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Indian National Strong Motion Instrumentation Network and Site Characterization of Its Stations

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ABSTRACT

Indian Institute of Technology, Roorkee (IITR) is operating a nationwide network of instruments for recording strong ground motion. Total 300 instruments are installed in seismic zone III, IV and V along Himalayan belt. Primary goal of this project is to acquire strong ground-motion (SGM) data for various studies in the field of earthquake engineering and seismology in general and in particular to understand propagation and site response characteristics of the sediments that underlie and are thought to produce large site amplification and seismic hazard. These data will complement laboratory data to characterize the properties of the soft soils underlying residential area so that engineers and architects can design appropriate earthquake-resistant structures for the region. The successful working of this network has laid the foundation of Earthquake Early Warning System (EEW) in India. A great number of strong motion records have been obtained and utilized to study local site and geological effects. The paper introduces outline of the IITR strong motion network and some of its recent studies.

Keywords: IITR; Amplification; SGM; Accelerographs; Earthquake; EEW

1. Introduction

Strong motion seismographs are instruments designed to record the time history of strong ground motions where the traditional high-gain seismographs used to routinely locate earthquakes go off scale. They are often called accelerographs because they measure acceleration of the ground. Ground motion time-histories recorded during past earthquakes in a region provide valuable information about the expected characteristics of ground motion at a site during a future earthquake in that region. These records are essential for evaluating earthquake resistant design procedures, estimation of attenuation characteristics, assessment of seismic hazard and earthquake risk. Accordingly, analysis of strong ground motion data leads to a better understanding of the potential effect of strong shaking during earthquakes. The ground motion characteristics determined from strong motion records are studied in various terrain and rock conditions and have been related to various earthquake parameters. The analysis of data has also helped in understanding the soil-structure interaction, effects of soil deposits, topography and other effects.

More than half of the area of India is susceptible to strong ground motions from earthquakes; therefore it is essential to know about the probable characteristics of strong ground motion of future earthquakes in this region. For earthquake engineering purposes, a number of different parameters are typically used to characterize strong motion records. These parameters include peak acceleration, peak velocity, peak displacement, duration of strong shaking, and response spectra. A rational assessment of the expected seismic hazard in different regions of the country will lead to substantial monetary savings in the design of structures and reduce potential losses from earthquakes.

India has a two-pronged earthquake problem. There is severe seismic hazard along the Himalayan belt and also at the western margin of the country in the state of Gujarat. IIT Roorkee is operating a network of 300 strong motion accelerographs in Himalayas and adjoining planes lying in seismic zomes V, IV and III of Indian seismic zoning map [1]. It is this network which is being discussed in detail in this paper. For monitoring earthquakes originating from Gujarat region, Indian Seismological Research (ISR) institute, Gandhinagar is operating a network of 43 strong-motion accelerographs [2].

The Indian plate pushes into the Asian plate at the high rate of 15 to 20 cm/year [3], and as a direct result of the collision between the Indian and the Asian plates the state of stress in the Indian plate is high, which in turn increases the earthquake hazard, particularly in northern India along the Himalaya collision zone. This process has given rise to three major thrust planes: (e.g., [4,5]) the

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Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT). The region has experienced several great earthquakes in the past hundred years or so (1897 Assam; 1905 Kangra; 1934 Bihar-Nepal; 1950 Assam). The Himalayan geodynamics and the occurrence of great earthquakes are well summarized by [6-8]. During the last episode of strain release, a 750-km-long segment, which lies between the eastern edge of the 1905 rupture zone and the western edge of the 1934 earthquake, remained unbroken (**Figure 1**). This segment, called the central seismic gap, continues to be under high strain [9]. Large earthquakes occurred in this seismic gap in 1803 and 1833, but the magnitudes of these earthquakes were less than 8, and, hence, they were not gap-filling events ([10,11]). Based on these considerations and on a shortening rate of 20 mm/yr across the Himalayas ([3,12-14]), [7] has estimated the probability of occurrence of a great Mw 8.5 earthquake in the gap in the next 100 yr to be 0.59.

The northeastern region of India is also regarded as one of the most seismically active regions worldwide. A seismic gap called Northeast Seismic gap is there between the 1950 Assam earthquake and the 1934 Bihar-Nepal earthquake (**Figure 1**), where no major earthquake occurred in recent time. The past seismicity data from 1897 shows that the northeastern region has experienced two great earthquakes with magnitudes above 8.0 and about 20 large earthquakes with magnitudes varying between 8.0 and 7.0 [15]. These devastating earthquakes occurred in northeastern India when population was 10 times less than at present; if such earthquakes were to occur in the near future, they would be much more devastating, thus emphasizing the need for

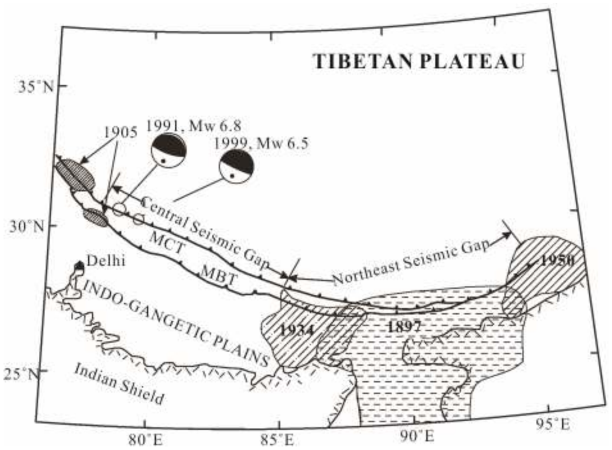

Figure 1. Tectonic map of the Himalayas. The different two seismic gaps are shown. The segment between the rupture areas of the 1905 and 1934 earthquakes is known as the central seismic gap and the segment between the rupture areas of the 1934 and 1950 earthquakes is known as the northeast seismic gap MCT, main central thrust; MBT, main boundary thrust (modified after [6]).

seismic hazard estimation in north eastern India as well. Studies related to hazard estimation depend on the availability of strong ground motion records from past earthquakes.

The strong motion programme in India was started in mid-sixties when an analogue accelerograph named as RESA (Roorkee Earthquake School Accelerograph) and another low cost strong motion instrument known as the Structural Response Recorder (SRR) were developed at Department of Earthquake Engineering (DEQ). Initially these instruments were installed in some river valley projects like Bhakra, Pong, Talwara, Tehri, etc. Later, in 1976, a research project INSMIN (Indian National Strong Motion Instrumentation Network) was funded, on the recommendation of the Planning Commission, by Department of Science and Technology (DST), Government of India, for fabrication, installation, maintenance and operation of RESA-V and SRRs.

