Seismic Response Analysis of Dehradun City, India

Rajiv Ranjan
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by

Rajiv Ranjan

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Thesis Assessment Board:

Chairman:	Prof. Dr. F.D. van der Meer (ITC)
ITC Member:	Dr. C.J. van Westen (ITC)
External Examiner:	Dr. R.C. Patel
IIRS Member:	Dr. P.K. Champati ray
Supervisors:	Dr. A.K. Mahajan

Thesis Supervisors:
Dr. A.K. Mahajan (WIHG)
Dr. P.K. Champati ray (IIRS)
Dr. C.J. van Westen (ITC)

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INDIAN INSTITUTE OF REMOTE SENSING, NATIONAL REMOTE SENSING AGENCY (NRSA), DEPARTMENT OF SPACE, DEHRADUN, INDIA
&
WADIA INSTITUTE OF HIMALAYAN GEOLOGY
DEHRADUN, INDIA

I certify that although I may have conferred with others in preparing for this assignment, and drawn upon a range of sources cited in this work, the content of this thesis report is my original work.
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DEDICATED TO MY PARENTS

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ABSTRACT

In an earthquake, the damage at a site is greatly influenced by the response of the soil. For designing of seismic resistant structures, spectral acceleration of the site has been used for a long time. In seismic response analysis, the site response is calculated in the form of response spectra for a particular site. Various parameters that are needed for seismic response analysis are soil profile and its thickness, depth to bedrock, geotechnical properties of the soil and shear wave velocity.

In the present study, to get shear wave velocity and soil thickness, one of the recent techniques Multi channel Analysis of Surface Waves (MASW) method is used. By using this technique, 31 sites have been covered in the study area to know the shear wave velocity variation and the material depth in the city for upper 30 m, which is considered as ideal for seismic response analysis world over. The calculated shear wave velocity of different sites is compared with tube well lithologs and local geology to know the different material type.

SHAKE 2000 a computer programme, which is a widely used one-dimensional method, has been used for site response modelling. In this study shear wave velocity is considered as the main parameter for site response analysis. On the basis of present analysis whole city has been classified in to different zones of shear wave velocity and spectral acceleration.

Key words: *Site response, shear wave velocity, multichannel analysis of surface waves (MASW), spectral acceleration.*

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1. Introduction

1.1. General Introduction

Natural disasters are inevitable and it is not possible to get full control over them. The history of human civilization reveals that man has been combating with natural disasters from its origin but natural disasters like floods, cyclones, earthquakes, volcanic eruptions have various times not only disturbed the normal life pattern but also caused huge losses to life and property, and interrupted the process of development.

With the technological advancement man tried to combat with these natural disasters through various ways like developing early warning systems for disasters, adopting new prevention measures, proper relief and rescue measures. But unfortunately it is not true for all natural disasters. Earthquakes are one of such disaster that is related with ongoing tectonic process; it suddenly comes for seconds and causes great loss of life and property. So earthquake disaster prevention and reduction strategy is a global concern today. To combat with any disaster proper planning is needed, which is a component of Disaster Management. Figure 1-1 is representing the various aspects of disaster management.

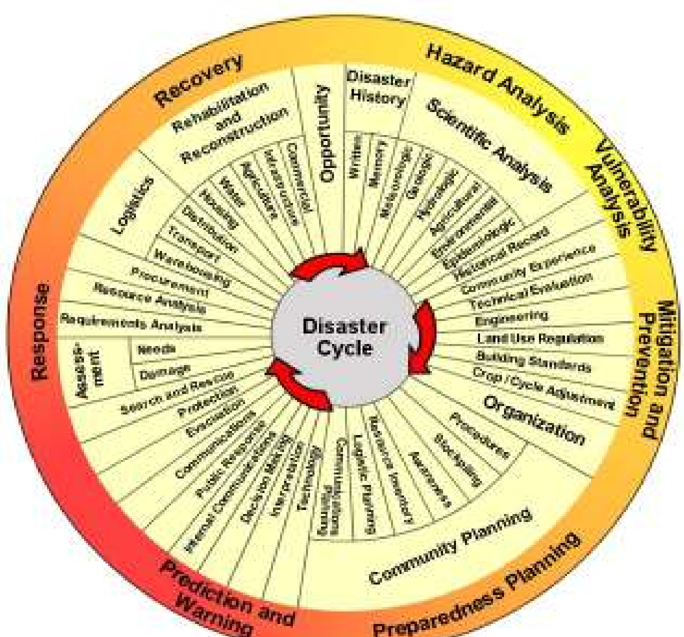


Figure 1-1: Major aspect of natural disaster management after Fred Col (URL 1, 2004)

Recognition of the hazard is one of the most important components of Disaster Management. This thesis deals with hazard analysis, i.e. Seismic Hazard Analysis and also the first step towards the mitigation and prevention from the earthquake as the final result will be useful to define building codes for the city as well as the land use planning.

For any Hazard analysis, zonation of the area is very important. For seismic hazard analysis there are two methods of zonation-Macrozonation and Microzonation. Macrozonation is used for seismic zonation at regional level on small scale considering broad parameters, while microzonation is mainly used for urban area considering local parameters and site conditions for seismic hazard analysis, at large scale. Local soil conditions has significant role on amplification of seismic waves, it being experienced in the past earthquakes (Ansal et. al, 2004: Slob et. al 2001: Olieveira, 2004; Street et al., 2001). Seismic response analysis is useful to predict the design ground motion site for microzonation (Presti et al., 2004)

India has a long history of earthquakes. The earliest earthquake is described in "The Mahabharata" the great Indian epic, and occurred about 1500 BC in Kurukshetra, Haryana (Bilham, 2004). In the last fifty years the population of India is doubled and it resulted in very rapid growth of settlements, especially in urban areas. Presently about 50 million people in India living in Himalayan region are at risk from earthquakes (Bilham et al, 2001).

The Himalayas are very young from geological point of view and hence very unstable. Most of the parts of North India and North-eastern India are mapped as either seismic zone IV or V in the seismic zonation map of India (IMD, 2004). According to Mahajan and Kumar (2001) most of the seismicity in the Himalayan region is concentrated along a shallow north dipping plane, which indicates under thrusting of the Indian plate. Some of the recent earthquakes in this area are the Uttarkashi earthquake of 1991 (6.4 mb) and Chamoli earthquake of 1999 (6.8 mb).

The International Institute for Geoinformation Science and Earth Observation (ITC) started a Research Project "Strengthening local Authorities in Risk Management " (SLARIM) with the objective to develop a methodology for risk assessment and decision support systems specially for an urban areas in developing countries (Van-Westen, 2004). Under this research programme between ITC, Indian Institute of Remote Sensing (IIRS) and Wadia Institute of Himalayan Geology (WIHG), Dehradun has been selected to develop a methodology for seismic microzonation. The present work is a part of this project.

Seismic wave propagation in the top layers of the earth's crust controls the spread of earthquake disaster in an area (Aggarwal et al., 2003). The main aim of seismic response analysis is to determine the effect of seismic waves at the time of an earthquake for a specific site, as seismic hazard or risk which is dependent on seismic source, filter function of transfer media, local geology, type of structures and soil structure interaction (Figure 1-2). The most important parameter for seismic response analysis is shear wave velocity that give the information about the subsurface condition that plays significant role in amplification or deamplification of the seismic waves. In this research work for response analysis shear wave velocity measured at the various site and used for seismic response analysis.

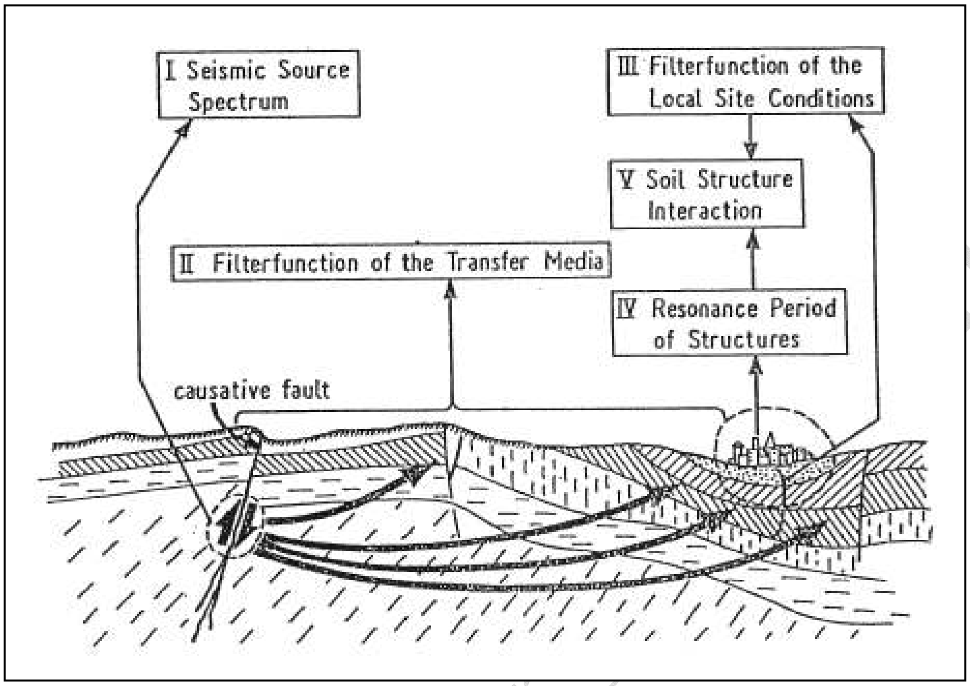


Figure 1-2: Components of earthquake that causes damage to structures due to earthquake

1.2. Problem Definition:

Every site has a specific seismic response at which ground shaking can be amplified, and if it matches with the fundamental frequency of the manmade structures there is maximum probability of damage. In the past several earthquakes like Mexico earthquake (1985), San Francisco earthquake (1989), Los Angeles earthquake (1995) have established the fact that local site conditions has significant role in the amplification of ground motion especially on those area, that located on unconsolidated young sedimentary materials (Hunter et al., 2002). In India during Bhuj earthquake 2001, Ahemadabad experienced a heavy damage in some parts, which were situated on younger alluvial deposits in spite of its greater distance from the epicentre. In India the Himalayan region has experienced various earthquakes in the past, which caused great loss of life and property. Doon valley, which is an intermontane valley between Lesser Himalaya and the Siwaliks witness of various earthquakes.

Geologically, Doon valley is a synclinal basin, filled with coarse clastic fan deposits of late Pleistocene and Holocene age known as Doon gravel (Choubey et al., 2001). It is controlled by many tectonic faults and the Main Boundary Thrust (MBT), which is in the North of the city that may cause a severe earthquake in the future (Virdi, 2003). The outcome of recent paleoseismological studies around Dehradun indicates displacement in the soft sediments (Mahajan, 2003). The city has experienced serious damage during 1905-Kangra earthquake (Middlemiss, 1910). In the recent past it experienced two moderate earthquakes of Uttarkashi (1991) and Chamoli earthquake (1999).

Recently Dehradun has been declared as the capital of the newly formed Uttaranchal state, which might lead to an even more rapid urban development of the area in a haphazard manner.
Seismic Response Analysis of the city will be very useful for the preparation of a microzonation map which may be useful for future planning purposes as well as risk analysis and mitigation of earthquake. For this a detailed study about the properties of soil, at different locations is needed.

1.2.1. Hypothesis

It is possible to obtain a reliable seismic response on the basis of geophysical reflection survey data of the upper 30 meters of the soil cover under Dehradun city.

1.3. Research Objectives

The main objectives of this research are:

1. To measure Shear wave velocity and material depths using Multi Channel Analysis of Surface Waves (MASW) method with an Engineering seismograph.
2. To verify the geophysical data with existing data such as tube well data or existing geological model.
3. To estimate ground motion from soil site response
4. To calculate natural frequencies, response spectra and spectral acceleration for different locations.
5. To prepare spectral acceleration map at different frequency.

1.4. Research Questions:

1. What is the uncertainty in the distribution of shear wave velocity and soil thickness of different soil types in Dehradun?
2. What will be the most likely earthquake scenarios for the study area? Which strong motion records to use for site response analysis?
3. What is the variation of natural frequencies in Dehradun, and will we be able to define that given the uncertainty in soil information?
4. How the amplification varies with soil conditions?
5. What is the minimum length of ground for such type of survey to collect geophysical data?

1.5. Method and Materials

1.5.1. Input data

The basic information, which is needed for seismic response analysis for microzonation of Dehradun, is as follow:

- Base map of the city on 1:25000 scale.
- Geotechnical data, which include:
    1. Shear wave velocity,
    2. Unit weight,
    3. Shear modulus and
    4. Damping
- Borehole/Tube well data that include the information of different soil layers, and their thickness for different locations.
- Depth to bedrock level for different locations.

1.5.2. Methodology:

Subsurface soil condition can amplify or deamplify the seismic waves, so for seismic response analysis it is necessary to know the soil properties and the variability in shear wave with change in soil properties. For this research work a new technique MASW (Multichannel Analysis of Surface Waves technique) being used to collect shear wave velocity and the soil profile of different locations in the city.

Multichannel Analysis of Surface waves method is a non-invasive technique of geophysical survey that gives this shear-wave velocity (Vs) information in either 1-D (depth) or 2-D (depth and surface location) format in a cost-effective and time-efficient manner. In this method Rayleigh waves are recorded by multiple receivers deployed on an even spacing and connected to Engineering seismograph which is a common recording device to record ground roll.

The basis of the site selection was its topography, geology, the population density and the availability of open spaces in the particular area. Generally it requires an open space having more than 100 m in length and about 50 m wide.

These recorded data will be processed to get dispersion curve in SurfSeis (Kansas Geological Survey, 2003) that will be inverted to get shear wave velocity for a shot location at a specific site. The shear wave velocity for all the shot location, for a particular site will give a 2D profile of shear wave velocity and depth along the survey line. This soil profile when compared with the nearby tube well or Bore well data and the local geology it gives the information about different layers of soils and the shear wave velocity with variability in changing layers.

These data works as input for SHAKE 2000 the one dimensional ground response modelling software. The complete methodology for seismic data processing to get shear wave velocity and the SHAKE 2000 analysis discussed in chapter four and chapter five. Analysis in SHAKE 2000 gives Response Spectra, Average shear wave velocity, and Spectral Acceleration at different frequency for specific location as output. These values can be added in the attribute table of the location point map in GIS environment to get spectral acceleration map at different frequency and shear wave velocity map. Complete methodology adopted for this study shown in Figure 1-3.

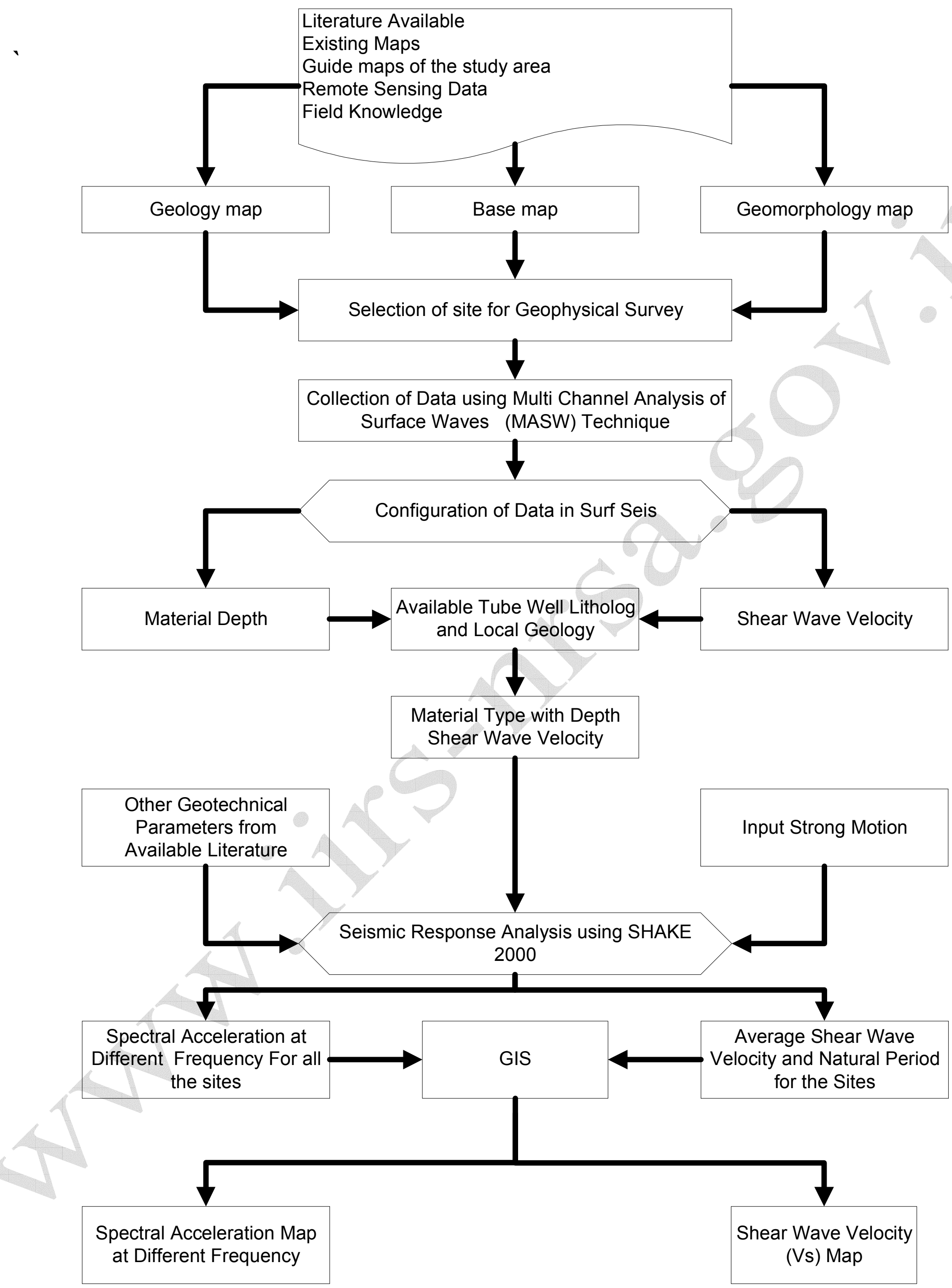


Figure 1-3: Flow chart of the methodology for the research.

1.5.3. Data Collection

For this research work the most important work was to collect shear wave velocity data from different parts of the city. The first phase of the fieldwork was started in last week of July and continued till the middle of August, but due to heavy raining the data collection had to be stopped on 15th August 2004. In this period data was collected from 10 different sites. In the second phase, which was of 20 days and started in the 1st week of September, data was collected for another 23 different sites of the city, finally the fieldwork for the data collection ended on 28th September. Therefore the shear wave velocity data being collected from 33 sites but two of them could not be used for the research work due to their quality. At one site data being collected with change in spacing between the sensors to see the effect on shear wave velocity and the variation in depth. At some places the spacing between geophones being changed to get the answer of the fifth research question, which added later during the thesis work.

17 different stations had been earlier covered to get shear wave velocity by Dr. Mahajan (Mahajan, personal communication). So in the site selection it has been tried to not repeat the same stations that earlier covered. The data collected in the field for this research work is shown in Figure 1-3 and the name of the site and their id are given in table 1-1.

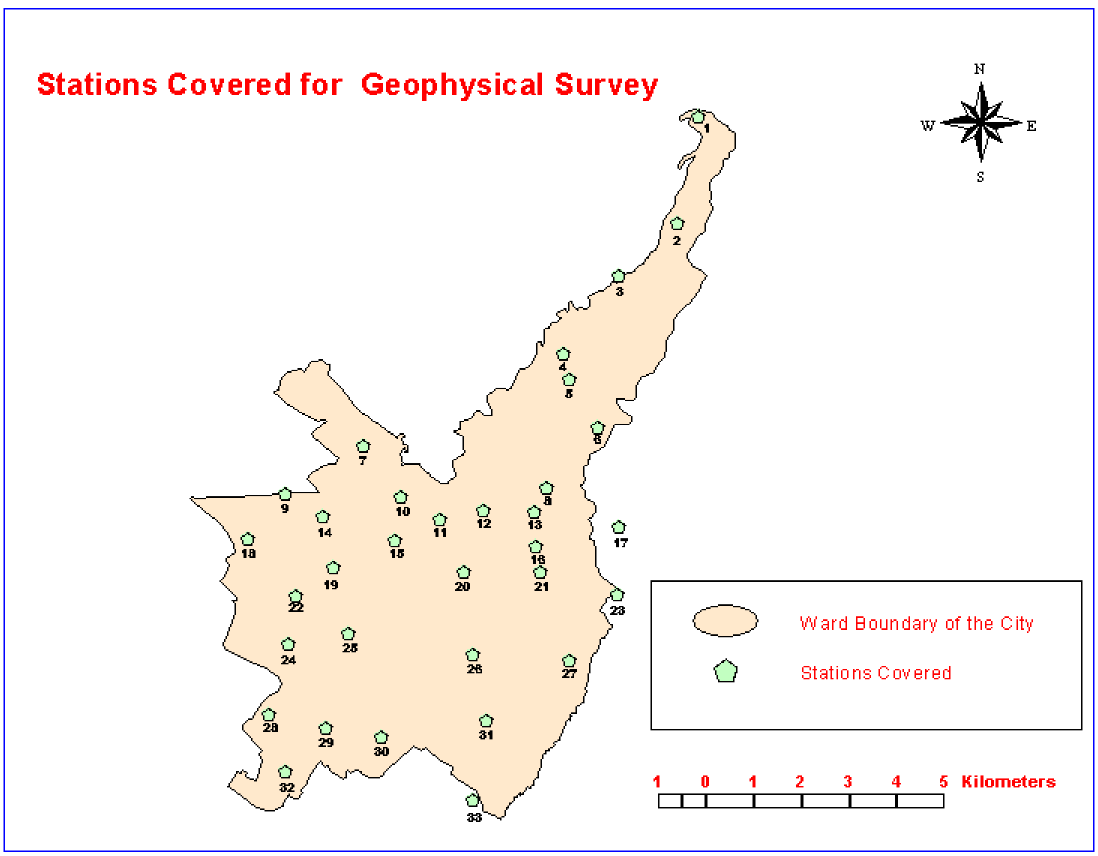


Figure 1-4: The sites covered for the geophysical survey

Site -ID	**Location**	**Site -ID**	**Location**
1	Shehanshahi Ashram, Rajpur	18	GRRP School, Vasant Vihar
2	SOI Ground, Rajpur Road	19	SRP School, Kawali
3	Malsi Estate, Mussorrie Road	20	Mahadevi K.P
4	Dairy Farm, Rajpur Road	21	Welhem Boys School, Dalanwala
5	Blind School, Rajpur Road	22	Engineers Enclave
6	GRRP School Ground, Sahastradhara Road	23	Ladpur
7	Central School, Rajendernagar	24	Olympus School, Niranjanpur
8	Kanya Gurukul, Aryanagar	25	GRRP School Patelnagar
9	Ballupur	26	Dharampur
10	Doon School, Chakrata Road	27	Rajiv Nagar
11	Chukhuwala	28	Raja Ram Mohan Academy,Majra
12	St. Joseph Academy, Rajpur Road	29	Radha Swamy Satsang Ground, Ajabpur
13	DBS college, Karanpur	30	Ajabpur Bypass
14	Wadia Institute	31	Thomas College Ground, Ajabpur
15	GRRP School Khurbura	32	Clementown
16	B.B School, Dalanwala	33	River Terrace of Rispana River
17	Raipur		

Table 1-1: Site name covered for the survey and their id.

2. Literature Review

It has been evident from the past earthquake events that have taken place all over the world that the amplification of ground motion is highly dependent on the local geological, topography and geotechnical conditions. Many research papers are available on these earthquake effects (Phillips and Aki, 1986.; Pitilakis, 2004; Semblat et al., 2000; Slob et al., 2002; Stewart et al., 2003; Topal et al., 2003,; Wills and Siliva, 1998). Different types of soil, having different geotechnical properties will behave differently to seismic waves. Therefore it is important to give special importance to seismic response analysis of specific sites in seismic hazard analysis of an area. The early seismic hazard maps prepared by Algermissen and Perkins (1976) for parts of the USA were based on regional seismic activity and soil conditions (Nath et al., 2000).

The objective of this chapter is to give a brief overview of the literature on seismic hazard analysis, microzonation and seismic response modelling.

2.1. Seismic Hazard Analysis

Seismic Hazard Analysis is the quantitative evaluation of ground shaking hazard at an individual site through the identification and characterization of all potential sources of seismic activity, which may give rise to significant ground motions at the specific site (Kramer, 1996).

There are two different approaches for seismic hazard analysis: a probabilistic and a deterministic one.

2.1.1. Probabilistic Approach

This approach for seismic hazard analysis was developed by Cornell (1968). It allows incorporating the effects and frequencies of all earthquakes that could impact a site. Probabilistic Seismic Hazard Analysis (PSHA) can easily incorporate model and parameter uncertainties (Panel on Seismic Hazard Evaluation, 1997). The PSHA procedure can be divided in four steps demonstrated in Figure 2-1.

1. The identification of earthquake sources such as active faults, which may affect the study area.
2. To determine magnitude/frequency relations for each of the selected earthquake source zones based on the historic earthquake events from a catalog;
3. The third step of this approach is to select a specific attenuation relationship that relates the median value of the ground motion parameter to be mapped to the magnitude of the earthquake and distance from the source (Finn et al., 2004).
4. The final step of the approach is to compute the hazard curve between acceleration and probability of exceedance on the basis of the first three steps.

Under the Global Seismic Hazard Assessment Program (GSHAP), which was launched in 1992, the International Lithosphere Programme and other supporting agencies prepared a global seismic hazard map using advanced methods for probabilistic seismic hazard assessments (Giardini et al., 1999).

