquake (MCE) for each considered site based on the deterministic seismic hazard analysis. Thereafter, acceleration time history at basement level is computed at each site using stochastic finite-fault method with dynamic corner frequency and the geometry as well as rupture-dimension of the respective MCE. The basement ground motion is numerically transferred to the free surface using the rheological parameters and thickness of sediment layers overlying the quartzite basement. Different maps of earthquake engineering interest like peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGV) at basement level and the free surface level are developed and analysed for earthquake implications. The obtained range of PGA (0.08-0.30g), PGV (3.34-26.58cm/s) and PGD (0.55-7.2cm) at the free surface and fundamental frequency of the sediment deposit (0.4-7.0Hz) reveals that the NCT Delhi needs special attention by the planners, engineers and decision makers for earthquake disaster preparedness.

Key Words:

Finite-fault stochastic ground motion simulation, dynamic corner frequency, seismic microzonation of Delhi, local site effects

Declarations

Ethical statements: We consciously assure that the manuscript contains our own original work, which has not been previously published elsewhere. The paper reflects Our own research and analysis in a truthful and complete manner.

Funding: Not applicable

Conflicts of interest / competing interests: The authors declare that there is no conflict of interest.

Availability of data and material: Some or all data that support the findings of this study are available from the first author upon reasonable request.

Code availability: The inquiries about the program availability, compilation or usage details may be requested from the first author.

Authors Contribution: Both the authors contributed to the study conception and design. All simulations were performed by Luxman Kumar. The first draft of manuscript was written by Luxman Kumar and both the authors contributed towards the final version of the manuscript.

1. INTRODUCTION

The seismic microzonation of an area taking into account the source, path and site effects is essential for the prediction of relevant seismic parameters for the earthquake engineering designs, land use planning, retrofitting, seismic disaster reduction, building insurance and risk assessment (Oprsal et al., 2005; Wang, 2008; Anbazhagan and Sitharam, 2008; Shiuly and Narayan, 2012). Earthquake engineers estimate design forces considering PGA and the response spectra as per building to be designed (IS-1893:2002 (Part 1)). The response spectra to some extent takes into account the effects of fundamental and higher modes of vibration of structure. However, under double resonance condition, the dynamic forces during earthquake may be much larger than that of predicted using current practice and building may not survive. The dynamic force may increase by a factor of 3-5 times under double resonance condition (Romo and Seed 1986; Kumar and Narayan, 2018). For example, the unexpected selective damage to the high-rise buildings in the Ahmedabad city at epicentral distance more 350 km took place due to the occurrence of double resonance during the 2001 Bhuj earthquake (Narayan et al., 2002). The seismic microzonation of NCT Delhi (The capital of India) seems essential considering highly lateral variation of local geology (thickness and rheological parameters of the sediment deposits above the quartzite rock) due to the presence of exposed central quartzite ridge, Badarpur-Okhala hillocks and the Yamuna river, high population density (11,320 per sq km), the accelerated

development of super structures like surface and sub-surface metro-lines, road-bridges, fly-overs, underground gas pipelines, commercial complexes and high-rise buildings (Agrawal and Chawla, 2006). The heights of buildings may be even more than 50-stories in future due to day-by-day increase of population (Growth rate 2.94%). The NCT Delhi falls under the seismic zone IV as per the seismic zoning map of India (IS:1893 (part 1) -2002) and the assigned peak ground acceleration (PGA) for the zone IV is 0.24 g. The NCT Delhi has witnessed moderate to strong shaking due to earthquakes triggered in Himalayan and on local seismogenic sources (Iyengar 2000; GSI, 2000; Sharma et. al., 2003; Manisha and Teotia, 2011; Prakash and Shrivastava 2012). Further, earthquake shaking is always reported by the residents of high-rise buildings in the case of even distant earthquakes (epicentral distances >1000 km) due to the favourable condition for the occurrence of double resonance.

Many researchers carried out microtremors recordings at certain locations but not well distributed in the entire NCT Delhi to compute the fundamental frequency (F_0) of sediment deposits using H/V ratio method (Mukhopadhyay et al., 2002; Satyam and Rao, 2008; Mundepi et al.. 2010). Some of the researchers have used ambient noise measurement for the estimation of bedrock depth (Mundepi et al.. 2010). Iyenger and Ghosh (2004) considered the standard penetration test (SPT) data up to a depth of 30 m at 17 locations of the Delhi for the computation of F_0 and spectral amplifications using SHAKE-91 program (Parvez et al., 2004; Mandal et al., 2014). The local and regional earthquake records have been used to compute F_0 and spectral amplifications at few locations in the NCT Delhi using the standard spectral ratio (SSR) method (Nath et al., 2003; Mittal, 2011; Mittal et al., 2013). Recently, Sandhu et al. (2017) computed F_0 of sediment deposit and spectral amplifications as well as average spectral amplification (ASA) at few locations in the NCT Delhi using horizontal to vertical spectral ratio (HVSR) of the earthquake records. The extensive literature review reveals that almost all the research works carried out in the past for the quantification of F_0 and spectral amplifications in the NCT Delhi were limited to some locations only, particularly in the New Delhi region using either earthquake records (Nath et al.,2003; Mittal et al., 2013) or rheological parameters of sediment thickness limited to 30 m (Iyenger and Ghosh, 2004; Parvez et al., 2004). However, National Center for Seismology (NCS) and Ministry of Earth Sciences (MoES), Government of India have conducted microtremors recordings, SPT tests and MASW mapping on a dense array for the computation of F_0 and spectral amplifications in the entire NCT Delhi (NCS-MoES, 2016). Recently, Kumar and Narayan (2020) numerically computed the F_0 of sediment deposit above the quartzite rock (Basement) and corresponding

spectral amplifications in the entire NCT Delhi taking into account the rheological parameters and the thickness of each sediment layers.

Sharma et. al. (2003) have carried out seismic hazard zonation at bedrock level for the NCT Delhi using probabilistic seismic hazard analysis (PSHA). Iyengar and Ghosh (2004) also computed seismic hazard at bedrock level over a part of NCT-Delhi using PSHA (Sarkar and Sankar, 2017). Neelama and Rao (2009) computed the bedrock motion (PGA) deterministically for the Delhi region using stochastic finite-fault simulation technique using a maximum credible earthquake on different local seismic sources. Jayalakshmi and Raghukanth (2016) numerically simulated the ground motion at some locations in NCT Delhi. Sharma et al. (2004) carried out seismic microzonation of a part of the NCT Delhi (in and around the New Delhi district of NCT Delhi). Similarly, Mohanty et al. (2007) prepared a seismic microzonation map in and around the central Delhi ridge using geographic information system (GIS) and reported PGA range 0.06-0.21g at the free surface. The comprehensive literature review on the seismic microzonation of the NCT Delhi reveals that there are few studies and are limited to a small area of the NCT Delhi. However, NCS-MoES (2016) first time prepared a report on the "seismic hazard microzonation of NCT Delhi" on a 1:10,000 scale, wherein researcher of different disciplines worked at government level. In the NCS-MoES (2016) report, the seismic microzonation maps for peak ground acceleration (PGA) at engineering bedrock level corresponding to the maximum considered earthquake (MCE) and design basis earthquake (DBE) using PSHA approach with 2% probability of exceedance in 50 years for the return period 2500 years and 10% probability of exceedance in 50 years for the return period 475 years, respectively are given. The engineering-bedrock depth was considered where S-wave velocity was equal to 760 m/s. Further, the bedrock depth was obtained after an extrapolation of the available S-wave velocity up to a depth of 30 m only at most of the locations. The response spectrum compatible ground motion at engineering-bedrock level at all the 449 considered sites were computed using 5% damping. Thereafter, the ground motion was transferred to the free surface using the rheological parameters of the 1D layered sediment deposit above the engineering-bedrock with the help of DYNEQ software. But, as per Central Ground Water Board (CGWB) report for the year 2011-12, the range for sediment thickness is 100 m to 300 m at most of the western part of the NCT Delhi (CGWB (2011-12)). Means, the use of sediment deposit above engineering-bedrock for transferring the engineering-bedrock motion to free surface is not appropriate one and there is need of seismic microzonation of the NCT Delhi taking into account the entire sediment deposit above the quartzite basement rock so that effects

of sediment resonance and low frequency amplification on ground motion characteristics can be incorporated.

This paper manifests the deterministic seismic microzonation of the NCT Delhi taking into account the spatial variation of thickness of sediment deposit above the quartzite basement. The dynamic properties of sediment layers and basement depth at all the well distributed 158 locations in the NCT Delhi (Table 1) are mostly taken from Kumar and Narayan (2020) and the reports of NCS-MoES (2016) and CGWB (2010-11). First, we have computed the peak ground acceleration (PGA) using deterministic seismic hazard analysis (DSHA) at each site corresponding to MCE on each local seismogenic sources to finalise the MCE for every considered sites in the NCT Delhi. Thereafter, stochastic ground motion time histories at the basement level at all the 158 sites of the NCT Delhi are simulated using respective MCE and corresponding fault parameters, rupture dimension and position. We have used EXSIM program to simulate the stochastic ground motion at the basement level which is based on dynamic corner frequency with a finite-fault dimension. EXSIM is an open-source stochastic finite-source simulation algorithm that generates time series of ground motion for earthquakes (Motazedian and Atkinson, 2005; Boore, 2009). Finally, the computed velocity time history at basement level is transferred to the free surface using the rheological parameters of each sediment layer with the help of fourth-order accurate staggered-grid viscoelastic SH-wave finite-difference program written by Narayan and Kumar (2013). The free surface ground motion acceleration and displacement time histories are computed using the free surface velocity ground motion. The PGA at the free surface is also predicted using the average spectral amplifications (ASA) in a frequency band 0-10 Hz and the computed PGA at the basement level using EXSIM program. The fundamental frequency of sediment deposit at different locations is also documented to infer the expected level of damage to different type of buildings under the double resonance condition. We have developed maps for the PGA, peak ground velocity (PGV) and peak ground displacement (PGD) at the basement level as well as at the free surface level for the NCT Delhi and analysed for their earthquake engineering implications.

2. GEOLOGY AND SEISMOTECTONICS OF NCT DELHI AND ADJOINING AREA

In the NCT Delhi, the presence of NE to NNE trending Aravali Ranges, known as the Delhi Central Ridge, the outcropping Aravali formation from Okhla to Wazirabad and Yamuna Rive is responsible for the highly variable sediment cover. The topography has changed considerably

due to anthropogenic activity and many lines and natural ponds have been altered or obliterated. The oldest exposed geological section in the region is middle to upper Proterozoic Delhi Super-group. The Delhi Super-group is overlain by older Alluvium (unconsolidated Quaternary sediments) of Late Pleistocene and recent Alluvium Holocene epoch. The Delhi Super-group composed of gritty quartzite, quartzite, arkosic grit with lean intercalations of micaceous schist. Delhi Super-group rock intruded through quartz and pegmatite veins. The older Alluvium mainly composed of occasionally white micaceous, yellowish-brown, medium to fine sand, silty-clay, silt, clay and kankar. The Recent Alluvium is limited to the flood plain of Yamuna stream and primarily comprises grey micaceous medium to fine-grained sand, intercalations of clay and sediment along fine nodular kankar. NCT Delhi has mainly three extensive Geomorphological units called exposed rock Quartzite, older Alluvial smoothly undulating surface along rolling topography and low lying surface of Yamuna River flood plain (Kazim et al., 2005).

Figure 1 depicts the seismotectonics of the NCT Delhi and adjoining region in an area 26.5^0N-30.5^0N and 75^0E-80^0E. The Himalayan tectonic belt lies in the North-eastern part of the study area. The southern part is covered through the Proterozoic Delhi fold belt and gneissic batholithic complex. Delhi-Moradabad and Kasganj-Ujhani are the two tectonic sub-provinces which are separated away with a trace of the Moradabad fault zone. The Moradabad fault zone shaping the boundary of these two tectonic sub-provinces has been found to have a general NE-SW trend. Delhi fold belt extended as North-Northeast Ridge towards Himalaya and is well known as the Delhi-Hardwar ridge. The Himalayan Frontal Fold region and exposed Delhi Fold belt of Proterozoic outline the northern and south-western boundaries of the Delhi-Moradabad tectonic province. The surface trace of great boundary fault (GBF) is depicted as well-defined Chittaurgarh-Machilpur lineament as a result of the presence of different geomorphic units on either side. GBF together with its subsidiaries, exhibits trace of frequent reactivation at totally different evolutionary history stages of this belt. The north-east trending Mahendragarh-Dehradun subsurface fault (MDF) expands up to foothills of Himalaya. On the premise of remote sensing studies, it has been found that a few major geomorphological features known as Lahore-Delhi edge, Delhi Haridwar ridge, Himalayan Frontal Fold region and Delhi axis of folding are following the regional trends (Srivastava and Roy, 1982). Criss-cross lineaments near Delhi (Hukku, 1966; Mehta et al., 1970 and Gupta and Sharda, 1996) indicate the complexity of the zone probably due to conjoining of the aforementioned geological structures. Geological Survey of India has mapped an N-S trending fault appearing from Sohna to the west of Delhi called as Sohna fault. The Mathura fault is trending in NE-SW direction. Figure 1 depicts that the study region is surrounded

by local tectonic geological structures namely Mathura fault, Sohna fault, Delhi-Hardwar ridge, Delhi-Lahore ridge, Mahendragarh-Dehradun fault, Aravalli-Delhi fold, Moradabad fault, Great Boundary fault and several minor lineaments. The distant tectonic structure is known as Main Boundary Thrust (MBT) and Main Central Thrust (MCT) in the Himalaya.

The NCT Delhi is shaken many times by both the local earthquakes and distant Himalayan earthquakes (GSI, 2000; Sharma et. al., 2003; Manisha and Teotia, 2011). The M6.5 earthquake of July 15, 1720 near Delhi (Sohna fault) caused heavy damage to the houses. The shaking due to the M6.7 Bulandshar earthquake of October 10, 1956 was reported to be felt in the entire NCT Delhi. The epicenter of M6 earthquake of August 27, 1960 was between Delhi Cantonment and Gurgaon. During this earthquake two people died and about 100 people sustained injuries and many buildings in the epicentral tract developed cracks. The maximum seismic intensity due to this earthquake was estimated VII on the Modified Mercalli Intensity (MMI) scale. The M5.6 Moradabad earthquake of August 15, 1956 caused loss of lives and damage to property in the NCT Delhi. In addition, the earthquakes originating in Himalayas and Hindukush region are occasionally experienced in and around NCT Delhi. The recent Chamoli earthquake of March 29, 1999 caused shaking of the order of intensity VI to VII on MMI scale in the NCT Delhi.