Further, on the recommendation of the International Association of Earthquake Engineering, funds were sanctioned by the National Science Foundation, U.S.A. in 1982 to DEQ for installation of an array of 50 analogue accelerographs in Shillong region of North-Eastern India from which fifty analogue accelerographs (imported) were installed. In 1986, through funding from DST about 50 instruments in Himachal Pradesh, about 40 in Western U.P. hills and about 30 instruments in Arunachal Pradesh, Assam and Bihar were installed [16]. All these instruments have now outlived their life and most of them are nonfunctional and unrepairable. However, during their life time this instrumentation has provided useful strong ground motion data which was disseminated and widely used for research.

Strong motion instrumentation programme in our country got big boost and was substantially strengthened in 2004 when DST sanctioned a project for installation of 300 strong motion accelerographs in this region [17]. Under this project, state of the art instruments were procured and successfully installed in different parts of country covering seismic Zone IV and V and some of the thickly populated areas of Zone III of seismic zoning map of India [1]. This network was further strengthened in 2007 when another project entitled "Strong Motion Instrumentation Network in Delhi" was sanctioned by DST to IITR. Under this project 20 digital strong motion accelerographs were installed in the Delhi region [18].

2. Strong Motion Network and Performance

The main objective of the seismic instrumentation is to record the ground motion arising due to natural and manmade disturbances and, in particular, to monitor the seismicity of a given region. This project is also a first step toward developing a "Rapid Response and Damage Prediction System" for India where near real-time strong

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ground-motion records can be used to compute ground-shaking maps showing the area most strongly affected by earthquakes.

The Strong motion instrumentation network of IITR covers the Indian Himalayan range from Jammu and Kashmir to Meghalaya. In total, 298 strong motion stations have been installed in the states of Himachal Pradesh, Punjab, Haryana, Rajasthan, Uttarakhand, Uttar Pradesh, Bihar, Sikkim, West Bengal, Andaman and Nicobar, Meghalaya, Arunachal Pradesh, Mizoram and Assam. 20 instruments out of 298 are installed in Delhi, the national capital of India. **Figure 2** shows location of stations of this network along the Himalayan belt while **Figure 3** shows location of stations installed in Delhi. **Appendixes 1** and **2** give location of these instruments as well as site characteristics of each station.

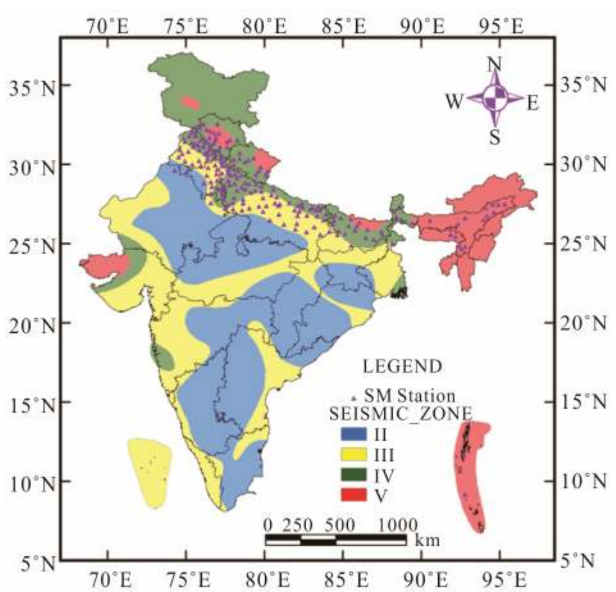

Figure 2. Map showing the location of instruments along the Himalayan belt.

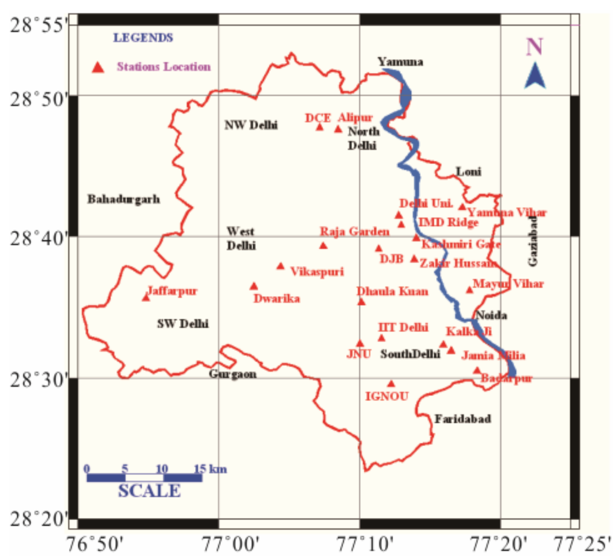

Figure 3. Map showing the location of instruments in Delhi.

2.1. Installation

Seismic networks have been costly to install and maintain. A seismic station requires a sensor to record the ground motion, a computer to save the data, a GPS for accurate timing and location, V Sat/Lease line equipment to send the data back to a central processing house and a power source to run the equipment. Each seismic station is a self-contained system that can take several hours to install. While these stations provide high-quality, reliable data, currently costs and other factors prohibit increasing the density of stations over a large region such as India. Based on these, site selection for instrument installation has been generally a compromise between network geometry, logistics, and safe installation. The ground floor of one or two storied government owned buildings were marked for installation in order to ensure safety and 220 v AC power supply. The average station to station spacing was decided to be 40 - 50 km in plains and less (25 - 35 km) in hilly regions.

However, all 20 stations in Delhi have been installed in open space on a pedestal.

2.2. Connectivity

Networking of instrumentation has created capability of almost real time availability of strong ground motion data. More than 225 of these installations are connected for remote interrogation (from Roorkee) for health monitoring of instruments and data downloading using NICNET of National Informatic System (NIC) and State Wide Area Network (SWAN) of various states. Telecommunication links to the entire instrumentation is planned so that each instrument can be accessed from headquarter or from other remote locations. Data flows through VSAT/Leased line from these field stations to NIC headquarters in Delhi. From Delhi to Roorkee data flows on a 2 MBPS leased line of Bharat Sanchar Nigam Limited (BSNL) (**Figure 4**). All the twenty installations of Delhi are connected to Roorkee through the MahaNagar Telephone Nagar Limited (MTNL) network.

