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STRONG MOTION NETWORK IN TEHRI DAM AND KOTESHWAR DAM IN UTTARAKHAND HIMALYA

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Abstract

Tehri dam with a height of 260.5 m is the fifth tallest dam in the world. It is constructed on confluence of Bhagirathi river and Bhilangana river, in the Garhwal Himalaya of Uttarakhand state of India. According to Seismic Zoning map of India this region falls in Seismic Zone IV (IS: 1893 - Part 1, 2002) and lies in a ~ 700 km seismic gap in western parts of.In last three decades several moderate earthquakes have been observed in Uttarkhand region, namely the 1991 Uttarkashi earthquake (M_w~6.6) and the 1999 Chamoli earthquake (M_s~6.3). From last 200 years, no great earthquakes have been recorded in this seismic gap. Great earthquake with recurrence interval of about 290-980 years has been estimated for Dehradun region which is approximately 27 km from Tehri region. So it is of paramount importance to study the behavior of dam body during occurrence of such earthquake, if it occurs. This can be achieved by deploying the strong motion instrumentation network inside the dam body.

In March, 2015, Tehri Hydro Development Corporation India Ltd. (THDCIL), Rishikesh had completed the complete instrumentation of Tehri dam and its Power House, as well as Koteshwar dam. On the request of THDCIL, Department of Earthquake Engineering (DEQ) of Indian Institute of Technology Roorkee (IITR) is providing guidance within a framework of Memorandum of Understanding (MOU) between DEQ, IITR and THDCIL, to monitor the health of various Strong Motion Accelerometers (SMA's) installed by THDCIL inside the Tehri dam, and its power house as well as in Koteshwar dam. From year 2015 to till date the SGM network has recorded thirteen earthquakes having magnitudes varying from 3.2 to 7.9. The analysis of strong ground motion data of acceleration time histories is done in form of PGA, its FFT and acceleration response spectra. The maximum PGA value 13.52 cm/sec^2 has been recorded in TIG. The observed PGA for recorded acceleration time histories has been compared with NGA models, 2008.

Keywords: Tehri Dam, PGA, Response Spectra, Garhwal Himalaya

1. Introduction

Tehri dam with a height of 260.5 m is the fifth tallest dam in the world. It is located in the Garhwal-Kumaon Himalaya of Uttarakhand state of India. It is constructed on the confluence of Bhagirathi river and Bhilangana river. According to Seismic Zoning map of India this region falls in Seismic Zone IV ([1] and lies in a ~ 700 km seismic gap in western parts of Himalayan [2]. In last more than two decades several moderate earthquakes have been observed in this region, namely the 1991 Uttarkashi earthquake (M_w 6.6) and 1999 Chamoli earthquake (M_s 6.4). From last 200 years, no great earthquakes have been recorded in this seismic gap. Great earthquake with recurrence interval of about 290-980 years has been estimated for Dehradun region which is approximately 27 km from Tehri region [3]. Various studies based on seismological records and recent space geodetic measurement; suggest that a region has high potential for occurrence of a great earthquake in future [4]. So it's of paramount importance to study the behaviour of Tehri dam body during occurrence of such earthquake, if it occurs. This can be achieved by deploying the strong motion instrumentation network inside the dam body. Records of such strong motion instruments installed inside Tehri dam during earthquake will be required for two important purposes: (a) to calibrate the analytical tools which were used during design phase for seismic analysis of dam. These records are the only way to get the feedback on actual earthquake response of the dam and compare the same as predicted by analytical model. These records will give estimate on deterioration of material properties of dam using system identification and will useful to estimate response of dam during future earthquakes, (b) These records can also be used to guide the search for possible damages in the dam during an earthquake. It may also be useful for establishment of rehabilitation measures. Along with this, a recording of free field ground motion is always an essential part of such studies. During the design stage the response of dam for future earthquake has been carried out using generally synthetically generated earthquake time histories as input to the mathematical model of dam structure. Record of an actual earthquake is like a test or calibration of synthetically generated time histories used for analysis. It is therefore essential that a standalone Strong Motion Accelerograph (SMA) for recording free field ground motion should be installed in the vicinity of dam. For free field motion, this instrument must be located far enough from dam so that it is not affected by the presence of dam and at the same time should be close enough to record ground motion which should be representative for the site. Approximately a distance of free field accelerograph must be 3 to 4 times of the dam height from the foot of dam is quite appropriate. Recording of abutment/canyon motions during an earthquake is quite essential for understanding the behavior of dam -foundation interface caused by various aspects of soil- structure interaction. This understanding can contribute significantly in accurate analysis for the response of dam. It is therefore essential to record motion of the canyon at the top level and at the base.

