Seismic Microzonation: Principles, Practices and Experiments

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ABSTRACT

This paper presents an over view of the seismic microzonation and the grade/level based study along with methods used for estimating hazard. The principles of seismic microzonation along with some current practices are discussed. Summary of seismic microzonation experiments carried out in India is presented. A detailed work of seismic microzonation of Bangalore has been presented as a case study. In this case study, a seismotectonic map for microzonation area has been developed covering 350 km radius around Bangalore, India using seismicity and seismotectonic parameters of the region. For seismic microzonation Bangalore Mahanagar Palike (BMP) area of 220 km^2 has been selected as the study area. Seismic hazard analysis has been carried out using deterministic as well as probabilistic approaches. Synthetic ground motion at 653 locations, recurrence relation and peak ground acceleration maps at rock level have been generated. A detailed site characterization has been carried out using borehole with standard penetration test (SPT) "N" values and geophysical data. The base map and 3-dimensional sub surface borehole model has been generated for study area using geographical information system (GIS). Multichannel analysis of surface wave (MASW) method has been used to generate one-dimensional shear wave velocity profile at 58 locations and two-dimensional profile at 20 locations. These shear wave velocities are used to estimate equivalent shear wave velocity in the study area at every 5m intervals up to a depth of 30m. Because of wider variation in the rock depth, equivalent shear for the soil overburden thickness alone has been estimated and mapped using ArcGIS 9.2. Based on equivalent shear wave velocity of soil overburden thickness, the study area is classified as "site class D". Site response study has been carried out using geotechnical properties and synthetic ground motions with program SHAKE2000. The soil in the study area is classified as soil with moderate amplification potential. Site response results obtained using standard penetration test (SPT) "N" values and shear wave velocity are compared, it is found that the results based on shear wave velocity is lower than the results based on SPT "N" values. Further, predominant frequency of soil column has been estimated based on ambient noise survey measurements using instruments of L4-3D short period sensors equipped with Reftek 24 bit digital acquisition systems. Predominant frequency obtained from site response study is compared with ambient noise survey. In general, predominant frequencies in the study area vary from 3Hz to 12Hz. Due to flat terrain in the study area, the induced effect of land slide possibility is considered to be remote. However, induced effect of liquefaction hazard has been estimated and mapped. Finally, by integrating the above hazard parameters two hazard index maps have been developed using Analytic Hierarchy Process (AHP) on GIS platform. One map is based on deterministic hazard analysis and other map is based on probabilistic hazard analysis. Finally, a general guideline is proposed by bringing out the advantages and disadvantages of different approaches.

Keywords: Seismic microzonation, hazard, site characterization, site response study, liquefaction and hazard index.

INTRODUCTION

Many earthquakes in the past have left many lessons to be learned which are very essential to plan infrastructure and even to mitigate such calamities in future. The hazards associated with earthquakes are referred to as seismic hazards. The practice of earthquake engineering involves the identification and mitigation of seismic hazards. Microzonation has generally been recognized as the most accepted tool in seismic hazard assessment and risk evaluation and it is defined as the zonation with respect to ground motion characteristics taking into account source and site conditions [TC4-ISSMGE, 1999]. Making improvements on the conventional macrozonation maps and regional hazard maps, microzonation of a region generates detailed maps that predict the hazard at much smaller scales. Seismic microzonation is the generic name for subdividing a region into individual areas having different potentials hazardous earthquake effects, defining their specific seismic behavior for engineering design and land-use planning. The role of geological and geotechnical data is becoming very important in the microzonation in particular the planning of city urban infrastructure, which can recognize, control and prevent geological hazards (Bell et al., 1987; Legget, 1987; Hake, 1987; Rau, 1994; Dai et al., 1994, 2001; Van Rooy and Stiff, 2001). The basis of microzonation is to model the rupture mechanism at the source of an earthquake, evaluate the propagation of waves through the earth to the top of bed rock, determine the effect of local soil profile and thus develop a hazard map indicating the vulnerability of the area to potential seismic hazard. Seismic microzonation will also help in designing buried lifelines such as tunnels, water and sewage lines, gas and oil lines, and power and communication lines.

In the last three decades, large earthquakes have caused massive loss of lives and extensive physical destruction throughout the world (Armenia, 1988; Iran, 1990; US, 1994; Japan, 1995; Turkey, 1999; Taiwan, 1999, India 2001, Sumatra 2004, Pakistan, 2005). India has been facing threat from earthquakes since ancient times. In India, the recent destructive earthquakes are Killari (1993), Jabalpur (1997), Bhuj (2001), Sumatra (2004) and Indo-Pakistan (2005). Seismic activity of India is evident from these recent earthquakes within the intra plate and along the boundaries of Indo-Australian Plate and Eurasian Plate. Many researchers address the intra plate earthquakes and seismicity of South India (Purnachandra Rao, 1999; Ramalingeswara Rao, 2000; Iyengar and Raghukanth, 2004).

Very preliminary process of reducing the effects of earthquake is by assessing the hazard itself. As part of the national level microzonation programme, Department of Science and Technology, Govt. of India has initiated microzonation of 63 cities in India (Bansal and Vandana, 2007). Some of them are finished and some of them are ongoing. As an initial experiment, seismic hazard analysis and microzonation was taken up for Jabalpur city in Madhaya Pradesh. Further, for many other cities such as Sikkim, Mumbai, Delhi, North East India, Gauwhati, Ahmedabad, Bhuj, Dehradun and Chennai an attempt has been made to carryout microzonation considering geomorphological features and detailed geotechnical studies. Among the above Jabalpur, Sikkim, Gauwhati and Bangalore microzonation works have been completed. However, for Sikkim and Gauwhati, microzonation reports are already available and the report on microzonation of Bangalore is in the final stages which will be released within few months.

This paper presents the state-of-art practices of microzonation along with brief summary of the Indian experiments. Further, a detailed case study of seismic microzonation of Bangalore has been presented. Seismic microzonation of Bangalore is addressed in four parts: In the first part, estimation of seismic hazard using seismotectonic and geological information. Second part deals about the site characterization using geotechnical and shallow geophysical techniques. In the third part, local site effects are assessed by carrying out one-dimensional (1-D) ground response analysis (using the program SHAKE 2000) using both borehole SPT data and shear wave velocity survey data within an area of 220 km^2. Further, field experiments using microtremor studies have also been carried out (jointly with NGRI) for evaluation of predominant frequency of the soil columns. The same has been assessed using 1-D ground response analysis and compared with microtremor results. Further, Seed and Idriss simplified approach has been adopted to evaluate the liquefaction susceptibility and liquefaction resistance assessment. As the study area is fairly flat in most of the region except in north and northwestern, landslide possibility is considered as remote. Fourth part discuss about the integration of all the hazard parameters and developing a final hazard index map for BMP area using Analytic Hierarchy Process (AHP) on GIS (Geographical Information System) platform.

PRINCIPLES OF SEISMIC MICROZONATION

The earthquake damage basically depends on three groups of factors: earthquake source and path characteristics, local geological and geotechnical site conditions, structural design and construction features. Seismic microzonation should address the assessment of the first two groups of factors. In general terms, seismic microzonation is the process of estimating the response of soil layers for earthquake excitations and thus the variation of earthquake characteristics is represented on the ground surface. Seismic microzonation is the initial phase of earthquake risk mitigation and requires multidisciplinary approach with major contributions from geology, seismology and geotechnical engineering.

Seismic Microzonation falls into the category of “applied research”. That is why it needs to be upgraded and revised based on the latest information. The microzonation is defined as subdivision of a region into zones that have relatively similar exposure to various earthquake related effects. This exercise is similar to the macro level hazard evaluation but requires more rigorous input about the site specific geological conditions, geotechnical characteristics of site, ground responses of soil column to earthquake motions and their effects, ground conditions which would enhance the earthquake effects like the liquefaction of soil, the ground water conditions and the static and dynamic characteristics of foundations or of stability of slopes in the hilly terrain.

The microzonation shall be graded based on the scale of the investigation and details of the studies carried out. The technical committee on earthquake geotechnical engineering (TC4) of the International society of soil mechanics and foundation engineering (TC4-ISSMGE 1999) states that the first grade (Level I) map can be prepared with scale of 1:1,000,000 – 1:50,000 and the ground motion was assessed based on the historical earthquakes and existing information of geological and geomorphological maps. If the scale of the mapping is 1:100,000-1:10,000 and ground motion is assessed based on the microtremor and simplified geotechnical studies then it is called second grade (Level II) map. In the third grade (Level III) map ground motion has been assessed based on the complete geotechnical investigations and ground response analysis with a scale of 1:25,000-1:5,000.

For the estimation of site effects (local soil and topographical effects) and induced effects (land instability and liquefaction), the knowledge of bed rock where ground motion being applied is required. Bed rock can be divided as two types, one seismic bed rock and other one engineering bed rock. Seismic bed rock is the rock having the shear wave velocity of more than 3000 m/s used for earthquake simulation and modeling. Seismic bed rock characteristics are included in the source and path effects of ground motions. Engineering bed rock is the rock having shear wave velocity of 700 m/s and above, where usually engineers rest their deep foundation.

SEISMIC HAZARD AND MICROZONATION STUDIES:

Literature shows that in the area of seismic hazard and microzonation lot of work has been carried out from Nineties in many countries. There are guidelines for seismic microzonation studies, French Association for Earthquake Engineering Titled "Guidelines for Seismic Microzonation Studies; 1995" (Bard et. al., 1995). The recent guideline from General Directorate of Disaster Affairs, Republic of Turkey Ministry of Public Works and Settlement titled as Seismic Microzonation for Municipalities Manual, February 2004 (DRM, 2004). A typical case study using updated information is also presented for Microzonation of Pilot Areas of Adapazari, Gölcük, İhsaniye And Değirmendere (DRM, 2004; Ansal et al, 2004). This study presents site classification map, site amplification/ground motion map, liquefaction susceptibility map and landslide hazard map separately using GIS. Even though detailed studies have been carried out and maps are generated for different components of seismic microzonation for the above area, no integrations of hazard parameters has been presented.

EXPERIMENTS IN INDIA

This section presents the summary of seismic hazard analysis and microzonation works carried out in Indian urban centers.

Seismic Microzonation of Jabalpur Urban Area

Very first work in India towards microzonation of Indian cities, was initiated as an experiment and example by the Department of Science & Technology, New Delhi (PCRSMJUA, 2005). This work was carried out by the nodal national agencies viz. Geological survey of India, Central Region Nagpur, Indian Metrology Department New Delhi, National Geophysical Research Institute (NGRI), Hyderabad, Central Building Research Institute(CBRI), Roorkee and Government Engineering College, Jabalpur. Seismic hazard analysis was carried out deterministically and deterministic peak ground acceleration map published based on the attenuation relation developed by Joyner and Boore (1981). The extensive work on ground characterization was presented based on the experimental study of geology, geotechnical and geophysical investigations. Based on this information, the first level microzonation map was published. The liquefaction hazard assessment was carried out using geotechnical data and simplified approach of Seed and Idriss (1971). Shear wave velocities from geophysical method of multichannel analysis of surface wave were measured and used for classification of sites in Jabalpur based on 30m equivalent shear wave velocity. Site response studies were carried out by conducting the experimental test of Nakamura type studies and receiver function type studies. The predominant frequency and peak amplification maps were developed and presented. The vulnerability and risk analyses have been carried out and second level microzonation map and preliminary seismic risk maps were produced. Figure 1 shows the final hazard map prepared for Jabalpur.

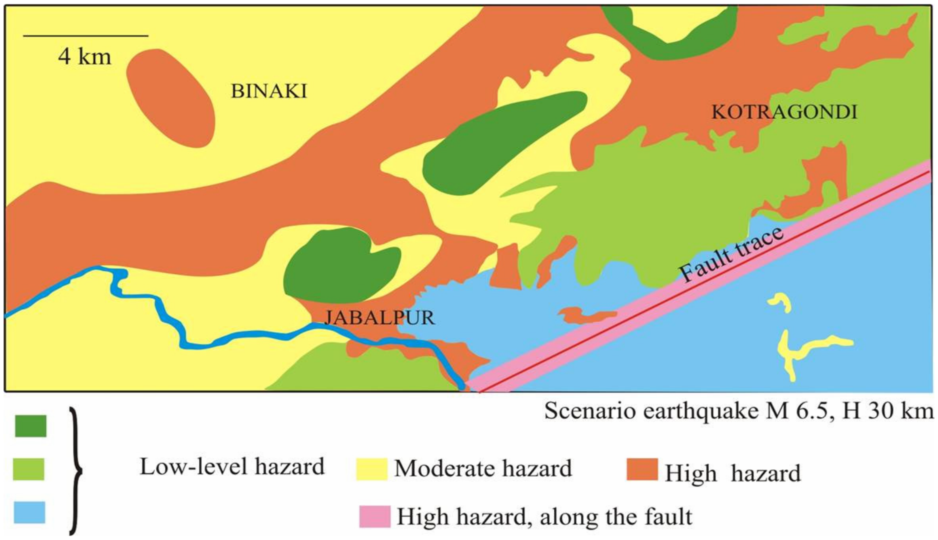


Figure 1: Final hazard map of Jabalpur (after PCRSMJUA, 2005)

Microzonation of Delhi

The Microzonation of Delhi has been carried out by a working group comprising of members from various institutions. The seismic microzonation maps prepared for Delhi on 1:50,000 scale include, base map, geology, seismotectonic, ground water, bedrock depth, site response, liquefaction susceptibility, and shear wave velocity, peak ground acceleration and seismic hazard. The area has been grouped into three hazard zones i.e. low, moderate and high. Figure 2 shows the final hazard map of Delhi (Bansal and Vandana, 2007). Iyengar and Ghosh (2004) carried out complete seismic hazard analysis by both deterministic as well as probabilistic by considering the seismotectonic parameter around 300 km radius for Delhi. They presented probabilistic seismic hazard analysis of an area of 30 km x 40 km with its centre at India Gate, Delhi city with quantified hazard map in terms of the rock level peak ground acceleration value on a grid size of 1 km x 1 km, for a return period of 2500 years. Further they also carried out site amplification and local site effects using the geotechnical borelogs and SHAKE91, presented the frequency response functions at the seventeen sites and variation of natural frequency with depth.

