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STUDY ON THE VARIATIONS OF GROUND MOTION PARAMETERS WITH DISTANCE FOR M_w 6.9 SIKKIM 2011 EARTHQUAKE

Shiv Shankar Kumar*, A. Murali Krishna** and Anbazhagan P.***

*Assistant Professor, School of Civil Engineering, Kalinga Institute of Industrial Technology Bhubaneswar
Odisha-751024, India, E-mail: shivshankar.mit@gmail.com

**Associate Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati
Assam-781039, India, E-mail: amurali@iitg.ac.in

***Associate Professor, Department of Civil Engineering, Indian Institute of Science
Bangalore-560012, India, E-mail: anbazhagan@civil.iisc.ernet.in

ABSTRACT

This paper presents the variations of ground motion parameters with distance, for M_w 6.9 Sikkim 2011 earthquake, based on the ground motion records obtained from sixteen locations. Ground motions recorded at different stations located within 35-1000 km from the epicentre were collated and analysed for their ground motion parameters. It has been seen that the peak ground acceleration (PGA) near the source zone is high but as distance increase the value of PGA decreases. Based on the comparison between recorded PGA and estimated PGA from attenuation curves, it was observed that there is a need to revisit the ground motion predication equations and provide other correlations for better prediction of future structural design parameters. Predominant period also needs to be estimated region-specifically considering the prevalent seismicity, since the regional geology, source to site distance and site conditions vary place to place.

KEYWORDS: Sikkim 2011 Earthquake, Ground Motions, Distance, Ground Motion Parameters

INTRODUCTION

Seismic hazard at any place predominantly governed by the ground motion and its associated parameters (Kumar et al., 2018). The ground motion parameters, such as peak ground acceleration (PGA), predominant frequency and effective duration of the ground motion affect the responses of various structures, which vary place to place as a function of distance from the epicentre and local geological soil conditions (Kramer, 1996). The devastation during earthquake of any area or location depends upon the intensity of ground motion parameters and soil stratification present in that area.

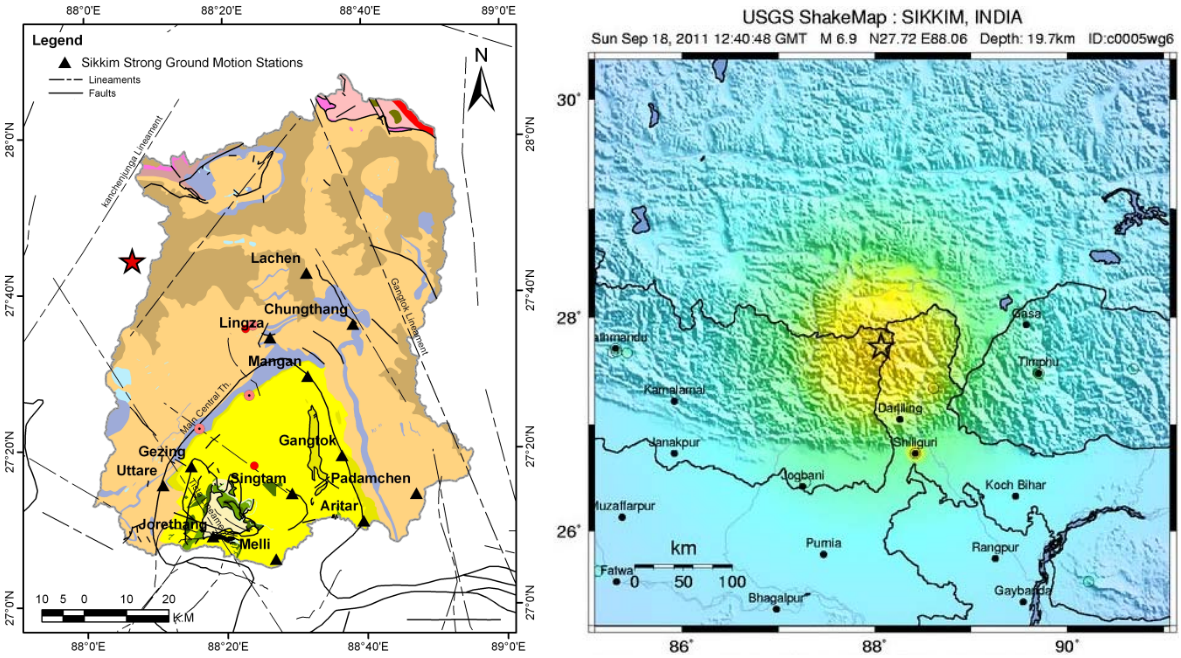
For proper design of earthquake resistant structures one need to know about ground motion parameters and dynamic behaviour of soil. In the absence of data, predictive relationships are very useful to estimate the variation of ground motion parameters with distance (Kramer, 1996). The most commonly used ground motion parameters are vertical and horizontal PGA, damped spectral acceleration (s_a), peak ground velocity *(PGV)* because these are directly related to the dynamic behaviour induced in the structures. When seismic waves travel away from the fault, their higher frequency components are scattered and absorbed more rapidly than lower frequency components. Predominant period of an earthquake increases with increasing distance (Kramer, 1996). Thus, the different geology and geotechnical conditions like the distance between source and site can affect the amplitude, frequency content and duration of the ground motion during an earthquake.

A recent major earthquake of moment magnitude (M_w) 6.9 in Indian subcontinent was the Sikkim earthquake that was occurred on September 18, 2011 at 18:10:48 IST. Its epicentre located at 27.72°N, 88.08°E near India-Nepal border region, about 68 km NW of Mangan (Gangtok) at a focal depth of 19.7 km and lasted about 30 to 40 seconds (Rai et al., 2011). The seismic tremors were felt in many cities of North-Eastern (NE) states of India. Ground motions resulted due to this seismic event were recorded at various seismic stations located within 35-1000 km from the epicentre.

This paper presents the ground motions recorded during Sikkim 2011 earthquake and, the variations in their associated parameters at several locations. Various ground motion parameters were determined for each ground motion record and analysed their variation with distance from the epicentre.