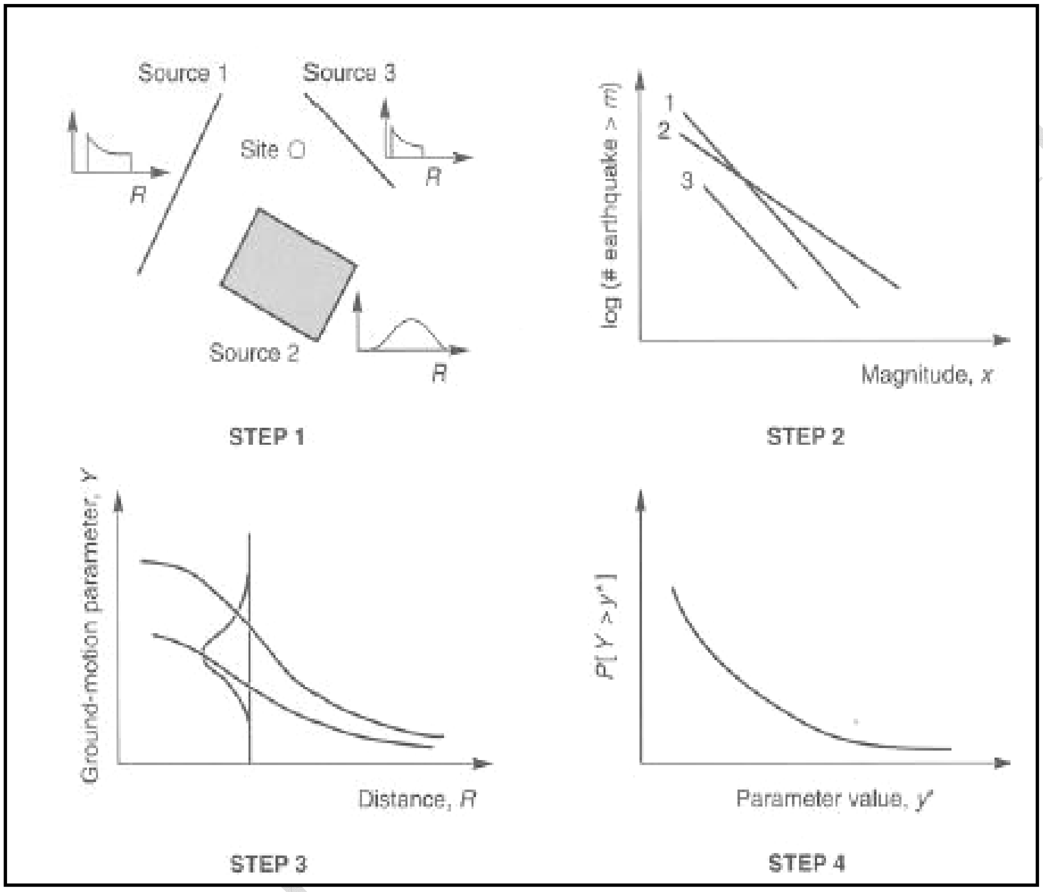


Figure 2-1: Different steps for Probabilistic Seismic Hazard Analysis (Kramer, 1996)

An example of PSHA is given by Stepp et al. (2001) who used the method to estimate ground motion and fault displacement hazards at Yuca Mountain Nevada.
In India lot of work has been done in the field of seismic hazard analysis. Mahajan et al. (2002) using Probabilistic technique, has prepared a seismic hazard map of northwest Himalaya which and indicates two major regions of seismic activity as Kangra-Chamba region and Dehradun-Chamoli region.

2.1.2. Deterministic Approach:

On the other hand, Deterministic Seismic Hazard Analysis (DSHA) is based on the calculation of the acceleration related to a particular earthquake scenario which occurs at the closest possible distance from the site of interest, without considering the likelihood of its occurrence during a specified exposure period (Gupta, 2004).The methodology for this analysis has also four steps (See Figure 2-2):

1. Identification and characterization of the entire earthquake catalogue, and the earthquake sources which may cause ground motion in the study area.
2. Selection of the specific parameters for the earthquake source zones, such as epicentre distance, depth and magnitude.
3. Selection of relevant attenuation relationships and calculating the median value of the ground motion parameter as a function of the magnitude of the earthquake and distance from the hypocenter.
4. Evaluating the values for all the earthquake sources and selecting the largest value.

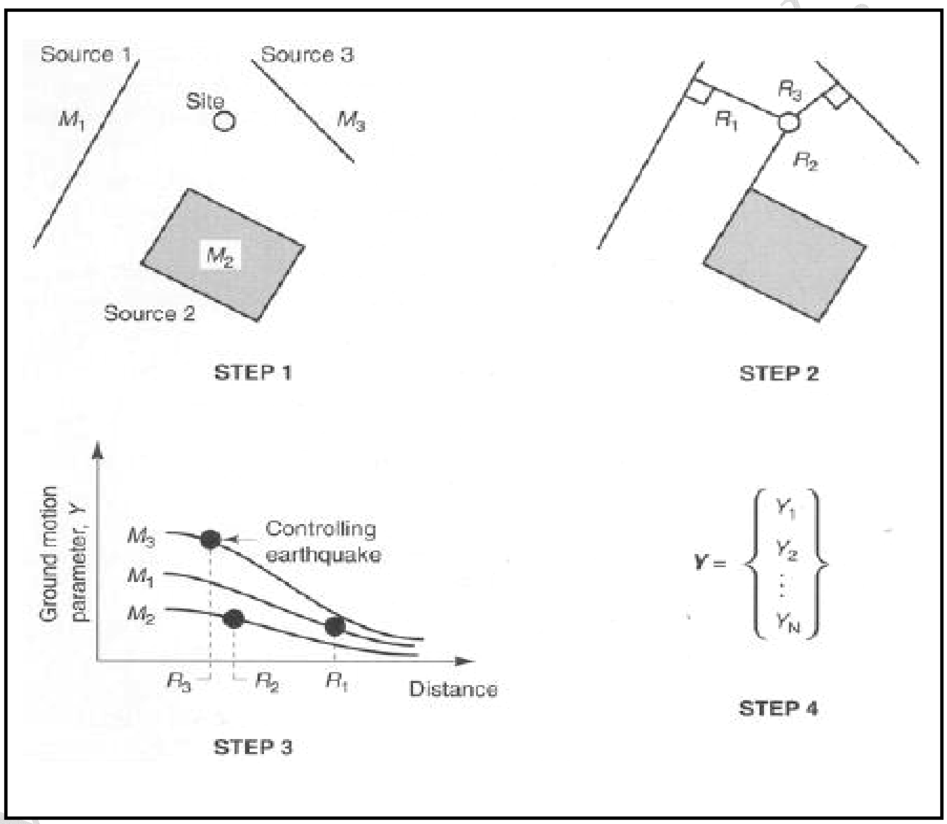


Figure 2-2: Different steps for Deterministic Seismic Hazard Analysis (Kramer, 1996)

On the basis of the examination, the seismic hazard in Oakland, California it has been suggested that probabilistic approach is better for more complex decisions, while deterministic approach is better for simpler decisions and well understood seismicity. It is also suggested that in some cases it is advisable to apply both probabilistic and deterministic methods (McGuire, 2001; Krinitzsky, 2003). Table 2-1 gives an overview of the recommended application of the two methods:

Decision	Quantitative aspects of decision	Predominant approach
Seismic design levels	Highly quantitative	Probabilistic
Retrofit design	Highly quantitative	Probabilistic
Insurance/reinsurance	Highly quantitative	Probabilistic
Design of redundant industrial system	Quantitative or qualitative	Both
Trainning and plan for emergency response	Mostly qualitative	Deterministic
Plans for post earthquake recovery	Mostly qualitative	Deterministic
Plans for long term recovery, local	Mostly qualitative	Deterministic
Plans for long term recovery, regional	Mostly quantitative	Deterministic

Table 2-1: Different methods of seismic hazard analysis and their different applications (McGuire, 2001)

2.2. Microzonation

Seismic microzonation is a multi-disciplinary work, which deals with geology, geophysics geotechnical engineering and anthropology or civil administration (Mishra, 2004). In microzonation study seismic hazard and seismic induced hazard like landslide, flood, and fire both are considered. So it estimates total seismic hazard from ground shaking. It is one of the most effective tools in land use planning, pre earthquake disaster mitigation and to define building code for a seismic prone area.

The main objective of microzonation is to prepare a seismic hazard map on a large scale especially for an urban area considering local site conditions and to propose a guideline for urban planners to mitigate earthquake risk (Ansal et al., 2004; Slob et al., 2002).
Noack et al. (1997) proposed a qualitative technique for microzonation of Basel city in Switzerland, considering geological and geotechnical data. A rating system was developed for different soils type and their capabilities to amplify seismic waves. All these parameters were framed in 25x25 m grid and the summation of all these has given the final zonation map (Noack et al., 1997).

Topal et al. (2003) considered various parameters for microzonation such as geological, geotechnical, seismotectonic and hydrogeological conditions and on the basis of these, four different zones for the Yeneshir an urban centre in Turkey, was proposed. They also emphasized on the secondary natural hazards like liquefaction, flooding, and landslides, which may be triggered by the earthquake. Finally they found that there is neither a landslide nor a flood problem in the city, but due to presence of clayey soil in the southern part of the city it may be susceptible to liquefaction (Topal et al., 2003)

Slob et al. (2002) presented a technique for microzonation for the city of Armenia in Colombia. In this study they used a 3-D layer model in GIS, combined with a 1-D calculation of seismic response using SHAKE to get the spatial variation in seismic response which was checked with the damage assessment of Armenia (Colombia). They concluded that the amplification was high in the 5 Hz range, that corresponds to the natural frequencies of houses with 2 stories, it become true after the earthquake, in which low rise building experienced more damage than high rise building (Slob et al., 2002).

Ansal et al., (2004) adopted a probabilistic approach in a microzonation study for the city of Siliviri (Turkey). To determine the local geological and geotechnical condition they prepared geology map at 1:5000 scale and used it to plan detailed site investigations. For site response analysis they divided the area in 500 x 500 meters grid and a hypothetical soil profile was prepared on the basis of the available borehole data and laboratory test result. For site characterization the average shear wave velocity was used, that was determined from seismic refraction tests by which spectral amplification was computed using the equation proposed by Medorikawa (1987):

$$A_k = 68 \times V_s^{-0.6}$$

Where A_k is the spectral amplification and V_s is the shear wave velocity.

Spectral amplification map was prepared on the basis of the output. For site response analysis they used six different ground motion data to get spectral acceleration and its average considered for site response analysis. The final zonation map was prepared considering all these outputs (Ansal et al., 2004).

Mishra (2004) proposed a detailed methodology for the microzonation study of Jabalpur city (India). He adopted a hierarchical approach for his study and completed the microzonation map in four stages. In the first stage, first level microzonation map was prepared on the basis of preliminary geological concept of seismic rigidity and impedance contrast in the litho column. In the second stage, second level microzonation map was prepared considering geotechnical inputs on liquefaction potential and site response pattern. In the third level microzonation map, the results of numerical modelling and geoscientific map were characterized as hazard map with ground motion, which was defined in the terms of amplification and response spectra. In the final stage or fourth level microzonation map Risk microzonation map was prepared on the basis of various parameters of Vulnerability.

2.3. Seismic Response or Site Response Analysis

There are various methods used for seismic response analysis of site effects, which can be grouped into experimental, numerical, empirical and semi-empirical. Most of these methods are based on the assumption that the response of a soil deposit is caused by the upward propagation of horizontally polarized shear waves from the underlying bedrock formations.

Experimental methods are used for the analysis on the basis of frequency domain. The most popular experimental techniques are Standard Spectral Ratio, generalized inversion scheme and horizontal to vertical spectra ratio technique.

The Standard Spectral Ratio (SSR) method was introduced by Borcherdt (1970) and was very popular in the last decade for the site response analysis. It gives the frequency dependent site response amplitude or amplification relative to the rock site (Figure 2-3). Theoretically this method is very simple as the seismic response for a site is computed on the basis of the ratio between Fourier amplitude spectra of the site and the nearby rock site for the same earthquake. But practically it is difficult to find the reference site nearby as the reference site must be free from any amplification, which is not possible in all the cases.

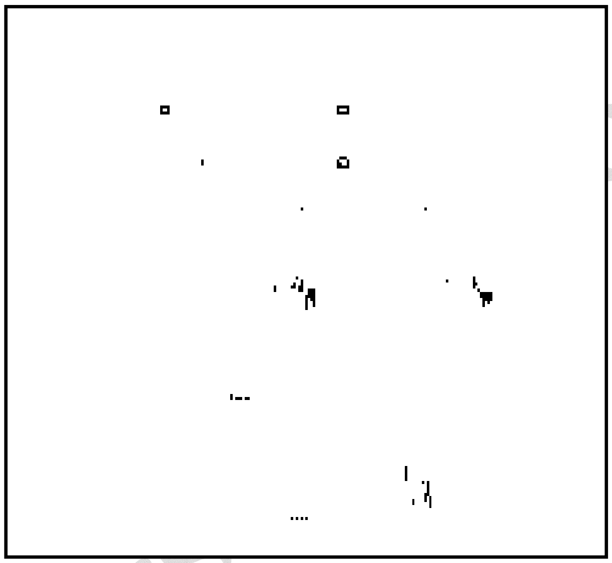


Figure 2-3: Spectral Ratio Technique (Pitilakis, 2004)

The Single Spectral Ratio method was introduced by Nakamura (1989). In this technique microtremor low amplitude vibration is used to compute site response. The advantage of the technique is that it does not require any reference site.

In the seventies a new technique was introduced, based on the ratio between the Fourier spectra of the horizontal and vertical components of ambient vibrations well known as “microtremors" or "ambient noise” (Nogoshi and Igarashi, 1971). It was later modified by (Nakamura, 1989) and is now being popular as the Nakamura method. He found that the ratio between the horizontal and vertical component increases at the resonance frequency so it shows peak at this frequency (Nakamura, 1989) (Figure 2-4). It is observed that there is not much effect of noise so it is ideal for site response analysis in urban areas and various researchers support this technique. The technique is time saving and very simple (Jensen, 2000) and has become very popular in the world for the site response analysis. But some researchers question its theoretical background and its limitations for different sites (Coutel and Mora, 1998; Ohta et al., 1978; Field and Jacob, 1995; Lermo and Chavez-Garcia, 1994). But it is useful in the case of simple geology and is able to estimate site fundamental frequency in the range of 3.0 to 5.0 Hz.

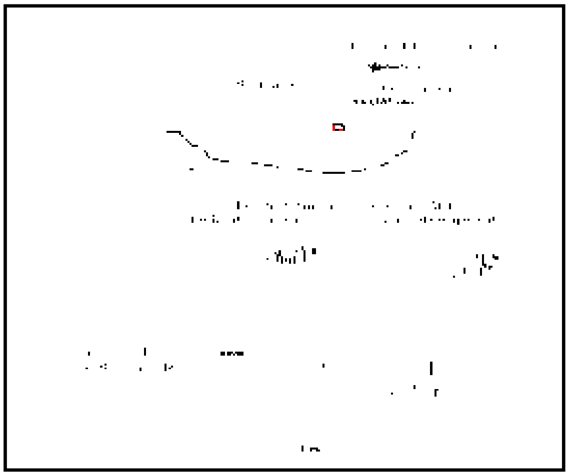


Figure 2-4: Description of H/V technique (Pitilakis, 2004)

Shear wave velocity is considered as one of the important parameters for seismic response analysis (Kramer, 1996). The National Earthquake Hazard Reduction Programme (NEHRP) used shear wave velocity up to a depth of 30 m to classify sites according to soil type for earthquake resistant designing (BSSC, 1997). In NEHRP classification the shear wave velocity for upper 30 m was determined and 6 soil profile types were recognized from soft soil (F) to hard rock (A), shown in table 2-2:

Soil Profile Type	**Rock/Soil Description**	**Average Shear wave Velocity for upper 30 m (in m/sec)**
A	Hard Rock	>1500
B	Rock	760-1500
C	Very Dense soil/ Soft Rock	360-760
D	Stiff soil	180-360
E	Soft soil	<180
F	Special soils requiring site-specific evaluation	

Table 2-2: NEHRP soil profile types on the basis of shear wave velocity for upper 30 m

Building seismic safety council (2000) has recommended this for International building code that adopted in 2002 (Williams et al., 2003).

To measure the shear wave velocity and material thickness seismic surveys have long been used. All the seismic surveys are based on the propagation of seismic waves and the elastic properties of the soil. There are two methods of seismic survey reflection and refraction, which may be of invasive or non invasive in nature. Bore hole tests are invasive in nature used to calculate shear wave velocity, which includes down hole test, up hole test and cross-hole test. In these three methods down hole test and cross hole test are very popular and widely used to calculate shear wave velocity. In down hole test, seismic waves generated at the surface and recorded by geophones in the bore holes. In cross hole test seismic waves generated at a particular level in one bore hole and these seismic wave recorded at the same level in one or more neighbouring bore holes. It gives the distance travelled by the wave and on the basis of these (distance and time) velocity can be calculated by dividing distance with time. The bore hole methods give very accurate result in measuring the shear wave velocity (Hunter et al., 2002).The disadvantage of this method is its destructive nature, so it is not so useful in urban area. In non invasive method the seismic waves generated on the surface and recorded through various receivers. There are various techniques of seismic surface survey to measure shear wave velocity and the thickness of material for a site, but among them two are very popular as Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW). Both methods are based on the dispersive property of surface waves. Dispersion is the variation of Rayleigh wave (phase velocity) with frequency.

SASW method was introduced by Nazarian and Stokoe (1983). In SASW method surface waves are generated through different source of energy at a point and the seismic waves that propagate through soil profile recorded at a single pair of receivers (Figure 2-5). It has been used in many engineering problems for last two decades (Sanchez-Salinero et al., 1987; Hiltunen and Woods, 1990).

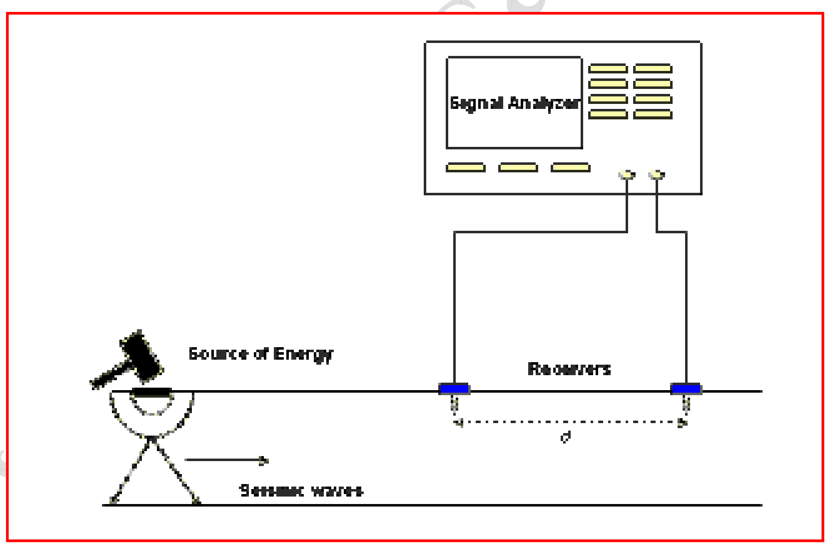


Figure 2-5: Field configuration of SASW method

MASW method was introduced by Miller et al. (1999) and Xia et al. (2000), in this method more than two receivers are used to record the seismic waves that are generated through different source of energy at different points along a line (Survey line) at a site (Figure 2-6).

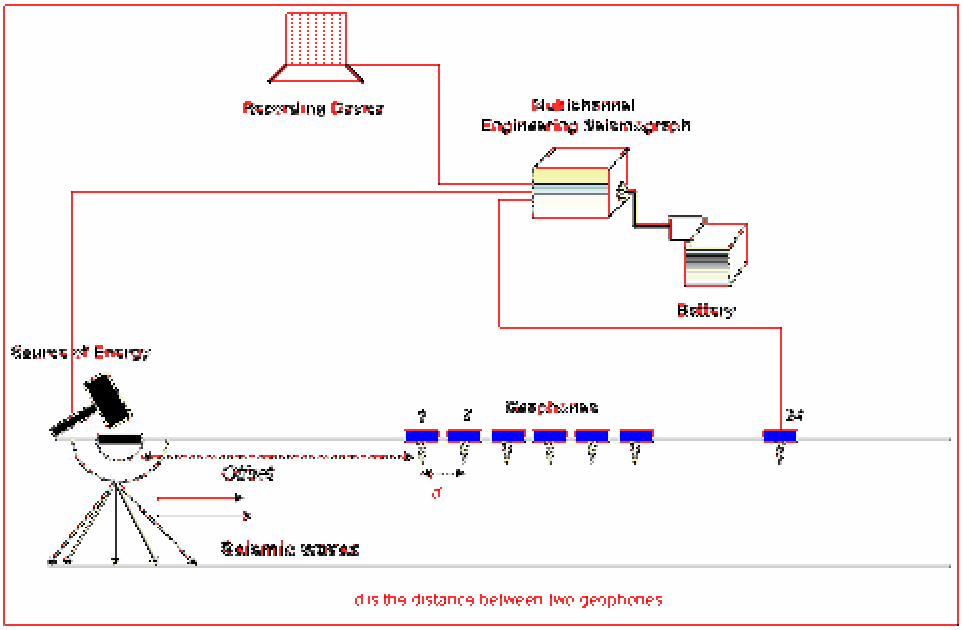


Figure 2-6: Field configuration of MASW method

Using this technique a 2D profile (Depth vs. Shear wave velocity) of the site along the survey line using this method soil profile of a site can be determined. MASW method is considered better than SASW technique as it avoid spatial aliasing (Hayashi and Suzuki, 2004). Xia et al (2000) compared the results of MASW technique with bore hole results at sites in Kansas, British Colombia and Wyoming. They found the difference between the shear wave velocity measured by these methods were less than 15%. Hunter et al. (2002) also compared the shear wave velocity measured through bore hole method and MASW technique for several sites in the Fraser river delta and found the difference between the results was only 9%.

Empirical and semi empirical methods are also used for seismic response analysis. By using empirical methods a quick evaluation of the ground amplification, fundamental frequency of the soil profile and amplification ratio can be computed. It is based on empirical attenuation laws that were derived on the basis of available ground motion data. The Empirical Green Function technique (EGF) is one of the empirical methods, which is useful for generating near field motions. (Rosset et al., 1998) checked the validity of this method for Barcelona city and they found that it is useful for the regions of higher seismic activity with an appropriate seismic network. So the main problem with this method is the lack of a seismic network. Recently there is one development to fill this gap in Japan through Kyoshin Net that sends strong motion data on the Internet, which is obtained from the 1000 different observation centres of Japan (K-Net., 2002) for different sites recoded from the boreholes.

In the Semi-empirical methods the history of earthquake motion are computed considering large scenario earthquakes by combining recorded ground motions due to small seismic activity. When the geotechnical characteristics and topography of a site are known numerical methods can be used for the soil response analysis.

One dimensional response of a soil column is the most prominent numerical method for seismic response analysis, which is widely used all over the world and is based on the reflection theory of S-waves in horizontally layered deposits. It is based on some assumptions as all boundaries are horizontal and the shear waves propagate vertically from underlying bedrock and the soil and bedrock surface extend infinitely in the horizontal direction (Kramer, 1996).In one-dimensional response analysis geotechnical characteristics of the soil in linear or non-linear behaviour are calculated to estimate ground response for a specific ground motion. These parameters can be measured through drilling or laboratory testing or using empirical relations. SHAKE 2000 software is very popular for these calculations. The other popular computer programme, which are used for the one dimensional response analysis are CyberQuake (CyberQuake, 1998) and Proshake (ProShake, 2004).

2.4. Conclusion

The aim of this literature review was to review some significant publications on seismic hazard analysis, microzonation and the research topic seismic response analysis. There is a lot of literature available on these topics especially on seismic response or ground response analysis. Experimental methods are not so useful for Dehradun city, the study area, due to its complex geology and topography. Empirical and semi empirical methods are not relevant for this area due to lack of a seismic network. Advanced methods are very complex and time consuming and are also not possible for this M.Sc. research. To follow a numerical method which seems the most appropriate for the study area geological and geotechnical data are needed. In the case of Dehradun some tube well litholog information is available with Uttaranchal Jal Sansthan (State Irrigation office) but it is not well distributed throughout the study area and it has not been prepared. So it was decided to get subsurface structure and the distribution of shear wave velocities within the study area through a detailed geophysical survey for different sites of the city using MASW technique.

3. Study Area: Geology and Geomorphology

3.1. Study Area

India is one of the biggest countries of the world comprising 28 states and 7 union territories. Uttaranchal, one of the border states, lies in the northern part of India covering an area of 53483 sq Km. It is also known as Dev Bhumi (Abode of God) due to presence of various pilgrimage places and temples. It has International boundary with China in the northeast and Nepal in the east. Dehradun city, which is part of the Doon valley, located in the western part of the state. The valley is bounded by the Himalya in the North, Siwalik in the South, river Ganga in the East and the Yamuna river in the West. The location map of the city shown in Figure 3-1.

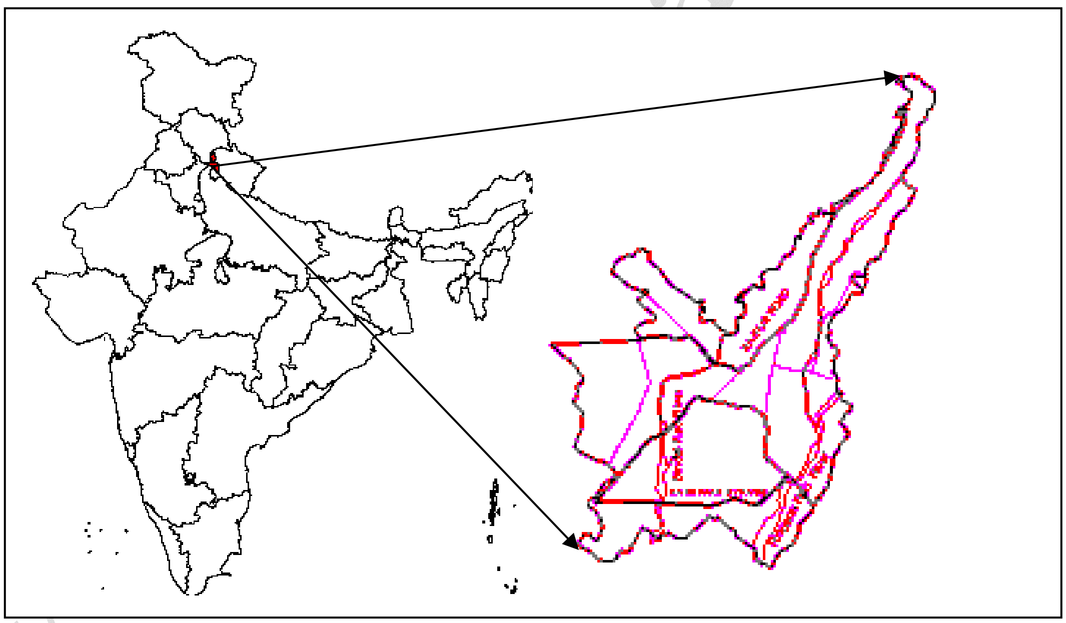


Figure 3-1: Location of the study area

After declaring as the capital of the newly formed state of Uttaranchal it has been emerging as a big business centre in the state and its population is increasing rapidly, which ultimately resulted in haphazard urbanization. The presence of various educational and training Institutions and Government organizations such as Indian Military Academy (IMA), Survey of India (SOI), Forest Research Institute(FRI), Oil and Natural Gas Corporation (ONGC), Indian Institute of Remote Sensing (IIRS) and Wadia Institute of Himalayan Geology (WIHG) makes it strategically and culturally more important. The study area comprises of 45 wards covering an area of 6500 hectares.