National disaster management authority (NDMA) in 2011 reported a potential M7.1 in the NCT Delhi and surrounding region (Jayalakshmi and Raghukanth, 2016). The historic earthquake catalogue indicates the occurrence of a great earthquake in 1505 AD with MMI intensity XII near Agra (Iyengar, 2000). The recent seismicity data reveals that most of the events that occurred in and around Delhi are close to the proximity of Mahendragarh-Dehradun Fault (Iyengar, 2000; Iyengar and Ghosh 2004; Prakash and Shrivastava 2012). So, an earthquake with Mw7.1 is considered on MDF taking in to account its seismic acivity and length, although, there are no recentaly occurred earthquake of this magnitude on this source (Jayalakshmi and Raghukanth, 2016). Based on the geological and tectonic set up of the region around the site, the seismotectonic features as identified are given in figure 1. The spatial distribution of the past earthquakes in this region shows that they occur mostly along significant geological and tectonic features such as the Mahendragarh Dehradun Fault, Moradabad Fault and great Himalayan Boundary fault zone, etc and the predicted maximum credible earthquakes (MCE) on these features based on the past publications are given in table 2 (Iyengar, 2000; GSI, 2000; Sharma et. al., 2003; Iyengar and Ghosh 2004; Manisha and Teotia, 2011; Prakash and Shrivastava 2012; Jayalakshmi and Raghukanth, 2016).

3. STOCHASTIC GROUND MOTION SIMULATION AT BASEMENT LEVEL

The stochastic point-source simulation was first developed by Boore (1983), which deliberates both the deterministic and stochastic aspects of the ground motion (Brune, 1970; Hanks and McGuire, 198; Boore, 2003). The stochastic aspects of ground motion are modelled as Gaussian white noise with the specified underlying spectrum (Boore, 1983; 2003). The deterministic aspects are defined by the mean Fourier spectrum as the multiplication of the omega square source model, path effect and site effects (Brune, 1970). The extension of stochastic method to finite-fault is carried out by Beresnev and Atkinson (1997), and Hartzell et al. (1999). The finite fault stochastic method takes into consideration the effect of the geometry of fault in near-source by discretizing the fault into sub-faults (point sources) and generates ground motion at the observation point by adding the computed time series with a proper time-delay. Recently, Boore (2009) have presented systematic comparisons of the point-source and finite-fault stochastic formulations.

Motazedian and Atkinson (2005) modified the classical finite fault stochastic technique by replacing the static corner frequency of the sub-faults with the dynamic corner frequency concept to subside the dependency of the results on the sub-fault size. The Fourier amplitude spectrum for the horizontal ground motion ($A_{i,j}(f)$) from each sub-fault is mathematically expressed as

$$A_{i,j}(f) = CM_{0\,i,j}H_{i,j}\left[\frac{(2\pi f)^2}{1+\left(\frac{f}{f_{0\,i,j}(t)}\right)^2}\right]e^{\left(\frac{-\pi f R_{i,j}}{Q(f)\beta}\right)}G(R_{i,j})D(f)e^{(-k\pi f)} \quad (1)$$

Where $C = \frac{F_S R_P}{4\pi\rho\beta^3}$ is scaling factor, R_P is the radiation coefficients averaged over the range of azimuth and take off of angle, F_S is free surface effect, ρ is the density (g/cc) of crust at the focal depth and β is the shear wave velocity (km/s) in the source zone. $H_{i,j}$ is a normalization factor that aims to conserve high-frequency spectral level of ijth sub-fault. $f_{0\,i,j}(t)$, $M_{0\,i,j}$ and $R_{i,j}$ represent ijth sub-fault corner frequency, seismic moment and distance of site from the sub-fault, respectively. The terms $G(R_{i,j})$ and Q(f) represent the geometrical spreading and quality factor, respectively. $D(f)$ and $e^{(-k\pi f)}$ represent the spectral amplification factors and high frequency spectral decay, respectively and k is the Kappa value (Anderson and Hough, 1984). The corner frequency for a particular sub-fault is computed using the following formula

$$f_{0_{ij}}(t) = 4.9 * 10^6 (N_R(t))^{-1/3} N^{1/3} \beta \left(\frac{\Delta\sigma}{M_0}\right)^{1/3} \quad (2)$$

Where $N_R(t)\ and\ \Delta\sigma$ represents the cumulative number of ruptured sub-faults at time t and stress drop. The input parameters like stress drop (set as 50 bars), fault geometry, Q values and subfault distribution as well as additional factors like site amplification, Kappa (k) are needed to be determined for the stochastic simulations.

Six local seismogenic sources namely Mathura fault, Sohna fault, Delhi-Hardwar ridge, Mahendragarh-Dehradun fault, Moradabad fault and Great Boundary fault have been delineated and shown in figure 1 and table 2 (GSI, 2000). The maximum credible earthquake (MCE) for the aforesaid seismogenic sources is finalised using pervious published literature and the occurrence of maximum magnitude earthquake on and around the local sources ((Iyengar, 2000; GSI, 2000; Sharma et. al., 2003; Manisha and Teotia, 2011; Prakash and Shrivastava 2012; Jayalakshmi and Raghukanth, 2016). The seismicity data has been taken from Earthquake Engineering Studies (2012) related to Khurja thermal power project (EQ:2012-39). First, deterministic PGA at the basement level at each of the considered locations (158 sites) of the NCT Delhi have been computed using MCE on the local seismic sources and Boore and Atkinson (2008) attenuation relation. The seismogenic source which is producing largest PGA at a site is considered as the MCE for that site. Finally, it is inferred that MCE for all the sites are associated with only three faults namely Mathura fault, Sohna fault and Mahendragarh-Dehradun fault. Further, in the case of SF, eight epicenters for the MCE are considered (Table 2). The DSHA analysis reveals that most of the sites in the NE and NW are primarily controlled by the Mahendragarh-Dehradun fault, while the SW and SE parts of the NCT Delhi are controlled by the Sohna and Mathura faults, respectively.

After finalizing the MCE for each site, we have computed stochastic ground motion time histories at all the 158 sites of NCT Delhi at the basement level using respective MCE, corresponding fault parameters and rupture dimension and position (Table 2). We have used EXSIM program to simulate the stochastic ground motion at the basement level which is based on dynamic corner frequency with a finite-fault dimension (Motazedian and Atkinson, 2005; Boore, 2009). The velocity and displacement time histories are obtained using the computed acceleration time history. Tandon et al. (2015) reported a range of S-wave velocity and density as 2400-3500 m/s and 2.6-2.8 g/cc, respectively for the quartzite rock (Mahajan et al., 2011). We have also taken S-wave velocity and density for the homogeneous basement rock as 3200 m/s and 2.7 g/cc,

respectively. The used quality factor ($800f^{(0.42)}$) and Kappa (0.04) in simulations are taken from Singh et al. (2002) and Mittal et al. (2016), respectively. The geometrical spreading and path duration effects are applied using the approach of Mittal et al. (2016) and Berensev and Atkinson (1998), respectively. The contour maps for PGA, PGV and PGD are developed at the basement level, as given in figures 8-10, respectively.

4. GEOTECHNICAL DATA FOR THE STUDY AREA

The sediment thickness in the NCT Delhi is highly variable from one site to the another site due to the exposed quartzite rock as well as the Yamuna river. The presence of super structures like fly-overs, bridges, surface and subsurface metros and high rise buildings calls the consideration of transfer function of entire sediment deposit above the quartzite basement rock for seismic microzonation of NCT Delhi. In order to compute the transfer function and fundamental frequency of the sediment deposit above the quartzite basement the rheological parameters like density, quality factor, S-wave velocity, anelastic coefficients, unrelaxed shear modulus and thickness of the various sediment layers are requisite at different locations in the NCT Delhi. Kumar and Narayan (2020) have developed empirical relationships to predict the average S-wave velocity (m/s) up to basement depth (m) for each location using available velocity up to a depth of 30 m for different layers from the published research works up to the basement depth (Iyenger and Ghosh, 2004; Mundepi et al., 2010; NCS-MoES, 2016; Sandhu et al., 2017) and the power law. The S-wave velocity up to a depth of 67 m and 55 m was available at two locality only namely Swarup Nagar and Chhatarpur, respectively (NCS-MoES, 2016). Kumar and Narayan (2020) derived the basement depths at considered sites using the available depth contour map from CGWB (2011-12) annual report (Fig. 2) and published literature (Mohanty et al., 2009; Mundepi et al., 2010; Manisha and Teotia, 2011). For example, the developed empirical relationship for the site-114 (Model Town) using velocity and depth information up to a depth of 50 m (Table 3) and power law is given in equation 3.

$$V_S = 134.4 * (D)^{0.35} \quad (3)$$

The estimated S-wave velocity for the sediment layer of thickness 100 m above the basement at site-114 is 689 m/s (Table 3).

The density (ρ) in gm/cc of each sediment layer is computed in terms of Vs (m/s) using an empirical relationship (Eqn. 4) developed by Kumar and Narayan (2020).

$$\rho = 1.65475 + 0.000264\mathrm{V_S} \quad (4)$$

The quality factors (Q) for sediment layers with S-wave velocity in range of 175 m/s to 610 m/s are obtained using the empirical relation proposed by Iyasen (1996) and for Vs more than 610 m/s, Q is taken as simply 10% of Vs (Rao et al., 2006).

$$Q_S = 0.08V_S + 6.99 \quad (5)$$

In order to incorporate frequency dependent damping in the time domain simulations using GMB-EK rheological model, it is assumed that the obtained S-wave velocity and quality factor in each layer are measured in the field using the signal with 1.0 Hz frequency (Emmerich and Korn, 1987).

5. GROUND MOTION SIMULATION AT FREE SURFACE

The current trend of seismic microzonation in most of the countries is to predict the ground motion at basement level using probabilistic seismic hazard assessment (PSHA) or DSHA and then transfer it to the free surface incorporating the 1D S-wave response of the local sediment column (Oparsal et al., 2005; Anbazhagan and Sitharam, 2008; Shiuly and Narayan, 2012). A fourth-order accurate velocity-stress staggered-grid viscoelastic SH-wave finite-difference (FD) program developed by Narayan and Kumar (2013) is employed to transfer the basement velocity time history to the free surface. The frequency-dependent damping in the time-domain simulation is implemented on the basis of acknowledge GMB-EK rheological model (Emmerich and Korn, 1987; Kristek and Moczo, 2003; Narayan and Sahar, 2014). Anelastic coefficients for each sediment layers at each site are determined using quality factor, four relaxation frequencies, Futtermann relation (Futtermann, 1962) and least-square optimization technique. Thereafter, the unrelaxed rigidity for each sediment layers are calculated using phase velocity at a reference frequency 1.0 Hz. For example, table 4 depicts the computed unrelaxed rigidity and anelastic coefficients at four 0.02 Hz, 0.2 Hz, 2.0 Hz and 20 Hz relaxation frequencies for the site-114 (Model Town). The Stress imaging approach is implemented as a free surface boundary condition at the free surface (Narayan and Kumar, 2008). The sponge absorbing boundary condition is utilized at the model edges to avoid edge reflections (Israeli and Orszag, 1981; Kumar and Narayan, 2008). The derived velocity time history at basement level at each site from the stochastically computed acceleration time histories is transferred to the free surface numerically using the dynamic properties of different sediment layers overlying the basement. Thereafter, the transferred velocity time histories at the free surface are used to compute the acceleration and displacement time histories for that site.

First, 1D basin models are prepared for each site using the parameters of sedimentary layers and the underlying quartzite basement rock. For example, at site114 (Model Town), there are 11-sediment layers above the quartzite basement (Table 4). There are 10 layers within top 30 m and thickness of the considered 11th layer is around 70 m. So, total thickness of sediment deposit at site114 is 100 m. The S-wave velocity at the base of 11th layer is obtained using developed empirical relation as 689 m/s. In the 11th sediment layer, a continuous increase of S-wave velocity, shear modulus, quality factor and density with depth is considered. The 1D basin model for site114 is discretised with a grid size of 1.5 m in the horizontal direction and in the vertical direction it is 1.5 m up to a depth of 330 m and 10 m thereafter. Time step is taken as 0.0003s to avoid stability problem. A plane horizontal SH-wave front is generated in the numerical grid at a depth of 325 m using various point sources along a line. The obtained velocity time history from the stochastic simulation is used to incorporate a particular point source in the FD grid. The simulated velocity time history at the free surface in the absence of sediment deposit is used to generate a factor to normalise the simulated motion in the presence of sediment layers for all the sites. The left and right panels of figure 3b show the transferred velocity time history at the free surface and the same at the basement level for the site114, respectively. We have generated acceleration and displacement time histories using the velocity time history at free surface for site114, as shown in left panels of figure 3a & 3c, respectively. Similar exercise is carried out for all the considered 158 sites.

In order to study the effect of sediment thickness on the transferred ground motion at the free surface, we have considered another two sites namely site2 and site96 where sediment thickness is large (320 m) and very less (9m), respectively. The computed acceleration, velocity and displacement time histories as well as corresponding basement time histories for site2 and site96 are shown in figures 4 and 5, respectively. An analysis of figures 3-5 depicts drastic reduction of PGA and minor increase of duration with an increase of epicentral distance at the basement level. The obtained increase of vigils in the case of acceleration time history at free surface as compared to the basement at site96 indicates the larger amplification of higher frequencies. On the other hand, reverse is the case at site2, where sediment thickness is 320 m. The amplification of PGA, PGV and PGD at site2 are 1.7, 1.4 and 1.3 times, at site114 are 1.9, 1.5 and 0.8 times and at site96 are 2.2, 0.9 and 0.6, respectively. Further, at a particular site, the amplification of PGA is largest and that of PGD is least. A decrease of amplification of PGD and an increase of PGA with decrease of sediment thickness can be inferred. But, in the case of PGV, there is not such clear trend with variation of sediment thickness. There is de-amplification of PGD when sediment

thickness is lesser. For example, amplification factor is 0.8 and 0.6 at site114 and site96 where sediment thickness is 100 m and 9 m, respectively.

In order to infer the variation of PGA, PGV and PGD due to epicentral distance, MCE, focal mechanism and fault parameters at a particular site, the variation of these engineering parameters at site114 (Model Town) are computed using the MCEs on MDF (Mw7.1), MF (Mw6.5) and SF (Mw6.0) and shown in figures 3, 6 & 7, respectively. The obtained PGA at site114 is more or less same corresponding to MCEs on MDF, MF and SF. This may be due to the effect of epicentral distance, frequency dependent earth-filtering, radiation pattern and the magnitude. But, PGD is largest in the case of MCE Mw7.1 on MDF (1.93 cm) and least in the case MCE Mw6.0 on SF (0.87 cm) at the basement level; which is in accordance with the Brune's model (Brune, 1970). Further, the obtained different sediment amplification factors for a particular parameter (say PGA) in the case of ground motion due to MCEs on MDF, MF and SF at site114 may be due to the change of spectra with magnitude, fault parameters, focal mechanism and epicentral distance.

In the past, some of the scientists have used average spectral amplification (ASA) caused by sediment deposit to transfer the predicted PGA at the basement level to compute the same at the free surface. For example, the computed PGA at free surface at site2, site114 and site96 using ASA are 2.0, 1.6 and 1.5 times larger than that obtained at free surface based on the wave propagation, respectively (Table 1). In the case of PGA prediction using ASA, the over prediction of the PGA is increasing with the increase of sediment thickness, which is obvious one. So, it may be concluded that basement ground motion should be transferred to the free surface using seismic wave propagation taking into account the rheological parameters and thicknesses of the sediment layers above the basement.