SIKKIM: SEISMICITY AND FAULT ORIENTATIONS

Sikkim is a small Himalayan state in North-East India situated between 27° 00' 48" to 28° 07' 48"N latitude and 88° 00' 58" to 88° 55' 25" E longitude. As per the IS: 1893 (2016), the entire region of Sikkim lies in zone IV with a zone factor of 0.24. The Modified Mercalli Intensity (MMI) also indicates that the seismic zone IV is associated with seismic intensity VII. Sikkim state is surrounded by various well known seismic features and faults such as: Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT) oriented in the E-W and N-S direction which are responsible for the most of the earthquake occurrence in this region (Gahalaut, 2011; Rai et al., 2012a; Kumar et al., 2012; Hazarika and Kumar, 2012). Other significant geological/tectonic features in and around Sikkim include: Tista lineament, Kanchenjunga lineament, Purnea-Everest lineament, Arun lineament and Dhubri fault in the southeast as shown in Figure 1 (Gahalaut, 2011; Mahajan et al., 2012; www.imd.gov.in/section/nhac/dynamic/eq.pdf.



(a) **(b)**

Fig. 1 Tectonic setup of Sikkim and USGS Shake Map of the magnitude 6.9 Sikkim earthquake, Sept. 2011. (Source: (a) Sikkim Strong Ground Motion Station-Geology, IIT Kharagpur (b) http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/c0005wg6/

Several high and moderate intensity earthquakes have occurred in the state of Sikkim and adjoining areas. Some noticeable earthquakes that have affected the region are 1869 Cachar earthquake (M_w: 7.5), 1897 Shillong plateau earthquake (M_w: 8.7), 1923 Meghalaya-India earthquake (M_s: 7.1), 1930 Dhubri earthquake (M_w: 7.1), 1934 Bihar-Nepal Border earthquake (M_w: 8.3), 1941 Assam earthquake near Tezpur (M_s: 6.5), 1943 Assam earthquake Near Hojai (M_s: 7.2),1947 Arunachal Pradesh earthquake (M_s: 7.7), 1950 Great Assam earthquake of (M_w: 8.5), 1954 Arunachal Pradesh earthquake (M_s: 7.7), 1957 Arunachal Pradesh earthquake (M_s: 7), 1984 Silchar earthquake (M_w: 6.0), 1988 Nepal-India Border earthquake (M_w: 6.4), 2006 Sikkim earthquake (M_w: 5.7), 2009 Bhutan earthquake (M_w: 6.2) (Nandy, 2001; Thakur et al., 2012). Based on the seismic gap, Narula and Sharda (1997) reported the possibility of a large scale earthquake in Sikkim region after 1897 and 1934 earthquake events. Bilham et al. (2001) reported that the area between 1934 and 1950 events is seismic gap for Sikkim region. According to hazard map by the Global Seismic Hazard Assessment Programme (GSAP), NE region of India can be expected to have a peak gravitational acceleration (PGA) of 0.24g-0.48g and MMI intensity IX. The occurrence of high intensity earthquake in this region is mainly due to continuous thrusting of Indian-Australian plate against South-Eurasian Plate in N to NNE-SSW direction (De and Kayal, 2003; Nath et al., 2000; Rai et al., 2012b).

SIKKIM 2011 EARTHQUAKE

An earthquake of moment magnitude (M_w) 6.9 struck near the Nepal-Sikkim border on September 18, 2011, at 18:10 local time. The Seismic Monitoring Network of India Meteorological Department (IMD) reported that the epicentre of this earthquake was located at 27.7°N and 88.2°E, with focal depth of 10 km as a result of the reverse-faulting mechanism at thrust interface (Rai et al., 2012a; Gahalaut, 2011). EERI (2012) reported that the strike, dip and focal depth of the fault plane were 313°, 73° and 35 km, respectively. The other source parameters such as seismic moment, source radius, corner frequency and stress drop of this earthquake are in the range of 7.9×10^{21}-6.31×10^{23} dyne-cm, 0.225-0.781 km, 1.8-6.5 Hz and 47.59-389.1 bar, respectively (Hazarika and Kumar, 2012). Since, the epicentre of this Sikkim earthquake lies in Alpide-Himalayan seismic zone, which is seismically high active zone of Himalayan belt, the main shock was followed by a few significant aftershocks (as shown in Table 1) of magnitude 5.0, 4.5 and 4.2 which were also felt in many parts of the country like Assam, West Bengal, Bihar, Orissa, Uttar Pradesh, Delhi. The maximum damage, including at least 100 lives, was observed due to this moderate earthquake event in Northern Sikkim and Western Sikkim because of landslides, failure of retaining walls, foundation failures, and road damages (Thakur et al., 2012; Maheshwari et al., 2012; Kumar et al., 2012; Rajendran et al. 2011; Rai et al., 2012b; Chakraborty et al., 2012). Sharma et al. (2012) and Prajapati et al. (2013) have reported that the intensity of Sikkim 2011 earthquake near the epicentral region was greater than VIII, however, the intensity was decreased with the increase in distance. Tremors of this event were felt in India, China, Bangladesh, Nepal, and Bhutan. The ground accelerations recorded at various stations in India have been considered in the study.

Table 1: Epicentral location of main shock and aftershocks of Sikkim 2011 earthquake (after Rajendran et al., 2011)

Date	Time	Latitude (°N)	Longitude (°E)	Depth (km)	M_w	Data source
18/09/2011	12:40:51.78	27.72	88.14	50	6.9	NEIC/USGS
18/09/2011	18:11 (IST)	27.70	88.20	10	6.8	IMD
18/09/2011	13:11:59:58	27.48	88.50	35	4.8	NEIC/USGS
18/09/2011	13:11:59:00	27.60	88.50	-	5.0	IMD
18/09/2011	13:54:20.01	27.28	88.30	35	4.7	NEIC/USGS
18/09/2011	13:54:17:00	27.50	88.40	-	4.5	IMD
18/09/2011	21:51:52:00	27.60	88.40	-	4.2	IMD
22/09/2011	16:44:43:00	27.60	88.40	-	3.9	IMD

GROUND MOTION RECORDING STATIONS

Ground motion records obtained during Sikkim 2011 earthquake at different ground motion recording stations (as shown in Figure 2) operated by different government agencies were collated and analysed. Details of the recording station locations along with the station geology, site class and distance from epicentre to the recording stations are presented in Table 2. The recording stations located at a distance ranging from 35 km to 1000 km from the epicentre. The places very near to epicentre like Gezing, Chungthang, Mangan, Melli felt high Intensity (VIII$^+$-MMI scale) of shaking while the farthest places like Sibsagar, Chamoli, Champawat, Pithoragarh felt low intensity (V-MMI scale).

