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Local Site Effect Due to Past Earthquakes in Kolkata

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ABSTRACT

Kolkata, capital of West Bengal, India, presently congested with moderate to high rise buildings, has undergone low to moderate damages due to past earthquakes. The city is situated on the world's largest delta island with soft thick alluvial soil layer. In this study, an attempt has been made to study ground response due to a number of past earthquakes, 1897 Shillong earthquake, 1964 Calcutta earthquake and 2011 Sikkim earthquake, for the purpose of preliminary microzonation of the Kolkata city. For this, synthetic ground motions have been generated at bedrock level by stochastic method. By using 1D wave propagation technique, the synthetic ground motion has been computed at surface level for 144 borehole locations in the city. Contours of PGA, PGV and PGD parameters in the city have been drawn for these three earthquakes. Response spectra for these three earthquakes have also been computed and an optimum response spectrum has been determined. A good correlation has been obtained with predicted ground motion at surface level of the city with the reported intensity and damages occurred in buildings of Kolkata during past earthquakes. The scenario of simulated ground motion for the past three earthquakes depicts that Kolkata city is very much prone to damages even due to moderate far and near source earthquakes.

INTRODUCTION

Kolkata megacity, the capital of West Bengal, India, is situated in Bengal basin at latitude 22º23'47" N and longitude 88º23'34" E, on the east bank of river Hooghly. The city has shaken during 1897 Shillong earthquake (M=8.7; epicentral distance 470 km), 1918 Srimangal earthquake (M=7.6, epicentral distance 350 km), 1934 Bihar-Nepal earthquake (M=8.3, epicentral distance 480 km), 1964 Calcutta earthquake (m_b=5.2; epicentral distance 106 km) (Oldham, 1899, Dunn et al., 1939, Jhingran et al., 1969, Seeber and Armbruster, 1981, G.S.I. (Geological Survey of India) 2000, Shiuly and Narayan 2012), 2011 Sikkim earthquake. This indicates that Kolkata, with high rise buildings, industrial establishment, congested business places, hospital, school and colleges may undergo severe damages during far and near source earthquakes and thus needs safety against earthquake hazards in the city. The threat may further increase due to presence of thick soft low velocity sediment layers and several satellite township developing on reclaimed land / filled up ground (Nandy, 2007) around Kolkata.

Large amplification was recorded over a 40 meter thick layer of soft lake soil deposits in Mexico city during 1985 Mexico earthquake (Seed et al. 1988; Reiter 1990, Zeevaert, 1991; Dobry et al. 2000). In the October 19, 1989 Loma Prieta earthquake (Kramer 1996; Kayen and Mitchell, 1997), PGA in the east bank of San Francisco lying on rock and stiff alluvium, was found to range from 0.09 g to 0.12 g, while amplification due to soft and deep cohesive soil deposits underlying artificial fills caused peak acceleration from 0.11 g to 0.29 g. During 1995 Kobe earthquake (Kawase and Aki, 1989) the PGA was in the range 0.3 g to 0.6 g at natural soil site but in the reclaimed land area it varies from 0.7 g to 0.8 g. In this case the ground motion amplified 1.5 to 2 times due to deep sedimentary layer. Further, damages occurred due to local site effects during many earthquakes, like, 1971 San Fernando earthquake (Boore, 1972), the 1983 Coalinga earthquake (Çelebi, 1991), 1985 Chille earthquake (Celebi, 1987) and 1987 Superstition earthquake (Çelebi 1991), 1994 Northridge earthquake (Davis, 2000), 2003 Bam Iran earthquake (Jafari et al., 2005) etc.

In India, local site effects on earthquake response was noticed during 2001 Bhuj earthquake (M_w=7.7) (Narayan et al., 2002, Govindaraju et al., 2004). A number of moderate to high rise buildings suffered extensive damages in Ahmedabad city, which is located 300 km away from the epicenter. The investigation revealed that the double resonance occurred due to the sub-soil of the city during the earthquake.

Site specific ground motion studies in different megacity of India were conducted by several researchers. Seismic microzonation of Delhi for ground-shaking site effects was carried out by Mukhopadhyay et al. (2002) by H/V ratio method. Seismic zonation of Delhi at bedrock level was computed probabilistically by Sharma et al. (2003). Raghukanth and Iyengar (2006) estimated the seismic hazard at Mumbai city using state of art probabilistic analysis and the seismotectonic details of the region. Design spectrum was developed by incorporating uncertainties in location, magnitude and recurrence of earthquakes. Influence of local site condition was accounted by providing design spectra for A, B, C and D type sites separately. The effect of local soil sites in modifying ground response were studied by Phanikanth et al. (2011) by conducting one dimensional equivalent linear ground response analysis for Mangalwadi site, Walkeswar site, BJ Marg near Pandhari Chawl site of Mumbai city. Using the 2001 Bhuj earthquake input motion The PGA amplification factors were obtained about 2.50, 2.60 and 3.45 respectively. Desai and Choudhury (2015) conducted site-specific probabilistic seismic hazard and one-dimensional equivalent linear ground response analysis of Jawaharlal Nehru port, Mumbai port, Bhabha Atomic Research Center and Tarapur Atomic Power Station in Mumbai city. Anbazhagan and Sitharam (2008) conducted seismic hazard analysis for Bangalore city using deterministic and probabilistic approach and also developed peak ground acceleration map and hazard curves. They developed 3-D sub-surface modeling of the geotechnical data using SPT test and borehole information. Measurement of shear wave velocity and evaluation of dynamic properties of soil in Bangalore was done using multi-channel analysis of surface wave (MASW). Site amplification was computed by both by MASW result and one dimensional wave propagation technique SHAKE 2000.

Probabilistic seismic hazard analysis at bedrock level of Kolkata city was carried out by Mohanty and Walling (2008b). Site specific modeling of SH and P-SV were carried out by Vaccari et al. (2011) using metro rail soil profile of the city. From their study high values of spectral amplification were obtained. Roy and Sahu (2012) conducted site specific seismic study using SMSIM and 1D wave propagation software, SHAKE 2000 and PGA were computed at surface level.

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Deterministic seismic hazard analysis was carried out by Shiuly and Narayan (2012) at bed rock level for Kolkata city and PGA obtained was 0.077g. The amplification due to soil was computed by 2D fourth order finite difference method at 44 locations in the City. Variations of PGA values at surface level were found to be in the range of 0.12g to 0.6g. Site Specific earthquake response study of the city was performed by Govindaraju and Bhattacharya (2012) using wavelet based method by software WAVEGEN. Site amplification was carried out for four type of soil using SHAKE2000. The Study revealed that amplification of ground motion in the range of 4.46 to 4.82, whereas maximum spectral acceleration in the range of 0.78g to 0.95g. Variation of shear wave velocity and soil site classification in Kolkata was performed by regression and sensitivity analysis by Chatterjee and Choudhury (2013). Ground motion amplification scenario in Kolkata megacity was carried out by Shiuly et al. (2014) using 4rth order finite difference algorithm. PSHA at surface level has been carried out by Shiuly et al. (2015). The study conducted by Chatterjee and Choudhury (2016) reveals that that the PGA at the ground surface may amplify by 4.1 times for 2001 Bhuj motion. Further, at Rajarhat area for 2001 Bhuj earthquake motion and 2011 Sikkim earthquake motion the Fourier amplification factor and spectral acceleration at 5 % damping was obtained as 10.15 and 3.84 g respectively. Site specific seismic hazard analysis of Kolkata has been conducted and response spectra have been determined by regression analysis by Shiuly et al. (2017).

In this study, an attempt has been made to evaluate response of Kolkata during three important past earthquakes- 1897 Shillong earthquake, 1964 Kolkata earthquake and 2011 Sikkim Earthquake, for the purpose of preliminary microzonation in the Kolkata city. During these three earthquakes Kolkata have undergone several damages. Synthetic time histories have been generated at surface level considering all soil layers of 144 borehole locations, considered in the present study, above engineering bedrock level. Using the synthetic ground motion contours of PGA, PGV and PGD have been drawn for the three earthquakes. A comparison of the predicted ground motion parameters has also been made with the reported damages in the area.

