GENERATION OF SHAKE MAPS

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the award of degree of

MASTER OF TECHNOLOGY

in

EARTHQUAKE ENGINEERING

(With Specialization in Seismic Vulnerability and Risk Assessment)

By

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CANDIDATE'S DECLARATION

I, hereby, declare that the study, which is being presented in this dissertation report, entitled **"GENERATION OF SHAKE MAPS"** in partial fulfillment of the requirements for the award of degree of MASTER OF TECHNOLOGY in EARTHQUAKE ENGINEERING with specialization in SEISMIC VULERABILITY AND RISK ASSESMENT, submitted in the Department of Earthquake Engineering, IIT Roorkee, is an authentic record of my own work under the supervision of **Dr. H.R. Wason,** Emeritus Fellow, and **Dr. M.L. Sharma**, Professor in Department of Earthquake Engineering, Indian Institute of Technology Roorkee.

I have not submitted the matter embodied in this dissertation report for the award of any other degree.

Date:

Place: Roorkee

Ashish Kumar Verma

CERTIFICATE

This is to certify that above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

The purpose of a Shake map is to provide rapid estimate of strong ground shaking which provides emergency response organizations useful information in case of a damaging earthquake. This report investigates the existing hybrid procedures for computation of Shake map in near real time and also how local site conditions affect the ground motion prediction analysis. Further, a strategy to generate Shake maps for Uttarakhand Himalayan region for a moderate size to large magnitude earthquake recorded at one or more stations within Uttarakhand Himalayan region is outlined. To validate the method, 29th March, 1999 Chamoli earthquake and 20th October, 1991 Uttarkashi earthquake in this region has been chosen and the corresponding shaking map has been generated. This shaking map has been compared with a recorded peak ground acceleration of the same event and the has been found to be acceptable. Lastly, some scenario shaking maps have been generated to better understand the seismic risk to Uttarakhand Himalayan region from nearby tectonics features.

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CHAPTER 1

GENERAL INTRODUCTION

A method to develop and implement Shake Maps for significant earthquake events in Himalayan region from Nepal to Kangra region has been proposed in this study. In this report, Chamoli Earthquake (1999) and Uttarkashi Earthquake (1991) have been considered for Uttarakhand Region. The concept of Shake Maps was originally conceived by Wald *et al.* (1999) and was implemented utilizing a dense strong motion network in California. The implementation of this concept in Chamoli District and Uttarkashi District poses new challenges such as sparse seismographic network and unreliable and incomplete event data sets.

Some basic terms that need to be introduced and understood for the development of shaking maps has been discussed below.

1.1 EARTHQUAKE

An Earthquake may be defined as an event which leads to ground shaking and release of seismic energy due to the sudden slip along a fault, volcanic or magmatic activity, or any other sudden changes in stress in soil-rock layers. Terms such as seismic activity and seismicity refers to frequency and size of earthquake which is experienced in an area over a period of time. The most common scale on which earthquakes are reported nowadays is the moment magnitude scale which is based on seismic moment (Hanks and Kanamori, 1979). However, different national seismological observatories report earthquakes on the magnitude scales, the body wave magnitude scale (m_b), the surface wave magnitude scale (M_s) and Richter scale (M_L). All these scales have been found to be numerically similar and valid over a range. These scales however have been found to be affected by scale saturation at larger magnitudes. M_s has been found to saturate above 8.0, M_L starts saturating over 7.0, and m_b saturates above 6.0 magnitudes. Moment magnitude scale however is not affected by saturation and hence has been found to be best suited for the purpose of earthquake source on the basis of seismic moment. Earthquakes which have a magnitude 3 or less are generally very weak and unnoticeable whereas those events which have a magnitude of 7 or more have the potential to cause serious damage even at large distances from the epicentre depending on the depth of the focus of the event. Different agencies employ different Intensity scales to measure the intensity of shaking, e.g. MMI, MSK, MCS, and JMA. But the basic philosophy remains, that a shallow earthquake will cause greater damage than a deep one considering all other parameters remain constant. An earthquake event generally manifests itself onto the ground surface in the form of shaking and sometimes also leads to the displacement of the ground surface. The point at which the initial rupture of the earthquake event takes place is called the focus or hypocentre. The epicentre is defined as the point which lies directly above the hypocentre.

1.2 STRONG GROUND MOTION

Strong ground motion is defined as the strong shaking produced by an earthquake in the close proximity (less than about 50 km) of a causative fault. When strong ground motion occurs the shaking strength triggers the seismometer to start recording the event. This concept of strong ground motion also covers the variations associated with fault ruptures pertaining to total displacement, released energy and the velocity of rupture. The most widely accepted and used measure of strong ground motion studies is Peak Ground Acceleration (PGA). The PGA is defined based on the handling of the two horizontal components of the triaxial ground motion records of the accelerograms.

The acceleration response spectra is the most important parameter of strong ground motion pertaining to seismic design. However, nowadays displacement and energy spectra are being used for the same. This change in recent years of moving away from the traditional force based seismic design is due to new research into the fact that earthquakes are not controlled by acceleration alone and damage is better prevented by designing for displacements and energy dissipation.

1.3 SHAKE MAPS

A Shake Map or a shaking map is basically a seismologically based interpolation algorithm which exploits data of observed ground motions and the available knowledge of seismology to determine maps that represent ground motion at local and regional scales. A Shake map is basically a pictorial representation of the ground shaking that is produced by an earthquake. The basic difference between a Shake map and a normal epicentral map is that the later represents the magnitude and epicenter whereas a Shake map concentrates on the shaking produced due to the earthquake. As a result of this an earthquake has one magnitude and epicenter but experiences a wide array of ground shaking intensities at different regions depending on factors ranging from distance from the epicenter, rock and soil strata conditions and also owing to complex structure of the Earth's crust.

One of the reasons to generate rapid-response ground motion maps is to establish the best format which is reliable for presenting the maps to the diverse audience that it is meant to cater to, this includes scientists, businesses and companies, emergency response agencies and teams, media agencies and also the general public. So, keeping these points in mind scientists and organizations have developed the intensity maps on MMI scales which simplify and also maximize the volume of information that is being passed on to the public. These maps also make it easier for the general populace to relate to the recorded ground motions that are reported by seismologist to the expected felt and damage that can be expected by the affected. The instrumental Intensity map is primarily based on a combination of regressions of recorded peak accelerations and the velocity amplitudes.

CHAPTER 2

SHAKEMAP PACKAGE-
UNITED STATES GEOLOGICAL SURVEY

2.1 INTRODCUTION

Following an earthquake the parameters that are immediately available are magnitude and epicentral distance. These parameters are usually computed by the United States Geological Society within 15 minutes of the occurrence of the event. However, these computed parameters cannot be used to predict the level of shaking or the damage potential of said event. Hence, we can conclude that these parameters alone are not sufficient to predict the shaking level a region can experience after a large earthquake event alone (Wald et al., 1999). Hence, the need arises for the generation of maps that can show the level of shaking that can be expected following a significant event to assist in dissipating information about the ground shaking on regional scales. It may be noted here that even events which produce low to medium ground shaking is of interest to operators of critical facilities like nuclear power plants etc. so that they can perceive and take an educated decision on how to proceed after an event.

The important information that comes out of shaking maps is that it indicates an earthquake event has occurred and it also identifies the area that is affected and the potential damage scenario in that region. These maps which are made available immediately following an earthquake event and are of immense value at a time when there is lack of detailed information to the extent of ground shaking.

These maps are used extensively by various organizations at federal, state and local levels which include both private and public agencies involved in response and recovery. The information that it provides is also of immense scientific value to scientists and researches which may help in preparing and planning for future scenarios.

2.2 HISTORY AND DEVELOPMENTS

As part of the research and development efforts of the "TriNet" group the Shake Map concept was first implemented utilizing the existing strong motion network in California. The popularity of the Shake Map concept is due to its real time utility and it has spread across the US due to the efforts of the United States Advanced National Seismic System (ANSS) and regional seismic networks.

Shake Maps provide information that is far more different then which is provided by seismological parameters such as location and magnitude. Magnitude is defined as a number which is singular and representative of the energy that is released by an earthquake event based on a logarithmic scale. But the definition of intensity fundamentally varies from this and represents the strength of shaking at a site and is based on the Modified Mercalli Intensity (MMI) scale and it varies from site to site. Thus from this it may be concluded that an earthquake event has a single magnitude but may have different intensities which vary from site to site. The MMI scale which was developed by Wood and Newmann (1931) accounts for the perception of humans and buildings that are located in the area of concern.

The MMI scale also accounts for cracks or ground displacements and even takes into account whether or not landslides have taken place. The scale varies from MMI I which denotes that people did not feel any movement to MMI X which represents most buildings and foundations have been destroyed and large landslides have occurred. Previously MMI values were compiled over a period of several weeks as questionnaires were filled out and posted from the affected areas. But with the Shake Map concept maps are now generated almost instantaneously utilizing different ground motion prediction equations and the recordings from the seismometers.

Table1. Description of Modified Mercalli Scale

Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felto nly by a few persons at rest,especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

2.3 CASE STUDIES

Shake Map case studies of some recent significant earthquakes have been briefly discussed below:

1999 HECTOR MINE, CALIFORNIA EARTHQUAKE

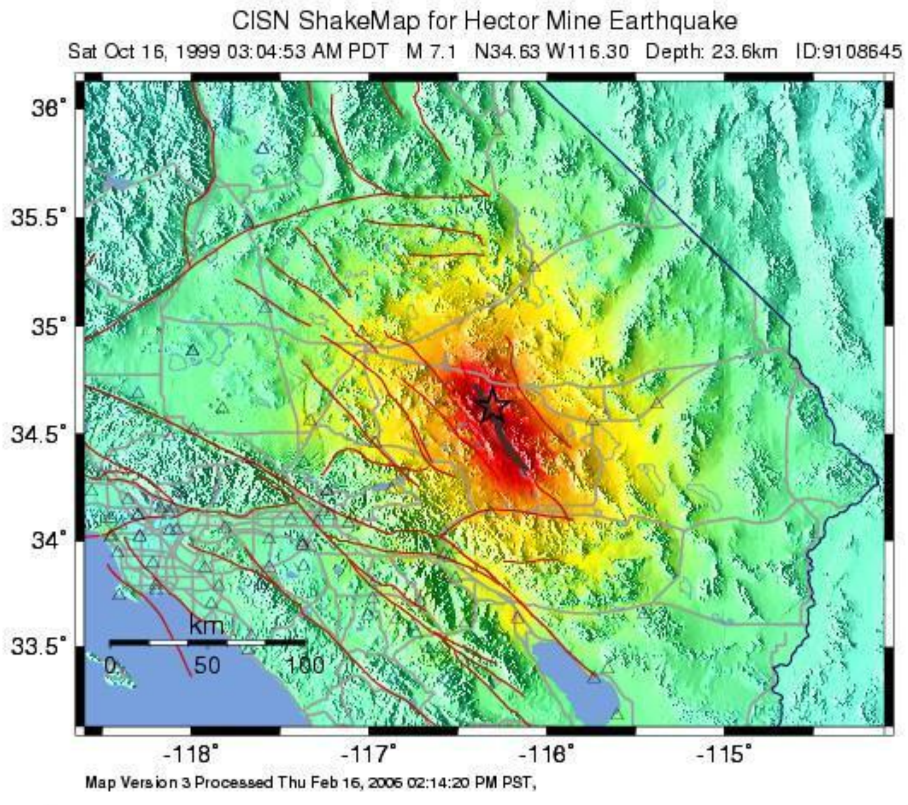
This was one of the largest events to have been recorded by the TriNet network and the Shake Map was prepared for this event. The epicenter was in the Mojave Desert which is a remote and mostly uninhabited place and hence there was very less damage and injuries but still this event provided a good opportunity for researchers to test out the effectiveness and quality of the maps that were produced by the system.

Figure1. Epicentre of Hector Mine earthquake

Table2. Earthquake parameters-Hector Mine earthquake

Date	**October 16, 1999**
Magnitude	**7.1 M_W**
Depth	**0.1 km**
Epicenter	**34.6°N 116.267°W**
Max Intensity	**VII**
Peak Acceleration	**California, USA**

The TriNet real time streaming system had approximated the event magnitude to 7.0 within the first minute of the earthquake event and the corresponding map of shaking was available within 4 minutes. The Hector Mine Earthquake was felt as far as Los Angeles but the Shake Map predicted that large scale emergency response was not necessary as the shaking intensity was not dangerous. The Shake Map also indicated that some ground motion amplification in Coachella Valley had taken place and also drew attention to several triggered events under the Salton Sea which is about 2km from the San Andreas Fault. Because the event had taken in a place which was very sparsely populated the seismic station spacing was also very sparse and hence a lot of interpolation had been done.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure2.TriNet Rapid Instrumental Intensity map for Hector Mine earthquake (USGS).

1989 LOMA PRIETA EARTHQUAKE, SAN FRANCISCO BAY AREA

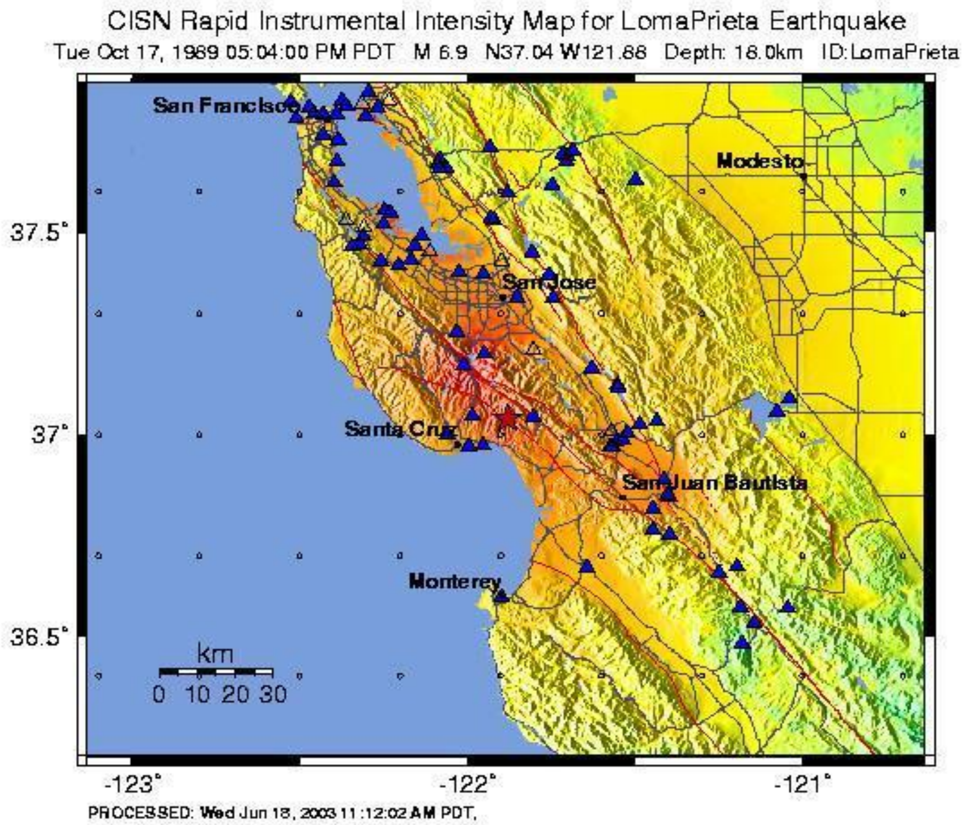
The epicenter of the Loma Prieta earthquake was in the forest of Nisene Marks state park and the earthquake was named after the Loma Prieta peak in the nearby Santa Cruz Mountains. The damage was largest in Santa Cruz County, Oakland and San Francisco because of the unstable soil. The earthquake was due to the activity along the San Andreas Fault which had been quiescence since the 1906 San Francisco earthquake and was labeled a seismic gap.