Table 2: Details of ground motion recording stations for M_w 6.9 Sikkim 2011 earthquake

Station	Latitude (°N)	Longitude (°E)	V_s^{30} (m/sec)	Station Geology	Site Class	Distance (km)
Gezing	27.30	88.25	700-1620	Rock	A	34
Mangan	27.49	88.52	700-1620	Rock	A	39
Chungthang	27.60	88.64	700-1620	Rock	A	49
Gangtok	27.35	88.62	700-1400	Rock	A	69
Melli	27.10	88.45	700-1620	Rock	A	62
Silliguri	26.71	88.43	200-375	Alluvial fill	C	101
Coonchvihar	26.32	89.44	200-375	Not known	C	198

Malda	25.00	88.15	200-375	Not known	C	289
Raxaul	26.98	84.84	200-375	Not known	C	381
RRL Guwahati	26.16	91.65	200-375	Alluvial fill	C	400
IIT Guwahati	26.18	91.69	-	Rockoutcrop	A	400
Sibsagar	26.99	94.63	200-375	Not known	C	718
Pithoragarh	29.57	80.20	700-1400	Not known	A	915
Champawat	29.33	80.09	700-1400	Not known	A	953
Udham Singh Nagar	28.99	79.40	200-375	Not known	C	989
Chamoli	30.41	79.32	700-1400	Not known	A	1035

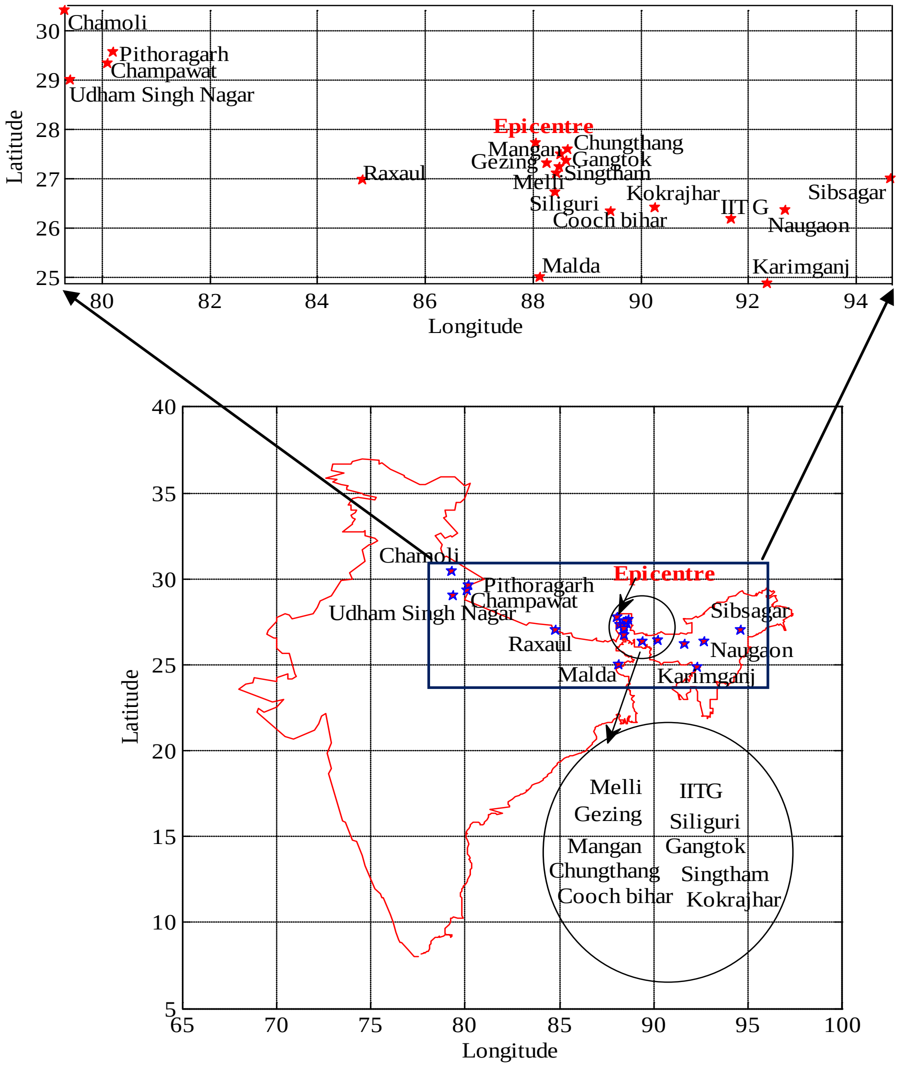


Fig. 2 Locations of recoded ground motion during 2011 Sikkim earthquake

GROUND MOTIONS AND GROUND MOTION PARAMETERS

The wave produced by sudden slip of fault either by strike-slip or reverse faulting mechanism causes the release of huge amount of strain energy and travel through the earth and along its surface in the form of body wave or surface wave. Thus, the ground motion recorded at a station is the result of the movement of soil particles which further depends up on the variation of fault rupture, displacement, energy released, rupture velocity etc. The ground motion record, in terms of acceleration history, of an earthquake is one of the fundamental need to study ground motion parameters. Engineering ground motion parameters such as amplitude, frequency content and duration of strong ground motion, can be used to predict the damaging potential of an earthquake and also to describe the involved characteristics of an earthquake (Kramer, 1996; Danciu and Tselentis, 2007).

Acceleration Histories

Acceleration time histories of 18th September 2011 Sikkim earthquake motion, recorded at sixteen stations, are presented in Figure 3. Ground motion parameters of these acceleration histories are shown in Table 3. It shows that the earthquake intensity decreases with increase of distance because the reduction of specific energy of stress wave with distance. Some part of this specific energy might absorbed by material through which stress waves travel (Kramer, 1996). Table 3 indicates that PGA near to the epicentre is very high and thus high intensity of shaking. At Gezing station PGA was recorded at rock level 0.45 g while at IIT Guwahati station PGA at rock level was 0.02 g and another station in Guwahati at alluvium soil was 0.04 g. The amplification from rock level to alluvium soil surface is mainly the function of the stiffness and damping characteristics of soil through which seismic waves travel.

