

# Deterministic Investigation of Effect of Stress Drop on Seismic Site Response Analysis of Allahabad City

**Keshav Kumar Sharma**

National Institute of Technology Jamshedpur, India

**Kumar Pallav** (✉ [kumarpallav23@gmail.com](mailto:kumarpallav23@gmail.com))

Cape Peninsula University of Technology <https://orcid.org/0000-0003-3785-3181>

**Shashi Kant Duggal**

Motilal Nehru National Institute of Technology

---

## Research Letter

**Keywords:** Amplification, Stochastic simulation, Response Spectra, Stress Drop, Allahabad

**Posted Date:** June 29th, 2020

**DOI:** <https://doi.org/10.21203/rs.3.rs-32328/v1>

**License:**  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

---

# **Deterministic investigation of effect of Stress drop on Seismic Site Response Analysis of Allahabad City**

**Keshav Kr. Sharma<sup>1</sup>**

<sup>1</sup> Assistant Professor, Department of Civil Engineering, NIT Jamshedpur-, India

Email: kksharma.ce@nitjsr.ac.in

**Kumar Pallav<sup>2</sup> (Corresponding Author)**

<sup>2</sup> Sr. Lecturer, Department of Civil Engineering and Surveying, CPUT Bellville, Capetown, 7530, RSA , Email: kumarp@cput.ac.za, kumpallav23@gmail.com;

**S. K. Duggal<sup>3</sup>,**

<sup>2</sup> Professor, Department of Civil Engineering, MNNIT Allahabad-211004, India

Email: shashikantduggal@gmail.com

## **Abstract**

Due to the high stress of Faizabad ridge close to Allahabad city and the absence of strong-motion records for any engineering studies, it is essential to use a stochastic model to study the deterministic earthquake scenario of Allahabad city. The work investigates the effect of stress drop for an earthquake on 30 sites (83 boreholes) located across the city using 1-D seismic site response analysis. The ground motion has been simulated for Allahabad fault using stochastic finite fault model for stress drop ranges from ~70 bar to ~200 bars. Simulation results show the Peak Ground Acceleration (PGA) value of 0.026 g and 0.085 g at 70 and 200 bars stress drops, respectively. Site response results reveal that Indian Standard IS: 1893-2002 underestimates the PGA at higher stress drop compared to the estimated spectral acceleration values. Further, the lower stress drop can give a higher mean spectral acceleration at a long-period. Contour plot of surface-level PGA, low and high period spectral acceleration with response spectra for Allahabad city shows the variation with stress drop.

**Keywords:** Amplification, Stochastic simulation, Response Spectra, Stress Drop, Allahabad

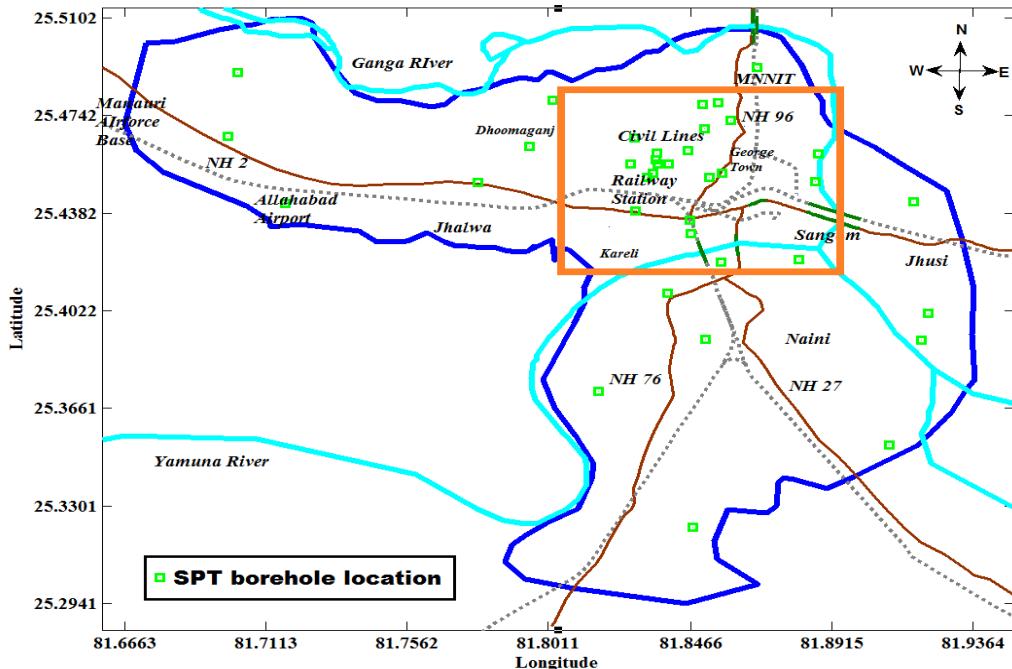
## **1.0 Introduction**

Researchers in the early 1960's understood that the effect of an earthquake is not alike on every type of soil. Medvedev (Medvedev, 1962) has correlated intensity increment with the surface geology for the events that happen in the Asian region. Many other similar relationships were developed for other cities California (Evernden and Thomson, 1988), Japan (Shabestari *et al.*, 2004), Turkey (Picozzi *et al.*, 2009), Darfield (Bradley, 2012) and Xanthi (Stamati, Klimis and Lazaridis, 2016) are used to know the response of an earthquake on local surface geology. Regional soil site characteristics play a significant role in determining the damage potential of arriving seismic waves. Destruction of Mexico City after Michoacan earthquake (1985) is an example of the effects of local surface geology on-site response (Avilés and Pérez-Rocha, 1998). The impact of amplified ground motion is having a destructive effect on structures when periods matches with the site periods. In the Loma-Prieta earthquake (1989), soft soil sites were severely affected in the San Francisco, while adjacent hard rock sites were amplified by 2 to 4 times (Housner and Thiel, 1990; Segall, Bürgmann and Matthews, 2000). Substantial damages have been reported at Ahmedabad due to Bhuj earthquake (2001) despite a large epicentral distance (160 miles) because of site amplification of thick alluvial deposit under Ahmedabad (Sitharam and Govindaraju, 2004). Many studies have performed on the site-specific response by considering local soil properties of sub-surface layers of SPT-N values. As per authors knowledge, none of the studies reported on the effect of stress drop on-site response analysis. Parameters such as thickness, type of soil, density, plasticity index, groundwater table and shear wave velocity (calculated by the existing relationship between shear wave velocity and SPT-N values) are required. Pitilakis (2004) stated that to estimate the site classification based on SPT-N or shear wave velocity along with site response couple with response spectra is the most efficient way to account for site effects. Further, no attempt was made to determine the site classification and site response of Allahabad city, which lies in the eastern section of Indo-Gangetic plains (IGP).

## **2.0 About Prayag city**

Allahabad formerly known as Prayag (place of offerings) is one of the most important cities of Uttar Pradesh. It is situated in the north-central section of the country in the southeastern section of the state. Allahabad city lies between latitude  $25^{\circ}30' .04.1''$  N to  $25^{\circ}29'58.3''$  N with its centre coordinates as  $25.45^{\circ}$  N &  $82.5^{\circ}$  E. and situated at the intersection of river Ganga and Yamuna. The city hosts the world's largest religious gathering (about 100 million people) known as '*MahaKumbh*' held after every 12 years and '*ArdhKumbh*' after every six years. Further, the one-month carnival takes place every year, known as '*Magh Mela*'. All Saints Cathedral, KhusroBagh, Allahabad Highcourt, Alfred Park, Anand Bhavan and New Yamuna Bridge are important heritage structures. Allahabad is 7<sup>th</sup> most crowded city of the state and 36<sup>th</sup> most populous in the country with an approximate population of 1.11 million (*Census*, 2011).

Allahabad is strategically vital for politics, education, economy and tourism. Headquarters of North-Central Railway and four National Highways (NH), viz., NH 2, NH 27, NH 76 and NH 96. NH 2 is also known as Grand Trunk road which connects Delhi to Kolkata via Allahabad. NH 2 is a part of Asian Highway AH 1. the Waterway 1, the longest in India connects Allahabad and Haldia (Kolkata) (Figure 1). There are seven bridges out of six are in use for connectivity across the rivers. Allahabad (now Prayag) is well known for its academics. It is an education hub of the state and establishment of headquarters of the world's largest examining body viz., '*Board of High School and Intermediate Education*'. The city has renowned universities, Research Institutions, and Technical and Medical Institutions which attract students from across the country. Many Infrastructural projects for residence, industrial projects, roads, metro rail, flyovers and hospital buildings, etc., have been planned. As a result, the seismic vulnerability of the city needs proper attention. Many of the existing structures were designed using IS codes recommendation but didn't consider the local soil site conditions and restitution characteristics of the earthquake.



**Fig. 1** Borehole location of all the 30 sites (83 Boreholes) of Allahabad city, India

## 2.1 Geology of Allahabad District

Geologically, the city is situated at *IGP*, a vast fore-deep region of Himalayas. As per Dasgupta. (Dasgupta, 2000), the study area has characterised into Ganga alluvial plain, Yamuna alluvial plain and Vindhyan plateau. The geomorphic features of the area as follows: (1) Active flood plains, confined in the vicinity of the river system; (2) Older alluvial plains, defined by depositional and erosional terraces, generally existing in patches along the active plain; and (3) Rocky surface (Denudational hills), mainly of quartzite in nature and prominently found in the

Trans-Yamuna area. The surface lithological behaviour is found to be quite different in Trans Ganga and Trans Yamuna area, with some hard rock strata in the northern part of Trans-Yamuna area (Pandey, 2008). This is the reason that the borehole data is only up to 10m. The Ganga basin, which dominates the geological setup of the region is a part of IGP, with most massive modern alluvial sedimentary terrain having a length of about 1000 km and width varying from 200 - 450 km, being more extensive in the western part and narrower in the east (Singh, 1996)(Bagchi and Raghukanth, 2017) (Singh 1996; ). The *IGP*, a down-warp of the Himalayan foreland converted into alluvial plains of variable sediment depth.

Table 1 Density of stones present at bed level

<b>Stone</b>	<b>Density (kg/m<sup>3</sup>)</b>
Shale	2400 – 2800
Sandstone	2200 – 2800
Limestone	2300 – 2700

Source:(Alden, 2020)

The deep borehole collected from *Central Ground Water Board, Ministry of Water Resources* for investigation of Allahabad. Sulemsari area with the highest depth of 278.12 m and *Yamuna River* area with the lowest depth of 90 m in the city. Shale, Sandstone and Limestone were found at the basement level. The present study considered the average depth of the basement as 250 m and a density of 2533 kg/m<sup>3</sup> in the site response analysis. Table 1 shows the density of stones found at the bed level. In this research work, the average rock density of 2533 kg/m<sup>3</sup> is used for site response analysis.

## 2.2 Seismotectonic Setup

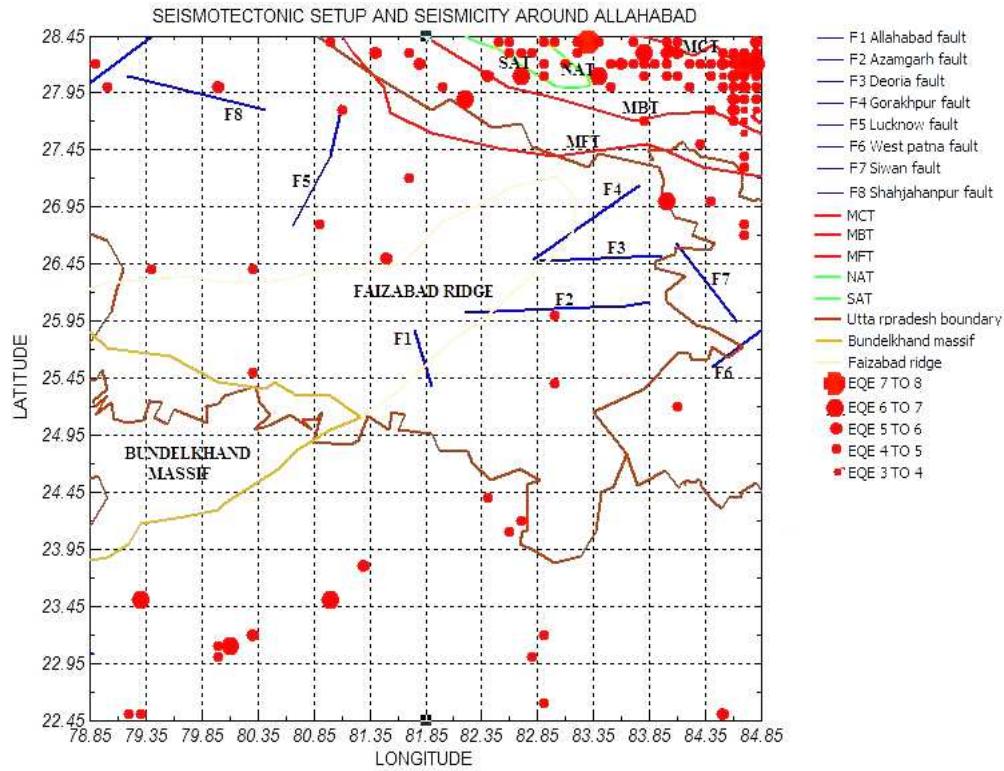
The *IGP* is the most significant contemporary alluvial sedimentary plain that inhibits a population of more than 200 million people. These plains exhibit several faults having three prominent trends, *viz*, *North North East (NNE)-South South West (SSW)* to *North East (NE)-South West (SW)*, *North North West (NNW)- South South East (SSE)* to *North East (NE)- South East (SE)* and *East (E)-West (W)*. Out of these, the *E-W* trending fault set in *Azamgarh-Gorakpur* area defines the *Mirganj Graben*(Szulc *et al.*, 2006). The *E-W* elongated *IGP* shaped in response to the collision of the Indian plate, and Eurasian Plate that caused the uplift of Himalaya initiated in the Palaeogene is an active foreland basin (DEWEY JF and BIRD JM, 1970), (Singh, 2013)(Acharyya and Saha, 2018). The region integrates numerous covered faults and ridges in its basement (Valdiya, 1970) (Acharyya and Saha, 2018). In the *IGP*, groups of significant ridges added due to seismotectonic movements of the basements. The *Faizabad ridge* and *Munger ridge*, close to Allahabad, are bounded by various faults. They are a prolongation of *Bundelkhand massif* and *Satpura massif* (Singh, 2015). Quittmeyer and Jacob (Quittmeyer and Jacob, 1979) compared the seismicity of the *IGP* with Himalaya and considered it as moderately seismic. (Sinha, R; Tandon, SK; Gibling, MR; Bhattacharjee, PS; Dasgupta, 2005) studied all these ridges bounded by faults and its tectonic extension from the Indian shield.