In view of above, the deployment of 10 stationed Strong Motions Network (SGM) has been completed by THDCIL in March 2015 inside Tehri dam, its Power House and one free field station to measure the strong motion records at different level of Tehri dam and its Power House. In addition to that 3 station network have also been deployed in Koteshwar dam which is constructed 14 miles downstream of Tehri dam having capacity of 400 MW.

The present paper consists the information about the distribution of strong motion network deployed in Tehri dam and its Power house as well as the numbers of records have been obtained till date due to occurrence of local and regional earthquakes in the region. The entire network is being maintained by Department of Earthquake Engineering, Indian Institute of Technology Roorkee (IIT Roorkee) and the study is sponsored by the Tehri Hydro Development Corporation India Limited (THDCIL), Rishikesh.

2. Strong Motion Network

A 13-station strong motion network has been deployed in Tehri dam, its Power House and Koteshwar dam. The distribution of these strong motion instrumentaion are discussed in this section.

2.1 Tehri Dam

Fig. 1 shows the locations of seven accelerometers installed in Tehri dam. Five accelerometers named as S1, S2, S3, S4 and S5 respectively have been deployed inside Top Inspection Gallery (TIG) at an elevation of 835 m above mean sea level and all these five accelerometers were connected to DAS-1, which is placed inside TIG. One accelerometer is deployed in the Middle Inspection Gallery (MIG) at an elevation of 680 m above mean sea level and one accelerometer is deployed in the Approach Gallery in Right Abutment Bed River (AGRBR) at an elevation of 572 m above mean sea level. Accelerometer deployed in MIG and AGRBR are connected to DAS-2 deployed in Terminal House (at EL. 638 m) lie outside portal of AGRBR.

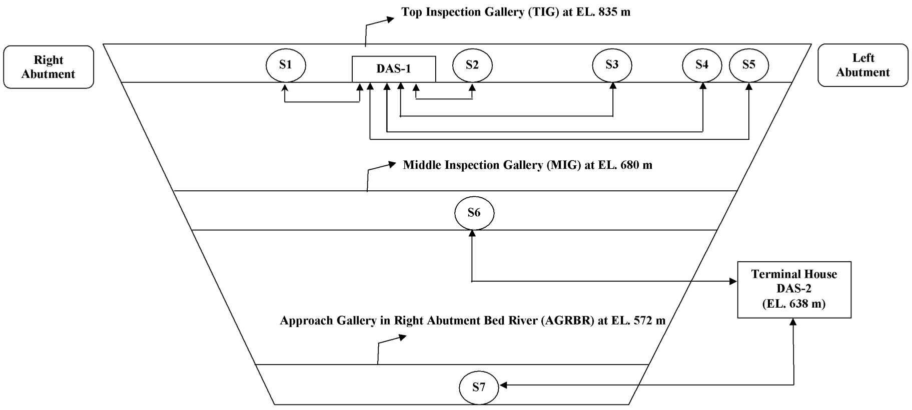


Fig. 1 - Schematic diagram of Seven SMA's deployed in Tehri dam with their connection to DAS-1 and DAS-2 respectively

2.2 Power House (Tehri Dam)

Two standalone accelerographs are deployed inside power house, one at an elevation 622 m near battery room and another at an elevation 584 m near unit 4, as shown in **Fig. 2.** One free field stand alone accelerograph is deployed nearer to entry gate of Power house, which is approximately 1 km from the bottom of Tehri dam.

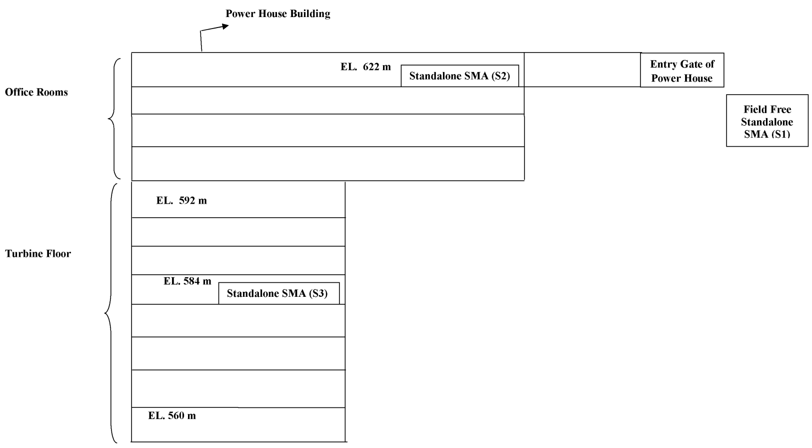


Fig. 2 - Schematic diagram of Standalone SMA's deployed inside Power House of Tehri dam and Free field location.