Rao and Neelima Satyam (2005) used computer code FINSIM, a finite fault simulation technique (Beresnev and Atkinson, 1998) to generate the PGA map at bedrock for five different sources in Delhi. A Geotechnical site characterization was carried out by using collected borehole data from various organizations. These data points were spread throughout Delhi region except in some parts of northwestern Delhi. Also site characterization of Delhi was carried out using geophysical testing at 118 sites and average shear wave velocity at 30m depth i.e., V_S30 were calculated. Estimation of soil amplification was carried out by using DEGTRA software and microzonation map for amplification was generated. The seismic response of soil was also estimated using the microtremor measurements at 185 sites in Delhi exactly at the same locations where seismic refraction and MASW testing was done. Analysis was carried out using VIEW

2002 software and the average H/V resonance spectra were obtained. Based on the shape of the resonance spectra, H/V amplitude, predominant frequency and fundamental frequency map of Delhi was presented. With the collected bore hole data, liquefaction assessment was carried out using SPT based three methods e.g. Seed and Idriss (1971), Seed and Peacock (1971) and Iwasaki et al. (1982) and using SHAKE 2000 software, the liquefaction potential map was presented (Rao and Neelima Satyam, 2007). Mohanty et al (2007) prepared a first order seismic microzonation map of Delhi using five thematic layers viz., Peak Ground Acceleration (PGA) contour, different soil types at 6 m depth, geology, groundwater fluctuation and bedrock depth, integrated on GIS platform. The integration was performed following a pair-wise comparison of Analytical Hierarchy Process (AHP), wherein each thematic map was assigned a weight in the scale of 5:1 depending on its contribution towards the seismic hazard. Following the AHP, the weightage assigned to each theme is: PGA (0.333), soil (0.266), geology (0.20), and groundwater (0.133) and bedrock depth (0.066). The thematic vector layers were overlaid and integrated using GIS.

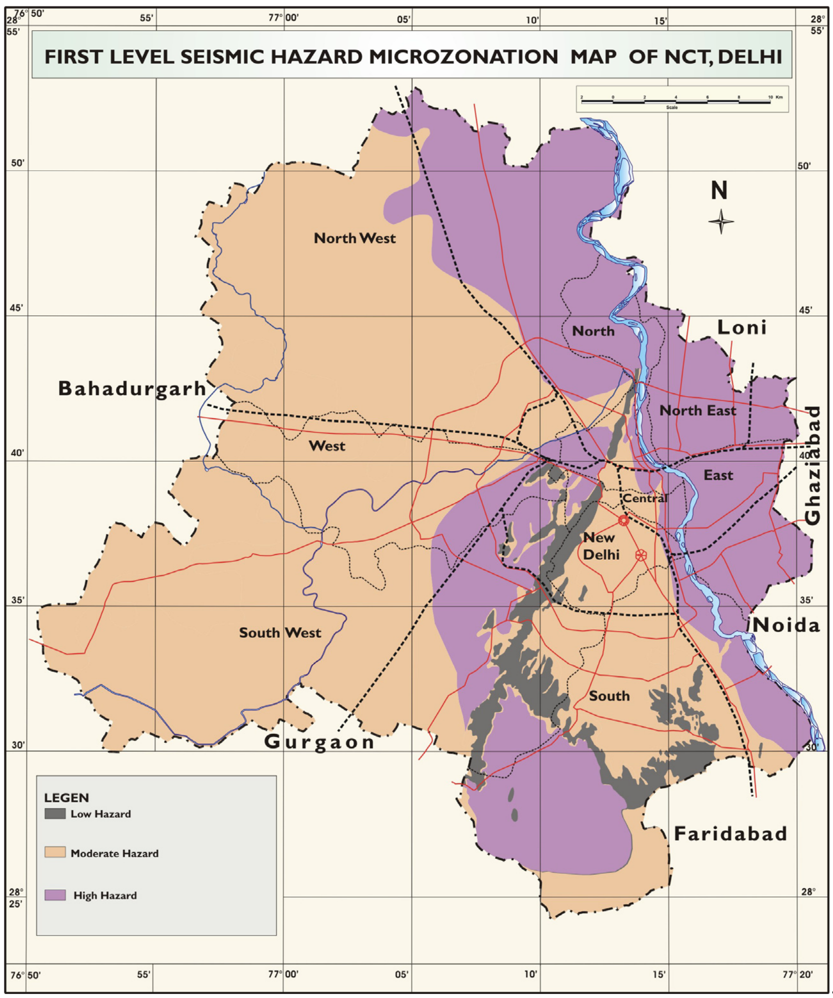


Figure 2: Final hazard map of Delhi (after Bansal and Vandana, 2007)

Seismic Hazard and Microzonation Atlas of the Sikkim Himalaya

Seismic Hazard and Microzonation Atlas of the Sikkim Himalaya was prepared by Nath (2006) from research work of seismicity of Sikkim Himalaya and microzonation of Sikkim region funded by the Department of Science & Technology. Seismic Hazard analysis was carried out deterministically by considering the seismotectonic parameters and presented maximum credible earthquake for Sikkim. Site response study analyses were carried out using the techniques receiver function and generalized inversion considering the strong motion data. Also he presented the simulation of spectral acceleration and hazard scenario assessment for Sikkim. From the above studies he developed new attenuation relation for Sikkim Himalaya, and finally he developed seismic microzonation map using geographical information system (GIS). Seismic microzonation map was presented in the form of geohazard map and quasi-probabilistic seismic microzonation index map. The geohazard map was prepared by integrating the weights and ratings of soil, surface geology, rock outcrop and land slides. Probabilistic seismic microzonation index map was prepared by integrating the weights and ratings of site response, peak ground acceleration, soil, rock outcrop and land slides. Figure 3 shows the microzonation map of Sikkim (Nath, 2007).

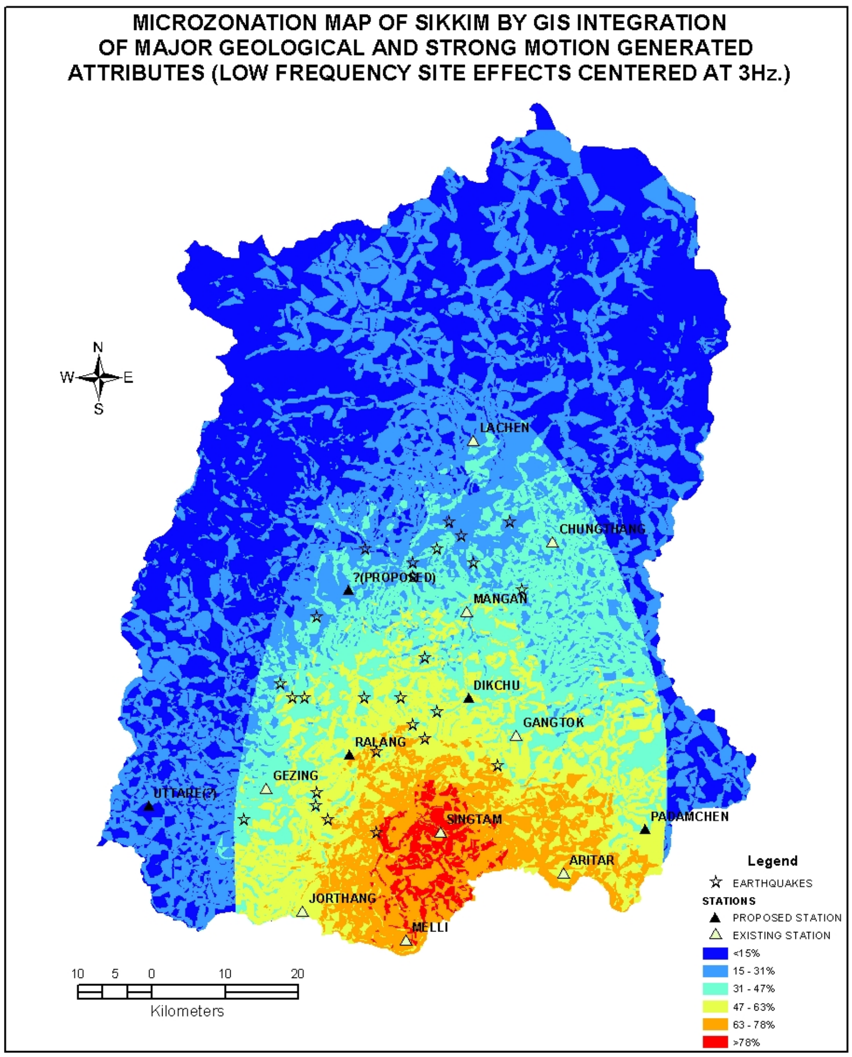


Figure 3: Microzonation Map of Sikkim (after Nath, 2007)

Seismic Microzonation of Guwahati

Baranwal et al (2005) prepared the first level microzonation map of Guwahati based on amplification of ground motion, slope of exposed rocks, shape and constituents of overburden material inferred from geophysical surveys. They categorized soil profiles in terms of their susceptibility to amplification. Where bedrock is very deep, the soil susceptibility category of the uppermost 35 m of soil profile that generally has the greatest influence on amplification was considered. The soil susceptibility categories were defined based on soil type, thickness and stiffness, which were used as a basis for defining mapping units. Considering these factors, map has been prepared which depicts the thickness of soils above bedrock based on geophysical results. The resistivity surveys were carried out and analyzed in the area. The seismic studies carried out in the area shows that Vs ranges from 166 to 330 m/s and corresponding amplification ratios varies from 3.1 to 2.2. The damage ratio (DR) calculated from these values were found to be 0.2 and 0.05.

Microzonation of Guwahati contains important maps on different themes including, geology and geomorphology, seismotectonics, soil characteristics, pre-dominant frequencies, peak ground acceleration, seismic hazard, demography and preliminary risk etc. The total area has been grouped into five zones based on the hazard index values, categorized as very high (>0.50), high (0.40-0.50), moderate (0.30-0.40), low (0.20-30) and very low (< 0.20). Most of the residential area falls in a moderate zone. Figure 4 shows the hazard index map of Guwahati (Nath, 2007).

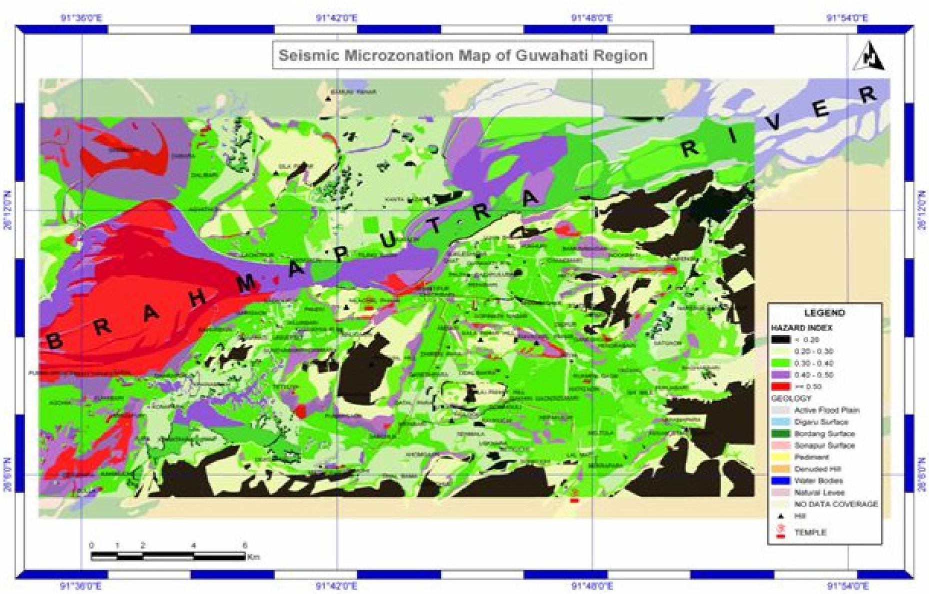


Figure 4: Hazard index map of Guwahati (after Nath, 2007)

Seismic Microzonation of Dehradun

Seismic Hazard Assessment and Site Response Study for Seismic Microzonation of Dehradun were initiated by the International Institute for Geo-Information Science and Earth Observation Enschede, Netherlands with Indian Institute of Remote Sensing, National Remote Sensing Agency (NRSA), Department of Space, Dehradun, India. The Seismic microzonation of Dehradun was carried out has three components by Anusuya Barua (2005), Rajiv Ranjan (2005) and Brijesh Gulati (2006).

Anusuya Barua (2005) acquired, interpreted, compiled and analyzed information on geology and geomorphology of Doon valley in regional scale and subsurface strata at local scale for Dehradun city to aid study of seismic hazard assessment and seismic microzonation for ground shaking at specific site. The database generated for the seismic microzonation contains information on lithology, tectonic, landforms and associated neotectonics activity in regional scale as well as subsurface information in city part. These data of geological and geomorphological information has been used for study of seismic hazard assessment, liquefaction hazard modelling and seismic microzonation.

Rajiv Ranjan (2005) carried out the field study at 31 locations and measured shear wave velocity and soil thickness using MASW. Measured shear wave velocities of different sites were compared with tube well lithologs and local geology. Then he used SHAKE2000 program with measured shear wave velocity and recorded ground motion for the site response study of Dehradun. Also he developed microzonation spectral acceleration map of Dehradun at different frequency (see Figure 5).

Brijesh Gulati (2006) carried out the earthquake risk assessment (ERA) of buildings using HAZUS program in Dehradun, India. The HAZUS is one of the ERA tools developed in the United States, which assesses the earthquake loss for the built environment and population in urban areas. He has analyzed the applicability of HAZUS model for the assessment of earthquake risk of buildings in India. He highlighted shortcomings in the HAZUS approach for using it in India and suggested modifications in terms of parameters to fill the gaps identified and to find the strength of using this model in India.