DESCRIPTION OF STUDY REGION

Geology, Seismotectonic and Geotechnical Settings of Bengal Basin

The formation of Bengal basin was started during breakup of Gondwanaland along the rifted margin of Indian plate. Finally at the time of Cretaceous Indian plates were detached from Gondwanaland and moved north words. Bengal basin was formed in two distinct phase– Gondwana phase and post-Gondwana phase. Non-marine sediment was deposited in north-south direction during Gondwana phase. Sedimentation of marine deposit was started at Cretaceous time, after spreading of Rajmahal lava. The marine deposit covered practically the whole of the basin up to its western margin. Finally during Tertiary period a thick sedimentary prism was deposited (Nandy, 2007; Mohanty and Walling, 2008a).

Basin Margin Fault Zone, Shelf Zone, Hinge Zone and Deep Basin Zone–these are the four structural zones identified in the Bengal basin. Basin margin fault zone is the western part of basin spreads northwest to southwest direction and separates the basin from western metamorphic complex of Precambrian age sediment. Shelf zone is 100 km wide and spreads north to south. The Tertiary sedimentary prism thickens towards east and merges with the deep shelf beyond the hinge. The Hinge zone situated from northeast to southwest direction from the east of Kolkata and separates the post Eocene sediments in the west. The seismic refraction data reveals the change in basement slope along this zone. The deep basin part hosts a thick prism of 10 to 15 km of sediments which was made up of post middle Miocene deltaic deposit (Mukhopadhyay and Dasgupta, 1988; Nandy 2007; Mohanty and Walling 2008a). The major fault systems around Kolkata are Eocene Hinge Zone (EHZ), Garhomoyana-Khandaghosh Fault (GKF), Jangipur-Gaibandha Fault (GGF), Pingla Fault, DebagramBogra Fault (DBF), Rajmahal Fault (RF) and Dhubri Fault (DF) (Fig. 1).

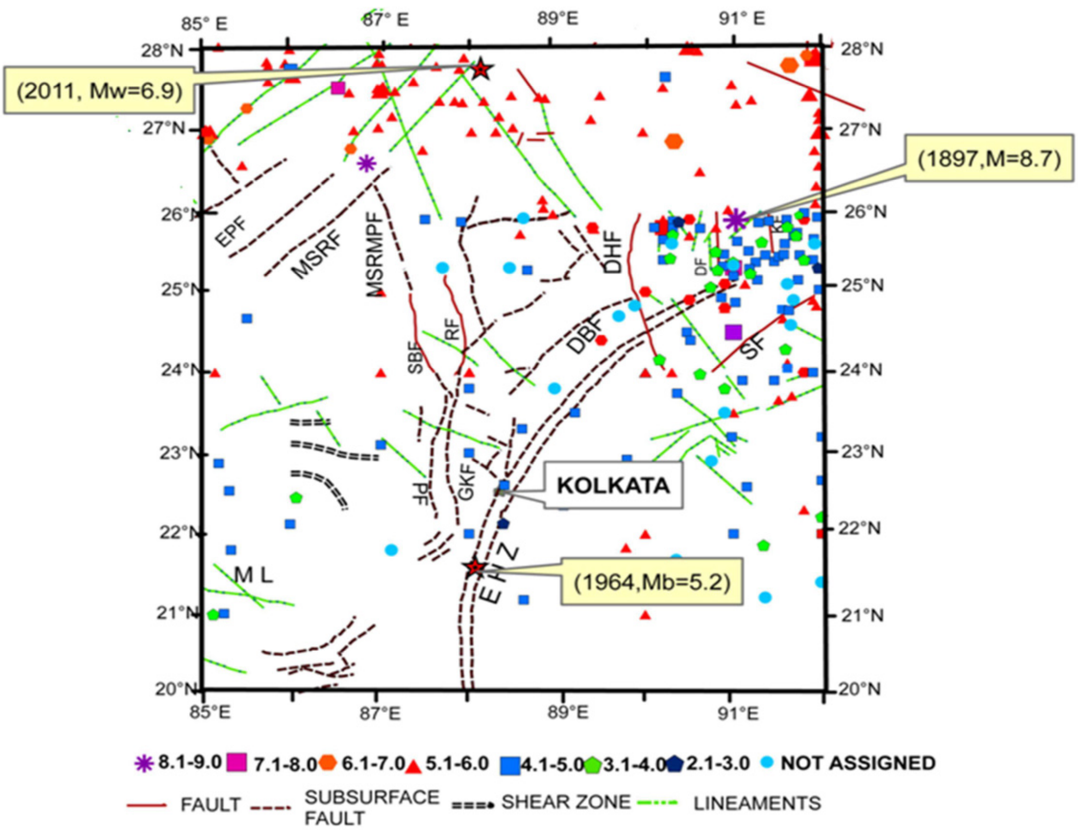

Fig.1. The seismotectonic of Kolkata city and surrounding region (After, GSI, IMD).

Kolkata city spread roughly north–south along the east bank of the Hooghly river. The elevation of the city is about 1.5 m (Banerjee and Sen, 1987). Much of the city was originally a wetland that was later reclaimed over the decades to accommodate a burgeoning population (Nandy, 2007). The top soil layer in Kolkata region consists of a fill layer whose thickness generally increases to a maximum value of 4m probably due to development of land over low-lying areas. Below this a thin layer of light brown silty clay layer exists with varying thickness and extends over all these sections. This is followed by a comparatively thick layer of weak blackish / dark grey silty clay/clayey silt with decayed wood of thickness 8 to10 m. The thickness and extent of the layer is also widely varying over different sections. This layer has a very low strength indicated by a very low SPT ‘N’ value in the range of 0 to 3. Below this layer stiff / very stiff bluish / brownish / mottled brown grey silty clay / clayey silt exists with typical variation in their thickness and extent. This is followed by a layer of brown laminated silt with fine sand and dense brown silty fine sand down to considerable depth below ground level (Som 1999). This deposit, in general, is termed as normal Kolkata deposit and covers most of the region. Besides this, there exists river channel deposit along the sides of Adi Ganga channel consisting of mainly thick silty sand down to considerable depth below ground level.

Seismic History of Kolkata

Recorded document for the last 300 years indicates that Kolkata had undergone damages due to several far and near source earthquakes. Two earthquakes 11th October 1737 and 2nd April, 1762 were reported in past. As per the earthquake catalogue of India (Oldham, 1883). Kolkata was shaken by about 30 earthquakes during period 1803 to 1869. Some of the strong earthquake that caused damages to Kolkata were 1st September, 1803 (Mathura/ Nepal); 26th August, 1833 (Nepal); 23rd March, 1839 (Burma); 11th November, 1842 (Bengal-Assam); 10th January, 1869 (Cachar, Assam). Kolkata was shaken by 31st December 1881 Nicober earthquake which generated tsunami in Andaman Island. Considerable damage including partial collapse of a number of buildings was reported in Kolkata due to 12th June, 1897 Shillong earthquake (Oldham, 1899). The intensity was 3 in Oldham scale which is equivalent to VII in MSK scale and VIII-IX in MCS scale (Panza et al. 1997, Panza et al. 1999). Kolkata suffered damages with development of serious cracks in buildings during 29th September 1906 Calcutta earthquake (Middlemiss, 1908). The intensity was reported VI-VII in Rossiforel scale which is equivalent to V-VI in MSK scale (Panza et al., 1997; Panza et al., 1999). On 8th July 1918 Srimangal earthquake was felt in Kolkata whose epicenter was 350 km N55E from the city (Stuart 1926). The shaking was 6 in Oldham scale which is equivalent to IV-V as per MSK scale. Kolkata city was also shaken due to 3rd July, 1930 Dubhri earthquake which epicenter was located 360 km towards N20°E from Kolkata. The intensity was reported 5 in Oldham scale which is equivalent to IV-V of MSK scale. On 15th January, 1934 at about 2:40 PM a strong shaking was felt due to Bihar-Nepal earthquake which was located 480 km N20°W of Kolkata city. The earthquake was felt about 5 minutes with considerable damages and movement in lake water (Dunn et al. 1939). Intensity was VII in MM scale which is equivalent to VI-VII in MSK scale in the city. Kolkata was shaken due to near source earthquake with high frequency seismic wave accompanied by sound. During 15th April, 1964 Calcutta earthquake located 106 km south of the city near Sagar Island caused damage with the development of serious cracks and fall of plaster in many old and new buildings. The intensity was assigned VI in MM scale which is equivalent to VI-VII in MSK scale. Recently Kolkata was shaken by 2004 Indonesia earthquake, 18th September 2011 Sikkim earthquake, 9th January 2013 Myanmar earthquake, 11th April 2012 northern Sumatra earthquake (http://www.iiserkol.ac.in/~supriyomitra/), 2015 Nepal earthquake and 2016 Manipur earthquake (*http://www.ndtv.com*). Figure 1 shows the seismotectonic map of Kolkata city and surrounding region.