2.3 Koteshwar Dam

In Koteshwar dam total three accelerometers have been deployed, as shown in **Fig. 1 (c)**. Accelerometer named as S1 placed at dam top on non-overflow section block no. 3 at about chainage (-)150 having an elevation 620 m, S2 at middle of dam body at an elevation 546 m and S3 at foundation of dam at an elevation 523 m. All three accelerometers were connected to DAS-3 placed at the dam top.

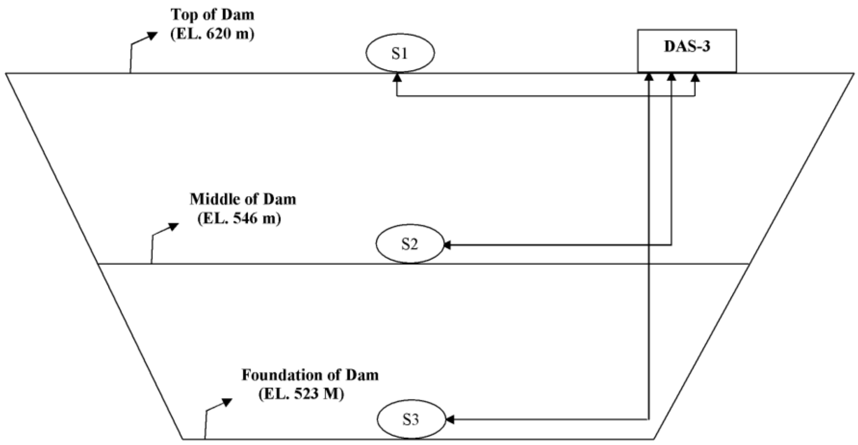


Fig. 3 - Schematic diagram of three SMA's deployed inside in Koteshwar dam with their connection to DAS-3.

3. Specifications of Equipments

For the purpose of sensing the ground motion at each proposed location inside the Tehri dam and Koteshwar dam, an Epi-Sensor (**Fig. 4 (a),** i.e. tri-axial force balance accelerometer (Model FBA ES-T manufactured by M/S Kinemetrics, USA) has been installed. These Epi-Sensors have user selectable full scale recording ranges ± 4g, ± 2g, ± 1g, ± 0.5g or ± 0.25g, and bandwidth of DC to 200 Hz with a dynamic range of 155 db. The output voltage levels of these Epi-Sensors are also user selectable at either 2.5V (5Vpp) or 10V (20Vpp) single ended, or ± 5V (10Vpp) or ± 20V differential (40 Vpp). The output of five Epi-Sensors deployed in TIG of Tehri dam are coupled to a 24 multiple channel DAS (**Fig 4 (b),** Model Granite, manufactured by Kinemetrics, USA). Similarly output of Epi-Sensors deployed in MIG and AGRBR of Tehri dam as well as Koteshwar dam are coupled to the 12 multiple channel DAS for the purpose of recording the digital data. The Granite DAS amplifies, digitizes and filters the recorded signal employing 24 bit digitizer. For each Epi-Sensor the digital data is being acquired at a sampling rate of 200 samples /sec. The trigger value for each Epi-Sensor is set to the value equal to 0.0015 g (i.e. 1.5 cm/sec2). Two standalone accelerograph (**Fig 4 (c),** Model Basalt, manufactured by Kinemetrics, USA) has been deployed inside power house of Tehri dam, whereas one standalone accelerograph for free field motion record is deployed outside the entry gate of Power House. Basalt has 4 channel recorders with 24 bit digitizers. Basalt acquired the digital data at a sampling rate of 200 samples / sec. The trigger value for Basalt is set to the value equal to 0.0015 g (i.e. 1.5 cm/sec^2).

(a) **(b)** **(c)**

Fig. 4 – (a) Epi-sensor (Model FBA ES-T), (b) Standalone SMA (Model Basalt) and (c) DAS (Model Granite).

4. Strong Ground Motion Database

From the year 2015 to till date thirteen local and regional earthquakes have been recorded by SGM network. The epicenter of local events occurred around Tehri dam are shown on the tectonic map of the region in **Fig 5.** The hypocentral parameters of these earthquakes, given by Indian Metrological Department (IMD), New Delhi, are listed in **Table 1.**