6. ANALYSIS OF SIMULATED RESULT

The stochastically simulated acceleration time history at basement level at all the 158 locations in the NCT Delhi using respective MCEs on MF, SF and MDF is used to generate velocity and displacement time histories at the basement level. The performance of low-rise (≤5 story), medium-rise (5-10 story) and high-rise (>10 story) buildings are more sensitive to PGA, PGV and PGD, respectively. Therefore, we have picked-up PGA, PGV and PGD from the acceleration, velocity and displacement time series, respectively for all the sites to develop the contour maps (Table 1). Figures 8-10 show the variation of PGA, PGV and PGD at basement level in the NCT

Delhi. The area east and west of the central ridge is mentioned as the eastern and western region of the NCT Delhi in this paper. Further, we have not considered the Himalayan thrusts (distance >225 km) in this study considering that the stochastic method is not appropriate for predicting the ground motion less than 1.0 Hz.

6.1 Ground motion at basement level

Figure 8 reveals that the range of PGA variation at basement level is from 0.04g (sites129 and 156) to 0.18g (site12, Qutubgarh). Similarly, figures 9&10 show that the range for PGV and PGD variation at basement level is from 2.64 cm/s (site72) to 17.01 cm/s (site13, Qutubgarh) and from 0.6 cm (site35) to 5.04 cm (site13, Qutubgarh), respectively. The analysis of figures 8-10 reveals very low values of PGA (<0.06g), PGV (<5.0 cm/s) and PGD (<1.3 cm) in localities falling on the exposed quartzite rock or underlain by shallow quartzite rock (sites with sediment thickness<30 m). For example, sites from Bakhtawarpur (site152), JNU (site153) to Pusta-4, Usmanpur (site29) on central ridge and from Sultanpur village (site98), Mandi village (sites101 and 102) and Asola village (site124) have very low value of PGA, PGV and PGD at basement level. Larger PGA (0.09-0.10g), PGV (8-9 cm/s) and PGD (1.7-2.0 cm) were obtained on the sites falling very near to the MF between Appolo Hospital, Jasola to Police station, Jaitpur (sites137, 138, 142, 143). At rest of the localities like Wazirabad, Gita Colony, Hauz Khas, Chhatarpur and Tugalakabad of the eastern region of the NCT Delhi, the PGA, PGV and PGD were between these two extremities.

On the other hand, relatively larger PGA, PGV and PGD are obtained in the western region as compared to the eastern region of the NCT Delhi. The range of PGA, PGV and PGD in the western region is 0.08g-0.18g, 6.0 cm/s-17.01 cm/s and 1.7 cm-5.04 cm, respectively at the basement level. Largest values of PGA, PGV and PGD are observed in the localities like Jatkhor, Puth Khurd, Dariyapur Kalan and Narela Mandi in the NW of the western region of the NCT Delhi due to proximity to the MDF. Similarly, somewhat locally larger PGA, PGV and PGD are also obtained in the Shikarpur and Dwarka localities falling on/near to the SF.

6.2 Ground motion at free surface

We have computed the acceleration and displacement time histories at free surface using the transferred velocity time histories from basement to free surface taking into account the sedimentary deposit. Thereafter, contours maps are developed using the obtained PGA, PGV and PGD from the time histories at different sites on the free surface (Table 1). The computed PGA at the free surface using the multiplication of PGA at the basement level with the average spectral amplification (ASA) of the SH-wave caused by the sediment deposit is denoted as PGA* in this paper (Table 1). The contour maps for PGA, PGA*, PGV and PGD are developed and shown in figures 11-14, respectively.

a. Peak ground acceleration

Figure 11 reveals that the PGA variation at the free surface is in a range 0.08g to 0.3g (Table 1). The lowest PGA of the order of 0.08g is observed in Baqargarh area (site4) and highest PGA of the order of 0.3g is observed in Khorjat area (site27). We obtained lower PGA (<0.12g) at localities from Bhaktawarpur to Wazirabad on the central ridge and surrounding area (sites152, 153, 96, 156, 154, 115, 117, 99), which are underlain by either out-cropping or shallow quartzite rock. In the eastern region, PGA<0.12g was obtained in localities south of Chandanhal (sites101, 102, 103), localities east of Hauz Khas (sites155, 157, 158), Asola village (site124) and near Gita Colony (sites135, 136). We got 0.12g ≤PGA< 0.20g at localities from Chhattarpur to South of Hauz Khas (sites98, 100, 120, 117), localities from Appolo Hospital Jassola to Jaitpur (sites137, 138, 139) and localities NE of the Yamuna River (sites131, 32, 141). PGA≥0.20g was obtained at some sites in Jaitpur area (sites142, 143) due to their proximity to the MF. The PGA less than 0.12g was also obtained in the western region of the NCT Delhi in some of the localities like Sardar Bazar to Karol Bag (sites75, 93), Ashok Vihar (sites92, 94) and Model town (sites112, 114) situated just west of the central ridge. Larger PGA (≥0.20g) is observed around Jalkhor, Puth-Khurd and Narela Mandi (sites12, 17, 26, 27, 28, 44, 45, 49, 57, 63) due to proximity to the MDF. Similarly, PGA more than 0.20g is also obtained in Dwaraka and Shikarpur localities (sites24, 42, 56) due to proximity to the SF. At rest of the localities of the western region, the obtained PGA is in a range 0.12g -0.20g.

The pattern of spatial variation of PGA* at the free surface in the NCT Delhi is shown in figure 12. The range of PGA* variation in the NCT Delhi is 0.12g to 0.53g, which is much larger than the range of PGA at free surface (0.08g-0.30g). Further, the obtained PGA* is larger than PGA at all the sites. This may be due to the obtained range of ASA variation for all the sites of the NCT Delhi is 2.25-4.89. So, it may be concluded that the basement/bedrock ground motion should be

transferred to the free surface based on the seismic wave propagation approach and not the just multiplication of ASA with the basement PGA to avoid the over prediction of PGA at the free surface.

b. Peak ground velocity

Figure 13 depicts the variation of PGV in the NCT Delhi at the free surface. The range for PGV variation is 3.34 cm/s (site156; Rani Khera) to 26.58 cm/s (site46; Sultanpur Dabas). The amplification of PGV at a particular site as compared to that at basement level is highly dependent on the sediment thickness. For example, almost no amplification or minor amplification/de-amplification of PGV was obtained at the sites located on the central ridge area where sediment thickness is less than 30 m (sites156, 96, 129). The PGV amplification of the order of 2.0 was obtained at Sultanpur Debas (site46) and Qutubgarh (site12) where depth of basement is deep. We obtained the lower PGV (≤8 cm/s) at localities from Bhaktawarpur to Wazirabad on the central ridge and surrounding area (sites152, 153, 96, 156, 154, 115, 128, 129). In the eastern region, PGV≥15 cm/s was obtained at site near Jaitpur Police station (site143) and at rest of the sites 8 cm/s <PGV<15 cm/s (sites101, 102, 103, 155, 157, 158, 124, 131, 132, 135, 136). We got large PGV (≥15 cm/s) at localities of the western region like Nazafgarh (site40), Dwarka (sites56, 57), Jharodha (sites18, 19), Jalkhor, Puth-Khurd, Dariyapur Kalan (sites12, 17, 26, 27, 28, 45, 49) and Narela Mandi to Palla (sites43, 44, 144, 60, 61, 63, 79). At rest of the localities of the western region, the range for PGV variation is 8 cm/s to 15 cm/s.

c. Peak ground displacement

The spatial variation of PGD at the free surface in the NCT Delhi is shown in figure 14. The lowest PGD value of the order of 0.55 cm is obtained in Pusta-4, Usmanpur (site129) and highest one as 7.2 cm in Narela locality (site76). The computed effect of sediment thickness based on the seismic wave propagation on the PGD is very interesting. The thick sediment deposit is amplifying the PGD and reverse is the finding in the case of shallow sediment deposit. For example, amplification of PGD is obtained at localities like Qutubgarh (sites12, 13) and Jharoda Kalan (site19) where sediment thickness is more than 300 m; and deamplification is obtained at localities lying on central ridge from Bhakhtawarpur (site152) to Pusta-4, Usmanpur (site129) where sediment thickness is less than 30 m (Table 1). Almost no amplification of the low frequency seismic waves due to shallow sediment deposit may be the reason behind this observation. We

obtained very less PGD (<1.0 cm) at localities from Bhaktawarpur to Wazirabad on the central ridge and surrounding area (sites152, 153, 96, 156, 154, 115, 117, 99), which are underlain by either out-cropping or shallow quartzite rock. In the eastern region, 1.0 cm<PGD<3.0 cm is obtained at sites which are near or east of the Yamuna River (sites131, 132, 135, 136, 140, 141, 150, 138, 142, 143) and at rest of the sites PGD is <1.0 cm. In the western region, large PGD (>3 cm) was also obtained in localities like Nazafgarh (site40), Jharodha (sites18, 19), Karol Bagh (sites75, 76), Jalkhor, Puth-Khurd, Dariyapur Kalan (sites12, 17, 26, 27, 28, 45, 49) and Narela Mandi (sites43, 44, 144, 60, 61, 63, 66, 79). At rest of the localities of the western region, the range for the PGD variation is 1 cm to 3 cm.

7. EARTHQUAKE ENGINEERING IMPLICATIONS

Most of the buildings of the NCT Delhi can be grouped in to two categories namely “B” type and “C” type, as per MSK intensity scale. “B” type buildings are ordinary brick buildings and stories ≤4 and “C” type buildings are mostly well build RC buildings. In order to achieve a specified level of performance of the building when exposed to seismic hazard, the performance-based design reflects a more general design criterion. Design based on displacement can be regarded as a subset of performance-based design. The pseudo spectral acceleration (PSA) corresponding to the resonance frequency of building can increase by a factor more than 4 under double resonance condition (Kumar and Narayan, 2018). The same may be the amplification scenario for the velocity and displacement response spectra. So, an increase of level of damage to a structure under double resonance condition may be equivalent to an increase of intensity value by a factor of 1-2 units, as was observed in Ahmedabad city during the 2001 Bhuj earthquake (Narayan et al., 2002). Therefore, we have also considered the PGV and PGD in order to infer the expected level of damage to medium and high-rise buildings, respectively under double resonance condition. The expected grade of damage (G1-G5) which may occur to the buildings in the NCT Delhi as per predicted ground motion parameters is described taking in to consideration the MSK intensity scale and a relation between acceleration and the intensity (IS: 1893 (Part 1), 2002).

a. Region of NCT Delhi underlain by shallow/out-cropping quartzite rock

The obtained PGA, PGV and PGD in the central ridge and surrounding regions is less than 0.12g, 8.0 cm/s and 1.0 cm, respectively (Table 1). The fundamental frequency of sediment deposit is mostly larger than 2.0 Hz (Kumar and Narayan, 2020). For example, it is more than 5 Hz at Bakhtawarpur, JNU and Shalimar Bagh (sites152, 153, 156), Karol Bagh (sites115, 154) as well

as more than 2 Hz at site128 and site129. Under non-double resonance condition, many B-type buildings may suffer with G1 and few G2 grade gamage and few low-rise C-type buildings may suffer with G1 grade damge. However, under double resonance condition, the low-rise B-type buildings may suffer with G3 grade and low-rise C-type buildings may suffer with G2 grade damge. However, the high-rise and medium-rise buildings are safe in this region due to less values of PGV and PGD. However, relatively larger PGA (0.12-0.18g) and PGV (<10 cm/c) are obtained at Delhi Univ. (site116; F_0 around 2.5 Hz) and sites lying east of river Yamuna (sites131,133 with F_0 1.3-1.5 Hz). In these localities under non-double resonance condition, many B-type buildings may suffer with G2-G3 grade gamage and many low-rise C-type buildings may suffer with G1-G2 grade damge. However, under double resonance condition, B-type buildings may suffer with G3-G4 grade and low-rise as well as medium-rise C-type buildings may suffer with G2-G3 grade damage.

b. Eastern part of the NCT Delhi

In the eastern part of the NCT Delhi, the obtained PGA and PGV are less than 0.12g and 10 cm/s, respectively in the localities (sites101-103, 124, 155, 157, 158), Hauz Khas, AIIMS, UPSC, Akshardham (site150), Gita colony, Gokulpur (site134), Mansarovar Park (site135), Arjun Nagar (site136) and near Ghazipur (site140) (Fig. 11). The F_0 of sediment is more than 2.0 Hz in the localities (sites101-103, 124, 155, 157, 158), Hauz Khas, AIIMS, UPSC and between 1.0 Hz to 1.6 Hz in Akshardham (site150), Gita colony, Gokulpur (site134), Mansarovar Park (site135), Arjun Nagar (site136) and near Ghazipur (site140). As mentioned above, in the localities with F_0>2.0 Hz and under non-double resonance condition, many B-type may suffer with G1-G2 grade and few C-type may suffer with G1 grade damage. However, the B-type and low-rise C-type buildings in these localities may sufer with G2-G3 grade and G2 grade damage, respectively under double resonance condition. On the other hand, the medium-rise buildings in localities falling east of river Yamuna like Gita colony, Gokulpur (site134), Mansarovar Park (site135), Arjun Nagar (site136) and near Ghazipur (site140) may suffer with only G2 grade damage since PGV is less than 8-10 cm/s.