METHODOLOGY

Geotechnical Data Processing

The Bengal basin was formed by the sedimentation of Ganga-

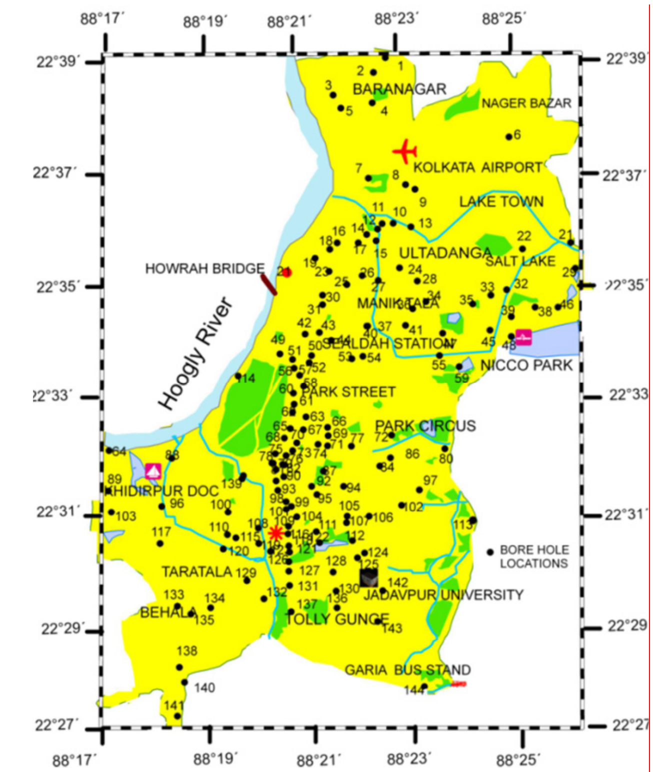

Fig. 2. Map showing important features, places and BH locations in Kolkata city.

Table 1 Sample N value correction at BH 130 and conversion of V_s from corrected N value.

Thickness (m)	From Top	Field N value	Density kN/m^3	Vs m/s
3	3	2	19.3	101.5
7	10	2	17	101.5
6	16	8	19.9	171.2
10	26	31	19.7	285.1
5	31	14	20	211.3
8	39	22	19.8	250.6
3.4	42.4	50	19.7	341.4
4	46.4	29	20.1	278.1
4	50.4	69	2.03	385.4
	>100	2.10	>443.02	

Brahmaputra-Barak River and its tributaries. Kolkata is situated east side of Hooghly river, a branch of Ganga river. 144 well scattered borehole (BH) data obtained from unpublished report of C. E. Testing India Pvt. Ltd., S Ghosh and Associates, ITD Cementation and Jadavpur University Databank Project were used in the present study. Fig. 2 shows important features, places and borehole (BH) locations in Kolkata city. Typical soil profile of BH 130 along with soil properties at different depths are shown in Fig. 3. The uncorrected N values have been used for obtaining the shear wave velocity (V_S) in different soil layers using the relationships proposed by Chatterjee & Choudhury (2013):

$$V_S = 78.21\, N^{0.37669} \qquad \text{(All Soils)} \qquad (1)$$

Table 1 shows the N value corrections and predicted from corrected N values upto about 50 m for BH 130. Below this field 'N' value is >100. The engineering bedrock in the present study was considered to be at a depth of 50m from the ground surface where N value is greater than 100.

Stochastic Synthesis of Ground Motion at Site

The deterministic point source spectrum at a site $\gamma(M, R, f)$ takes into consideration of point source spectrum $\phi\ (M, f)$, path effects $\Gamma\ (R, f)$ consisting of both the geometrical spreading and damping and site effects $\psi\ (f)$ (Boore 2003).

$$\gamma(M, R, f) = \phi\ (M, f)\ \Gamma\ (R, f)\ \psi\ (f) \qquad (5)$$

Where R is the distance from source to site and M is the moment release in dyne-cm.The details of point source spectrum calculation like corner frequency, radiation pattern, partition of S wave energy, free surface effect etc as given in Boore (2003) model has been used for computation of displacement source spectrum (Brune, 1971). Raghukanth and Somala (2009) computed the stress drop for Bengal Basin as 156 to 258 bars. In the present study a stress drop of 250 bars has been considered. Path effect has been computed as stated by (Singh et al. 1999). The frequency dependent quality factor Q(f) has been computed using function $Q(f) = 224*f^{0.93}$, where f is the frequency in Hz (Raghukanth and Somala, 2009; Nath, 2004). In order to obtain ground motion at engineering bed rock level SMSIM-2013 program has been used (Boore, 2013) considering above mentioned source and path effect. This program is also capable to restrict high frequency component using a filter based diminution parameter, which is function of magnitude. The soil effect has been computed by using 1D seismic wave propagation software SHAKE2000 for all 144 borehole (BH) locations considering all soil layers. The seismic motion computed by above mention procedure at engineering bedrock level, has been used as input in this software and seismic motion at surface level has been obtained considering effect of all soil layers. Figure 4 shows the amplification of borehole BH 130.

RESULTS AND DISCUSSION

In this section, the computed variations of PGA, PGV and PGD for the three earthquakes are presented in the form of contours. Figures 5 - 7 depicts the synthetic time histories of 1897 Shillong Plateau earthquake, 1964 Calcutta earthquake and 2011 Sikkim earthquake respectively. An attempt has also been made to correlate computed ground response corresponding to 1897 Shillong Plateau earthquake

Depth	Strata	Soil Description	G/Gmax curve	Damping curve
3.2m		Fill with blackish/deep grey, claye silt. (N=5, D=1.98)	Clay Pl=10-C2 G/Gmax-C2 (CLAY Pl=10-20, Sun et al. 198)	Soil Pl=15, Damping- Soil with Pl=15 ,OCR 1-8 (Vucetic and Dobry, JGE 1/91)
6.0m		Soft to stiff, brownish /deep grey, claye silt. (N=11, D=1.57)	Clay Pl=20-C2 G/Gmax-C2 (CLAY Pl=20-40, Sun et al. 198)	Soil Pl=30, Damping- Soil with Pl=30 ,OCR 1-8 (Vucetic and Dobry, JGE 1/91)
16.8m		Very soft to soft deep grey silty clay/ claye silt, observed decomposed wood and organic matter (N=3, D=1.8)	Clay Pl=40-80-C4 G/Gmax-C2 (CLAY Pl=10-20, Sun et al. 198)	Soil Pl=50, Damping- Soil with Pl=50,OCR 1-8 (Vucetic and Dobry, JGE 1/91)
21m		Very stiff to stiff, steel brownish grey, silty clay /claye silt.(N=12, D=1.81)	Clay Pl=10-C2 G/Gmax-C2 (CLAY Pl=10-20, Sun et al. 198)	Soil Pl=15, Damping- Soil with Pl=15 ,OCR 1-8 (Vucetic and Dobry, JGE 1/91)
32.9m		Moderately dense to very dense yellowish/ brownish grey silty fine sand (N=52, D=1.81)	Sand Avg. G/Gmax-SAND, Average (Seed and Idriss 1970)	Sand Damping for SAND, February 1971
37m		Very stiff to hard, brownish/ steel grey silty clay. (N=30, D=2.06)	Clay Pl=10-C2 G/Gmax-C2 (CLAY Pl=10-20, Sun et al. 198)	Soil Pl=15, Damping- Soil with Pl=15 ,OCR 1-8 (Vucetic and Dobry, JGE 1/91)
50.0m		Very stiff to hard brownish grey claye silt/silty clay (N=50, D=2.03)	Clay Pl=10-C2 G/Gmax-C2 (CLAY Pl=10-20, Sun et al. 198)	Soil Pl=15, Damping- Soil with Pl=15 ,OCR 1-8 (Vucetic and Dobry, JGE 1/91)