2.3. Instrumentation

All the strong-motion accelerographs (except 12 in Delhi) consist of internal AC-63 GeoSIG triaxial forced balance accelerometers based on the latest Micro Electro-Mechanical Systems (MEMS) technology with a dynamic range of >120 dB effective at ±3 g full scale and band width DC to 100 Hz. All accelerographs have GSR-18 GeoSIG 18-bit digitizers with external GPS. The GSR-18 Strong Motion Recorder has a dynamic range of 111 dB

@100 SPS and 108 dB @200 SPS. The standard 3 channel system has selectable sampling rates from 100 to 250 SPS. A variety of sensors can be connected to the GSR-18 offering solutions for applications in miscellaneous fields. Geodas software developed by GEOSIG is used for communicating with instruments installed in field. GeoDAS is a graphical Microsoft Windows-based application running under Windows 2000/XP/Vista/7. **Figure 5** shows the setup of instruments in field.

The 12 strong motion accelerographs installed in Delhi are K-2 (Kinemetrics K-2s) with internal accelerometer (model Episensor) and 18-bit digitizer. The recording for all instruments is in trigger mode at a sampling frequency of 200 sps. The triggering threshold was initially set at 0.005 g for all the instruments. Later on threshold was reduced to 0.002 g for instruments installed in hilly region (*i.e.* Himachal Pradesh, Uttarakhand and some part of northeast) and 0.001 for all instruments installed in Delhi. The recording is done on a 256-MB GeoSIG or 1-GB Kinemetrics compact flash card.

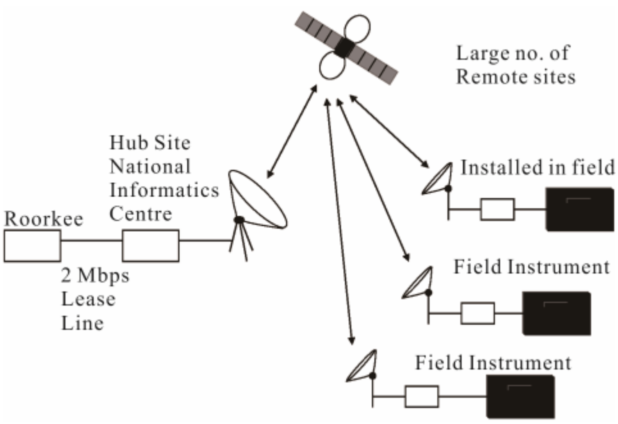

Figure 4. A diagram showing the networking of instruments installed in field to Roorkee (the central station).

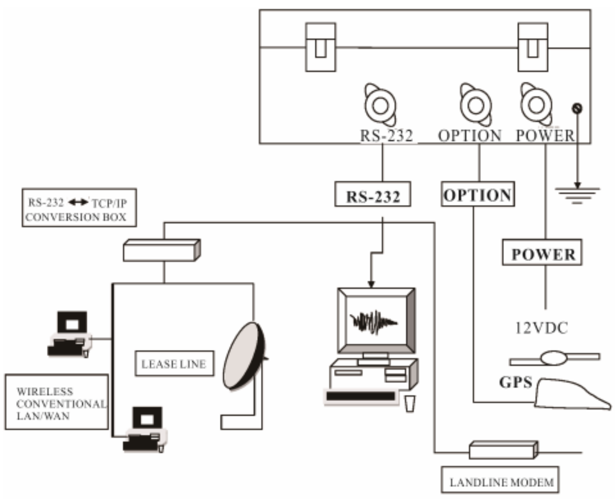

Figure 5. A figure showing the setup of instruments in field.

Each seismic station is powered by external 12-volt batteries with regular charging through a 220 volts alternating current (VAC) line. The health of the instruments is monitored routinely by connecting instruments twice/thrice a day. The central recording station at the IIT receives seismic data from all 298 seismic stations. There are four servers to receive the data, each having approximately 75 stations connected.

2.4. Objectives

Since there is considerable gap between the occurrence of moderate to strong earthquakes it is essential that the instruments are maintained in long term basis. As a result maintenance of strong motion instruments installations in the field becomes very important task. The main goals of the project are both to collect data with a wide range of magnitude, thus allowing us to increase knowledge of the Himalayan area; and to assure the recovery of high quality datasets in cases of strong events. Strong ground motion records during earthquakes provide the basic information for earthquake engineering. These records are input for evaluation of attenuation characteristics and seismic hazard of an area, in perfecting design practices and eventually the basics of earthquake engineering research. The analysis of data from this network will help in validating existing attenuation relationship and making attenuation relationship and/or neural network model most suitable for our country. Advancement in communication in our country has substantially enhanced the importance of strong motion instrumentation network. In future, this network should not only generate crucial data set for ground motion studies but should provide almost real time ground motion scenario immediately after major events which will be of great value for disaster management. Further development of this instrumentation should lead to earthquake early warning system, a dream which is well within our grasp.

2.5. Achievements

The IIT network is equipped with all the latest seismic instruments, and quality seismic data are being produced that will be very helpful in seismological/engineering research. This instrumentation network has recorded around 180 earthquakes in a span of 5 years. Several prominent earthquakes in the Northern Himalayas as well as in the Northeast Himalayas were recorded. Records were obtained for near-source earthquakes at distances of 10 km, and for a far-source earthquake at a distance of 1350 km. **Figure 6** shows example of a strong motion accelerograph record from the *Mw* 6.8 Sikkim-Nepal Border region earthquake that occurred on 18 September 2011, and **Figure 7** shows a strong motion accelerograph record from the *Mw* 7.4 Southwestern Pakistan earthquake