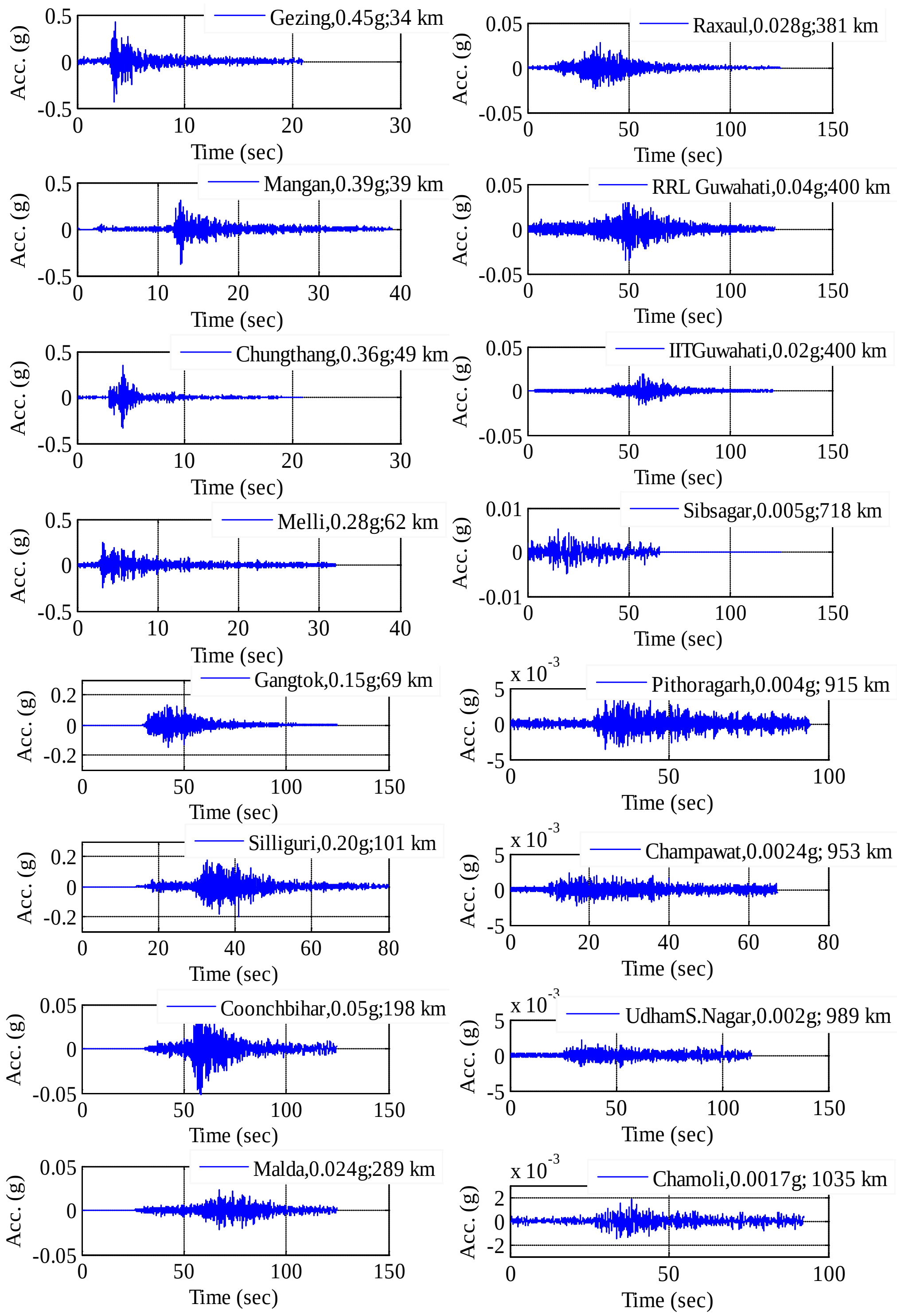


Fig. 3 Plot of acceleration time history of strong motion recorded at various stations

Table 3: Ground motion parameters of M_w 6.9 Sikkim 2011 earthquake at different stations

Stations	Distance (km)	Predominant Period (s)	Mean Period (s)	Bracketed Duration (s)	Significant Duration (s)	PGA (g)	PSA (g)
Gezing	34	0.12	0.12	20.79	8.76	0.45	1.8
Mangan	39	0.12	0.16	75.58	26.54	0.39	2.0
Chungthang	49	0.10	0.11	11.94	4.40	0.36	2.0
Gangtok	69	0.14	0.27	74.45	31.69	0.15	0.6
Melli	62	0.08	0.09	31.96	17.91	0.28	1.26
Silliguri	101	0.20	0.29	63.36	21.25	0.20	1.0
Coonchvihar	198	0.38	0.57	126.12	84.37	0.05	0.28
Malda	289	0.44	0.53	113.90	58.33	0.024	0.09
Raxaul	381	0.20	0.45	124.06	46.54	0.028	0.10
RRL Guwahati	400	0.36	0.39	121.97	59.53	0.040	0.16
IIT Guwahati	400	0.38	0.63	117.93	36.57	0.020	0.06
Sibsagar	718	0.30	0.72	64.64	51.61	0.005	0.02
Pithoragarh	915	0.20	0.24	66.84	56.43	0.004	0.019
Champawat	953	0.18	0.22	67.14	48.44	0.0024	0.013
Udham Singh Nagar	989	0.28	0.45	113.73	75.41	0.002	0.008
Chamoli	1035	0.54	0.51	64.21	43.34	0.0017	0.011
Note: PGA – Peak Ground Acceleration; PSA – Peak Spectral Acceleration							

Ground Motion Spectra

A plot between Fourier amplitude versus frequency is known as Fourier amplitude spectrum. Fast Fourier Transformations (FFT) analysis is generally performed to obtain the Fourier amplitude spectrum of a strong ground motion that shows how the amplitude of the motion is distributed with respect to frequency (or period) and denotes the variations in the energy content of a strong motion (Kramer, 1996). FFT plots of all the recorded ground accelerations motions are presented in Figure 4. It is observed that, for all recorded signals, the peak or maximum value of acceleration was found at different frequencies (periods) for one earthquake event. This is mainly due to the local geology and site conditions beneath the strong motion recording point. Acceleration response spectra i.e. the maximum acceleration response versus structural natural frequency at 5 % damping ratio are shown in Figure 5, which provides the information on the potential effects of an input motion on different structures. The response spectrum describes the maximum response of a single degree of freedom (SDOF) system to a particular input motion as a function of the natural frequency and damping ratio of the SDOF system (Kramer, 1996). Figure 6 shows the results of the frequency corresponding to the peak energy content obtained from FFT as well as response spectra for all recorded motions. It can be observed that the frequency obtained by both Fourier analysis and response spectra gives approximately same values.