The range of F_0 of sediment deposit in the Chhatarpur basin and nearby semiclosed basin is 1.8 - 3.2 Hz and the range of obtained PGA is 0.12g – 0.17g. In the localities like Silampur (site130), Harsh Vihar (site132) and Gazipur (site141), the range of PGA is same but range of F_0 of sediment deposit is 1.30 Hz to 1.50 Hz. So, many B-type buildings in these localities may sufer with G2-grade and few with G3-grade damage under non-double resonance condition. Similarly,

603 many C-type low-rise buildings may suffer with G2 grade damage under non-double resonance.
604 However, under double resonance condition B-type and low-rise C-type buildings may suffer with
605 G3-G4 grade and G3-grade damage, respecively. On the other hand, C-type medium-rise
606 buildings in the Silampur (site130), Harsh Vihar (site132) and Gazipur (site141) area may suffer
607 with G2-grade damage double resonance condition since PGV in these localities is less than 10
608 cm/s. No damage reported to the 73 m high Qutab minar (tallest brick masonry minaret in the
609 world; situated near the site98) during past 800 years may be because of the non-occurrence of
610 double resonance and the obtained low value of PGD (0.93 cm) due to the local earthquakes.
611
612 The range of PGA and F_0 is 0.22g to 0.27g and 1.22 to to 5.0 Hz in the localities from Jaitpur to
613 Jasola (including Tuglakabad) falling near the MF. The range of PGV is 10 cm/s to 18 cm/s from
614 Jaitpur to Aksherdham (site150) (Fig. 13). So, in the localities falling between Jasola to Jaitpur
615 (sites137, 138, 142, 143), most of the B-type and low-rise C-type buildings may suffer with G3-
616 grade and G2-G3 grade damage under non-double resonance condition. However, under double
617 resonance condition, the grade of damage may be G4-G5 and G3-G4 to the B-type and low-rise
618 C-type buildings, respectively. The medium-rise C-type buildings (5-10 storey) of the localities
619 from Jaitpur to Aksherdham may also suffer with G4 grade damage under double resonance
620 condition since PGV in these localities is relatively larger (10-18 cm/s). However, the high-rise
621 buildings (>10 storey) situated in the eastern part of the NCT Delhi are relately safer during
622 occurrence of local earthquakes since PGD is less than 2 cm amd may suffer with G2-G3 grade
623 damage.
624
625 **c. Western region of the NCT Delhi**
626 In the left part of the western region of the NCT Delhi, the range for F_0 of sediment is 0.41-0.65
627 Hz in a strip more or less parallel to the central Delhi ridge in the localities from south to north
628 Dhansa, Mandela, Nizampur, Jatkhor, Puth Khurd, Dariyapur Kalan, Narela Mandi. Further, at
629 most of the sites falling west of the central ridge have dominant frequency (F_D) which is on an
630 average 2-2.5 times larger than the F_0 of sediment deposit. It means medium-rise and high-rise
631 buildings may fall in double resonance condition with either F_0 or F_D. Figures 11, 13 and 14 reveals
632 that in the localities like Nizampur (sites17, 31, 32), Jatkhor (sites14, 15, 30, 27), Puth Khurd
633 (sites28, 29, 46, 47), Dariyapur Kalan (sites11, 12, 25, 26, 45) and Narela Mandi (sites43, 44,
634 144, 60, 61, 62, 63, 65, 66), the range of PGA, PGV and PGD variations are 0.2g-0.3g, 18 cm/s-
635 26 cm/s and 3.0 cm-7.0 cm, respectively. Many B-type buildings may suffer with G3-G4 damage
636 and few may collapse. Under non-double resonance condition, many low-, medium- and high-rise

C-type buildings may suffer with G2-G3 grade damage and few with G4-grade damage. However, under double resonance condition, medium-rise and high-rise C-type buildings may suffer with G4-G5 damage. The obtained range of obtained PGA (0.08-0.18g), PGV (8-12 cm/s) and PGD (2-3 cm) in localities like Dhansa (sites6, 8, 9, 10) and Mandela (sites1, 2, 3) and Jharoda (sites18, 19, 20) reveals that many B-type and low-rise C-type buildings may suffer with G2-G3 grade and G1-G2 grade damage, respectively. However, under double resonance condition, medium and high-rise C-type buildings may suffer with G2-G3 grade and few G4 grade damage.

In the middle part of the western region of the NCT Delhi, in a strip more or less parallel to the central ridge, the range for F_0 of sediment is 0.65-1.0 Hz in localities from south to north Rawa, Shikarpur, Nazafgarh, Pashchim Vihar, Rithola, Rohni, Alipur and Palla. It means medium and high-rise buildings may fall in double resonance condition with either F_0 or F_D. The obtained large PGA (0.2-0.3g) due to proximity to SF, many B-type and low-rise C-type buildings may suffer with G3-G4 grade and G2-G3 grade damage, respectively in the localities like Sikarpur (site24). Similar level of damage to medium- and high-rise buildings may occur even under double resonance condition since the values of PGV and PGD are somewhat lower. The obtained PGA (0.16-0.20g), PGV (12-18 cm/s) and PGD (2-4.5 cm) at localities like Paschim Vihar (sites33, 34, 71, 73, 52, 91), Rohini to Alipur (sites151, 69, 68, 84, 85), Rithola (site52) and Palla (sites77, 79, 82) reveals that most of B-type and low-rise C-type buildings may suffer with G2-G3 grade and G2-grade damage, respectively. Under double resonance condition including Nazafgarh area (sites21, 40), the medium and high-rise C-type buildings may suffer with G3-G4 grade damage. At rest of the sites falling in this middle part of the western region, the damage level to medium- and high-rise C-type buildings may be lesser, even after occurrence of double resonance due to lesser PGA, PGV and PGD, respectively.

Similarly, the right part of the western region of the NCT Delhi, a strip more or less parallel to the central ridge, the range for F_0 of sediment is 1.0 – 1.5 Hz in localities from south to north Bijwasan, IGI Airport, Dwarka, Narayana, Janakpuri, Raja Garden, Jahangirpuri and Buradi. It means medium-rise and low-rise buildings may fall in double resonance condition with either F_0 or FD. The obtained larger PGA (0.2-0.3g) in the Dwarka (sites56, 57) and Buradi (sites108, 110, 111) reveals that many B-type and low-rise C-type buildings under non-resonance condition may suffer with G3-G4 grade and G2-G3 grade damage and under double resonance condition may suffer with G4-G5 grade and G3-G4 grade damage. However, under double resonance condition, medium-rise buildings may suffer with similar level of damage (PGV=12-15 cm/s), but high-rise

buildings may suffer with lower grade damage since the PGD (≅2 cm) is lesser. The medium-rise and high-rise C-type buildings in Narela (sites75, 76) may suffer with G4 and G5 grade damage, respectively under double resonance condition due to the larger PGV (17 cm/s) and PGD (7 cm) values. At rest of the localities of the right part of the western region, the obtained lower values of PGA, PGV and PGD reveals that under non-double resonance condition many B-type and C-type may suffer with G2 and G1-grade damage, respectively. However, under double resonance condition many B-type and low- and medium-rise buildings may suffer with G3 and G2-G3 grade damage, respectively.

8. CONCLUSIONS

The analysis of computed PGA and PGA* reveals that the basement ground motion should be transferred to the free surface using 1D seismic wave propagation in order to predict the PGA, PGV and PGD and not using simply a multiplication of ASA caused by sediment deposit with the PGA, PGV and PGD at the basement level. The PGA is more amplified at localities where sediment thickness is lesser and reverse is the case for the PGD. The PGA amplification at a site is also depedent on the corresponding MCE and the epicentral distance. The obtained range of the computed PGA, PGV and PGD at the free surface in the NCT Delhi as 0.08g-0.30g, 3.34cm/s-26.58cm/s and 0.55cm-7.2cm, respectively and range of fundamental frequency of the sediment deposit as 0.4Hz-7.0Hz depicts that the NCT Delhi needs special attention by the planners, engineers and decision makers for earthquake disaster preparedness, particularly the occurrence of double resonance phenomenon (Romo and Seed, 1986; Narayan et al., 2002; Kumar and Narayan, 2020).

The obtained PGA (<0.12g), PGV (<10cm/s) and PGD (<2cm) in the central ridge and surrounding region, outcropping quartzite rock in the eastern part of the NCT Delhi including licalities like Akshardham (site150), Gita colony, Gokulpur (site134), Mansarovar Park (site135), Arjun Nagar (site136) and near Ghazipur (sites140, 141) reveals that all sorts of buildings are relatively safe and may suffer with minor damage only. However, C-type medium-rise buildings in localities falling east of river Yamuna like Gita colony, Silampur (site130), Harsh Vihar (site132), Gokulpur (site134), Mansarovar Park (site135), Arjun Nagar (site136) and near Ghazipur (sites140, 141) may suffer with G2-G3 grade damage under double resonance condition. The B-type and Low-rise C-type buildings of the Chhatarpur basin and nearby semiclosed basin may suffer with G3 and G2-G3 grade damage under double resonance condition. The obtained range of PGA (0.22-

0.27g) and PGV (10-18 cm/s) in the localities from Jaitpur to Jasola (including Tuglakabad) falling near the Mathura Fault reveals that under double resonance condition the B-type and low- to medium-rise C-type buildings may suffer with G4-G5 grade and G4-grade damage, respectively. However, the high-rise buildings situated in the eastern and central ridge parts of the NCT Delhi are relatively safer during local earthquakes since PGD is less than 2 cm and may suffer with minor damage (G1-G2 grade) only.

All types of buildings in the NW region of the NCT Delhi are at high seismic risk due to their proximity to the MDF and thick sediment deposit. Under double resonance condition, even well-built medium- to high-rise C-type buildings may suffer with G4-G5 damage. Similarly, buildings located in Sikarpur (site24), Dwarka (sites56, 57), Buradi (sites108, 110, 111) and locality near sites73 and 91 are also somewhat at high risk. The medium- and high-rise buildings in Narela (sites75, 76) and Nazafgarh area (sites21, 40) may suffer with G3-G4 grade damage Under double resonance condition due to the larger PGV and PGD values. At rest of the localities, the obtained lower values of PGA, PGV and PGD reveals that under non-double resonance condition many B-type and low- and medium-rise C-type buildings may suffer with G2 and G1-grade damage, respectively. However, under double resonance condition many B-type and low- and medium-rise buildings may suffer with G3 and G2-G3 grade damage, respectively.

References

- Anderson J, Hough S (1984) A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. Bull Seism Soc Am 74:1969–1993
- Anbazhagan P, Sitharam TG (2008) Seismic microzonation of Bangalore. J Earth Syst Sci 117(S2):833–852
- Agrawal SK, Chawla J (2006) Seismic hazard assessment for Delhi region. Curr Sci 91:1717–1724
- Beresnev IA, Atkinson GM (1997) Modelling finite fault radiation from the ω^n spectrum. Bull Seismol Soc Am 87:67–84
- Beresnev IA, Atkinson GM (1998) FINSIM: a FORTRAN program for simulating stochastic acceleration time histories from finite faults. Seismol Res Lett 69:27–32
- Boore DM (1983) Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bull Seismol Soc Am 73:1865–1894
- Boore DM (2003) Simulation of ground motion using stochastic method. Pure Appl. Geophys 160:635–676
- Boore DM, Atkinson GM (2008) Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. Earthquake Spectra, Vol. 24, No.1, pp. 99-138.
- Boore DM (2009) Comparing stochastic point-source and finite-source ground-motion simulations: SMSIM and EXSIM, Bull. Seismol. Soc. Am. 99, 3202–3216
- Brune JN (1970) Tectonic stress and spectra of seismic shear waves from earthquakes. J Geophys Res 75:4997–5009
- CGWB (2012) Ground water year book (2011–12). National Capital Territory Delhi, Central Ground Water Board, Ministry of water resources, Govt. of India.
- Earthquake Engineering Studies (2012) Site-specific design earthquake parameters for Khurja thermal power plant site, Uttar Pradesh (EQ:2012-39), EQD, IIT Roorkee.
- Emmerich H, Korn M (1987) Incorporation of attenuation into time-domain computations of seismic wave fields. Geophysics 52:1252–1264
- Futterman WI (1962) Dispersive body waves. Journal of Geophysical Research, 67(13), 5279–5291.
- GSI (2000) Tectonic and geological maps of India. Geological Survey of India, Calcutta
- Gupta SK, Sharda YP (1996) A geotechnical assessment of Delhi earthquake of July 28, 1994. Proc. Int. Conf. Dis. Mitin., Madras, v.1, pp. A1/26–/31.
- Hanks TC, McGuire RK (1981) The character of high frequency strong ground motion. Bull Seismol Soc Am 71:2071–2095
- Hartzell S, Harmsen S, Frankel A, Larsen S (1999) Calculation of broadband time histories of ground motion: Comparison of methods and validation using strong-ground motion from the 1994 Northridge earthquake. Bulletin of the Seismological Society of America, 89(6), 1484-1504.
- Hukku BM (1966) Probable causes of earthquake in the Delhi-Sonipat area. Proc III Sysmp. Earthquake Engg. Roorkee, v.II, pp.75–80.

- IS-893 (Part 1) (2002) Criteria for earthquake resistant design of structures—part 1: general provision and buildings, Bureau of Indian Standards
- Israeli M, Orszag SA (1981) Approximation of radiation boundary conditions. J Comp Phys 41:115–135
- Iyisan R (1996) Correlations between shear wave velocity and in situ penetration test results (in Turkish). Chamb Civil Eng Turk, Teknik Dergi 7(2):1187–1199
- Iyengar RN (2000) Seismic status of Delhi megacity. Curr Sci 78(5):568–574
- Iyengar RN, Ghosh S (2004) Microzonation of earthquake hazard in greater Delhi area. Curr Sci87(9):1193–1202
- Jayalakshmi S, Raghukanth STG (2016) Regional ground motion simulation around Delhi due to future large earthquake. Nat Hazards (2016) 82:1479–1513, DOI 10.1007/s11069-016-2254-8
- Kazim M K, Rajinder Kumar, Hemant Kumar, A. K. Gupta, J. Bagchi and S.S Srivastava (2005) A field investigation of geological and geomorphological mapping of NCT Delhi on 1:10,000 scale. Contributed by Geological survey of India, Northern Region. item code No. STM/C/NR/PHH/2005/002.
- Kristeck J, Moczo P (2003) Seismic wave propagation in viscoelastic media with material disconuties- a 3 D 4th order staggered grid finite difference modeling. Bull Seismol Soc Am 93:2273–2280.
- Kumar, N. and Narayan, J.P., 2018. Quantification of site–city interaction effects on the response of structure under double resonance condition. Geophysical Journal International, 212(1), pp.422-441.
- Kumar, S. and Narayan, J.P., 2008. Absorbing boundary conditions in a fourth-order accurate SH-wave staggered grid finite difference algorithm. Acta Geophysica, 56(4), pp.1090-1108.
- Kumar L, Narayan JP (2020) Computation of Ground Motion Amplification Scenario in NCT Delhi for Earthquake Engineering Purposes and Seismic Microzonation. Pure Appl Geophys 177:3797–3829. https://doi.org/10.1007/s00024-020-02420-4
- Mandal, H S, Khan PK, Shukla AK (2014) Soil responses near Delhi ridge and adjacent regions in Greater Delhi during incidence of a local earthquake. Natural Hazards, 70(1), 93–118.
- Manisha KD, Teotia SS (2011) Seismic hazard based on simulated accelerograms due to moderate/strongearthquakes in National Capital (Delhi) region. J Ind Geophys Union 15(1):77–83
- Mahajan, AK, Shukla AK, Pandey A, Chauhan M, Chauhan N, Rai N (2011) Shear wave velocity investigation for ten representative sites of national capital territory, New Delhi, India. International Journal of Geotechnical Earthquake Engineering (IJGEE), 2(1), 29–43.
- Mehta P, Hukku BM, Krishnaswamy VS (1970) Geoseismological studies for the aseismic design of the Kot and Dhauj Dam project, Gurgaon district, Haryana. Proc. Earthq. Engg. Roorkee, v.IV, pp.411–418.
- Mohanty, WK, Walling MY, Nath SK, Pal I (2007) First order seismic microzonation of Delhi, India using geographic information system (GIS). Natural Hazards, 40(2), 245-260.