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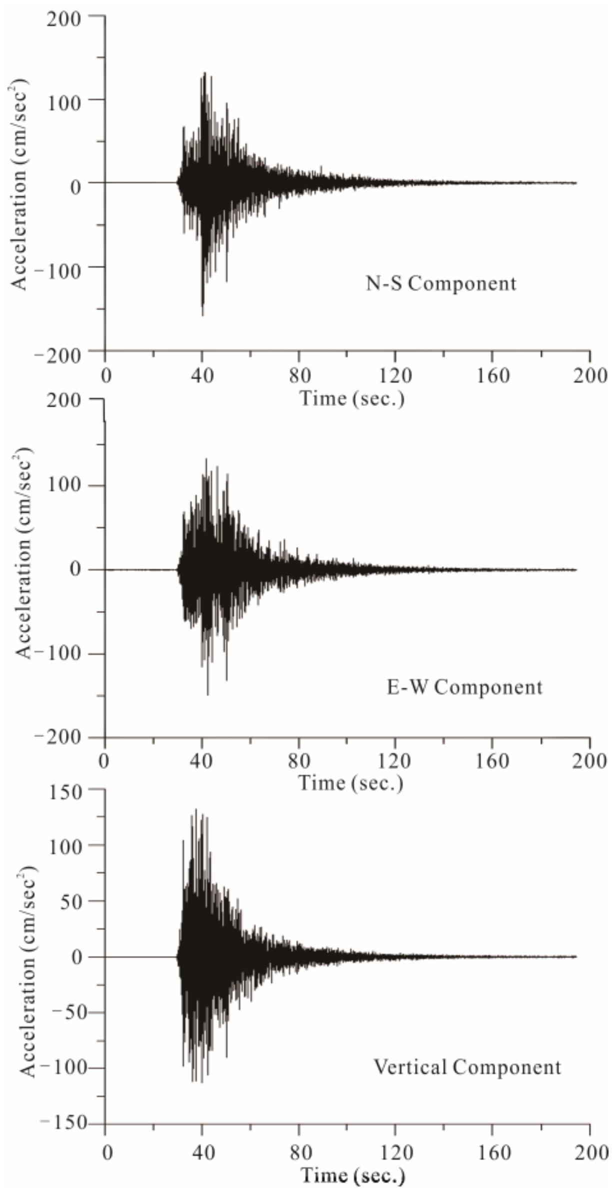

Figure 6. A sample strong motion record of an *Mw* 6.8 earthquake from the Sikkim-Nepal border region recorded at the Gangtok station (epicentral distance 58 km) on 18 September 2011.

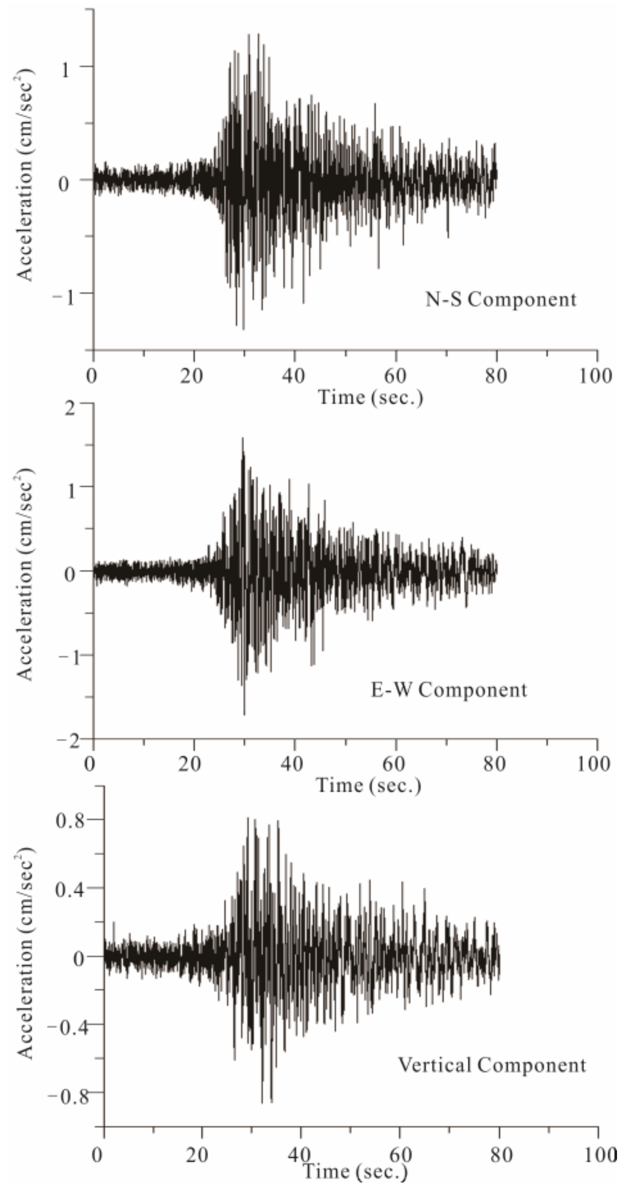

Figure 7. A sample strong motion (Geosig) record of an *Mw* 7.4 earthquake from the Southwestern Pakistan recorded at the Acharya narender Dev College station in Delhi (epicentral distance 1293 km) on 18 January 2011.

that occurred on 18 January 2011.

2.6. Data Processing

Presently, all data processing is carried out in offline mode on different softwares. All downloaded accelerograms are processed before dissemination. Data is processed using two different computer programs for Geosig and Kinemtrics record [18]. In general, both computer programs read headers of ASCII files of records, generate the output header, baseline correct the record, and rotate the horizontal components to get N-S and E-W components.

3. Site Characterization

The local site conditions play an important role in the recorded time history of earthquake ground motions. Different site conditions can induce amplifications of different period ranges in the response spectra ([19,20]). Therefore, the local site conditions become important in ground motion analysis and in earthquake resistant designs. This network has recorded large numbers of ground motion histories. These data are invaluable for strong-motion studies and site effect analyses, as well as for the study of a practical site classification system. The objective of site classification is to classify a group of strong-

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motion station sites into several classes so that the conditions within the same site class are similar and design engineers may understand the general site condition by the class that it belongs to.

Because quantitative subsurface soil properties are not commonly available for every site, the use of surface geology becomes important in understanding the subsurface geologic conditions.

Most site effect studies of earthquake ground motion are based on the soil properties in the upper 30 meters. Some researchers had combined the use of surface geology and shear-wave velocity for site classification [21].

Site characterization is a must for strong ground motion studies. Ideally, detailed geotechnical investigation using bore hole of 20 to 30 meter depth should be carried out at each site. Such data base is available for large number of strong motion stations of Japan. However, such tests are costly and therefore other simple approaches for site characterization are being employed at several places.

Characterization of strong motion stations in India was done by modifying [21] classification which is as shown in **Appendixes 1** and **2**. Classification is based on physical descriptions of the near surface materials by modifying [21] as shown in **Appendix 3**. Hence, classification is mainly based on rock/soil types.