3.2. Geology:

3.2.1. Evolution of the Valley:

Dehradun valley was formed as an intermontane valley between lesser Himalaya in the north and the Siwaliks in the south. The present Doon valley is developed in two phases. In the first phase, around 18 million years ago there was an upliftment in the Himalaya around the Main Boundary Thrust (MBT) that raised the Mussorie Range and the Lower Himalaya. It resulted in the formation of a synclinal depression known as Doon Syncline, in which the eroded sediments of the uplifted part were deposited and this continued for the long period. In the second phase, around 0.5 million years ago another tectonic event uplifted the Siwalik Range strata along the Himalayan Frontal Thrust (HFT) and the Doon valley came into existence (Thakur, 1995)

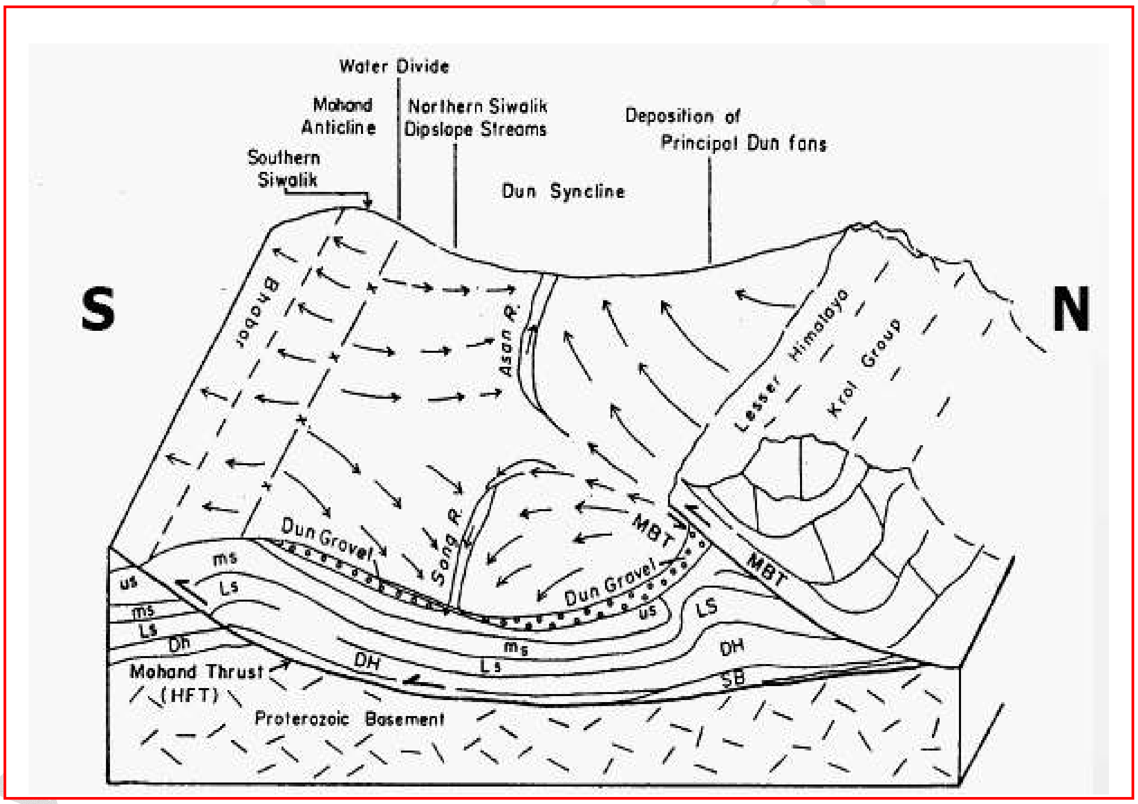


Figure 3-2: Evolution of Doon valley showing Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT), tectonically controlled drainage (Song river, Asan river) Subathu Formation (SB), Dharamsala Formation (DH), Lower Siwalik (LS), Middle Siwalik (MS) and Upper Siwalik (US) (After Thakur, 1995)

3.2.2. Lithostratigraphy of the Valley:

Doon valley is an intermontane valley located in the lap of the Siwalik Hills. The large part of the valley is occupied by a broad synclinal depression. Geologically whole Doon valley can be divided into three regions of Lesser Himalaya, the Siwalik group and the Doon Gravels (Table 3-1)

Age	**Geological units/ Formations**	**Lithology**
Recent	River Alluvium	Loose unconsolidated materials of sand, silt and clay derived from Upper Siwalik and Lesser Himalaya
Sub Recent to Late Pleistocene	Young Doon Gravel	Sub rounded boulders and gravels of sandstone and quartzite derived from Siwalik and Lesser Himalaya
	Old Doon Gravel	Big angular and sub-rounded boulders of quartzite and sandstones embedded in clay
Unconformity		
Late Pliocene To Middle Miocene	Upper Siwalik	Coarse boulders, conglomerates and clay
	Middle Siwalik	Hard and soft sand stone and clay intercalation in pockets
	Lower Siwalik	Hard sandstone, interbeded with mudstone
Main Boundary Thrust		
Palaeocene to Early Eocene	Subathu Formation	Red shale and lenticular bands of sandstone
Krol Thrust		
Pre-Tertiary	Tal	Quartzites
	Krol	Dolomitic limestone, cherty red shale, sandstone, black shale.

	Blaini / Infra Krol	Boulder beds, slate, dark shale, pink dolomite, violate quartzite and shale
	Nagthat	Quartzite and slate
	Chandpur	Phyllite, slate and limestone
	Damta	Grey slate, quartzite and turbidites

Table 3-1: Litho-stratigraphy of Doon valley (After Thakur, 1995; and Patel and Kumar, 2003.)

Lesser Himalaya

The lesser Himalaya is extended towards the north-eastern part of the valley to the south eastern part of the valley (Figure 3-3). The oldest formation of the group is the Damta formation comprising of slate, quartzite and turbidites are predominantly in the eastern part of the valley. This formation overlaid by Chandpur formation comprising of phyllite, slate and limestone is well exposed in the north eastern and eastern part of the valley in a narrow band. Nagthat formation overlaid Chandpur formation comprising of Quartzite and slate is well dominated in the eastern part of the valley. The next formation, Blaini formation is well exposed in the eastern and north eastern part of the valley in a narrow band in the north eastern part of the valley. The Blaini formation is conformably overlaid by Krol formation comprising of dolomitic limestone, red shale sandstone and black shale found in the north-eastern part of the valley. The Krol rocks are overlaid by Tal formation well exposed in the north eastern part of the valley consisting of lower Tal and upper Tal. Upper Tal consists of white to pink coloured quartzite sandstone whereas the lower Tal consists of quartzites with sandstone and brown shale. The next formation is the Subathu formation comprising of red shale and lenticular bands of sandstone. But it is not well exposed in the vicinity of the study area.

The Siwalik Group

This group consists predominantly of fluvial sequences which were deposited during middle Miocene to late Pliocene period. It is further classified into Lower, Middle and Upper Siwalik.

The Lower Siwalik is well exposed in the isolated outcrops in the northern part of the valley (Figure 3-3) comprises of coarse grained sandstone interbeded with mudstone.

The Middle Siwalik group can be distinguished by the presence of course boulder conglomerates and well exposed in the south eastern to south western part of the valley in a small patch in the north-eastern part of the valley. At many places in Doon valley (north-eastern part) these rocks are directly overlaid by Old Doon Gravels.

The Upper Siwalik group can be distinguished by the presence of course boulders conglomerates. It conformably lies over the middle Siwalik, and is well exposed at many places in the south western part of the valley.

Doon Gravel

The post Siwalik sediments are Doon Gravels that can be further classified into Older Doon Gravel, Younger Doon Gravel and Alluvium. Doon Gravels originated due to erosional activity by the streams, which eroded the Siwalik formation as well as the pre tertiary rocks and brought them to the synclinal depression.

Older Doon gravel consists of rounded to sub rounded upper Siwalik boulders and angular pebbles of quartzites, slates and shale as well as limestone pebbles from the pre tertiary rocks like Nagthat, Chandpur, Tal and Krol formations. It lying unconformably over the Middle and Upper Siwaliks and at places directly over Chandpur Phyllites (Bartarya, 1995). It is exposed in the Rajpur hill forest in the northern part of Dehradun city and in Galjwari forest area west of the Rajpur forest (Figure 3-3).

Younger Doon Gravels resting unconformably over the old Doon Gravels are characterised by very large boulders and braided river deposits. It consists of poorly sorted mixture of clay sand gravels and large boulders. The major part of the valley is occupied by younger Doon Gravels in the form of large fans and is known as principal Doon fans. Piedmont zone, which is formed due to merging of a number of fans descending from the Siwalik range, consisting of younger Doon gravel (Figure 3-3).

Alluvium consists of very fine materials like clay and partly sand. In case of a fan, the heavier and massive material tend to get deposited at the head of fan whereas finer material travel further to the toe part of the fan and deposited there in form of thick clay beds. Due to this reason clay material is found in the southern part of the city. At some other places clay is found in between adjacent fans.

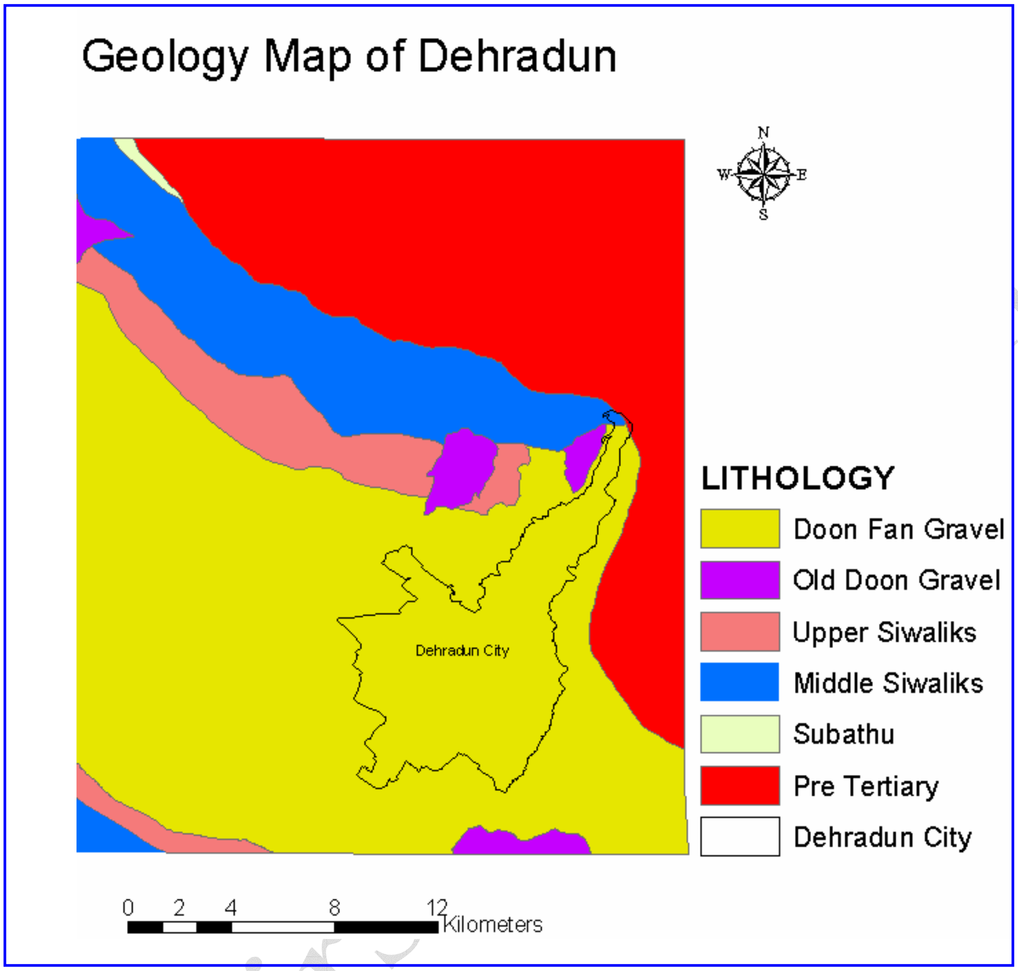


Figure 3-3: Geological map of Dehradun based on satellite imagery interpretation of LISS III and available literature and geological maps (After Nossin 1971; Rupke, 1974; Raiverman et al., 1984; Thakur, 1995).

3.2.3. Structure:

The valley is bounded to north by Main Boundary Thrust (MBT) and in the south by Himalayan Frontal Thrust (HFT). The MBT separates the Precambrian rocks of the Krol belt from the Cainozoic sediments of the outer Himalaya (Thakur, 1992), whereas the HFT locally known as Mohand Thrust brought the Siwalik Group rocks against the recent alluvium of the Indo Gangatic plain. In the south of the valley an anticline is present which is called Mohand anticline. There are two transverse faults, Ganga tear fault in the east and Yamuna tear fault in the west limits the boundary of the valley towards east and west respectively. The major structures of Dehradun shown in Figure 3-4.

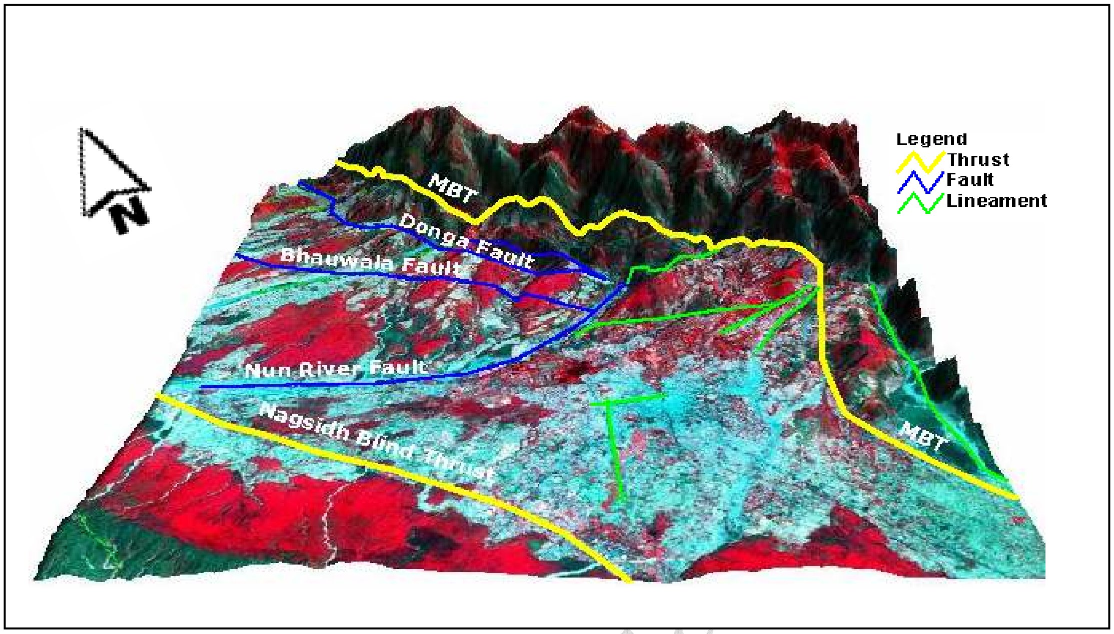


Figure 3-4: Structural Map of Dehradun draped on DEM (After Raiverman et al., 1984; Sati and Rautela, 1996, Singh et al., 2001)

In the central part of the valley to the south of the Nagsidh hill there is a North-west south-east trending thrust called Nagsidh thrust (Raiverman et al., 1984). This thrust is believed to be extending to the west parallel to the Asan river as a blind thrust as reported by Raiverman (1984) and Sati and Rautela (1996). Singh et al. (2001) identified Nun River fault along the Nun river.

3.2.4. Neotectonic Activity

Three distinct neotectonically active domains have been identified in the valley:

- The northern Siwalik belt experiencing active normal faulting.
- The central zone with south directed thrusting and
- The southern belt with prominent back thrusting **(**Sati and Rautela, 1999).

The presence of two strike faults parallel to each other in the valley is also an evidence of neotectonic activity in the valley as the Bhelonwala fault (Bhauwala fault) which marks the sudden and abrupt termination of Siwaliks outcrops south of it and Donga fault which brings Middle Siwalik beds in the south against either Langha Boulder bed or Doon fan gravels in the north (Rao, 1977).

3.3. Geomorphology:

Dun valley is the largest intermontane synclinal longitudinal valley in the sub Himalayan region. Many rivers such as Ganga, Yamuna, Sitla Rao, Jhakan Rao, Suswa and Asan contributed in the formation of local landforms of the valley. For different type of formations there is change in drainage pattern , as in the pre tertiary formations drainage pattern is dendritic and trellis, in the Siwaliks it is sub-parallel and dendritic whereas in the recent formations it is parallel and sinuous (Patel and Kumar, 2003). Geomorphologically the landforms in the area are formed due to erosion, deposition and tectonic activity. Nossin (1971) concluded that the valley has been uplifted by 315 to 420 meter due to differential movement along the MBT and Krol thrust. He recognised different level of fans in the valley that consist of Doon Gravel of pliestocene to recent age.

Nakata (1972) suggested that the valley was formed by an intricate superimposition of alternate depositional and erosional phases caused by the climatic changes and crustal movement.

The major geomorphological classes of Dehradun are (Figure 3-5):

- Pre Tertiary Denudational Structural Hill
- Upper Siwalik highly dissected structural hill
- Middle Siwalik moderately dissected structural hill
- Residual Hill
- Doon fan gravel Dissected Terrace
- Doon fan gravel Terrace
- Doon fan gravel Dissected Terrace
- Fan terrace
- River Terrace
- Piedmont terrace

Broadly the main geomorphological units are can be categorised into Pre tertiary of the Lesser Himalaya, the Siwaliks and the Doon fan gravels. The pre tertiary hills form the most elevated landforms of the valley in the form of Mussorie Range, with elevation up to 2000 m. The Siwaliks are exposed both in the northern and the southern part of the valley in the form of dissected structural hill at elevation of 600 to 700 m in the south and about 900 m in the north. They form a typical hog back landform in the southern part of the valley. Majority portion of the city is covered by gravely material brought down by the streams from both the northern and southern hills. They are deposited in the form of fans popularly known as Doon Fans. In the central part of the valley the fans merged together to form a broad piedmont zone. The remnants of the old Doon gravels are exposed in the form of residual hills near Rajpur and Galjwari reserve forest near by Rajpur hills. In some part of the valley terraces are formed due to depositional activity of rivers, such as Asan and Song river.

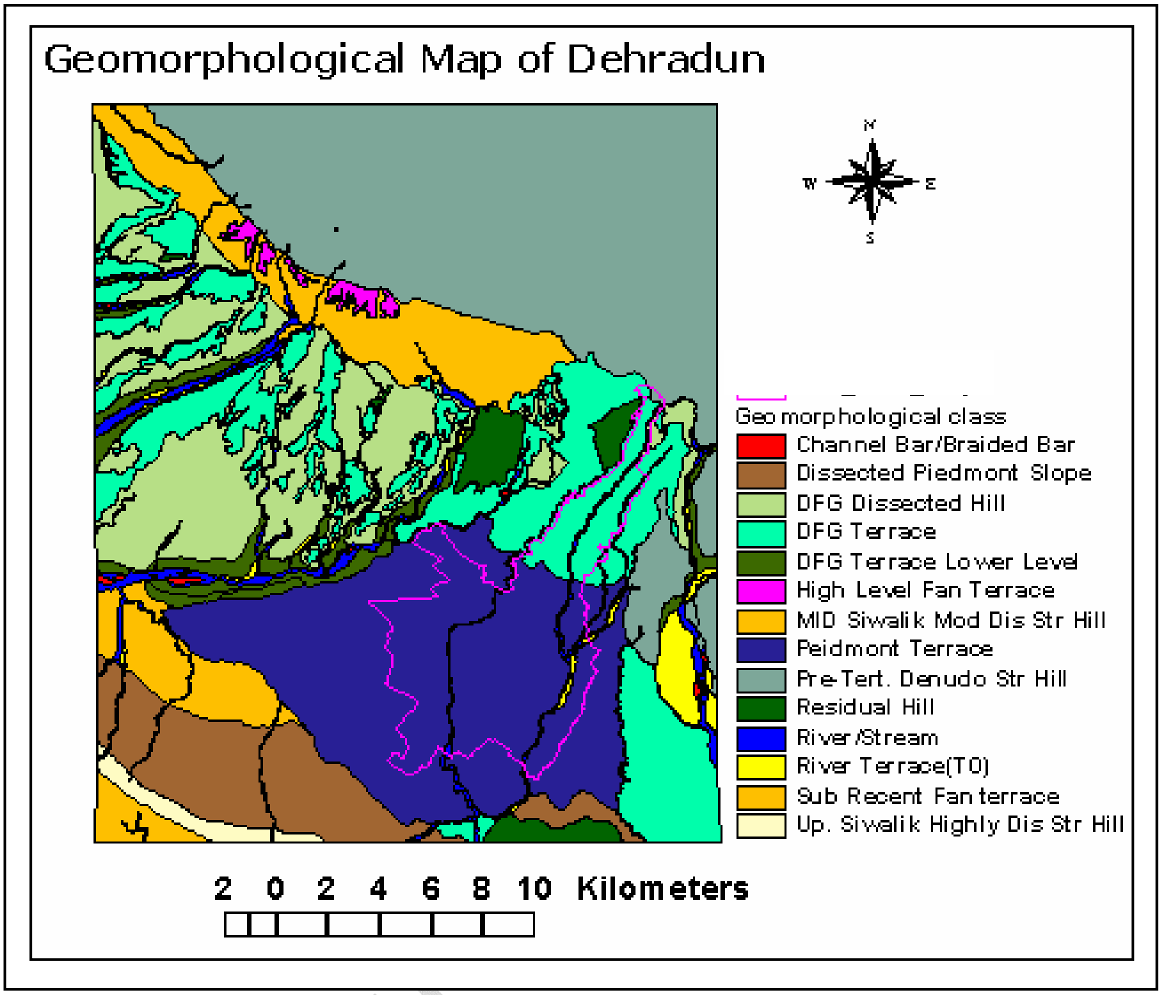


Figure 3-5: Geomorphological Map of Dehradun after Nakata, 1972; Nossin, 1971; Rao, 1977 and Patel and Kumar, 2003.

3.4. Seismicity:

The Himalayan foothills are witness of many seismic activities, that's why whole Uttaranchal comes under either zone IV or zone V of Indian seismic zonation map. (Lyon-Caen and Molnar, 1985) and Power et al. (1998) described the presence of a tectonic displacement zone between the Indian plate and the Himalayas with a convergence rate of 10-15 mm per year. Almost whole Himalaya is considered as seismically potential, as it is shaken by mild to strong earthquake frequently. It has experienced various moderate to major earthquake besides the 1905 great Kangra earthquake and 1934 Bihar Nepal earthquake two recent earthquake that affected the area were 1991 Uttarkashi earthquake (6.6) and 1999 Chamoli earthquake (6.8).
Recently Bhatia et al. (1999) under GSHAP programme calculated the seismic hazard for the Indian region using probabilistic approach stated that for the north-west Himalaya region it varies to 0.35 g to 0.40 g for 500 years return period. Dehradun has not its own seismic history, but its location, geology makes it important for seismic study. It experienced higher seismic intensities

during Kangra earthquake (Middlemiss, 1910; Rajal et al., 1986; Sati and Rautela, 1999). Levelling surveys carried out by the Survey of India (SOI) before and after the Kangra earthquake (1905) in May 1904 and in May and Oct 1905 respectively along the Main Boundary Thrust (MBT) revealed that Dehradun was elevated more than 13.4 cm with respect to the village of Mussorie (Middlemiss, 1910; Rajal et al., 1986;Sati, 1999). Patel and Kumar (2003) have concluded that the valley is highly exposed to the seismic hazard and can experience acceleration of 300 cm/sec^2 to 600 cm/sec^2 due to future earthquake in the region.

Therefore it can be said that the whole Doon valley is tectonically unstable, there is possibility of one or more great earthquakes in the area in near future (Bilham, 2004). This is one of the reasons that this area being considered for microzonation study.

4. Geophysical Investigation For Dehradun City

As a result of significant earthquakes such as those that have affected Mexico City (1985), San Francisco (1989), Los Angeles (1995) and Ahemadabad (2001), it has become apparent that the structure of the unconsolidated materials of young sedimentary basins can have a profound effect on the spatial distribution of ground motion amplification, resulting in variability in the severity of damage to buildings, transportation corridors and other lifeline infrastructures. So site amplification is one of the important factors that control damage in urban areas from large and moderate earthquakes. Recently many studies have demonstrated the role played by the surface geology in altering the observed seismic motion. The amplitude and frequency content of the ground motion from an earthquake can be greatly affected by properties e.g. impedance contrast and texture of the near surface material. In sedimentary basins where large shear wave velocity contrasts occur at the sediment-bedrock interface or within the unconsolidated sediments of the basin, studies have shown that in addition to shear wave velocity these boundaries support the development of reflections which can constructively interfere (or resonate) to intensify ground motion amplification over narrow frequency bands (Street et al., 2001). Moreover, seismic hazard calculations utilize attenuation functions, which include effects of rupture, effect of surface geology, soil column thickness and soil homogeneity.