- Mohanty WK, Prakash R, Suresh G, Shukla AK, Yanger Walling M, Srivastava JP (2009) Estimation of coda wave attenuation for the National Capital Region, Delhi, India using local earthquakes. Pure appl Geophys 166:429–449
- Mittal H (2011). Estimation of ground motion in Delhi, Ph.D. Thesis, Indian Institute of Technology Roorkee, India.
- Mittal H, Kumar A, Kumar A (2013) Site effects estimation in Delhi from the Indian strong motion instrumentation network. Seismol Res Lett 84(1):33–41
- Mittal H., Yih-Min Wu, Da-Yi Chen, Wei-An Chao (2016) Stochastic finite modeling of ground motion for March 5, 2012, Mw 4.6 earthquake and scenario greater magnitude earthquake in the proximity of Delhi, Nat Hazards (2016) 82:1123–1146 DOI 10.1007/s11069-016-2236-x
- Motazedian D, Atkinson GM (2005) Stochastic finite-fault modeling based on dynamic corner frequency. Bull Seismol Soc Am 95:995–1010
- Mukhopadhyay S, Pandey Y, Dharmaraju R, Chauhan PKS, Singh P, Dev A (2002) Seismic microzonation of Delhi for ground-shaking site effects. Curr Sci 87:877–881
- Mundepi AK, Mahajan AK (2010) Site response evolution and sediment mapping using horizontal to vertical spectral ratios (HVSR) of ground ambient noise in Jammu city, NW India. J GSI 75:799–806
- Narayan JP, Sharma ML, Kumar A (2002) A seismological report on the 26 January 2001 Bhuj, India earthquake. Seism Res Lett 73:343–355
- Narayan JP, Kumar S (2008) A 4th order accurate SH-wave staggered grid finite-difference algorithm with variable grid size and VGR-stress imaging technique. Pure Appl Geophys 165:271–294
- Narayan JP, Kumar V (2013) A fourth-order accurate finite-difference program for the simulation of SH-wave propagation in heterogeneous viscoelastic médium. Geofizika 30:173–189
- Narayan JP, Sahar D (2014) 3D viscoelastic finite-difference code and modelling of basement focusing effects on ground motion characteristics. Comput Geosci 18:1023–1047
- Nath SK, Sengupta P, Srivastav SK, Bhattacharya SN, Dattatrayam RS, Prakash R, Gupta HV (2003) Estimation of S-wave site response in and around Delhi region from weak motion data. Proc Indian Acad Sci (Earth Plant Sci) 112:441–463
- NCS-MoES. (2016) A report on seismic hazard microzonation of NCT Delhi on 1:10,000 scale. National Center for Seismology, Ministry of Earth Sciences, Government of India.
- NDMA (2011) Development of probabilistic seismic hazard map of India. National Disaster Management Authority, New Delhi, India
- Neelima Satyam D, Rao KS (2009) Estimation of Peak Ground Acceleration for Delhi NCR Using FINSIM, a Finite Fault Simulation Technique. 02:215–223
- Oprsal I, Fah D, Mai PM, Giardini D (2005) Deterministic earthquake scenario for the Basel area: simulatingstrong motion and site effects for Basel, Switzerland. JGR 110:B4305. doi:10.1029/2004JB003188
- Parvez IA, Vaccari F, Panza, GF (2004) Site-specific microzonation study in Delhi metropolitan city by 2-D modeling of SH and P-SV waves. Pure and Applied Geophysics, 161,1165–1184. https://doi.org/10.1007/s00024-003-2501-2.

- Prakash R, Shrivastava J (2012) A review of the seismicity and seismotectonics of Delhi. J Geol Soc India 79:603–617.
- Rao NP, Kumar P, Tsukuda T, Ramesh DS (2006) The devastating Muzaffarabad earthquake of 8 October 2005: New insights into Himalayan seismicity
- Romo MP, Seed HB (1986) Analytical modelling of dynamic soil response in Mexico earthquake of September 19, 1985. In: Proceedings, ASCE international conference on Mexico Earthquakes-1985, Mexico City, pp 148–162
- Sarkar, S, Shanker D (2017) Estimation of Seismic Hazard Using PSHA in and around National Capital Region (NCR) of India. Geosciences, 7(4), 109-116.
- Sandhu M, Kumar D, Teotia SS (2017) Estimation of site amplification functions for the National Capital (Delhi) Region, India. Nat Hazards 85:171–195. https://doi.org/10.1007/s11069-016-2572-x
- Satyam N, Rao KS (2008) Seismic Site Characterization of Delhi Region Using Microtremor Method: A Case Study.
- Sharma ML, Wason HR, Dimri R (2003) Seismic zonation of the Delhi region for bedrock ground motion. Pure Appl Geophys 160:2381–2398. https://doi.org/10.1007/s00024-003-2400-6.
- Sharma ML, Narayan JP, Rao KS (2004) Seismic microzonation of Delhi region in India. In Proceedings of 13th World Conference on Earthquake Engineering (13WCEE) (Paper no. 2043) Vancouver, BC, Canada.
- Singh SK, Mohanty WK, Bansal BK, Roonwal GS (2002) Ground motion in Delhi from future large/great earthquakes in the central seismic gap of the Himalayan Arc. Bull Seismol Soc Am 92:555–569. https://doi.org/10.1785/0120010139
- Srivastava VK, Roy AK (1982) Seismotectonics and seismic risk study in and around Delhi region. In International Association of Engineering Geology. International congress. 4, 77-86.
- Shiuly A, Narayan JP (2012) Deterministic seismic microzonation of Kolkata city. Natural hazards, 60(2), 223-240.
- Tandon RS, Gupta V, Sen, K (2015) Seismic properties of naturally deformed quartzites of the Alaknanda valley, Garhwal Himalaya, India. Journal of Earth System Science, 124(6),1159–1175.
- Wang Z (2008) A technical note on seismic microzonation in the Central United States. J Earth Syst Sci 117(S2):749–756

Figures

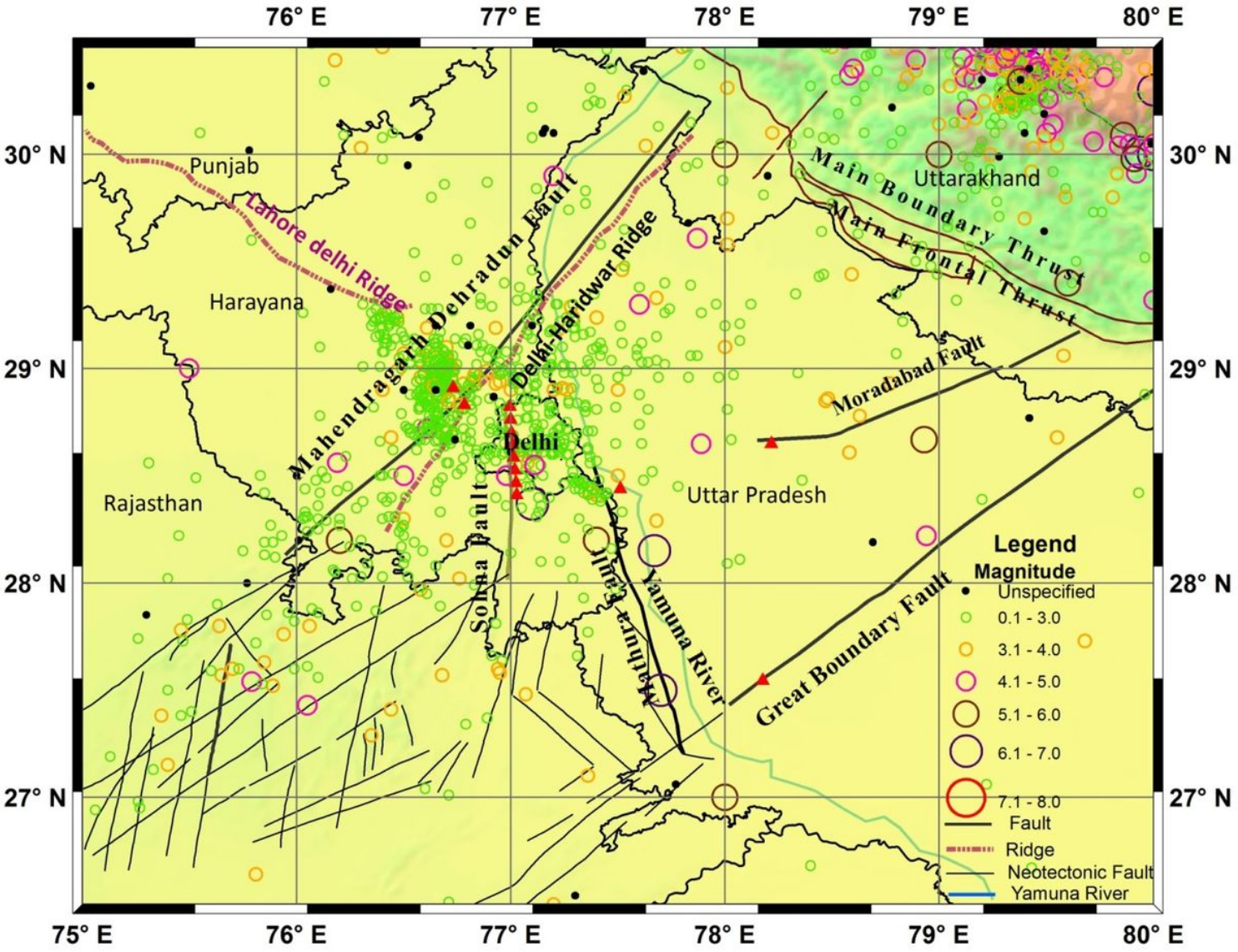

Figure 1

The study area and the seismotectonic setting and triangle represent six local seismogenic sources namely Mathura fault, Sohna fault, Delhi-Hardwar ridge, Mahendragarh-Dehradun fault, Moradabad fault and Great Boundary fault in the surrounding regions. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

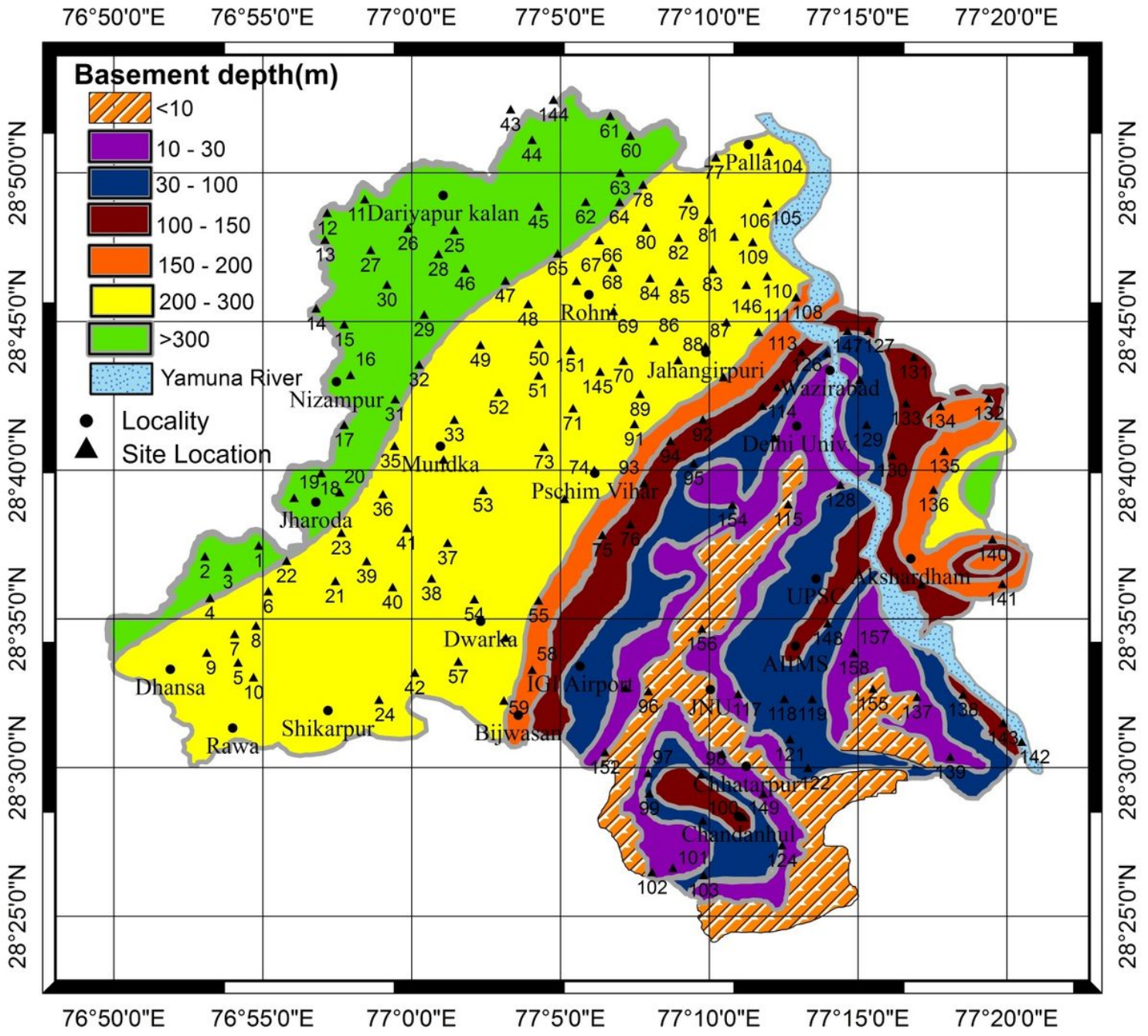

Figure 2

Map depicting important localities, considered sites (stations) and basement depth variation in NCT Delhi (Modified after CGWB (2010-11)). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

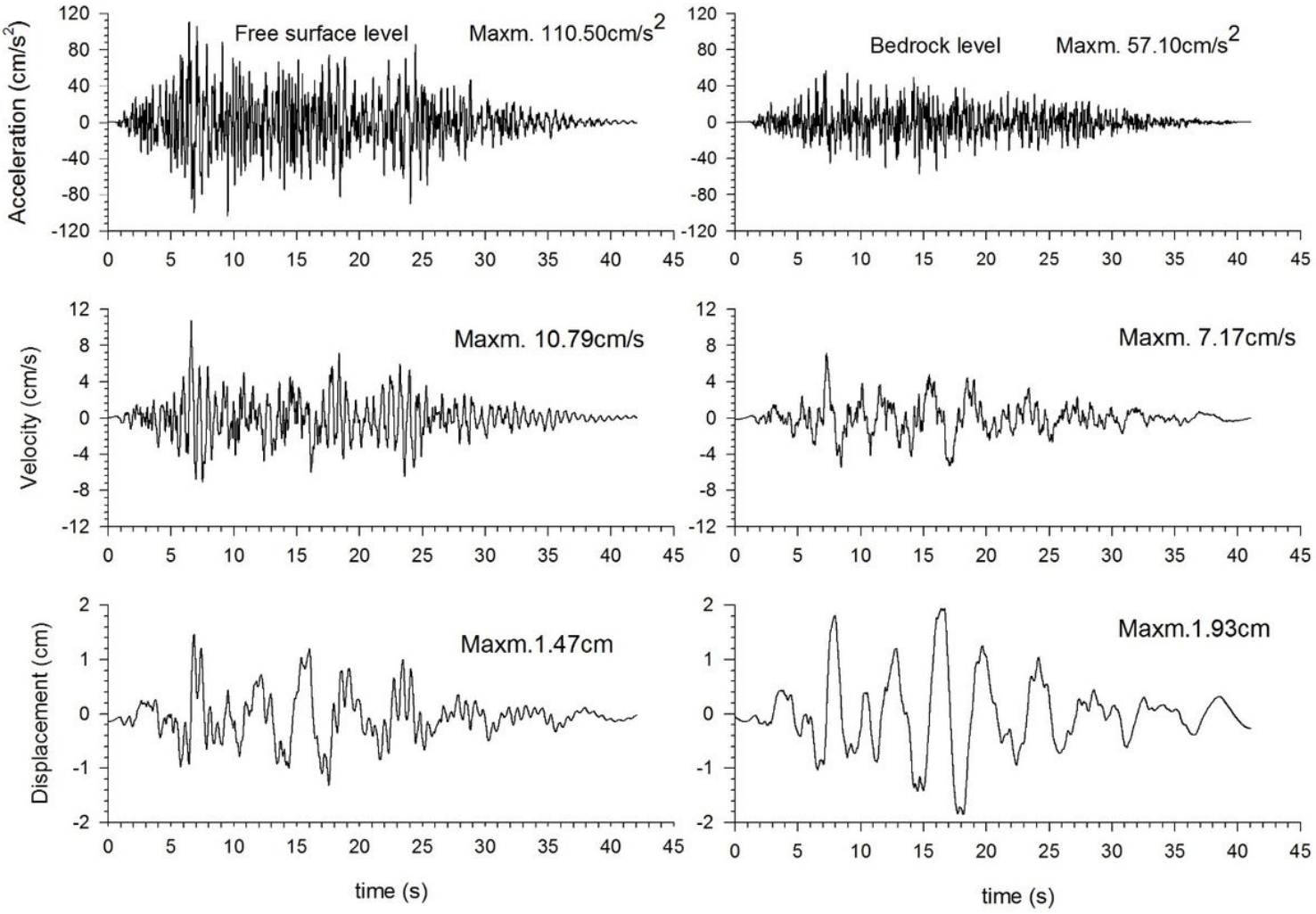

Figure 3

Deterministically predicted acceleration, velocity and displacement time histories at free surface (left panels) and basement level (right panels) at site114 (Model Town) with sediment thickness 100 m using corresponding MCE as MW7.1 on Mahendergarh Dehradun fault.