Information about the site geology have been gathered from maps viz., Seismotectonic Atlas of India and its Environs [22], Geological Maps of India [23] and books viz., Geology of Himachal Pradesh [24], Punjab, Haryana, Rajasthan [25], Uttarakhand [26], Bihar [27], Jharkhand [27], Assam [28], Arunachal Pradesh [29], Uttar Pradesh [26], and Geology and mineral resources of the states of Northeast India [30].

Information on rock types have been obtained based on color coding of the Seismotectonic Atlas of India representing particular rock type. For instance, the stations falling under pink color represent firm and hard quartzite and dolomite rocks and hence classed as A. The dark yellow represents sandstone, slates, limestone and dolomites and classed as B. Whereas, the strong motion stations falling in the region of light yellow color are represented by soil and classed as C which falls under CF according to the Seismotectonic Atlas means alluvial deposits along foredeep (**Figure 8**).

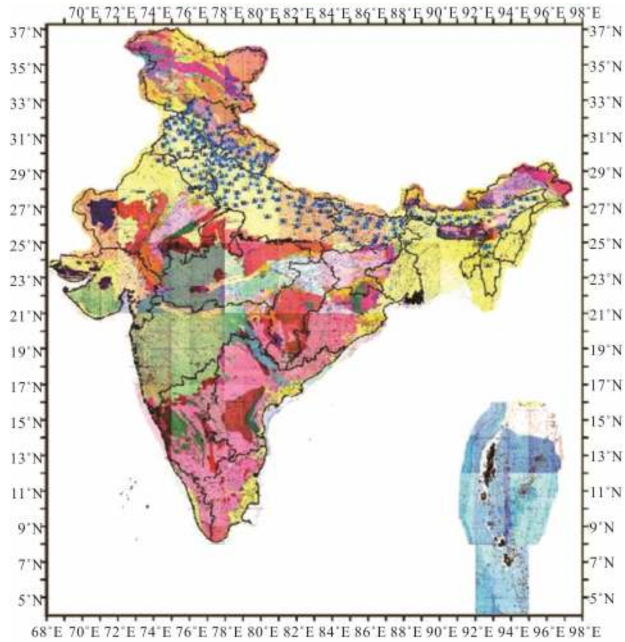

Figure 8. Location of strong ground motion accelerograph stations on different rock/soil type (after [31]).

4. Earthquake Early Warning System

The IIT network is planning to connect more stations, particularly strong-motion accelerograph stations, to the online network, so that a reliable earthquake early warning system (EEW) can be developed. The term EEW is used to describe real time earthquake information systems that have the potential to provide warning prior to significant ground shaking. This is possible by rapidly detecting the ground motion radiating from an earthquake rupture and estimating the resulting ground shaking that will occur later in time either at the same location or some other location. Warning times range from a few seconds to a little more than a minute and are primarily a function of the distance of the user from the epicentre.

EEW systems are operational in several countries/areas like Japan, Taiwan, Mexico, Turkey, Romania and are under development in USA, Switzerland, China and Italy. In countries/areas like Japan, Taiwan and Mexico this system has several success stories although one or two false/missed alarms have also been reported. In most cases alarms could be issued within first ten second of first detection of arrival of earthquake. Relevance and possibility of getting full advantage of EEW system in northern India is perhaps the maximum, in comparison to any other place in world. This is due to the fact that, for northern India, potential source of large earthquakes are located in Himalayas whereas centres of large population as well as big industrial hubs (including our capital Delhi) are in plains adjoining Himalayas. Thick population density and poor adherence to earthquake resistant practices has substantially increased the seismic vulnerability of this region. However, in case of a large earthquake in Himalayas, most of these places can have a lead time of 30 to 70 seconds before the damaging seismic waves arrive. If this real-time seismological information is adequately tuned to the operational requirements of technical systems, life and industrial loss could be significantly reduced. Needless to say, for earthquake disaster mitigation,

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a successful EEW system can be the keystone.

For last about two years, few students of Department of Earthquake Engineering at IIT Roorkee have done research related to EEW for their M. Tech/Ph.D. dissertation. Research is also in advanced stage in searching other attributes for issue of alarms from initial few seconds of P-onset like predominant period, peak displacement, seismic intensity and root square velocity. Relationship of these attributes with magnitude for varying window length is being studied. These results are being interpreted for Indian data set and data sets of other countries and it is expected that three to four attributes for issue of alarm will be identified. Alarm will then be decided with some voting mechanism between these attributes. As the alert/alarm will get updated at regular interval of time during the shaking, some attributes for S-phase of motion will also be searched.

Presently, the network is limited to offline processing. The IIT network is planning to install EEW in Himalays for which funds are awaited. IIT is also planning to make some of the stations real time, so that nearly shake maps can be developed.

5. Concluding Remarks

From this network wealth of strong motion data is getting available which are being used at National and International level by engineers and scientists. A website having address www.pesmos.in is developed through which data is being disseminated to registered users of the website. It is now extremely important that this national asset is nurtured so that it may flourish to serve the nation to its maximum capability. Since strong ground motion data from this network is now getting routinely available, it is essential to make use of this data and fill the gap in the research areas earlier caused due to paucity of data. Although the data base generated from this instrumentation is currently quite small (about 500 time histories from 180 earthquakes), but is good enough to stir substantial research activity. This project aims to use our strong ground motion data for reshaping and upgrading various prevalent relationships for earthquake ground motion parameters, which have been made using strong ground motion data sets from other parts of the world.

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Appendix 1

List of strong motion accelerographs (SMA) stations, their locations and site geology.