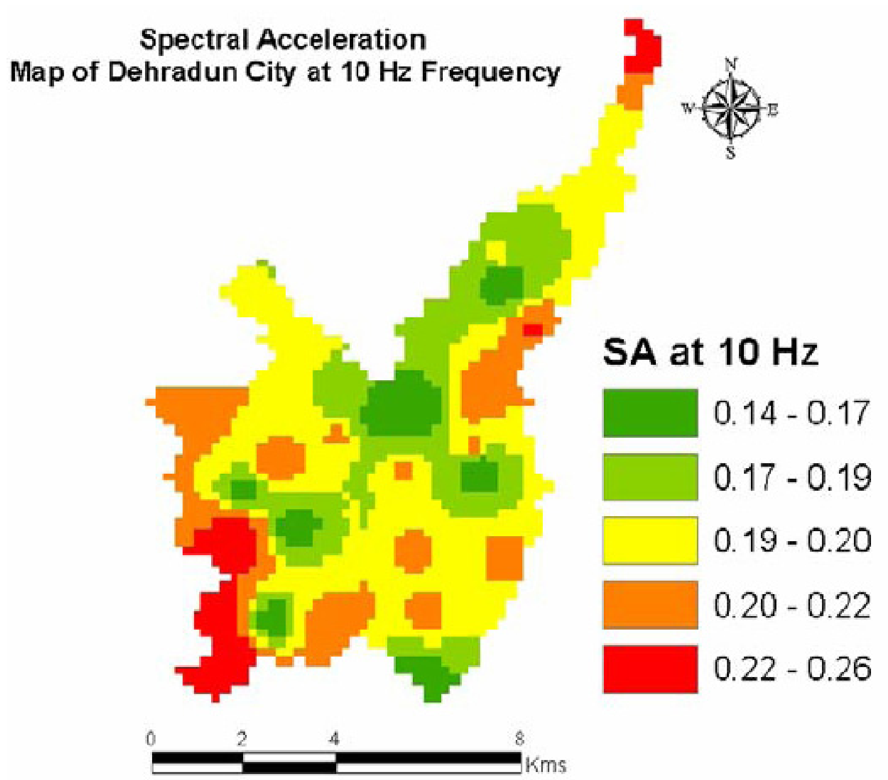


Figure 5: Spectral acceleration map of Dehradun (after Rajiv Ranjan, 2005)

Seismic Hazard Estimation for Mumbai City

RaghuKanth and Iyengar (2006) estimated the seismic hazard of Mumbai city using state-of-the-art probabilistic analysis considering the uncertainties in the seismotectonic details of the region. They developed design spectrum by incorporating uncertainties in location, magnitude and recurrence of earthquakes. Influence of local site condition was accounted by providing design spectra for A, B, C and D-type sites separately. They highlighted that the results presented can be directly used to create a microzonation map for Mumbai.

Ongoing Seismic Microzonation Studies of Other Cities in India

The Department of Science & Technology, New Delhi initiated the seismic microzonation of Bhuj, Kachchh, Ahmedabad, Chennai and Kochi. These projects are ongoing, which are briefly presented below.

As a part of the microzonation studies in Bhuj, after 2001 earthquake many studies are undertaken to understand the seismotectonic of regions, installation of arrays of strong motion and broad band seismographs, site response studies, liquefaction studies, etc. In particular, Mandal et al (2005), Parvez and Madhukar (2006), Trivedi et al (2006) and Mohanty (2006) are working towards microzonation of Bhuj, Kachchh and Ahmedabad based on microtremor survey. Mandal et al (2005) estimated the site response in Kuchchh region using H/V ratio of the aftershocks. Parvez and Madhukar (2006) presented the preliminary results on site-effects and shear wave velocity structures of sub-surface soil using microtremor arrays at twenty different sites in Ahmedabad. They highlighted that most of sites are having the fundamental resonance frequency of 0.6Hz and rest of them is having frequency of 2 to 6Hz using H/V spectral ratio. 1-D shear wave velocity obtained from microtremor array shows that, upper most layer having the shear wave velocity of 150-200m/s and below this 400-800m/s up to 60m depth. Trivedi et al (2006) carried out at 120 different stations and measurements were taken using velocity sensors for a period of 30 minutes at each station point by using microtremor of MR2002-CE vibration monitoring system. These tests were carried out exactly at the same locations where seismic refraction and MASW testing were conducted to study the detailed site response. Horizontal versus vertical (H/V) spectra using Nakamura method was estimated using VIEW 2002 software and compared with seismic refraction and MASW testing results. Mohanty (2006) carried out extensive study on identification and classification of seismic sources in the Kachchh and geological/ geophysical database was prepared using remote sensing and other conventional data sets (IRS WiFS, LISS-III & PAN images). Analyses and studies of the geological map of the region was used to establish empirical seismic attenuation model for Kachchh. Further, the authors computed probabilistic peak ground acceleration (PGA) values of the region. These PGA values computed for individual faults were superimposed to prepare a combined hazard zonation map of the area. They also planned to prepare a detailed seismic microzonation maps taking into account liquefaction.

Suganthi and Boominathan (2006) studied the site response behavior of Chennai soils as part of seismic hazard and microzonation of Chennai. They carried out the seismic hazard and site response study using SHAKE 91 and borelog information collected. They highlighted that the ground response analysis indicates that the occurrence of amplification is only in the low range of frequencies below 0.8Hz based on analysis at few regions in the study area.

Center for Earth Science Studies planned seismic Microzonation of Kochi city, in GIS environment. It is planned to use site response by measuring ambient noise (microtremor) with the help of a City Shark seismic recorder and triaxial 3- component 1s geophones and to relate the responses (ground amplification) with the available information on geology, geomorphology, lineament patterns, soil type/ lithology, structural features, earthquakes etc. in the region.

SEISMIC MICROZONATION ISSUES RELATED TO INDIA

Seismic microzonation in India was initiated in 2001. Even after seven years Indian seismic microzonation works has many problems, which needs to be properly addressed. These issues can be broadly classified into three major groups: seismology related, Grade and geology related and geotechnical related issues.

Issues related to seismology: Issues related seismology is the preparation of regional seismotectonic map and estimation of seismic hazards:

Preparation of seismotectonic map for the study area

Most of the microzonation works in India does not have a complete seismotectonic map. It is very much essential that before starting the microzonation work a detailed seismotectonic map for the study area need to be prepared. A seismotectonic map has to be prepared by considering up to date seismicity, geological and seismotectonic details for a circular area of radius 300km (approximately 200miles) around the study area as per Regulatory Guide 1.165(1997). This map can be used for the detailed hazard estimation.

Seismic hazard estimation

So far most of seismic microzonation maps published in India is based on the deterministic seismic hazard analysis by considering scenario earthquake. But seismic microzonation hazard estimation need to consider uncertainties involved in the earthquake and produce the hazard map with required probability and return periods. Hence, special attention may be given to the probabilistic seismic hazard estimation, where the uncertainty is quantified and hazards are represented with required probability exceeded in particular years.

Grade and Geology: The grade/level of the seismic microzonation maps is desired based on scale of the study and method of estimating hazard parameters as suggested by the TC4 committee of ISSMGE (1993). Geology is considered for initial stage of the seismic microzonation mapping. Most of the seismic microzonation maps produced in India, has given more importance to the geology. But recently, it is proved that considering the geological units as the only criteria in seismic microzonation is not appropriate (Ansal et al., 2004). It is also highlighted that geology map may be regarded as the basic information to plan detailed site investigations and to control the reliability of the results obtained by site characterizations and site response analyses.

Geotechnical Issues: Like hazard estimations, another key issue in the seismic microzonation is the estimation of effects of earthquake. Basically earthquake effect can be grouped as two major groups, site effects and induced effects. These effects are based on geotechnical properties and behavior during the earthquake of the subsurface materials. Hence, more importance needs to be given to the geotechnical properties rather then geology. Case studies summarized above shows that, geotechnical properties are not handled properly in India for assessing the site and induced effects. Site effects are combination of soil and topographical effects, which can modify the characteristics (amplitude, frequency content and duration) of the incoming wave field. Most of the Indian seismic microzonation studies show that the modification of waves is estimated using average 30m shear wave velocity (V_S^{30}) irrespective of locations. This practice needs to be completely revised, because V_S^{30} is not a standard parameter to reflect the site effects. Pitilakis (2004) shows inability of the V_S^{30} for estimation of site amplification of soil layers. Particularly large amplifications of the deep incident wave field are practically absent when amplifications are computed using the transfer ratio for shallower depths. The authors have also proved that use of V_S^{30} as a basis for site amplification is misleading in many cases. Hence it is necessary to use actual engineering rock depth (shear wave velocity more than 760 m/s) rather than V_S^{30} for amplification study. Another major issue is the estimation of induced effects such as liquefaction hazard and land slide hazard. Most of case studies summarized above shows that liquefaction hazard was estimated using the simple, outdated correlations and attenuation relation with out much of local geotechnical knowledge. It is always recommended the liquefaction hazard has to be estimated based on recent knowledge in earthquake geotechnical engineering. Most of the land slide hazards in seismic microzonation studies in India were estimated based on geological knowledge, but it requires detailed geotechnical inputs for precise mapping of landslide possible area during earthquake.

In this paper an attempt has been made to handle the above issues properly in the case study of seismic microzonation of Bangalore and to generate the final hazard index maps based on both deterministic as well as probabilistic approaches. A detailed microzonation study of Bangalore is summarized in the following sections.

SEISMIC MICROZONATION OF BANGALORE: A CASE STUDY

The area of study is limited to Bangalore Metropolis area (Bangalore Mahanagar Palike) of about 220 km^2. Bangalore is situated on a latitude of 12^o 58' North and longitude of 77^o 36' East and is at an average altitude of around 910m above mean sea level (MSL). For the seismic microzonation study, the base map is prepared using geographical information system (GIS) with several layers of information in ArcGIS 9.2. Some of the important layers considered are the boundaries (Outer and Administrative), Highways, Major roads, Minor roads, Streets, Rail roads, Water bodies, Drains, Landmarks and Bore locations. Study area with selected geotechnical boreholes for ground response analysis along with location of Bangalore in India map is shown in Figure 6.

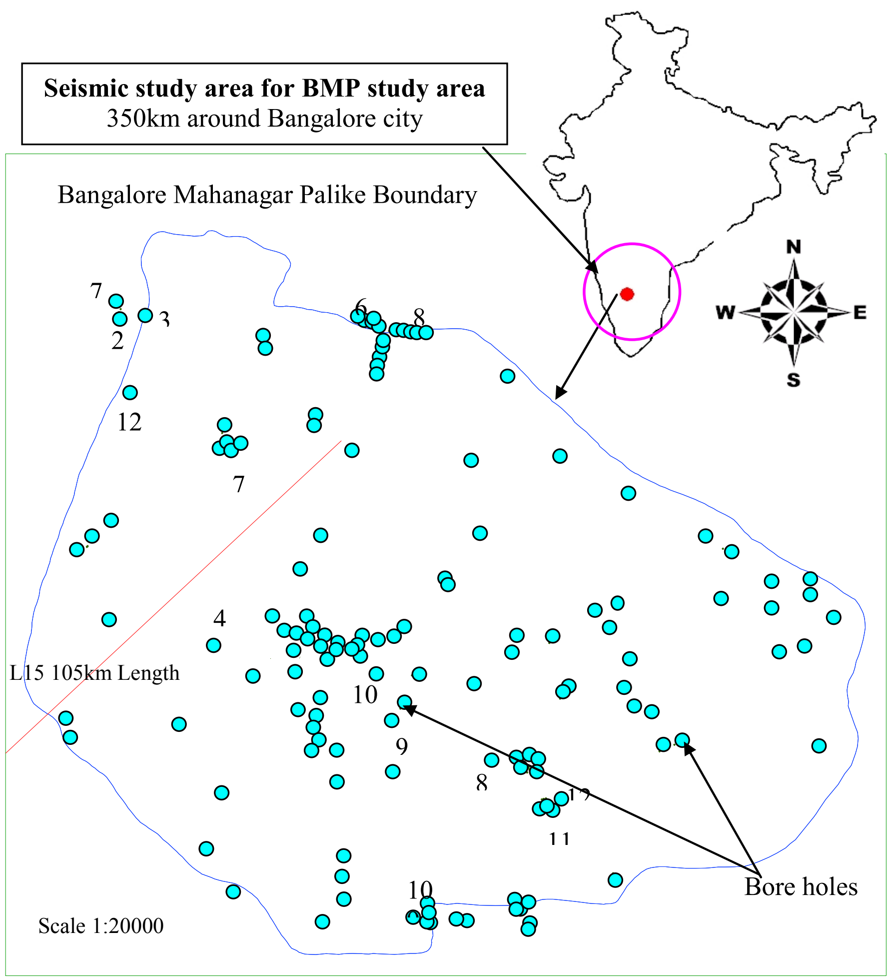


Figure 6: Study with borehole locations used for site response study

The present investigation was carried out with a scale of 1:20,000 and ground motions are arrived based on the detailed geotechnical/geophysical investigations and ground response analysis. Hence, this study can be graded as grade III (Level III) seismic microzonation. A generalized methodology has been formulated by considering essential five steps for seismic microzonation suitable for flat terrain, where landslide, tsunami possibilities are remote. The steps followed in seismic hazard and microzonation of Bangalore in the present investigation is illustrated in the form of a flow chart in Figure 7. The first step illustrates the assessment the expected ground motion using the deterministic and probabilistic seismic hazard analysis. The site characterization for the study area is done at local scale of 1:20,000 using geotechnical and shallow subsurface geophysical data and is discussed in the next step. Third step is the study of local site effects using first and second part output data and producing the ground level hazard parameters maps. Fourth step is the assessment of induced site effects such as liquefaction, land instability and Tsunami. Due to remote possibilities of land slides and Tsunami, figure 7 shows only the assessment of liquefaction potential in terms of factor of safety against liquefaction for fourth step. The fifth step shows the integration of hazard parameters and preparation of final seismic microzonation map using GIS.

SEISMIC HAZARD ANALYSIS

Seismic hazard analyses involve the quantitative estimation of ground shaking hazards at a particular area. Seismic hazards can be analyzed deterministically for a particular earthquake scenario, or probabilistically, in which uncertainties in earthquake size, location, and time of occurrence are explicitly considered (Kramer, 1996). A critical part of seismic hazard analysis is the determination of Peak Ground Acceleration (PGA) and response acceleration (spectral acceleration) for an area/site. Spectral acceleration (Sa) is preferred for the design of civil engineering structures. It is an accepted trend in engineering practice to develop the design response spectrum for the different types of foundation materials such as rock, hard soil and weak soils. To evaluate seismic hazards for a particular site or region, all possible sources of seismic activity must be identified and their potential for generating future strong ground motion should be evaluated. Analysis of lineaments and faults helps in understanding the regional seismotectonic activity of the area. The recent seismic activity of Bangalore has been studied based on the seismic sources and earthquake events in the area. A new seismotectonic map has been prepared by considering all the earthquake sources such as faults, lineaments, and shear zones.

Seismicity and seismotectonic map

Seismic study area having a circular area of radius 350km has been selected for the seismicity study as per Regulatory Guide 1.165(1997). Regional, geological and seismological details for the seismic study area have been collected by using available literature, study of maps, remote sensing data. Seismotectonic details include geology, rock type, fault orientation with length, lineaments with lengths, shear zones with length and seismic earthquake events. The seismic study area for microzonation area marked in the India map is shown in Figure 6. The seismic study region is a circular area having the center point as Bangalore city with a radius of 350km (which covers the latitude 9.8^{o}N to 16.2^{o}N and longitude of 74.5^{o}E to 80.7^{o}E). Seismic study area covers major part of the Karnataka state, northern part of Tamil Nadu state, portion of Kerala and Andhra Pradesh states.