Table 2 Details of seismic sources in the study area

Fault name	Nomenclature	Fault length (km)	Fault position	Strike (Degree)	Dip	Initial Latitude	Initial Longitude	Final Latitude	Final Longitude	$M_{max}$ (as per WC 1994)
Allahabad Fault	F1	57	Sub surface	166	50	25.382	81.9	25.873	81.745	6.3
Azamgarh Fault	F2	158	Sub surface	87	50	26	82.198	26.074	83.778	6.9
Deoria Fault	F3	106	Sub surface	87	50	26.48	82.866	26.530	83.930	6.6
Gorakhpur Fault	F4	118	Sub surface	51	50	26.482	82.8	27.150	83.722	6.7
Lucknow Fault	F5	126	Sub surface	25	50	26.78	80.67	27.808	81.207	6.8
Siwan Fault	F6	94	Sub surface	64	60	26.636	84.09	25.945	84.64	6.6
Shajhanpur Fault	F8	130	Sub surface	106	50	28.11	79.17	27.788	80.445	6.8
Great Boundary Fault	F9	314	Sub surface	50	60	27.12	77.62	28.963	80.058	7.3

Allahabad, a metropolitan city of Uttar Pradesh, lies in Seismic Zone-II in the seismic zonation map of India (IS 1893, 2016), with Zone factor of 0.1. Most of the adjoining regions in East & West of Allahabad lie in Seismic Zone-III while south part falls in Zone-II and north area falls in Zone-IV that is quite ambiguous. Seismotectonic Atlas of India defines the linear sub-surface faults as a potential seismic source around the study area. Presence of numerous faults around the study area increases the seismic hazard of Prayag city. Further, Table 2 shows a list of faults and various surface and sub-surface faults. The details of these faults like strike, dip and mechanism (thrust/reverse, normal, and strike-slip) are gathered from the work of Dasgupta et al. (2000); Singh et al. (2004) and Kayal (2008). In this study, only faults having the length of more than 50 km are considered and are shown in Figure 2. Figure 2 shows the presence of many potential seismic sources of *Home Affairs* has shown that Allahabad City lies near *Faizabad Ridge*, which is inactive over around thirty decades. The ridge is highly stressed due to a large seismic gap and can, therefore, cause a high magnitude earthquake shortly (Mishra, D. and Uniyal, 2010). Further, it also concluded that subduction of Indian plate under the Asian plate by 5.25 m could generate a *Great earthquake*(Anbazhagan et al., 2017). Due to the possible seismic gaps and tectonic set up of *IGP*, it is vital to carry out seismic site characterisation and the site-specific

seismic ground response of the city like Allahabad along with the effect of stress drop on ground motion response.



**Fig. 2** Seismotectonic setup along with Seismicity around Allahabad, India

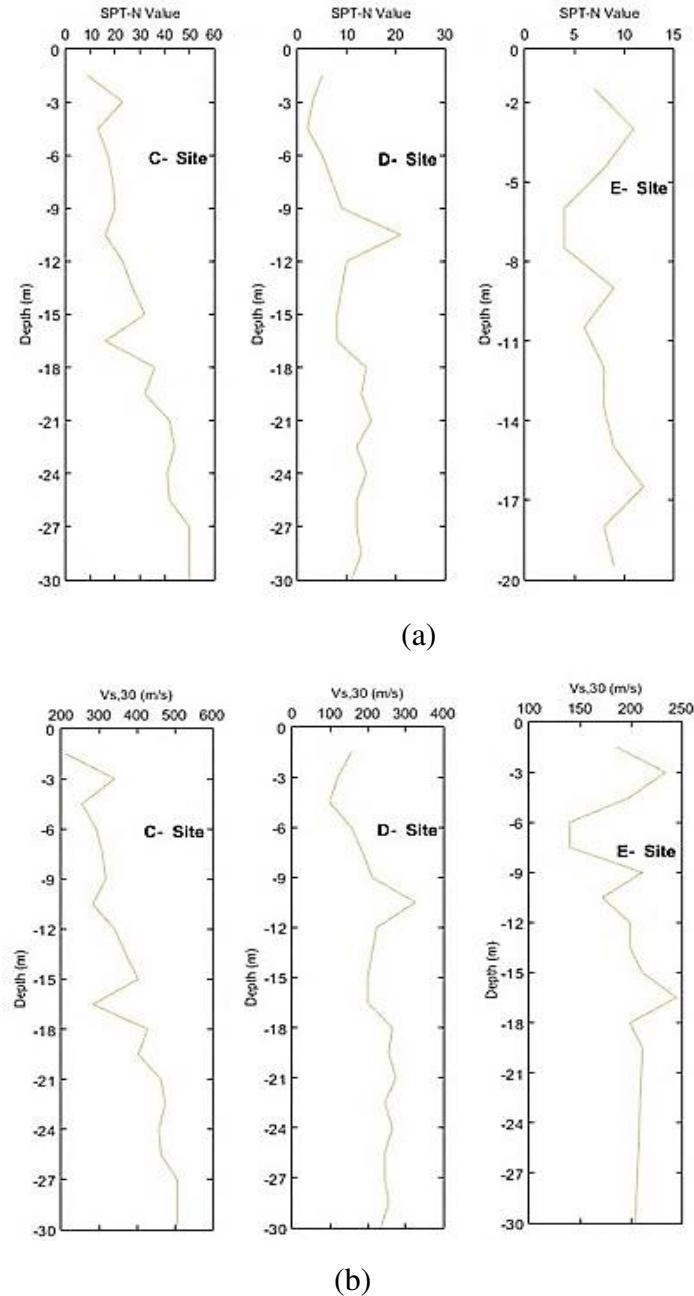
### 3.0 Local Soil Condition

Soil data obtained from various Government and private geotechnical agencies for 30 sites at Allahabad city(Fig. 2). Essential properties like a type of soil, density of soil, plasticity index, depth of groundwater table and SPT-*N* value extracted from the dataset. Shear wave velocity has calculated from the correlation established between SPT-*N* value and shear wave velocity proposed by (Anbazhagan, Kumar and Sitharam, 2013) for *IGP* for all type of soils.

$$V_s = 68.96 (N)^{0.51} \quad (1)$$

The shallow sub-surface soil characteristics play an important role in site-specific ground response analysis and also contribute to the amplification potential of a site. So it is necessary to account near-surface soil properties to determine surficial ground motion. The shallow depth (30 m) shear wave velocity profiles are unavailable for Allahabad city. However, soil characteristics and SPT-*N* values are available from bore log information of 83 boreholes drilled at 30 sites covering the main area of Allahabad city. The depth ranges from 10 m to 30 m in depth. The category of the sites is estimated as per its shear wave velocity using SPT-*N* value (*International Building Code*, 2009). Boore (Boore, 1983) methodology used to estimate shear wave velocity at 30 m from shallow depth boreholes. For 30 – 250 m soil column, a linear variation of shear wave velocity is assumed.

Out of 30 sites with 83 boreholes, 12 sites are of *C*-class ( $360 < V_s \leq 760$  m/s), 15 sites are of *D*-class ( $180 < V_s \leq 360$  m/s) and 3 sites are of *E*-class ( $V_s < 180$  m/s). Figs. 3 (a)-(b) shows the SPT-*N* values and estimated shear wave velocity profile for Jhalwa (C-type), Bargadghat (D-type) and Kilaghat (E-type).



**Fig. 3 (a)** Typical SPT-*N* values and **(b)** Shear wave velocity profile for C, D & E class sites

#### 4.0 Simulation of synthetic ground motion

Engineers are primarily interested in the strong ground motion, which can affect the people and their environment. In general, the earthquake strength is directly proportional to the amplitude

values if they last for sufficient duration. Much information inferred from the amplitude content, but a dynamic response of a structure is very sensitive to the frequency at which it loaded. In the present research work, the finite fault seismological model of Motazedian and Atkinson (Motazedian and Atkinson, 2005) has used in the simulation of rock level time history. It is a modified form of point source stochastic seismological model (Boore, 1983). The faults divided into  $N$  number of sub-faults, and every single sub-fault symbolises as the point source. Acceleration time histories of ground motion have calculated for the point source by using a stochastic seismological model. The simulated synthetic ground motions are added up by using time lags. Equation 2 shows the Fourier amplitude spectrum of ground motion provided by the point source seismological model due to  $i^{\text{th}}$  sub-fault.

$$A_i(f) = \left( \frac{M_i H_i (2\pi f)^2}{1 + (f/f_{0i}(t))^2} \right) \left( \frac{\sqrt{2} \langle R_{\theta\phi} \rangle}{4\pi\rho V_s^3} \right) \left( G e^{\frac{\pi f R_i}{V_s Q}} \right) (F(f) e^{-\pi f k_0}) \quad (2)$$

where,  $M_i$  =  $i^{\text{th}}$  sub-fault's moment magnitude;  $G$  = geometric attenuation ;  $V_s$  = Shear wave velocity (3.6 km/sec);  $R_i$  = site to sub-fault distance;  $Q$  = regional quality factor;  $H_i$  = scaling factor to convert sub-faults energy of high-frequency spectral level;  $f_{0i}(t)$  = dynamic corner frequency;  $F(f)$  = site amplification in comparison to the source; the average shear-wave velocity may be less than 1500 m/sec.  $e^{-\pi f k_0}$  = high cut filter (rapid spectral decay at high frequencies) (Boore, 2003)(Anderson and Hough, 1984).  $\langle R_{\theta\phi} \rangle$  =Average Radiation coefficient;  $\rho$  = density of the crust at the focal depth. The coefficient  $\sqrt{2}$ , is the product of the free surface amplification and partitioning of energy in orthogonal directions. The Moment of the  $i^{\text{th}}$  sub-fault from the slip distribution expressed as:

$$M_{0i} = \frac{M_0 D_i}{\sum_{i=1}^N D_i} \quad (3)$$

where,  $M_0$  = total seismic moment of all the sub-faults;  $D_i$ = average final slip acting on the  $i^{\text{th}}$  sub-fault.

The dynamic corner frequency  $f_{0i}(t)$ , the seismic moment  $M_0$  moreover, the stress drop  $\Delta\sigma$  relationship is shown in equation 4.

$$f_{0i}(t) = 4.9 \times 10^6 (N_R(t))^{-1/3} N^{-1/3} V_s \left( \frac{\Delta\sigma}{M_0} \right)^{1/3} \quad (4)$$

where,  $N_R(t)$  = cumulative number of ruptured sub-faults at time  $t$ .  $H_i$ , the relation is given in equation 5.

$$H_i = \left( N \frac{\sum_f \left( \frac{f^2}{1+(f/f_0)^2} \right)^2}{\sum_f \left( \frac{f^2}{1+(f/f_{0i}(t))^2} \right)^2} \right)^{1/2} \quad (5)$$

where,  $f_0$  = corner frequency at the end of the rupture, which obtained by substituting  $N_R(t) = N$  in Eq. (4). Motazedian and Atkinson recommended the abstraction of the pulsing area to recital the realistic model of earthquake rupture (Motazedian and Atkinson, 2005). Initially, a cumulative number of active sub-faults  $N_R(t)$  raise with time to acquire a constant magnitude at a few fixed percentage of the total area ruptured, which termed as pulsing percentage area. At the time of rupture of  $i^{\text{th}}$  sub-fault, parameter (i.e. pulsing area) ascertains the number of active sub-faults. The dynamic corner frequency is determined using all these sub-faults (Equation 4).