Fig.3. Variation of 'N' value and density of various layers of BH 130.

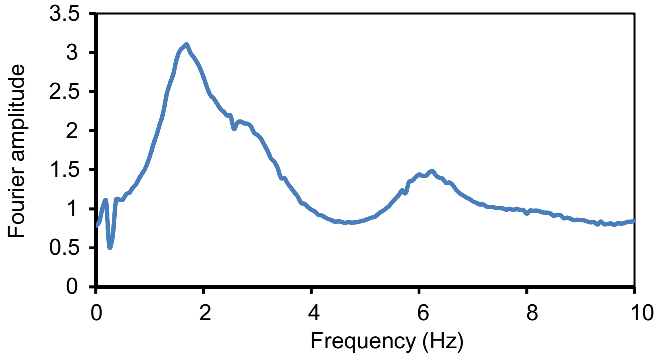

Fig. 4. The amplification due to soil of BH 130.

(M = 8.7; epicentral distance 464 km), 1964 Calcutta earthquake (Mw = 5.4; epicentral distance 106 km) and 2011 Sikkim earthquake (Mw = 6.9, epicentral distance 570 km) with the reported damages (intensity) during these earthquakes at different sites.

1897 Shillong Earthquake

There are some descriptions of damage in Kolkata city during Shillong earthquake of 1897 as reported by Mr. H. H. Hoyder, Assistant Superintend, Geological Survey of India (Oldham, 1899). According to him monuments in Park Street area, old cemetery was thrown down or probably broken. On Circular road, some of the buildings were badly damaged. The porch adjacent to Baptist Chapel which was not connected to main structure was broken. Mr. H. H. Hoyder reported violent vibration of houses and cracks of the order of 4 inches size on theatre road. On the theatre road, parapets of some buildings fell down. In Badeapara lane, Bhawanipur, two storey building tilted about 5° towards the north, may be due to the liquefaction effect. On Chowranghee road, western parapet and the verandah of some buildings fell down.

The damage survey report of Mr. G. E. Grimes, assistant superintendent of GSI, Calcutta Eastern Bengal, Cachar is also documented (Oldham, 1899). Mr. G. E. Grimes reported that in Park Street and Bowbazar area, there was no sign of damage to cutcha houses but a large number of pucca houses undergone damage. According to Mr. G. E. Grimes, buildings of St. Thomas Church and Boy's Free School developed large cracks. Collapse of some portion of Free Church of Scotland and St. James Church situated at Wellesly street and lower Circular road was reported. At Messers Trail & Co's business Premises, situated back of Great eastern hotel, the front portion of balcony completely destroyed and parapet wall fell down.

From the analysis, large PGA in the order of 0.053g to 0.06g is obtained in Salt lake and Khidirpur areas. This may be due to very large amplification in low frequency range and removal of most of the energy of high frequency seismic motion due to earth filtering because of very large epicentral distance (476 km) of 1897 Shillong earthquake from Kolkata city. At that time there was no high-rise building in this

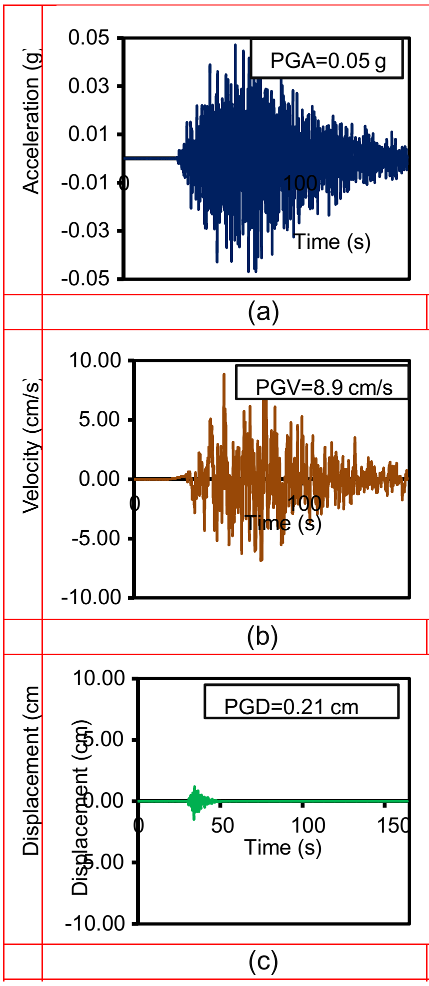

Fig. 5. a, b, c. The probable acceleration time history, velocity time history and displacement time history at surface level of BH 130 respectively of 1897 Shillong earthquake.

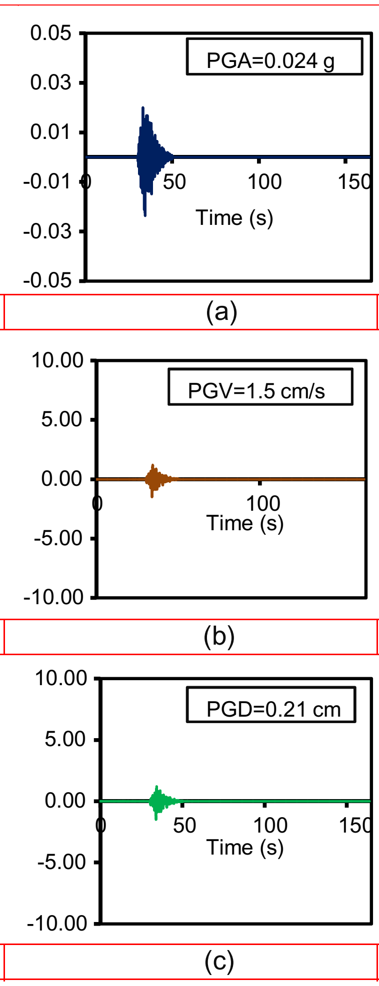

Fig.6. a, b, c. The probable acceleration time history, velocity time history and displacement time history at surface level of BH 130 respectively of 1964 Calcutta earthquake.