The Dehradun city has a long history of high-level seismic activity and it has witnessed lots of damage during 1905 Kangra and partly affected due to 1991 Uttarkashi and 1999 Chamoli earthquake. Mainly two conditions put the city of Dehradun in a critical situation, firstly the majority of the city is build on a thick sedimentary basin comprising Doon gravels and located close to the Main Boundary Thrust. Secondly, it has the largest population of Uttaranchal State. The objective of this research is to produce spectral acceleration maps for the Dehradun municipal area showing the spatial variability of spectral acceleration at different frequency for a given input strong motion data.

The necessary input for the modelling of the site response in Dehradun are soil profiles and geotechnical parameters such as shear-wave velocity, plasticity index (PI), and density. Unfortunately this information was not available till now for Dehradun city.

Seismic techniques have long been used for characterization of the subsurface geotechnical information (Telford et al, 1990). There are various techniques available for seismic survey. All these techniques are based on the measurement of travel time of seismic waves. They are categorized in invasive and non-invasive methods. In invasive technique generally borehole is used to measure shear wave velocity, whereas in non-invasive method seismic waves generated at the surface and recorded by receivers at the ground.

The elastic properties of the near surface material and their relation with seismic wave propagation are of great interest in engineering and environmental studies as the propagation of seismic waves depends upon the elastic properties of the soil. Earlier P-waves was very popular for the characterization of subsurface, but P waves can travel through any media so it is not useful for this purpose, S wave is widely used for this purpose as its velocity varies with subsurface material type.

Rayleigh waves can be also used for this purpose as relation between the Rayleigh wave velocity and shear wave velocity is known (Richart et al, 1970). For such type of survey now a days Rayleigh wave is widely used as it is sensitive to low velocity that may be due to rock heterogeneities (Sheriff and Geldart, 1995; Zhang et al, 2004) this velocity can be also used to measure shear wave velocity (Richart et al, 1970).

Rayleigh waves in theoretically assumed to be non-dispersive considering the subsurface homogeneous (Kramer, 1996), but in reality subsurface is heterogeneous, so Rayleigh wave will show a dispersive behaviour. Dispersion is the phenomenon where different frequencies (and different wavelengths) travel with different velocities through the media, so it can be used to define different layers of subsurface. To get the dispersion curve from the Rayleigh wave there are various methods, one of the methods that is recently developed gives a good dispersion curve removing noise is the 2D wave field transformation method that directly converts the multichannel record into an image (Park et al., 1999). Inversion of the dispersion curve is the process to determine the actual propagation velocity from the dispersion curve.

Multichannel analysis of surface waves (MASW), a newly developed technique by Miller et al. (1999) and Xia et al. (2000) has been used successfully in many studies to map bedrock and subsidence analysis. It is non destructive in nature, so very useful for urban area. The main advantage of the technique is that it can easily differentiate between signal and noise and separate noise at the time of data processing. This technique gives a 2D profile of shear wave velocity with depth that can be easily interpreted. To get the better result from this technique, it is necessary to eliminate near field effects, there should be sufficient length of walk-away for larger penetration. The thumb rule is the survey length must be as long as three times the maximum depth of interest.

For this research work, to get the shear wave velocity MASW method being used at different sites of the city to observe the variation of shear wave velocity distribution around the study area.

In MASW method the surface waves (Rayleigh wave) generated by a source from offset of Geophone array and the waves are recorded by a recordable device. This method uses the roll-along technique, as commonly applied in reflection seismic survey, with the difference that surface wave parameters (velocity and frequency) are extracted from ground roll waves. For this research work a 24-channel signal enhancement seismograph (GEODE, manufactured by Geomatrics Inc, USA), 14.5 Hz geophones and 10 kg sledgehammer and 21 Kg iron plate of 1 square feet as source of energy for generating elastic waves were used (Figure 4-1).

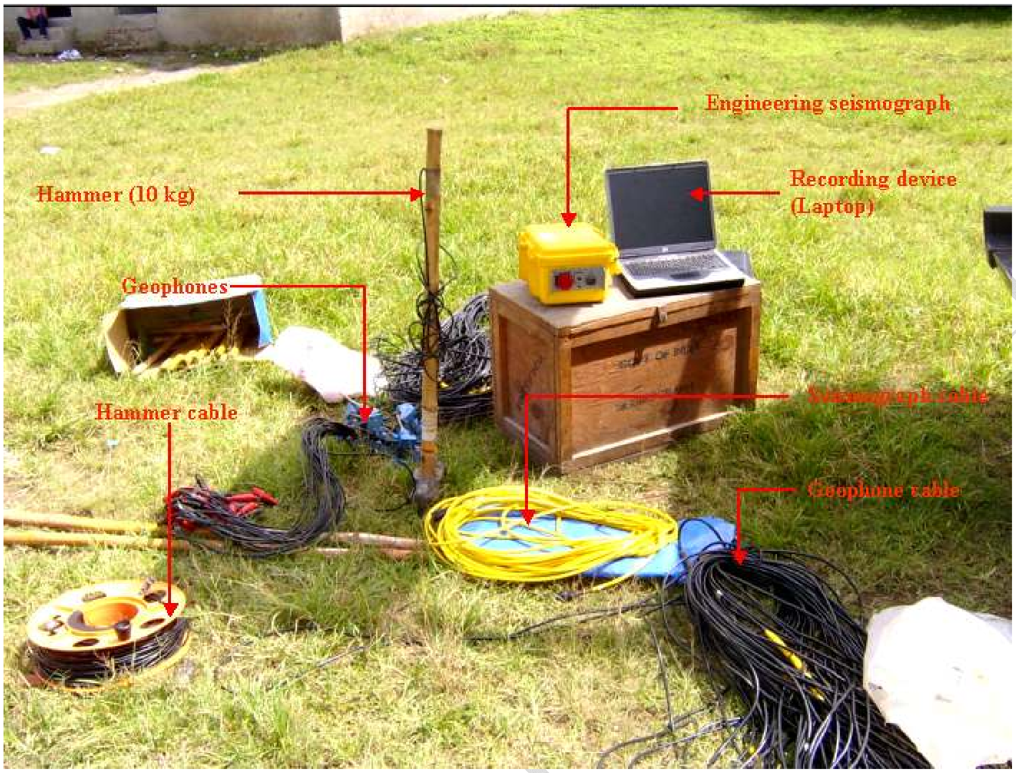


Figure 4-1: The equipments used for data acquisition

4.1. Methodology

4.1.1. Selection of Site

The most important parameter for the collection of shear wave velocity is the selection of the site. For this study selection of the site was based on local geology, previous damage due to various earthquake and availability of open spaces. City geology map was not available, but some literature was available regarding local geology (Nossin 1971; Rupke, 1974; Raiverman et al., 1984; Thakur, 1995; Thakur and Sriram, 2000) which was helpful for the site selection. To find out the open spaces in the city remote sensing data had been used as a basic tool that verified with field investigation to locate the open spaces. Efforts had been made to cover the sites at a distance of about 500 meter-1000 meter to cover the maximum sites in the city depending upon the availability of open grounds. Being a city it was not possible to find sites at all the places with desirable area to carry out the geophysical survey. That’s why one new research question added during the study ‘What is the minimum length of the ground for such type of survey?’ The sites covered for the survey is shown in figure 4-2.

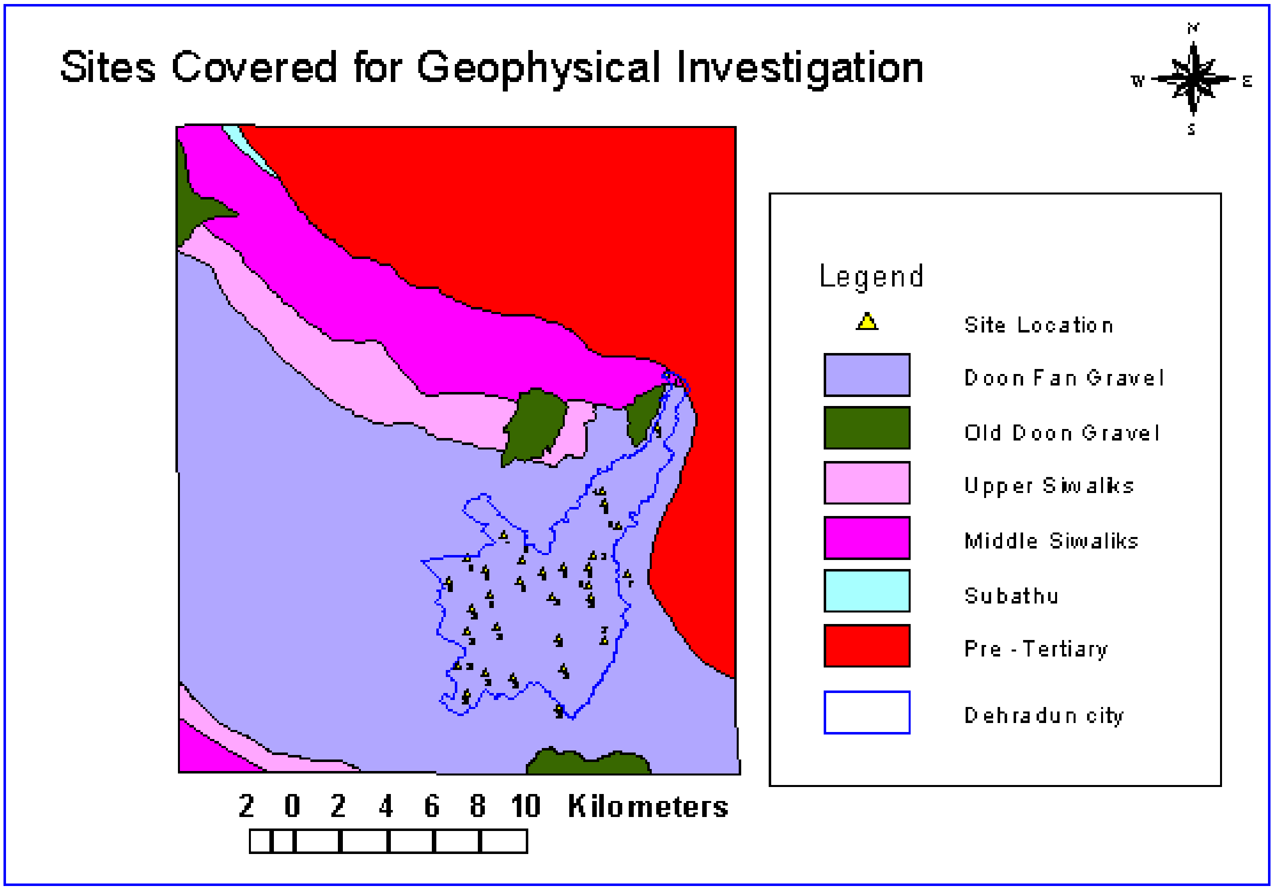


Figure 4-2: Geological map of Dehradun and the site locations for Geophysical Investigation

4.1.2. Data Acquisition:

Data was acquired at various sites using the above discussed method. There were only 24 geophones available for the study, so roll along technique was used, combining two to three strings of 12 geophones each into one of 36 geophones.

Site ID	Geophone Distance (in m)	Offset Far/Middle/Near
1	1.5	Middle and Near
2	2.0	Middle and Near
4	3.0	Middle and Near
5	2.0	Far, Middle and Near
6	2.0	Middle and Near
7	2.0	Far, Middle and Near
8	2.0	Far, Middle and Near

9	2.0	Middle and Near
10	2.0 and 3.0	Middle and Near
11	2.0	Far, Middle and Near
12	2.0	Far, Middle and Near
13	2.0	Far, Middle and Near
14	1.5	Near
15	2.0	Far, Middle and Near
16	2.0	Far, Middle and Near
17	2.0	Middle and Near
18	1.0	Middle and Near
19	2.0	Far, Middle and Near
20	2.0	Middle and Near
21	2.0	Far, Middle and Near
22	1.5	Middle and Near
24	1.5	Middle and Near
25	2.0	Far, Middle and Near
26	2.0	Middle and Near
27	2.0	Far, Middle and Near
28	2.0	Middle and Near
29	2.0	Far, Middle and Near
30	2.0	Middle and Near
31	2.0	Far, Middle and Near
32	3.0	Middle and Near
33	2.0	Far, Middle and Near

Table 4-1: Sites covered for geophysical survey and the offset for different site

For this research work at most of the stations the geophone interval was 2 meter but at some places where the open spaces were not so big to cover all the geophones at 2 meter interval, the spacing between geophones has been reduced to 1.5 meter and 1 meter (see table 1). Shot points were also changed with geophone spacing. The shot points for 2 meter spacing was 2 meter for short offset, 26 meter for middle offset and 50 meter for the far offset. In the case 1.5 meter geophone spacing they were 1.5 meter, 19.5 meter and 39 meter for short, middle and far offset respectively and for 1 meter spacing it was 1 meter, 13 meter and 25 meter for short, middle and far offset respectively.

4.1.3. Data Processing:

The acquired data was processed in SurfSeis 1.5 software, developed by Kansas Geological Survey. This software is used to generate 2D profile of shear wave velocity and depth for different surface location along the survey line after different steps of processing of the multichannel-recorded data for a site (Figure 4-3). For analysis purpose the acquired data format changed from SEG-2 format to KGS format. The KGS files have been preprocessed to get dispersion curve (the curve between frequency and phase velocity) for each data. During pre-processing number of parameters like phase velocity, natural frequency and apparent phase velocity are key parameters to get the dispersion curve and 1D profile under each geophone with depth. The dispersion curve of each data gives the 1D velocity model for the site after inversion (Figure 4-4). The selection of phase velocity and natural frequency are very important parameters in this analysis to get the lowest root mean square error (RMSE), which is calculated on the basis of matching of theoretical curve (based on the shear wave velocity profile) with the experimental curve. Multiple dispersion curve of a site when get inverted it gives 2D profile of the site that represents shear wave velocity and depth along the survey line.

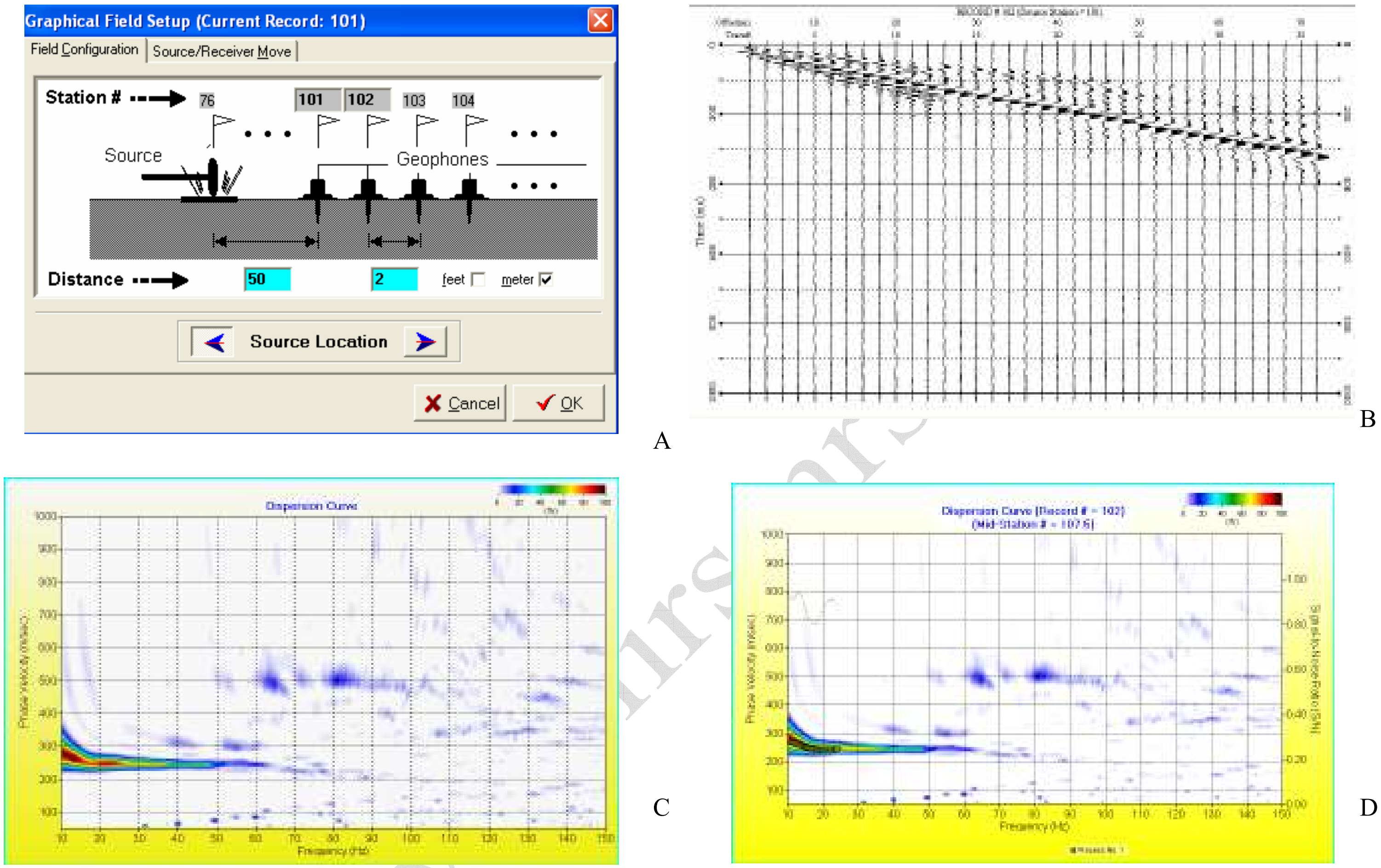


Figure 4-3: Data processing in SurfSeis for a shot location showing Field geometry (A), Walk-away (B) and Dispersion curve (C and D).

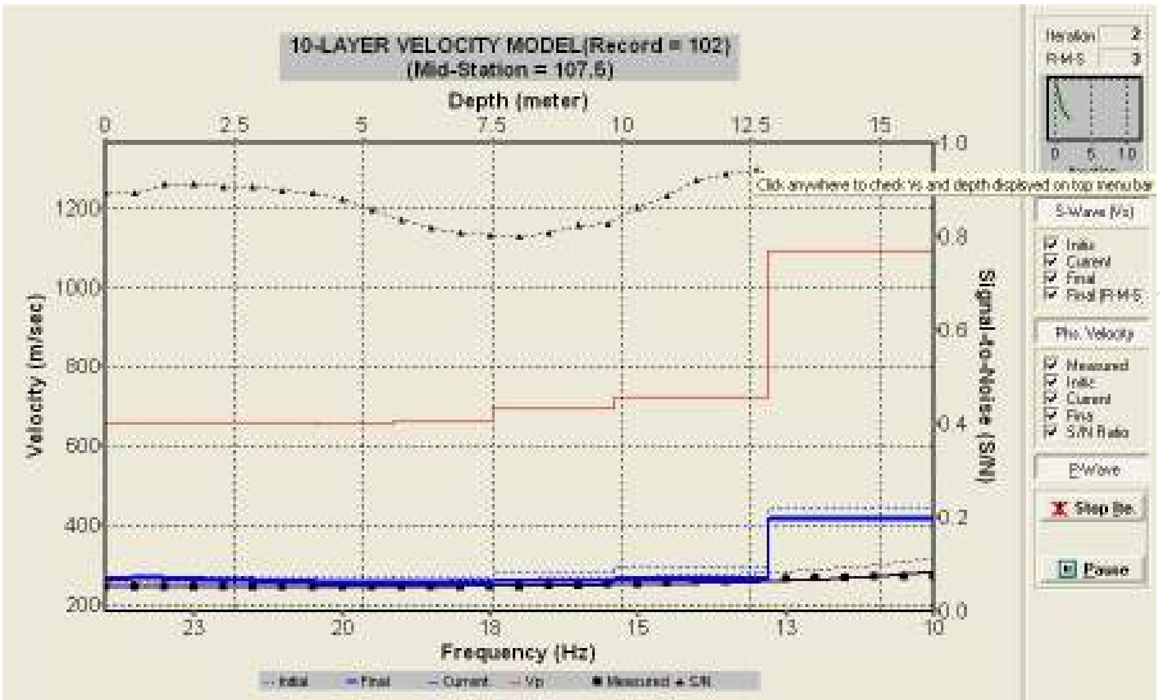


Figure 4-4: Velocity model of the same shot location

4.2. Data Analysis:

4.2.1. Shear wave Velocity distribution in Dehradun City:

For the analysis purpose, the city area has been divided into seven zones on the basis of geology, geo-morphology and active tectonics (Table 4-2).

Site ID	Velocity Zones	Site ID	Velocity Zones
1	Zone 1	18	Zone 5
2	Zone 1	19	Zone 5
4	Zone 1	20	Zone 7
5	Zone 1	21	Zone 2
6	Zone 2	22	Zone 5
7	Zone 6	24	Zone 5
8	Zone 2	25	Zone 6
9	Zone 6	26	Zone 7
10	Zone 6	27	Zone 2
11	Zone 6	28	Zone 3
12	Zone 6	29	Zone 3
13	Zone 2	30	Zone 3

14	Zone 5	31	Zone 3
15	Zone 7	32	Zone 3
16	Zone 2	33	Zone 4

Table 4-2: Sites and Shear wave velocity zones

Zone 1: This zone is situated in the northern part of the city. Geologically it comprises of pre tertiary older metamorphic rocks of Chandpur formation and Nagthat formation (Figure 4-2). Main boundary thrust (MBT) passes close to this zone. In this zone four sites (Site No. 1, 2, 4 and 5) with a survey length of 75-150 meters had been covered. The reflection profiles (Figure 4-5) of this area helped to delineate the shear wave velocity up to a depth of 21 to 30 meter. The root mean square error in the velocity measurement was from 1-2 m/s. Although each site has different shear wave velocity in different layers, in general three layers had been identified, with the top layer of about 5 to 15 meters having a velocity ranging from 250 m/s to 370 m/s. The second layer was at the depth of 7 to 32 meter with a velocity range of 258 m/s to 472 m/s. The third layer identified in the two sites (Site No. 2 and 4) was at a depth of 19 to 32 meter and having a velocity range of 364 m/sec to 406 m/s. The maximum shear wave velocity in this zone was 733 m/s for the half space.

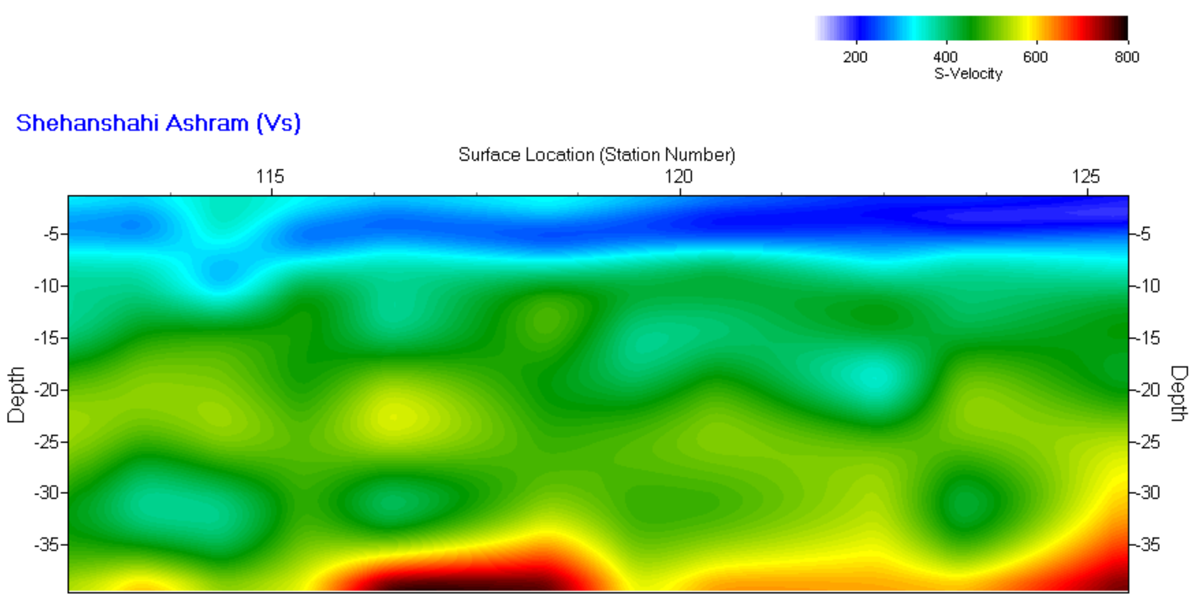
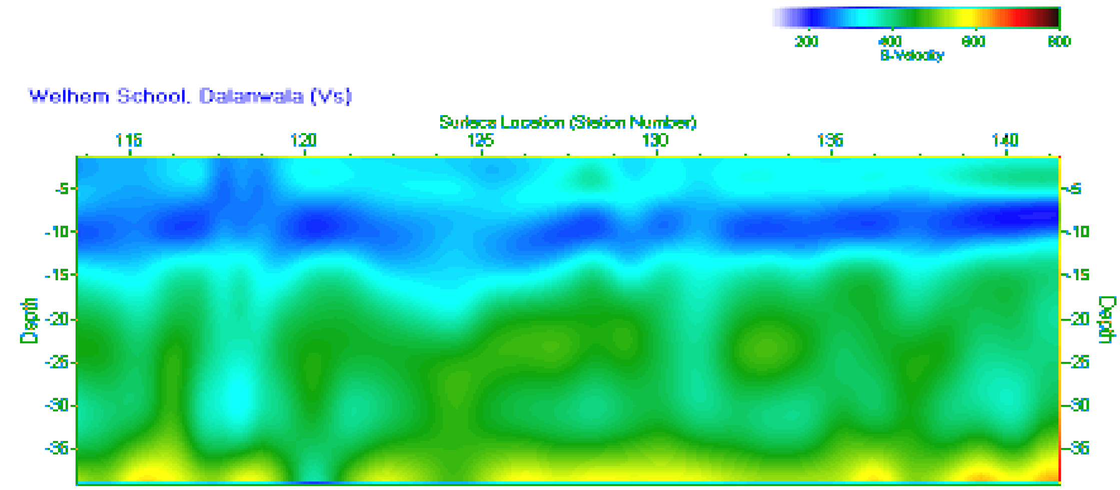
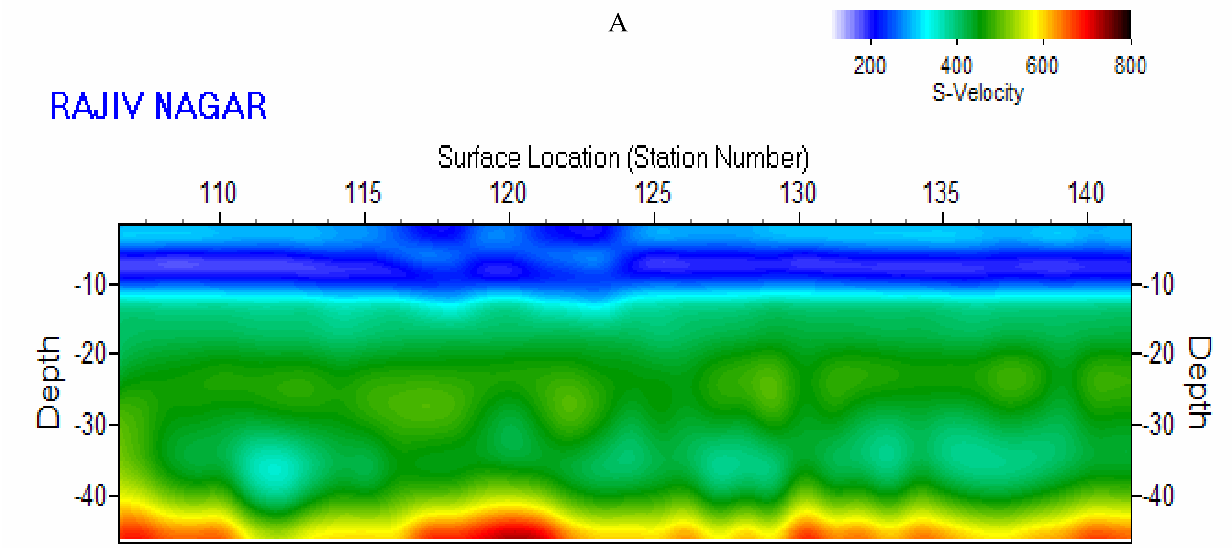


Figure 4-5: Reflection profile of site No.1

Zone 2: This zone is situated in the eastern and south-eastern part of the city (Figure 4-2). Geologically this zone is on alluvium, comprises of Doon gravels. In this zone seven sites (Site No. 6, 8, 13,16,17,21 and 27) with a survey length of 100 to 150 meter had been covered. The reflection profiles carried out in this area helped to delineate the shear wave velocity up to a depth of 21 to 37 meter. The root mean square error in the velocity measurement was from 1 to 3 m/s. Although each site has different shear wave velocity in different layers, in general two layers had been identified, with the top layer of about 10 to 22 meter depth, having a velocity ranging from 248 m/s to 399 m/s and the second layer was at a depth of 10 to 37 meter with a velocity range of 295 m/s to 439 m/s (Figure 4-6 A). The third layer identified at one site (Site No. 27) having a velocity range of 417 m/s to 471 m/s at 22-37 meter depth (Figure 4-6 B). The maximum shear wave velocity in this zone was 733 m/s for the half space.