The quarter wavelength method is used for modifying the ground motion between bedrock and A-type sites (Boore,DM. and Joyner, 1997). To determine the kappa factors from the average

shear-wave velocity in the top 30 m of soil, an empirical equation proposed by Chandler et al. (Chandler, Lam and Tsang, 2006) is shown in equation 8.

$$k_0 = \frac{0.057}{V_{s30}^{0.8}} - 0.02 \quad (6)$$

For simulating rock level ground motion at Allahabad, the kappa factor for soft rock site is obtained as 0.057 using Eq. (6). In the present study, Table 3 shows the parameters used to simulate the synthetic ground motion.

Further, the maximum magnitude of the earthquake  $M_w$  for all faults (Fig. 1) has been calculated from Wells and Coppersmith (1994) relation using fault rupture length as  $1/3 rd$  of total fault length (Wells and Coppersmith, 1994).

$$M_w = 4.38 + 1.49 * \log(RLD) \text{ (All rupture types)} \quad (7)$$

Where  $M_w$ = moment magnitude;  $SRL$ = surface rupture length (km);  $RLD$ = sub-surface rupture length (km).

Table 3 Parameters used to simulate ground motion

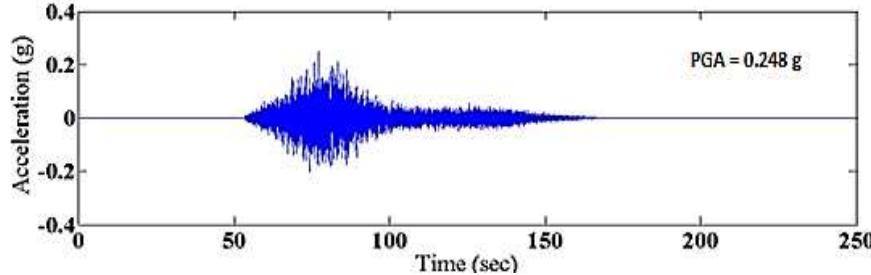
Parameter	Value used in this study
$V_s$ Shear-wave velocity and	3500 m/s,
$\rho$ Density at source	2.9 g/cc (Singh <i>et al.</i> , 1999) and (Mitra <i>et al.</i> , 2015)
$\Delta\sigma$ Stress Drops	50, 70, 100, 125, 150, 175, 200 bars (Kayal, 2008)
$Q(f)$ Quality factor	$142f^{1.04}$ (Mohanty <i>et al.</i> , 2009)
Geometric attenuation	$1/r$ ( $forr \leq 100 \text{ km}$ ); $\sqrt{1/(100r)}$ ( $forr > 100 \text{ km}$ ) (Singh <i>et al.</i> , 1999)
$k$ Kappa factor	0.057 for deep profiles (Eq. 8)
$\sigma$ Reference stress drop	100 bars
Pulsing percentage and Sub fault size	50% and $0.25 \text{ km} \times 0.25 \text{ km}$
Crustal amplification	ENA Hard rock amplification

Table 4 Source parameters

Parameters	Value
$M_w$	7.8
$M_o(\text{Nm})$	$6.623 \times 10^{20}$
Strike ( $\phi$ )	$295^\circ$
Dip ( $\delta$ )	$10^\circ$
Rake ( $\lambda$ )	$101^\circ$
Focal depth (km)	15
Rupture Length (L) (km)	221
Rupture Width (W) (km)	45
Subfault length ( $dl$ ) (km)	5
Subfault width( $dw$ ) (km)	5
Rupture Velocity (km/s)	$0.8 \beta$

### Validation with KTP

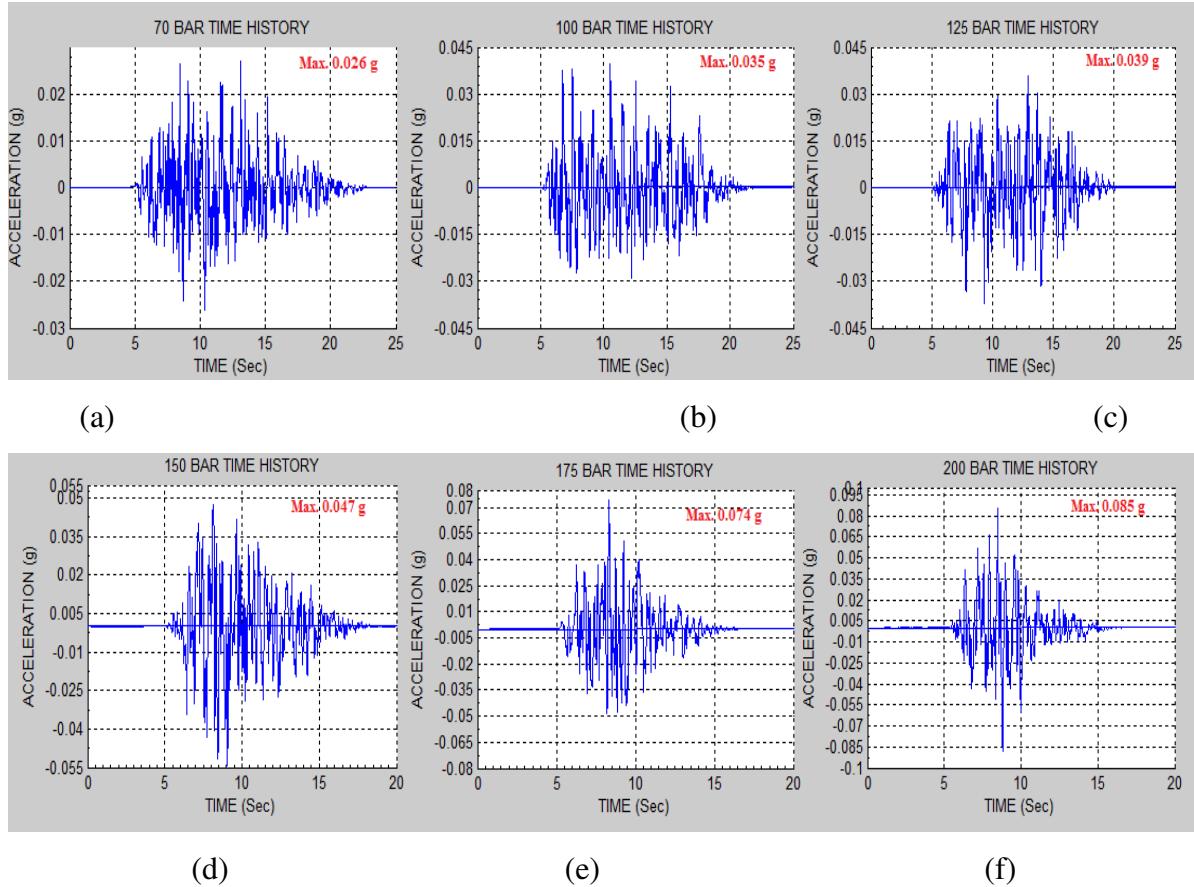
In the absence of recorded ground motion at Allahabad city, the validation is performed for the KTP (Kirtipur Municipality Office, Kirtipur) PGA of 0.26g for the 25 April 2015 Nepal earthquake ( $M_w$  7.8). The earthquake occurred in the western region of Nepal towards the North-West of Kathmandu (USGS, 2015) along the Main Frontal Thrust (MFT) active fault(Takai *et al.*, 2016). The ground motion has been simulated using Stochastic Finite-Fault Model for A-type site (hard rock site) is compared with recorded PGA at KTP station. Site amplification has ignored since the simulation is carried out for the A-type site. The shear-wave velocity and density of hard rock site are taken as 2.97 km/s and 2600 kg/m<sup>3</sup>, respectively. Kappa factor  $k = 0.005$  s at hard rock level (Khattri *et al.*, 1994). Stress drop and pulsing area were taken as 160 bars and 50 percent. Geometrical spreading  $G$  is taken as  $(1/R)$  for  $R < 100$ km and  $(1/10\sqrt{R})$  for  $R > 100$ km (Singh *et al.*, 1999),  $Q = 500f^{1.04}$  is used as a quality factor (Mitra *et al.*, 2015). The estimated Peak Ground Acceleration (PGA) is 0.248g, as shown in Fig. 4 whereas recorded PGA at KTP station is 0.260g Mainshock of the earthquake (also known as Gorkha earthquake), located at the village of Barpak (Longitude 84.708° E and Latitude 28.147° N at shallow Depth of 15.0 km) in the Gorkha district of Nepal. The epicentre of the earthquake was at Lamjung, around 80 km north-west of Kathmandu. USGS database provides the characteristics of fault like strike, dip and depth of the earthquake (USGS, 2015). *Center for Engineering Strong Motion Data* (CESMD, 2015) also provides the Peak Ground Acceleration (PGA), event location and fault distance. The square grid has been used to categorise sub fault size configuration. Table 4 provides the primary source parameters of Nepal earthquake.



**Fig. 4** Validation of Simulated time history for at A type (hard rock) for Nepal earthquake

#### 4.1 Simulated ground motion for Allahabad City

The ground motion at Allahabad city have simulated for the stress drops ranges from 70 bars to 200 bars at Allahabad fault(~70 km from city). Acceleration time history has been plotted using MATLAB, as shown in the Figs. 5 (a)-(f). The PGA ranges from 0.026g to 0.085g. The simulated time history is used in the scrutiny of stress drops on-site response analysis at a different time period.



**Fig. 5(a-f)** Simulated ground motion due to Allahabad Fault at Allahabad city for stress drop range of 70 to 200 bar.

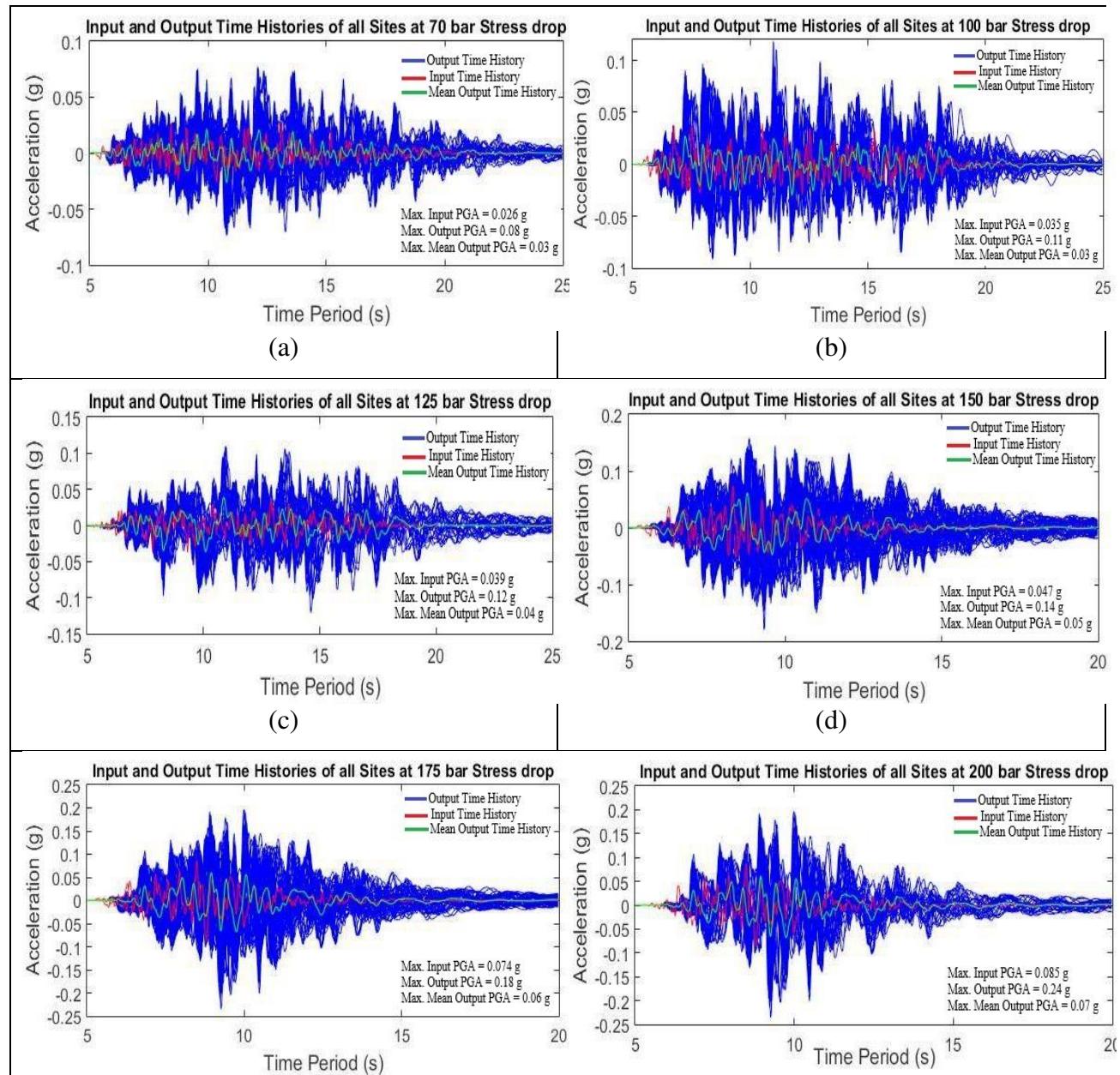
#### 4.2 Site response analysis

Local soil site conditions have proven a significant effect on ground surface parameters. The one-dimensional equivalent linear approach is used to carry out site response analysis for all 83 boreholes of the Allahabad city using 1-D analysis. The hyperbolic model is selected and calibrated for 250 m thick soil column using EPRI (Inst., 1993) curves data (Park and Hashash, 2005). Reference strain calculated for at the middle of each 100 m thickness. As the  $V_s$  profiles are not available for Allahabad city, so they have been computed using SPT- $N$  values from the correlation,  $V_s = 68.96 (N)^{0.51}$  (Anbazhagan, Kumar and Sitharam, 2013) which is based on IGP. To account for nonlinear behaviour of soil, damping ratio versus shear strain curves and shear modulus versus shear strain curves proposed by Vucetic and Dobry (1991) for clay and sand-based on plasticity properties. Synthetic ground motion developed for bedrock level is applied to carry out site-specific response analysis.