Seismicity of an area is the basic issue to be examined in seismic hazard analysis for evaluating seismic risk for the purpose of microzonation planning of urban centers. Detailed knowledge of active faults and lineaments and associated seismicity is required to quantify seismic hazard and risk. Indian peninsular shield, which was once considered to be seismically stable, has shown that it is quite active. Seismicity of India and Peninsular India has been addressed by many researchers in particular Kaila et al, (1972), Chandra (1977),

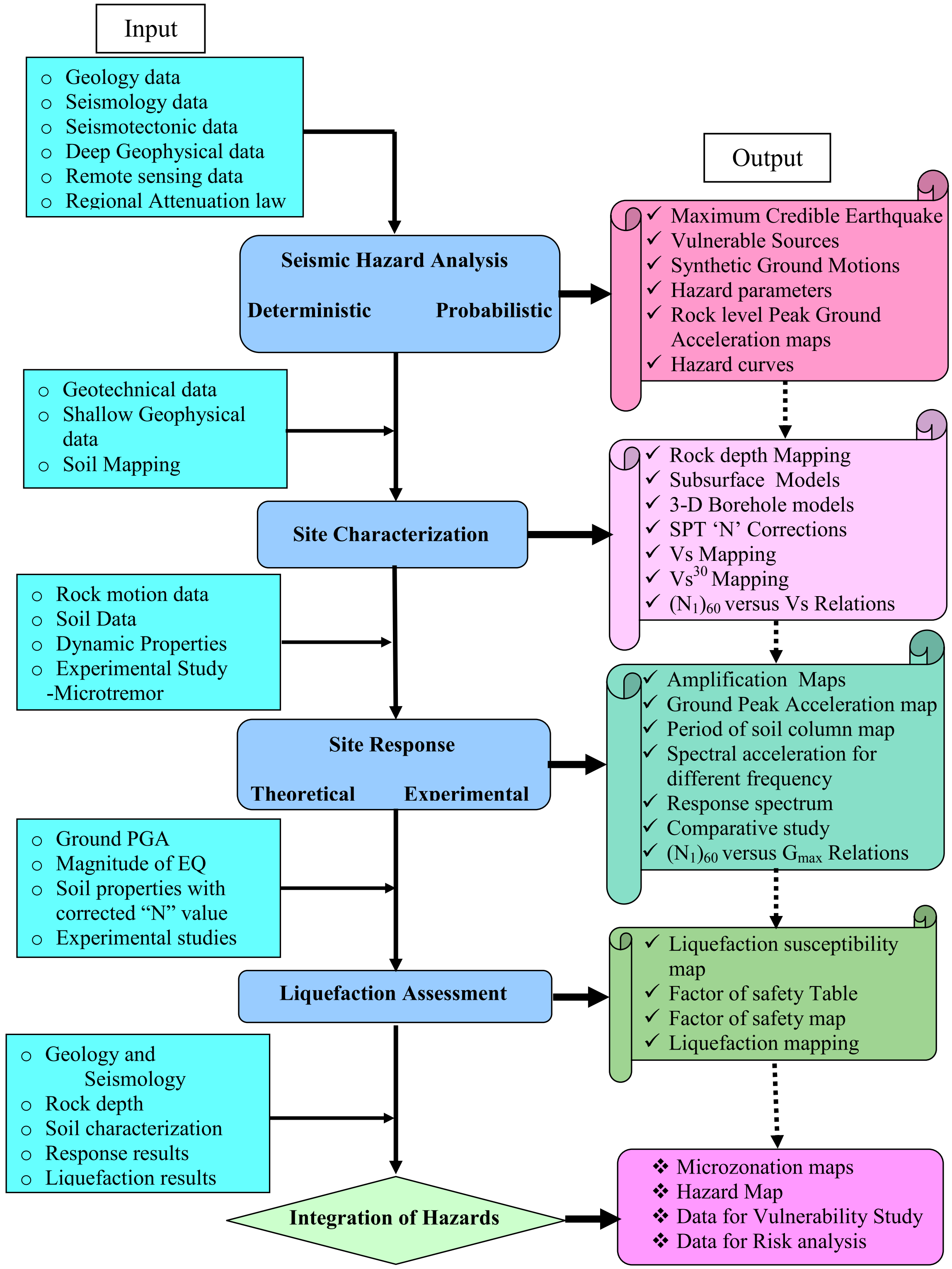


Figure 7: Flow chart for seismic microzonation

Ramalingeswara Rao and Sitapathi Rao (1984), Tandon (1992), Khattri (1992), SEISAT, (2000), Parvez et. al, (2003), Bilham (2004), and Iyengar and Raghu Kanth (2004). As per BIS 1893 (2002), study area falls in the upgraded zone III and zone II in the seismic zonation map of India. Srinivasan and Sreenivas (1977), Valdiya (1998), Purnachandra Rao (1999), Ramalingeswara Rao (2000), Subrahmanya (2002 and 1996), Ganesha Raj (2001), Sridevi Jade (2004), Ganesha Raj and Nijagunappa (2004), Sitharam et. al (2006) and Sitharam and Anbazhagan (2007) highlight that seismic activity in the peninsular India is increased when compared to the past. Most of the seismic data comes from Gouribidanur seismic array (GBA) and the GBA data is widely used for evaluating seismotectonic parameters in southern India (Arora, 1971; Krishna and Ramesh, 2000; Tseng and Chen, 2006).

Srinivasan and Sreenivas (1977) have used field studies of bore well yield data and discussed the reactivation of dormant or inactive lineaments inducing seismicity in relative stable terrains of the continents. Purnachandra Rao (1999) highlighted the occurrence of earthquakes in last few decades due to enhanced seismic activity in the interior of the Indian Plate which results from pre-existing faults under the influence of the ambient stress field due to the India-Eurasia plate collision forces, oriented NS to NNE. Ramalingeswara Rao (2000) carried out strain rate and heat flow study in southern India and characterized as medium to low seismicity region. Subrahmanya (2002 and 1996) highlights that the entire study area is becoming seismically active due to the up warp of Mulki-Pulicat Lake (MPL) axis which connects 13^{o}N in west to 13.4^{o}N in east. He concludes that there is a lot of seismic activity around this Mulki-Pulicat Lake axis and in particular he highlights that micro to meso-seimicity to the south and mega seismicity to the north of the MLP axis. In recent years much of the seismic activity in the state of Karnataka has been in the south, in the Mysore-Bangalore region (Ganesha Raj and Nijagunappa, 2004). Recently, Sridevi Jade (2004) has estimated the plate velocity and crustal deformation in the Indian subcontinent using GPS measurements. The authors conclude that southern peninsular India consists of large zones of complex folding, major and minor faults and granulite exposures, and this region cannot be classified as an area of low seismic activity. All these authors highlight that the seismic activity of the south India has shown an increasing trend.

Seismic data collected from various agencies [United State Geological Survey (USGS), Indian Metrological Department (IMD), New Delhi; Geological Survey of India (GSI) and Amateur Seismic Centre (ASC), National Geophysical Research Institute (NGRI),Hyderabad; Centre for Earth Science Studies (CESS), Akkulam, Kerala and Gauribindanur (GB) Seismic station] contain information about the earthquake size in different scales such as intensity, local magnitude or Richter magnitude and body wave magnitudes. These magnitudes are converted to moment magnitudes (Mw) to achieve the status of the uniform magnitude by using magnitude relations given by Heaton et al., (1986). The earthquake events collated are about 1421 with minimum moment magnitude of 1.0 and a maximum of 6.2. About 1421 earthquakes have been collated and their magnitudes were converted to moment magnitude scale. The data set contains 394 events which are less than moment magnitude 3, 790 events from 3 to 3.9, 212 events from 4 to 4.9, 22 events from 5 to 5.9 and 3 events which are more than moment magnitude 6. Maximum earthquake magnitude out of about 1421 events reported in the study area is 6.2. Out of 1421 seismic data, about 1340 data was collected from the record of Gauribidanur seismic array (GBA), which is in operation for long time, having geographic coordinates of the array center point, 13^{o}36'15''N, 77^{o}26'10"E. GBA seismic station is about 85km away from the center of the study area. The GBA has an L-shaped configuration with dimensions of about 22 x 22 km^2 and a tight station interval of about 2.5 km (see Figure 8). Data set is unique; it is the only array data available in the public domain to study seismic properties of the south India. GBA data is widely used for evaluating seismotectonic parameters in south India in particular by Arora(1971) for earth's crust study, Krishna and Ramesh (2000) for the study of propagation of crustal wave guide characteristics, Tseng and Chen (2006) for profiling P-Wave receiver-function for south

India. Seismic data collected from 1977 to 1995 from GBA is used for this study. Other agencies have been established seismic stations recently and data for the last 10 years are also collected and used in this study. On January 29th of 2001, earthquake of magnitude 4.3 in Richter scale hit the Mandya area, its epicenter was about 65 km southwest of Bangalore. More than 50 buildings are reported to be damaged at Harohalli/ Kanakapura. It caused widespread panic in Bangalore and schools were closed. Minor damages are reported at Austin town and airport road in Bangalore. Even the Killari earthquake of 30th September 1993 and Bhuj earthquake 2001 were felt in Bangalore. Sumatra earthquake of 2004 had triggered tremors of intensity IV in Bangalore.

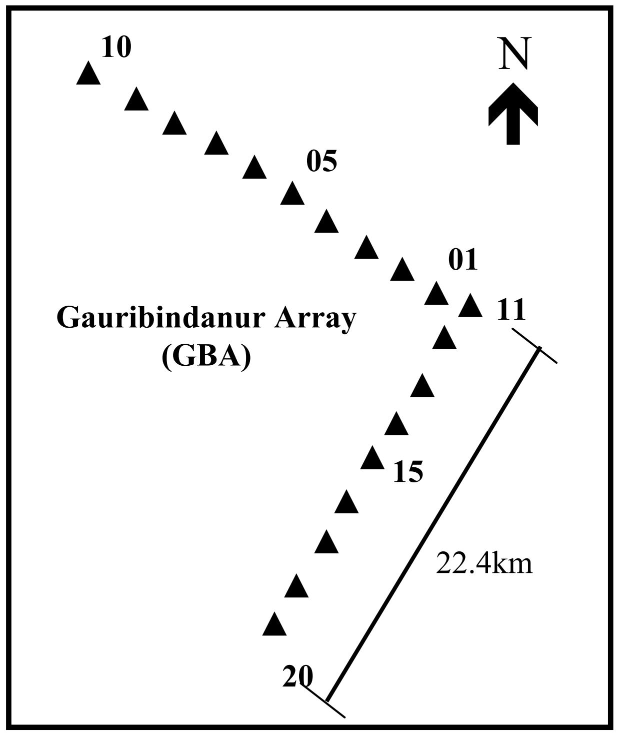


Figure 8: Pattern of the location of receivers in Gauribindanur Array.

The well defined and documented seismic sources are published in the Seismotectonic Atlas-2000 published by Geological Survey of India. Geological survey of India has compiled all the available geological, geophysical and seismological data for entire India and has published a seismotectonic map in 2000. Seismotectonic atlas (SEISAT, 2000) contains 43 maps in 42 sheets of $3^o x 4^o$ sizes with scale of 1:1 million, which also describes the tectonic frame work and seismicity. SEISAT is prepared with intention that it can be used for the seismic hazard analysis of Indian cities. In this analysis about 6 SEISAT maps are merged, seismic sources are digitalized with in the seismic study area to prepare seismotectonic map. Seismicity and activity of the plate tectonic will always change based on neotectonic activity of the region. Thus it is necessary that any seismic hazard should include recent seismicity. An extensive literature has been carried out to collect seismic sources from recent publications. Ganesha Raj and Nijagunappa (2004) have mapped major lineaments of Karnataka State with length more than 100 km using satellite remote sensing data and correlated with the earthquake occurrences. They have highlighted that there are 43 major lineaments and 33 earthquake occurrences with magnitude above 3 (since 1828) in the State. About 23 of these earthquakes were associated with 8 major lineaments, which they have named as active lineaments. The Mandya-Channapatna-Bangalore lineament, Lakshman Thirtha-KRS-Bangalore lineament, and Chelur-Kolar-Battipalle lineament are some of the seismically active lineaments identified by the authors. They have also stated that earthquakes are confined to the southern part of the state indicating that south Karnataka is seismically more active. The authors have also recommended the need to upgrade the seismic zonation map of Karnataka especially for areas surrounding Mandya, Bangalore, and Kolar. Karnataka lineaments published by Ganesha Raj and Nijagunappa (2004) using remote sensing data are also considered in the present study.

The sources identified from SEISAT (2000) and remote sensing studies are compiled and a seismotectonic map has been prepared using Adobe Illustrator version 9.0. The seismotectonic map contains 65 numbers of faults with length varying from 9.73 km to 323.5km, 34 lineaments and 14 shear zones. The converted earthquake events have been super imposed on source map with available latitudes and longitudes. The earthquake events collated are about 1421 with minimum moment magnitude of 1.0 and a maximum of 6.2 and earthquake magnitudes are shown as symbols with different shape and colours. Seismotectonic map showing the geology, geomorphology, water features, faults, lineaments, shear zone and past earthquake events has been prepared for Bangalore which is as shown in Figure 9. From the Figure 9, there are cluster of earthquakes having a moment magnitude (Mw) of 2 to 2.9 found at intersection of 10.8^o N and 76.9^o E, 12.5^o N and 76.5^o E, 13.0^o N and 76.5^o E, 14.3^o N and 78.0^o E and 14.5^o N and 78.6^o E. Mw of 3.to 3.9 at more frequently occurred at intersection of 15.1^o N and 76.8^o E, Mw of 4-4.9 distributed through out the study area and clustered at two locations (13.2^o N and 75.1^o E and 15.1^o N and 76.6^o E). The range of 5 to 5.9 randomly distributed in the study area and reported close to the study area. Magnitude 6 and above (3 events) are reported around Coimbatore and Bellary within the study area.