Station no.	Station name	Latitude	Longitude	Site class	Site geology according to seismotectonic atlas
1	Almora	29.60	79.66	A	Schist, granodiorites, gneiss
2	Bageshwar	29.83	79.77	A	Quartzite, dolomites
3	Chamoli	30.41	79.32	A	Quartzite, dolomites
4	Champawat	29.33	80.09	A	granite
5	Dehradun	30.32	78.04	C	Soil (slope washed)
6	Haridwar	29.97	78.07	C	alluvium
7	Nainital	29.38	79.46	B	Sandstones/slates/limestones/dolomites
8	Pauri	30.15	78.78	A	phyllites
9	Pithoragarh	29.58	80.21	A	Phyllites/slates/limestones blue with dots
10	Rudraprayag	30.29	78.98	A	Quartzite/slates
11	Tehri	30.37	78.43	A	Phyllites
12	Udham Singh Nagar	29.00	79.40	C	Soil (slope washed)
13	Uttarkashi	30.73	78.44	A	Quartzite/slates
14	Barkot	30.81	78.21	A	Granite/phyllite/slates
15	Chakrata	30.69	77.90	B	slitstones/slates
16	Dhanaulti	30.43	78.24	B	Slates/siltstones/limestones/sandstones
17	Dharchula	29.85	80.55	A	Phyllites/slates/limestones
18	Dhumakot	29.75	79.02	A	Phyllites
19	Garsain	30.05	79.29	A	Schist, granodiorites, gneiss
20	Ghansali	30.43	78.66	A	Quartzite/slates
21	Haldwani	29.22	79.53	C	Soil (slope washed)
22	Joshimath	30.57	79.58	A	Granite/gneiss/quartzite
23	Kapkot	29.94	79.90	A	Dolomite/limestones
24	Kashipur	29.21	78.96	C	Soils (slope washed)
25	Khatima	28.92	79.97	C	Soils (slope washed)
26	Kotdwar	29.75	78.52	B	Sandstones/shales
27	Laksar	29.74	78.03	C	Alluvium
28	Lansdown	29.84	78.68	A	Schist, granodiorites, gneiss
29	Munsyari	30.07	80.24	A	Schist, granodiorites, gneiss
30	Patti	29.41	79.93	A	Schist, granodiorites, gneiss
31	Ranikhet	29.64	79.43	A	Schist, granodiorites, gneiss
32	Rishikesh	30.12	78.28	C	Soils (slope washed)
33	Tanakpur	29.07	80.11	C	Alluvium
34	Didihat	29.77	80.30	A	Schist, granodiorites, gneiss
35	Vikasnagar	30.45	77.75	C	Soils (slope washed)

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36	Bilaspur	31.34	76.76	B	Sandstones/shales
37	Chamba	32.55	76.13	A	Granitoids
38	Dharamshala	32.21	76.32	B	Sandstones/shales
39	Hamirpur	31.69	76.52	B	Sandstones/shales
40	Keylong	32.56	77.01	A	Phyllite, quartzite, schist
41	Kullu	31.96	77.11	A	Phyllite, quartzite, schist, gneiss
42	Mandi	31.71	76.93	B	Sandstones/shales
43	Nahan	30.56	77.30	B	Sandstones/shales
44	RekongPeo	31.54	78.27	A	Granitoids and basic volcanics, gneiss and magmatites
45	Shimla	31.11	77.17	A	Quartzite, gneiss, schist
46	Solan	30.91	77.10	A	Limestones, dolomite, sandstones
47	Una	31.47	76.26	C	Soils (slope washed)
48	Amb	31.69	76.12	C	Soils (slope washed)
49	Dadahu	30.60	77.43	B	Sandstones/shales
50	Dalhousie	32.52	75.96	A	Quartzite, gneiss, schist, phyllite
51	Dehra	31.88	76.22	B	Sandstones/shales
52	Jubbal	31.11	77.66	A	Granitoids and basic volcanics, gneiss and magmatites
53	Kasauli	30.90	76.96	B	Sandstones/shales
54	Manali	32.25	77.19	A	Phyllite, quartzite, schist, gneiss
55	Nalagarh	31.04	76.72	B	Sandstones/shales
56	Nathhpa	31.55	77.92	A	Gneissic complex
57	Jogindernager	31.99	76.80	B	Sandstones/shales
58	Nurpur	32.30	75.88	B	Sandstones/shales
59	Pachchhad	30.72	77.19	B	Sandstones/shales
60	Palampur	32.11	76.54	B	Sandstones/shales
61	Paonta Sahib	30.44	77.62	B	Sandstones
62	Puh	31.76	78.58	A	Phyllite, quartzite, schist
63	Rampur	31.45	77.63	A	Granitoids and basic volcanics, phyllite
64	Saluni	32.70	76.06	A	Granitoids
65	Sundernagar	31.52	76.88	A	Sandstones, shales, dolomite
66	Tisa	32.84	76.15	A	Phyllite, quartzite, schist
67	Amritsar	31.64	74.86	C	Alluvium
68	Bhatinda	30.20	74.95	C	Alluvium
69	Faridkot	30.68	74.76	C	Alluvium
70	Fathehgarh Saheb	30.65	76.39	C	Alluvium
71	Firozpur	30.93	74.61	C	Alluvium
72	Gurdaspur	32.04	75.41	C	Alluvium

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73	Hoshiarpur	31.52	75.93	C	Alluvium
74	Jallandhar	31.32	75.59	C	Alluvium
75	Kapurthala	31.38	75.38	C	Alluvium
76	Ludhiana	30.90	75.84	C	Alluvium
77	Mansa	30.00	75.41	C	Alluvium
78	Moga	30.83	75.15	C	Alluvium
79	Muktsar	30.47	74.54	C	Alluvium
80	Nawanshahar	31.12	76.12	C	Alluvium
81	Patiala	30.35	76.38	C	Alluvium
82	Rupnagar	30.98	76.52	C	Alluvium
83	Sangrur	30.25	75.84	C	Alluvium
84	Mohali	30.73	76.72	C	Alluvium
85	Taran Taran	31.45	74.93	C	Alluvium
86	Ajnala	31.84	74.76	C	Alluvium
87	Anandpur Saheb	31.24	76.49	C	Alluvium
88	Batala	31.82	75.20	C	Alluvium
89	Chamkaur saheb	30.89	76.42	C	Alluvium
90	Dasua	31.81	75.66	C	Alluvium
91	Dera Baba Nanak	32.04	75.02	C	Alluvium
92	Dhar Kalan	32.41	75.80	C	Alluvium
93	GarhShankar	31.23	76.13	C	Alluvium
94	Khanna	30.70	76.24	C	Alluvium
95	Mukerian	31.95	75.61	C	Alluvium
96	Nakodar	31.12	75.49	C	Alluvium
97	Pathankot	32.27	75.66	C	Alluvium
98	Phagwara	31.21	75.77	C	Alluvium
99	Ambala	30.37	76.77	C	Alluvium
100	Bhiwani	28.81	76.14	C	Alluvium
101	Fatehabad	30.65	76.39	C	Alluvium
102	Faridabad	28.38	77.32	C	Alluvium
103	Gurgaon	28.45	77.03	C	Alluvium
104	Hisar	29.13	75.71	C	Alluvium
105	Jhajjar	28.60	76.66	C	Alluvium
106	Jind	29.31	76.34	C	Alluvium
107	Kaithal	29.80	76.42	C	Alluvium
108	Karnal	29.69	77.00	C	Alluvium
109	Kurukshetra	29.97	76.87	C	Alluvium