Figure3. Epicenter of Loma Prieta earthquake

Table3. Earthquake parameters-Loma Prieta earthquake

Date	**October 17, 1989**
Magnitude	**6.9 M_W**
Depth	**19 km**
Epicenter	**37.04°N 121.88°W**
Type	**Oblique-slip**
Max Intensity	**IX**
Peak Acceleration	**0.65*g* (at epicenter)**
Areas affected	**Central Coast (California) San Francisco Bay Area, USA**

The earthquake was a significant one since it was the first earthquake to have been reported and experienced live on national television because of the 1989 World Series game that was being held at Candlestick Park in San Francisco. Because of the four year drought in the area the effects of liquefaction were not so prominent but there still were close to 4000 landslides.
The Shake Map for this event was created later since this was a significant earthquake event and information relating to this event could be utilized as planning and training tools for future earthquake emergency scenarios.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure4.USGS/UCB/CDMG Rapid Instrumental Intensity Map for Loma Prieta earthquake (USGS).

2.4 ALGORITHM OF SHAKEMAP PROGRAM AND MODIFICATIONS

The software package that is required to generate the ground shaking maps is basically known as the Shake Map package. This software and other software's that are required in this process were developed by a group of programmers and researchers at the California Institute of Technology and the California Division of Mines and Geology. This package was initially developed for the region of southern California and requires a number of modifications before it can be implemented in a different area.

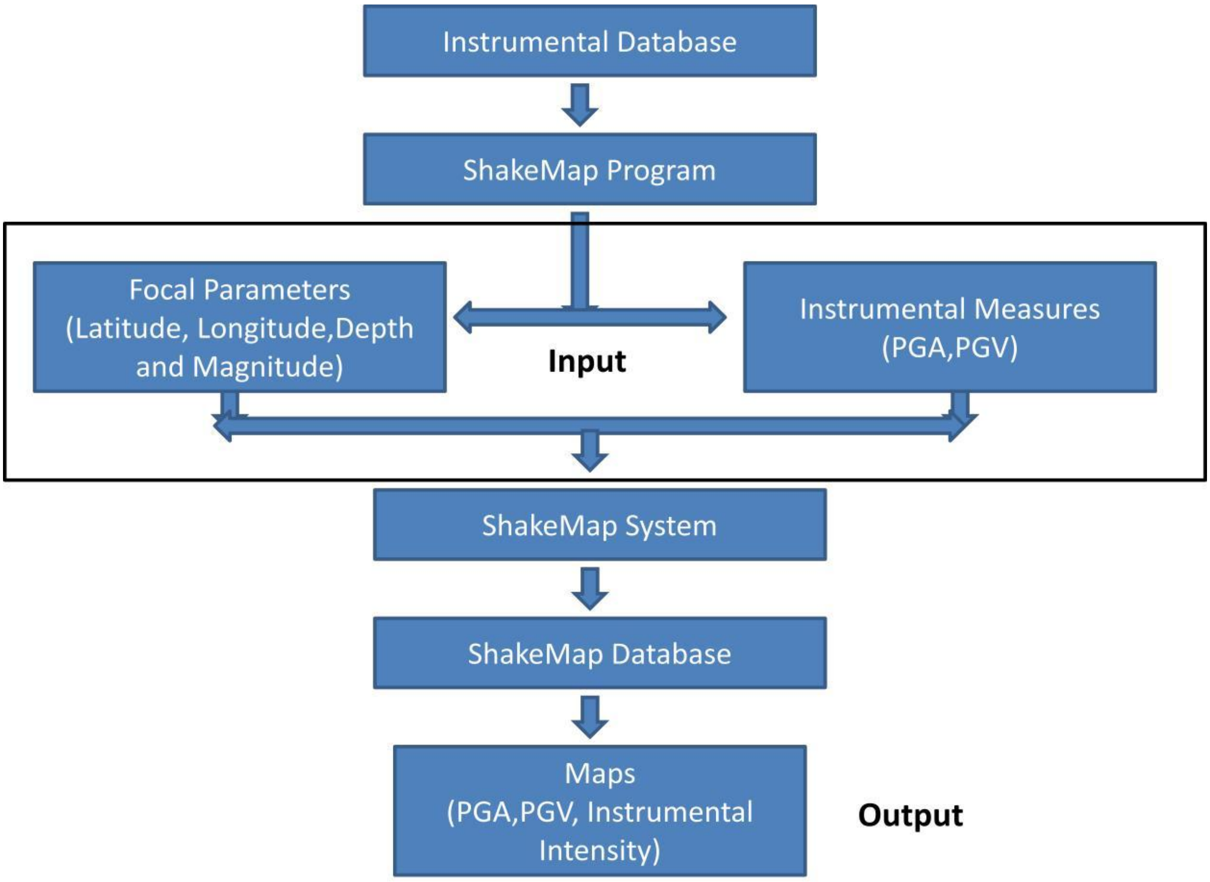


Figure5. Flowchart of the Process Tree followed by USGS Shake Map package

Some of the important features of this software package are:

- It is a collection of PERL modules. My SQL server is used as a database.
- Generic Mapping Tools (GMT) created by Wessel and Smith in 2004 is used to produce the Maps from the output data files.
- Image Magic and Ghost Script are used to connect the file formats
- All components have been built from free open source packages

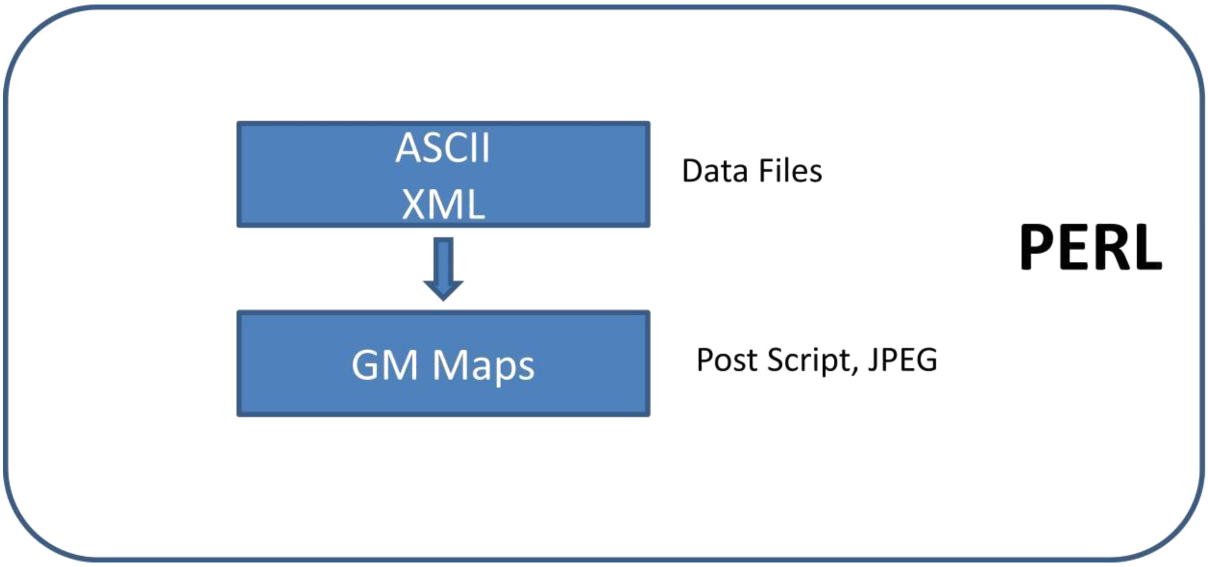


Figure6. PERL Framework which runs USGS Shake Map package

The modifications that are needed for its implementation in an area of interest:

1) Region specific features such as major city names, contour intervals, topography, station parameters and locations have to incorporated into the program
2) The seismic network should be upgraded and necessary hardware should be installed so that the station data may be streamed at near real time to the processing hub.
3) Installation of event detector program or algorithm to detect significant events from the real time data stream.
4) Establishing appropriate ground motion prediction equations for the area taking into account a wide range of distances and magnitudes.
5) Establishing a relationship between instrumental measure and MMI at the area of concern.
6) Appropriate modifications have to be made to the centroid program proposed by Kanamori (1993) so as to provide an appropriate estimate of magnitude and location initially.
7) Establishing soil response and site amplification factors in the area of concern.

2.5 APPLICATIONS OF USGS SHAKEMAP

1. **Emergency Response and Loss Estimation**
2. **Public Information and Education**
3. **Earthquake Engineering and Seismological Research**
4. **Planning and Training: Shake Map Earthquake Scenarios**

CHAPTER 3

SHAKEMAP SYSTEMS OF OTHER COUNTRIES

Besides the United States (Shake Maps), Taiwan and Japan are two countries that also produce ground shaking maps in addition to epicentral and magnitude maps following earthquake events. New systems and programs are under installation and development in Italy, Turkey, New Zealand, Canada and Iran.

3.1 SHAKEMAP IMPLEMENTATION IN ITALY

The Italian Civil Protection since the starting of 2005 has funded and commissioned many projects that aim at the rapid assessment of ground shaking following any seismic event (Michelini *et al.*, 2008). The final objective of these projects are to produce maps that can assist in search and rescue efforts if any large damaging event takes place in the future. As part of this project the Italian authorities have adopted the Shake Map program that was developed by USGS and this is designed to produce maps of ground shaking within 30 minutes of the earthquake event. This program utilizes a location that is manually revised. The package is programed to produce maps of peak ground motion parameters like PGA, PGV and instrumental intensities similar to the one that is used in the United States which has been described in the previous chapter.

This system utilizes the regional attenuation laws and local site amplifications along with the V_{s30} values that have been collected from the entire region. It should be noted that these maps are of relevance only during the first hours after an earthquake as they provide crude maps of ground shaking patterns and become irrelevant as more information becomes available. The shaking maps produced initially lose their relevance as the attenuation laws and site amplifications that have been assumed may not be appropriately valid across all situations.

3.2 SHAKEMAP IMPLEMENTATION IN TAIWAN

Since the early 1990s Taiwan has been developing and implementing a system (Wu *et al.,* 2000) which is producing maps of ground acceleration in the island nation. This system is maintained by the Central Weather Bureau of Taiwan and it produces acceleration based intensity maps very rapidly within a time frame of about 2 minutes following any seismic events. This system proved to be very useful during the Chi-Chi earthquake of 1999 and provided researchers with vast amount of scientific data to analyse the event and to plan for future earthquakes. Their system consists of over 80 seismic stations that report ground motion in real time in addition to 700 strong motion sites over which the site amplification factors have been well calibrated.

After the Chi-Chi earthquake the government authorized CWB to report Instrumental Intensities by the rapid reporting system which inter relates PGV
to Intensity utilizing a system that is quite similar to the USGS Shake Map package. These warnings are rapidly dissipated to fire services, transport networks and heavy industries.

3.3 SHAKE MAP IMPLEMENTATION IN JAPAN

The Shake Map concept had been implemented in Japan after the 1995 Kobe earthquake that measured 6.9 on the Richter scale. The Japanese authorities namely the JMA have been regularly producing maps (Kanezashi *et al.,* 1997) of instrumental intensities after the Kobe event. Japan has close to 4500 stations which report in real time, due to the density of their station network the data obtained from each station can be directly used to produce a detailed map of shaking patterns and no interpolation for sparse areas has to be done as is done with the Shake maps produced in the United States. Following significant events maps are automatically produced and warnings are aired on national television. Also the maps are used as input to rapidly assess the damage following an event by using these maps as input along with census, building and geographical data in loss estimation and hazard programs. Several other organizations have also installed station networks to issue warnings and shut down critical services in case of a dangerous event. The Tokyo Gas system is one such system that relies on these networks and deploys emergency shutdown protocol following seismic events that may cause damage to its installations and gas pipelines.

3.4 SHAKEMAP IMPLEMENTATION IN IRAN

The PeeqMap is a software package that has been developed by the Earthquake Research Centre at Ferdowsi University of Mashhad in Iran (Sadeghi *et al.,* 2011). The software can utilize its flexible algorithm to generate a Shakemap in any different region. This procedure essentially does not require any other programs for determining magnitude and epicenter. An advantage of this software is using of an accurate method for estimation of moment magnitude. This software coded in user-friendly Matlab environment that benefit from computational and plotting capabilities. The software is capable to produce both urban and regional Shake Maps. This software was used to generate a scenario Shakemap for the Zanjiran Earthquake of 1994 which was an M_w= 5.9 event and the results for found to be in agreement with data that was collected from other sources. The other advantage of this software is that the output file that is obtained in .txt extension can be used as an input file for loss estimation and GIS softwares.

CHAPTER 4

OVERVIEW OF SEISMICITY AND GEOLOGY OF HIMALAYAN REGION

4.1 INTRODUCTION

Uttarakhand Himalayans are one of the seismically active regions of the world and have experience earthquake since times immemorial. The region has also experienced tectonics movements. This is evident from the several thrust and faults present in and around the state. Two regional tectonic features in Uttarakhand, which have earthquake potential, are the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT). In fact, these tectonic features are present all along the entire Himalayan tectonic belt.