#### 5.0 Results and Discussions

A comprehensive set of analyses is conducted to understand the effect of stress drop on surface-level ground motion and response spectra of the sites. The simulated ground motion has used as

an input motion at bedrock level to known the response of all 83 boreholes at 30 sites. The ground motions due to fault 1 (Allahabad fault) for different stress drops (70, 100, 125, 150, 175 and 200 bars) with 0.06 kappa factor has used at the level of 250 m thick soil columns (below the 30 m depth). Simulated acceleration time history was used as input ground motion, applied at bedrock level to carry out seismic site response analysis for Allahabad city. From the results of site response analysis, surface-level acceleration time history has extracted for all the sites at different stress drops. Input ground motion, output ground motion and mean of all the 30 sites acceleration time history for Allahabad city was plotted and has shown in Figures. 6 (a)-(f). Finally, output response spectra have compared with Indian standard response spectra IS: 1893 (IS 1893, 2016). The variation of ground motion has shown in the form of contour plots for 200 bar stress drop.



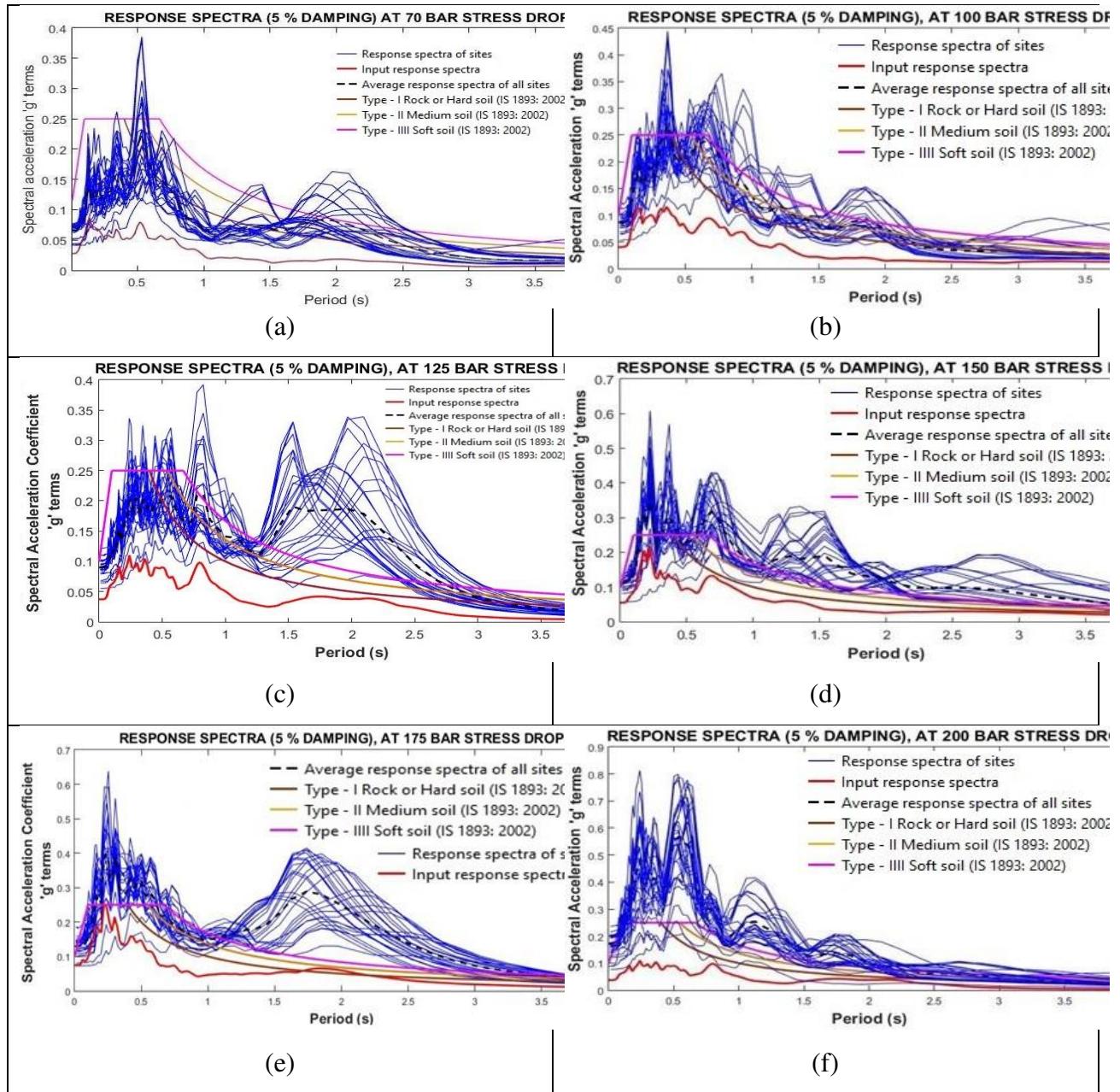
(e)	(f)
-----	-----

**Fig. 6(a-f)** Comparison of input & output acceleration-time history for different stress drops

Figures. 6 (a-f) shows that input and output PGA increases with the stress drop from 70 – 200 bars. Input PGA varies from 0.026 g to 0.085 g, and output PGA is in the range of 0.03 g to 0.24 g at 70 bar & 200 bar, respectively. Maximum mean acceleration values for all the sites also increase with the stress drop and are in the range of 0.03 g to 0.07 g. Table 5 shows the Maximum input, maximum and minimum output PGA values with their occurrences at similar sites. Government Press (Civil Lines) which lies in the centre of the city shows maximum output PGA for all the stress drops except 125 bar whereas minimum PGA value has observed at Kilaghat which is near to river having shallow bedrock depth. Maximum average PGA was found to be 0.12 g at Government Press (Civil Lines) while a minimum of 0.05 g at Kilaghat. Results demonstrated that the Civil lines area is more susceptible to ground motion amplification. Table 6 shows the amplification of PGA for all stress drops. Response spectrum for Allahabad city has been plotted at 5 % damping for different stress drops and compared with suggested response spectrum by Indian Standard code IS: 1893-2002 and are shown in Figures. 7 (a)-(f). All response spectrum is discussed below in terms of amplification/de-amplification for different time period ranges.

Table 5 Maximum and Minimum PGA occurrence for different stress drops at different sites

Stress Drop (bar)	Max. Input PGA (g)	Max. Output PGA (g)	Max. Output PGA (g) Sites	Min. Output PGA (g)	Min. Output PGA (g) Sites
70	0.026	0.08	MNNIT Allahabad, Rawatpur, Government Press (Civil Lines)	0.03	1. Kila ghat
100	0.035	0.12	Government Press (Civil Lines)	0.03	1. Kila ghat
125	0.039	0.13	District Women Hospital, Narayani Ashram, Narayani Group Naini	0.05	1. Kila ghat
150	0.047	0.14	George Town, District Court, MNNIT Allahabad, Government Press (Civil Lines)	0.06	1. Kila ghat
175	0.074	0.18	Government Press (Civil Lines)	0.06	1. Kila ghat
200	0.085	0.24	Government Press (Civil Lines)	0.06	1. Kila ghat



**Fig. 7(a-f)** Comparison between Response Spectra for all 30 sites with IS:1893  
**Period: Zero – 0.1 sec**

It shows from Figures. 7 (a)-(f), for Zero to 0.1 sec, that all the sites get amplified for all stress drops. Maximum estimated value of spectral acceleration between this period is 0.14 g, 0.21 g, 0.17 g, 0.19 g, 0.29 g and 0.34 g for 70, 100, 125, 150, 175 & 200 bars, respectively. The maximum estimated spectral acceleration value is below the proposed curve of response spectra as given by Indian Standard code IS: 1893-2002 except for 175 and .200 bar stress drops. For 175 bar, the response of all the sites is close to the proposed response curve of Indian Standard while at 200 bar the response of most of the sites exceeds the proposed curve. Further, the mean of site response for all the sites at each stress drop between this period is below the proposed curve. The maximum mean spectral acceleration from zero period to 0.1 sec of all the 30 sites

are 0.09 g, 0.14 g, 0.11 g, 0.14 g, 0.17 g and 0.23 g for 70, 100, 125, 150, 175 & 200 bars, respectively.

**Table 6** Amplification of PGA for different stress drops at different sites

Stress Drop (Bar)	70	100	125	150	175	200	Mean
Max. Input PGA	0.026	0.035	0.039	0.047	0.074	0.085	0.051
Max. Output PGA	0.08	0.12	0.13	0.14	0.18	0.24	0.15
Amplification	3.1	3.2	3.1	3.0	2.4	2.8	2.9

#### **Period: 0.1 – 0.67 sec**

Figures. 7 (a)-(f), shows that period between 0.1 – 0.67 sec, all the sites amplified for all the stress drops. The Maximum spectral acceleration between this period are 0.39 g, 0.44 g, 0.33 g, 0.61 g, 0.64 g and 0.81 g for 70, 100, 125, 150, 175 & 200 bars, respectively. For 70, 100 and 125 bar stress drop, uniform and wide peaks have observed with few concentrated peaks that exceed the proposed curve of response spectra. At 150, 175 and 200 bar stress drop for almost all the sites are found to be above the proposed response curve. Maximum mean spectral acceleration values have found above the proposed curve for this period range for all stress drop except at 70 bar. Maximum estimated value of mean spectral acceleration is 0.22 g, 0.26 g, 0.24 g, 0.36 g, 0.39 g and 0.57 g for 70, 100, 125, 150, 175 & 200 bars, respectively.

#### **Period: 0.67 – 4.0 sec**

As in the given long period from 0.67 sec to 4 sec the fluctuations in response spectra is quite random and hence the period is further categorised into four-part, i.e., 0.67 sec to 1 sec, 1 sec to 2 sec, 2 sec to 3 sec and 3 sec to 4 sec.

#### **Period: 0.67 – 1 sec**

In this period it can be demonstrated from the Figures. 7 (a)-(f) that all sites get amplified for all stress drops, only very few sites de-amplify in the said period. It was observed that the nature of soil sites are well above the Type-III (soft soil) category of IS: 1893-2002. Curves of all sites are showing the decreasing trend for 150, 175 and 200 bar stress drops while concentrated peaks are observed for other stress drops. For 150 bar the trend of the sites are in between of Type-I (rock or hard soil) and Type-III (soft soil), but more inclination is towards soft soil. Maximum estimated value of spectral acceleration in this range are 0.23 g, 0.36 g, 0.39 g, 0.43 g, 0.31 g and 0.55 g for 70, 100, 125, 150, 175 & 200 bars, respectively. Maximum estimated value of mean spectral acceleration is 0.15 g, 0.24 g, 0.21 g, 0.31 g, 0.22 g and 0.36 g for 70, 100, 125, 150, 175 & 200 bars, respectively. The mean spectral acceleration exceeds the proposed curve for 150 and 200 bars.

#### **Period: 1 – 2 sec**

Figures. 7 (a)-(f), for period 1– 2-sec amplification of all the sites are in the range of 3 to 4 times of input response spectra. Maximum estimated value of spectral acceleration is 0.16 g, 0.19 g, 0.34 g, 0.33 g, 0.41 g and 0.42 g for 70, 100, 125, 150, 175 & 200 bars, respectively. For 125, 150 & 175 bar stress drops, high peaks have observed in the period range of 1.25 - 1.75 sec, 1.1 - 1.5 sec & 1.6 – 2.0 sec, respectively which shows that sites have highly amplified for the structure ranges in this particular periods. Maximum estimated value of mean spectral acceleration is 0.09 g, 0.11 g, 0.19 g, 0.18 g, 0.28 g and 0.25 g for 70, 100, 125, 150, 175 & 200 bars, respectively.