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110	Mewat	28.09	77.00	C	Alluvium
111	Narnaul	28.06	76.11	C	Alluvium
112	Panipat	29.40	76.95	C	Alluvium
113	Panchkula	30.70	76.87	C	Alluvium
114	Rewari	28.18	76.61	C	Alluvium
115	Rohtak	28.90	76.59	C	Alluvium
116	Sirsa	29.55	75.05	C	Alluvium
117	Sonipat	29.00	77.00	C	Alluvium
118	Yamunanagar	30.15	77.29	C	Alluvium
119	Ballabhgarh	28.34	77.32	C	Alluvium
120	Hansi	29.09	75.96	C	Alluvium
121	Hodal	27.89	77.38	C	Alluvium
122	Palwal	28.13	77.33	C	Alluvium
123	Sadhura	30.38	77.22	C	Alluvium
124	Alwar	27.57	76.59	A	Gneiss/schist
125	Bharatpur	27.21	77.51	C	Aeolian
126	Hanumangarh	29.63	74.29	C	Aeolian
127	Jammu	32.73	74.87	B	Sandstones/shales
128	Car Nicobar	9.18	92.82	B	Sandstones/shales
129	Port Blair	11.66	92.74	B	Sandstones/shales
130	Agra	27.18	78.01	C	Alluvium
131	Aligarh	27.91	78.07	C	Alluvium
132	Azamgarh	26.06	83.19	C	Alluvium
133	Badaun	28.02	79.13	C	Alluvium
134	Bahraich	27.57	81.59	C	Alluvium
135	Balia	25.77	84.14	C	Alluvium
136	Balrampur	27.44	82.17	C	Alluvium
137	Bareilly	28.34	79.42	C	Alluvium
138	Basti	26.79	82.72	C	Alluvium
139	Bijnor	29.38	78.13	C	Alluvium
140	BulandShahar	28.40	77.85	C	Alluvium
141	Devria	26.50	83.78	C	Alluvium
142	Eta	27.56	78.65	C	Alluvium
143	Faizabad	26.77	82.13	C	Alluvium
144	Farrukhabad	27.36	79.64	C	Alluvium
145	Gaziabad	28.67	77.45	C	Alluvium
146	Gazipur	25.57	83.57	C	Alluvium

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147	Gonda	27.13	81.94	C	Alluvium
148	Gorakhpur	26.75	83.37	C	Alluvium
149	Hardoi	27.40	80.13	C	Alluvium
150	Hathras	27.58	77.98	C	Alluvium
151	Jaunpur	25.73	82.69	C	Alluvium
152	Kannauj	27.03	79.92	C	Alluvium
153	Kanpur	26.48	80.35	C	Alluvium
154	KushuNagar	26.75	83.76	C	Alluvium
155	Lakhimpur	27.95	80.79	C	Alluvium
156	Lucknow	26.85	80.93	C	Alluvium
157	Maharaj Ganj	27.14	83.54	C	Alluvium
158	Mainpuri	27.24	79.05	C	Alluvium
159	Mathura	27.47	77.69	C	Alluvium
160	Meerut	28.99	77.72	C	Alluvium
161	Moradabad	28.85	78.77	C	Alluvium
162	MuzaffarNagar	29.47	77.70	C	Alluvium
163	Noida	28.51	77.48	C	Alluvium
164	Pratap Garh	25.92	81.99	C	Alluvium
165	Pilibhit	28.65	79.82	C	Alluvium
166	Rai Bareilly	26.21	81.25	C	Alluvium
167	Rampur	28.79	79.01	C	Alluvium
168	Saharanpur	29.95	77.55	C	Alluvium
169	Shahjahanpur	27.89	79.92	C	Alluvium
170	Sidharth Nagar	27.28	83.07	C	Alluvium
171	Sitapur	27.57	80.68	C	Alluvium
172	SultanPur	26.26	82.07	C	Alluvium
173	Anoop Sahar	28.35	78.27	C	Alluvium
174	Baheri	28.78	79.50	C	Alluvium
175	Bansi	27.17	82.93	C	Alluvium
176	Baraut	29.10	77.26	C	Alluvium
177	Bisalpur	28.29	79.80	C	Alluvium
178	Biswan	27.49	81.00	C	Alluvium
179	Chandausi	29.46	78.79	C	Alluvium
180	Chandpur	29.15	78.26	C	Alluvium
181	Chhata(kosi)	29.72	77.50	C	Alluvium
182	Deoband	29.68	77.68	C	Alluvium
183	Dhampur	29.31	78.50	C	Alluvium

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184	Garh Mukteshwar	28.79	78.09	C	Alluvium
185	Gola Gokarnath	28.09	80.46	C	Alluvium
186	Hapur	28.73	77.78	C	Alluvium
187	Jansath (Khatauli)	29.33	77.86	C	Alluvium
188	Kashganj	27.81	78.64	C	Alluvium
189	Laharpur (Tambaur)	27.41	80.89	C	Alluvium
190	Mankapur	27.06	82.21	C	Alluvium
191	Nakur (Gangoh)	29.92	77.30	C	Alluvium
192	Nautanwa	27.44	83.42	C	Alluvium
193	Nazibabad	29.61	78.35	C	Alluvium
194	Nichlaul (Siswa)	27.31	83.72	C	Alluvium
195	Palia	28.43	80.58	C	Alluvium
196	Pharenda	27.11	83.27	C	Alluvium
197	Sambhal	28.59	78.58	C	Alluvium
198	Shamli	29.46	77.34	C	Alluvium
199	Shikohabad	27.11	78.58	C	Alluvium
200	Tulsipur (Jarwa)	27.53	82.40	C	Alluvium
201	Utraula	27.31	82.41	C	Alluvium
202	Ara	25.56	84.66	C	Alluvium
203	Araria	26.13	87.47	C	Alluvium
204	Banka	24.89	86.91	C	Alluvium
205	Bettiah	26.80	84.52	C	Alluvium
206	Bhagalpur	25.26	86.99	C	Alluvium
207	Bihar Shariff	25.20	85.52	C	Alluvium
208	Chapra	25.78	84.74	C	Alluvium
209	Darbhanga	26.12	85.90	C	Alluvium
210	Gopalganj	26.47	84.44	C	Alluvium
211	Jamui	24.93	86.23	C	Alluvium
212	jehanabad	25.20	84.99	C	Alluvium
213	Katihar	25.56	87.55	C	Alluvium
214	kishanganj	26.10	87.95	C	Alluvium
215	Madhubani	26.35	86.07	C	Alluvium
216	Motihari	26.63	84.90	C	Alluvium
217	Munger	25.38	86.46	C	Alluvium
218	Muzzafarpur	26.12	85.38	C	Alluvium
219	Navada	24.89	85.54	C	Alluvium
220	Patna	25.62	85.15	C	Alluvium