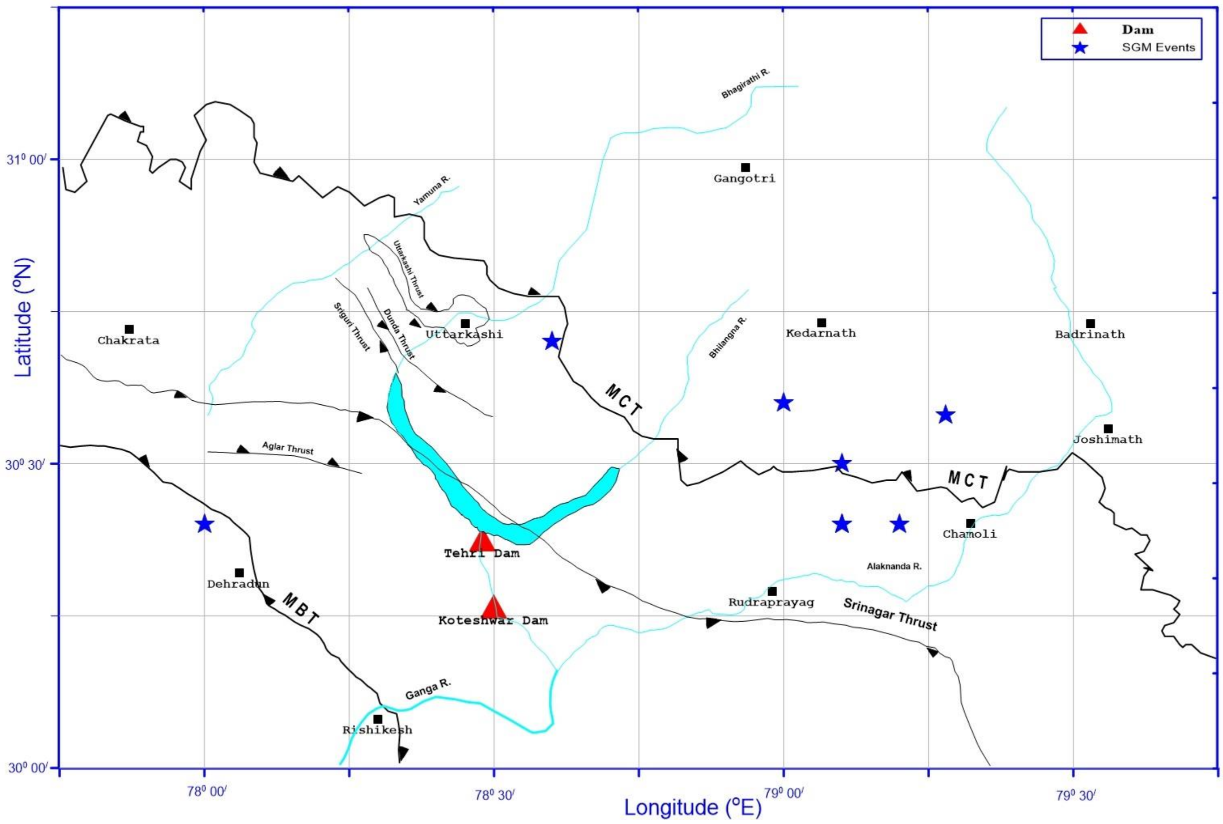


Fig. 5 - Epicenters of local earthquakes that produced strong motion records at Tehri & Koteshwar dams.

Table 1 – Hypocentral parameters of earthquakes given by IMD, New Delhi.

Date	Origin Time (UTC)	Location		Focal Depth (km)	Mag.	Region of occurrence	Recorded Station
		Lat. (° N)	Long.(°E)				
25/04/2015	06:11:25	28.1	84.6	10	7.9	Nepal	MIG, AGRBR
23/06/2015	20:33:21	30.4	78 .0	10	3.2	Uttarakhand	Free Field
26/10/2015	09:09:31	36.5	70.8	190	7.5	Afganisthan	MIG, Koteshwar
01/12/2016	16:52:48	29.8	80.6	10	5.2	Nepal-India Border, Uttarakhand	Koteshwar
06/02/2017	17:03:08	30.5	79.1	33	5.8	Distt. Rudraprayag, Uttarakhand	MIG, Koteshwar
06/02/2017	20:21:45	30.6	79.0	10	3.6	Distt. Rudraprayag, Uttarakhand	Koteshwar
07/04/2017	10:32:58	30.4	79.1	10	4	Distt. Rudraprayag, Uttarakhand	Koteshwar
10/04/2017	08:50:34	30.7	78.6	10	3.8	Distt. Uttarkashi, Uttarakhand	TIG, Free Field
06/12/2017	15:19:54	30.4	79.1	30	5.5	Distt. Rudraprayag, Uttarakhand	TIG, MIG, Free Field, Koteshwar
28/12/2017	11:17:28	30.4	79.2	33	4.7	Distt. Rudraprayag, Uttarakhand	Koteshwar
24/09/19	11:01:55	33.1	73.7	10	6.0	Pakistan India (JK Border Region)	TIG
13/12/19	11:26:46	30.58	79.28	11.5	4.4	Chamoli	MIG, Free Field
20/12/19	11:39:51	36.5	70.5	190	6.1	Hindukush	MIG, Free Field