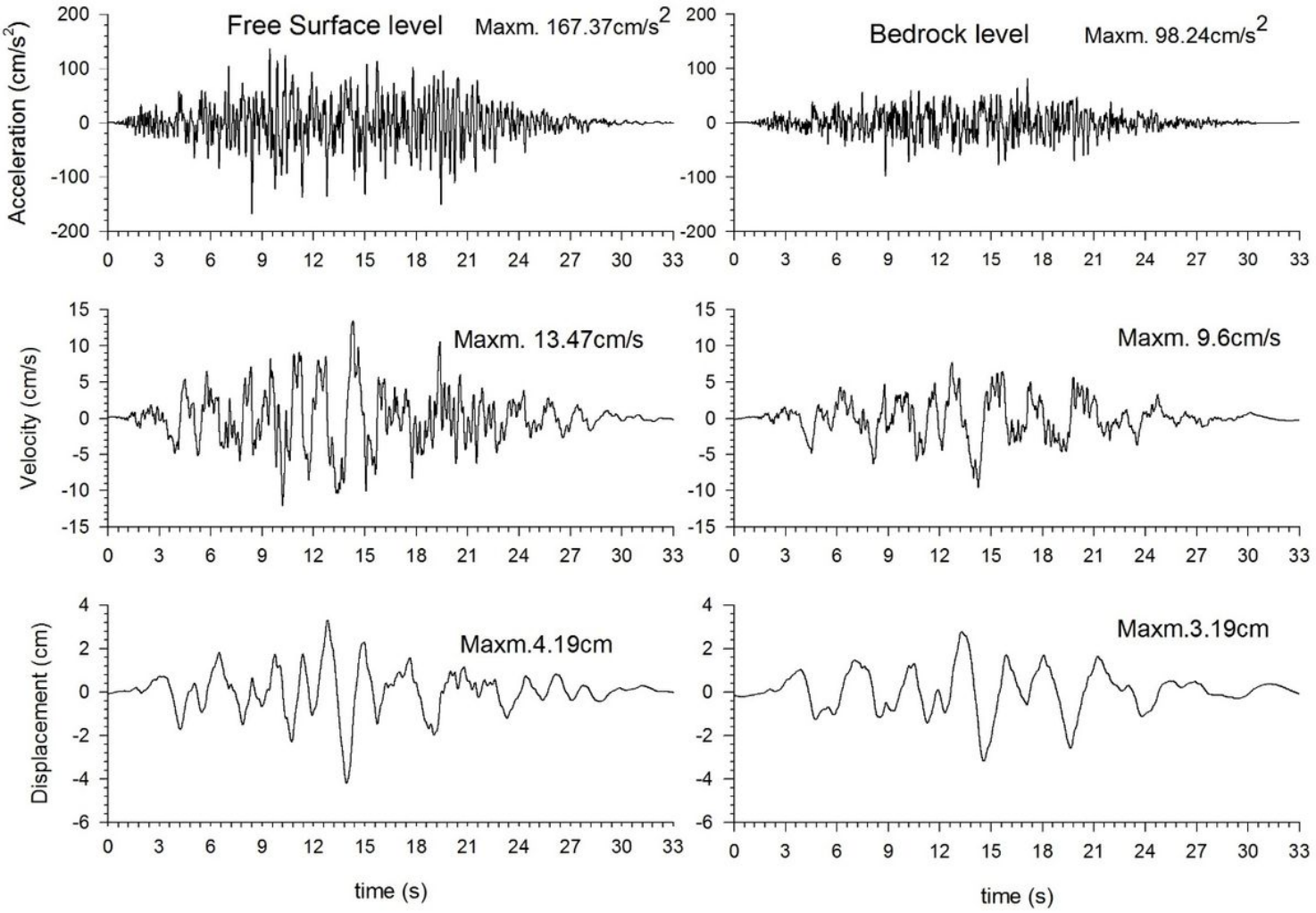

Figure 4

Deterministically predicted acceleration, velocity and displacement time histories at free surface (left panels) and basement level (right panels) at site2 (Mandhela Khurd) with sediment thickness 320 m using corresponding MCE as MW7.1 on Mahendergarh Dehradun fault.

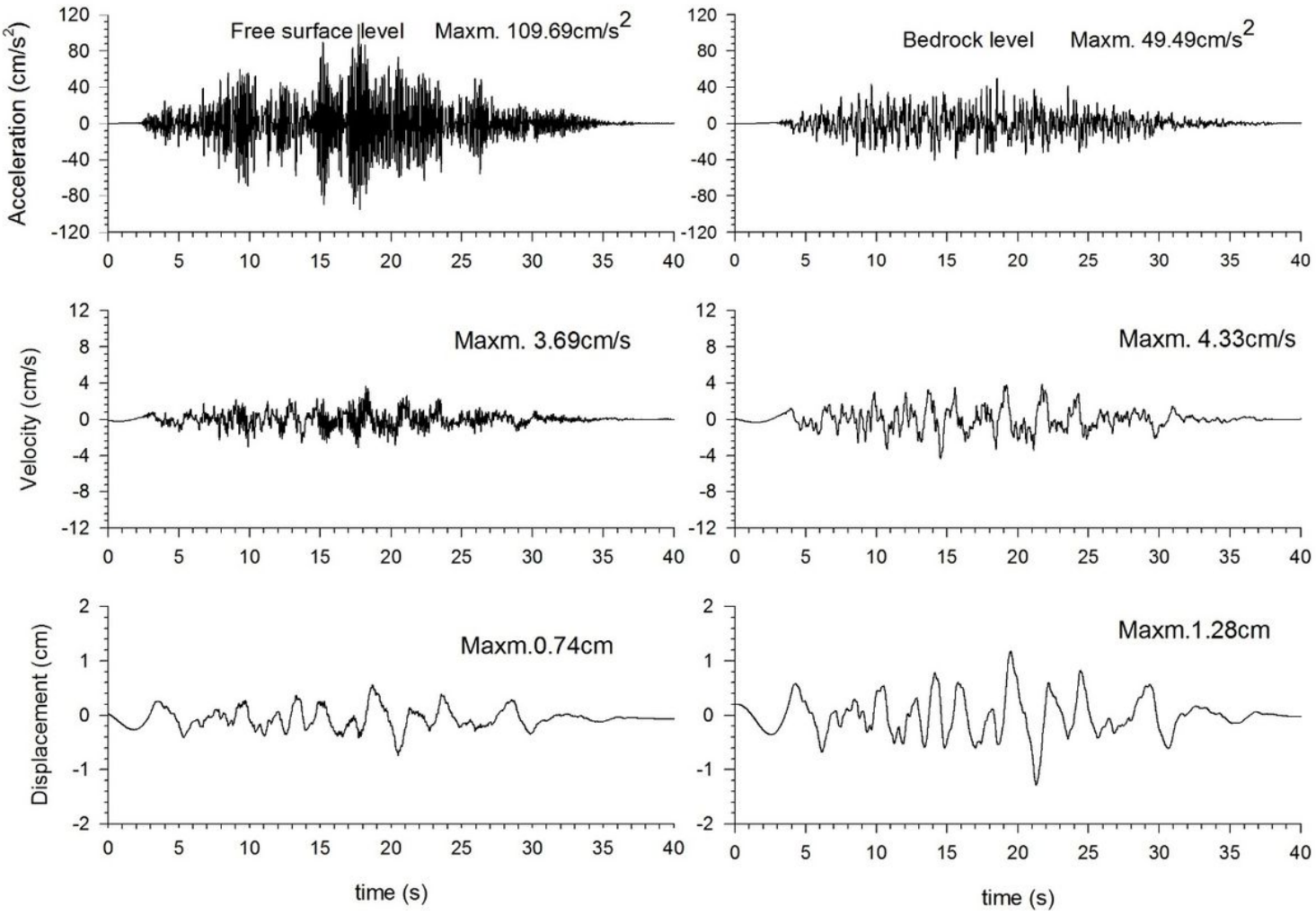

Figure 5

Deterministically predicted acceleration, velocity and displacement time histories at free surface (left panels) and basement level (right panels) at site96 (CISF Rd., Mahipalpur Extn.) with sediment thickness 9 m using corresponding MCE as MW7.1 on Mahendergarh Dehradun fault.

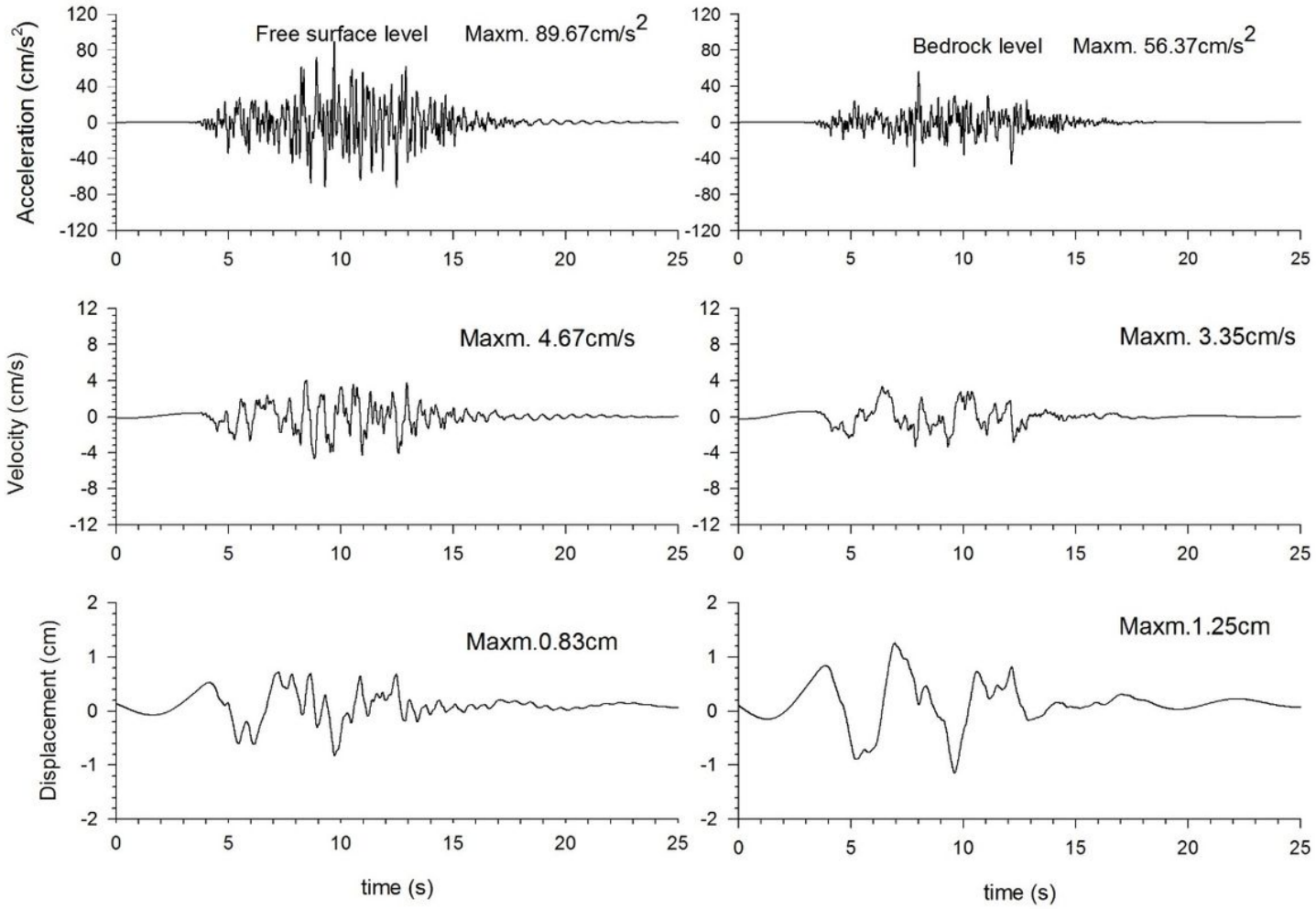

Figure 6

Deterministically predicted acceleration, velocity and displacement time histories at free surface (left panels) and basement level (right panels) at site114 (Model Town) with sediment thickness around 100 m using corresponding MCE as MW6.5 on Mathura Fault.