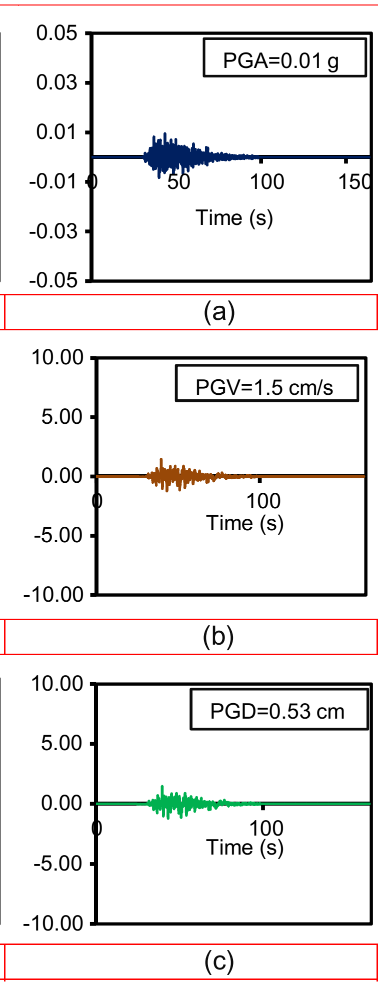

Fig.7 a, b, c. Probable acceleration time history, velocity time history and displacement time history at surface level of BH 130 due to 2011 Sikkim earthquake.

area, so no damage description was available regarding low frequency effect or double resonance. But low frequency effect to some extent was reported in Chowringhee road area during Shillong earthquake. Two storied buildings were badly damaged but almost there was no sign of damage in single storied and low height mud houses. Fig. 8 – 10 and Table 1 show the computed PGA, PGV and PGD for this earthquake. On an average PGA varies from 0.038g to 0.06g while PGV varies from 6.3cm/sec to 10.8cm/sec. High PGV, varying from 9.8cm/s to 10.8cm/s has been obtained at BH 103(Garden reach area) and BH 55 (Beleghataarea). In north Baranagar and DumDum area PGD has been found to vary 5.3 cm to 6.8 cm, while in Ultadanga and Maniktala area, larger values of PGD ranging from 9 cm to 12 cm has been estimated. This may be due to the thicker soft clay layer in Ultadanga and Maniktala area compared to that at Baranagar and DumDum area. Further, low frequency effect of earthquake dominated as the high frequency wave attenuated with distance due to filtering effect of earth. The PGA and PGD predicted in Park Street area (BH 77) were 0.053g and 7.07cm respectively which was quite sufficient to cause damages and generate cracks in masonry buildings (Oldham 1899).

According to Oldham scale the intensity in Kolkata was III which is equivalent to VIII in MM scale and VIII-IX in MCS scale and the corresponding ranges of PGA, PGV and PGD for same intensities were 0.05g to 0.20g, 5 cm/s to 130 cm/s and 3 cm to 13 cm respectively (Panza et al. 1997, Panza et al. 1999). The reported damage patterns in different localities were within 5km of Park Street area (BH 77). This indicates there is a good correlation of predicted PGA, PGV and PGD in Kolkata City and reported damage description and intensity.

1964 Calcutta Earthquake

The nearest earthquake for which damage pattern is documented was 15April, 1964, Calcutta earthquake. The magnitude of the earthquake was 5.2 (m_b) and epicentral distance was 106 km south of Kolkata near Sagar Island (Jhingran et al. 1969). This earthquake magnitude (m_b) may be converted to moment magnitude according to the formula of Das (2008).

Jhingran et al. (1969) reported that Kolkata and nearby areas experienced a mild shock at 10.05 PM (IST) immediately followed by a severe second shock of about 40 seconds duration on 15th April, 1964. Almost all the people within Kolkata area heard sounds like distant thunder preceding the earthquake shock. Many persons felt that the direction of the movement of ground was in N-S direction. Several cracks were developed of varying types and dimensions in many buildings. A 27 m long, 10 cm wide and 2.5 cm deep E-W crack was observed on the northern part of the ceiling over the Rock Gallery of the Indian Museum at 27, J.N. Road, which was constructed in the year 1875. In the same floor, angular cracks were observed, just starting from the arch above the doors, and extending up to ceiling on both sides. A newly constructed multi-storied building at 24B, Park Street, developed cracks trending N20E-S20W and E-W. Both sets of cracks are straight and were developed along the corners in the 4rth floor. Such cracks are seen on the walls of all the rooms on that floor. A prominent crack about three meters from the top was developed in the spire of St. Andrew's Church in Dalhousie square. One 200 year old 2-storeyed building in a poor state of maintenance situated at 19, Synagogue street in the China bazaar area, was badly damaged. Several prominent cracks were developed in the Calcutta blind school building, Behala area. In New Alipur some people felt NE-SW shocks and heard sounds of heavy thundering underground. Several other parts of Calcutta were examined but nowhere serious damage to any particular area or building could be seen.

Figures 11- 13 and Table 2 show the predicted PGA, PGV and PGD in Kolkata city. In most of the locations the predicted PGA varied from 0.015 g to 0.034 g. High PGA in order of 0.034 g to 0.04 g was obtained beside Ganga river (BH 19 and BH 21). PGV varied 0.83 cm/s to 1.32 cm/s in the city. PGD varied in most of the locations 1.37 cm to 1.57 cm. Low value PGD in order of 1.07 cm to 1.37 cm was obtained in north Baranagar, Dum Dum and along Tollynala area in South.

The epicenter of earthquake is only 106 km away. So both high and low frequency content wave were present during earthquake. Recorded damaged patterns also indicate that damage occurred in low as well as high rise buildings.

According to MM scale the intensity was VI which is equivalent to VII in MCS scale. The ranges of PGA, PGV and PGD for same intensities are 0 .025 g to 0.05 g, 2 cm/s to 5 cm/s and 1.5 cm to 3 cm respectively (Panza et al., 1997; Panza et al., 1999). The present simulation also nearly agrees with the damage pattern and intensity.

2011 Sikkim Earthquake

A magnitude earthquake epicenter 572 km northeast of Kolkata city struck 6.11 pm on 18th September 2011. In Kolkata, the tremors that lasted nearly a minute were felt most strongly.

Figures 14- 16 and Table 2 show the predicted variation of PGA, PGV and PGD in the study area. PGA has been estimated in same locations as 1897 Shillong earthquake in Saltlake area, Khidirpore area and were found to be in order of 0.0097 to 0.0106g. In most of the locations PGA varied from 0.0083 to 0.0097g. Comparatively lesser PGA was obtained beside Tolynala area (BH 100, BH 132, BH 137, BH 139) RabindraSarobor (BH 16, BH 22) and in north (BH 8, BH 9). The PGV varied from 0.087 cm/s to 1.43 cm/s. In most of the locations PGD varies 0.06 cm to 0.07cm.In northof the study region PGD obtained wasfrom 0.45 cm to 0.6 cm, while in Maniktala, Ultadanga and some part of Saltlake area it was found to range from 0.7 cm to 0.93 cm.

Due to large epicentral distances (567 km) low frequency effect was found to be predominant and as a result shaking of high rise building was observed during earthquake. Even 0.77 cm PGD was found to cause damage in Ultadanga police quarter (Near BH 130) (10 storied building).

Comparatively high values of PGD have been obtained due to filtering of earthquake of high frequency seismic wave because of large epicentral distances (567 km). Due to low frequency effect shaking of high rise building was observed during earthquake. Due to high PGD values (0.77 cm), Ultadanga police quarter (Near BH 130) (10 storied building) was badly affected.

According to USGS instrumental intensity during Sikkim earthquake was II-III. For this intensity PGA and PGV may be 0.0017g to 0.014g and 0.1 to 1.1cm/s respectively. In this study the predicted PGA and PGV also lies in the range.

1897 Shillong earthquake and 2011 Sikkim earthquake were far source earthquake. So high frequency content of wave will be filtered by earth during travelling a long path. Only low frequency wave will be present. The Fig. 18 clearly depicts the same phenomenon and for these two earthquakes spectral acceleration at higher time period is more than that for 1964 Calcutta earthquake. For this reason during 2011 Sikkim earthquake high rise buildings were shaken tremendously. Several cracks were observed in 10 storied Ultadanga police quarter. The cracks are shown in Fig. 19. The high response spectral acceleration of 1897 earthquake depicts that if such earthquake occurs there will be much more damages in high rise buildings.

LIMITATION OF THE PRESENT STUDY

The present study has been conducted by generating synthetic ground motion using the SMSIM model developed by Boore (2013). However, the present result must be verified with the original earthquake record, recorded in the Kolkata city. Moreover, present ground response analysis has been performed using the borehole data.