5. Strong Ground Motion Parameters

The ground motion that cause severe damage to loss of human life and its habitat is referred as Strong Ground Motion (SGM). Earthquake engineers have keen interest to study these strong ground motions and it characteristics. Time history is the most common way to describe the ground motion. It defines its amplitude as function of time. Ground acceleration, velocity and displacement time histories are the most common time domain parameters of strong ground motion. Acceleration time history show high frequency content of motion, whereas velocity time history shows intermediate and displacement time history emphasis on low frequency content of ground motion. One of these parameters is measured directly with the use of instrumentation; while other can be computed indirectly by using mathematical process i.e. integration or differentiation. Peak Ground Acceleration (PGA), most easily obtained and widely used parameter to describe ground motion. **Fig. 6 (a)** depict example of longitudinal acceleration time history recorded by free field standalone SMA deployed approximately 1 km away from the bottom of Tehri dam nearer to the entry gate of Power House. **Fig's 6 (b) and 6(c)** depict longitudinal velocity and displacement time histories which are obtained by process of integration. The analysis of recorded earthquakes acceleration time histories are done in form of PGA, its FFT and acceleration response spectra.

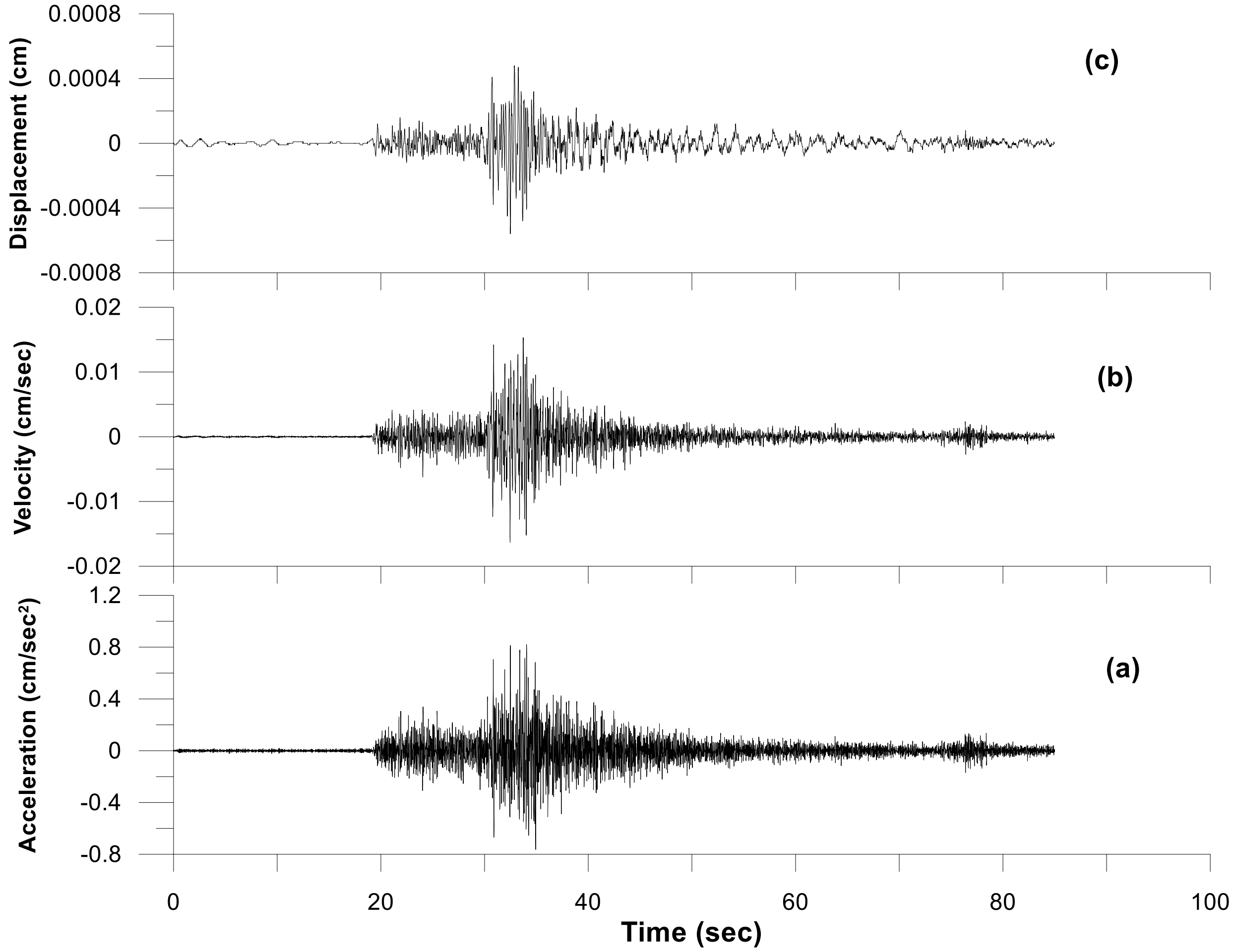


Fig. 6 - Acceleration (a), velocity (b) and displacement time history of the December 13, 2019 Chamoli earthquake (mag.~4.4) recorded at Free field Standalone SMA deployed outside the entry gate of Power House (Tehri Dam) (epi. dist.-80 km).

During an earthquake, the dynamic response of structures (i.e. buildings, bridges etc) is very sensitive to the frequency at which they are loaded. Therefore, complete knowledge about the frequencies which is carried by ground motion during an earthquake occurrence has been critical for research purposes. The frequency content describes how the amplitude of a ground motion is distributed its energy among different frequencies. Ground motion frequency contents can be easily computed by transforming the