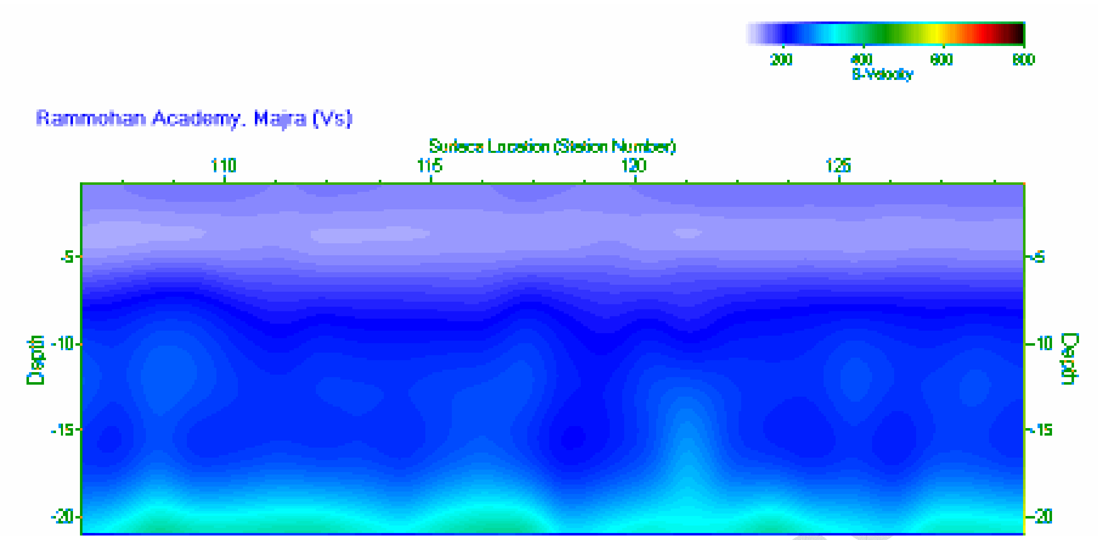
A



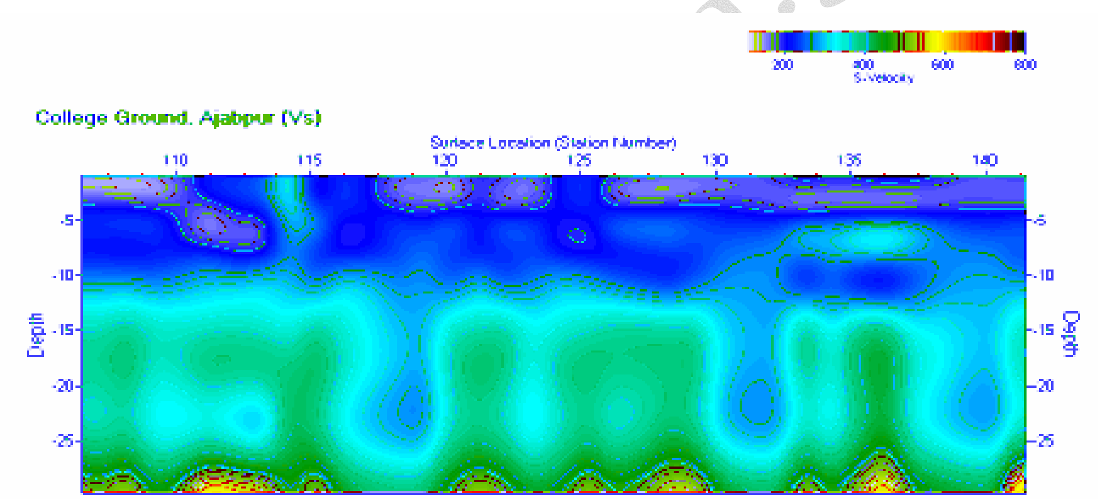
B

Figure 4-6: Reflection profile of site No.21 (A) and site No. 27 (B)

Zone 3: This zone is lying in the southern part of the city (Figure 4-2), situated in the lower part of piedmont terrace, finer alluvium sediments that came from the northern part of the valley. In this zone five sites (Site No. 28, 29, 30, 31 and 32) with a survey length of 100 to 150 meters had been covered. The reflection profiles of this area helped to delineate the shear wave velocity up to a depth of 17 to 30 meter. The root mean square error in the velocity measurement was from 1 to 3 m/s. At four sites (Site No. 28,29, 30 and 32) two layers had been identified (Figure 4-7 A), with a top layer of about 5 to 8 meter having a velocity ranging from 156 m/s to 252 m/s. The second layer was at the depth of 5 to 30 meter with a velocity range of 202 m/s to 369 m/s. At one site the third layer was also being identified in the velocity range of 298 m/s to 377 m/s at depth of 10 to 24 meter (Figure 4-7 B). The maximum shear wave velocity in this zone was 613 m/s for the half space.



A



B

Figure 4-7: Reflection profile of site No.28 (A) and site No.31 (B)

Zone 4: This zone is lying in the extreme southern part of the city (Figure 4-2). This site is situated on river terrace comprises of alluvium. Only one site (Site No. 33) had been covered in this zone. The reflection profile of this site helped to delineate the shear wave velocity up to a depth of 31 meters. The root mean square error in the velocity measurement was from 1 m/s to 2.5 m/s, three layers had been identified for this site. The first layer was at a 10 meter depth with a velocity range of 262 m/s to 278 m/s and the second layer was at a depth of 10 to 31 meters with a velocity range of 295 m/s to 363 m/s. The velocity at the base layer (Half space) was 576 m/s (Figure 4-8).

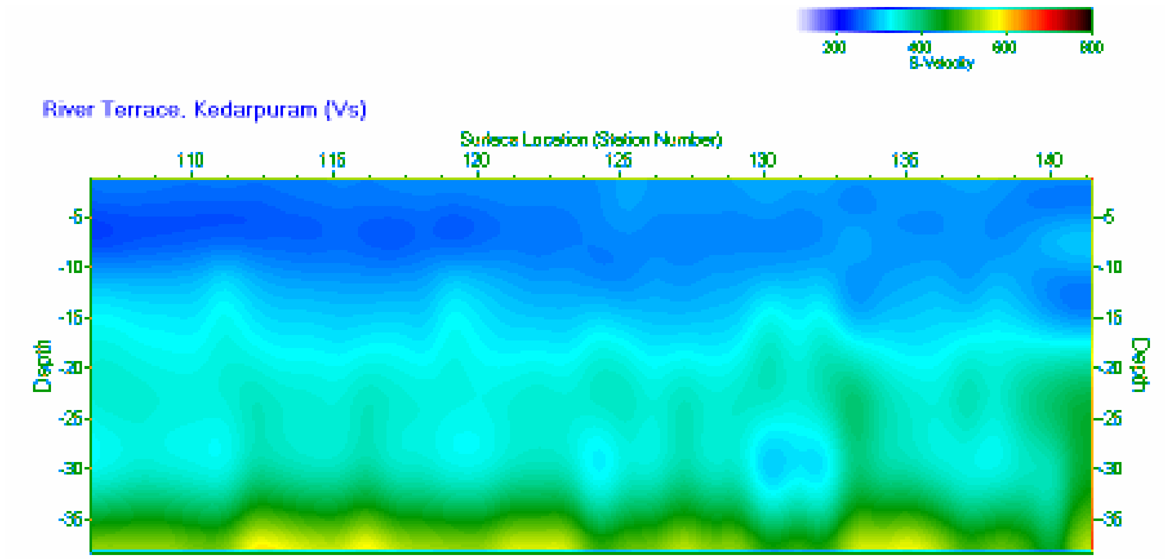
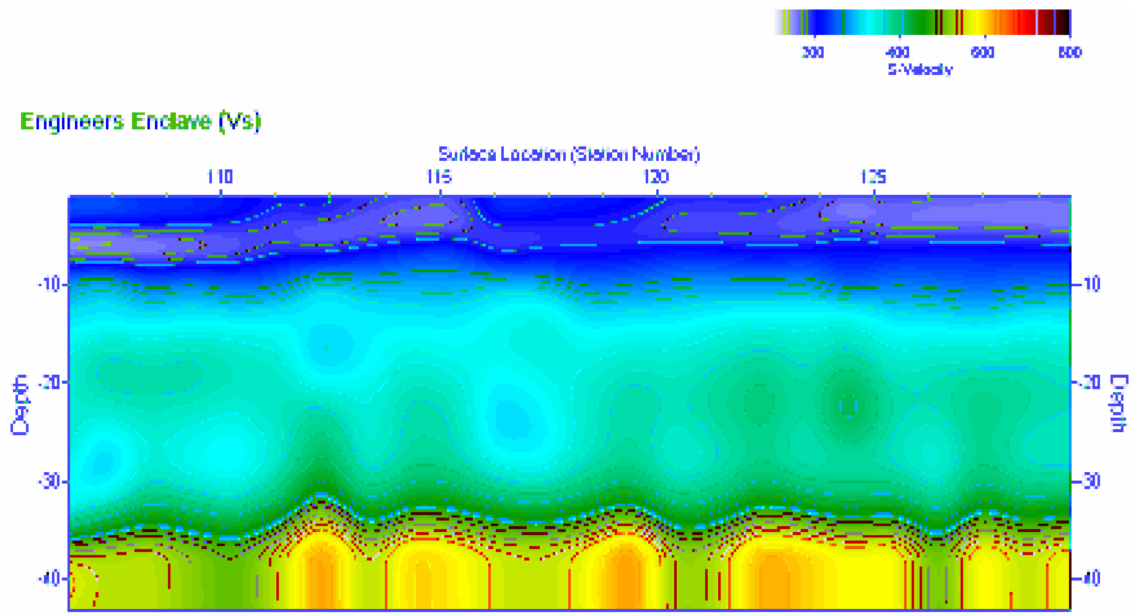
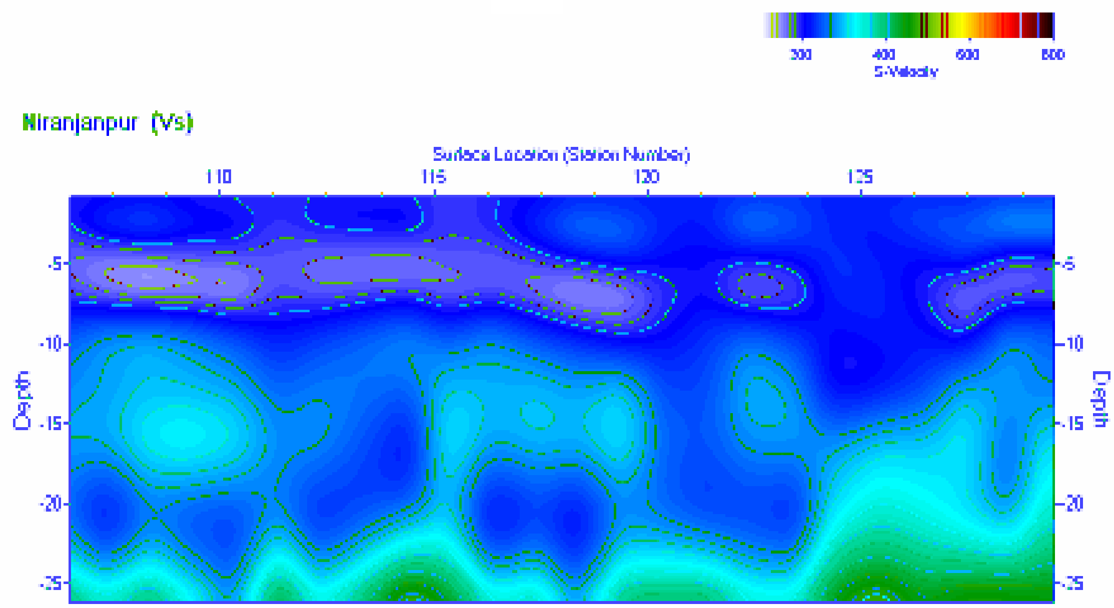


Figure 4-8: Reflection profile of site No.33

Zone 5: This zone is in the southwest part of the city covering five sites (Site No. 14, 18, 19, 22 and24), situated on alluvium comprises of clay material and Doon gravels (Figure 4-2). The survey line length for all the sites were in the range 75-150 meter. The shear wave velocity delineated for a depth of 21 to 30 meter on the basis of the reflection profile. The root mean square error in the velocity measurement was in the range of 1 to 4 m/s. In general three layers had been identified for three sites (Site No. 18,19,22) with the first layer at 5 to 13 meter depth having a velocity range of 198 m/s to 249 m/s and the second layer at a depth of 5 to 23 meter having a velocity range of 213 m/s to 316 m/s. The third layer was identified in the depth range of 7 to 30 meter having velocity range of 269 m/s to 346 m/s (Figure 4-9 A). At two sites (Site No.14 and 24) only two layers were identified (Figure 4-9B). The first layer was at a depth of 7 to 17 meter having shear wave velocity in the range of 195 m/s to 275 m/s and the second layer was at a depth range of 7 to 22 meter having velocity range of 221 m/s to 301 m/s. The maximum shear wave velocity in the zone is 561 m/s for the half space. Profile of site No. 22 indicates, some erosion in the in the past.



A



B

Figure 4-9: Reflection profile of site No.22 (A) and site No.24 (B)

Zone 6: This zone is lying in the central-western part of the city. Six sites (Site No. 7, 9,10,11,12 and 25) had been identified in this zone. The survey line lengths for all the sites were 100-150 meters. Geologically this part of the city has karst topography. Lime bearing water coming from the lesser Himalayas cemented the gravel material to produce the local conglomerates well exposed near Tap-keshwar (a place) and Robbers Cave. The shear wave velocity delineated for a depth of 24 to 28 meter on the basis of the reflection profile. The root mean square error in the velocity measurement was in the range of 1 to 4 m/s. In this zone at three sites (Site No. 7, 9 and 10), three layers were identified with the topmost layer of 5 to 8 meter depth having a velocity range of 227 m/s to 262 m/s, the second layer for was at a depth of 5 to 20 meter having velocity range of 261 m/s to 338 m/s and the third layer at a depth of 14-26 meters depth having velocity range of 309 m/s to 369 m/s (Figure 4-10). At three sites (Site No. 11, 12 and 25) only two layers were identified with the topmost layer at the depth of 5 to 12 meters having velocity in the range of 231 m/s to 266 m/s and the second layer was at a depth of 5 to 28 meter having velocity range of 261 m/s to 335 m/s (Figure 4-11). The maximum velocity in this zone was 606 m/s for half space. The seismic profile of site No. 11 indicates lots of subsidence along the survey line.

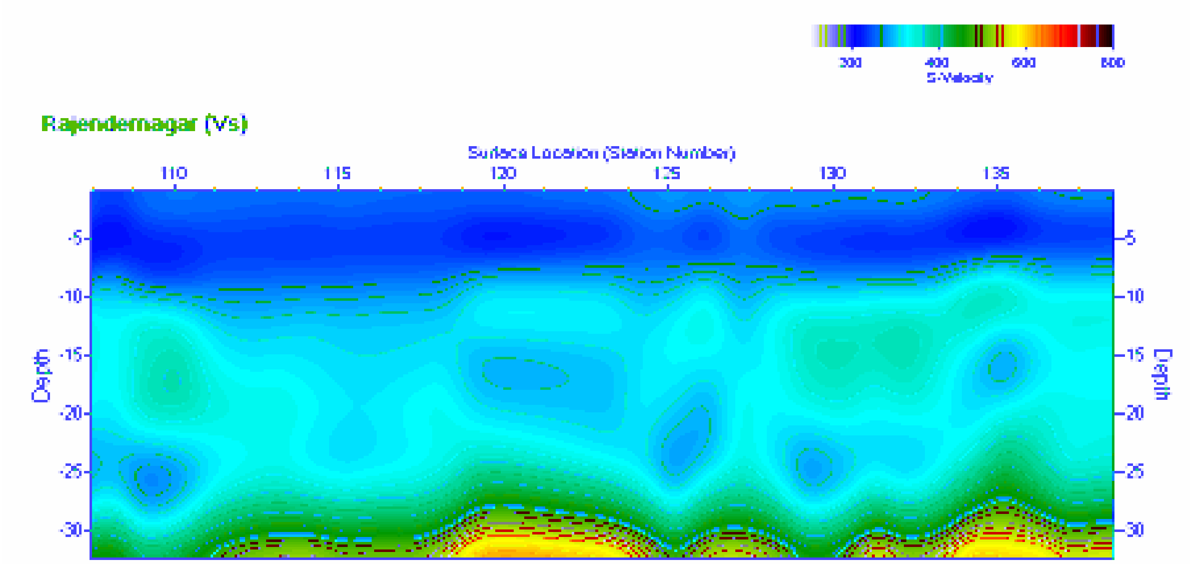


Figure 4-10: Reflection profile of site No.7

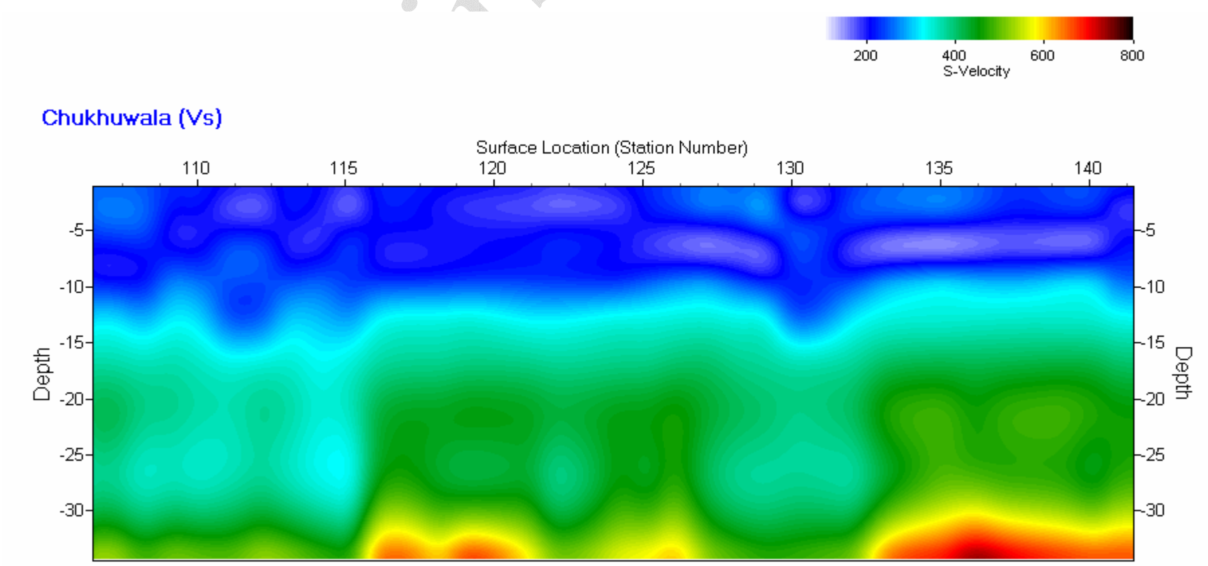
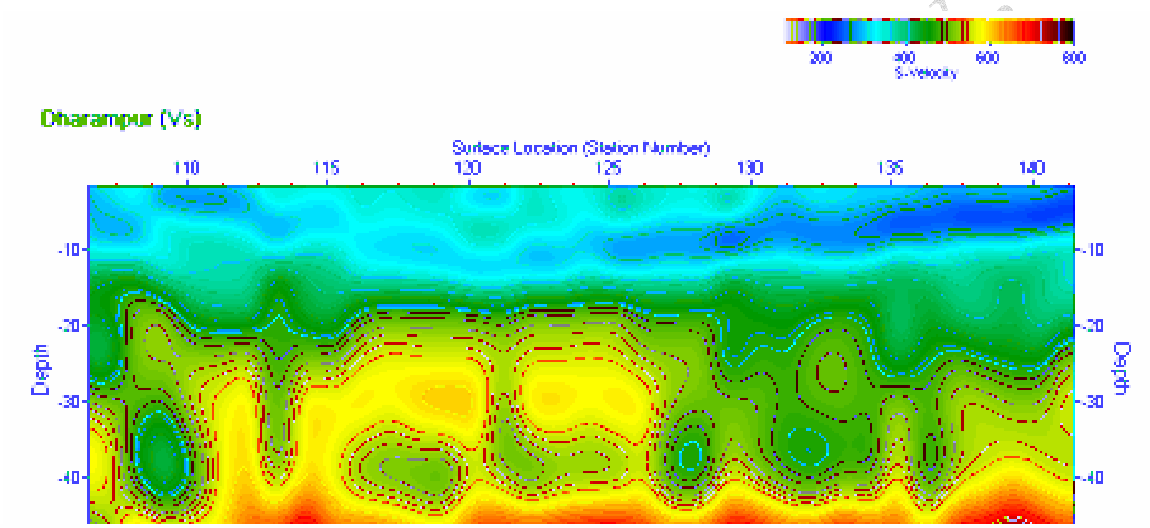


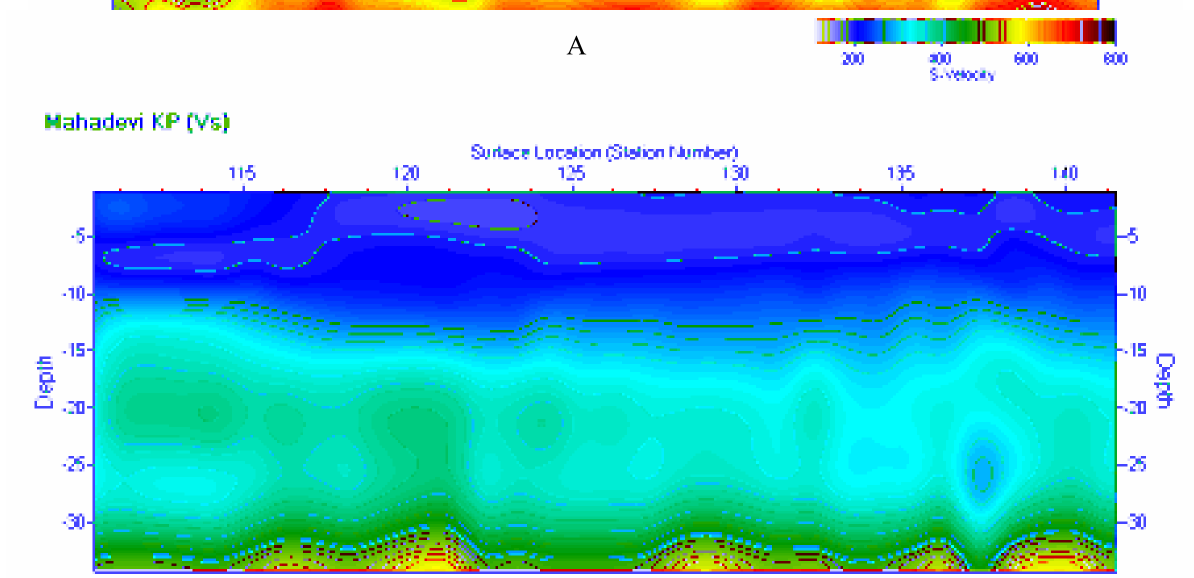
Figure 4-11: Reflection profile of site No.11

Zone 7: This zone is situated in the central part of the city (Figure 4-2). Three sites (Site No. 15, 20 and 26) had been identified in this zone. The reflection profiles of this area helped to delineate the shear wave velocity up to a depth of 28 to 40 meter. The root mean square error in the velocity measurement was from 1 m/s to 3 m/s. At two sites (Site No. 15 and 26) two layers were identified with the topmost layer at about 13 to 15 meter having a velocity range from 296 m/s to 363 m/s. The second layer was at a depth of 13 to 40 meters having shear wave velocity in the range of 363 m/s to 475 m/s (Figure 4-12 A).