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221	Purnia	25.77	87.47	C	Alluvium
222	Saharsa	25.89	86.59	C	Alluvium
223	Samastipur	25.86	85.78	C	Alluvium
224	Saupaul	26.13	86.61	C	Alluvium
225	Sitamari	26.56	85.52	C	Alluvium
226	Siwan	26.23	84.36	C	Alluvium
227	Bagha	27.13	84.06	C	Alluvium
228	Bahadurganj	26.26	87.83	C	Alluvium
229	Forbesganj	26.30	87.25	C	Alluvium
230	NarkatraGanj	27.10	84.46	C	Alluvium
231	Raghopur	26.30	86.84	C	Alluvium
232	Raxaul	26.98	84.84	C	Alluvium
233	Darjeeling	27.05	88.26	A	Gneiss/schist
234	Jalpaiguri	26.52	88.73	C	Alluvium
235	Kooch Vihar	26.32	89.44	C	Alluvium
236	Malda	25.00	88.15	C	Alluvium
237	Siliguri	26.71	88.43	C	Soils (slope washed)
238	Gangtok	27.35	88.63	A	Gneiss/schist
239	Barpeta	26.33	91.01	C	Alluvium
240	Bongaigaon	26.47	90.56	C	Soils (slope washed)
241	Dhemaji	27.47	94.56	C	Alluvium
242	Dhubri	26.02	90.00	C	Alluvium
243	Dibrugarh	27.47	94.91	C	Alluvium
244	Diphu	25.84	93.44	B	Shale/sandstones
245	Goalpara	26.16	90.63	C	Alluvium
246	Golaghat	26.51	93.97	B	Sandstones
247	Guwhati	26.19	91.75	C	Alluvium
248	Hailakandi	24.68	92.56	C	Alluvium
249	Jorhat	26.76	94.21	C	Alluvium
250	Karimganj	24.87	92.35	C	Alluvium
251	Khokrajhar	26.40	90.26	C	Soils (slope washed)
252	Mangaldai	26.44	92.03	C	Alluvium
253	Morigaon	26.25	92.34	C	Alluvium
254	Nalbari	26.45	91.43	C	Alluvium
255	Naogaon	26.35	92.69	C	Alluvium
256	North Lakhimpur	27.24	94.11	C	Alluvium
257	Sibsagar	26.99	94.63	C	Alluvium

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258	Silchar	24.83	92.80	C	Alluvium
259	Tejpur	26.62	92.80	B	Alluvium
260	Tinsukia	27.50	95.33	C	Alluvium
261	Boko	25.98	91.23	C	Alluvium
262	KataKhal	24.82	92.62	C	Alluvium
263	Cherapunji	25.30	91.70	A	quartzite
264	Jowai	25.44	92.20	B	Sandstones
265	Nongpoh	25.92	91.88	A	Granite
266	Nongstoin	25.52	91.26	A	Granite
267	Shilong	25.57	91.89	A	Quartzite
268	Tura	25.51	90.22	B	Sandstones
269	William nagar	25.51	90.60	A	Gneiss complex
270	Aizawl	23.72	92.73	B	Sandstones
271	Kolasib	24.23	92.68	B	Sandstones
272	Bhalukpong	27.02	92.64	B	Sandstones
273	Bomdila	27.26	92.42	A	Gneiss/schist
274	Itanagar	27.09	93.61	B	Sandstones
275	Seppa	27.28	92.91	A	Gneiss/schist
276	Yupia	27.15	93.72	B	Sandstones/shale
277	Zero	27.54	93.81	B	Quartzite/schist/gneiss
278	Dimapur	25.90	93.73	C	Soils (slope washed)

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Appendix 2

List of strong motion accelerographs (SMA) stations in Delhi with locations and site geology.

Station no.	Station name	Latitude	Longitude	Site class	Site geology according to seismotectonic atlas
1	ANDC, Govindpuri	28.54	77.26	C	Alluvium
2	DCE, Bawana Road	28.80	77.12	C	Alluvium
3	University of Delhi	28.69	77.21	C	Alluvium
4	Dhaula Kuan	28.59	77.17	C	Alluvium
5	Raja Garden	28.66	77.12	C	Alluvium
6	Indraprastha University	28.66	77.23	C	Alluvium
7	IGNOU	28.49	77.20	C	Alluvium
8	DJB, Karol Bagh	28.65	77.19	A	Quartzite
9	Alipur	28.80	77.14	C	Alluvium
10	Jamia Millia Islamia	28.53	77.27	C	Alluvium
11	IIT Delhi	28.55	77.19	C	Alluvium
12	JNU	28.54	77.17	A	Quartzite
13	NSIT, Dwarka.	28.61	77.04	C	Alluvium
14	Maharaja Agrasen College, Mayur Vihar	28.60	77.30	C	Alluvium
15	IGIPE, Vikas Puri	28.63	77.07	C	Alluvium
16	Jafarpur Kala	28.59	76.91	C	Alluvium
17	Zakir Hussain College	28.64	77.23	C	Alluvium
18	NPTI, Badarpur	28.51	77.30	C	Alluvium
19	Bhim Rao Ambedkar Colleger, Delhi	28.70	77.29	C	Alluvium
20	Ridge Observatory, IMD (NDI)	28.68	77.21	A	Quartzite

Appendix 3

Site class for strong motion accelerographs (SMA) station by modifying [21].

Site class	General description	Shear wave velocity
A	Firm/hard rocks (Fresh and compact metamorphic e.g. gneiss, schist, migmatites, phyllites, quartzites, dolomites and igneous rocks e.g. granites, granodiorites, granitoids, basic volcanics).	700 m/sec - 1620 m/sec
B	Soft to firm rocks (Sedimentary rocks e.g., sandstone, sltstone, shale, limestone).	375 m/sec - 700 m/sec
C	SOILS (Alluvium, slope wash material, Aeolian).	200 m/sec - 375 m/sec

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