ground motion from time domain to frequency domain through Fourier transformation. In the frequency domain, the Fourier amplitude spectrum is used in the quantification of strong ground motion. A plot of Fourier amplitude versus frequency is known as Frequency Amplitude Spectrum (FAS) [5]. For earthquake like time history, FAS is broader as it contains wide range of frequencies due to jagged and irregular nature of time history. **Fig. 7** shows an example of Fourier amplitude spectra for acceleration time history recorded by Free field Standalone SMA due to 13th December, 2019 Chamoli earthquake (Fig 2).

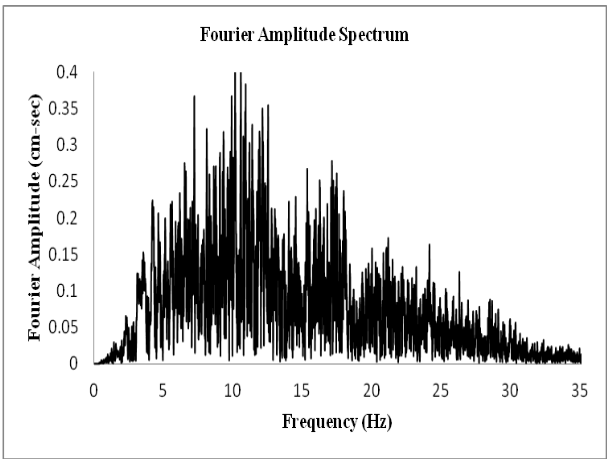


Fig. 7 - Fourier Amplitude Spectra for acceleration time history recorded at the Free field Standalone SMA due to 13th December, 2019 Chamoli earthquake having magnitude 4.4. (Fig 2).

Another very important description of frequency content of earthquake time history is response spectra. Response Spectra (RS) is the most fundamental engineering tool to characterize ground motion in earthquake engineering and forms the strong basis for most design and analysis of structures. The concept of response spectrum is defined as the maximum response of a Single Degree of Freedom (SDOF) system to a particular ground motion as a function of natural frequency and damping of the SDOF system [6, 7]. Response spectra are an indirect way of reflecting strong ground motion characteristics, since they are filtered by response of SDOF systems. For design purposes, engineers have to incorporate natural period or natural frequency in the design of a structure using seismic codes, which are developed using response spectrum analysis. Earthquake parameters such as epi-central distance, magnitude, duration, and local soil conditions at the recording station and source characteristics influence the shape and amplitude of response spectra. **Fig. 8** shows an example of the acceleration response spectra of the 13th December, 2019 Chamoli earthquake recorded by Free filed Standalone SMA Station for 5 % damping.

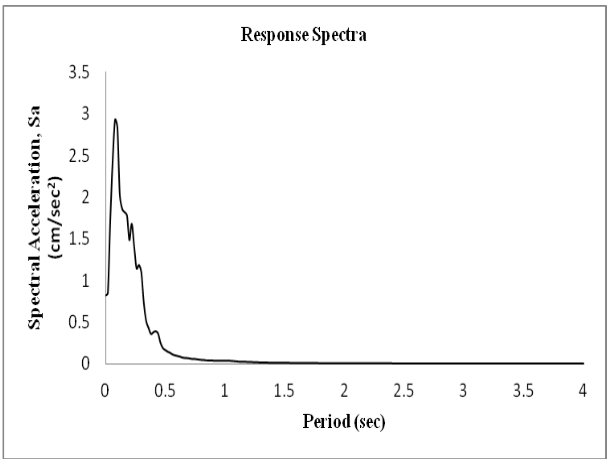


Fig. 8 - Acceleration response spectra for 5 % damping at Free field station due to 13th December, 2019 Chamoli earthquake having magnitude 4.4. (Fig 2).