For the third site (Site No. 20) three layers were identified at depth of 12 meter, 21 meter and 28 meter respectively from the surface. The velocity ranges for the three layers were from 280 m/s to 300 m/s for the first, 324 m/s to 350 m/s for the second and 368 m/s for third layer (Figure 4-12 B). The maximum shear wave velocity in this zone was 699 m/s for the base layer.



A



B

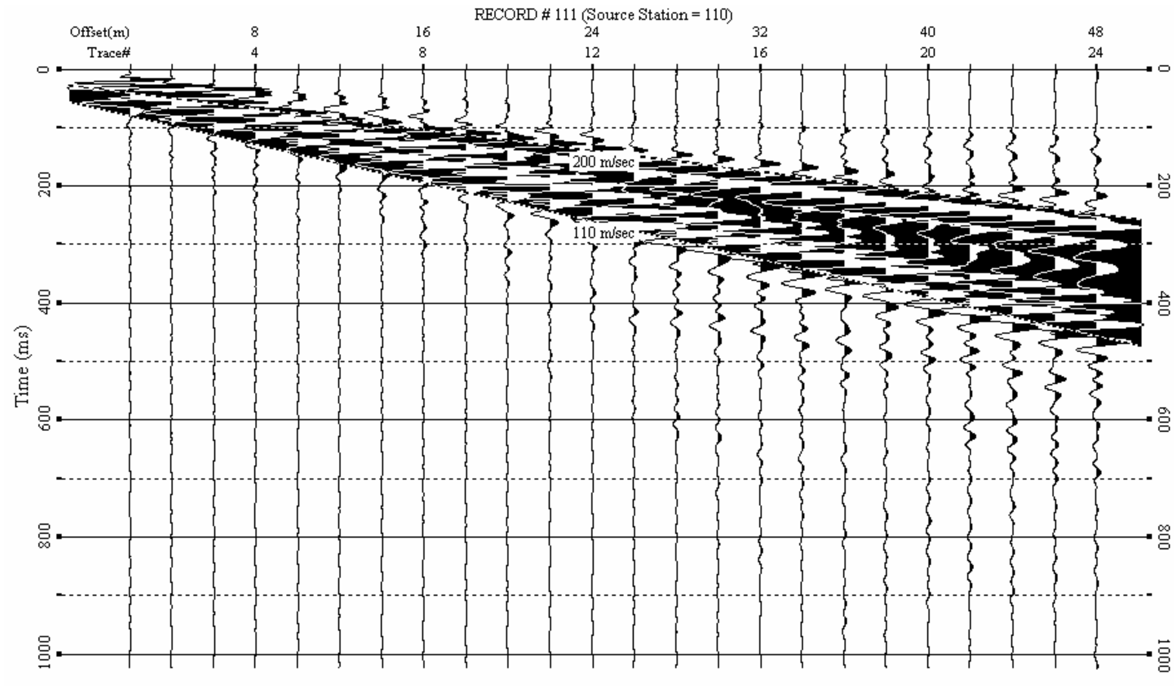
Figure 4-12: Reflection profile of site No.26 (A) and site No.20 (B)

4.2.2. Sensitivity to Geophone spacing:

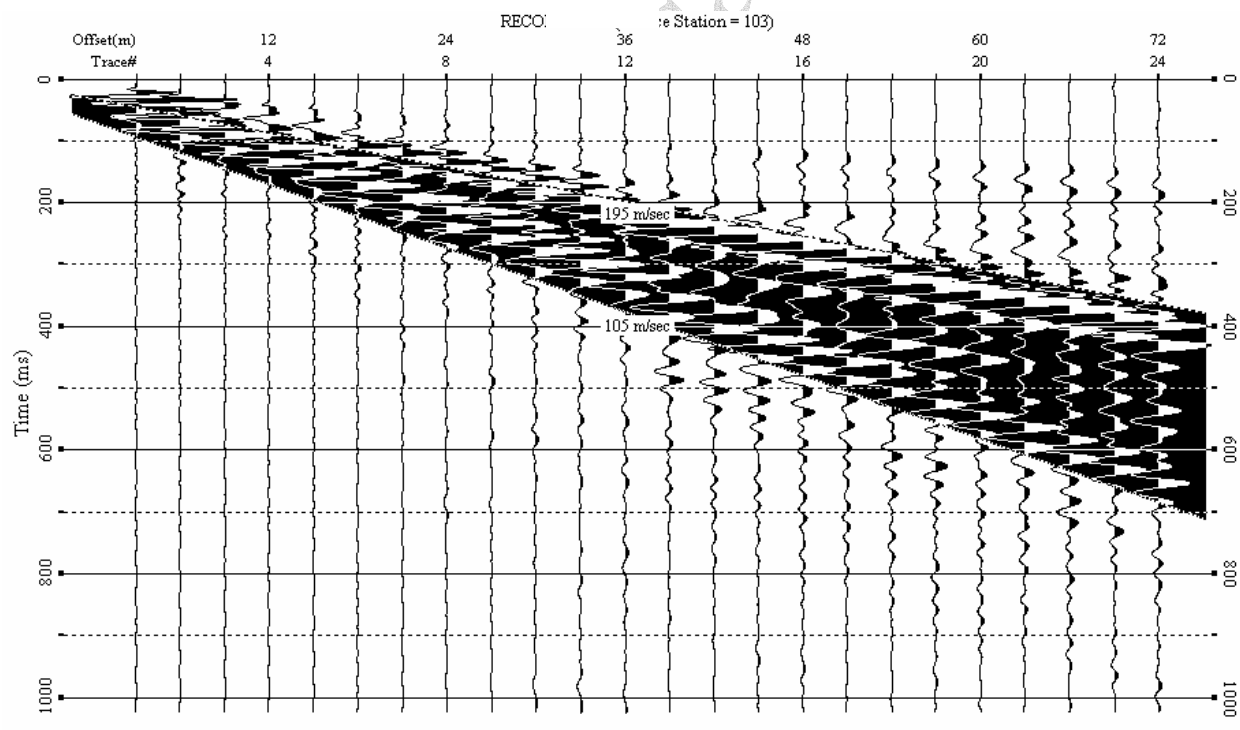
For this research work to get the answer of sixth research question (that added during the study) and to observe the effect of change in geophone spacing on depth penetration and the shear wave velocity, geophone spacing changed to 1 meter, 1.5 meter and 3 meter from the usual 2 meter (see Table 4-1).

At most of the sites, where the geophone spacing was 2 meter, the maximum penetration was up to 40 meter and the minimum was 17.5 meter. But at most of the site the penetration was more than 30 meter. For 1 meter geophone spacing the maximum penetration was 21 meter. The spacing of 1.5 meter was tested at 3 sites (see Table 4-1), in which at two sites the penetration was more than 30 meter while at the third site it was just 21 meter. When the 3 meter geophone spacing (see Table 4-1) was tested at three different sites (Site No. 4, 10 and 32) the penetration depth was 32 meter, 20 meter and 17 meter respectively.

At one site (Site No. 10) 2 and 3 meter geophone spacing were used to compare the result in shear wave velocity and depth penetration (Figure 4-13 A and 4-13 B). During analysis it was found that in the case of 3 meter spacing the signal to noise ratio was in the range of 27% to 45% while at 2 m spacing it was in the range of 60% to more than 80% (Figure 4-14 A and B). At 2 meter spacing the fundamental mode was at low frequency and given a coherent result, whereas at 3 m spacing the high frequency dominated and it did not allowed to penetrate more than 20 meter (Figure 4-15 A and B). It has been found that in the case of Dehradun 2 meter and 1.5 meter geophone spacing has given good penetration with an accuracy of 1 to 3 m/s in shear wave velocity and high signal to noise ratio.

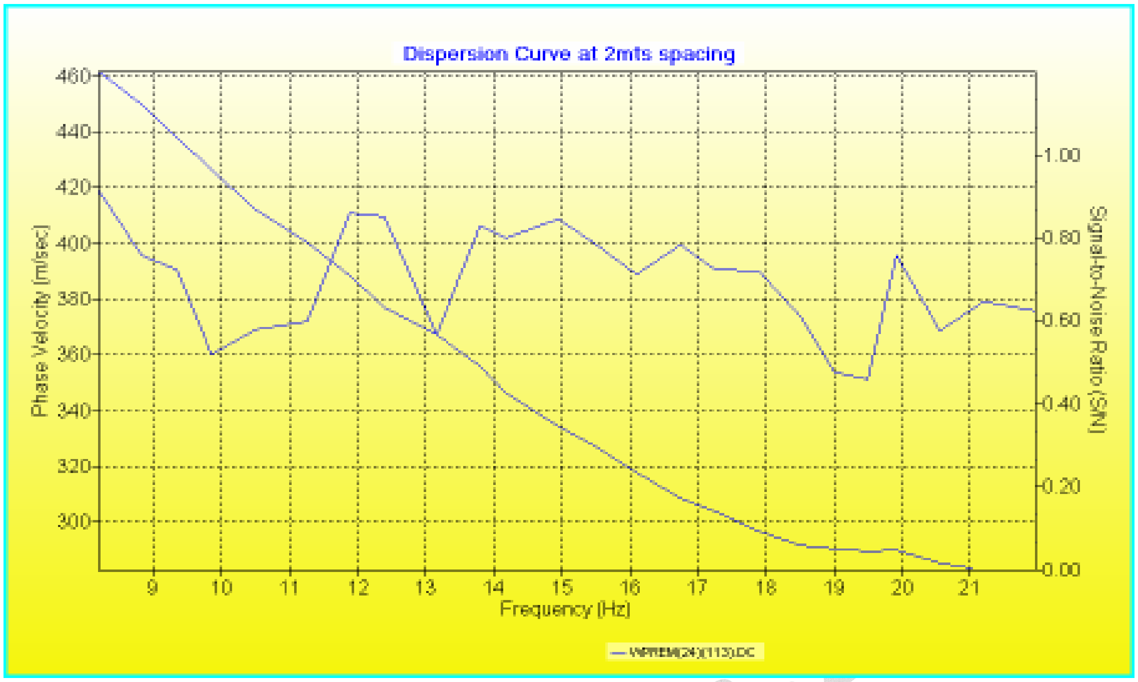


A

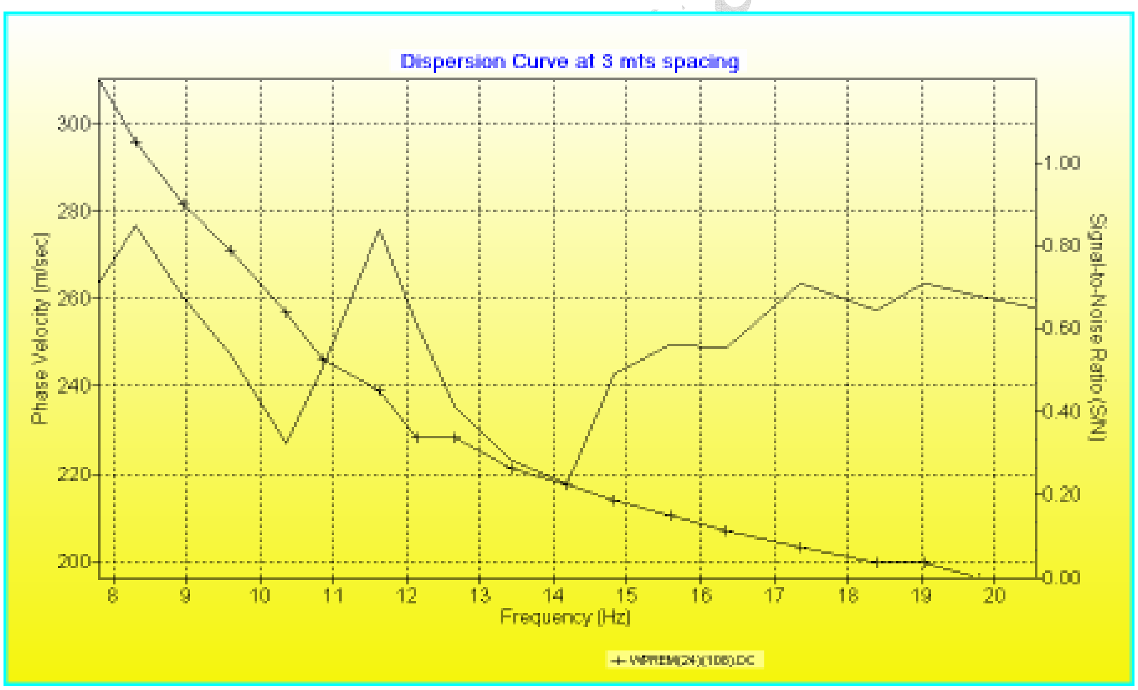


B

Figure 4-13: The walk-way at site No. 10 at geophone distance 2 m (A) and 3 m (B)

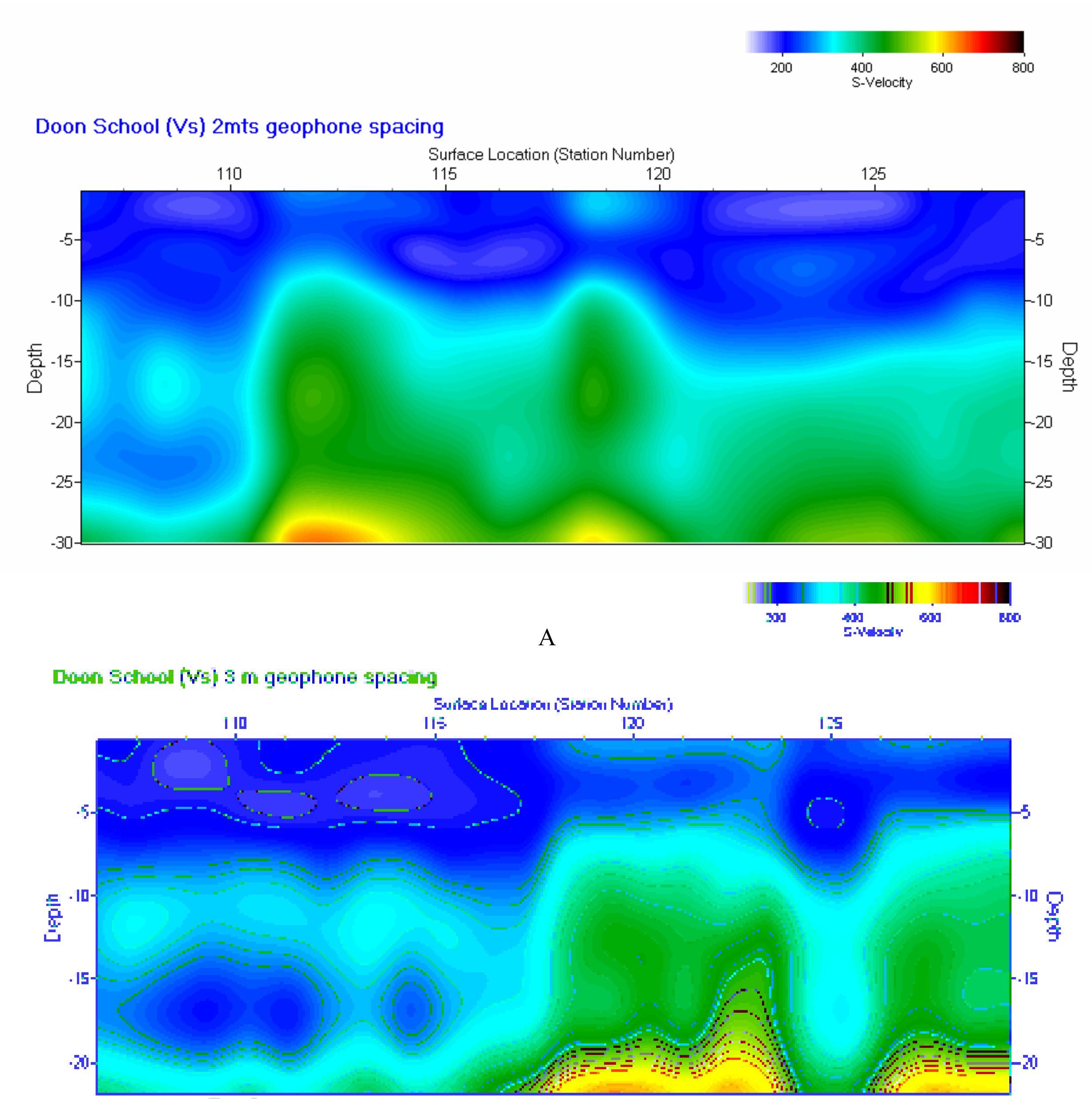


A



B

Figure 4-14: Dispersion curve at same shot location at site No. 10 at geophone distance 2 m (A) and 3 m (B)



A

B

Figure 4-15: Seismic Profile of site No.10 at 2 m geophone spacing (A) and 3 m geophone spacing (B)

5. Modelling of Spectral Acceleration for Dehradun City

Accurate prediction of earthquake ground motion response in thick soils requires knowledge of shear wave velocities, attenuations and their variations laterally and in depth. This chapter deals with the analysis of the seismic soil response in Dehradun using 1-D modelling on a number of soil profiles. The material types and shear wave velocity of the upper soil column has been investigated using geophysical measurements (See chapter 5). The sites had been selected to represent typical geological/geomorphological areas within the city. For site response analysis one-dimensional method is used, which is based on two assumptions. Firstly all boundaries are horizontal and soil and bedrock are extended infinitely in the horizontal direction up to the base layer known as half space and secondly the propagation of waves in the underlying bedrock and the soil deposits. In the present study one dimensional analysis method is carried out using the SHAKE 2000 software.

SHAKE 2000 is a Windows-based computer programme used for the analysis of geotechnical earthquake engineering problems. It is an advanced version of the earlier developed computer programme SHAKE (Schnabel et al., 1972) and SHAKE EDIT by integrating them and adding some new features and making it more user friendly.

The minimum input parameters required for SHAKE 2000 are

- **Shear wave velocity:** Shear wave velocity is important as it is dependent on material properties and depth and is used to characterize the strength of the soil. The strength of the soil is very important as it supports piles and buildings.
  If the shear wave velocity is not known then shear modulus (ratio of stress and strain) can be used to measure the strength of the soil.
- **Material type with thickness:** A profile of the site is helpful to know the material types and the thickness of the various soil layers. On the basis of the available information from borehole data (Tube well lithologs) and the local geological information from literature and available maps (Nossin, 1971; Rupke, 1974; Raiverman et al., 1984; Thakur, 1995; Bartatarya, 1995; Sati and Rautela, 1996; Patel and Kumar, 2003) these material types and depths have been identified. For each material type a damping curve and a modulus reduction curve have been selected from SHAKE 2000 database.
- **Unit weight:** It is one of the parameter used to measure the degree of compaction of the soil. It is also known as bulk density, soil density and weight density and be defined as the weight of a unit volume of soil. For this study unit weight for the materials derived from literature (Koloski et al., 1989). It is generally measured in kN/m^3. In SHAKE 2000 the unit used to measure unit weight is pound cubic feet.
- **Damping ratio:** In general damping acts as force opposing the vibrations due to ground motion and is responsible to decrease the amplitude of free vibrations ((US Army Corps of Engi-

neers, 2001). It is the ratio of viscous damping coefficient and critical damping coefficient. It is considered due to non-linear behaviour of the soil (Ordonez, 2002).
It is calculated by

$$é = c/2 \sqrt{k\ m}$$

Where 'é' is the damping ratio coefficient; 'c' is the viscous damping coefficient, 'k' is the stiffness and 'm' represents the mass.
In this study the damping ratio curves taken from SHAKE database considering the material type (please see table 5-1).

- **Input motion data:** It consists of the actual recorded or simulated strong motion data shown in figure 5-1:

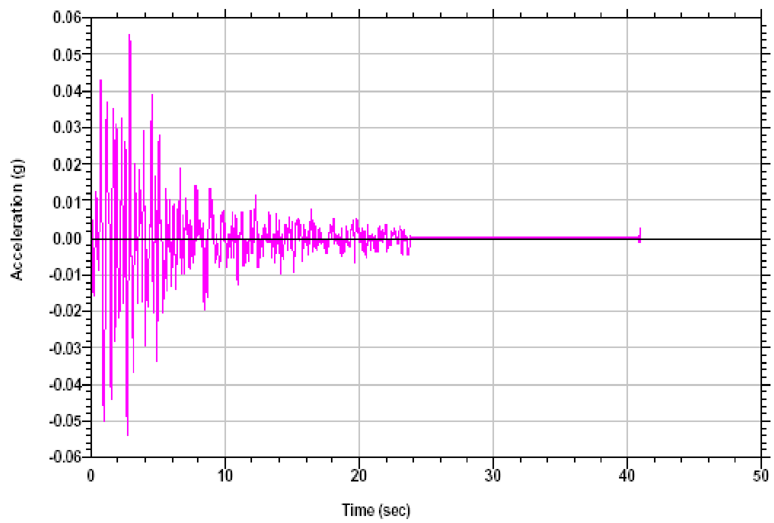


Figure 5-1: Plot of acceleration time history of strong motion data recorded at Tehri for Chamoli earthquake 1999 a place near by the study area

5.1. Methodology:

The summarized methodology used for the analysis is shown in figure 5-2. SHAKE 2000. It starts with the main menu (Figure 5-3) where a new file can be created or created files can be edited. When a new file is created or edited SHAKE 2000 allows the user to enter various data through options in a new window 'Earthquake Response Analysis' (Figure 5-4). It stores all the information in two-output files, Output file No. 1 and Output file No. 2. The first output file is used to save information about the material properties, soil column, ground motion, peak acceleration, response spectra, etc and the second output file is used to save acceleration and shear strain/stress time histories. The software processes the first and second output file to give the final results in the form of table, graphs and a report.
The discussed parameters in section 5.1 are entered under the various options. Option 1 to option 5 is used to input various parameters for the analysis, while option 6, 7, 9 and 11 are analysis options for SHAKE 2000.