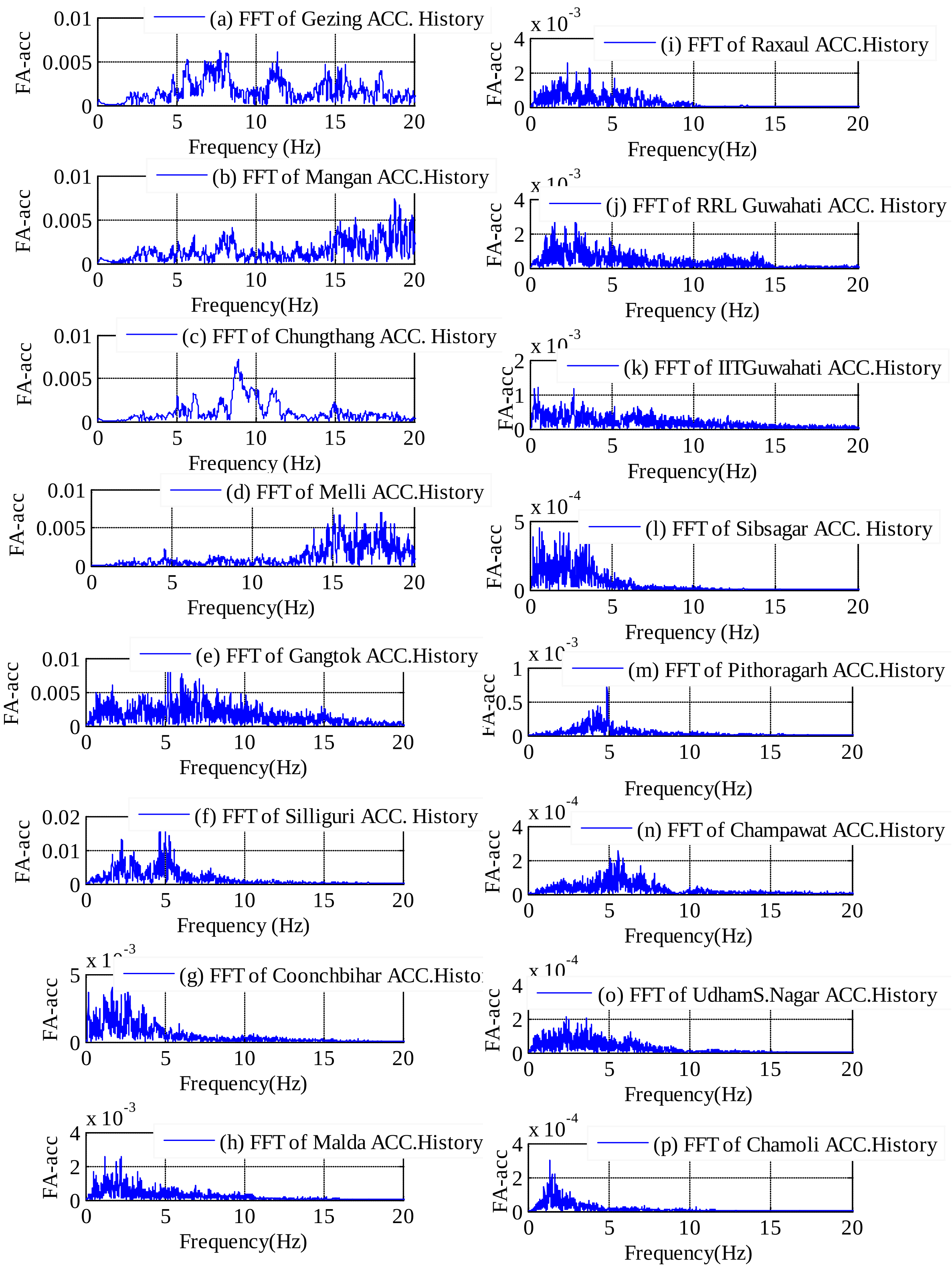


Fig. 4 (a-p) FFT plot of strong motion at various stations

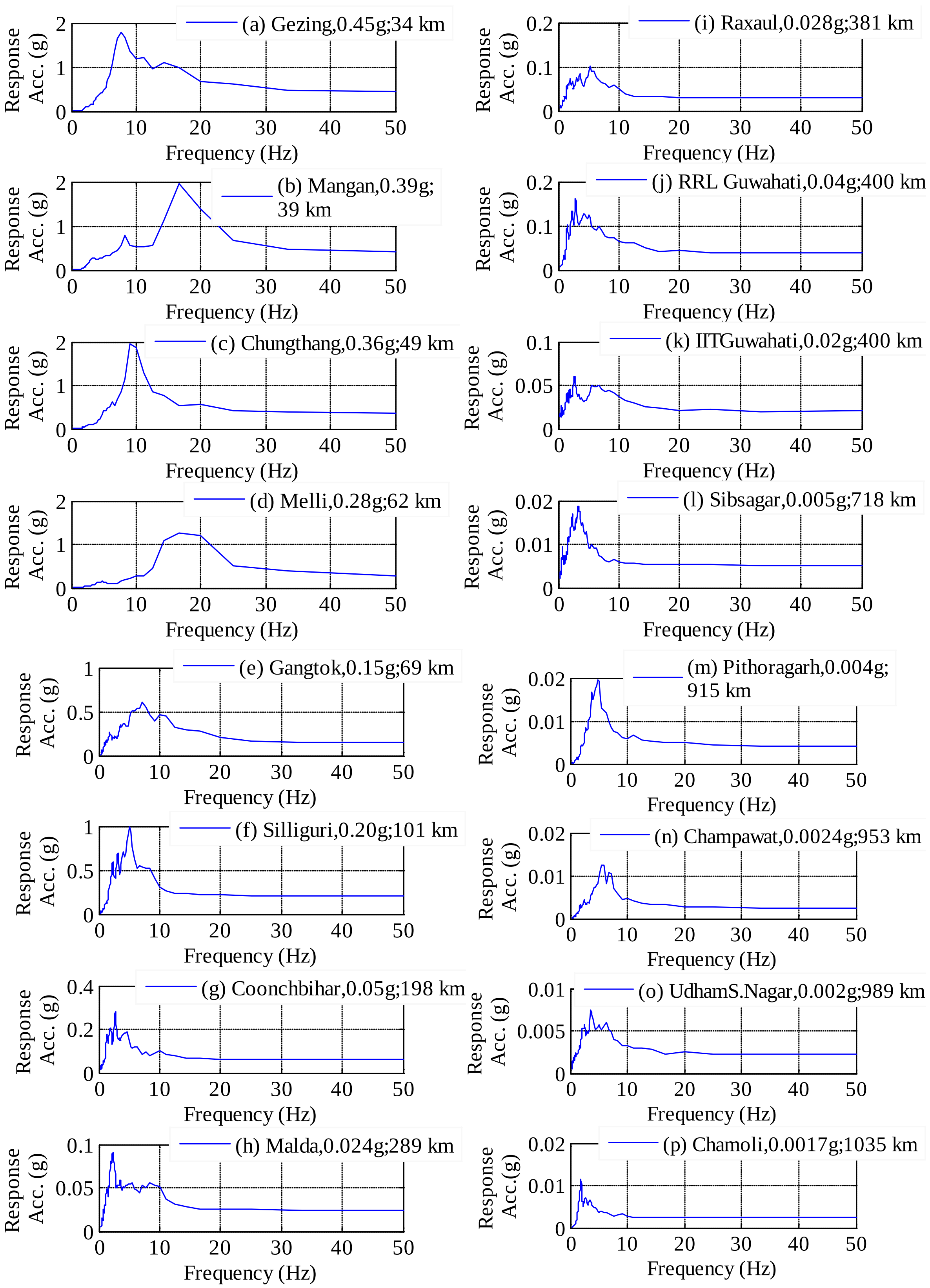


Fig. 5 (a-p) Response spectra of strong motions at various stations

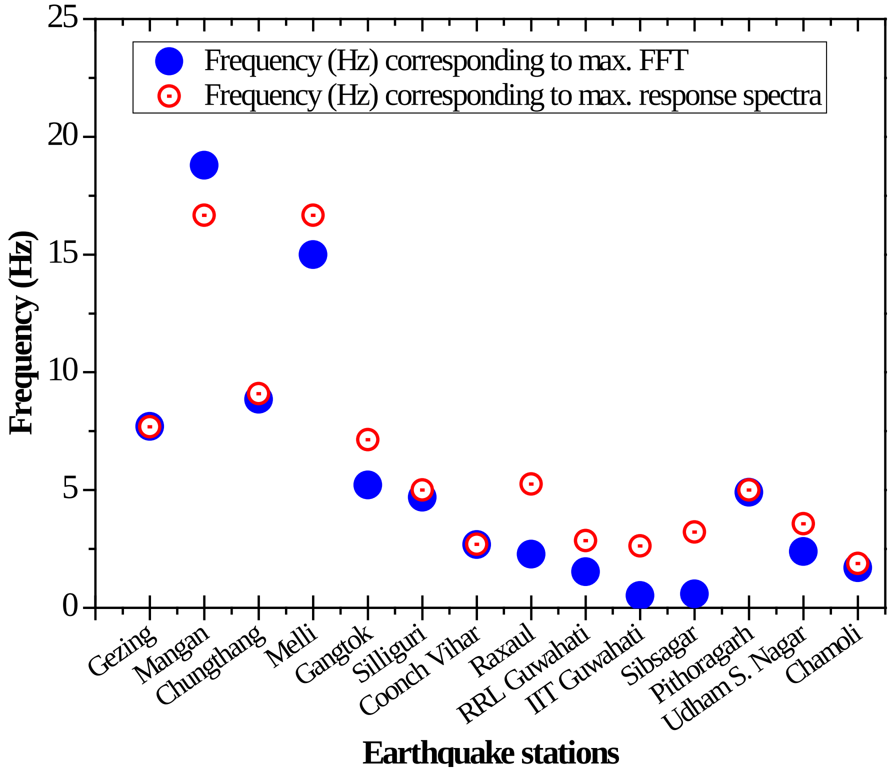


Fig. 6 Variation of frequency at different stations corresponding to the max. FFT and response spectra

Peak Ground Acceleration and Attenuation Relationships

The peak ground accelerations (PGA) of strong motions, during Sikkim earthquake, reported at different locations are presented in Figure 7, which indicates that the intensity of earthquake motion decreases with increasing distance. The highest PGA value 0.45 g was recorded at a station 'Gazing' which is at a distance of 34 km from the epicentre whereas, lowest PGA value 0.0017 g was recorded at the station 'Chamoli' 1035 km from the epicentre (Figure 7a). A mathematical expression, to estimate any particular ground motion parameter (for example, PSA or PGA) in terms of quantity that strongly affects the seismic design of engineering structures, is called attenuation or predictive relationship. Attenuation relationships play an important role in seismic design, if recoded ground motion data are not available (Kramer, 1996). Since peak acceleration is the most commonly used ground motion parameter in seismic design, many peak acceleration attenuation relationships have been developed worldwide. Several researchers were proposed the attenuation relationships, for the earthquakes of M_w range 3.0–8.5 and epicentral distance $\leq$ 300 