6. Processing and Analysis of Strong Motion Data

For an earthquake engineering applications, the amplitude (i.e. Peak ground motion) and Frequency content (i.e. Fourier Amplitude Spectra and Response Spectra) are of prime significance as discussed in section 5. Therefore, the analysis of recorded earthquakes acceleration time histories are done in form of PGA, its FFT and acceleration response spectra. The hierarchy of various steps to be followed to measure the amplitude, Fourier spectra and response spectra for recorded strong ground motion are described in **Fig 9.** The maximum observed value of PGA's for recorded earthquakes events that are mentioned in Table 2 with their respective epi-central distance from dam site location are given in Table 2.

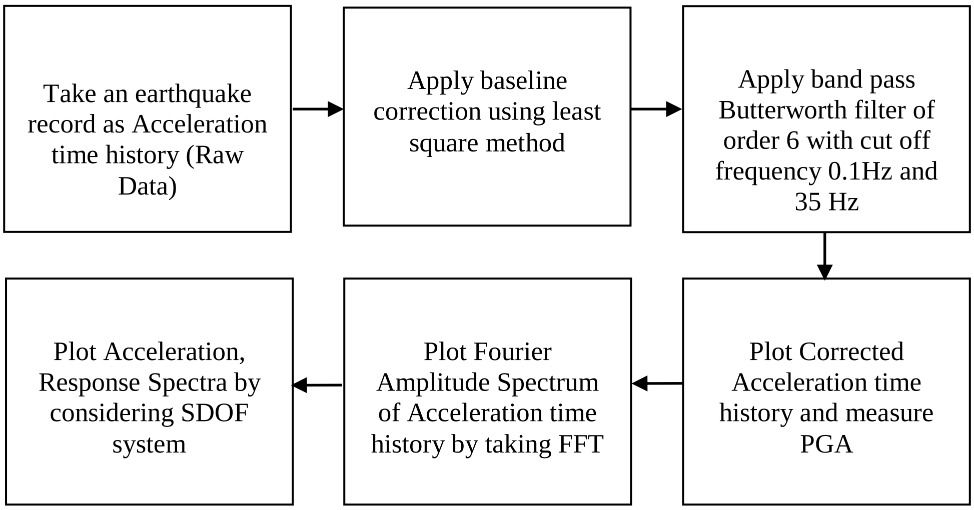


Fig. 9 - Various steps follow to process strong ground motion records.

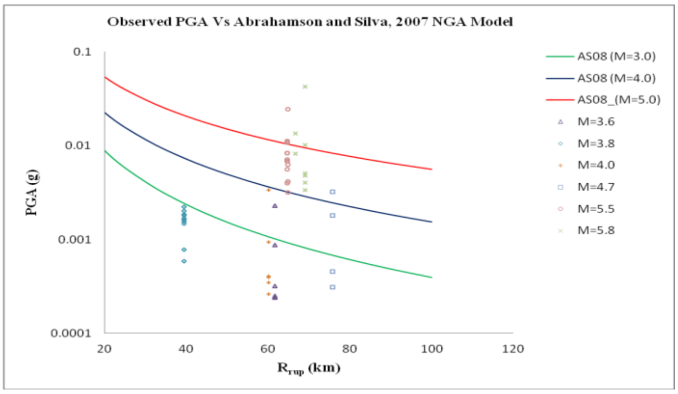
Table 2 – Maximum PGA value recorded by network for each earthquake events recorded by SGM network in last 5 years.

Date	**Origin Time (UTC)**	**Eq. Mag.**	**Distance From Tehri Dam (km)**	**Max. PGA Record (cm/sec^2)**
25/04/2015	06:11:25	7.9	651	2.69
23/06/2015	20:33:21	3.2	46	5.70
26/10/2015	09:09:31	7.5	1016	4.86
01/12/2016	16:52:48	5.2	208	2.59
06/02/2017	17:03:08	5.8	61	41.68
06/02/2017	20:21:45	3.6	61	2.23
07/04/2017	10:32:58	4	61	3.32
10/04/2017	08:50:34	3.8	39	1.74
06/12/2017	15:19:54	5.5	59	24.10
28/12/2017	11:17:28	4.7	69	3.17
24/09/19	11:01:55	6.0	544	2.58
13/12/19	11:26:46	4.4	80	1.11
20/12/19	11:39:51	6.1	1004	0.513