Deterministic seismic hazard analysis

Deterministic Seismic Hazard Analysis (DSHA) for Bangalore has been carried out by considering the past earthquakes, assumed subsurface fault rupture lengths and point source synthetic ground motion model. Source magnitude for each source is chosen from the maximum reported past earthquake close to that source and shortest distance from each source to Bangalore is arrived from the newly prepared seismotectonic map. Using these details and regional attenuation relation developed for southern India by Iyengar and Raghukanth (2004), the peak ground acceleration (PGA) has been estimated. The analysis shows that the minimum PGA value is 0.001g and maximum PGA value is 0.146g (caused from Mandya-Channapatna-Bangalore lineament, see L15 in Figure 9). Totally 10 sources have generated higher PGA values close to Bangalore. Among the 10 sources, the active lineament of Mandya-Channapatna-Bangalore lineament having a length of about 105km (which is 5.2km away from the Bangalore city center) causing a PGA value of 0.146g due to an earthquake event (Mw of 5.1 occurred on 16th May 1972; corresponds to a latitude of 12.4oN and longitude of 77.0oE). This is a measured earthquake event having a surface wave magnitude (ms) of 4.6. To estimate the expected magnitude for seismic source, a parametric study has been carried out to find subsurface rupture length of the fault using past earthquake data and Wells and Coppersmith (1994) relation between the subsurface lengths versus earthquake magnitudes. About more than 60% of earthquake magnitude matches with the subsurface length corresponding to 3.8% of the total length of fault. The expected maximum magnitude for each source has been evaluated by assuming that the seismic source can be ruptured at subsurface level for a length of 3.8% of the total length of source. The expected magnitude calculated matches well with occurred earthquake for many sources. Expected magnitude are lower (in the range of 0.5 to 1.5) than occurred magnitude for 12% of the total sources and higher than (in the range of 0.5 to 1.5) occurred magnitude for 25% of the total sources. In general, estimated magnitudes are lower for the larger occurred magnitudes (>5.7) and higher for the smaller occurred magnitudes (<4.6). The PGA for Bangalore has been estimated using expected magnitudes and regional attenuation relation. The

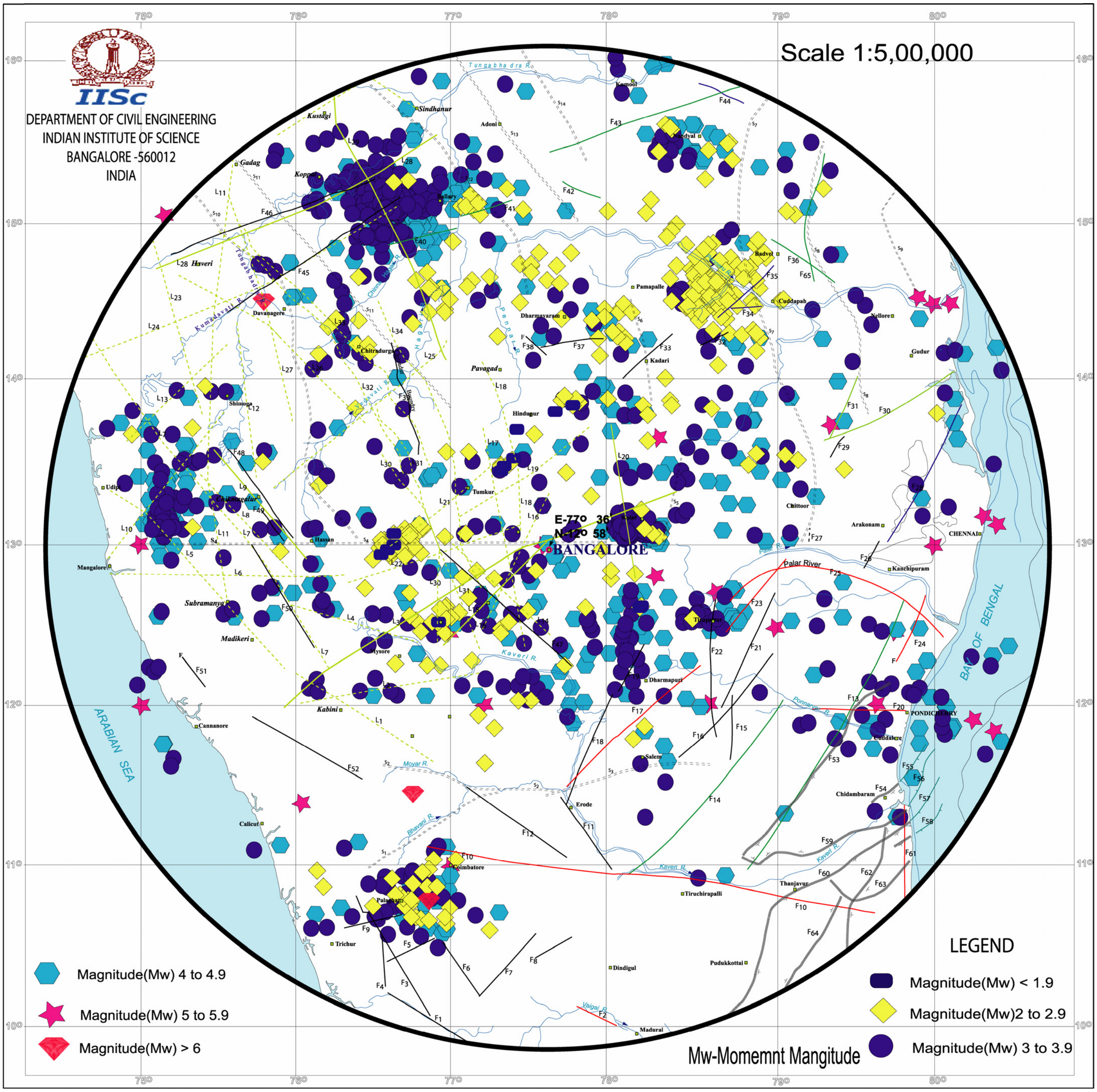


Figure 9: Seismotectonic map of Bangalore and surroundings

estimated PGA using expected magnitude varies in between 0.001g to 0.153g. In total, 9 sources have generated PGA values of more than 0.045g at rock level for Bangalore region. Among the nine sources, 3 sources have generated considerably higher PGA values for Bangalore, (i) the Arkavati fault (F47 in Figure 9) which is 51.24km away from Bangalore and having a length of about 125km gives PGA of 0.047g (0.025g for occurred earthquake). (ii) Chelur-Kolar-Battipalle Lineament (L20 in Figure 9) having a length of about 111 km, which is 57.6km away from Bangalore causing a PGA value of 0.038g (0.037g for occurred earthquake). (iii) Mandya-Channapatna-Bangalore lineament having a length of about 105km which is 5.2km away from

Bangalore causing a PGA value of 0.153g (0.146g for occurred earthquake). This study shows that expected magnitude of Mw 5.1 is close to L15 causing maximum PGA to Bangalore and hence this magnitude is considered as maximum credible earthquake for Bangalore. Microzonation requires the estimation of site effects for a maximum earthquake estimated arrived from hazard analysis. To study the effects of earthquake in the local scale level, the particular earthquake record/ground motion in the form of time series is required. For the area having poor seismic record, synthetic ground motion models is the alternative. In this study, seismological model developed by Boore (1983, 2003), SMSIM program, has been used to generate synthetic ground motions considering regional seismotectonic parameters, more details found in Sitharam and Anbazhagan (2007). Considering seismogenic source L15 and MCE of 5.1, the synthetic ground motions are developed corresponding geotechnical and geophysical test locations. The rock level PGA has been arrived from the synthetic ground motions developed at 653 locations in the BMP area. Using these PGA values at rock level PGA map has been prepared, which is as shown in Figure 10. The rock level PGA values determined from model matches well with the regional attenuation relation and shape of the synthetic spectral acceleration matches with the shape of uniform hazard spectrum.

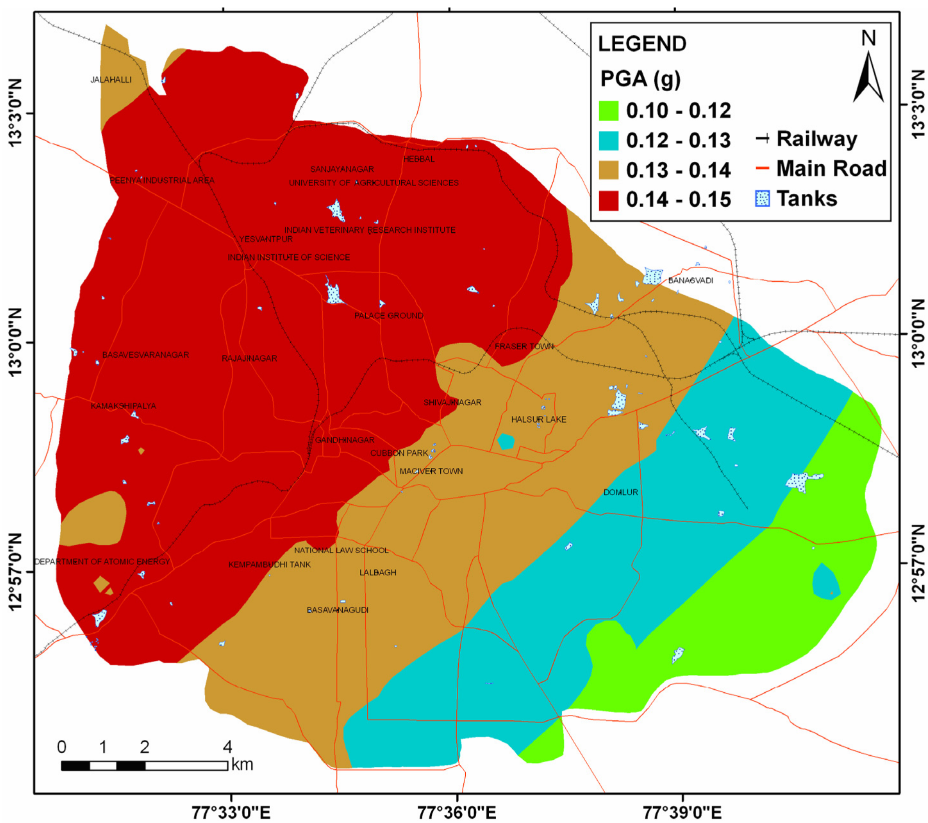


Figure 10: Peak ground acceleration map using DSHA

Probabilistic seismic hazard analysis

Even though DSHA gives the higher PGA based on the seismogenic source and MCE, it does not consider the uncertainty involved in distance, size of magnitude and attenuation relation and also it is not developed for a specific return period. Hence this section presents estimation of PGA using the probabilistic approach, which includes effects of all the earthquakes expected to occur at different locations during a specified life period which are considered along with associated uncertainties and randomness of earthquake occurrences and attenuation of seismic waves with distance. The probabilistic seismic hazard analysis evaluates the hazard in terms of composite probability distribution functions for a selected strong ground motion at a site of interest due to all the earthquakes expected to occur during a specified exposure period in the area around the site. PSHA is the most commonly used approach to evaluate the seismic design load for the important engineering projects. PSHA method was initially developed by Cornell (1968) and its computer form was developed by McGuire (1976 and 1978) and Algermissen and Perkins (1976). McGuire developed EqRisk in the year 1976 and FRISK in the year 1978. Algermissen and Perkins (1976) developed RISK4a, presently called as SeisRisk III. Site ground motions are estimated for selected values of the probability of ground motion exceedance in a design period of the structures or for selected values of annual frequency or return period for ground motion exceedance. The probabilistic approach offers a rational framework for risk management by taking account of the frequency or probability of exceedance of the ground motion against which a structure or facility is designed. The occurrence of earthquakes in a seismic source is assumed as the Poisson distribution. The probability distribution is defined in terms of the annual rate of exceeding the ground motion level *z* at the site under consideration ($\nu(z)$), due to all possible pairs (M, R) of the magnitude and epicentral distance of the earthquake event expected around the site, considering its random nature. The probability of ground motion parameter at a given site, *Z*, will exceed a specified level, z, during a specified time, *T* and it is represented by the expression:

$$P(Z > z) = 1 - e^{-\nu(z)T} \leq \nu(z)T \qquad (1)$$

Where $\nu(z)$ is (mean annual rate of exceedance) the average frequency during time period *T* at which the level of ground motion parameters, *Z*, exceed level *z* at a given site. The function $\nu(z)$ incorporates the uncertainty in time, size and location of future earthquakes and uncertainty in the level of ground motion they produce at the site. It is given by:

$$\nu(z) = \sum_{n=1}^{N} N_n(m_0) \int_{m=m^0}^{m^u} f_n(m) \left[\int_{r=0}^{\infty} f_n(r \mid m) P(Z > z \mid m, r) dr \right] dm \qquad (2)$$

Where N_n (m_0) is the frequency of earthquakes on seismic source *n* above a minimum magnitude m^0 that is taken as 4.0 in this work (magnitude less than 4 is considered to be insignificant). $f_n(m)$ is the probability density function for minimum magnitude of m^0 and maximum magnitude of m^u; $f_n(r|m)$ is the conditional probability density function for distance to earthquake rupture; $P(Z>z|m, r)$ is the probability that given a magnitude '*m*' earthquake at a distance '*r'* from the site, the ground motion exceeds level *z*.