The past records of the seismic events along the Himalayan belt in Himachal-Uttarakhand-Nepal, stated to the geological, structural, seismic observation stations, provides the principle means for evaluating the potential for future earthquakes. After the Kangra (1905) earthquake, this area has experienced many earthquakes of lower magnitude, which has caused in many areas formation of lakes by one earthquake and it was damaged by another earthquake, caused the flood (1978) in Bhagirathi and Alaknanda rivers in the geological past in Uttarakhand Himalaya. The Uttarkashi earthquake Oct., 1991, on 6.8 Richter scale and Chamoli Earthquake March 28, 1999, on 6.4 Richter scale caused destruction with a lot of deaths, injuries and loss of properties and development of cracks on the ground, hill slopes and many neotectonic activities such as reactivation of landslides, hill slopes, and mass movement. Both these earthquakes located in the 200 km wide Main Central Thrust zone areas.

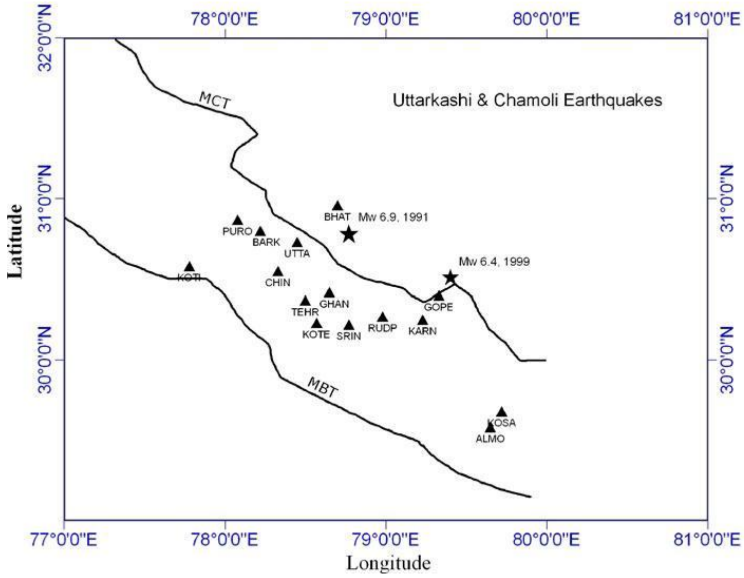


Figure7. Stations of strong-motion array in Himalayan shown by solid triangles that have recorded Uttarkashi and Chamoli earthquakes. The epicenters of Uttarkashi and Chamoli earthquakes are shown by solid stars

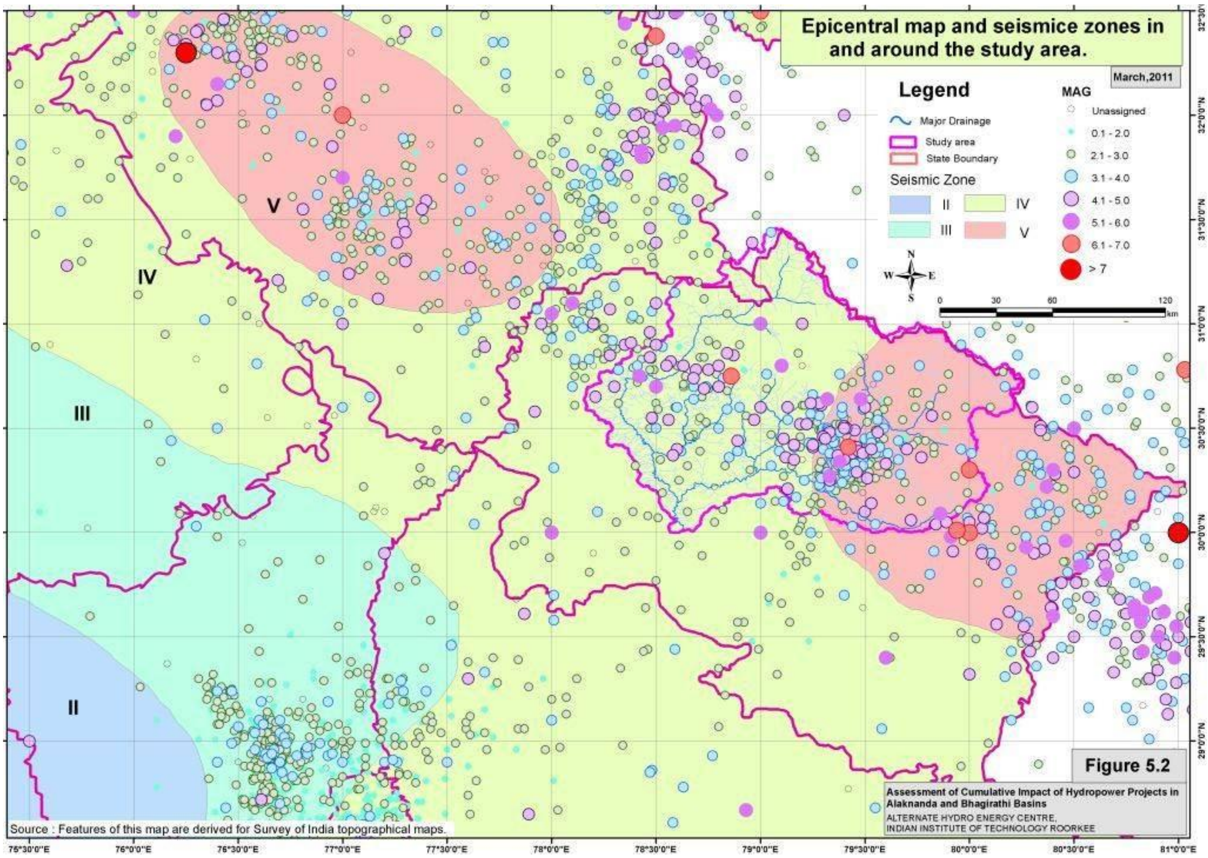


Figure8. Epicentral map of the area in and around Alaknanda and Bhagirathi valley for the from 15.07.1720 to 31.01.2009 (Source IMD)

Table4. *Earthquake probability in thrusts zone areas*

HIMALAYAN REGION

Name	Probable Earthquake	Length(km)
Main Central Thrust (MCT)	8	350
North Almora Thrust (NAT)	6.9	280
Main Boundary Thrust (MBT)	8	450
Alaknanda Fault	5.5	51
Ropar Fault	5	35
Ramgarh Fault	5	37
South Almora Thrust (SAT)	6.5	130

4.2 BEDROCK TOPOGRAPHY

The geology of the region shows the Himalaya is the young mountain in the world. During early Mesozoic times, or the secondary geological period, the land mass now covered by them was occupied by the great geosynclinals Tethys Sea. The probable data of the commencement of the elevation of the Himalayas is about the close of the Mesozoic period, but the unraveling of the story of their structure has only just begin, and in many cases no dating of the rocks is yet possible, though they include ancient and relative recent crystalline intrusive, rock and sediments allied to the peninsular part of India.

4.3 SHEAR WAVE VELOCITY

The shear wave velocity data from most of the localities of Uttarakhand Himalayan region are not available in the literature. Out of 19 seismic stations, V_{s30} data is available for only three stations which reveal that they are mostly on rocky stratum. It is also clear from geology of region that most of localities of the region are situated on rock itself. So, as justifiable assumption, the stations and localities for which V_{s30} data is not available is assumed to be on rocky soil and the V_{s30} value has been taken as the lower limit specified for such soil to be on conservative side.

CHAPTER 5

EARTHQUAKE EMERGENCY MAP ALGORITHM

The methodology that has been adopted for generation of shaking map for Himalayan Uttarakhand region in this report is based on the PeeqMap system that is currently under development in Iran. The methodology is principally based on the procedure that is used by USGS for generation of Shake Map.

5.1 ALGORITHM FOR GENERATION OF SHAKING MAPS

The map producing steps according to the method of Wald *et al*. (1999) are:

i. Collecting peak ground motions of available stations on the network

ii. Magnitude and location determination and estimation of strong motion in the rock site located in areas far from recording stations.

iii. Site effect correction and interpolation of recorded and estimated values for a fine grid of points.

iv. Amplifying values in the fine grid network based on site conditions.

5.1.1Earthquake Location and Magnitude Determination

Epicenter location and magnitude of earthquake are most basic information that after occurrence of any event are available quickly. The software, takes as input the epicenter and magnitude. However, in the absence of this information, it determines location of Strong Motion Centroid (CMT) using recorded Peak Ground Acceleration (PGA) values and regional attenuation relations. Locating is done by nonlinear fitting the bivariate regional attenuation relation to the PGA values. Equation (10) is the attenuation relation of Sharma (2000).That can be used for locating earthquakes in the Himalayan Region.

$$\text{Log}(A) = -2.87 + 0.634M - 1.16 \log(X + e^{0.62M}) \qquad (1)$$

where, A is the peak ground vertical acceleration (g), M is the magnitude and X is the hypocentral distance from the source.

After locating the earthquake, using obtained distances between stations and centroid we apply rapid magnitude estimation relation of Sadeghi *et al.* (2011) at each station, and average them to obtain final event magnitude. This relation uses the integration of absolute acceleration recorded at each station from equation (1) and hypocentral distance as an independent variable.

$$\sqrt{ES} = \int_{T_1}^{T_2} \sqrt{V^2 + N^2 + E^2}\, dt \qquad (2)$$

where, *ES* is total effective shaking equal to integration of absolute acceleration. *V*, *N* and *E* are three perpendicular components of accelerograms. T_1 is the P wave arrival time and T_2 is 5 second after last 20 percent of absolute acceleration amplitude.

5.1.2 Interpolation in Areas with Sparse Station Spacing

In areas with sparse coverage for reduction the error of interpolation, we apply a method proposed by Wald *et al.* (1999) based on regional attenuation relation which estimates peak of ground motion parameters for rock sites. The virtual stations which are laid closer than specified distance from recording stations will be removed from initial arrangement. Peak values at these stations are estimated using bias corrected attenuation relation by software. The bias correction factor obtained from equation (2) is multiplied to computational values to results bias corrected values.

$$BF = \frac{\sum_{i=1}^{n} \left(\frac{PGP(\mathrm{i}) + PGP_{att}(i)}{PGP_{att}(i)} + 1 \right)}{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

where *PGP* (*i*) is observed peak value of ground motion parameter in *i*th station. $PGP_{att}(i)$ is estimated value in *i*th station position by attenuation relation, and *n* is the number stations.

5.1.3 Estimation of Site Effect

In order to considering the effect of difference in various sites, frequency and amplitude dependent empirical amplification factors proposed by Borcherdt (1994) are used. These factors correct amplitudes to a common reference site condition. Usually the reference site condition is a rock site. For peak ground acceleration amplitudes, short term (0.1-0.5 Sec.) correction factors and for amplitudes of ground velocity, midterm (0.4-2.0 Sec.) correction factors are applied proposed by Wald *et al.* (2006) are used. We calculate short term correction factors, using Borcherdt (1994) methodology.

5.1.4 Numerical Interpolation

A 2D spline is used to approximate values between sample pointes. Since 2D spline is defined in the piecewise situation, creating a kind of partition between sample points on the surface domain is necessary. Triangulation with the algorithm of Delaunay is a very useful partitioning method. Delaunay triangulation in combination with spline interpolation is applied for estimating values in fine and regular network with certain distance.

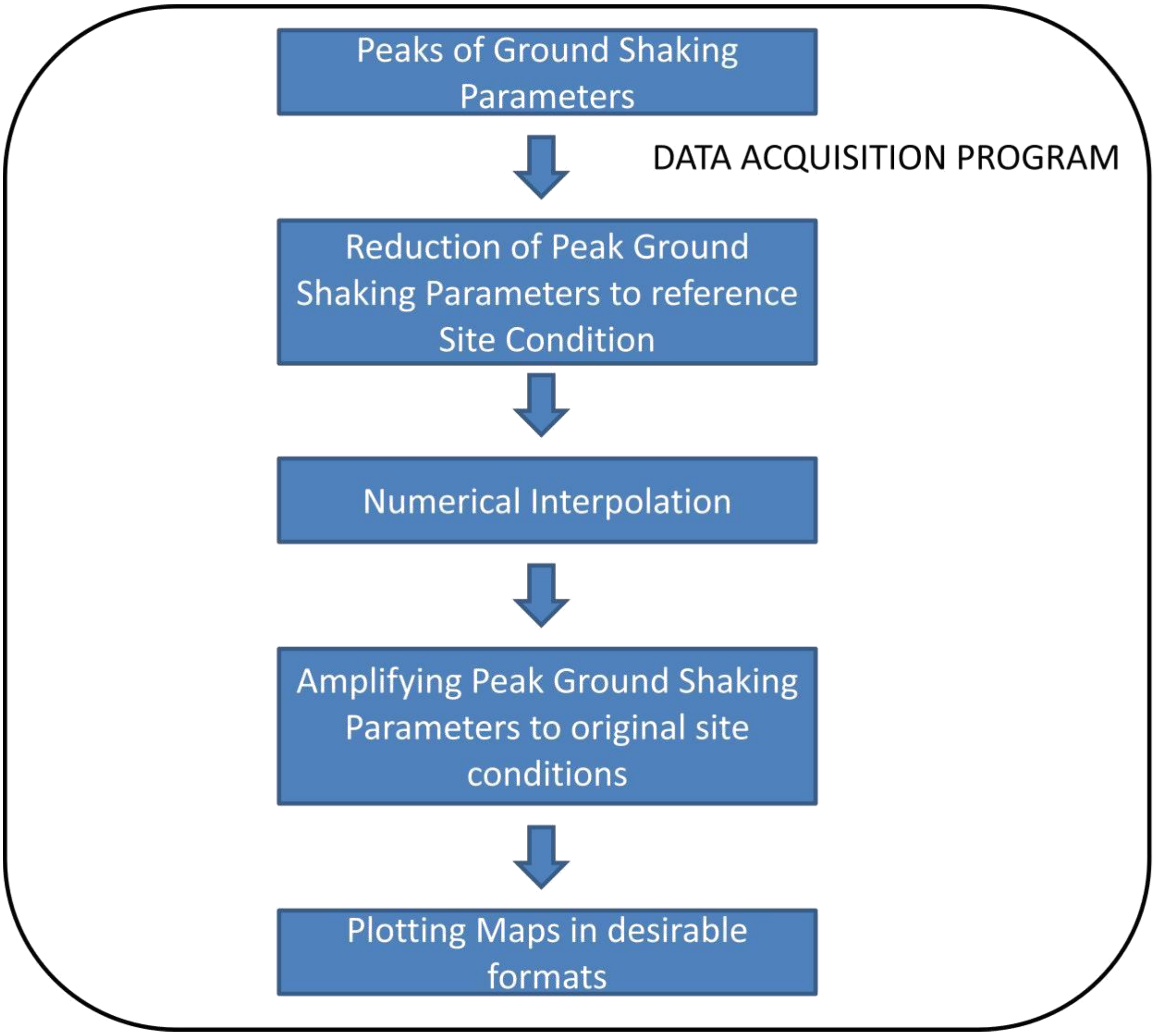


Figure9. The Matlab algorithm followed by PeeqMap for urban networks.