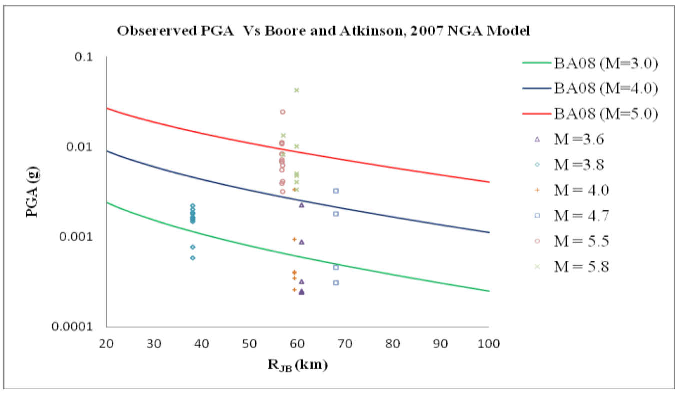
7. Results

The observed PGA for given recorded acceleration time histories has been compared with NGA models (Next Generation of Ground-Motion Attenuation Model), it is a multidisciplinary program of USA conducted in 2008 by Pacific Earthquake Engineering Research Center (PEER) in conjunction with Geological Survey and The South California Earthquake Center. The prime objective of this programmed is to develop a new ground-motion prediction relations through a comprehensive and highly interactive research program. Under this project, a total five sets of ground motion models were developed namely: Abrahamson and Silva, 2007 [9]; Boore and Atkinson, 2007 [10]; Campbell and Bozorgnia, 2007 [11]; Chiou and Youngs, 2006 [12]; Idriss, 2007 [13]; to predict PGA, PGV and response spectral ordinates for periods up to 10s. Here we do not discuss these models in details, for that we could refer to Special Issue on the NGA Project [14].

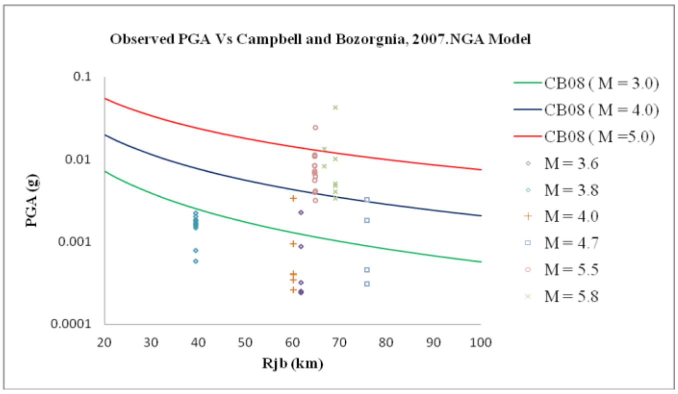
To compare the observed PGA values with NGA models, we consider all our sites as rock site with average V_{S30} = 1300 m/s. The style of faulting for each earthquake is taken from yearly report titled Seismological Network around Tehri Region, EQ: 2015-19, submitted to THDCIL. Whereas various distance parameters like R_{rup}, R_{JB} are compute using programme name Z_{torr} (written in matlab, Unpublished). The scatter plot of observed PGA values versus estimated PGA with distance for Abrahamson and Silva, 2007 **(refer Fig. 10a);** Boore and Atkinson, 2007 **(refer Fig.10);** Campbell and Bozorgnia, 2007 **(refer Fig. 10c).**



(a)



(b)



(c)

Fig. 10 – Scatter plot of observed PGA versus estimated PGA with distance for (a) Abrahamson and Silva (2007), (b) Boore and Atkinson (2007) and (c) Campbell and Borzorgnia (2007) (NGA Model considering V_{S30} = 1300m/s, Type of Fault: Reverse Strike Slip).

8. Summary

During last 5 years, after the complete installation of SGM network in Tehri dam, its Power House and in Koteshwar dam, a total thirteen earthquakes have been recorded. This technical Paper contains the complete information about the maximum recorded PGA value for various site locations during the occurrence of strong earthquake. In **fig 10 (a), (b) and (c)** shows observed values of PGA for magnitude 5.5 and 5.8 magnitude are much higher than estimated values by all three NGA models, reason behind that all these three models have been developed using either earthquake data recorded at basement or ground level its does include the earthquake recorded at various floor levels of buildings, so it's completely exclude the effects of height of building where as, in our some of the PGA values are recorded at the top of dam. But in case of earthquake record of magnitude 5.5 recorded at free field site the observed PGA value is must closer to the estimated PGA by all three models. Whereas for magnitude 3.6 and 3.8 the PGA value are overestimated by all three NGA models. These entire three models are more reliable to estimate PGA value for earthquake having magnitude greater than 5

8 Acknowledgement

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