Recurrence relation for the region

Seismic data used in DSHA has been considered for the completeness analysis and to develop recurrence relationship. The seismic data completeness analysis has been carried out using Stepp (1972). For each magnitude interval the plotted points are supposed to define a straight line relation as long as the data set for the magnitude interval is complete. For a given seismic region the slope of the lines for all magnitude intervals should be same. Figure 11 shows the magnitude verse standard deviation calculated using earthquake data, it can be observed all magnitude intervals seems to be complete for last 40 years (1967-2006). The whole catalog shows that for the period 1807 to 1976, the data is poor may be due to lack of observations. However, it can be observed that moment magnitude greater than 3.5 is reported in this period. From 1976 – 1996, the better recording of the data can be observed. The data set has been divided as two parts, one historic data (1807 to 1960) and another is instrumented data (after 1960 to present) to develop the Gutenberg–Richter (1944) recurrence relation. Three recurrence relations have been developed: first one based on the historic data, second one based on the instrumented data and third one based on the total data (Anbazhagan et al.,2008). A simple and most widely used method to estimate the seismic hazard parameter ‘b’ is the Gutenberg–Richter (1944) recurrence law. It assumes an exponential distribution of magnitude and is generally expressed as:

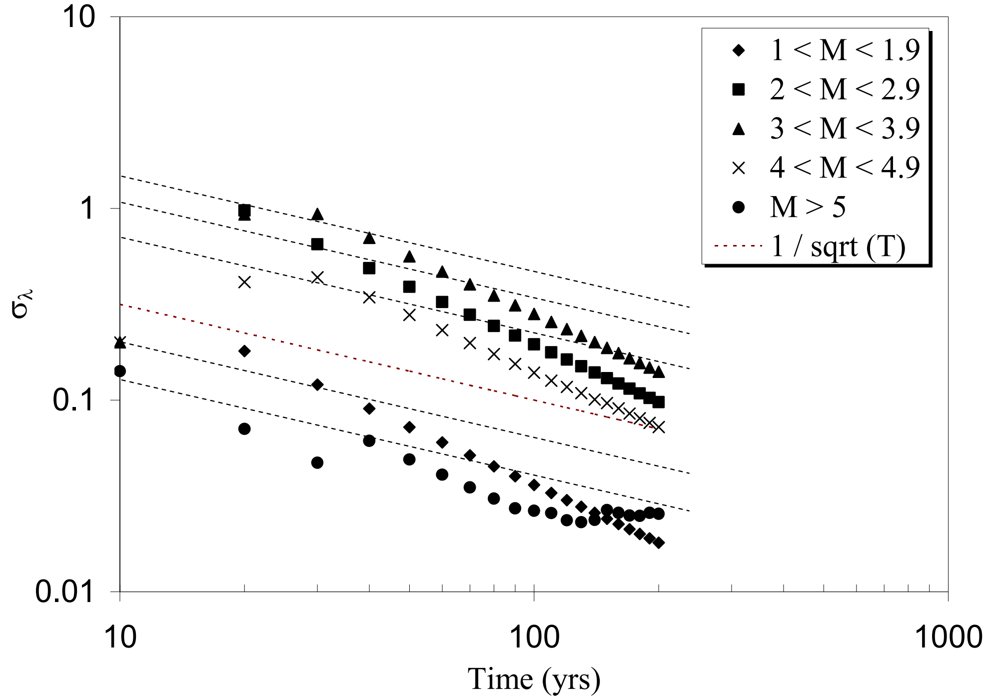


Figure 11: Variance of seismicity rate for different magnitude intervals and different lengths of moving time windows

$$LogN = a - bM \tag{3}$$

For a certain range and time interval, eq. (3) will provide the number of earthquakes, (N) with magnitude, (M). Where ‘a’ and ‘b’ are positive, real constants. ‘a’ describes the seismic activity (log number of events with M=0) and ‘b’ which is typically close to 1 is a tectonics parameter describing the relative abundance of large to smaller shocks. The number of earthquakes per decade was divided in to five magnitude ranges such as 2 = M < 3; 3 = M < 4; 4 = M < 5; M ≥ 5. The time history of historic data with the logarithm of the cumulative earthquake per year for M, where M is the magnitude in particular interval is developed for three cases by Anbazhagan et al (2008). An interval of 0.5 is taken for grouping the data while computing the ‘b’ value. Figure 12 presents the time history of historic and instrumented (total) data with corresponding frequency magnitude distribution plot which is as follows:

$$\log(N) = 3.52 - 0.86M \tag{4}$$

From the above three approaches, seismic parameter ‘b’ value of the region varies from 0.62 to 0.98. Further seismic hazard parameters were also evaluated using all the earthquake data set, which is also termed as mixed data set. Kijko and Sellevoll (1989, 1992) have presented a versatile statistical method based on the maximum likelihood estimation of earthquake hazard parameters for the mixed data set. Analysis was carried out using the computer program of Kijko and Sellevoll (HN2, Release 2.10, 2005). A threshold magnitude value of 3.0 and standard deviation value of 0.2 is used in the analysis. From the maximum likelihood solution, Mmax = 6 ± 0.5 and b’ value 0.87 ± 0.03 were obtained. From the analysis it was observed that, seismic parameter for the region with a ‘b’ value if 0.87 ± 0.03, which matches well with the ‘b’ estimated using Gutenberg-Richter relation. The ‘b’ value obtained in this study matches well with the previous studies of Ram and Rathor (1970), Kaila et.al., (1972), Ramalingeswara Rao and Sitapathi Rao (1984) and Jaiswal and Sinha, (2006) for southern India.

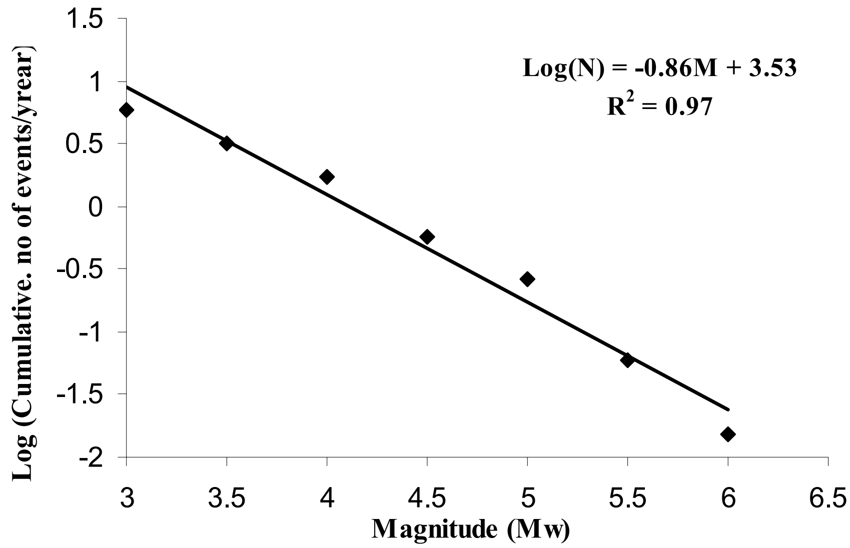


Figure 12: Frequency magnitude relationship for study area using historic and instrumented (total) data

Hazard mapping using probabilistic approach

These seismogenic sources are selected for the DSHA considered source associated with higher PGA (about 8 sources). Among the 8 sources, Subramanya - Byadagi Gadag lineament and Holalkere- Herur lineament are far away from Bangalore (more than 150 km and also moment magnitude of more than 4 are very few on these two lineaments), hence the remaining 6 sources are considered for the probabilistic seismic hazard analysis. The recurrence relation (equation 5) developed for the study area represents the entire region and it is not for the specific source. Each source recurrence is necessary to discriminate near by sources from far-off sources and to differentiate activity rate for the different sources. Deaggregation procedure followed by Iyengar and Ghosh (2004); RaghuKanth and Iyengar (2006) for PSHA of Delhi and Mumbai (in south India) have been used here to find the weightage factor for each source based on the length (α) and number of earthquakes (χ) for the corresponding source. The source recurrence relation weighting factors along with hypocentral distances for all the six selected sources are calculated.The magnitude recurrence model for a seismic source specifies the frequency of seismic events of various sizes per year. For hazard calculation, equation (4) determined using Gutenberg-Richter (G-R) magnitude-frequency relationship has been used. The recurrence relation of each fault capable of producing earthquake magnitude in the range m^0 to m^u is calculated using the truncated exponential recurrence model developed by Cornel and Van Mark (1969). In the PSHA, other uncertainty involved is the distance of each source to the site. Seismogenic sources are considered as the line sources. For each seismogenic source, each point/segment of the source can rupture and generate an earthquake. Thus the relative orientation of each source with respect to Bangalore becomes important. The shortest and longest distance from each source to grid point center has been evaluated from Bangalore seismotectonic map. The probability distribution for the hypocenter distances, from any site to the earthquake rupture on the source, is computed conditionally for the earthquake magnitude. Generally, the rupture length is a function of the magnitude. The conditional probability distribution function of the hypocentral distance R, for an earthquake magnitude $M=m$ for a ruptured segment, is assumed to be uniformly distributed along a fault and is given by Kiureghian and Ang (1977). In hazard analysis the ground motion parameters are estimated from the predictive ground motion relation in terms of PGA and spectral acceleration. These attenuation relations are obtained from regression, which is associated with the randomness of predictive equations. Uncertainty involved in these equations can be accounted by calculating the probability of exceedance of a particular value by the attenuation equation. The normal cumulative distribution function has a value which is most efficiently expressed in terms of the standard normal variables (z) which can be computed for any random variables using transformation as given by Kramer (1996).

The summation of all the probabilities is termed as hazard curve, which is plotted as mean annual rate of exceedance (and its reciprocal is defined as the return period) versus the corresponding ground motion. The mean annual rate of exceedance has been calculated for six seismogenic sources separately and summation of these representing the cumulative hazard curve. Analyses have been carried out using a MATLAB program which has been developed for this purpose. The hazard curves and UHRS 10% probability exceedance in 50 years are calculated for about 1400 grid points. The mean annual rate of exceedance versus peak ground acceleration for all the sources at rock level for all the grid point. This clearly highlights that the sources close to Bangalore produce more hazard when compared to the sources far away from Bangalore. Further to define the seismic hazard at rock level for the study area, PGA at each grid point has been estimated. These values are used to prepare PGA distribution maps for 10% probability exceedance in 50 years, which corresponds to return periods of 475 years. Rock level PGA distribution map for Bangalore is shown in Figure 13, PGA values varies from 0.17g to 0.25g. These values are comparable with the PGA map at rock level using deterministic approach. Similar to the mean annual rate of exceedance calculation for PGA, the spectral acceleration at period of 1 second and 5% damping are also evaluated for all the sources. For the design of structures, a uniform hazard response spectrum (UHRS)/ equivalent hazard spectrum is used. UHRS is developed from a probabilistic ground motion analysis that has an equal probability of being exceeded at each period of vibration. For finding the UHRS, seismic hazard curves of spectral acceleration (S_a) are computed for the range of frequencies. From these hazard curves response spectra for a specified probability of exceedance over the entire frequency range of interest are evaluated. PGA values determined in this study are quite higher than the GSHAP study for India by Bhatia et.al., (1999) (which considers the focal depth of 10km). From this study, PGA at bed rock level for the focal depth of 15km is much higher than PGA obtained in GSHAP. If the focal depth of 10km is considered, hazard values will be much higher. The lesser PGA resulting from GSHAP study may be due to i) the study was carried out on a macro scale, ii) attenuation relation (Joyner and Boore, 1981) used in that study was proposed for else where and iii) few seismic zones (source) based on the locales of the major earthquakes were used. GSHAP sources are described based on concentration of seismicity but in this study seismic sources are based on fault and lineament mapping.

SITE CHARACTERIZATION USING BOREHOLE DATA

A complete site characterization is essential for the seismic site classification. Site characterization along with site response studies can be used together for the seismic microzonation. Site Characterization should include an evaluation of subsurface features, sub surface material types, subsurface material properties and buried/hollow structures to determine whether the site is safe against earthquake effects. Site characterization should provide data of the following:

- Site description and location
- Geotechnical data
- Soil conditions

❖ Geological data
❖ Hydrogeology/ ground water data
❖ Aquifer or permeable characteristics

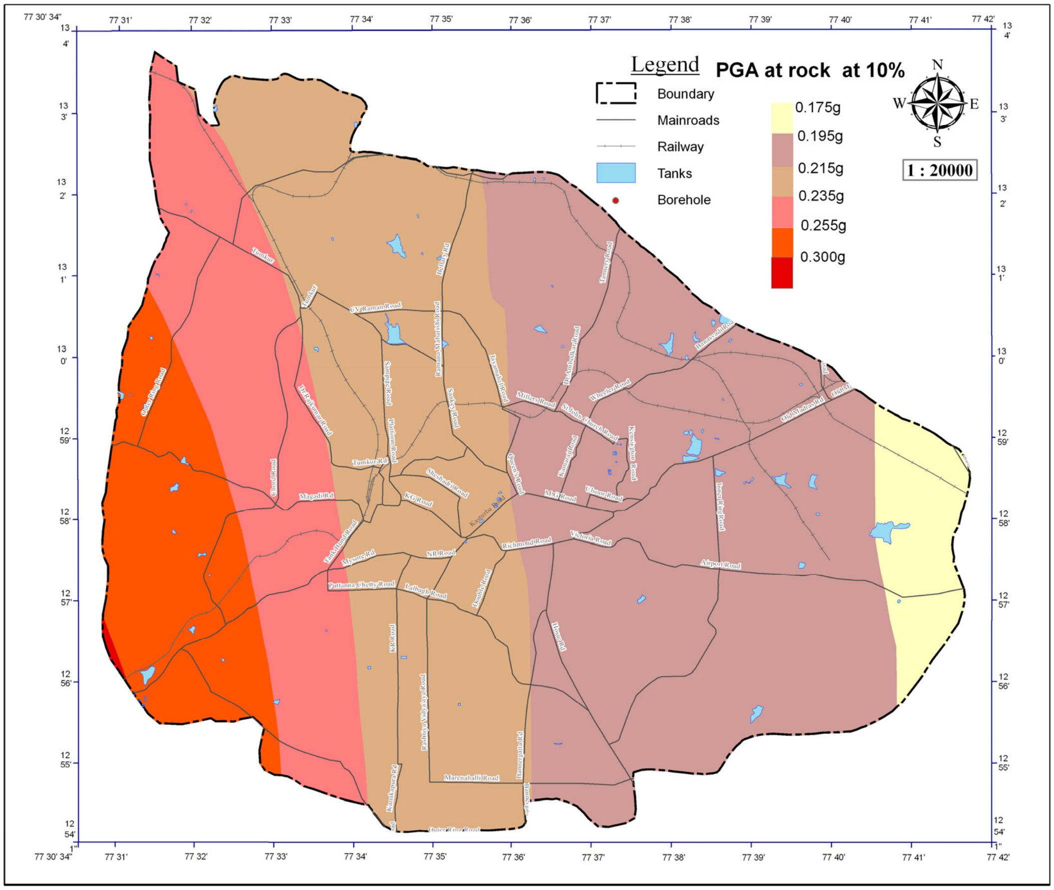


Figure 13: Peak ground acceleration contours at rock level with 10% probability of exceedance in 50 years.

Assessment of available data should include an analysis of the sufficiency and validity of the data in relation to the proposed application/ study.

As part of the site characterization, experimental data should be collected, interpolated and represented in the form of maps. The representation maps can be further used for the site classification and seismic studies. Here, an attempt has been made to characterize Bangalore site using geotechnical and geophysical experimental data. About 850 collected geotechnical borehole information with standard penetration “N” values and 58 geophysical test data using multichannel analysis of surface wave are used for Bangalore site characterization.