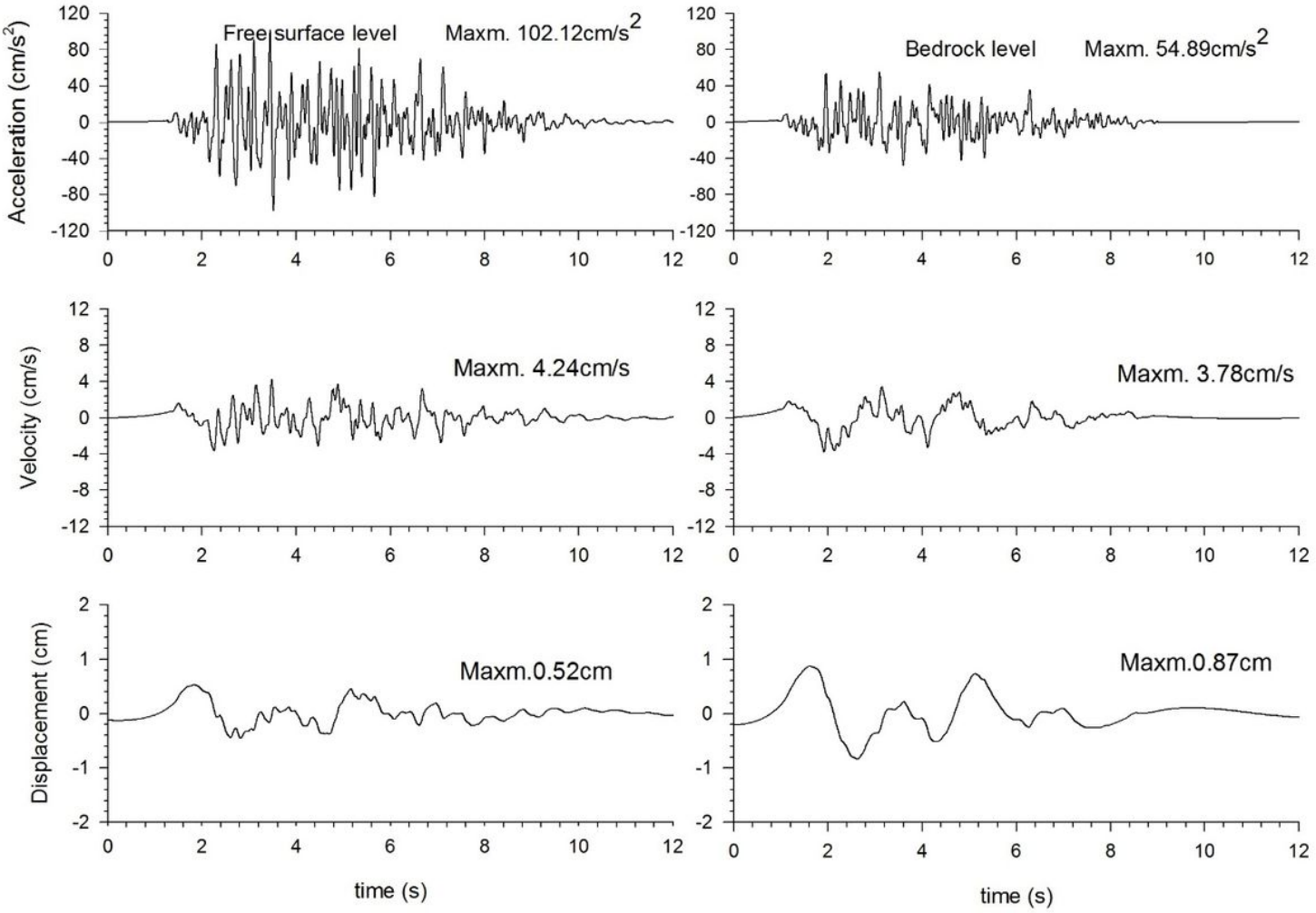

Figure 7

Deterministically predicted acceleration, velocity and displacement time histories at free surface (left panels) and basement level (right panels) at site114 (Model Town) with sediment thickness around 100 m using corresponding MCE as MW6.0 on Sohna Fault.

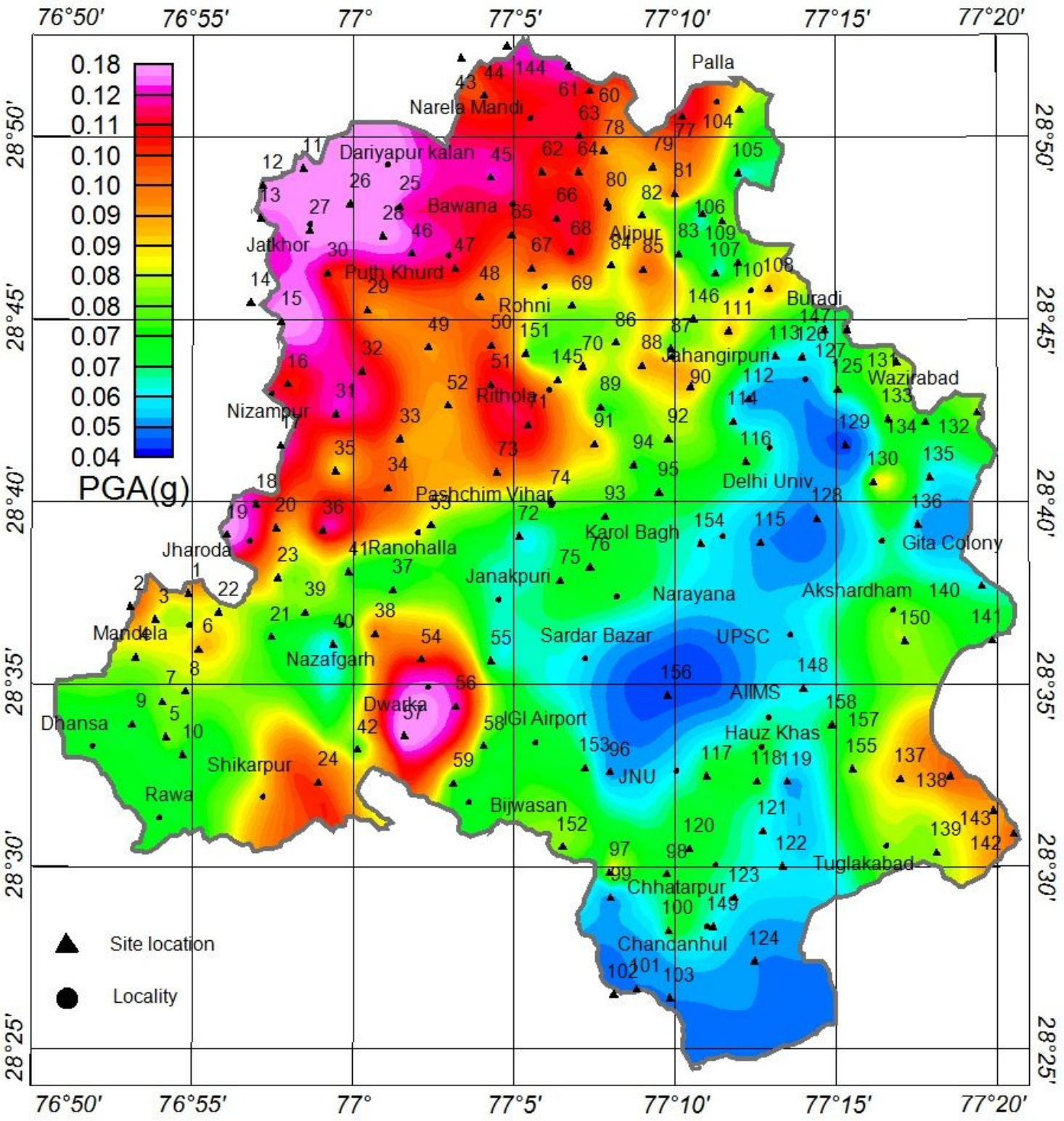

Figure 8

Map depicting the variation of peak ground acceleration (PGA) at basement level in the NCT Delhi region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

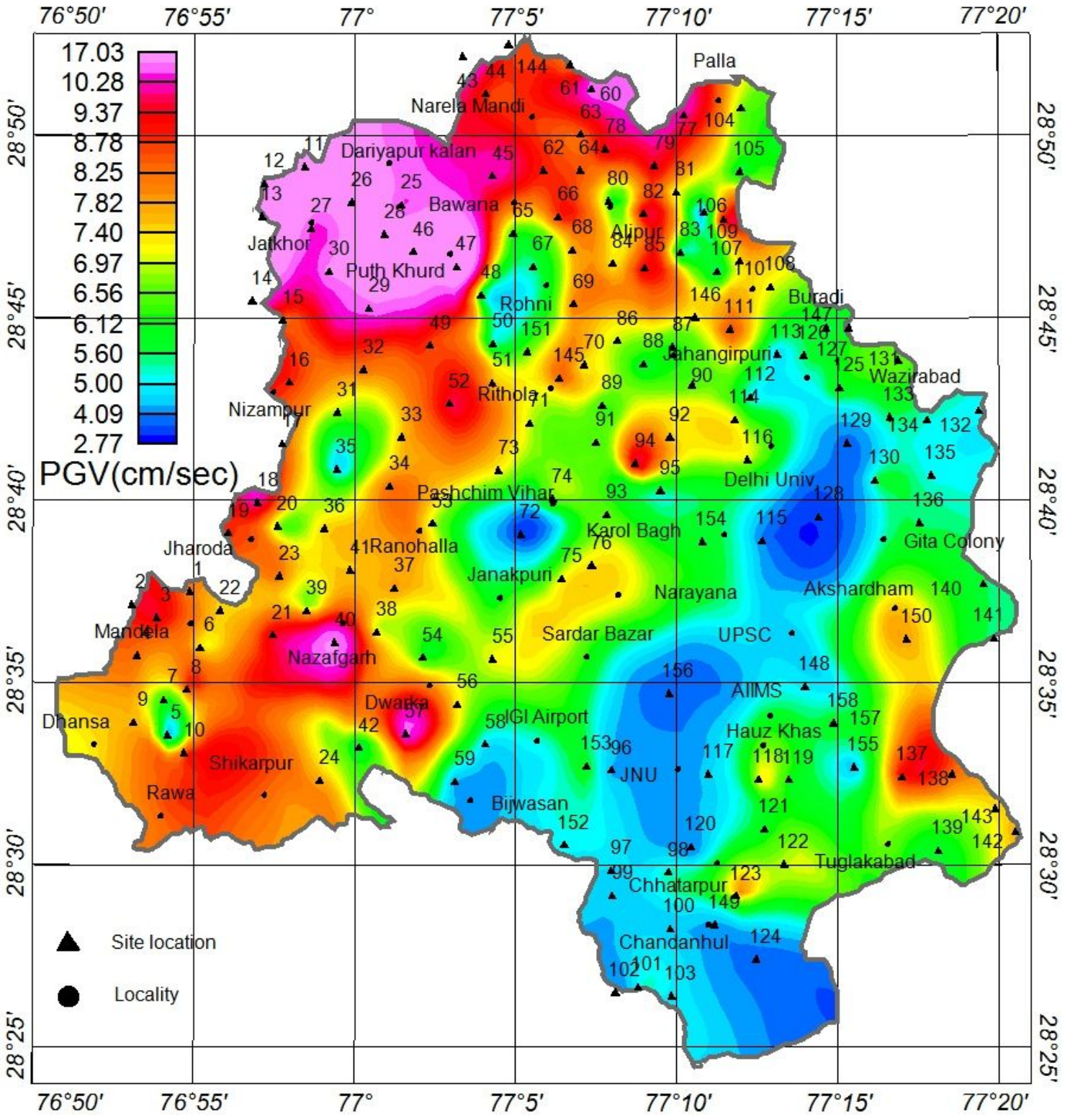

Figure 9

Map depicting the variation of PGV at basement level in the NCT Delhi region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

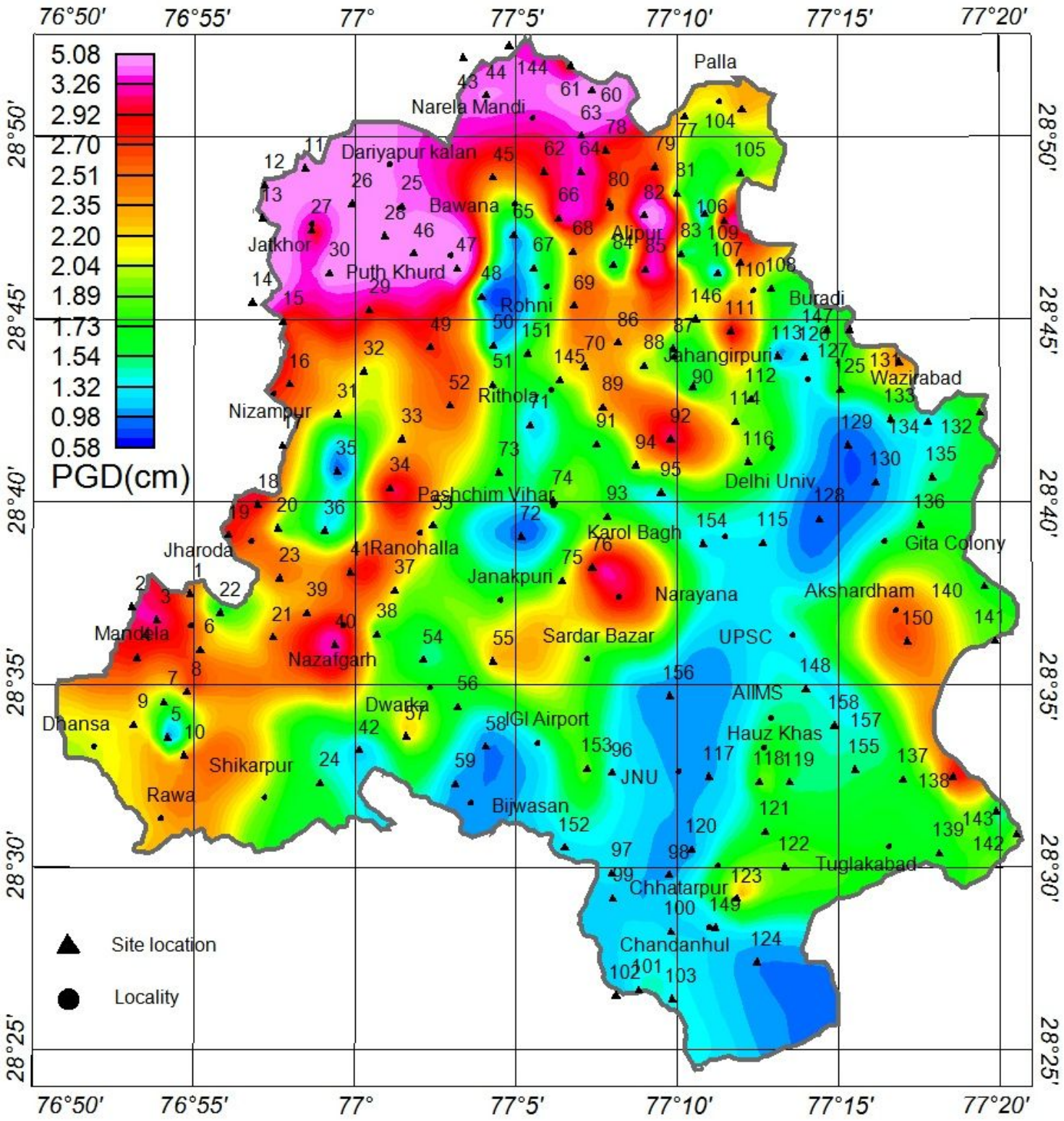

Figure 10

Map depicting the variation of PGD at basement level surface in the NCT Delhi region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