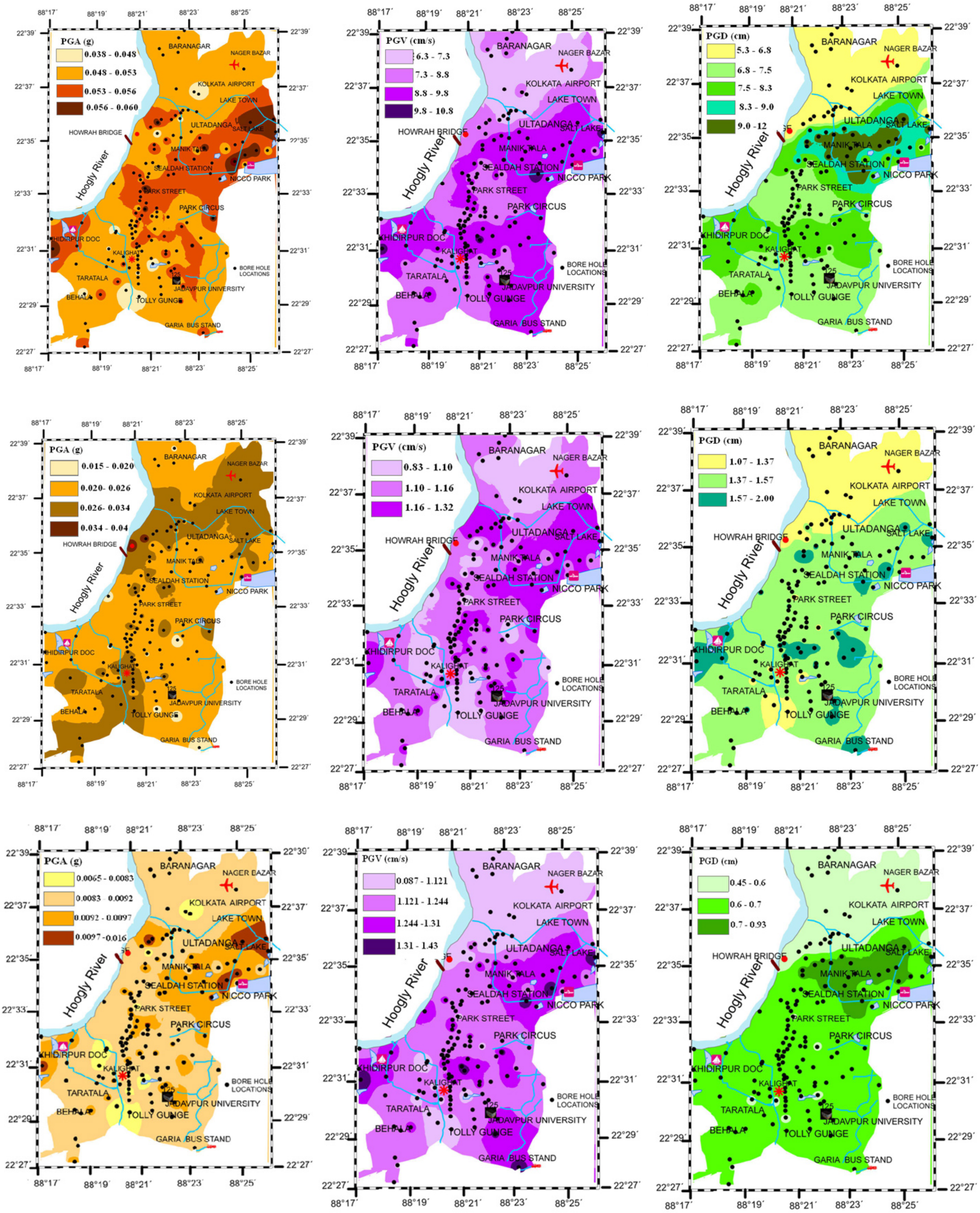

Fig.8. Peak ground acceleration (PGA) map of Kolkata city in 1897 Shillong earthquake. **Fig.9.** The probable peak ground velocity (PGV) map of Kolkata city in 1897 Shillong earthquake. **Fig.10.** The probable peak ground displacement (PGD). map of Kolkata city in 1897 Shillong earthquake. **Fig.11.** The probable peak ground acceleration (PGA) map of Kolkata city in 1964 Calcutta Earthquake. **Fig.12.** The probable peak ground velocity (PGV) map of Kolkata city in 1964 Calcutta earthquake. **Fig.13.** The probable peak ground displacement (PGD) map of Kolkata city in 1964 Calcutta earthquake. **Fig.14.** The probable peak ground acceleration (PGA) map of Kolkata city in 2011 Sikkim earthquake. **Fig.15.** The probable peak ground velocity (PGV) map of Kolkata city in 2011 Sikkim earthquake. **Fig.16.** The probable peak ground displacement (PGD) map of Kolkata city in 2011 Sikkim earthquake.

Table 2. PGA, PGV and PGD obtained for three earthquakes at different BH locations.