The geotechnical data was collected from Archives of Torsteel Research Foundation, Bangalore and Indian Institute of Science, Bangalore. GIS based model helps in data management, to develop geostatistical functions, 3-dimensional (3-D) visualization of subsurface with geo-processing capability and future scope for web based subsurface mapping tool. This is envisaged not only in economizing geotechnical investigations and to aid in detailed site investigations for major projects. For the geotechnical site characterization three major tasks has been carried out are as presented below:

(1) Development of digitized map of Bangalore city with several layers of information.

(2) Development of GIS database for collating and synthesizing geotechnical data available with different sources.

(3) Development of 3-dimensional view of subsoil stratums presenting various geotechnical properties such as location details, physical properties, grain size distribution, Atterberg limits, SPT 'N' values and strength properties for soil and rock along with depth in appropriate format.

GIS has been used in geosciences for data collection, organization and distribution of geological data and maps. Visualization is another GIS activity, which is very useful for the purpose of microzonation. ArcGIS 9.2 has been used here with 3-D analyst extension. The 3-D subsurface model with geotechnical data has been generated with development of base map of study area (220 km^2) with several layers of information (such as Outer and Administrative boundaries, Contours, Highways, Major roads, Minor roads, Streets, Rail roads, Water bodies, Drains, Landmarks and Borehole locations). GIS database for collating and synthesizing geotechnical data available with different sources and 3-dimensional view of soil stratum presenting various geotechnical parameters with depth in appropriate format has been developed. The boreholes are represented as 3- dimensional objects projecting below the map layer in 0.5m intervals. Also image files of bore logs and properties table has been attached to location in plan. These 3-D boreholes are generated with several layers with a bore location in each layer overlapping one below the other and each layer representing 0.5 m interval of the subsurface. It consists of several donut elements in different layers placed coinciding one below the other. Topmost donut represents the 0.5m depth of surface strata and thereon each donut cumulates to 0.5m below ground level. Each borehole in this model is attached with geotechnical data along the depth. The data consists of visual soil classification, standard penetration test results, ground water level, time during which test has been carried out, other physical and engineering properties of soil. The model provides two options to view the data at each borehole in order to cater for various groups. In 2-D, clicking on a borehole will display the standard bore log information and the respective properties table consisting of index properties and shear strength parameters. Apart from this each donut of any borehole is attached with soil/rock properties at that particular depth. As such when this model is viewed in 3-D, geotechnical information on any borehole at any depth can be obtained by clicking at that level (donut). Figure 14 shows a view of some boreholes below Bangalore city map to get a 3-D projection. The data consists of visual soil classification, standard penetration test results, ground water level, time during which the test has been carried out, other physical and engineering properties of soil. Typical soil profiles for the purpose of general classification of soil layers the Bangalore area is shown in Table 1.

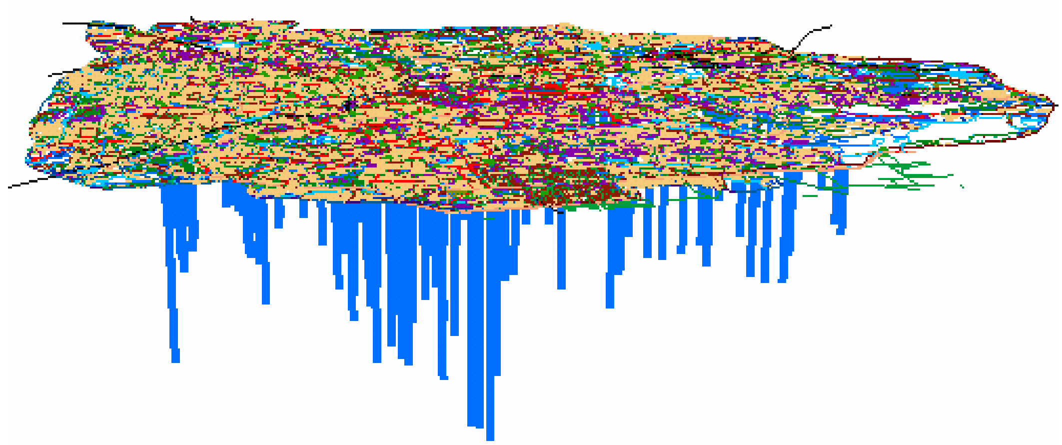


Figure 14: GIS model of borehole locations in 3-D view

Table 1: General soil distribution in Bangalore

Layer	Soil Description with depth and Direction			
	Northwest	Southwest	Northeast	Southeast
First Layer	Silty sand with clay 0-3m	Silty sand with gravel 0-1.7m	Clayey sand 0-1.5m	Filled up soil 0-1.5m
Second layer	Medium to dense silty sand 3m-6m	Clayey sand 1.7m-3.5m	Clayey sand with gravel 1.5m-4m	Silty clay 1.5m-4.5m
Third Layer	Weathered Rock 6m-17m	Weathered Rock 3.5m-8.5m	Silty sand with Gravel 4m-15.5m	Sandy clay 4.5m-17.5m
Fourth layer	Hard Rock Below the 17m	Hard Rock Below 8.5m	Weathered rock 15.5m-27.5m	Weathered Rock 17.5m-38.5m
Fifth Layer	Hard Rock	Hard Rock	Hard Rock Below 27.5m	Hard Rock Below 38.5m

The 'N' values measured in the field using Standard penetration test procedure have been corrected for various corrections, such as:(a) Overburden Pressure (C_N), (b) Hammer energy (C_E), (c) Bore hole diameter (C_B), (d) presence or absence of liner (C_S), (e) Rod length (C_R) and (f) fines content (C_{fines}) (Seed et al., 1983; Skempton, 1986; Youd et al., 2001 and Cetin et al., 2004). Corrected 'N' value i.e., $(N_1)_{60}$ are obtained using the following equation:

$$(N_1)_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R) \tag{5}$$

The corrected "N" Value $(N_1)_{60}$ is further corrected for fines content based on the revised boundary curves presented by Idriss and Boulanger (2004) for cohesionless soils as described below:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \tag{6}$$

$$\Delta(N_1)_{60} = \exp\left[1.63 + \frac{9.7}{FC + 0.001} - \left(\frac{15.7}{FC + 0.001}\right)^2\right] \tag{7}$$

FC = percent fines content (percent dry weight finer than 0.074mm).

The detailed procedures and constants considered are presented in Sitharam et al., (2007).

SITE CHARACTERIZATION USING GEOPHYSICAL DATA

Multichannel Analysis of Surface Wave (MASW) is a non-intrusive and geophysical method, can be used for geotechnical characterization of near surface materials. MASW identifies each type of seismic waves on a multichannel record based on the normal pattern recognition technique that has been used in oil exploration for several decades. MASW generates a shear-wave velocity (Vs) profile (i.e., Vs versus depth) by analyzing Raleigh-type surface waves on a multichannel record. MASW is also used to generate a 2-D shear wave velocity profile. The MASW has been found to be a more efficient method for unraveling the shallow subsurface material properties. MASW system consisting of 24 channels Geode seismograph with 24 geophones capacity have been used in this investigation. The seismic waves are created by impulsive source of 15 pound (sledge hammer) with 300 mmx300 mm size hammer plate with ten shots. These waves are captured by 24 vertical geophones of 4.5Hz capacity.

The MASW test locations are selected based on the space required for the testing and close to important building such as hospitals, temples, government buildings and schools. About 58 one-dimensional (1-D) MASW surveys and 20 two-dimensional (2-D) MASW surveys has been carried out. The test locations are selected such a way that these represent the entire city subsurface information. In total 58 one-dimensional (1-D) surveys and 20 two-dimensional (2-D) surveys have been carried out. Most of the survey locations are selected in flat ground and also in important places like parks, hospitals, schools and temple yards, etc. In about 38 locations MASW survey points are very close to the available SPT borehole locations and these are used to generate correlation between shear wave velocity and corrected SPT 'N' values.

In order to figure out the average shear wave velocity distribution in Bangalore, the average velocity has been calculated using the equation given below:

$$V_H = \frac{\sum d_i}{\sum \left(\frac{d_i}{v_i} \right)} \qquad (8)$$

Where $H = \sum d_i$ = cumulative depth in m

where d_i and v_i denote the thickness (in meters) and shear-wave velocity (at a shear strain level of 10^{-5} or less, m/s) of the i^{th} formation or layer respectively, in a total of n layers within the depth of H. The Vs average has been calculated for every 5 m depth interval up to a depth of 30 m and also average Vs for the soil overburden has been calculated based on the rock depth information. Even though the average shear wave velocity is calculated for every 5m depth intervals and up to a maximum depth of 30m, these maps does not show the average shear wave velocity of soil because of the wide variation in the soil overburden/ rock level. Site characterization using SPT data shows that, the soil overburden thickness in Bangalore varies from 1m to about 40m. Hence, the average shear wave velocity of soil has been calculated based on the overburden thickness obtained from bore holes close to the MASW testing locations. The average shear wave velocity for soil overburden in the study area is shown in Figure 15. Figure shows that whole study area has medium to dense soil with a velocity range of 180m/s to 360m/s falling in to "site class D" as per site classification as per NEHRP classification and also UBC classification (Uniform Building Code in 1997) [Dobry et.al.,. 2000; Kanli et. al, 2006]. More details can be obtained from Anbazhagan and Sitharam (2008).

LOCAL SITE EFFECTS AND SITE RESPONSE

Site amplification of seismic energy due to soil conditions and damage to built environment was amply demonstrated by many earthquakes during the last century. The wide spread destruction caused by Guerrero earthquake (1985) in Mexico city, Spitak earthquake (1988) in Leninakan, Loma Prieta earthquake (1989) in San Francisco Bay area, Kobe earthquake (1995), Kocaeli earthquake (1999) in Adapazari are important examples of site specific amplification of ground motion, even at location far away (100-300km) from the epicenter (Ansal, 2004). The recent 2001 Gujarat-Bhuj earthquake in India is another example, with notable damage at a distance of 250km from the epicenter (Sitharam et. al 2001, and Govinda Raju et. al 2004). These failures resulted from the effect of soil condition on the ground motion that translates to higher amplitude; it also modifies the spectral content and duration of ground motion. As seismic waves travel from bedrock to the surface, the soil deposits that they pass through change certain characteristics of the waves, such as amplitude and frequency content. This process can transfer large accelerations to structures causing large destruction, particularly when the resulting seismic wave frequency matches with the resonant frequencies of the structures. Site specific ground response analysis aims at determining this effect of local soil conditions on amplification of seismic waves and hence estimating the ground response spectra for future design purposes. The response of a soil deposit is dependent upon the frequency of the base motion and the geometry and material properties of the soil layer above the bedrock.

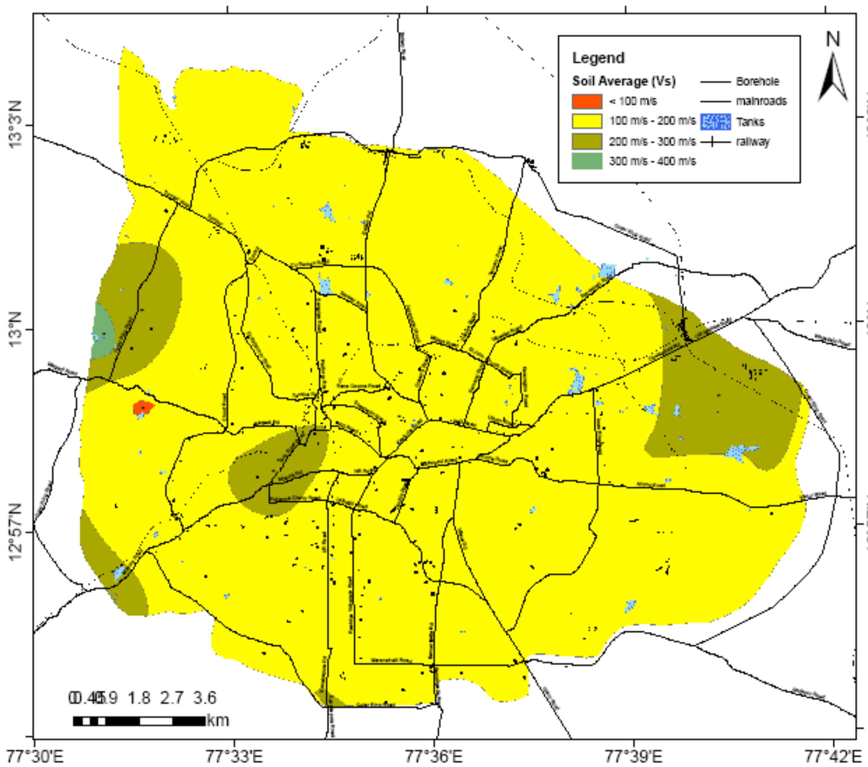


Figure 16: Equivalent shear wave velocity for soil

In the present study, an attempt has been made to study site response using Geotechnical, geophysical data and experimental studies. The subsurface profiling with about 170 bore logs is selected from the data base in the study area of 220 km^2 (see Figure 6). About 58 MASW data have been used to study the site response. The synthetic ground motion for each bore hole has been generated from the ground motion model developed in DSHA. The soil properties and synthetic ground motions for each borehole location are further used to study the local site effects using 1-D ground response analysis with program, SHAKE2000. The response and amplification spectrum have been evaluated for each soil layer at corresponding borehole location. The natural period of the soil column, peak spectral acceleration and frequency at peak spectral acceleration of each borehole has been evaluated and presented as maps. The predominant frequency obtained using SPT 'N' values and MASW shear wave velocities are compared. The site response studies is also carried out experimentally based on recording the ambient noise for a selected period of duration. The noise was recorded at 54 different locations using L4-3D short period sensors equipped with digital acquisition systems. The predominant frequency of soil column of each location is arrived using horizontal to vertical spectral ratios of recorded noise. The predominant frequency obtained by SHAKE2000 and experimental study are compared. Further, the uniform hazard response spectrum considering PSHA with local site condition has been developed.

Ground response using geotechnical data

Ground response analyses are used to predict ground surface motions for evaluation of amplification potential and for the development of design response spectrum. In the present study, equivalent linear one-dimensional ground response analysis has been carried out using SHAKE 2000 software in which motion of the object can be given in any one layer in the system and motions can be computed in any other layer. In equivalent linear approach, the non-linearity of the shear modulus and damping is accounted for by using equivalent linear soil properties by an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer. In this approach, first, a known time history of bedrock motion is represented as a Fourier series, usually using the Fast Fourier Transform (FFT). Second, the Transfer Functions for the different layers are determined using the current properties of the soil profile. The transfer functions give the amplification factor in terms of frequency for a given profile. In the third step, the Fourier spectrum is multiplied by the soil profile transfer function to obtain an amplification spectrum transferred to the specified layer. Then, the acceleration time history is determined for that layer by the Inverse Fourier Transformation in step four. With the peak acceleration from the acceleration time history obtained and with the properties of the soil layer, the shear stress and strain time histories are determined in step five. In step six, new values of soil damping and shear modulus are obtained from the damping ratio and shear modulus degradation curves corresponding to the effective strain from the strain time history. With these new soil properties, new transfer functions are obtained and the process is repeated until the difference between the old and new properties fit in a specified range. The basic approach of one dimensional site response study is the vertical propagation of shear waves through soil layers lying on an elastic layer of the rock which extends to infinite depth.