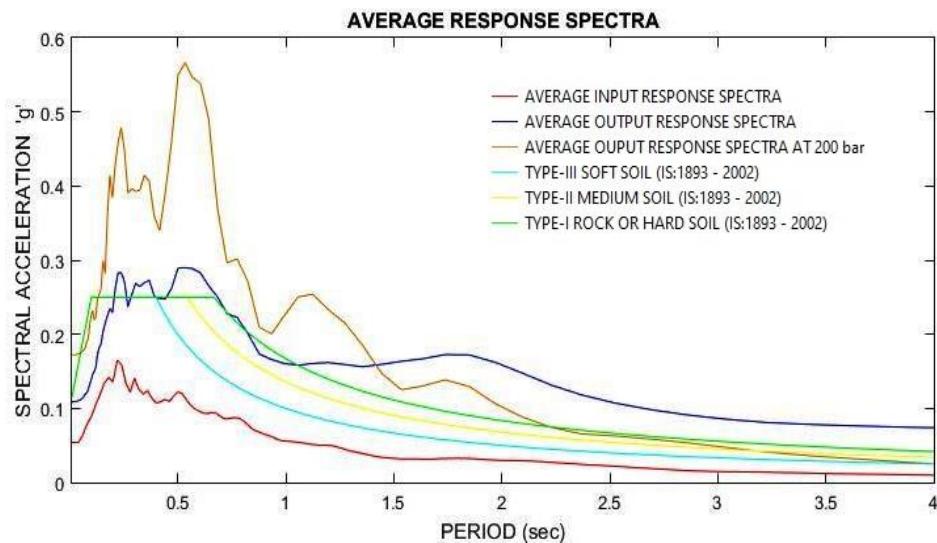
#### **Period: 2 – 3 sec**

In period 2 – 3 sec very less amplification is observed for all stress drops. Maximum estimated value of spectral acceleration is 0.05 g, 0.08 g, 0.28 g, 0.19 g, 0.28 g and 0.11 g for 70, 100, 125, 150, 175 & 200 bars, respectively. For 200 bar, all sites follow the proposed curve and mean spectral acceleration curve are in the same range as the proposed curve. Maximum estimated value of mean spectral acceleration is 0.02 g, 0.04 g, 0.15 g, 0.09 g, 0.19 g and 0.07 g for 70, 100, 125, 150, 175 & 200 bars, respectively.

#### **Period: 3 – 4 sec**

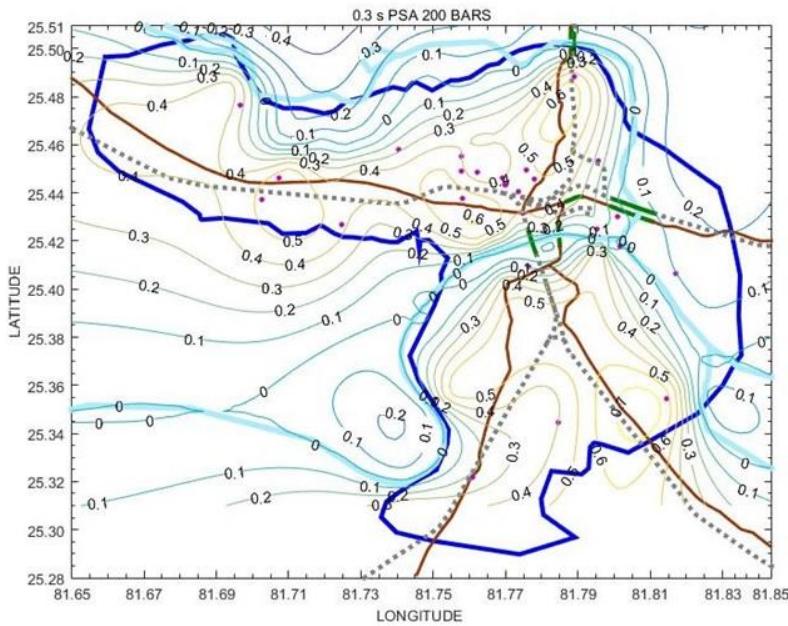
It shows from Figures. 7 (a)-(f), for period 3 – 4 sec very nominal amplification of 1.0 to 1.3 times of input response spectra observed for all stress drops. Maximum estimated value of spectral acceleration is 0.03 g, 0.09 g, 0.04 g, 0.14 g, 0.08 g and 0.08 g for 70, 100, 125, 150, 175 & 200 bars, respectively. For 70 & 100 bars, most of the sites are below the proposed soft soil curve for the period range of 3.0 – 4.0 sec. For 150 bar, almost all sites are above the proposed hard rock curve for the period range of 3.0 – 4.0 sec. For 125, 175 & 200 bar stress drops, estimated spectral acceleration curve for all sites showing the decreasing trend and are found below it at period 4.0 sec. For 100 bar stress drop mean estimated response spectra for the city follows the soft soil site curve of response spectra proposed by Indian Standard code IS: 1893-2002 while for 70, 125 & 175 bar stress drops it is below soft soil curve in the period range of 3.5 – 4.0 sec. For 150 bar, mean spectral acceleration curve is found above the hard rock curve of Indian code while it follows the hard rock curve in case of 200 bar stress drop for a period ranging from 3.0 – 4.0 sec. Maximum estimated value of mean spectral acceleration is 0.01 g, 0.03 g, 0.02 g, 0.07 g, 0.05 g and 0.04 g for 70, 100, 125, 150, 175 & 200 bars, respectively.

In addition to the above-detailed response spectra of the city, the average response spectra of all stress drops are also plotted and compared with response spectra proposed by IS: 1893 - 2002 (Fig. 8). The figure shows that average output is amplified almost 2 to 4 times for the entire range of period. At zero period (PGA), the value of mean spectral acceleration has estimated as 0.12 g, which is more than the recommended value of 0.1 g for the Allahabad city. Maximum mean spectral acceleration is found to be 0.14 g, 0.28 g, 0.22 g, 0.17 g, 0.13 g and 0.08 g for periods zero – 0.1 sec, 0.1 – 0.67 sec, 0.67 – 1.0 sec, 1.0 – 2.0 sec, 2.0 – 3.0 sec and 3.0 – 4.0 sec, respectively.

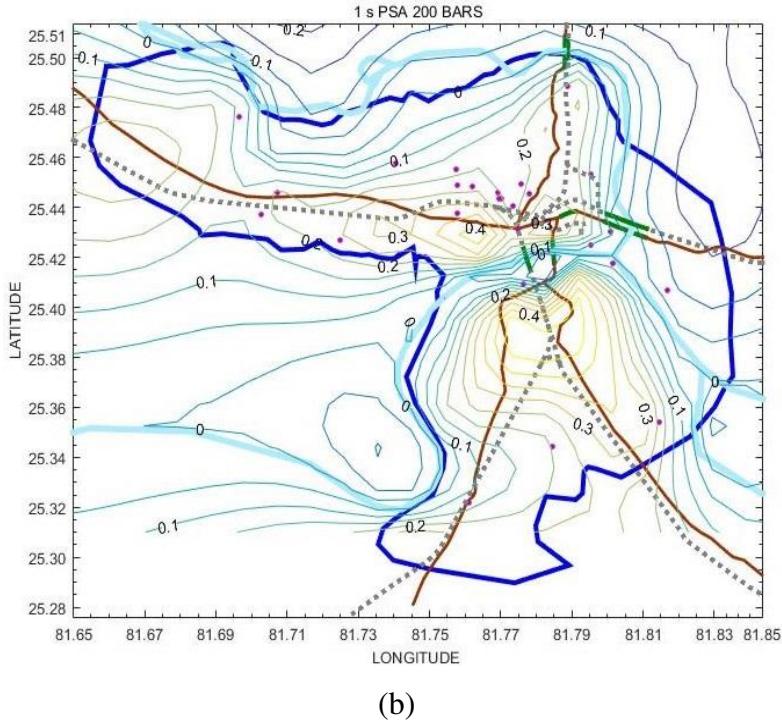


**Fig. 8** Comparison of Average Response spectra for Allahabad City with IS:1893

For period range (0.28 – 0.68 s) peaks are observed with maximum spectral acceleration value of 0.28 g and are above the proposed curve by Indian Standard. For period range (0.68 – 1.19 s), there is a downfall of peak and curves follows the path as of soft soil of Indian Standard. Further, for the entire time period, the estimated output curve is above as proposed by IS: 1893 - 2002. Further, the plot shows the outputs of average response spectra at 200 bar stress drop (which also gives critical spectral acceleration values) of all the sites. At zero period (PGA), the estimated value of mean spectral acceleration is found to be 0.17 g, which is 1.7 times the proposed value by Indian Standard response spectra. For the same stress drop, amplification w.r.t input response spectra was found to be 3.2, 2.6, 3.9, 4.0, 2.9, 2.3 at zero, 0.1 sec, 0.67 sec, 1.0 sec, 2.0 sec, 3.0 sec and 4.0 sec, respectively. Maximum and minimum mean spectral acceleration value of 0.56 g (at 0.53 sec) and 0.02 g (at 4.0 sec) are estimated for 200 bar stress drop.



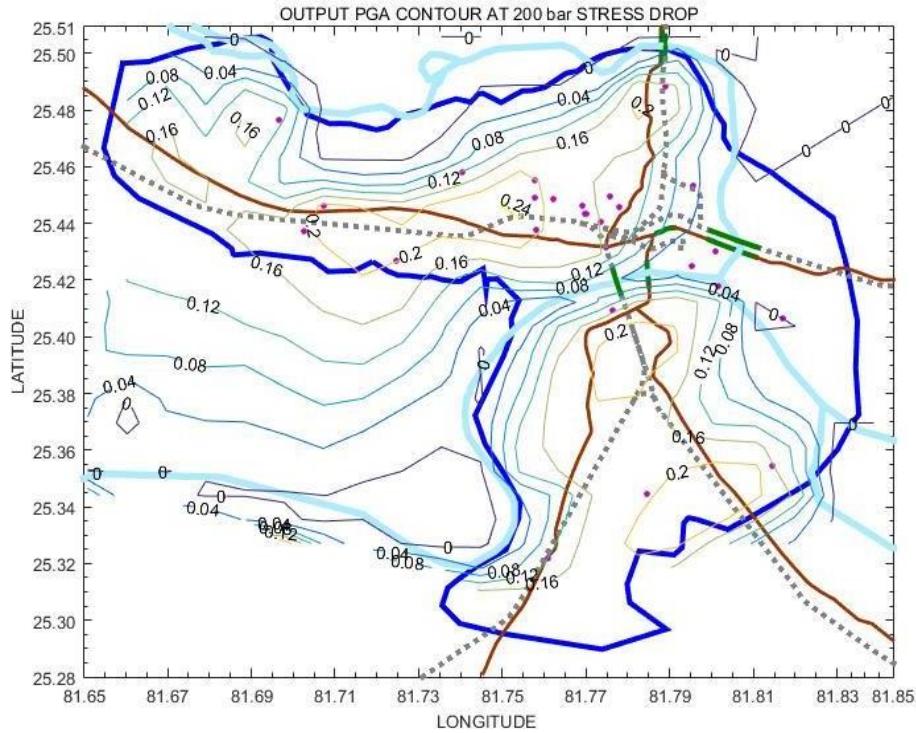
(a)



(b)

**Fig. 9** Surface level spectral acceleration at (a) 0.3 sec (b) 1 sec for 200 bar stress drop

Variation of ground motion throughout the city, contours have plotted as per periods recommended by IBC-2009 viz., PGA, 0.3 sec and 1.0 sec, which defines for a short period and long period durations of response spectra. Figures. 9 (a)-(b) shows the surface level spectral acceleration values at 5 % damping for 0.3 sec and 1.0 sec time periods. For shorter duration period (0.3 s) maximum PGA value of 0.57 g occurs at Government Press (Civil Lines) while minimum PGA value of 0.14 g was found at Kilaghat Figure. 9 (a). Figure. 9 (b), maximum PGA value of 0.35 g occurs at District court, while minimum PGA value of 0.12 g is at Kilaghat and Baluaghata. These contour maps show that the area like Civil Lines are more prone to seismic amplification, whereas Kilaghat and Baluaghata are earthquake amplification. The surface level PGA contour has been plotted only for 200 bar stress drop, which gives maximum PGA for all the sites (Fig. 10). Maximum and minimum estimated PGA value was found to be 0.24 g and 0.06 g, respectively.



**Fig. 10** Surface level output PGA at 200 bar stress drop

## 6.0 Conclusions

The study on the effect of stress drop on-site response analysis has been performed out for Allahabad city using six synthetic acceleration-time histories generated for Allahabad fault (~70km from Allahabad city). Thirty sites across the city are classified as per IBC-2009, out of which 12 are of *C* type, 15 are of *D* type, and 3 falls in *E* category. The response of Allahabad city for the simulated ground motion are presented in terms of response spectra, and its variation is shown in the form of contour plots (PGA contour maps low (0.3 s) and high (1.0 s) natural time periods).