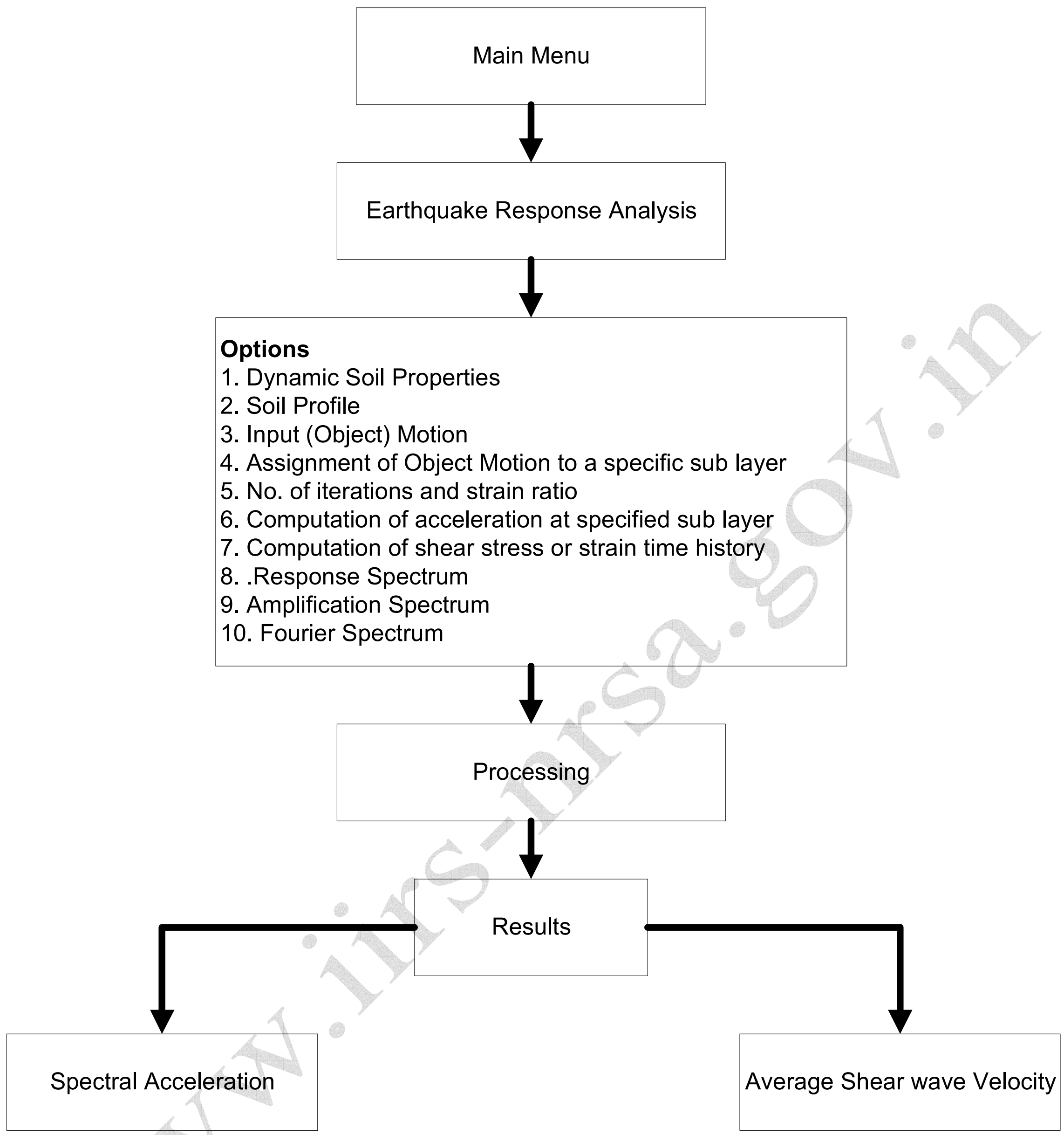


Figure 5-2: Flow diagram for the methodology (summarized) used for the analysis

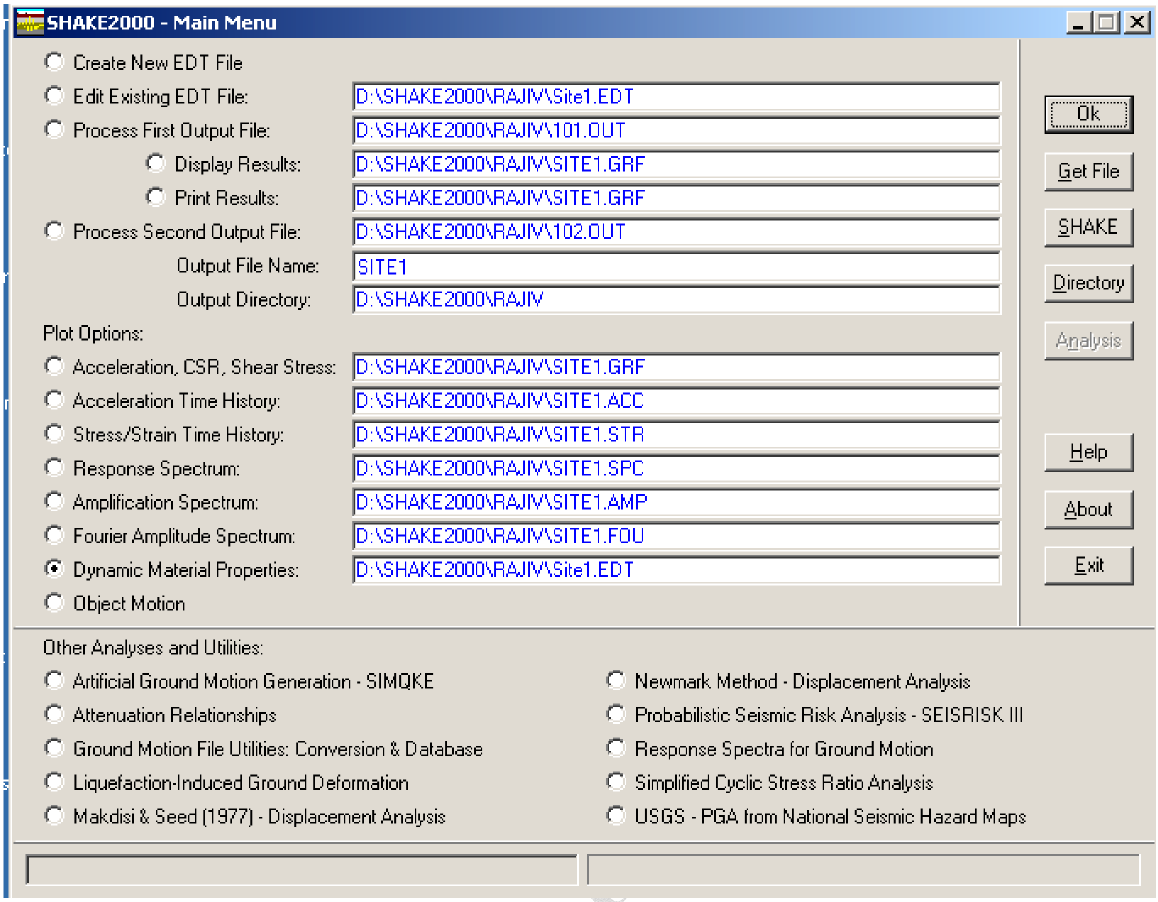


Figure 5-3: Main Menu window of SHAKE 2000

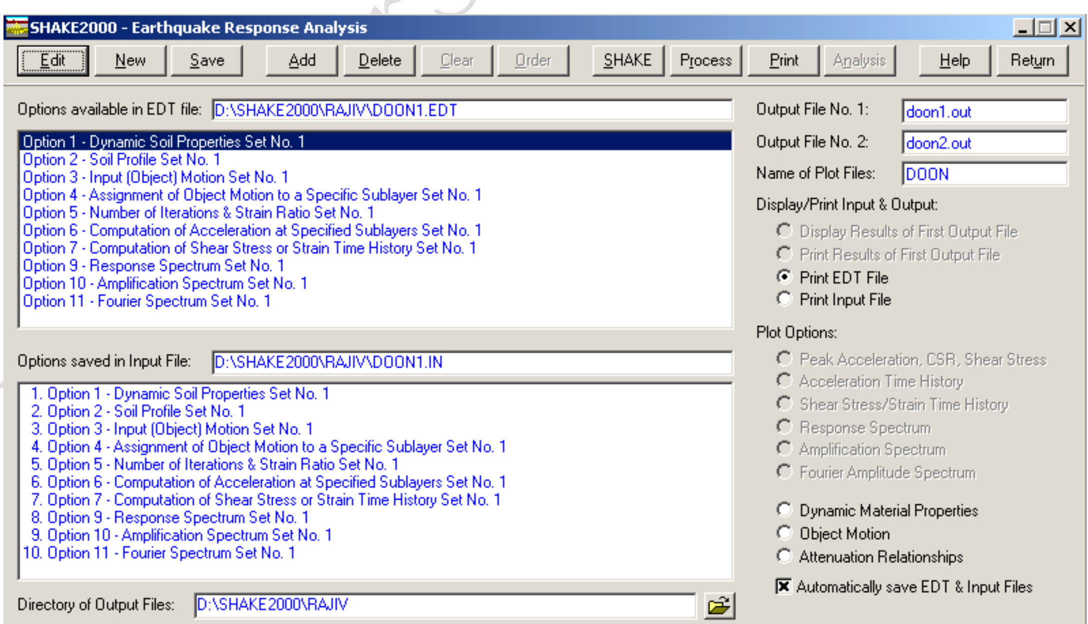


Figure 5-4: Earthquake Response analysis with various options in SHAKE 2000.

In the first option of dynamic soil properties, the modulus reduction curves and damping curves are chosen on the basis of the material type. To identify the boundaries and the material type in different layers for the sites covered, the seismic profile of the site was compared with the tube well lithologs data collected from Uttaranchal Jal Nigam (The state Irrigation office) and the local geology. But there are two problems in the comparison of tube well lithologs data with the shear wave velocity, firstly there is lack of availability of data of tube well lithologs in the city (Figure 5-5) and secondly the stratum of tube-well lithologs is not well defined. So for the modelling part with the help of available literature (BSSC, 1997), materials identified as soft soil, stiff soil and dense soil (please see Table 2-2), which further identified as clay, soil, gravel, rock fill on the basis of local geology available in literature or maps (Nossin, 1971; Rupke, 1974; Raiverman et al., 1984; Thakur, 1995; Bartatarya, 1995; Sati and Rautela, 1996; Patel and Kumar, 2003). The half space being considered as base rock for modelling. On the basis of these materials the corresponding modulus reduction curves and damping reduction curves were selected from the SHAKE 2000 database (see Table 5-1).

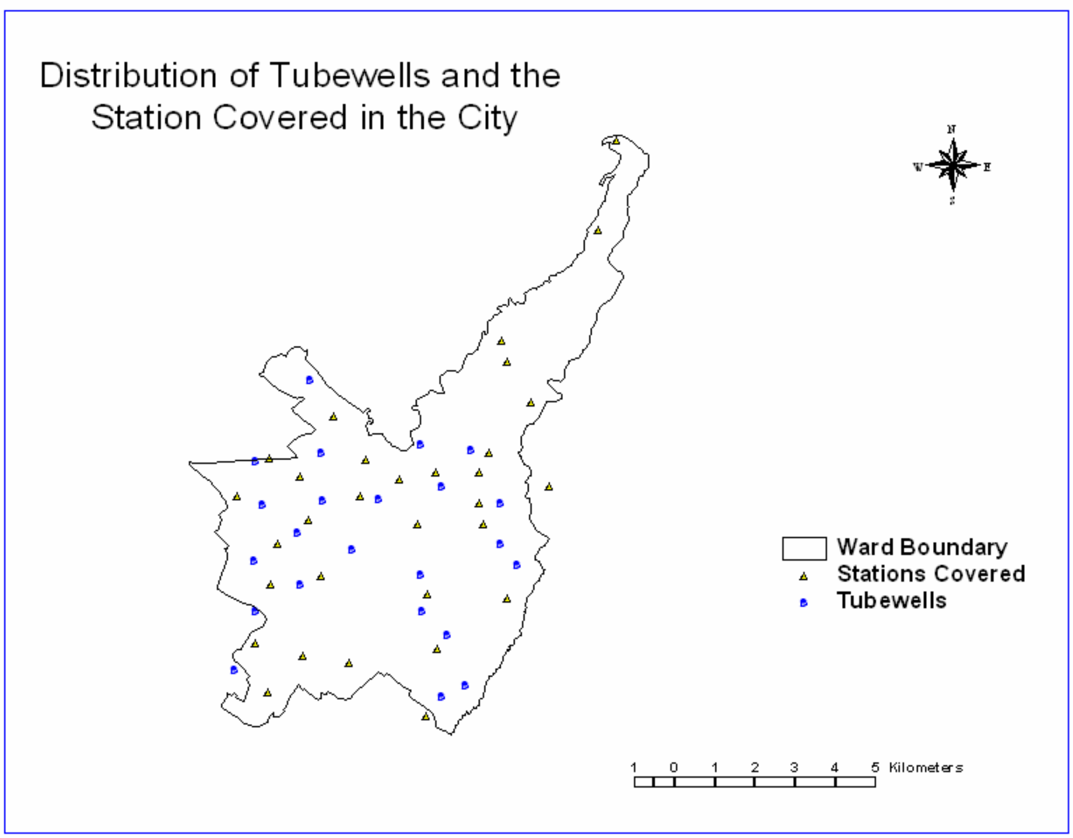


Figure 5-5: Tube well points and the covered stations in the city

In order to enter data for the second option various parameters related with the properties of the soil column of the site are required. It includes soil type, thickness of different layers, shear modulus/shear wave velocity (either of one is required), damping and unit weight (Figure 5-6). For this research work shear wave velocity has been considered as the main variable, and it is assumed that there is little effect from other factors like Unit weight; Damping and Modulus Reduction curves (see Table 5-1). A five percent default damping was taken for modelling.

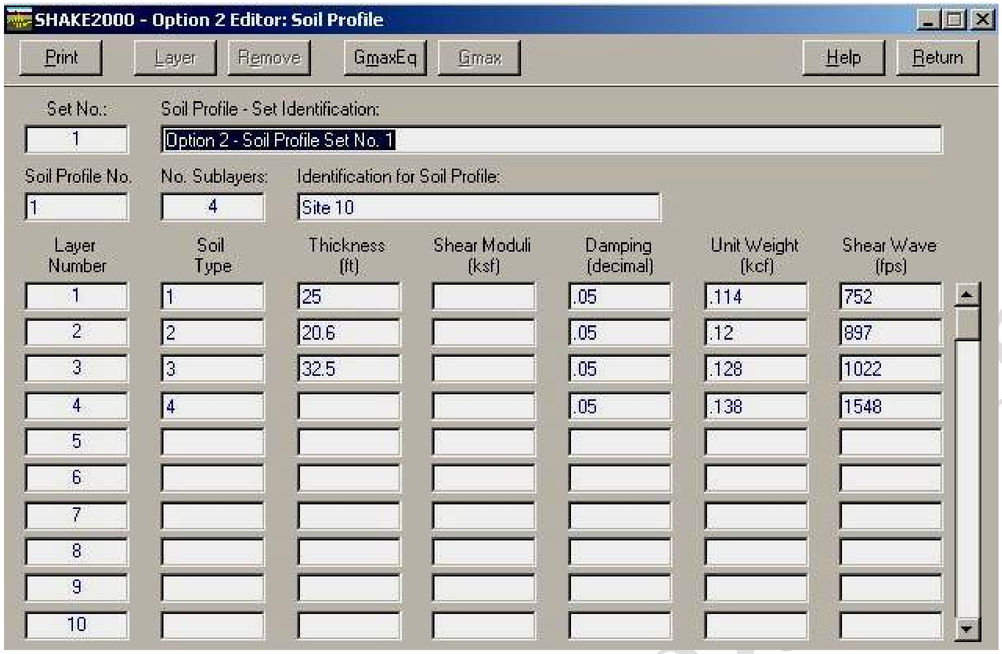


Figure 5-6: Soil profile parameters used in SHAKE 2000

Material Type	Modulus name (SHAKE 2000)	Damping	Unit weight (In kcf)
Clay	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972	0.108
Soil	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91)	0.114
Gravel	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)	.120
Rock fill	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)	.128
Half Space/ Base	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)	.138

Table 5-1: Dynamic material Properties used for analysis

In the third option the actual/simulated input motion data is entered or taken from the SHAKE 2000. In an ideal condition, the strong motion data that has been recorded for an earthquake nearby the study area and has caused the largest damage be considered for the analysis.
Dehradun city has experienced three larger earthquakes, i.e. Kangra earthquake (1905), Uttarkashi earthquake (1991) and Chamoli earthquake (1999). The largest damage was during Kangra earthquake, but unfortunately strong motion data was not available for this earthquake, although there is data of Chamoli earthquake recorded at different locations. For this research work the strong motion data recorded at Tehri (a place which is about 50 Km from Dehradun) was considered, as its distance is same (about 120 Km) as the epicentre near Chamoli.
In the fourth option, object motion to the sub-layers entered. For this research work the half space being considered as the rock and the object motion is applied within the soil profile (Idriss and Sun, 1992).
Option 5 is used to enter the strain ratio, which is the ratio of equivalent uniform strain and maximum strain. Schnabel et al. (1972) found that the responses are not much sensitive to this value. Generally it is in the range of 0.5 to 0.7 (Idriss and Sun, 1992) and can be calculated as:

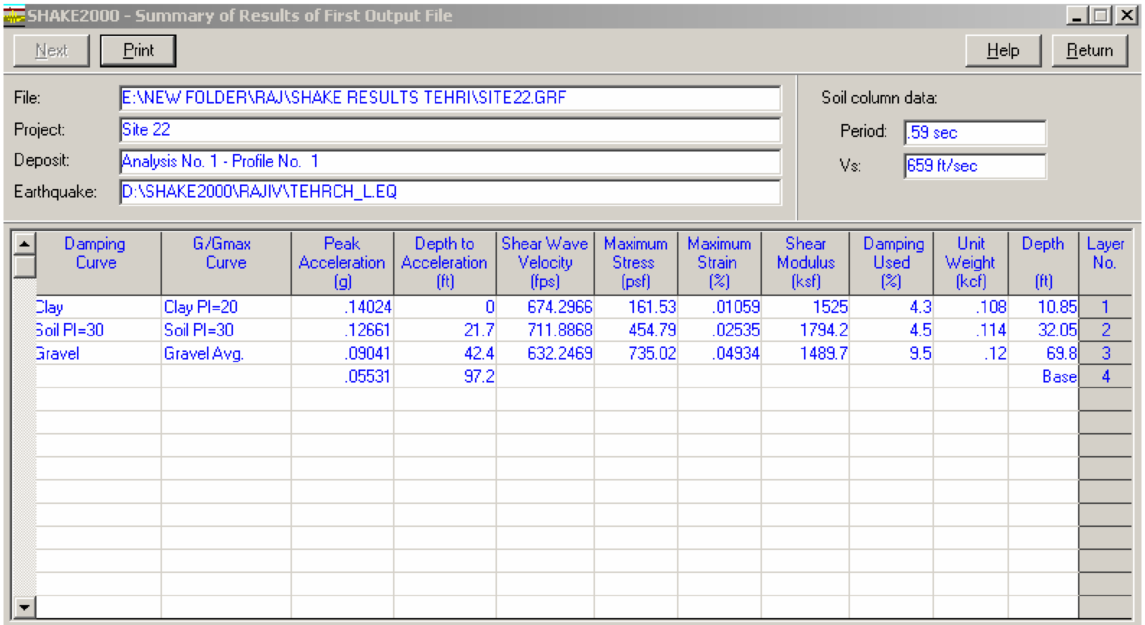
$$\text{Strain Ratio} = (M-1)/10$$

Where M is the magnitude of the earthquake.
For this research work the ground motion data of Chamoli earthquake (Magnitude 6.8) has been used. So the strain ratio was taken as 0.58 for all the sites.
After entering the data for option 1 to 5, in rest of the options data was entered on the basis of the previous data. The file is saved in two files as '.EDT' file and '.IN' file. The .EDT file has all the information about different options used as a database file to create '.IN' file which is used for the analysis by the programme. When all parameters are given to the programme, SHAKE 2000 can analyse all data and give outputs.
SHAKE 2000 works in different measurement units than the International System Unit (SI) so all data units are converted into SHAKE 2000 compatible format as shown in table 5-2.

Parameters	**International System Unit**	**Units used in SHAKE**
Thickness	1 meter	3.28 feet
Shear wave velocity	1meter/second	3.28 feet/second
Unit weight	1 Kilo Newton per meter cube	.0063 Kilo pound cubic foot
Shear modulus	1 Mega Pascal	20.88511 Kilo pound per square feet

Table 5-2: Conversion of International System Unit to SHAKE 2000 compatible unit

Just after the processing it gives the first result in 'Summary of Results of First Output' that gives information about natural period of the column, average shear wave velocity (Vs) and other parameters shown in figure 5-7.


SHAKE2000 - Summary of Results of First Output File

Next | Print | Help | Return

File: E:\NEW FOLDER\RAJ\SHAKE RESULTS TEHRI\SITE22.GRF
Project: Site 22
Deposit: Analysis No. 1 - Profile No. 1
Earthquake: D:\SHAKE2000\RAJIV\TEHRCH_L.EQ

Soil column data:
Period: .59 sec
Vs: 659 ft/sec

Damping Curve	G/Gmax Curve	Peak Acceleration (g)	Depth to Acceleration (ft)	Shear Wave Velocity (fps)	Maximum Stress (psf)	Maximum Strain (%)	Shear Modulus (ksf)	Damping Used (%)	Unit Weight (kcf)	Depth (ft)	Layer No.
Clay	Clay PI=20	.14024	0	674.2966	161.53	.01059	1525	4.3	.108	10.85	1
Soil PI=30	Soil PI=30	.12661	21.7	711.8868	454.79	.02535	1794.2	4.5	.114	32.05	2
Gravel	Gravel Avg.	.09041	42.4	632.2469	735.02	.04934	1489.7	9.5	.12	69.8	3
		.05531	97.2							Base	4

Figure 5-7: First output result after SHAKE analysis

Other results can be visualised through various plot options. For this research work response spectrum and average shear wave velocity of different sites have been analyzed. The response spectrum represents the maximum response of a single degree of-freedom (SDOF) system as a function of the natural frequency of the system and used to model the response of structures (Kramer, 1996). So it is widely used in the field of engineering for construction. According to Borcherdt (1994) the upper 30 meter soil column is considered to be responsible for site amplification. This has been incorporated by National Earthquake Hazard Reduction Programme (NEHRP, 1997) for classification of sites on the basis of shear wave velocity. Anderson et al. (1996) had also used the upper 30 meter column of the soil for ground response analysis. Recently a comprehensive study was performed by Romero and Rix (2001) to identify the soil deposits of susceptible to ground motion amplification in the Central United States. According to them "the 30- meter case is a conservative estimate at frequencies greater than 1 Hz but may slightly underestimate ground motions at frequencies less than 1 Hz. If little or no information is available for larger depths, the 30-meter assumption may be adequate to estimate site response" (Romero and Rix, 2001). In Dehradun city the seismic reflection profile has given the shear wave velocity with an accuracy of 1 to 3 m/s up to a depth of 30 meter used for the seismic response modelling.

5.2. Analysis:

In the analysis, the average shear wave velocity (Vs) and response spectra of different sites have been used. The results derived from all the sites shows that the average shear wave velocity for all the sites of upper 30 m soil column were in the range of 174 to 287 m/s.

According to National Earthquake Hazard Reduction Programme (NEHRP) code classification (BSSC, 1997) most of the sites were found in class 'D' except the two sites (Site No. 5 and 28) located in the northern and the south western part of the city.

The value of that average shear wave velocity of all the sites added in the attribute table of the site location map to prepare shear wave velocity map. For interpolation of the points, local geology, average distance (700 m) between two points and the survey profile line (about 100 m) have been considered, and 200 x 200 meter output cell grid size has been taken. For all spatial calculation Arc View and Arc GIS have been used. Classification is based on the natural groupings of data values. The programme identifies the breakpoints and classify the data in different number of classes that given by the user.

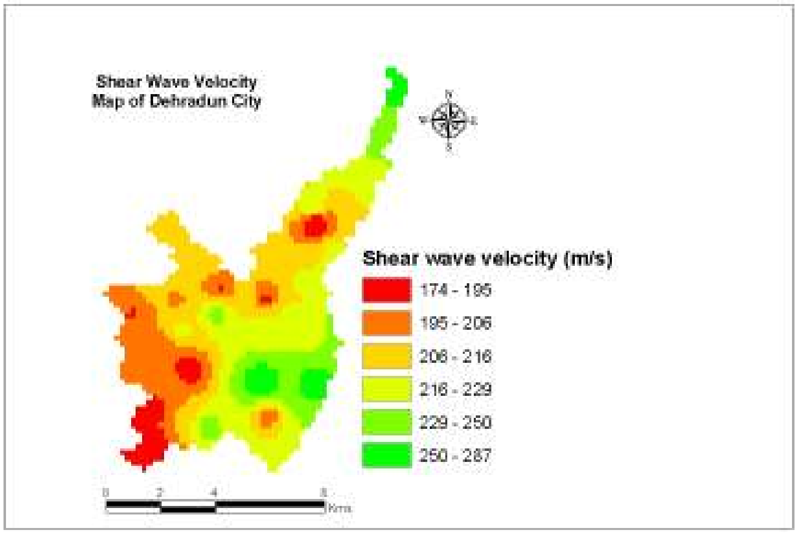


Figure 5-8: Shear wave velocity map of Dehradun city

Four velocity zones have been identified in the city with different velocity range (Figure 5-8). In the northern part of the city the velocity range was higher than the other region as it consists of older metamorphic rocks. In the central part of the city the velocity range was less than that of the northern part and the eastern part, which is basically located on thick gravel deposit. In the eastern part of the city a moderate to high velocity zones were identified. This area consists of Gravel sand and silt matrix. In the south western part of the city a low velocity zone has been identified, geologically this area consists of finer materials, which were deposited in the past as it is the lowest part of the city as well as the confluence zone of the northern and the southern piedmont fans.

5.2.1 Spectral Acceleration Distribution:

The spectral acceleration (SA) for all the sites computed at 1 Hz, 3 Hz, 5 Hz and 10 Hz as they represent the natural frequency of tall buildings, 3 storey buildings, 2 storey building and 1 storey building respectively (Kramer, 1996; Day, 2001).

At 1 Hz frequency there was not any significant variation in spectral acceleration (see Table 5-4) and its value for all the sites ranges from 0.6 to 0.9 g. There is not much variation in the shear wave velocity in this range and the value is very low. So for this frequency Spectral acceleration map was not prepared.

Site ID.	1 Hz	3 Hz frequency	5 Hz frequency	10 Hz frequency
1	0.08	0.66	0.32	0.24
2	0.08	0.39	0.26	0.19
4	0.08	0.40	0.28	0.19
5	0.08	0.32	0.2	0.15
6	0.08	0.51	0.3	0.22
7	0.08	0.38	0.24	0.19
8	0.08	0.52	0.3	0.21
9	0.08	0.51	0.28	0.20
10	0.08	0.39	0.25	0.18
11	0.08	0.34	0.21	0.15
12	0.08	0.31	0.21	0.14
13	0.08	0.43	0.27	0.20
14	0.08	0.44	0.24	0.19
15	0.08	0.42	0.3	0.20
16	0.07	0.61	0.28	0.20
17	0.09	0.43	0.32	0.20
18	0.07	0.47	0.25	0.20
19	0.08	0.52	0.3	0.21
20	0.08	0.40	0.25	0.20
21	0.08	0.28	0.23	0.15
22	0.08	0.30	0.25	0.16
24	0.08	0.91	0.33	0.26
25	0.08	0.32	0.22	0.15
26	0.08	0.43	0.31	0.20
27	0.08	0.43	0.31	0.20
28	0.07	1.11	0.31	0.24
29	0.08	0.29	0.23	0.15
30	0.08	0.44	0.32	0.21
31	0.08	0.50	0.28	0.20
32	0.06	1.36	0.37	0.26
33	0.08	0.28	0.22	0.14

Table 5-3: Spectral Acceleration of the sites at 3, 5 and 10 Hz frequency at 5% damping

However for 3 Hz frequency the SA value range was from 0.28 to 1.36 g (please see table 5-3). Maximum SA was found in the south western part of the city at site No. 32. Other adjacent sites had also high SA value at this frequency (Figure 5-9). In the northern part of the city at one site (Site No. 1) the value of SA at this frequency was higher than the adjacent site. At three sites, in the eastern part of the city (Site No. 6, 8 and 21) SA at this frequency was in the range of more than 0.50 g. While in the western part of the city at two sites (Site No. 9 and 19) SA at this frequency was also relatively higher than the adjacent sites.

In the central part of the city at most of the sites the value of SA at this frequency was less than 0.50 g. Geologically this part of the city is situated on thick sediments that came from the northern and the southern part of the valley and deposited here.