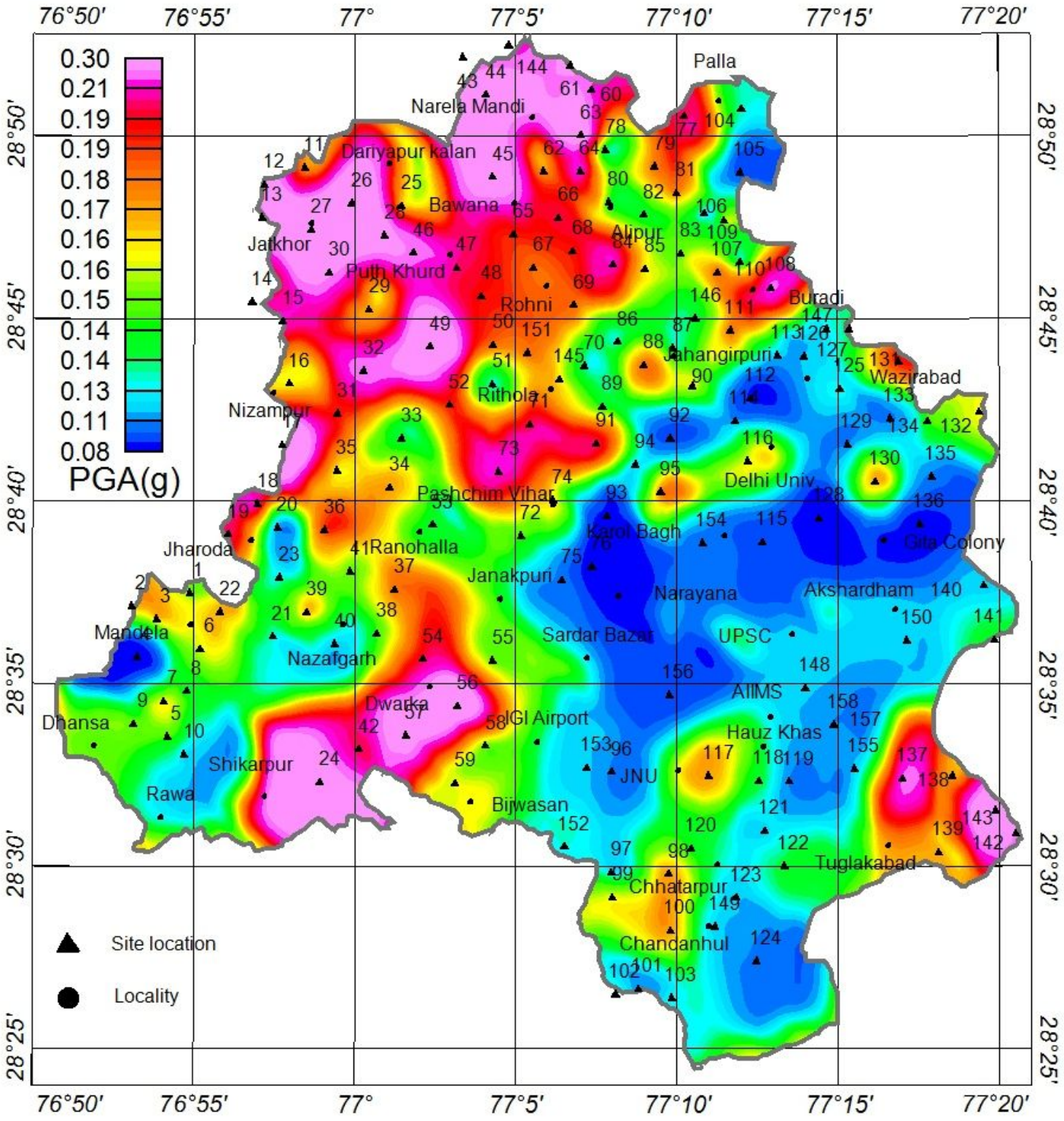

Figure 11

Map depicting the variation of PGA at the free level in the NCT Delhi region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

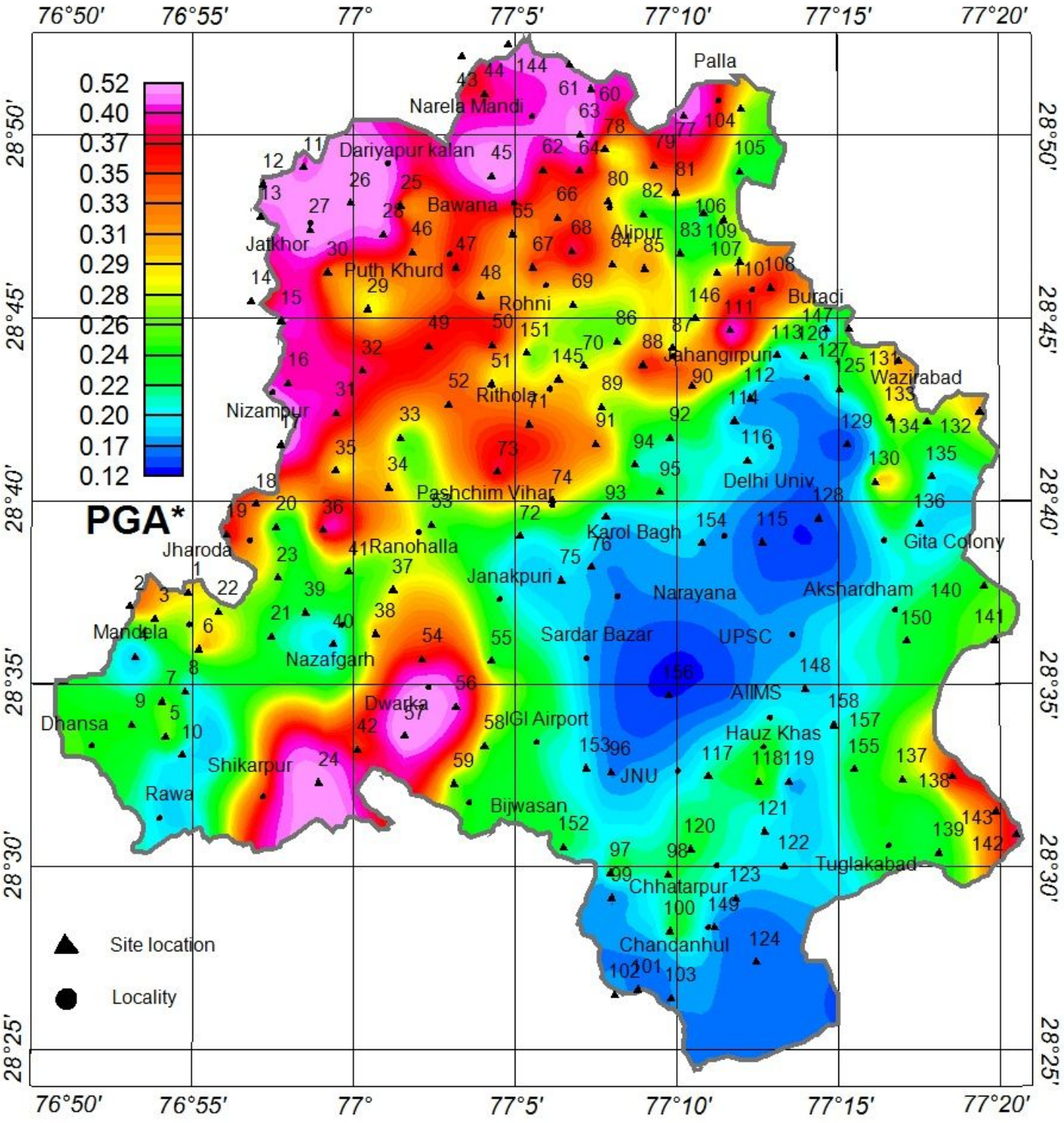

Figure 12

Map depicting the PGA* obtained using ASA at the free surface and its spatial variation in the NCT Delhi region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

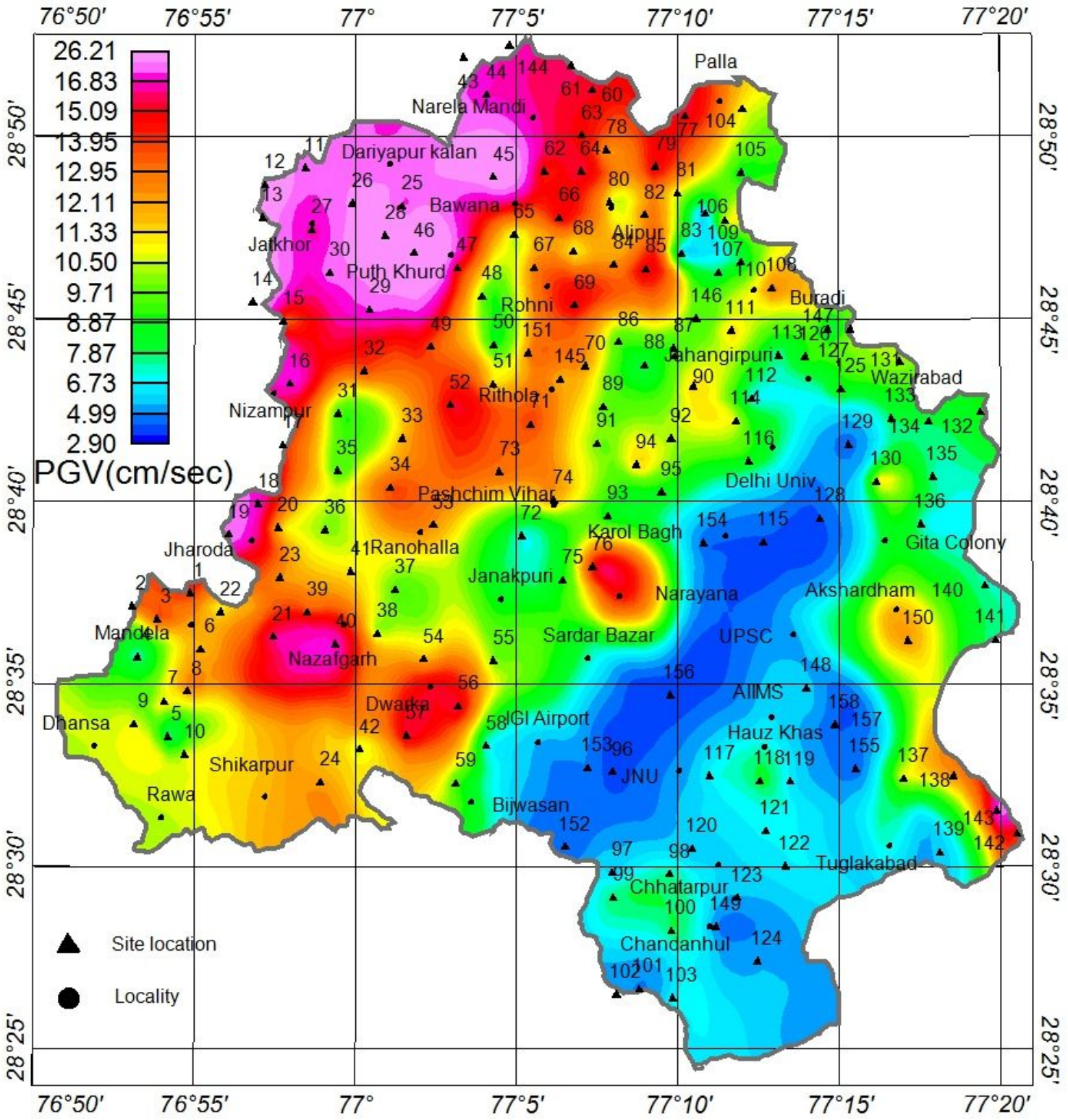

Figure 13

Map depicting the variation of PGV at the free surface level in the NCT Delhi region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

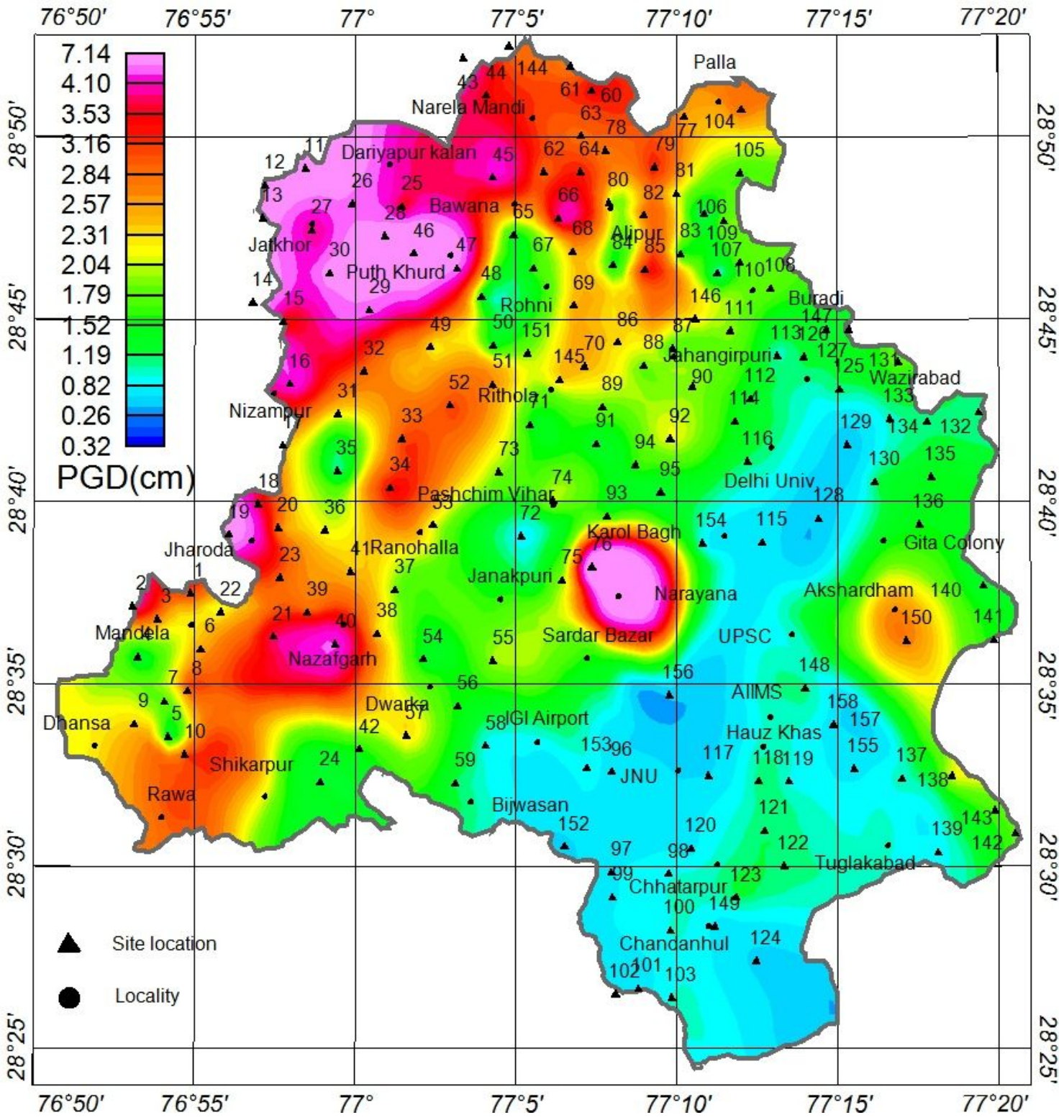

Figure 14

Map depicting the variation of PGD at the free surface level in the NCT Delhi region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.