For a short period, the maximum Spectral acceleration values observed for stress drop of 200 bar is 0.29g. It is observed that the civil lines area have significant amplification than the Kilaghat area. For period range (0.67-1.0 sec), mean spectral acceleration response at 100 bar is more than 125 bar whereas 150 bar response is more than 175 bar. Similarly, for the period range of 1.0 sec- 3.0 sec, mean spectral acceleration response at 175 bar is higher than 200 bar stress drop. Hence, it is not always that the higher stress drop produces significant amplification on the site; even the lower stress drop at long period can produce higher amplification. The site response analysis shows that almost all the sites in Allahabad are well above the recommended PGA values for Allahabad city.

Further, the civil lines area has 2.8 times higher amplification compared to the other parts of the city. The plotted response spectra may be used for designing structures in and around the Allahabad city. The contour plots may also give an idea for the selection of sites and re-designing/retrofitting of old structures.

**Declaration:**

Availability of data and materials: The Seismotectonic Atlas of India and its Environs is used to prepared fault map. Free data center (CESMD) strong motion data is used earthquake validation for Nepal earthquake. Simulation results can be available on request to author.

Competing interests: Not Applicable

Funding: Not Applicable

Authors' contributions: 1st Author performed data gathering and analysis, 2nd conceptualize and writing of the paper, 3rd Author provided his expertise in finalizing the article

Acknowledgements: Not applicable

## **References**

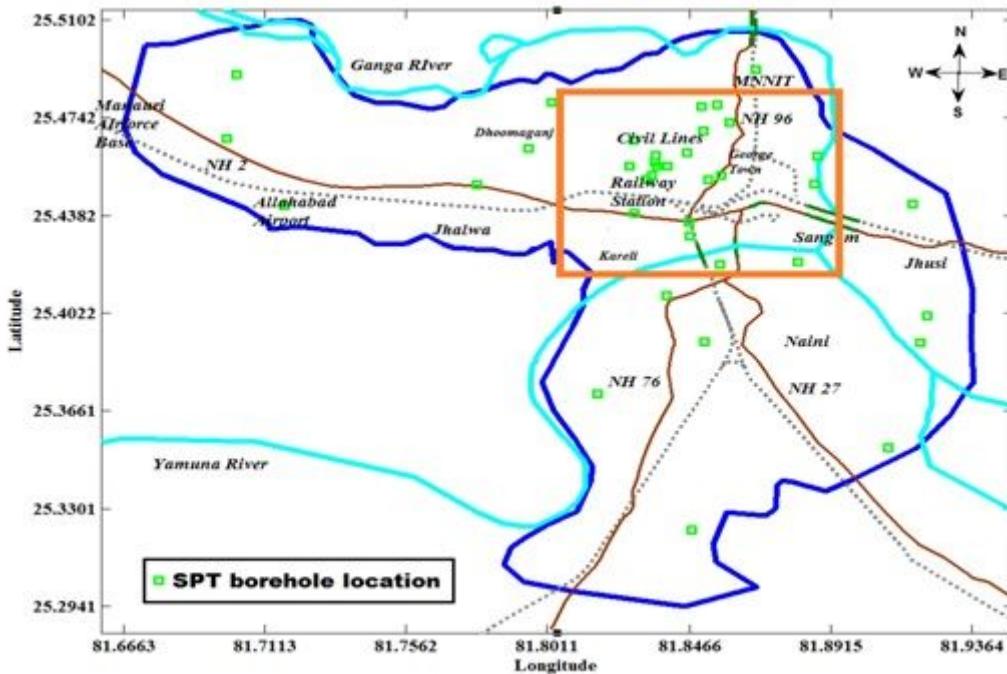
1. Acharyya, S. K. and Saha, P. (2018) 'Himalayan Paleogene Foreland Basin, its collision induced early volcanic history and failed rift initiation', *Journal of Asian Earth Sciences*. doi: 10.1016/j.jseaes.2018.04.031.
2. Alden, A. (2020) *Densities of Common Rocks and Minerals*. Available at: <https://www.thoughtco.com/densities-of-common-rocks-and-minerals-1439119>.
3. Anbazhagan, P. et al. (2017) 'Region-specific deterministic and probabilistic seismic hazard analysis of Kanpur city', *Journal of Earth System Science*. doi: 10.1007/s12040-016-0779-6.
4. Anbazhagan, P., Kumar, A. and Sitharam, T. G. (2013) 'Seismic Site Classification and Correlation between Standard Penetration Test N Value and Shear Wave Velocity for Lucknow City in Indo-Gangetic Basin', *Pure and Applied Geophysics*. doi: 10.1007/s00024-012-0525-1.
5. Anderson, J. G. and Hough, S. E. (1984) 'A model for the shape of the fourier amplitude spectrum of acceleration at high frequencies', *Bulletin of the Seismological Society of America*.
6. Avilés, J. and Pérez-Rocha, L. E. (1998) 'Site effects and soil-structure interaction in the Valley of Mexico', *Soil Dynamics and Earthquake Engineering*. doi: 10.1016/S0267-7261(97)00027-4.
7. Bagchi, S. and Raghukanth, S. T. G. (2017) 'Seismic Response of the Central Part of Indo-Gangetic Plain', *Journal of Earthquake Engineering*. doi: 10.1080/13632469.2017.1323044.
8. Boore, D. M. and Joyner, W. (1997) 'Site amplifications for generic rock sites', *Bulletin of the Seismological Society of America*, 87(2), pp. 327–341.
9. Boore, D. (1983) 'STOCHASTIC SIMULATION OF HIGH-FREQUENCY GROUND MOTIONS BASED ON SEISMOLOGICAL MODELS OF THE RADIATED SPECTRA', *Bulletin of Seismological Society of America*.
10. Boore, D. M. (2003) 'Simulation of ground motion using the stochastic method', *Pure and Applied Geophysics*. DOI: 10.1007/PL00012553.
11. Bradley, B. A. (2012) 'Strong ground motion characteristics observed in the 4 September 2010 Darfield, New Zealand earthquake', *Soil Dynamics and Earthquake Engineering*. DOI: 10.1016/j.soildyn.2012.06.004.
12. Census (2011) *Govt. of India*. Available at: <http://censusindia.gov.in/2011->

- Common/CensusData2011.html (Accessed: 25 August 2019).
13. CESMD (2015) *Center for Engineering Strong Motion Data*. Available at: <https://strongmotioncenter.org/>.
  14. Chandler, A. M., Lam, N. T. K. and Tsang, H. H. (2006) 'Near-surface attenuation modelling based on rock shear-wave velocity profile', *Soil Dynamics and Earthquake Engineering*. doi: 10.1016/j.soildyn.2006.02.010.
  15. Dasgupta, S. et al (2000) 'Seismotectonic Atlas of India and its Environs', *Geological Survey of India Special Publication*.
  16. DEWEY JF and BIRD JM (1970) 'MOUNTAIN BELTS AND THE NEW GLOBAL TECTONICS', *J Geophys Res.* doi: 10.1029/jb075i014p02625.
  17. Evernden, J. F. and Thomson, J. M. (1988) 'Predictive model for important ground motion parameters associated with large and great earthquakes.', *US Geological Survey Bulletin*.
  18. Housner, G. W. and Thiel, C. C. (1990) 'Competing against Time: Report of the Governor's Board of Inquiry on the 1989 Loma Prieta Earthquake', *Earthquake Spectra*. doi: 10.1193/1.1585592.
  19. Inst:, E. P. R. (1993) *Guidelines for determining design basis ground motions, rep., Palo Alto, CA, United States., 1993*. California. Available at: <http://www.ce.memphis.edu/7137/PDFs/EPRI 1993/TR-102293-V1.pdf>.
  20. *International Buiding Code* (2009). IL: INTERNATIONAL CODE COUNCIL, INC. Available at: [http://www.co.washington.ne.us/media/ICC-International\\_Building\\_Code\\_2009.pdf](http://www.co.washington.ne.us/media/ICC-International_Building_Code_2009.pdf).
  21. IS 1893 (2016) "Criteria for Earthquake resistant design of structures,Part 1:General Provisions and buildings", *Bureau of Indian Standards, New Delhi*.
  22. Kayal, J. R. (2008) *Microearthquake seismology and seismotectonics of South Asia, Microearthquake Seismology and Seismotectonics of South Asia*. doi: 10.1007/978-1-4020-8180-4.
  23. Khattri, K. N. et al. (1994) 'Seismic hazard estimation using modelling of earthquake strong ground motions: a brief analysis of 1991 Uttarkashi earthquake, Himalaya and prognostication for a great earthquake in the region', *Current Science*. doi: 10.1016/0148-9062(95)99036-w.
  24. Medvedev, J. (1962) 'Engineering Seismology', *Academic Nauk Press, Moscow*, p. 260.
  25. Mishra, D. and Uniyal, A. (2010) *UTTAR PRADESH STATE DISASTER MANAGEMENT PLAN FOR EARTHQUAKES*. Lucknow. Available at: [http://rahat.up.nic.in/sdmplan/Earthquake/Earthquake\\_Plan05March4pm.2010.pdf](http://rahat.up.nic.in/sdmplan/Earthquake/Earthquake_Plan05March4pm.2010.pdf).
  26. Mitra, S. et al. (2015) 'The 25 April 2015 Nepal earthquake and its aftershocks', *Current Science*.
  27. Mohanty, W. K. et al. (2009) 'Estimation of coda wave attenuation for the National Capital Region, Delhi, India using local earthquakes', *Pure and Applied Geophysics*. doi: 10.1007/s00024-009-0448-7.
  28. Motazedian, D. and Atkinson, G. M. (2005) 'Stochastic finite-fault modeling based on a dynamic corner frequency', *Bulletin of the Seismological Society of America*. doi: 10.1785/0120030207.
  29. Pandey, H. (2008) *GROUND WATER BROCHURE OF ALLAHABAD DISTRICT, U.P.* Allahabad, India. Available at: [http://cgwb.gov.in/District\\_Profile/UP/Allahabad.pdf](http://cgwb.gov.in/District_Profile/UP/Allahabad.pdf).
  30. Park, D. and Hashash, Y. M. A. (2005) 'Viscous damping formulation & high frequency motion propagation in non-linear site response analysis', *Proceedings of OCEANS 2005*

*MTSIEE*. doi: 10.1109/OCEANS.2005.1639939.