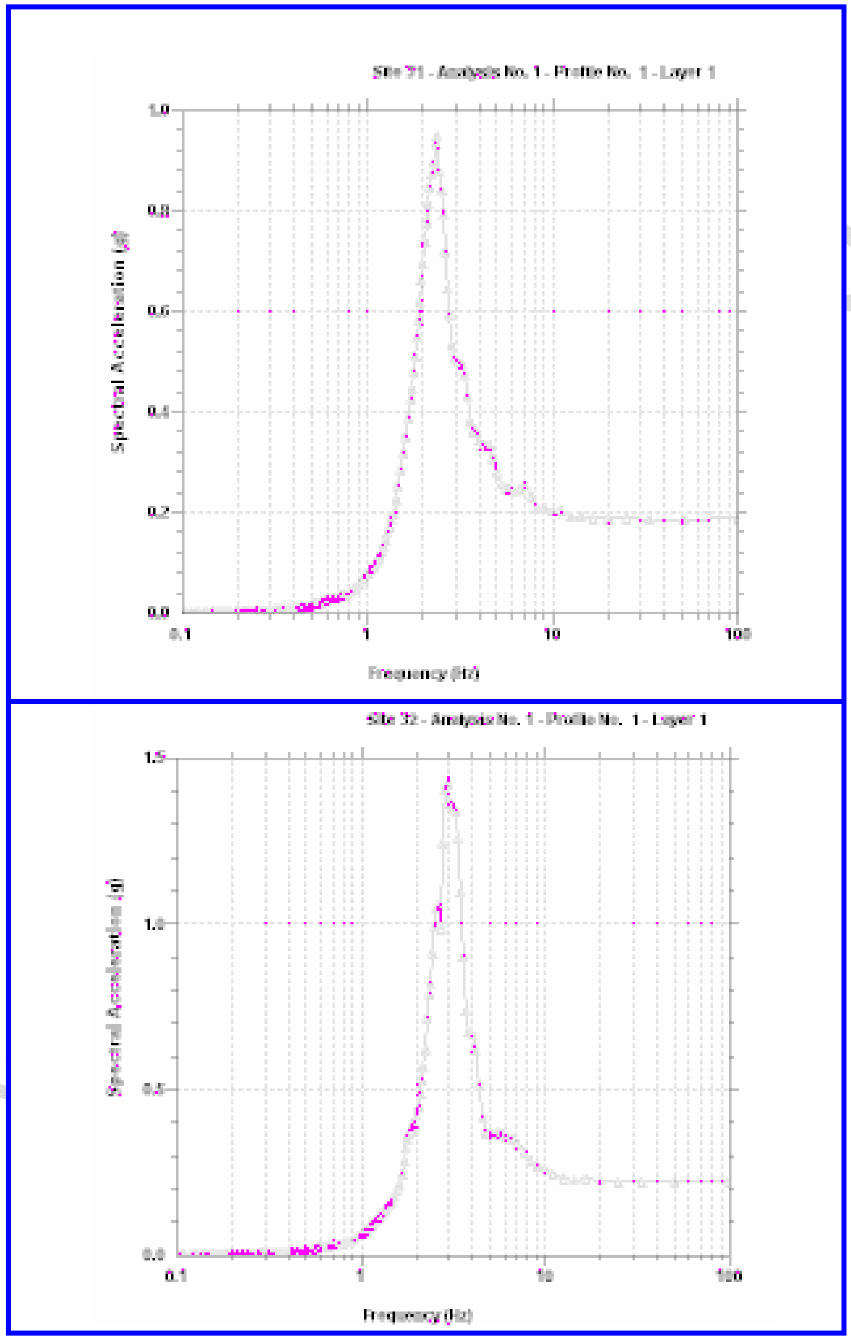


Figure 5-9: Spectral Acceleration plot of the two sites Site No. 31 and Site No. 32.

On the basis of these values spectral acceleration map prepared using interpolation technique shown in figure 5-10.

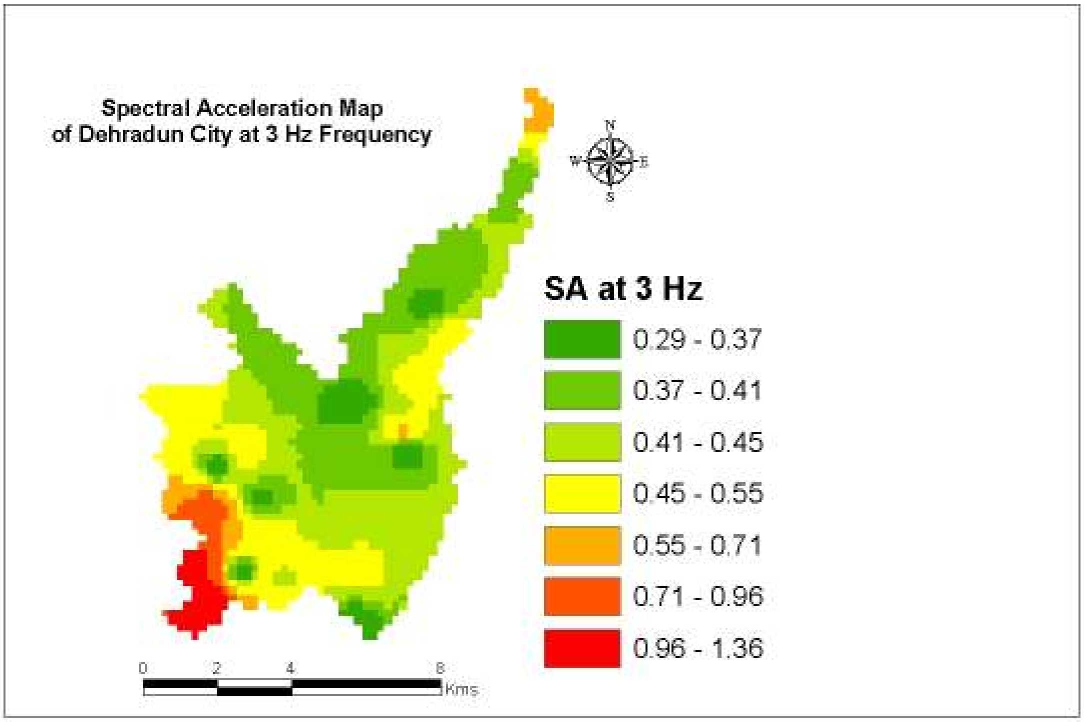


Figure 5-10: Spectral acceleration map of the city at 3 Hz frequency

Seven zones of spectral acceleration have been identified in the city on the basis of value of SA. The classification was based on the natural break points of the data. It shows that in the south western region the SA value was very high. While in the northern part of the city the SA value was relatively higher than the adjacent area. The value was lower in the central and eastern part of the city.

However at 5 Hz frequency the variation of spectral acceleration was in the range of 0.20 g to 0.39 g for all the sites (Figure 5-11). But it was unevenly distributed around the city. Maximum spectral acceleration for this frequency was 0.37 g at site No. 32 located in the south western part of the city. At this frequency also most of the sites that were situated in the south western part of the city had high SA value. In the northern part of the city at one site (Site No. 1) and in the eastern and southern part of the city at different sites (Site No. 17, 26 and 27) the value of SA was high at this frequency. Geologically these sites are located very near to pre tertiary formation, consists of older metamorphic rocks. At rest of the city the value of SA was relatively low to moderate at this frequency.

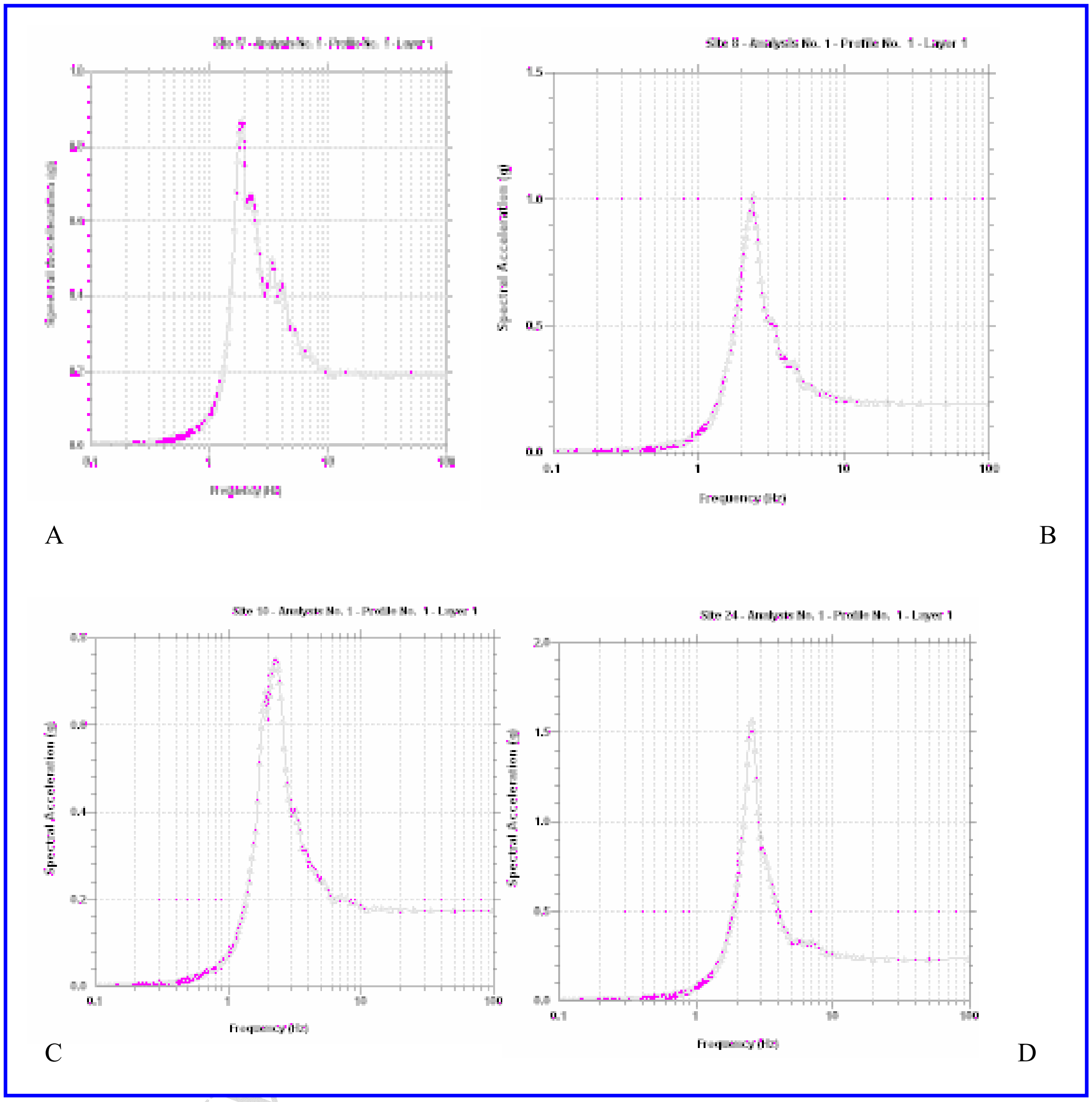


Figure 5-11: Response spectra plot of Site No. 17 (A), 8(B), 10(C) and 24.

The acceleration map has been prepared for this frequency to see the variation of SA at this frequency shown in figure 5-12:

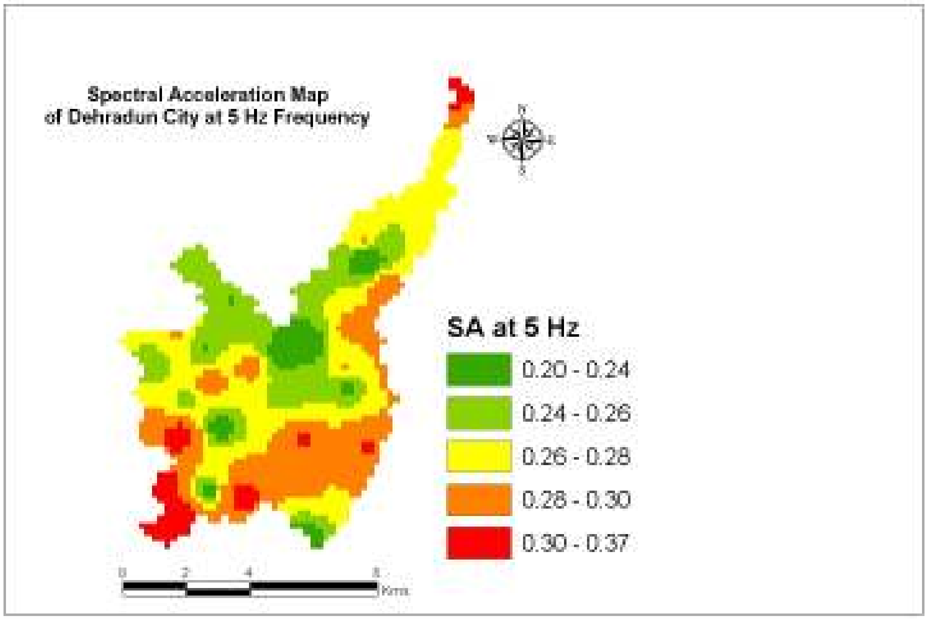


Figure 5-12: Spectral acceleration map of the city at 5 Hz frequency

At this frequency small patches of different zones had been identified on the basis of the value of SA. At this frequency, value of SA was very high in the south western and in the northern part of the study area, while in the central and the northern part of the city the value of SA was relatively low to moderate.

At 10 Hz frequency the variation of SA was in the range of 0.14 to 0.26 g. Maximum SA was found in the south western part of the city (Site No. 24, 28 and 32) (Figure 5-11) and in the northern part at Site No. 1. In the northern (at Site No. 1) and the south western part of the city (Site No. 24, 28 and 32) the value of SA at this frequency was found in the range of 0.22 to 0.26 g. In the eastern and the western and central part of the city at most of the site its value range varies from 0.19 to 0.22 g. In the central part of the city at some site at this frequency the value is lower than the adjacent site. In the northern part of the city for Site No. 2 and 4 its value was found 0.19 g while for the other sites (Site No. 5 and 6) the value was 0.15 and 0.22 g respectively.

SA map has been prepared for this frequency also (Figure 5-13). Different SA zones had been identified at this frequency, maximum acceleration had been found in the south western and in the northern part of the city, while at this frequency in the rest part of the city there were relatively low SA values had been found.

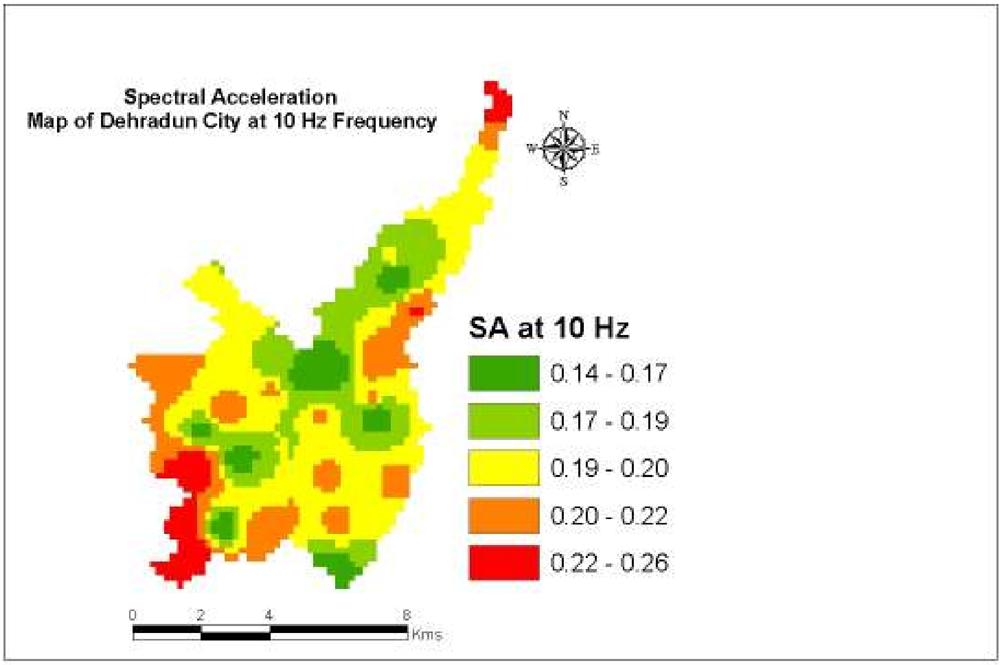


Figure 5-13: Spectral acceleration map of the city at 10 Hz frequency

In this map, Zone I has been identified in the western part of the city and as small patches in various parts of the city. Zone II has been identified in the measure part of the city situated on alluvium sediments consist of gravels. Zone III has been identified in the south western, south eastern and the northern part of the city. Geologically the northern and the south eastern part are located near the pre tertiary formations that consist of older metamorphic rock. Zone IV that has a maximum SA value range has been identified in the extreme south west corner of the city.

General results obtained from the analysis of average shear wave velocity and response spectra shows:

- There is large variation of spectral acceleration at different frequency for the city.
- The peak SA for all the sites was in the range of 2 and 3 Hz frequency.
- From all the maps it is clear that the northern part of the city (Rajpur) and the south western part of the city are more susceptible to earthquake, as it has evidenced from Kangra earthquake (1905) that Rajpur area was badly affected (Middlemiss, 1910).
- This analysis is based on the strong motion data recorded at Tehri, if the ground motion data recorded at Dehradun being used the results may vary from that result.

6. Discussion, Conclusions and Recommendations

6.1. Discussion:

Dehradun city is located in an intermontane valley in between Lesser Himalaya and the Siwaliks. The city had experienced damage in the previous earthquakes triggered in areas located around 200 to 300 km away from Dehradun, which indicates effect of low frequency and site amplification. It is important to study the site effects of the area because of the large amount of sediments (e.g. alluvium and Doon Gravels), which may greatly amplify seismic waves. Historic and recent records indicate that motion from nearby and larger, more distant earthquakes have been felt widely in the Dehradun area over the last century. Recently it was declared as the capital of the newly formed state of Uttaranchal, which has caused rapid urbanization and haphazard growth of the city. The growing urbanization and high seismic potential of surrounding areas which have very high hazard level of the order of 0.70 g 0.5 g in Kangra and Chamoli area respectively (Mahajan et al., 2002), it is pertinent to choose Dehradun city for site amplification studies. So Dehradun city has been chosen for the microzonation study.

The main objectives of this research were to measure shear wave velocity, to estimate site response and to calculate response spectra and spectral acceleration of different locations around the city. The shear wave velocity was measured at 31 different locations of the city. On the basis of shear wave velocity for the upper 30 m, it has been found that the variation of shear wave velocity was in the range of 174 to 287 m/s. In the northern part of the city it has been found that at one site (Site No. 1) the velocity was significantly high and reached up to 287 m/s. Geologically this site is situated on pre-tertiary formation consists of older metamorphic rocks. The velocity decreased gradually towards the southern area. In the south eastern part of the city at two sites (Site No. 26 and 27) the shear wave velocity was found higher as these sites were near to the pre-tertiary rocks. In the south western part of the city at most of the site the shear wave velocity was below 200 m/s, geologically this area consists of finer materials, which were deposited in the past, as it is the lowest part of the city as well as the confluence zone of the northern and the southern piedmont fans. In the rest part of the city shear wave velocity was found in the range of 200 to 240 m/s.

To verify the geophysical data with the existing boreholes such as tube well data or existing geological model, the tube well lithologs data collected from Uttaranchal Jal Nigam (The state Irrigation office) was used. But it has been found that the stratum of the tube well lithologs were not well defined and it was not well distributed in the city, but the depth of the stratum matched in some cases. There is lack of geological model for the city area so on the basis of literature and available maps four to five materials have been identified as clay, soil, gravel, rockfill and the half space, which considered as bed rock for modelling.

Spectral acceleration for all the sites has been computed at 1 Hz, 3 Hz, 5 Hz and 10 Hz frequency. It has been found that the maximum variation of SA was at 3 Hz frequency varies between 0.28 to 1.36 g. At this frequency in the south western part of the city at two sites (Site No. 28 and 32) the value of SA was more than 1 g. In the northern part of the city at site No. 1 the value of SA was more than 0.6 g. At 5 Hz frequency the SA value ranges from 0.20 to 0.39 g. At this frequency in the northern part of the city a value of 0.32 g is noticed at two sites having metamorphic rock or pre-tertiary rock in the subsurface, whereas in the south and south-western part of the city, SA was in the range of 0.30 to 0.37 g. In the eastern part of the city SA was in the range of 0.19 to 0.23 g for most of the site. At 10 Hz frequency SA for most of the site varies between 0.14 to 0.26 g. In the northern part of the city a value of 0.24 g found at one site, whereas in the south-western part, at one site the value was 0.26 g. In the eastern part of the city at most of the site SA was 0.20 g, however at one site the value was 0.22 g. For all the sites the value of peak SA acceleration was found at 2 to 3 Hz frequency in the range of 0.6 to 1.4 g.

The Spectral Acceleration map of the city has been compiled using interpolation technique in GIS environment for 3 Hz, 5 Hz and 10 Hz frequency shows that the structures of the northern part and the south western part of the city are more vulnerable to earthquake.

6.2. Conclusions:

- MASW technique is a non-destructive method to measure shear wave velocity and is useful to measure shear wave velocity in an urban area. This technique gives a 2D profile of shear wave velocity with depth that can be easily interpreted.
- At one site the geophysical data was recorded at 2 meter and 3 meter geophone spacing. During analysis it was found that in the case of 3 meter spacing the signal to noise ratio was in the range of 27% to 45% while at 2 meter spacing it is > 70%. At 2 meter spacing the fundamental mode was at low frequency and given a coherent result whereas at 3 meter spacing the high frequency dominated and it does not allowed to penetrate more than 20 meter. It has been found that in the case of Dehradun 2 meter and 1.5 meter geophone spacing has given good penetration with an accuracy of 1 to 3 m/s in shear wave velocity and high signal to noise ratio.
- The range of shear wave velocity for the upper 30 meter layer in the city was in the range of 154 m/s in the upper layer to 733 m/s for the base layer i.e. half space. In the northern, eastern and central part of the city shear wave velocity was higher, while in the southern and south western part of the city it is as low as 154m/s for the topmost layer.
- Analysis of the sites, show higher spectral values, are very well corroborated with the damage scenario of 1905 Kangra earthquake (Middlemiss, 1910).
- Most of the sites were found under class ‘D’ as per NEHRP code classification (BSSC, 1997). Only two sites (5 and 28) located in the northern part and south-western part respectively found under class ‘E’.
- At 5% damping, the range of SA at 1 Hz frequency was 0.06 g to 0.09 g, at 5 Hz frequency it was in the range of 0.20 g to 0.37 g, while at 10 Hz frequency it was in the range of 0.14 g to 0.28 g.

- For this research work the strong motion data recorded at Tehri (a place which is about 50 Km from Dehradun) was considered, as the distance of both Tehri and Dehradun is almost same from the epicentre (about 120 Km) i.e. Chamoli.

6.3. Recommendations

- Bore hole data with core sample up to bedrock depth require to verify shear wave velocity with the litholog samples.
- The geophysical investigation data can be used for the detailed subsurface geological mapping of the study area.
- There is a need of strong motion data recorded near by the study area to get the realistic SA value.
- A strong motion array needed in different type of buildings to record actual spectral acceleration to compare the result with the present study.
- Standard Penetration Test (SPT) in which number of counts is used to know the shear strength of the soil needs to be carried out at different site to compare the shear wave velocity with depth.

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Appendix 1

Input Data used for Spectral Acceleration modelling

Site ID	Material Type	Thickness (in feet)	Shear wave Velocity (Vs) (in feet/second)	Unit weight (in kcf)	Name of modulli curve	Name of Damping curve
1	Gravel	45.4	1188	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	58.6	1477	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2406	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
2	Soil	14.5	885	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	61.1	1089	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	22.7	1332	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2099	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

4	Soil	23.4	840	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	37.8	1022	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	43.6	1232	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		1950	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
5	Soil	22.6	745	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	48.5	873	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1325	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
6	Gravel	52.6	975	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	37.4	1281	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2026	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

7	Soil	27.1	815	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	38.4	1008	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	19.7	1207	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		1988	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
8	Gravel	50.3	1025	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	35.8	1210	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2066	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel1973)
9	Soil	17.3	826	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	42.1	998	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	17.8	1211	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		1919	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

10	Soil	25	752	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	20.6	897	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	32.5	1022	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		1548	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
11	Soil	39.4	822	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	50.9	1055	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1650	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
12	Soil	26	802	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	55.8	947	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1497	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

13	Gravel	54	1011	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	38.5	1195	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		1775	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
14	Soil	55	782	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	16.5	986	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1560	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
15	Gravel	49.8	1013	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	64.3	1284	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2024	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

16	Gravel	33	989	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	43	1162	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2001	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
17	Gravel	71.1	1049	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	50.6	1418	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2192	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
18	Clay	22.3	660	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
	Soil	18.7	820	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	29.2	1001	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1664	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

19	Gravel	50.3	1025	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	35.8	1210	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2066	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
20	Soil	39.4	798	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	30	1105	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	20.9	1206	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		1861	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
21	Soil	32.7	834	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	70	1073	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1754	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

	Clay	21.7	694	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
	Soil	20.7	771	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
22	Gravel	54.8	1032	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1843	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
	Clay	21.9	645	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
24	Soil	47	822	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Half Space		1365	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
	Soil	17.6	763	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
25	Gravel	61.1	925	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1457	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

26	Gravel	41.3	1090	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	88.5	1451	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2293	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
27	Soil	39	858	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	32.6	1141	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	51	1458	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2572	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
28	Clay	24.2	535	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
	Soil	31.3	734	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Half Space		1267	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

29	Clay	8.7	710	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
	Soil	13.6	780	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	77.3	1060	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1874	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
30	Clay	15.9	680	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
	Soil	18.3	820	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	28.6	1089	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Rockfill	44.7	1332	0.128	G/Gmax - Rockfill - Gazetas - Soil Dynamics and Earthquake Eng. 1992)	Damping for Rockfill (Gazetas - Soil Dynamics and Earthquake Eng. 1992)
	Half Space		2011	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

31	Clay	17.5	586	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
	Soil	16.6	812	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	44	1110	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		2011	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
32	Clay	25.1	544	0.108	G/Gmax - C3 (CLAY PI =20-40, Sun et al. 1988)	Damping for CLAY May 24 -1972
	Soil	32.5	785	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Half Space		1313	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)
33	Soil	32	871	0.114	G/Gmax - Soil with PI=30, OCR=1-15 (Vucetic & Dobry, JGE 1/91)	Damping - Soil with PI=30, OCR=1-8 (Vucetic & Dobry, JGE 1/91
	Gravel	68.7	1078	0.120	G/Gmax - GRAVEL, Average (Seed et al. 1986)	Damping for GRAVEL, Average (Seed et al. 1986)
	Half Space		1889	0.138	G/Gmax - ROCK (Schnabel 1973)	Damping for ROCK (Schnabel 1973)

Appendix 2

Shear Modulus Reduction Curve and Damping Curve used for modelling