BH No.	1897 Shillong EQ			1964 Calcutta EQ			2011 Sikkim EQ		
	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)
BH 1	5.06	7.42	5.70	2.33	1.11	1.34	0.89	1.09	0.48
BH 2	5.12	7.40	5.59	2.01	1.12	1.35	0.92	1.11	0.47
BH 3	5.28	7.37	5.63	2.24	1.16	1.34	0.93	1.10	0.47
BH 4	5.01	7.32	5.62	2.13	1.10	1.33	0.88	1.08	0.47
BH 5	4.82	7.06	5.55	2.47	1.07	1.26	0.84	1.03	0.44
BH 6	4.98	6.69	5.54	3.02	1.11	1.17	0.87	0.96	0.46
BH 7	5.04	6.93	5.59	2.77	1.11	1.23	0.88	1.01	0.46
BH 8	4.70	7.90	6.06	1.96	1.01	1.38	0.80	1.14	0.51
BH 9	4.57	6.78	5.76	2.73	1.00	1.16	0.78	0.95	0.48
BH 10	4.74	6.91	5.60	2.35	1.04	1.21	0.82	0.99	0.47
BH 11	5.23	6.29	5.32	3.61	1.15	1.07	0.91	0.87	0.44
BH 12	5.52	7.42	5.76	2.86	1.22	1.34	0.97	1.09	0.48
BH 13	5.16	6.99	5.56	2.92	1.15	1.22	0.90	1.11	0.46
BH 14	5.61	7.14	5.56	3.70	1.25	1.28	0.97	1.05	0.46
BH 15	4.26	6.26	5.48	2.29	1.25	1.06	0.74	0.87	0.45
BH 16	5.35	7.50	5.71	2.79	1.18	1.36	0.98	1.14	0.48
BH 17	5.34	7.15	5.70	2.71	1.18	1.28	0.93	1.05	0.47
BH 18	5.96	7.72	5.65	2.81	1.32	1.42	1.06	1.16	0.48
BH 19	5.40	7.08	5.59	3.94	1.20	1.26	0.93	1.03	0.47
BH 20	5.59	7.47	5.73	2.74	1.24	1.36	0.99	1.11	0.48
BH 21	5.09	7.10	5.61	3.75	1.12	1.25	0.86	1.02	0.49
BH 22	5.67	9.73	9.34	2.75	1.24	1.59	0.99	1.30	0.75
BH 23	4.13	8.50	8.96	1.98	0.89	1.28	0.71	1.05	0.71
BH 24	5.20	9.48	9.30	2.33	1.13	1.52	0.90	1.25	0.74
BH 25	5.39	9.91	9.51	2.33	1.17	1.61	0.93	1.32	0.77
BH 26	5.30	9.15	9.13	2.82	1.17	1.44	0.92	1.18	0.73
BH 27	5.30	9.77	9.43	2.25	1.15	1.59	0.92	1.30	0.76
BH 28	5.35	9.62	9.35	2.52	1.17	1.55	0.93	1.27	0.75
BH 29	5.76	10.43	9.63	2.08	1.24	1.75	1.00	1.43	0.78
BH 30	5.36	9.51	9.31	2.94	1.18	1.53	0.92	1.25	0.75
BH 31	5.51	9.30	9.13	2.43	1.01	1.98	9.62	1.22	0.73
BH 32	5.50	9.58	9.31	2.65	1.21	1.55	0.95	1.27	0.75
BH 33	5.50	9.58	9.31	2.65	1.21	1.55	0.95	1.27	0.75
BH 34	5.74	9.71	9.31	2.68	1.26	1.59	1.00	1.30	0.75
BH 35	5.05	9.71	9.48	2.00	1.09	1.56	0.87	1.28	0.76
BH 36	5.16	9.50	9.34	2.54	1.13	1.52	0.89	1.24	0.75
BH 37	5.39	9.67	9.35	2.33	1.11	1.34	0.94	1.29	0.75
BH 38	5.68	9.23	9.06	2.84	1.24	1.48	0.94	1.29	0.72
BH 39	5.70	9.51	9.20	2.33	1.11	1.34	1.00	1.27	0.74
BH 40	5.34	9.19	9.12	2.60	1.17	1.46	0.93	1.20	0.73
BH 41	5.45	9.63	9.31	2.27	1.19	1.57	0.95	1.28	0.74
BH 42	4.88	9.10	9.17	2.35	1.06	1.43	0.84	1.17	0.73
BH 43	5.24	8.45	7.41	2.87	1.15	1.42	0.91	1.15	0.61
BH 44	5.03	8.25	7.20	2.52	1.11	1.37	0.87	1.11	0.60
BH 45	6.08	9.62	7.47	2.47	1.33	1.69	1.06	1.38	0.65
BH 46	5.20	8.55	7.29	2.44	1.13	1.46	0.90	1.19	0.61
BH 47	5.30	8.63	7.49	2.60	1.13	1.50	0.93	1.19	0.62
BH 48	5.12	8.70	7.57	2.63	1.21	1.50	0.89	1.20	0.63
BH 49	5.42	9.08	7.67	2.54	1.15	1.49	0.94	1.27	0.64
BH 50	5.20	8.79	7.42	2.60	1.13	1.50	0.90	1.22	0.62
BH 51	5.51	8.76	7.44	2.63	1.21	1.50	0.95	1.22	0.62
BH 52	5.27	8.77	7.51	2.54	1.15	1.49	0.91	1.21	0.62
BH 53	5.44	8.95	7.53	2.65	1.19	1.53	0.94	1.24	0.63
BH 54	5.44	8.49	7.53	2.65	1.19	1.53	0.94	1.24	0.63
BH 55	5.57	10.81	11.99	2.31	1.21	1.64	0.97	1.36	0.93
BH 56	5.18	8.75	7.37	3.24	1.13	1.47	0.88	1.20	0.62
BH 57	5.37	9.13	7.37	2.00	1.17	1.58	0.94	1.28	0.64
BH 58	5.94	7.38	7.01	2.33	0.86	1.15	0.67	0.93	0.57
BH 59	5.54	9.07	7.60	2.45	1.21	1.56	0.97	1.27	0.63
BH 60	5.45	9.20	7.63	2.37	1.19	1.59	0.94	1.29	0.64
BH 61	5.54	9.34	7.56	2.42	1.20	1.61	0.96	1.32	0.64
BH 62	5.23	9.16	7.50	2.18	1.13	1.56	0.90	1.28	0.63
BH 63	5.58	8.74	7.53	2.71	1.23	1.49	0.98	1.21	0.62
BH 64	5.24	8.51	7.43	2.27	1.14	1.44	0.92	1.17	0.61
BH 65	5.09	8.73	7.39	2.33	1.11	1.48	0.88	1.20	0.62
BH 66	5.39	8.70	7.48	2.68	1.27	1.59	1.01	1.29	0.64
BH 67	5.79	9.19	7.73	2.41	1.18	1.48	0.94	1.20	0.62
BH 68	5.39	8.70	7.48	2.95	1.15	1.37	0.90	1.11	0.60
BH 69	5.22	8.25	7.27	2.29	1.10	1.46	0.87	1.19	0.62
BH 70	5.58	8.72	7.38	2.69	1.23	1.50	0.97	1.21	0.61
BH 71	5.28	8.80	7.51	2.10	1.15	1.51	0.92	1.22	0.62
BH 72	4.87	8.20	7.19	2.44	1.07	1.37	0.84	1.11	0.60

Table 2. PGA, PGV and PGD obtained for three earthquakes at different BH locations.