CHAPTER 6

SCENARIO EARTHQUAKES CASE STUDY

6.1 GENERATING SHAKING MAPS

All Shake map depending on used network could be divided into regional and urban categories. Following an earthquake, obtained data from each network is specifically processed, for producing Shake maps in favorite format and scale. In many cases, dense urban networks are as a part of a regional network with lower station density.

Table5. Locations and site geology of Uttarakhand seismic stations

Recording Station	Latitude(^{0}N)	Longitude(^{0}E)	Site Geology	Site Class
Almora	29.58	79.65	Rocky strata	A
Barkot	30.80	78.22	Rocky strata	A
Chinayliswer	30.55	78.33	Sedimentary Rock	B
Ghansiali	30.42	78.65	Rocky strata	A
Gopeshwar	30.40	79.33	Sedimentary Rock	B
Joshimath	30.55	79.57	Rocky strata	A
Lansdown	29.83	78.70	Rocky strata	A
Roorkee	29.86	77.89	Alluvium Soil	C
Tehri	30.37	78.50	Rocky strata	A
Ukhimath	30.50	79.10	Rocky strata	A
Uttarkashi	30.73	78.45	Sedimentary Rock	B
Bhatwari	30.80	78.60	Rocky strata	A
Karnprayag	30.25	79.23	Rocky strata	A
Kosani	29.68	79.72	Rocky strata	A
Koti	30.58	77.78	Rocky strata	A
Purola	30.87	78.08	Rocky strata	A
Rudraprayag	30.27	78.98	Rocky strata	A
Srinagar	30.22	78.77	Rocky strata	A

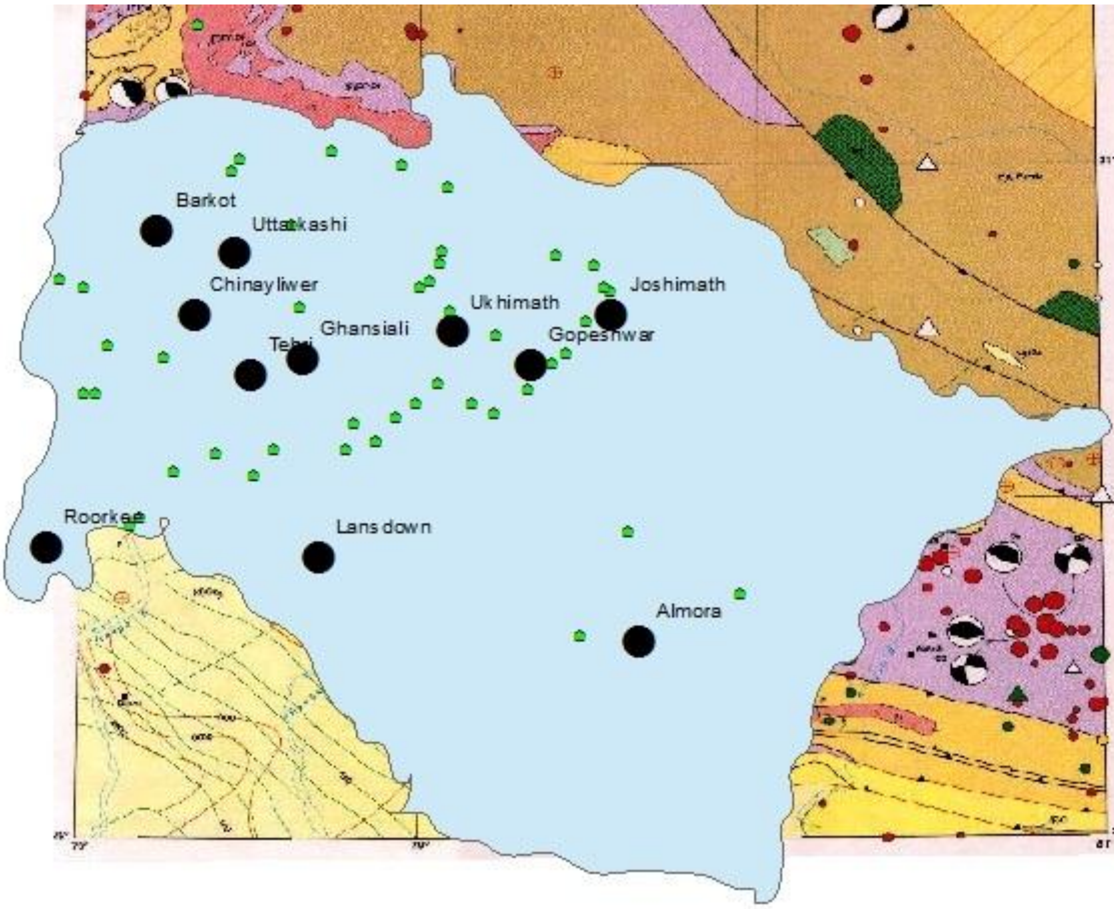


Figure10. Map showing the location of accelerographs and seismographs

An important component for the generation of shaking maps was collecting the depth wise shear wave velocity data for Uttarakhand region, in this report information from seismic ground motion recording stations were taken which are mostly on rocky stratum. For other region where the site amplification are to be calculated, the V_{s30} values are taken as the minimum value specified for site class A, i.e., rocky soil strata.

Table6. V_{S30} values of Uttarakhand at different locations

Location	**Latitute(^{0}N)**	**Longitute(^{0}E)**	**V_{S30}(m/sec)**
Gangotri	30.994	78.939	700
Kedarnath	30.734	79.066	700
Deheradun	30.316	78.032	289
Mussoorie	30.459	78.066	700
Dhanolti	30.426	78.237	700

Rudraprayag	30.284	78.981	700
Devprayag	30.145	78.599	700
Karnprayag	30.258	79.218	700
Rishikesh	30.086	78.267	305
Haridwar	29.945	78.164	294
Srinagar	30.224	78.798	700
Gopeshwar	30.141	79.332	700
Tungnath	30.486	79.221	700
Chopta	30.346	79.048	700
Guptkashi	30.522	79.077	700
Pauri	30.147	78.774	700
Tapovan	29.723	79.946	700
Baijnath	30.404	79.615	700
Chamoli	30.404	79.331	700
Neelkanth	30.729	79.404	700
Gauchar	30.289	79.15	700
Gaumukh	30.926	79.08	700
Bhatwari	30.818	78.618	700
Budakedar	30.571	78.641	700
Harshil	31.038	78.737	700
Gaurikund	30.652	79.025	700
Badrinath	30.743	79.493	700
Khirsu	30.172	78.867	700
Augustmuni	30.245	78.924	700
PipalKoti	30.433	79.43	700
Nandprayag	30.331	79.32	700

Vishnu Prayag	30.567	79.542	700
Shivpuri	30.136	78.388	700
Hanumanchatti	30.694	79.514	700
Yamunotri	31.013	78.459	700
GovindPashuVihar	31.142	78.338	700
Jankichatty	30.975	78.436	700
Kaudiyala	30.073	78.502	700
Sonprayag	30.632	78.995	700
Govindghat	30.618	79.561	700
Kalyani	29.925	78.134	700
Rambara	30.705	79.054	700
Bihari	30.408	79.39	700
Helong	30.53	79.49	700
Indiranagar	30.315	77.999	700
Pandukeshwar	30.634	79.547	700
Vikasnagar	30.468	77.774	425
Kotdwar	29.45	78.315	448

This report investigate an earthquake that had occurred on the 29thof March 1999 in Chamoli district, it was a M_L 6.4 event and 20th October 1991 in Uttarkashi district, it was a M_L 6.8 event Although this event were a moderate intensity event it still provide a good platform to investigate the effectiveness of the PeeqMap software.

6.2 MARCH 29, 1999 CHAMOLI EARTHQUAKE (M_L=6.8)

The 1999 Chamoli earthquake occurred on 29th March, 1999 in the Chamoli district in the Indian state of Uttar Pradesh (now in Uttarakhand).The earthquake was the strongest to hit the foothills of the Himalayans in more than ninety years. Approximately 103 people died in the earthquake.

The Himalayan Range has been undergoing crustal shortening along the 2,400 km long northern edge of the Indian Plate which resulted in the formation of several thrust planes including the

Main Central Thrust (MCT),the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT).The MCT consists of three sub-thrusts: MCT I, MCT II and MCT III. Many earthquakes have occurred along these faults. Academics believe the Chamoli earthquake in 1999 is associated with these faults systems.

Table 7. Earthquake epicenter-March 29, 1999

Date/Time	Longitude	Latitude	Magnitude
29.03.1999/00:35 IST	79.416 °E	30.408 °N	M_W= 6.4

Table 8. Recorded PGA at different stations during the 29 March, 1999 Earthquake

Station Name	Long(⁰E)	Lat(⁰N)	PGA(cm/sec²)		V_{s30} (m/s)
			L Comp	T Comp	
Almora	29.58	79.65	0.027	0.028	700
Barkot	30.8	78.22	0.017	0.023	700
Chinayliswer	30.55	78.33	0.052	0.045	600
Ghansiali	30.42	78.65	0.073	0.083	700
Gopeshwar	30.4	79.33	0.199	0.359	535
Joshimath	30.55	79.57	0.071	0.063	700
Lansdown	29.83	78.7	0.005	0.006	700
Roorkee	29.86	77.89	0.056	0.047	218
Tehri	30.37	78.5	0.054	0.062	700
Ukhimath	30.5	79.1	0.091	0.097	700
Uttarkashi	30.73	78.45	0.054	0.064	475

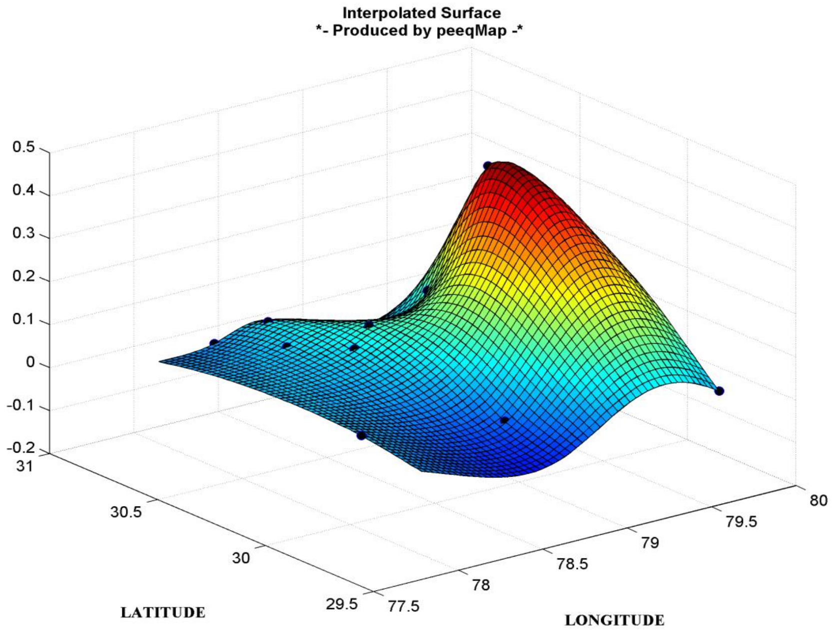


Figure11. Interpolated Surface for 1999 Chamoli earthquake produced by peeqMap

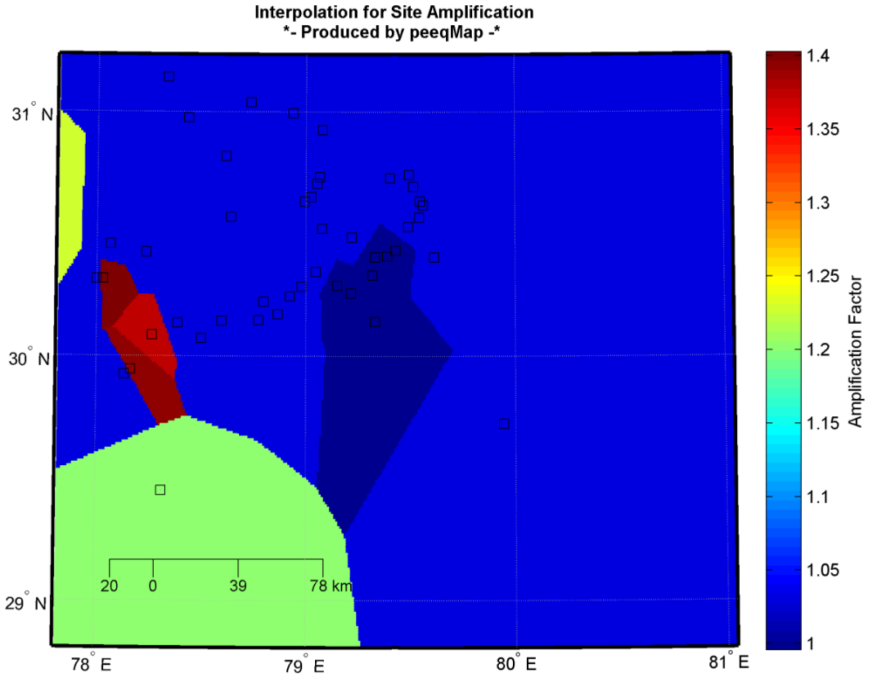


Figure12. Site Amplification Interpolation for 1999 Chamoli earthquake

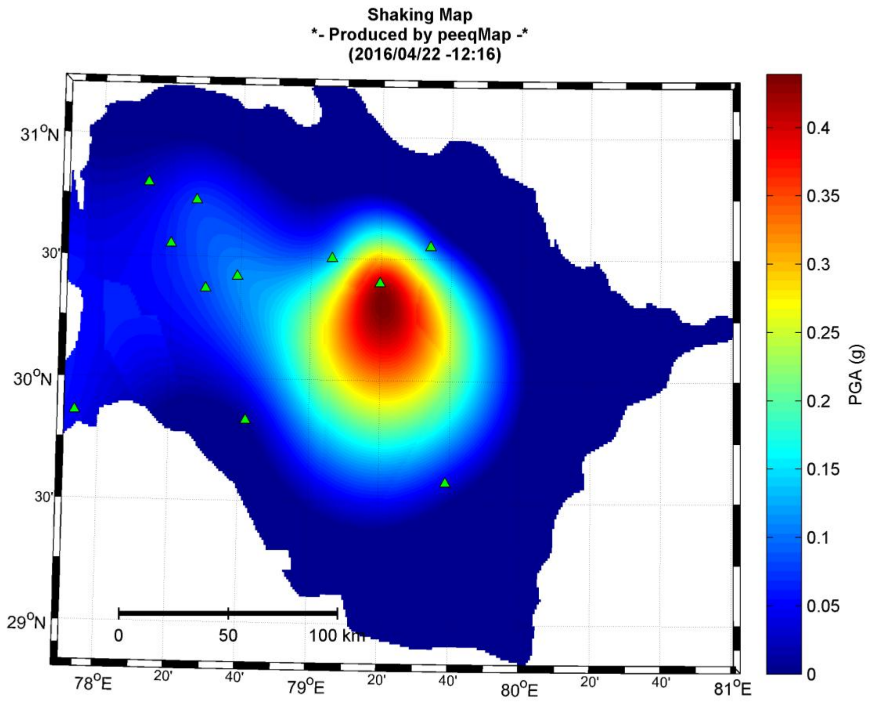


Figure13. Shaking Map of March 29th 1999 Chamoli earthquake

6.3 OCTOBER 20, 1991 UTTARKASHI EARTHQUAKE (M_W=6.8)

The 1991 Uttarkashi earthquake occurred on 20th October 1991 in the Uttarkashi and Gharwal regions of the Indian state Uttarakhand. The earthquake measured 6.8 on Moment magnitude scale and occurred within the main thrust system of the Himalayan. 1294 villages and more than 3,00000 people were affected with the quake,768 peoples died while 5066 were injured and 42,400 houses were damaged.