km, for Indian Himalayan region based on the different faulting mechanism such as strike-slip and reverse (Iyengar and Ghosh, 2004; Nathet al., 2005; Das et al., 2006; Sharma and Bungum, 2006; Raghu Kanthand Iyengar, 2007; Nath et al., 2009; Sharma et al., 2009; NDMA 2010; Anbazhagan et al., 2013). In geotechnical engineering design, the ground motions due to all causative sources in the radius of 300 km around a given site are considered, as per Regulatory Guide 1.165 (1997). Figure 7b presents the variations of recorded PGA along with predicted PGA using various attenuation relationships for M_w of 6.9. Among the presented values of predicted PGA based on the attenuation relationships, in Figure 7b, few relationships such as Kanno et al. (2006), Campbell and Bozorgnia (2008) and, Anbazhagan et al. (2013) shows more or less close to each other and also very close to recorded PGA. The estimated and recorded PGA indicates that the attenuation relationships for Indian tectonic feature, especially for active tectonic region, stable continental region and subduction zone, is a need to develop the attenuation relationships. Although, the attenuation relationship curves to predict the ground motion parameters are available, the development of an attenuation curve will provide the proper variations in the ground motion parameters with distance. Some differences were observed in the estimated and recorded PGA may be due to uncertainty in the local site conditions however, the presented curves, in Figure 7b, follow similar trend as of recorded PGA.