BH no	1897 Shillong EQ			1964 Calcutta EQ			2011 Sikkim EQ		
	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)
BH 73	5.24	8.67	7.49	2.42	1.14	1.48	0.91	1.20	0.62
BH 74	5.24	8.56	7.53	2.56	1.15	1.44	0.91	1.17	0.62
BH 75	4.97	8.59	7.69	2.51	1.08	1.42	0.85	1.16	0.63
BH 76	5.44	8.70	7.43	2.30	1.19	1.49	0.95	1.21	0.62
BH 77	5.31	7.69	7.07	3.31	1.17	1.32	0.92	1.07	0.58
BH 78	5.44	9.26	7.68	2.14	1.18	1.60	0.94	1.30	0.64
BH 79	5.60	8.87	7.44	2.90	1.23	1.52	0.97	1.23	0.62
BH 80	5.60	8.83	7.44	2.90	1.23	1.52	0.97	1.23	0.62
BH 81	5.19	8.93	7.48	2.23	1.13	1.52	0.89	1.24	0.63
BH 82	4.79	7.89	7.15	2.93	1.05	1.29	0.82	1.04	0.59
BH 83	4.90	8.27	7.28	2.34	1.07	1.38	0.85	1.12	0.60
BH 84	5.38	8.86	7.49	1.52	1.18	1.52	0.93	1.23	0.62
BH 85	4.27	9.15	7.78	2.26	0.97	1.44	0.71	1.16	0.67
BH 86	5.27	10.06	8.08	2.29	1.13	1.68	0.89	1.35	0.70
BH 87	5.15	9.53	8.03	2.38	1.12	1.56	0.88	1.25	0.69
BH 88	5.53	9.67	7.86	2.37	1.20	1.61	0.96	1.29	0.68
BH 89	5.56	9.69	7.89	2.60	1.21	1.62	0.95	1.30	0.68
BH 90	5.29	9.99	8.08	2.20	1.14	1.67	0.90	1.34	0.70
BH 91	5.36	9.85	8.01	2.14	1.16	1.65	0.92	1.33	0.69
BH 92	5.52	9.86	8.00	2.66	1.20	1.65	0.95	1.33	0.69
BH 93	5.19	9.36	7.96	2.84	1.13	1.51	0.89	1.21	0.68
BH 94	5.36	9.66	8.02	2.24	1.17	1.60	0.93	1.28	0.69
BH 95	5.22	10.00	7.99	1.88	1.12	1.67	0.89	1.34	0.69
BH 96	5.35	9.69	7.98	2.35	1.16	1.61	9.19	1.29	0.68
BH 97	5.14	9.48	7.99	2.20	1.12	1.55	8.85	1.24	0.68
BH 98	5.63	9.38	7.70	2.84	1.23	1.54	0.97	1.23	0.61
BH 99	5.25	9.72	8.02	2.34	1.14	1.61	0.90	1.29	0.69
BH 100	4.76	9.14	7.73	2.49	1.03	1.46	0.81	1.17	0.66
BH 101	5.29	9.52	8.06	2.86	1.15	1.56	0.91	1.25	0.69
BH 102	5.60	9.77	7.94	2.35	1.22	1.64	0.97	1.31	0.68
BH 103	5.75	10.03	8.24	2.29	1.24	1.74	0.99	1.40	0.71
BH 104	5.27	9.63	8.01	2.58	1.14	1.59	0.90	1.28	0.69
BH 105	5.27	9.63	8.01	2.58	1.14	1.59	0.90	1.28	0.69
BH 106	5.05	8.29	7.22	2.60	1.11	1.38	0.88	1.12	0.60
BH 107	5.64	9.27	7.71	2.03	1.22	1.61	0.99	1.31	0.64
BH 108	4.71	8.04	7.44	3.12	1.03	1.29	0.80	1.04	0.61
BH 109	5.10	8.94	7.84	2.59	1.10	1.51	0.87	1.23	0.65
BH 110	5.12	8.39	7.40	2.90	1.13	1.39	0.88	1.13	0.61
BH 111	4.94	8.50	7.57	2.42	1.08	1.41	0.85	1.14	0.63
BH 112	5.07	8.18	7.25	2.87	1.11	1.35	0.87	1.09	0.56
BH 113	4.90	8.57	7.65	2.29	1.07	1.42	0.84	1.15	0.63
BH 114	5.00	9.23	7.32	1.88	1.06	1.58	0.85	1.30	0.62
BH 115	4.92	8.79	7.43	2.23	1.06	1.49	0.84	1.21	0.62
BH 116	5.24	8.72	7.50	2.53	1.15	1.48	0.91	1.20	0.62
BH 117	5.20	8.68	7.66	3.03	1.13	1.45	0.88	1.18	0.63
BH 118	5.19	8.58	7.59	3.20	1.14	1.43	0.89	1.16	0.63
BH 119	5.50	9.02	7.58	2.17	1.20	1.56	0.96	1.26	0.63
BH 120	4.94	8.06	7.11	2.35	1.08	1.33	0.85	1.07	0.59
BH 121	5.54	9.26	7.69	2.54	1.21	1.60	0.96	1.30	0.64
BH 122	3.77	7.31	7.29	2.34	0.83	1.10	0.65	0.90	0.59
BH 123	5.03	7.76	6.92	3.06	1.11	1.27	0.87	1.03	0.57
BH 124	5.41	8.83	7.51	2.37	1.18	1.51	0.94	1.22	0.62
BH 125	5.57	8.28	7.41	2.52	1.22	1.49	0.98	1.21	0.62
BH 126	4.52	7.85	7.12	3.87	0.99	1.26	0.75	1.02	0.59
BH 127	4.93	9.56	7.31	1.71	1.03	1.62	0.83	1.33	0.63
BH 128	5.18	9.00	7.40	2.30	1.12	1.52	0.85	1.24	0.62
BH 129	5.57	8.30	7.35	3.15	1.23	1.37	0.97	1.11	0.61
BH 130	5.22	8.84	7.48	2.17	1.13	1.52	0.91	1.23	0.62
BH 131	5.11	8.08	7.10	2.80	1.11	1.33	0.88	1.07	0.59
BH 132	3.88	7.48	7.62	3.43	0.85	1.12	0.65	0.91	0.61
BH 133	4.53	8.22	7.31	2.28	1.08	1.45	0.85	1.18	0.63
BH 134	5.49	9.27	7.76	2.26	1.19	1.60	0.95	1.30	0.65
BH 135	5.29	8.80	7.61	2.60	1.16	1.49	0.91	1.21	0.63
BH 136	5.08	8.96	7.54	1.92	1.10	1.53	0.89	1.25	0.63
BH 137	4.52	7.87	7.44	3.12	0.99	1.24	0.71	1.01	0.61
BH 138	5.29	8.65	7.54	2.66	1.16	1.46	0.92	1.18	0.62
BH 139	5.00	8.03	7.23	1.86	1.09	1.31	0.81	0.86	0.60
BH 140	5.30	8.28	7.24	3.19	1.17	1.38	0.91	1.11	0.60
BH 141	5.40	9.27	7.65	2.35	1.16	1.51	0.93	1.22	0.62
BH 142	5.32	9.34	7.23	2.12	1.17	1.60	0.94	1.30	0.64
BH 143	5.32	9.34	7.32	1.98	1.14	1.61	0.92	1.32	0.63
BH 144	5.32	9.34	7.32	1.98	1.14	1.61	0.92	1.32	0.63

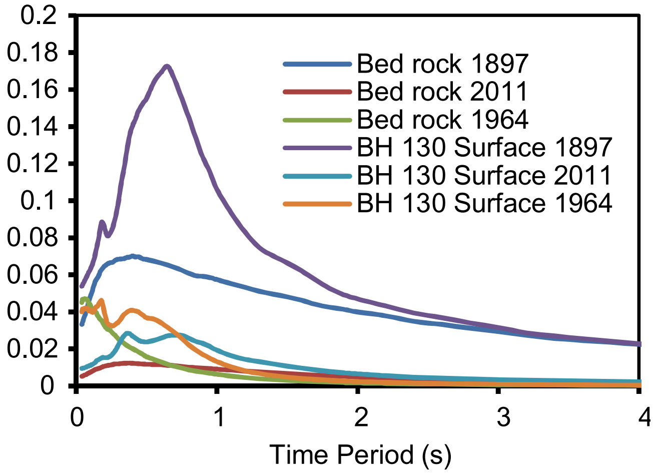

Fig.17. Response spectrum at bedrock level and surface level of BH 130.

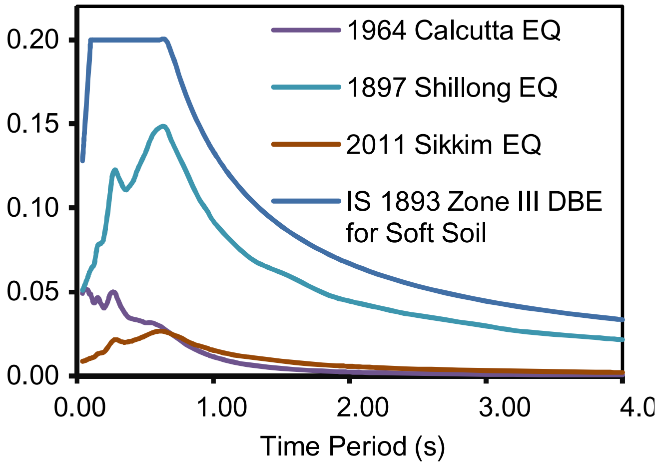

Fig.18. Optimum response spectra of 1897 Shillong earthquake, 1964 Calcutta Earthquake, 2011 Sikkim earthquake and Design Basis earthquake of IS 1893 (Part I):2002 zone III for soft soil.

But field tests like MASW provide more accurate result to obtain site response of Kolkata city.

CONCLUSIONS

The major findings from this study suggest that

- The intensity of the near and far source past earthquakes in Kolkata region was documented as VII-VIII in MM scale. For these earthquakes predicted PGA, PGV and PGD are shown to vary from 0.05g to 0.2g, 5cm/s to 25cm/s and 3cm to 13cm respectively. In the present study, the computed PGA, PGV and PGD values are quite close to them. A recent estimate (GSHAP 1999) also indicates that the city may expect PGA values in order of 0.08g to 0.13g in next 50 years with 10% probability.
- PGA is comparatively high in near source earthquake and PGD is comparatively high in far source earthquake. This is may be due to attenuation of high frequency wave as a result of filtering effect of earth during travelling of long path. So during far source earthquake the tall buildings will be more affected.
- The comparison of response spectra also reveals same scenario that spectral acceleration is high at high time period for distance earthquakes like 1897 Shillong Earthquake and 2011 Sikkim Earthquake due to low frequency amplification.
- The ground motion parameters as predicted in the present study were found to compare well with the observed damages in Kolkata

Fig.19. Observed cracks in Ultadanga police quarter (BH 130) during 2011 Sikkim earthquake (*www.ndtv.com)*

region during past near and far source earthquakes. So, it may be concluded that due to absence of recorded strong motion in Kolkata, the present procedure can be used for seismic microzonation of Kolkata city.

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