Uttarkashi lies in the main Alpine Himalayan belt, one of the most earthquake prone regions of the world. Crustal instability in this belt is ascribed to the movement of the Indian plate towards the Eurasian plate at the rate of about 50mm per year. Besides several local faults, two prominent thrusts tending northwest to southeast, from the conspicuous tectonic features.

Table 9. Earthquake epicenter-October 20, 1991

Date/Time	Longitude	Latitude	Magnitude
20.10.1991/02:30 IST	78.79 °E	30.74 °N	M_W= 6.8

Table10. Recorded PGA at different stations during the 20 October, 1991 Earthquake

Station Name	Long(⁰E)	Lat(⁰N)	PGA(cm/sec²)		V_{s30} (m/s)
			L Comp	T Comp	
Almora	29.58	79.65	0.018	0.006	700
Barkot	30.80	78.22	0.095	0.082	700
Bhatwari	30.80	78.60	0.253	0.247	600
Ghansiali	30.42	78.65	0.118	0.117	700
Karnprayag	30.25	79.23	0.062	0.079	600
kosani	29.68	79.72	0.029	0.032	700
Koteshwar	30.23	78.57	0.101	0.066	700
Koti	30.58	77.78	0.021	0.042	600
Tehri	30.37	78.5	0.073	0.062	700
Purola	30.87	78.08	0.075	0.042	600
Rudraprayag	30.27	78.98	0.053	0.052	600
Srinagar	30.22	78.77	0.067	0.05	700
Uttarkashi	30.73	78.45	0.242	0.309	475

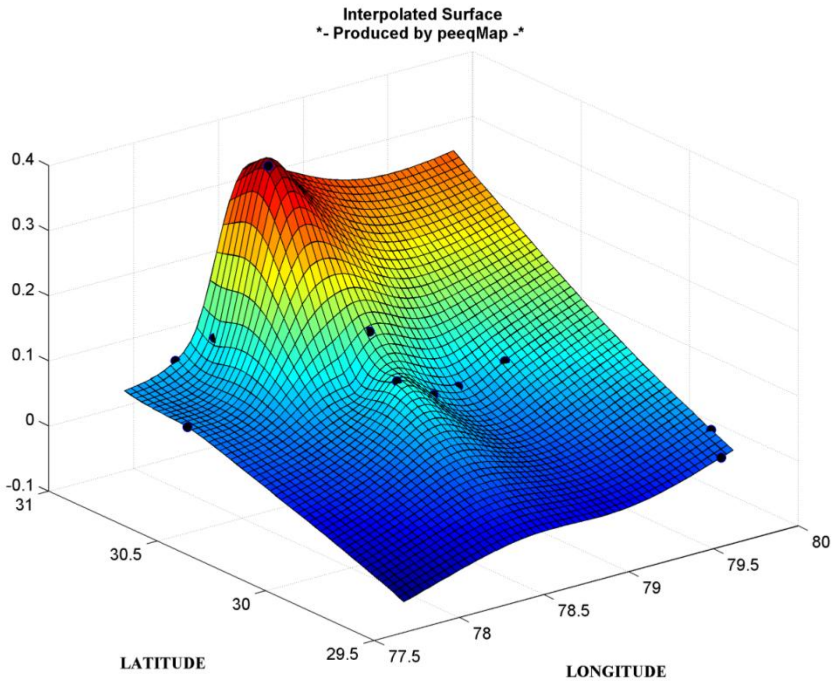


Figure14. Interpolated Surface for 1991 Uttarkashi earthquake produced by peeqMap

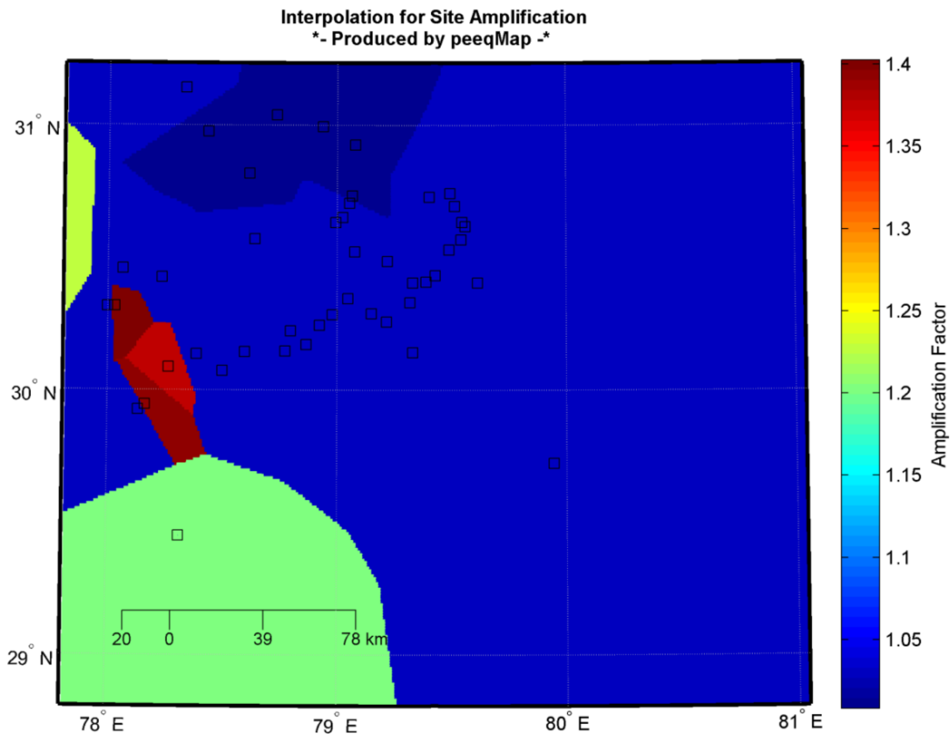


Figure15. Site Amplification Interpolation for 1991 Uttarkashi earthquake

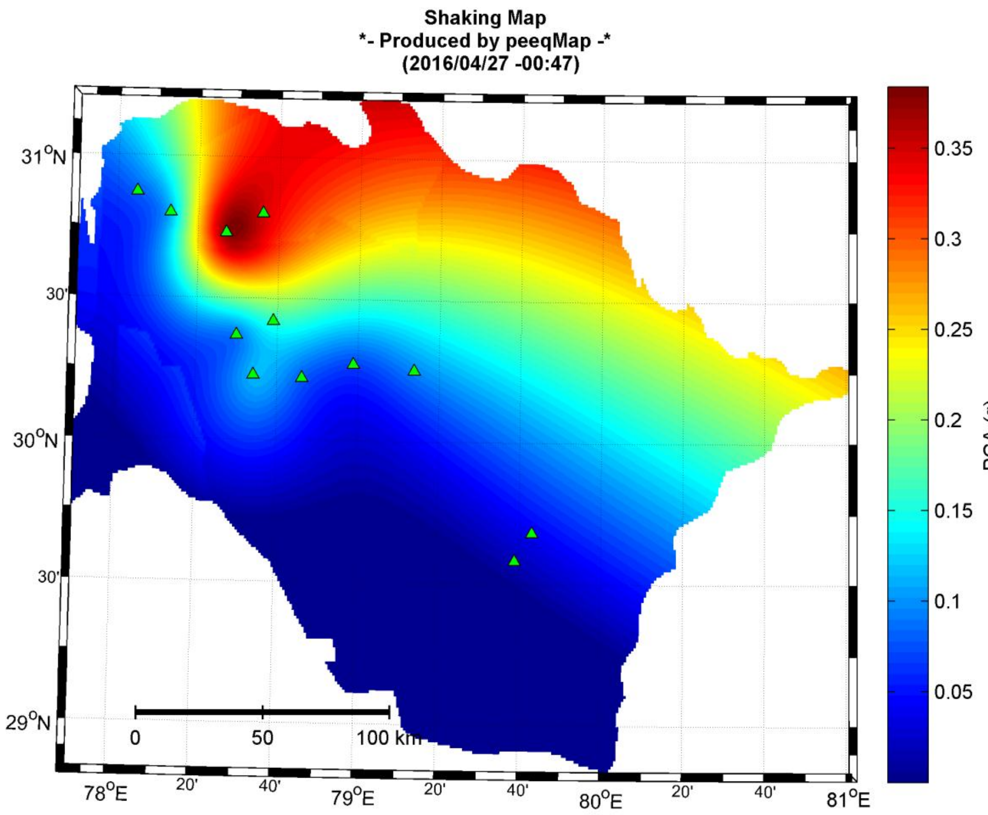


Figure16: Shaking Map of October 20th 1991 Uttarkashi earthquake

CHAPTER 7

EXSIM VALIDATION OF RESULTS

The EXSIM method is a modified stochastic method that was proposed by Motazedian and Atkinson (2005) and it is based on the dynamic corner frequency approach. This method has been used in this chapter to synthesize artificial ground motions at different locations and check them with the values of ground motion that have been obtained by the PeeqMap program in the previous chapter.

7.1 EXSIM METHODOLOGY

The Fourier acceleration spectral amplitude of the ground motion at a distance R from the source can be defined as (Boore, 1983)

$$A(f,R) = \frac{CS(f)e^{-\pi f R/\beta Q(f)}}{G(R)} \quad \textbf{(1)}$$

$$C = \frac{R_{\theta\emptyset} FP(2\pi)^2}{(4\pi\rho\beta^3)} \quad \textbf{(2)}$$

$$S(f) = f^2\dot{M}_0(f) \quad \textbf{(3)}$$

$$S(f) = \frac{f^2 f_c^2 M_0}{(f^2 + f_c^2)} \quad \textbf{(4)}$$

$$A(f,R) = \frac{R_{\theta\emptyset} FP}{(4\pi\rho\beta^3)} \cdot \frac{(2\pi)^2 f^2 f_c^2 M_0}{(f^2 + f_c^2)} e^{-\pi k f} e^{-\pi f R/\beta Q(f)} \cdot G(R) \quad \textbf{(5)}$$

where, M_0 (f) is the moment rate spectrum so that M_0 (f) $\rightarrow M_0$ as $f \rightarrow 0$, R is the hypocentral distance, β is shear-wave velocity, $Q(f)$ is quality factor which includes both an-elastic absorption and scattering, ρ is focal region density, $R_{\theta\phi}$; is average radiation pattern, F is free surface amplification, P takes into account the partitioning of energy in the two horizontal components. $G(R)$ is the geometrical spreading term and κ is spectral decay parameter called kappa, a value of near surface attenuation, which controls the path independent high-frequency decay of the spectrum (Anderson and Hough, 1984).

The ground motions of sub-faults are summed with a proper time delay to obtain the ground motion acceleration from the entire fault as

$$a(t) = \sum_{i=1}^{nl} \sum_{j=1}^{nw} a_{ij}(t + \Delta t_{ij}) \tag{6}$$

where, *nl* and *nw* are the number of sub-faults along the strike and dip of main fault, respectively, and t_{ij} is the relative delay time for the radiated wave from the *ij*th sub-fault to reach the observation point, calculated by the stochastic point-source method (Boore, 1983).

Motazedian and Atkinson (2005) introduced the concept of dynamic corner frequency by considering that the corner frequency is inversely proportional to the ruptured area. Motazedian and Atkinson (2005), in their modification, considered the corner frequency as a function of time. Based on the model by Motazedian and Atkinson (2005), the dynamic corner frequency of the *ij*th sub-fault, f_{cij} (t) is given by:

$$f_{cij} = \frac{4.9 \times 10^6 \beta}{N(t)^{1/3}} \left(\frac{\Delta\sigma}{M_{0\text{ave}}} \right) \tag{7}$$

where $M_{0\text{ave}} = M_0/N$ is the average seismic moment of sub-faults in dyne-cm, in which M_0 is the seismic moment of the entire fault, N is the total number of subfaults, $\Delta\sigma$ is the stress drop in bars, $N(t)$ is the cumulative number of ruptured sub-faults at time t.