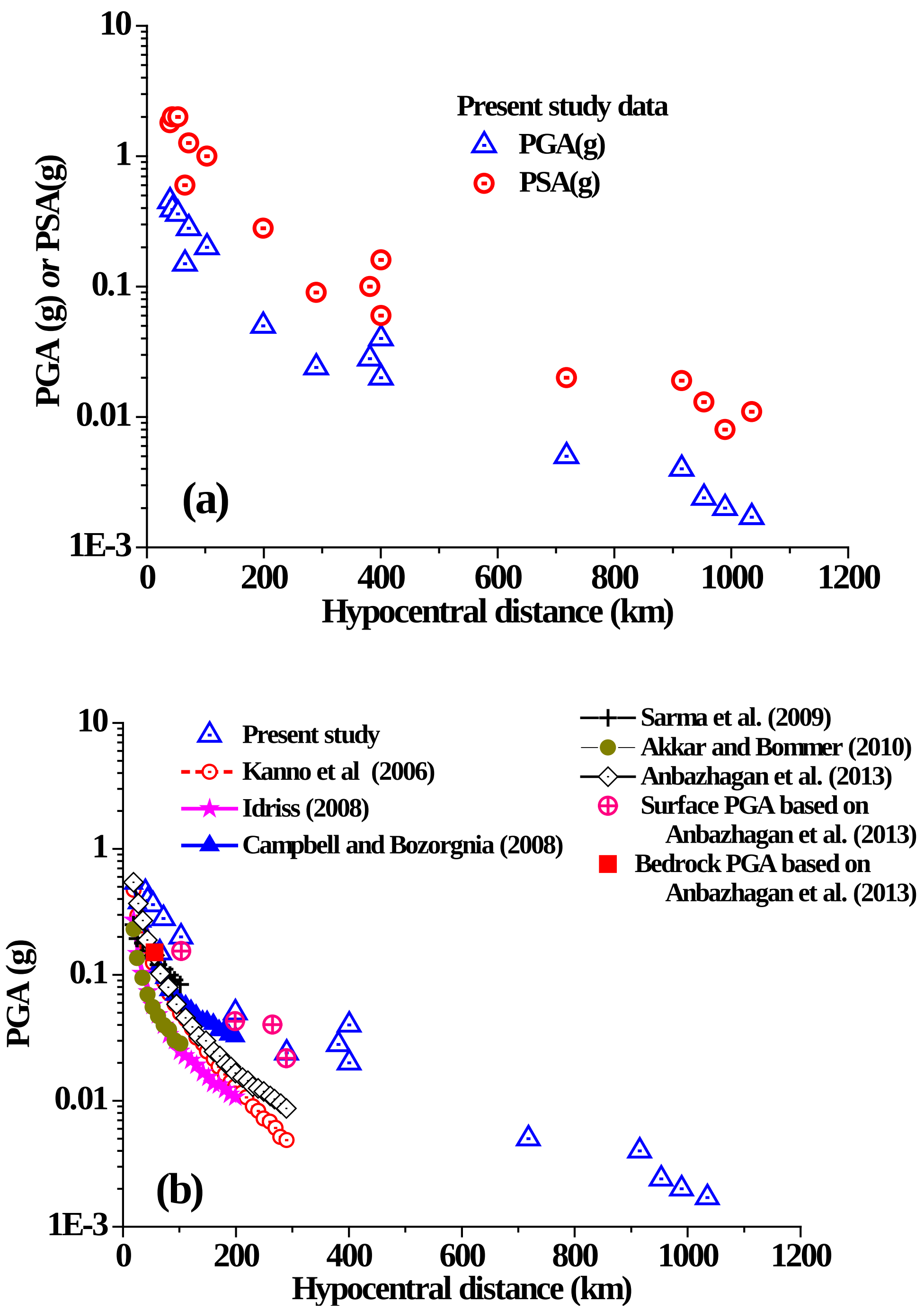


Fig. 7 (a) Variation of recorded PGA with hypocentral distance (b) predicted PGA using various attenuation relationships for M_w = 6.9

Variation of Predominant Period with Distance

The ground motion parameters like predominant period, mean period, bracketed duration and significant duration of any earthquake motions are also important parameters after the amplitude parameters. The duration of strong ground motion is related to the time required to release the accumulated strain energy, by the rupture/separation of tectonic plates along the fault line, which increases with earthquake magnitude. The period at which the maximum spectral acceleration found in an acceleration response spectrum at 5% damping is called predominant period. The predominant period and other parameters for Sikkim 2011 earthquake are derived using Seismo Signal program (www.SeismoSoft.com) and presented in Table 3. Figure 8 shows that, for M_w = 6.9 (Sikkim 2011 earthquake), the predominant period increases with increasing distance up to 300 km, which follows similar trends as that of M_w = 6.5, 7, and 7.5 reported by Kramer (1996). However, the obtained predominant period for M_w = 6.9 is significantly lesser than M_w = 6.5, 7, and 7.5 reported by Kramer (1996). Several researchers have reported that the variations in predominant period up to the radius of 300 km is significantly important for the seismic engineering interest (Seed et al., 1969; Kramer, 1996; Lang, 2004; Anbazhagan et al., 2013). The predominant periods beyond 300 km, presented in Table 3, showerratic pattern with distance, may be due to the subsoil topography, surface topography, and local soil geology near the recording stations.From Table 3, the higher bracketed duration was observed for the recording stations situated and site class C, in comparison to the stations at site class A (see Table 2), which clearly reflects the effect of local site condition on the ground motion parameters. Further, at larger distance stations also the durations of the ground motions appear larger which might be due to larger wave front and more reflected/refracted waves are arrive at such stations which may take longer time.