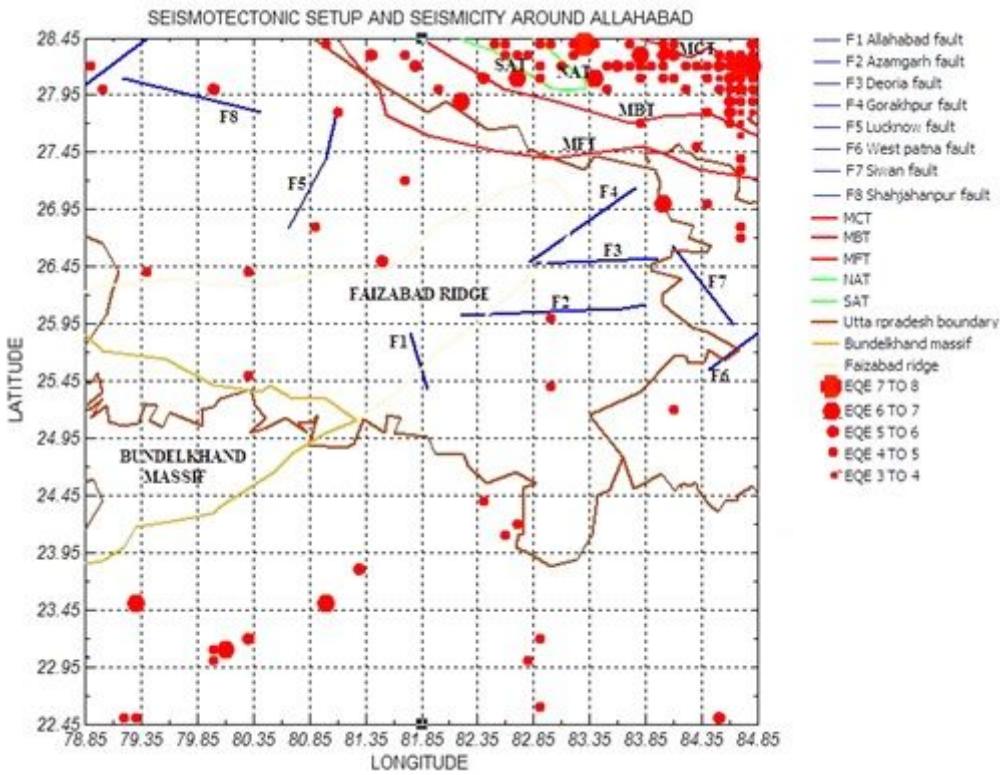
31. Picozzi, M. *et al.* (2009) 'Site characterization by seismic noise in Istanbul, Turkey', *Soil Dynamics and Earthquake Engineering*. doi: 10.1016/j.soildyn.2008.05.007.
32. Quittmeyer, R. C. and Jacob, K. H. (1979) 'Historical and modern seismicity of Pakistan, Afghanistan, northwestern India, and southeastern Iran.', *Bulletin of the Seismological Society of America*.
33. Segall, P., Bürgmann, R. and Matthews, M. (2000) 'Time-dependent triggered afterslip following the 1989 Loma Prieta earthquake', *Journal of Geophysical Research: Solid Earth*. doi: 10.1029/1999jb900352.
34. Shabestari, K. T. *et al.* (2004) 'Estimation of the spatial distribution of ground motion parameters for two recent earthquakes in Japan', *Tectonophysics*. doi: 10.1016/j.tecto.2004.03.031.
35. Singh, B. P. (2013) 'Evolution of the Paleogene succession of the western Himalayan foreland basin', *Geoscience Frontiers*. doi: 10.1016/j.gsf.2012.09.002.
36. Singh, C. (2015) 'Middle Ganga Plain; May be on the Verge of Seismic Shock', *Journal of Geological Society of India*, pp. 511–513. Available at: <http://www.geosocindia.org/index.php/jgsi/article/download/62933/49103>.
37. Singh, I. B. (1996) 'Geological Evolution of Ganga Plain - An Overview', *Journal of The Paleontological Society of India*.
38. Singh, S. K. *et al.* (1999) 'Crustal and upper mantle structure of Peninsular India and source parameters of the 21 May 1997, Jabalpur earthquake (Mw = 5.8): Results from a new regional broadband network', *Bulletin of the Seismological Society of America*.
39. Sinha, R; Tandon, SK; Gibling, MR; Bhattacharjee, PS; Dasgupta, A. (2005) 'Late Quaternary geology and alluvial stratigraphy of the Ganga basin', *Himalayan Geology*, (May), pp. 223–240.
40. Sitharam, T. G. and Govindaraju, L. (2004) 'Geotechnical aspects and ground response studies in Bhuj earthquake, India', *Geotechnical and Geological Engineering*. doi: 10.1023/B:GEGE.0000025045.90576.d3.
41. Stamati, O., Klimis, N. and Lazaridis, T. (2016) 'Evidence of complex site effects and soil non-linearity numerically estimated by 2D vs 1D seismic response analyses in the city of Xanthi', *Soil Dynamics and Earthquake Engineering*. doi: 10.1016/j.soildyn.2016.05.006.
42. Szulc, A. G. *et al.* (2006) 'Tectonic evolution of the Himalaya constrained by detrital 40Ar-39Ar, Sm-Nd and petrographic data from the Siwalik foreland basin succession, SW Nepal', *Basin Research*. doi: 10.1111/j.1365-2117.2006.00307.x.
43. Takai, N. *et al.* (2016) 'Strong ground motion in the Kathmandu Valley during the 2015 Gorkha, Nepal, earthquake 4. Seismology', *Earth, Planets and Space*. doi: 10.1186/s40623-016-0383-7.
44. USGS (2015) *M 7.8 - 36km E of Khudi, Nepal, USGS*. Available at: <https://earthquake.usgs.gov/earthquakes/eventpage/us20002926/executive>.
45. Valdiya, K. S. (1970) 'Simla Slates: The Precambrian flysch of the Lesser Himalaya, its turbidites, sedimentary structures and paleocurrents', *Bulletin of the Geological Society of America*. doi: 10.1130/0016-7606(1970)81[451:SSTPFO]2.0.CO;2.
46. Wells, D. L. and Coppersmith, K. J. (1994) 'New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement', *Bulletin - Seismological Society of America*.

# Figures



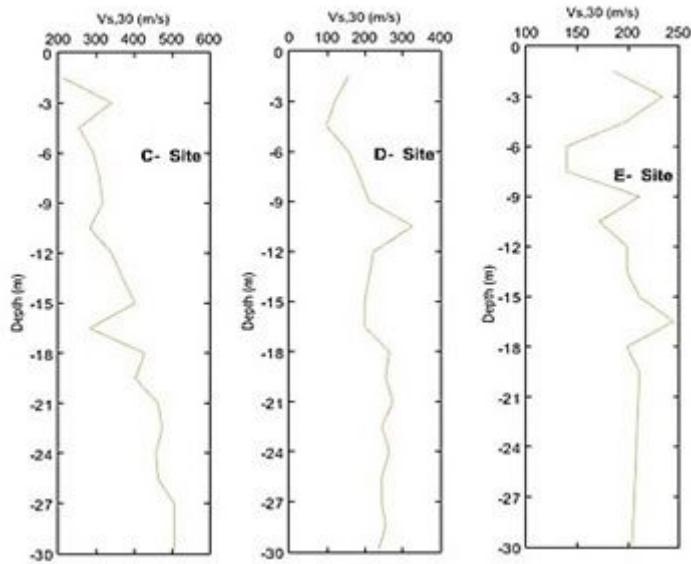
**Figure 1**

Borehole location of all the 30 sites (83 Boreholes) of Allahabad city, India



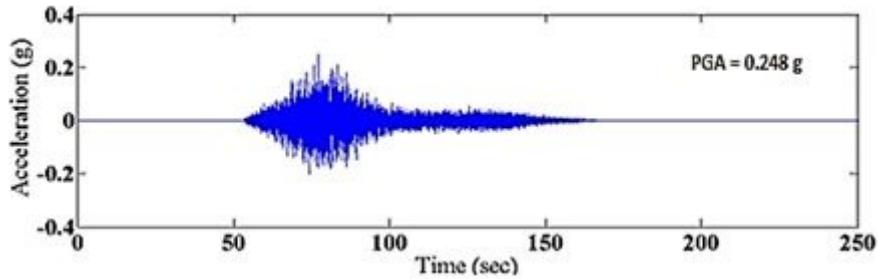
**Figure 2**

## Seismotectonic setup along with Seismicity around Allahabad, India



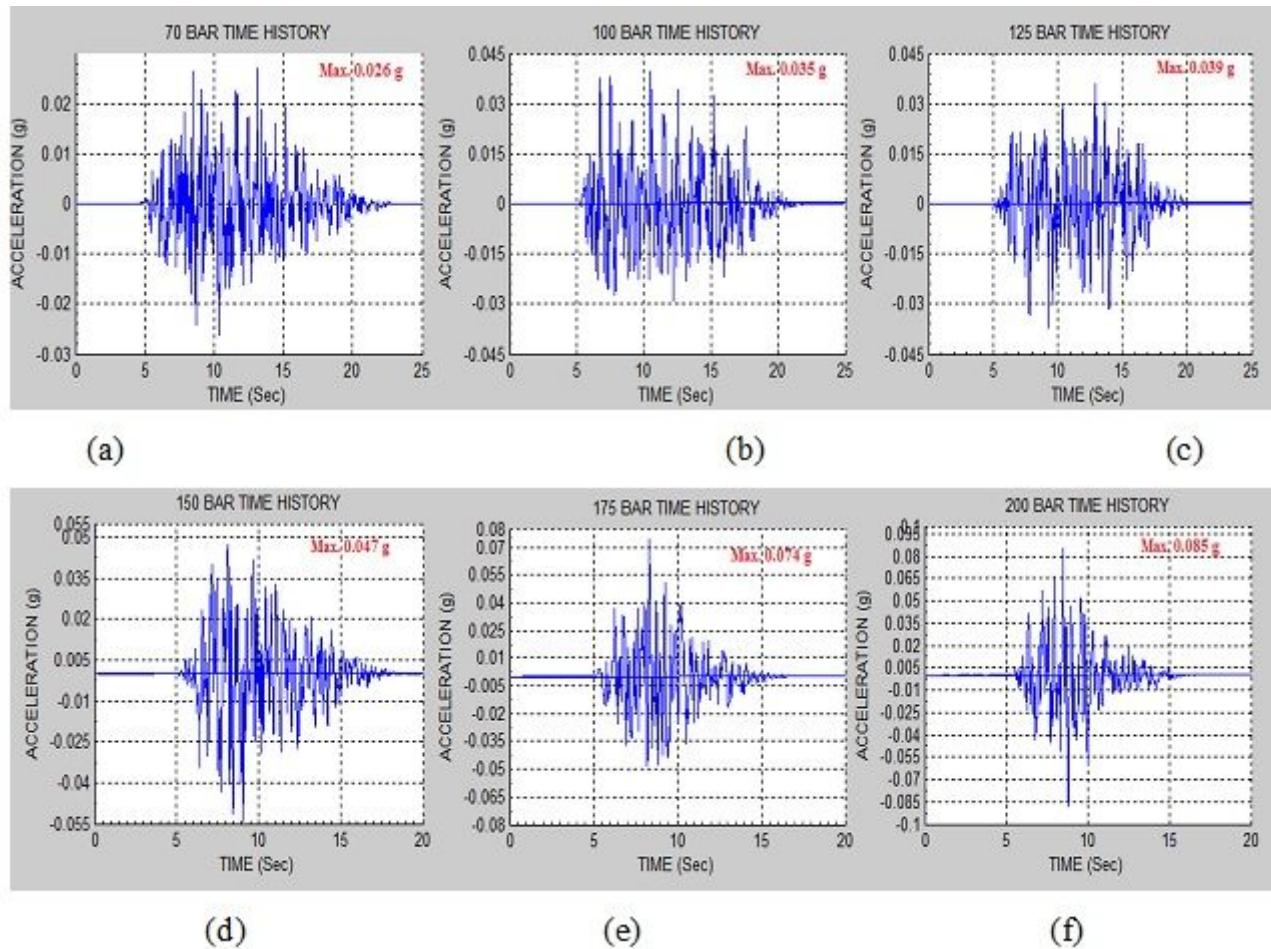
**Figure 3**

(a) Typical SPT-N values and (b) Shear wave velocity profile for C, D & E class sites



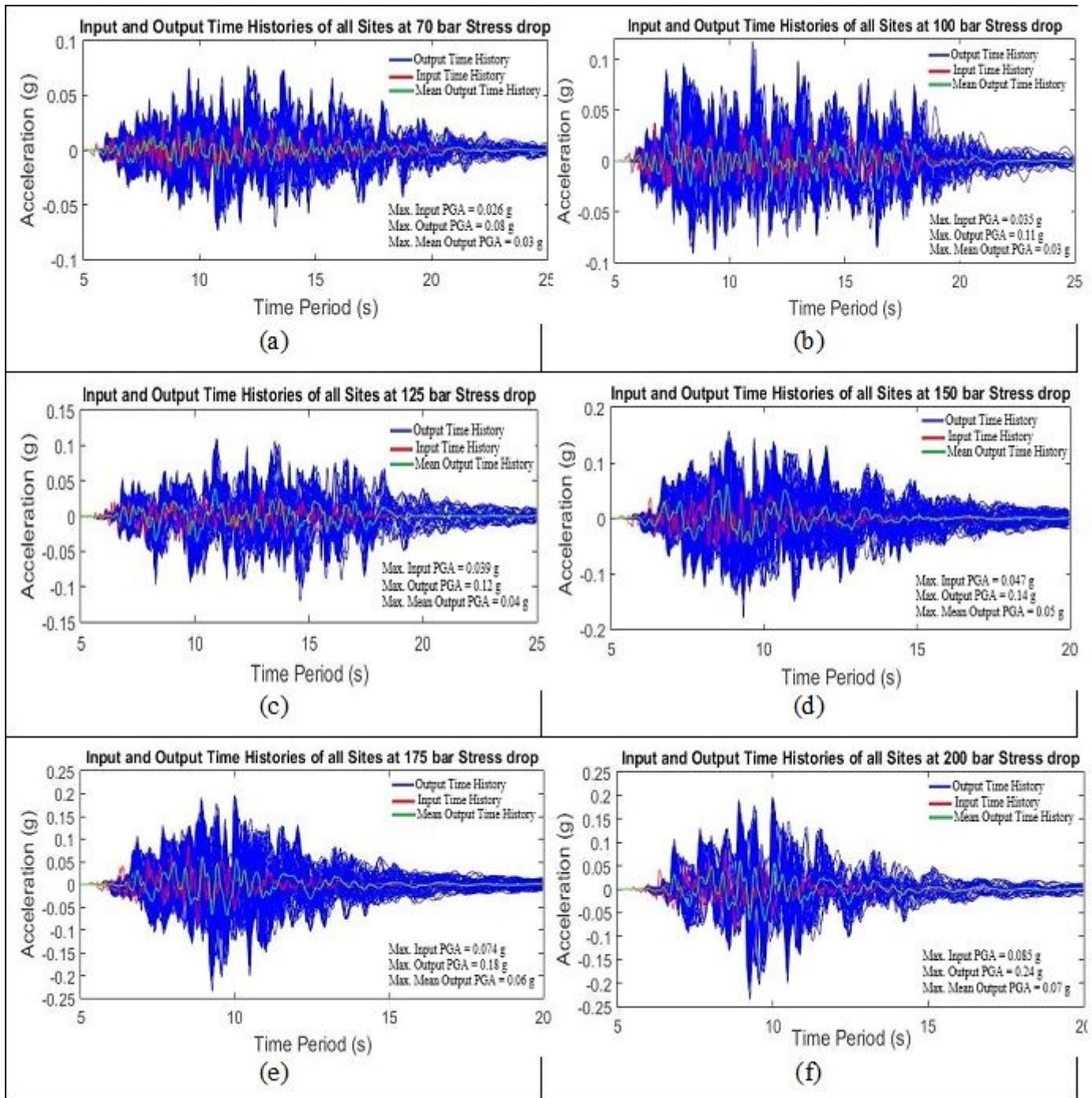
**Figure 4**

Validation of Simulated time history for at A type (hard rock) for Nepal earthquake