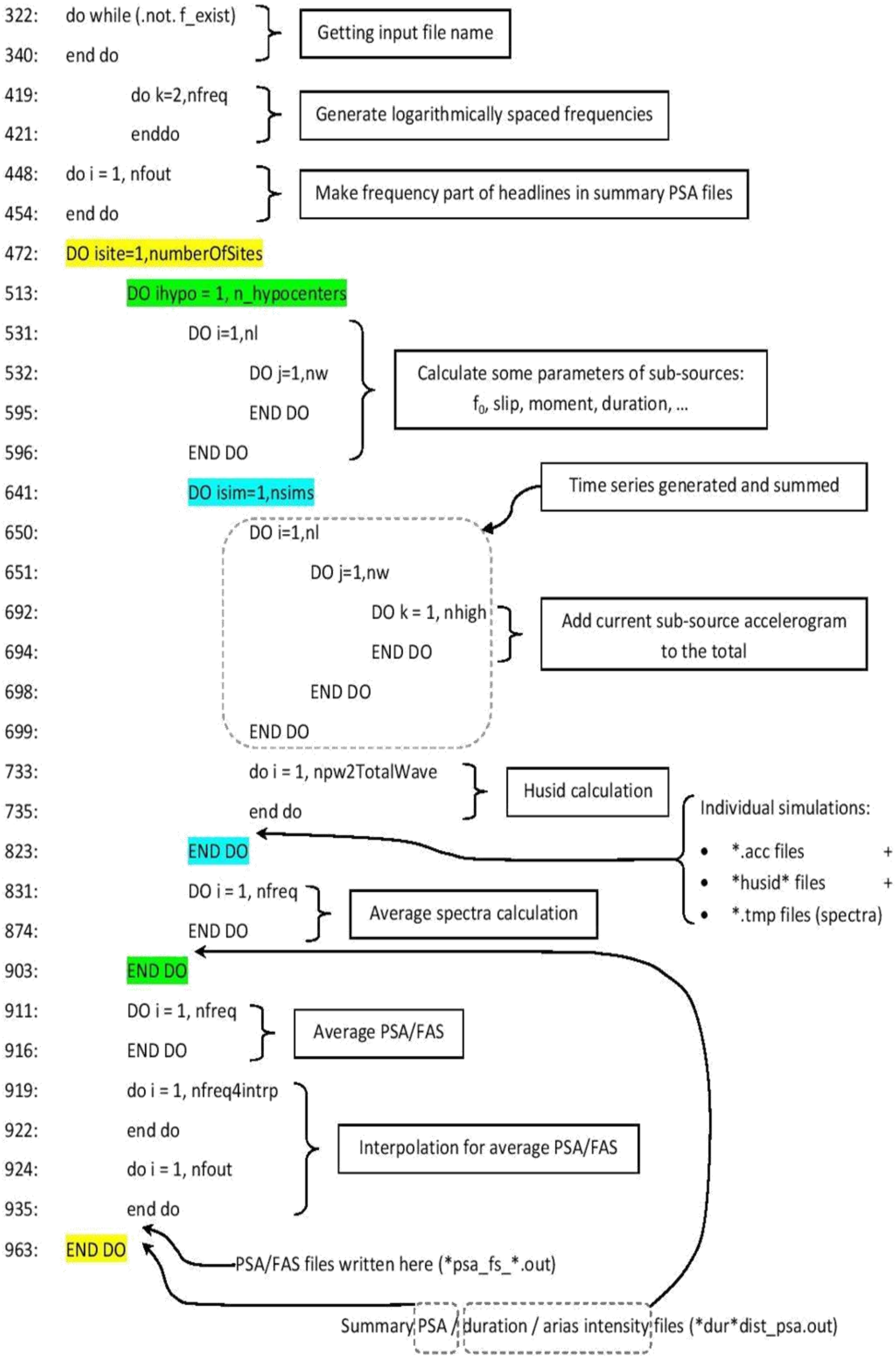
For $t = t_{\text{end}}$, the number of ruptured subfaults, $N_R(t = t_{\text{end}}) = N$. The corner frequency at the end of rupture is rewritten by

$$f_{cij(t_{\text{end}})} = \frac{4.9 \times 10^6 \beta}{N(t_{\text{end}})^{1/3}} \left(\frac{\Delta\sigma}{M_{0\text{ave}}} \right) \tag{8}$$

A scaling factor H_{ij} was applied by Motazedian and Atkinson (2005) to conserve the high-frequency spectral level of sub-faults. The factor is given as:

$$H_{ij} = \left(N \sum \{f^2/[1 + f/f_c^2]\}^2 \Big/ \sum \left\{f^2/\left[1 + f/f_{cij}^2\right]\right\}^2 \right)^{1/2} \tag{9}$$

Main EXSIM12 Program Loops



7.2 SIMULATION PARAMETERS

The modelling parameters that have been assumed in the simulation have been tabulated below.

Table11: Fault Plane solution of 29th March 1999 Chamoli Earthquake

	Strike(°)	Dip(°)	Slip (°)	Depth
NP 1	280	7	75	15 km
NP2	115	82	92	

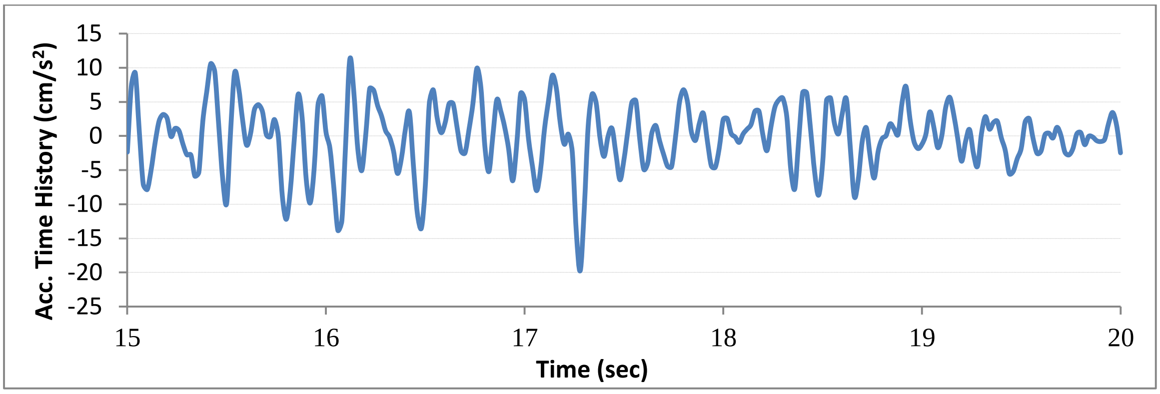
Table12. Modelling parameters for finite fault simulation of 1999 Chamoli earthquake with EXSIM

Parameters	Parameter Value	Source
Latitude(°N), Longitude(°E)	30.51,79.40	USGS
Fault length and width (km)	19x10	Wells and Coppersmith(1994)
Sub-faultdimensions (km)	1x1	
Moment magnitude	6.4	CMT Catalog
Stress drop (bars)	105	
Crustal shear wave velocity (km/sec)	3.6	
Crustal density (g/cm3)	2.8	
Rupture velocity (km/sec)	0.8 x(shear wave velocity)	
Attenuation, Q(f)	Q(f)=140*f*1.018	
Geometric spreading	$1/R^1$ (R≤100 km) 1/√R (R>100 km)	Singh *et al.* (1999)
Partition factor(H)	0.71	
Radiation Pattern(R)	0.55	
Free surface factor (F)	2	
f_{max}(Hz)	10	
Slip Distribution	Random slip for all sub-faults	
Depth of corner on upper edge of fault(Km)	13.86	
Lat-Long of corner on upper edge of fault	30.45(°N),79.49(°E)	

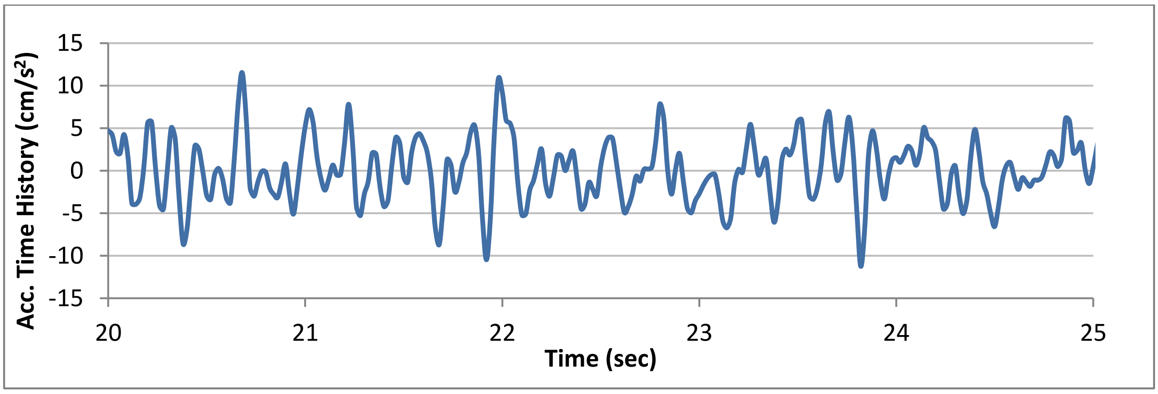
7.3 COMPARISON BETWEEN SIMULATED AND ACTUAL ACCELERATION TIME SERIES

Table13. Recorded and Synthesized PGA at different stations during the 29th March 1999 Earthquake

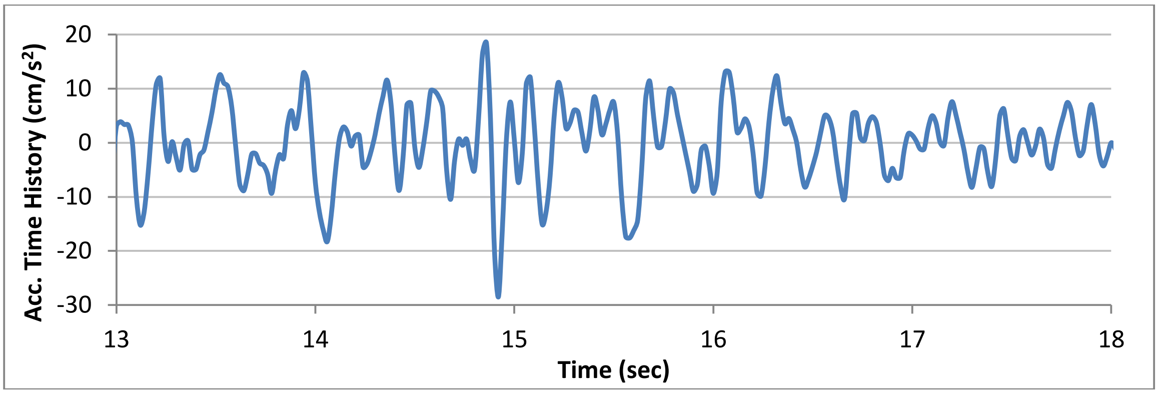
Station Name	Long (°E)	Lat (°N)	Recorded PGA (cm/s^2)	Synthesized PGA at Bedrock (cm/s^2)
Almora	29.58	79.65	27.46	19.74
Barkot	30.8	78.22	22.56	11.53
Chinayliswer	30.55	78.33	44.14	28.49
Ghansiali	30.42	78.65	81.42	59.21
Gopeshwar	30.4	79.33	352.17	172
Joshimath	30.55	79.57	69.65	49.40
Lansdown	29.83	78.7	10.79	10.09
Roorkee	29.86	77.89	54.93	22.38
Tehri	30.37	78.5	60.82	24
Ukhimath	30.5	79.1	95.15	86
Uttarkashi	30.73	78.45	62.78	44.44