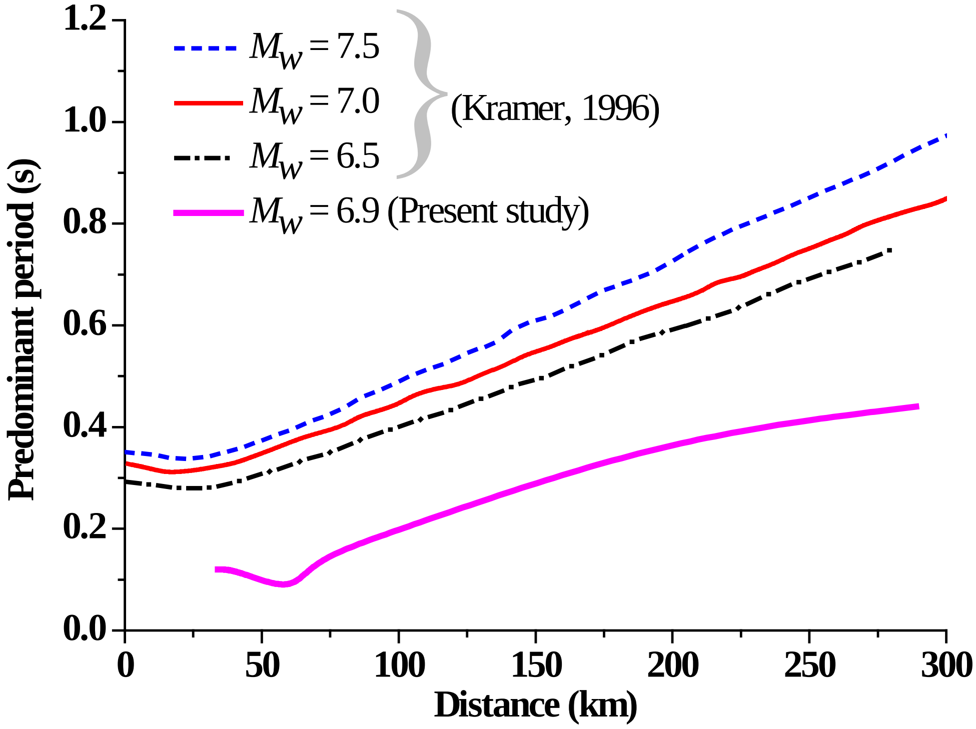


Fig. 8 Variations in predominant period with distance from epicentre

Response Spectrum of Recorded Motion and Design Spectrum

Ground motion and related hazards are generally described in terms of peak ground acceleration (PGA). However, it is well recognized that PGA does not uniquely influence damage in man-made structures. Hence, engineers prefer the response spectrum as a better descriptor of seismic hazard, which is directly applicable in the design of structures. The peak ground acceleration (PGA) and spectral acceleration (SA) values at ground surface may vary significantly from the values at bed rock level. These variations, either amplification or de-amplification, are depend on the local site conditions, geological formation, magnitude and hypocentral distance (Vipin et al., 2009; Chopra and Choudhury, 2011). The response spectrum of accelerations at different recording stations are evaluated and presented in Figure 9 and, also compared with the response spectra proposed by Indian seismic code IS:1893 (Part 1): 2016. The values of PSA are obtained at Gezing, Mangan, Chungthang and Melli are 1.8, 2.0, 2.0 and 1.26, respectively, corresponding to the subsequent PGA 0.45 g, 0.39 g, 0.36 g, and 0.28 g. Some of the places where soil encountered, at large distance from epicentre, showed high PGA value which might be due to the acceleration amplitude and frequency content characteristics of local site conditions. It was observed that the response spectrum at all recording stations are relatively lesser and different in shape than the proposed response spectrum curves by IS:1893 (2016). It is also seen that the response spectrums of recorded ground motions in rocky sites does not match with the spectrum of hard soil based on IS:1893 (2016). This is due to the fact that IS:1893 considered the design ground motion corresponding to 2% or 10% probability of exceedance in a period of 50 years or a return period of 475 years, which might be one of the highest magnitude of earthquake than the 2011-Sikkim earthquake magnitude (NEHRP 2000). This actually satisfy the maximum considered earthquake (MCE) conditions considering adequate factor of safety to estimate the expected dynamic loads on a structure for a very conservative design.

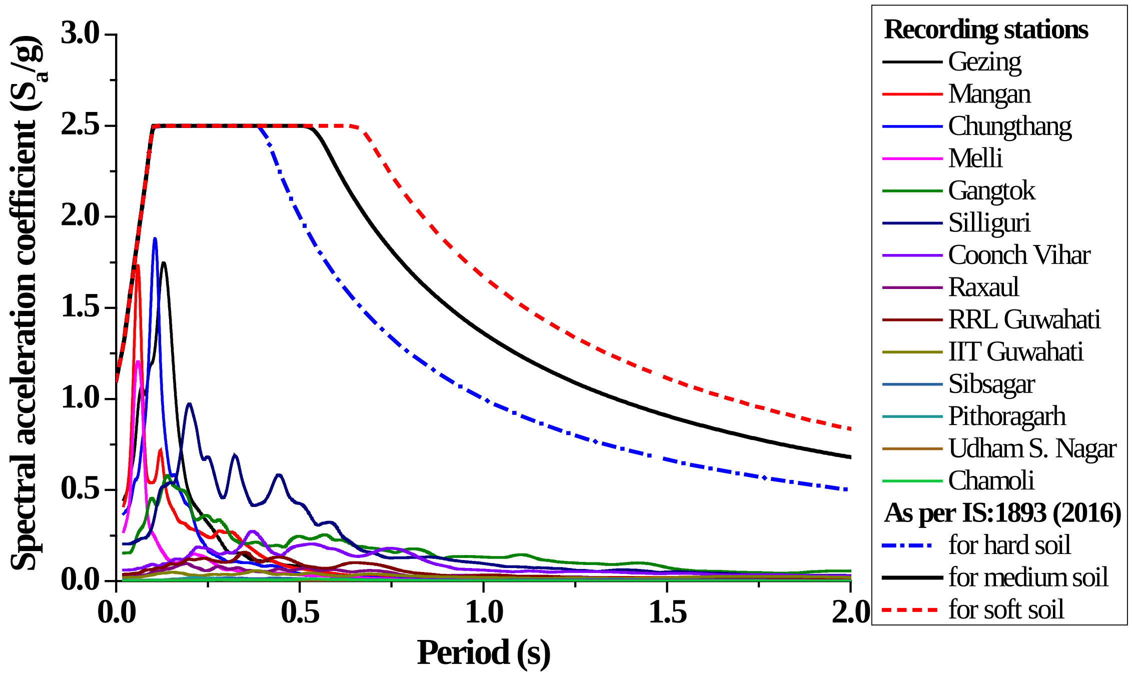


Fig. 9 Response spectrum at different recorded stations along with the design spectrum proposed by IS:1893 (2016)

CONCLUDING REMARKS

Ground motions recorded at different locations during 2011 Sikkim earthquake were collected and analysed the variations of ground motions parameters with distance. It was found that for similar magnitude of earthquake, the variations in predominant period with hypocentral distance, for 2011 Sikkim earthquake, is significantly different from the existing literatures. Based on the comparison between recorded PGA and estimated PGA from the attenuation curves, the ground motion predication equations are needed to be redefined for better prediction of design parameters for earthquake resistant structures. Response spectrum, one of the important design parameters for the construction at any site, decreases with increasing distance.

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