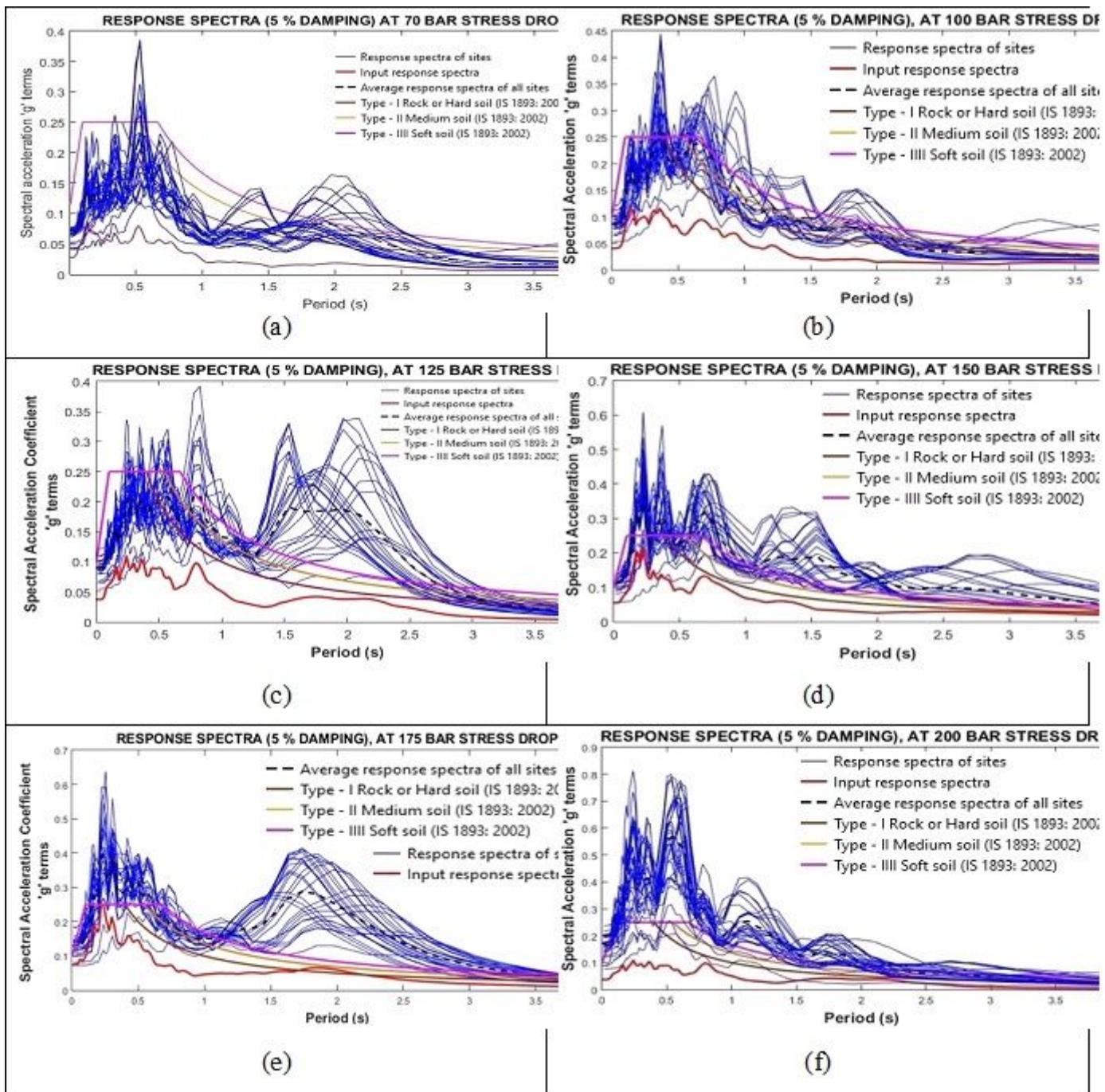
**Figure 5**

(a-f) Simulated ground motion due to Allahabad Fault at Allahabad city for stress drop range of 70 to 200 bar.



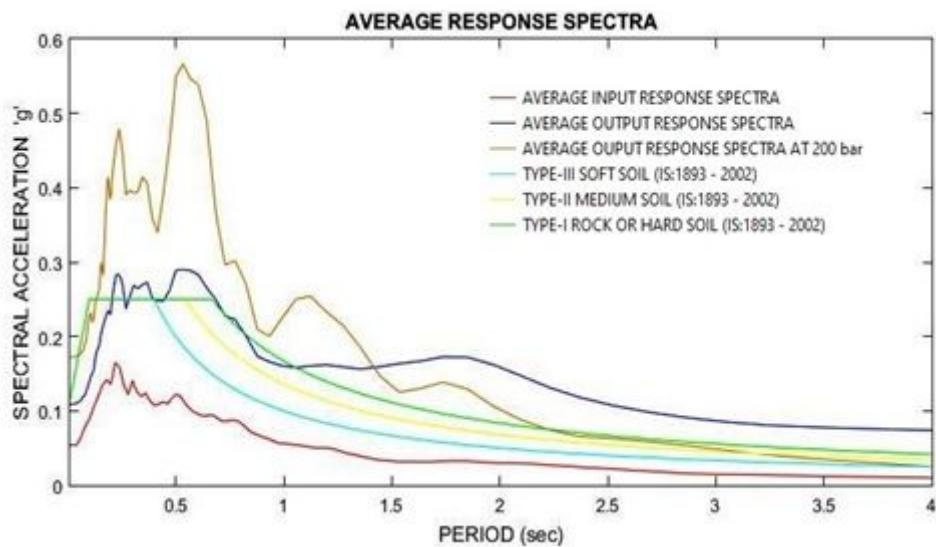
**Figure 6**

(a-f) Comparison of input & output acceleration-time history for different stress drops



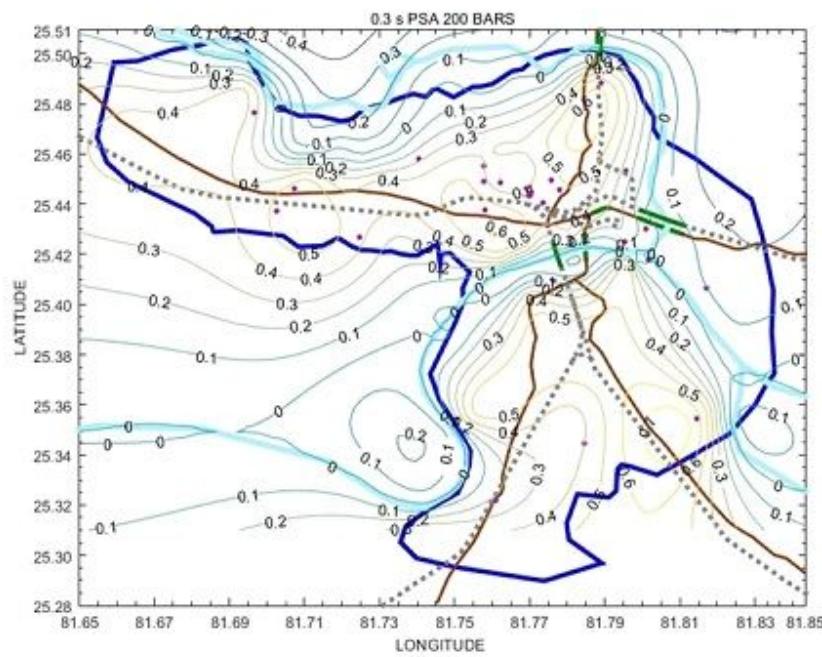
**Figure 7**

(a-f) Comparison between Response Spectra for all 30 sites with IS:1893

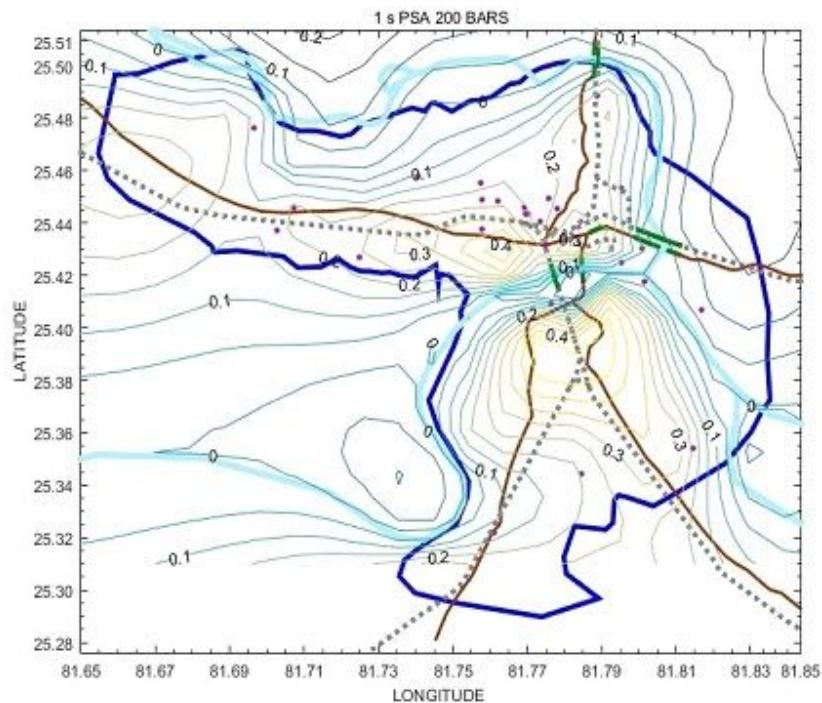


**Figure 8**

Comparison of Average Response spectra for Allahabad City with IS:1893



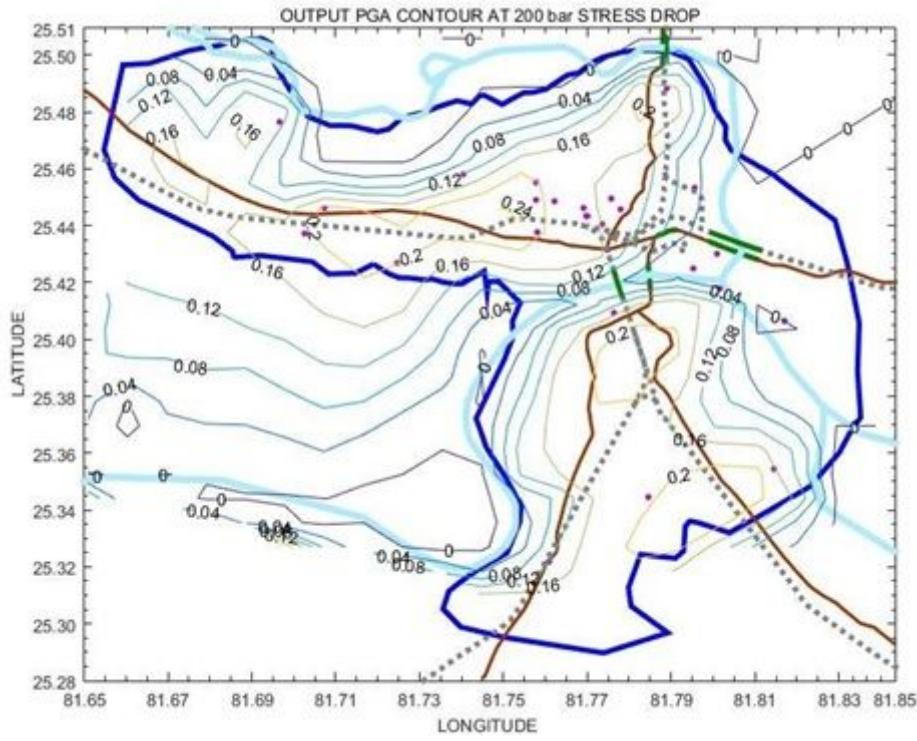
(a)



(b)

**Figure 9**

Surface level spectral acceleration at (a) 0.3 sec (b) 1 sec for 200 bar stress drop



**Figure 10**

Surface level output PGA at 200 bar stress drop