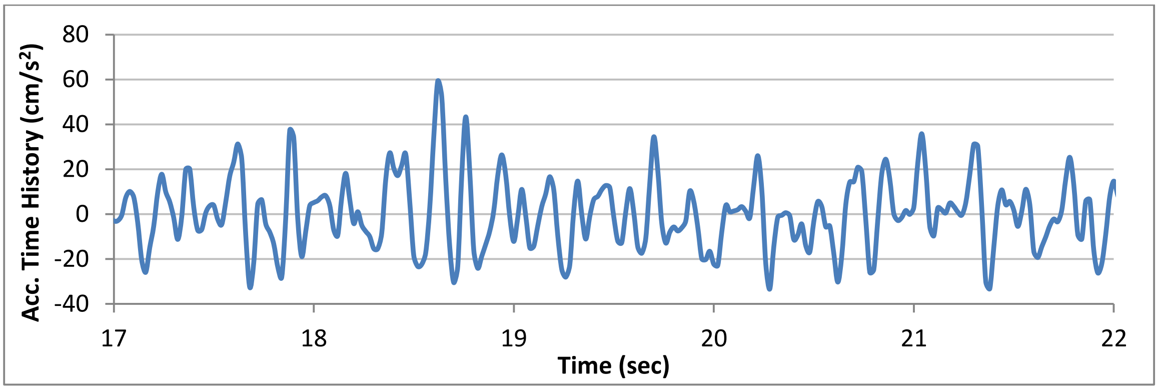
(a). Almora



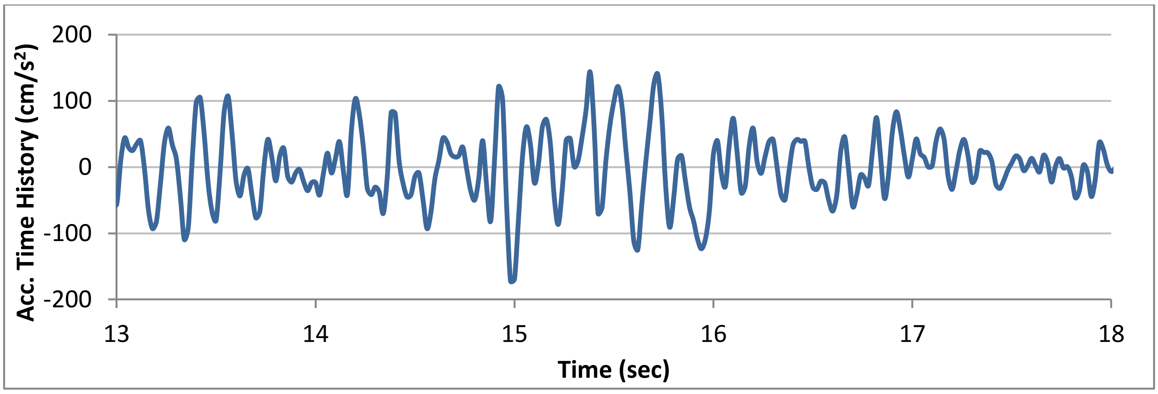
(b). Barkot



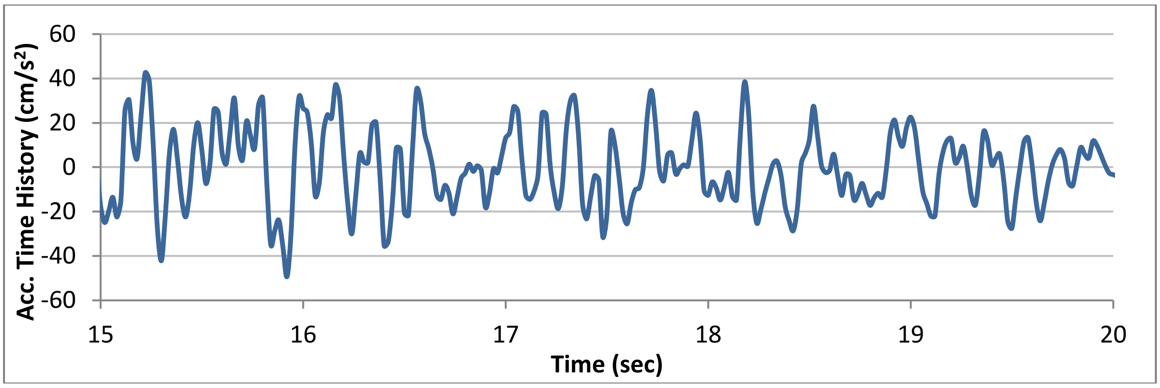
(c). Chinaylishwar



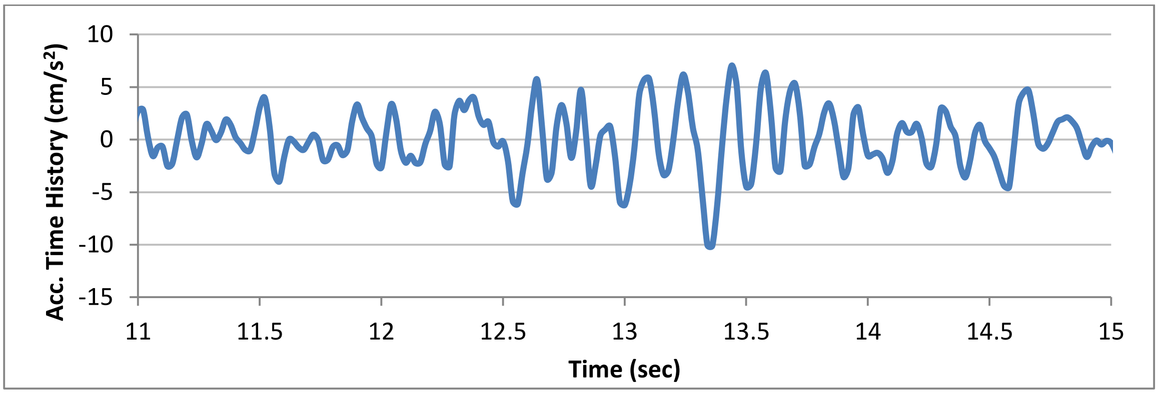
(d). Ghansiali



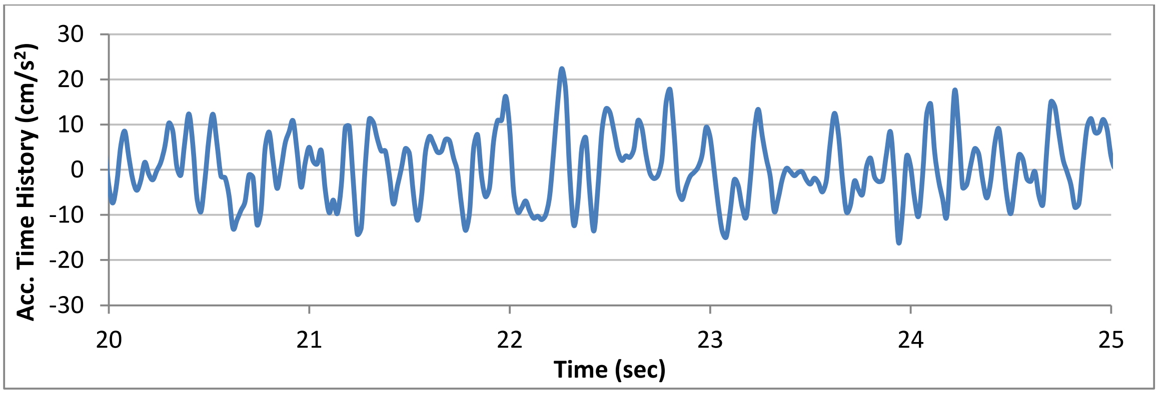
(e). Gopeshwar



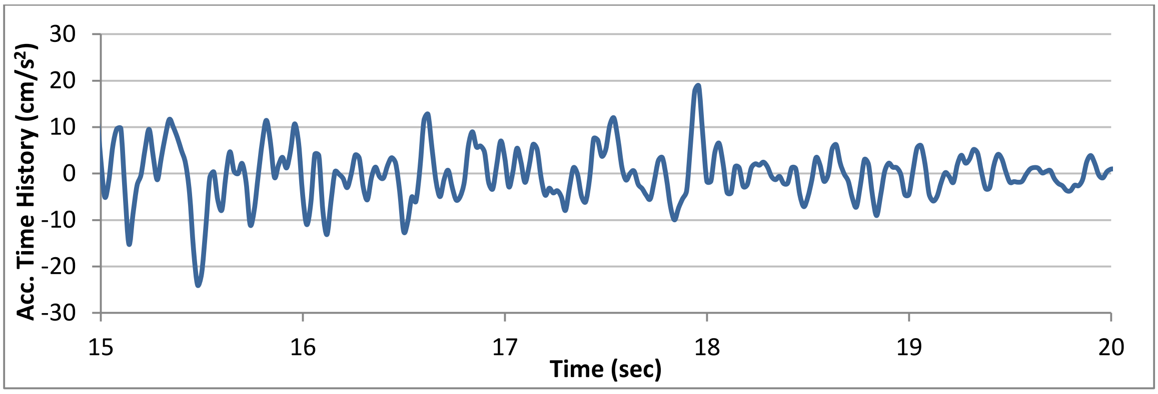
(f). Joshimath



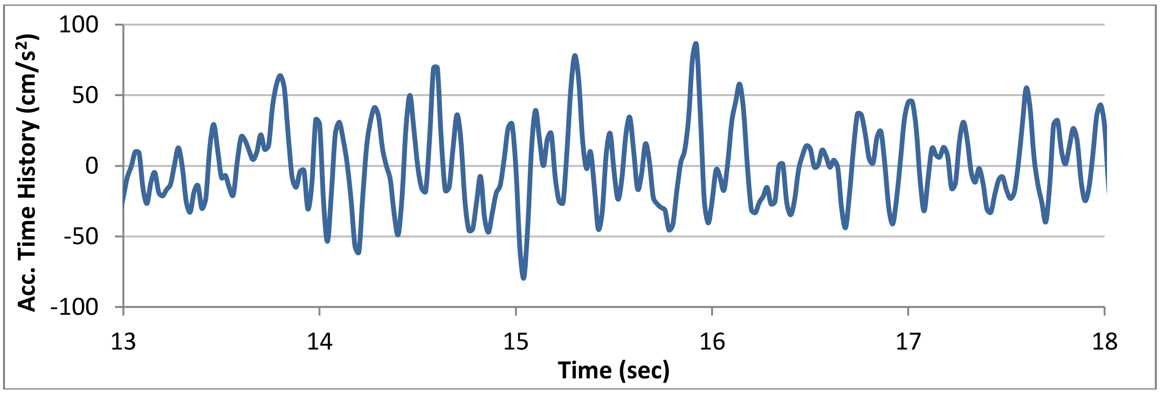
(g). Lansdowne



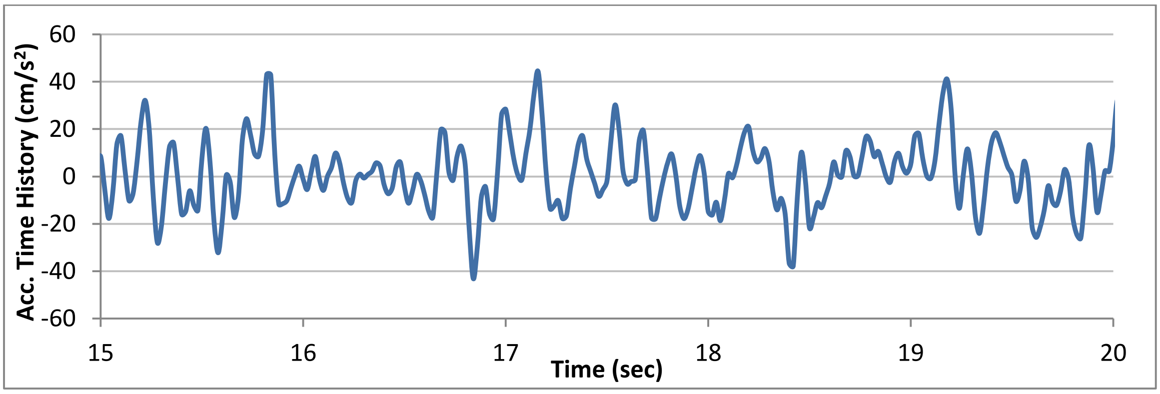
(h). Roorkee



(i). Tehri



(j). Ukhimath



(k). Uttarkashi

CHAPTER 8

SCENARIO SHAKING MAPS

An important component of any shaking map program is to make available to its users scenario shaking maps, i.e., maps showing what level of shaking can be expected due to seismic events originating from different seismic sources having different magnitudes. These maps help concerned agencies better understand the seismic susceptibility of a region and also plan emergency drill and response trainings.

In this chapter, an effort has been made to present some scenario shaking maps utilizing the peeqMap methodology and program that has been described in Chapter 7. The ground motions at different stations have been synthesised using the EXSIM methodology that has been discussed in the previous chapter.

8.1 28th March, 1999 CHAMOLI EARTHQUAKE

Table14. Modelling parameters for finite fault simulation of 28th March,1999 Chamoli earthquake

Parameters	Parameter Value	Source
Latitude(°N), Longitude(°E)	30.51,79.40	USGS
Fault length and width (km)	19x10	Wells and Coppersmith(1994)
Sub-fault dimensions (km)	1x1	
Moment magnitude	6.4	CMT Catalog
Stress drop (bars)	105	
Crustal shear wave velocity (km/sec)	3.6	
Crustal density (g/cm3)	2.8	
Rupture velocity (km/sec)	0.8 x(shear wave velocity)	
Attenuation, Q(f)	Q(f)=140*f*1.018	
Geometric spreading	$1/R^1$ (R≤100 km) 1/√R (R>100 km)	Singh *et al*. (1999)
Partition factor(H)	0.71	
Radiation Pattern(R)	0.55	
Free surface factor (F)	2	
f_{max}(Hz)	10	
Slip Distribution	Random slip for all sub-faults	
Depth of corner on upper edge of fault(Km)	13.86	
Lat-Long of corner on upper edge of fault	30.45(°N),79.49(°E)	

Table15. Synthesized PGA at different stations of 1999 Chamoli earthquake

Station Name	**Long** (°E)	**Lat** (°N)	**Synthesized PGA at Bedrock (cm/s2)**
Almora	29.58	79.65	19.74
Barkot	30.8	78.22	11.53
Chinayliswer	30.55	78.33	28.49
Ghansiali	30.42	78.65	59.21
Gopeshwar	30.4	79.33	172
Joshimath	30.55	79.57	49.40
Lansdown	29.83	78.7	10.09
Roorkee	29.86	77.89	22.38
Tehri	30.37	78.5	24
Ukhimath	30.5	79.1	86
Uttarkashi	30.73	78.45	44.44

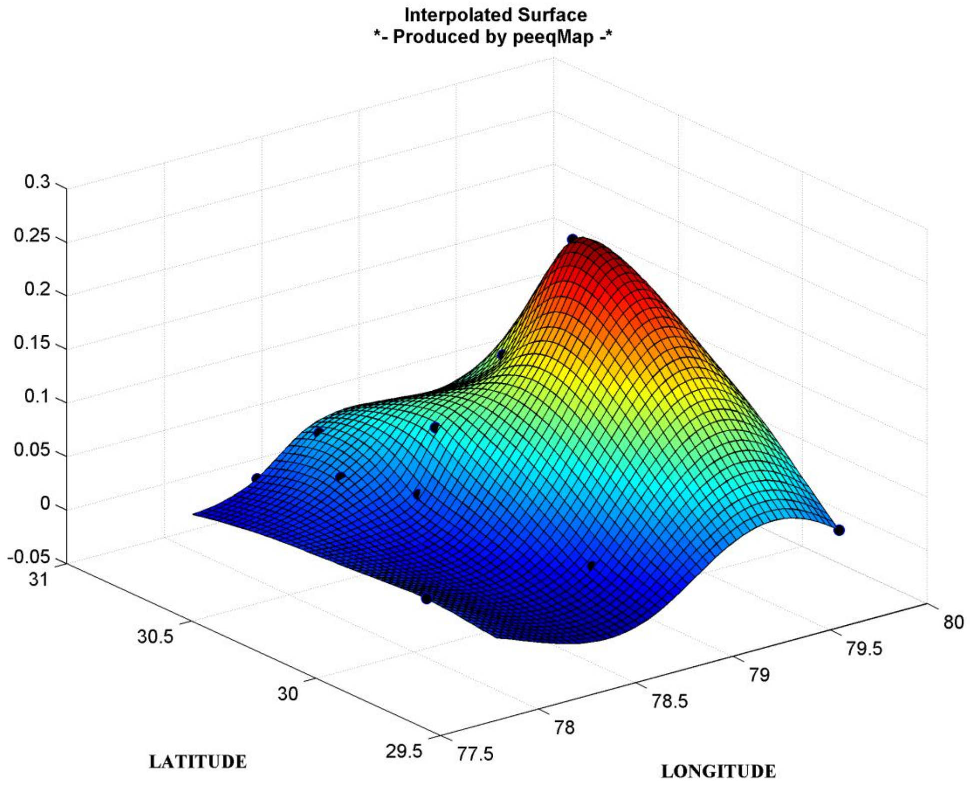


Figure17. Interpolated surface for 1999 Chamoli earthquake produced by peeqMap

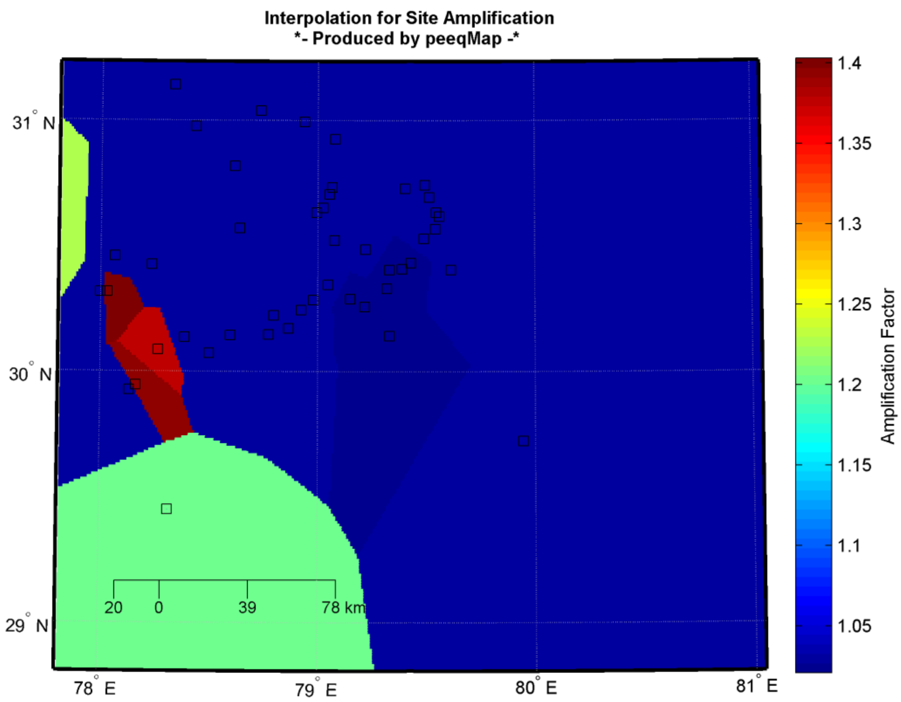


Figure18. Site Amplification Interpolation for 1999 Chamoli earthquake .

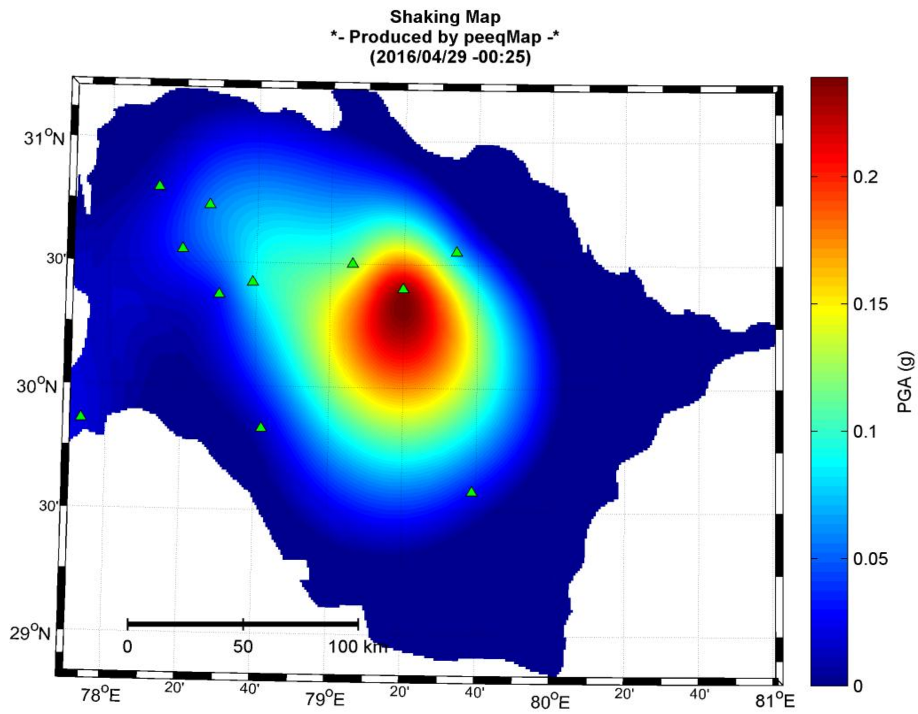


Figure 19. Shaking Map of 1999 Chamoli earthquake.

8.2 20th Oct., 1991 UTTARKASHI EARTHQUAKE

Table16. Modelling parameters for finite fault simulation of 20th Oct.1991 Uttarkashi earthquake

Parameters	Parameter Value	Source
Latitude(°N), Longitude(°E)	30.51,79.40	USGS
Fault length and width (km)	19x10	Wells and Coppersmith(1994)
Sub-fault dimensions (km)	1x1	
Moment magnitude	6.4	CMT Catalog
Stress drop (bars)	105	
Crustal shear wave velocity (km/sec)	3.6	
Crustal density (g/cm3)	2.8	
Rupture velocity (km/sec)	0.8 x(shear wave velocity)	
Attenuation, Q(f)	$Q(f)=140f^{1.018}$	
Geometric spreading	$1/R^1$ ($R\leq 100$ km) $1/\sqrt{R}$ ($R>100$ km)	Singh *et al.* (1999)
Partition factor(H)	0.71	
Radiation Pattern(R)	0.55	
Free surface factor (F)	2	
f_{max}(Hz)	10	
Slip Distribution	Random slip for all sub-faults	
Depth of corner on upper edge of fault(Km)	13.86	
Lat-Long of corner on upper edge of fault	30.45(°N),79.49(°E)	

Table17. Synthesized PGA at different stations of 1991 Uttarkashi Earthquake

Station Name	Long (°E)	Lat (°N)	Synthesized PGA At Bedrock(cm/s^2)
Almora	29.58	79.65	12.34
Barkot	30.80	78.22	63.4
Bhatwari	30.80	78.60	198
Ghansiali	30.42	78.65	102
Karnprayag	30.25	79.23	61.6
kosani	29.68	79.72	24.7
Koteshwar	30.23	78.57	78.2
Koti	30.58	77.78	37.9
Tehri	30.37	78.5	45.34
Purola	30.87	78.08	37.2
Rudraprayag	30.27	78.98	54.7
Srinagar	30.22	78.77	59
Uttarkashi	30.73	78.45	279.8

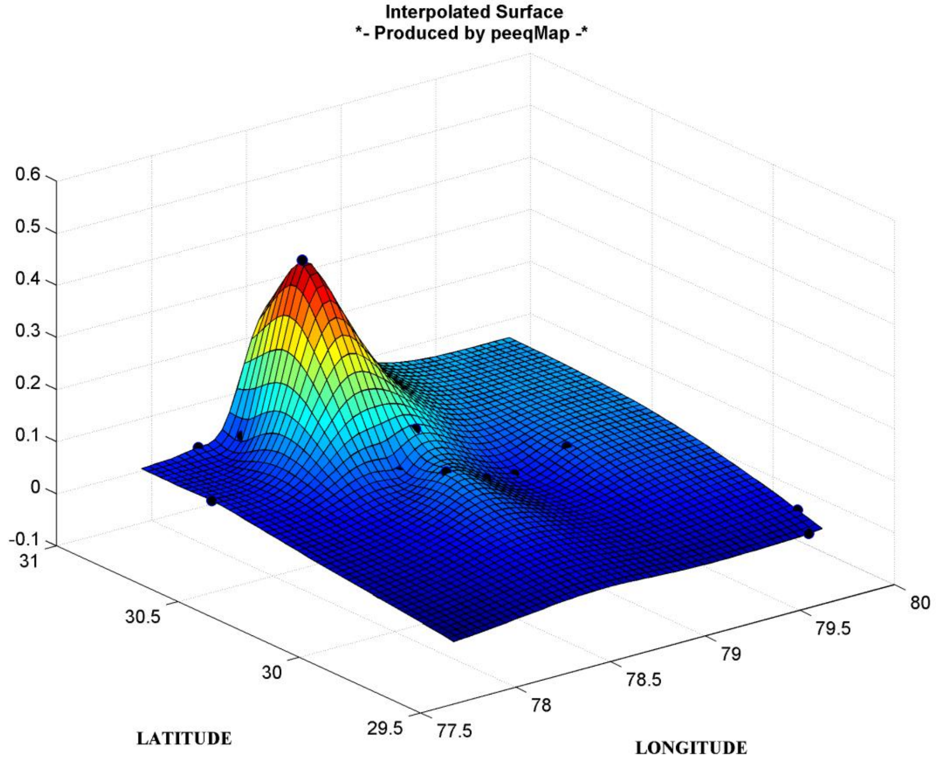


Figure20: Interpolated surface for 1991 Uttarkashi earthquake produced by peeqMap

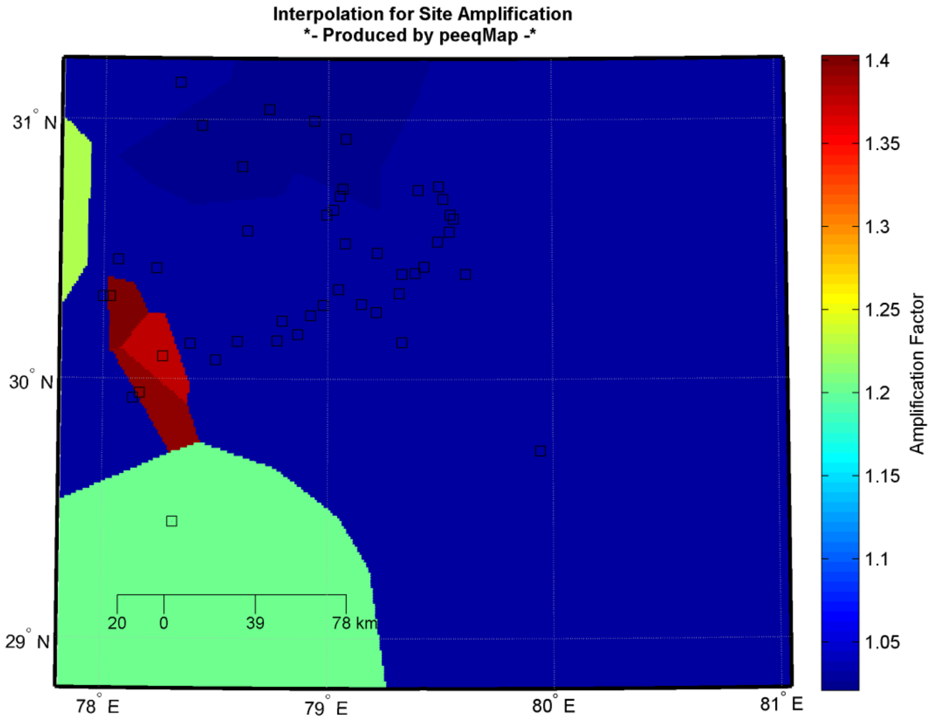


Figure21. Site Amplification Interpolation for 1991 Uttarkashi earthquake

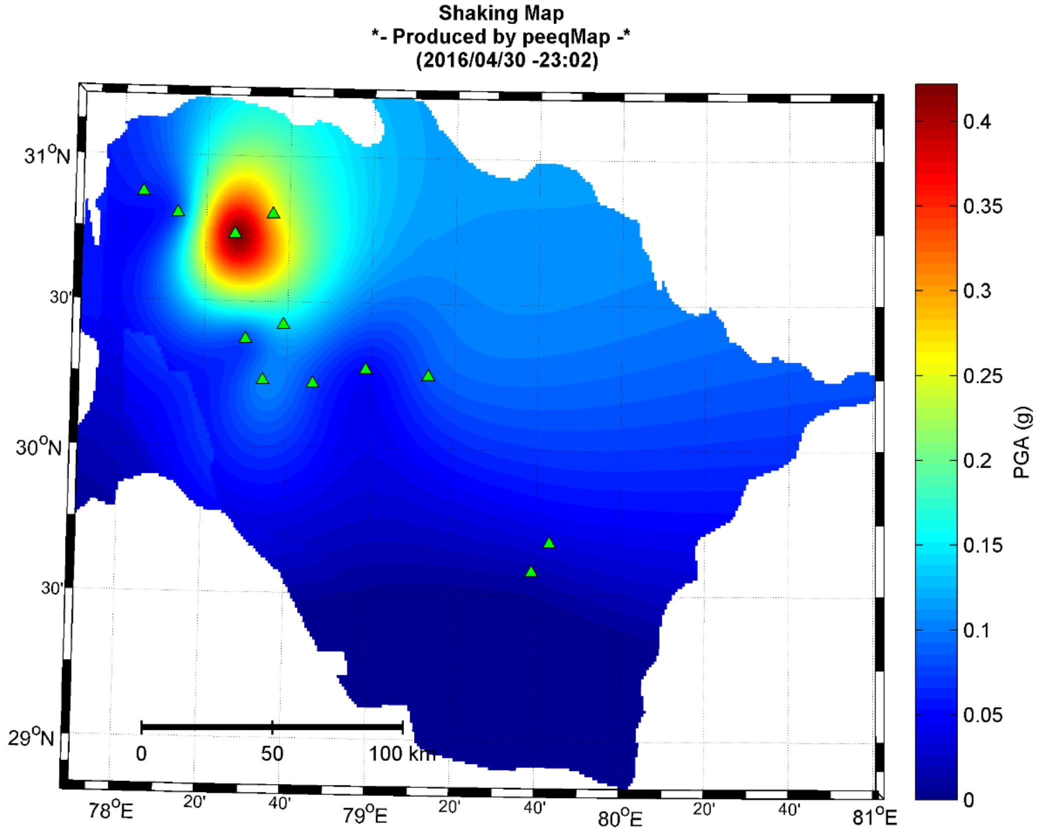


Figure 22. Shaking Map of 1991 Uttarkashi earthquake

CHAPTER 9

SUMMARY

The Shake Map system is designed in such a way that it is automatically triggered whenever an earthquake greater than a specified magnitude is impending on the region where it is installed. The data estimated by the package is immediately made available via a host of internet platforms to the scientific community & disaster management and response agencies so that an effective measure is taken well within time.

The PeeqMap methodology has been implemented for Himalayan Uttarakhand region for two particular scenario earthquakes, i.e., Chamoli Earthquake of 1999 and Uttarkashi earthquake of 1991. Attempt has been made to predict the ground motion parameters for scenario earthquakes so as to validate the results obtained from the method. The recorded and the synthesized data were compared and found to be acceptable. However, the variation in the data may be attributed to the scarcely available data in the region and absence of dense seismology network. Also, the V_{s30} value for most the recording stations used were assumed to be in rocky strata due to the unavailability of the test data which may not be accurate enough to generate authentic results for the scenario earthquakes. Further to these assumptions, the Peak parameters that are generated are at the bedrock level and not at the surface of the stations, which also counts for the deviation from the original data.

Although the maps generated are acceptable, further improvement in the results are possible if proper transfer functions are used in the method so as to obtain the acceleration values at the ground surface to get a more realistic evaluation of the parameters. Also, the actual soil properties evaluated from the borehole tests of the stations should be included so as to implement the methodology in real world situation.

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