Out of the available 850 borelogs, 170 bore logs were carefully selected for the evaluation of the bed rock depth (borehole locations are marked in Figure 6). Bed rock depth in each borehole has been evaluated from the rock characterization results presented in borelog, which are used for the site response study. For the 170 boreholes selected in this study the overburden thickness vary from 1m to about 40m, and with their wide distribution in the study area, these bore holes are considered to represent the typical features of soil profiles. Subsurface profile information like unit weight, ground water level, SPT values are thus obtained and compiled for the above selected bore holes and used for the shake analysis using SHAKE2000 program. Due to lack of strong motion data in this region, authors have developed synthetic ground motion by using Boore's model (1983, 2003) SMSIM program (Sitharam and Anbazhagan, 2007). The same model has been used to generate the synthetic ground motion at 170 borehole locations and it is used as input ground motion to the site response study. The duration of all the synthetic strong motion is about 3.5 to 5 seconds; spectral acceleration at rock level is generated for all locations; typical one is shown in Figure 16.

The rock motion obtained from synthetic ground motion model is assigned at the bedrock level as input in SHAKE to evaluate peak acceleration values and acceleration time histories at the top of each sub layer. A soil property of each layer is modeled by using modulus reduction (G/G_{max}) and damping (β) versus shear strain curves. The degradation curves for sand and rock used for the present work are those proposed by Seed and Idriss (1970) and Schnabel (1973) respectively.

Response spectra at the top of the bedrock and at ground surface and amplification spectrum between the first and last layer at a frequency step of 0.125 are obtained. Typical results obtained for borehole location 103 (see Figure 6) are illustrated in Figures 17 a-c. The variation of peak acceleration with depth is shown in Figure 17a. At this borehole, the basement is 15m deep, the top 3.5m is composed of silty sand with clay and the layers below (3.5m -15m) is made of dense silty sand. The top layer of silty sand with clay shows highest amplification values, the peak occurring at 0.36s. The response spectrum of soil is shown in Figure 17b, the first peak of 0.9g occurred at 5Hz and second peak of 1.1 g occurred at 14 Hz , the similar peaks are identified in amplitude spectrum which is shown in Figure 17c. In the amplification spectrum the maximum amplification ratio occurred at 5 Hz frequency, which is the predominate frequency of the soil column in that location.

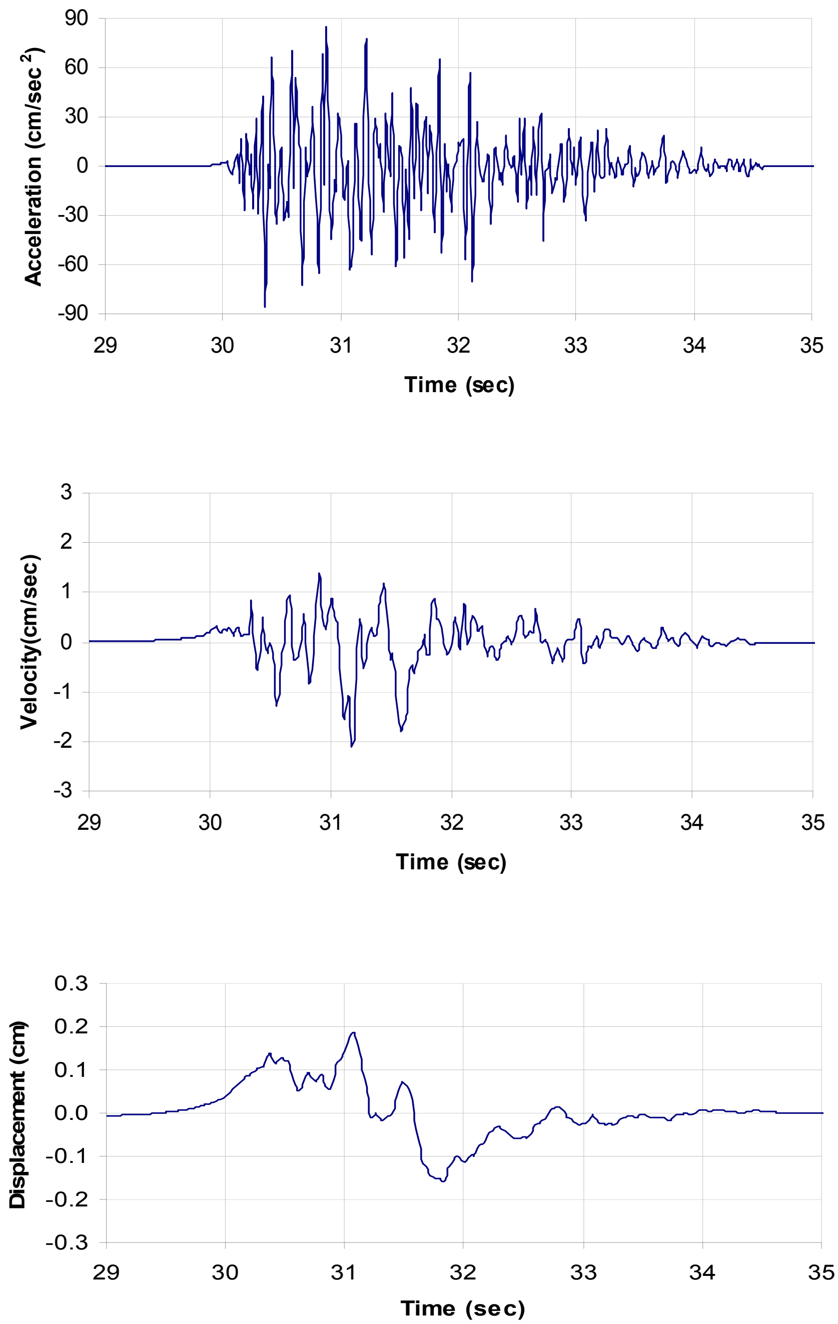


Figure 16: Typical Input Ground Motion used for analysis

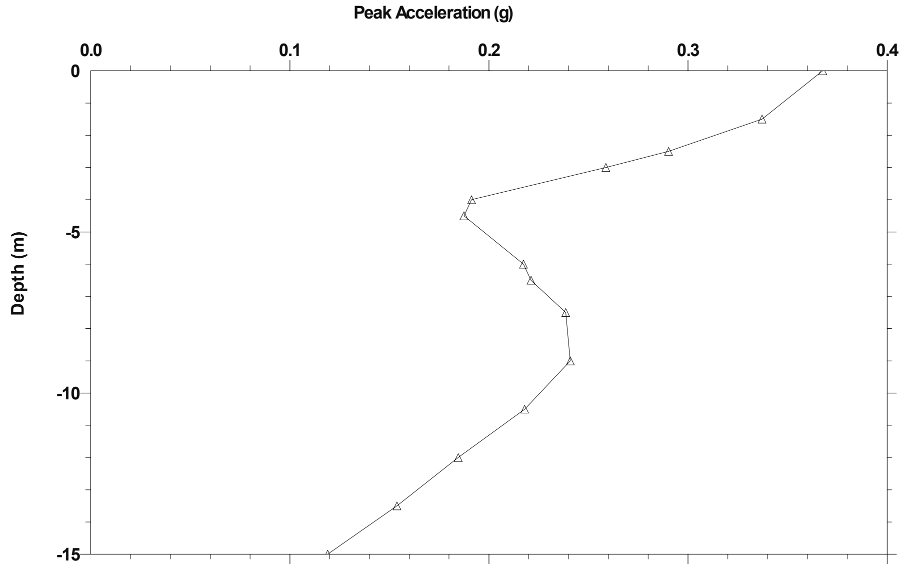


Figure 17 (a): Variation of peak acceleration with depth

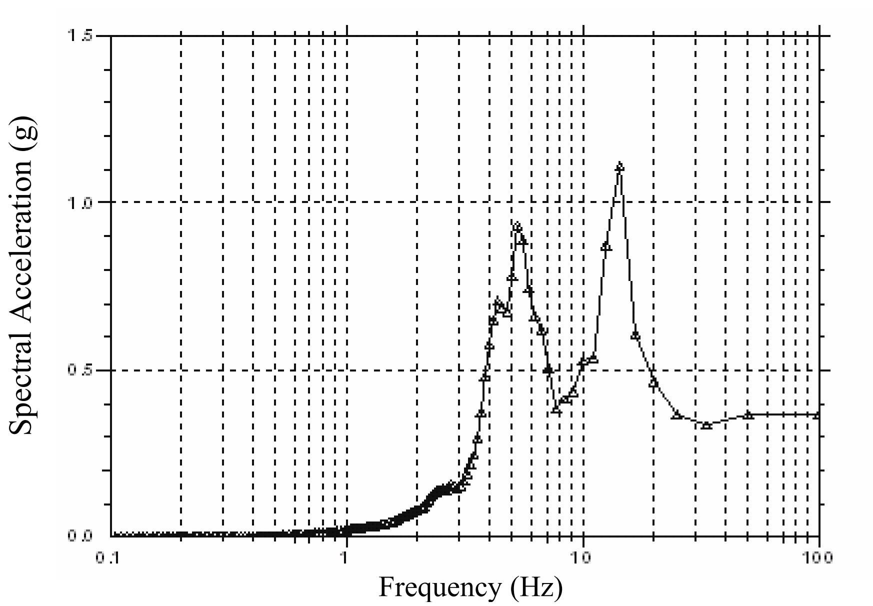


Figure 17(b): Response Spectrum for 5% damping at Ground surface

The parameters obtained from the analysis are presented as maps, which are developed by interpolating the finite point values using the natural neighborhood interpolation technique to depict the variation of various parameters in the study area. The map represents different parameters of the site response study and amplification potential of Bangalore. The map showing the peak acceleration at the ground surface, amplification factor, period of the soil column, peak spectral acceleration, frequency corresponding to the peak spectral acceleration and the response spectrum at the ground surface of frequency of 1.5 Hz, 3 Hz, 5 Hz, 8 Hz and 10 Hz for a 5% damping ratio.

Ground motions with high peak accelerations are usually more destructive than motions with lower peak accelerations thus indicating that regions in this zone having PGA greater than 0.4g and are seismically more unstable than the other regions. However, very high PHA values

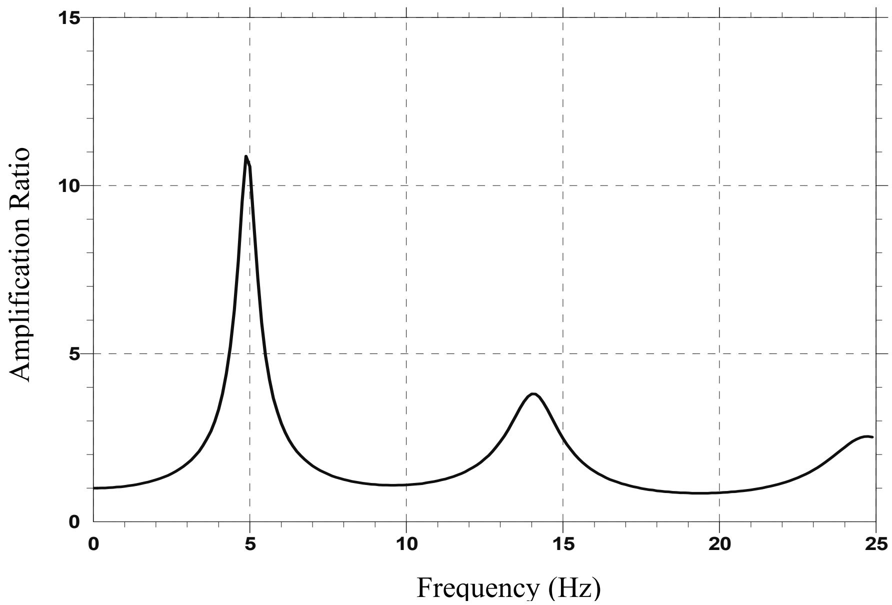


Figure 17 (c): Amplification Spectrum between the bedrock and ground surface

that last only for a very short period of time and have very high frequencies may cause little damage to many types of structures. Hence a better estimate of the regions of high seismic vulnerability can be made by identifying regions susceptible to higher amplification of the bedrock motion. The term "Amplification Factor" is hence used here to refer to the ratio of the peak horizontal acceleration at the ground surface to the peak horizontal acceleration at the bedrock. This factor is evaluated for all the borehole locations using the PHA at bedrock obtained from the synthetic acceleration time history for each borehole and the peak ground acceleration obtained as a result of ground response analysis using SHAKE 2000. The amplification factor thus calculated ranged from 1 to 4.8. These results were interpolated as described earlier to prepare the amplification map. Bangalore city can be divided into four zones based on the range of amplification factors assigned to each zone. The amplification factor map for Bangalore City is shown in Figure 18. Lower amplification values indicate lesser amplification potential and hence lesser seismic hazard. It can be observed that the amplification factor for most of Bangalore region is in the range of 2 to 3. From this it can be concluded that most of study area has a moderate amplification potential.

With the development of geophysical methods, particularly SASW (spectral analysis of surface wave) and MASW are being increasingly used for the site response study and microzonation of cities world wide. Shear wave velocities (Vs) measured using geophysical method are widely used to get better results of site response studies than SPT data. Because, wave propagation theory shows that ground motion amplitude depends on the density and shear wave velocity of subsurface material (Bullen, 1965; Aki and Richards, 1980). Usually density has relatively little variation with depth but shear wave velocity is the logical choice for representing site conditions. In this study an attempt has been made to study the site response of study area using measured shear wave velocity obtained from MASW presented earlier. Site response study using SHAKE2000 and MASW data has been presented here for Bangalore. Similar to site response study using geotechnical data, site response study using SHAKE2000 and MASW data has been carried out. Here instead of calculating shear modulus using empirical correlations (inbuilt in SHAKE2000) based on SPT corrected "N" value, it has been calculated directly using shear wave velocity and density. Other steps and inputs (ground motions and modulus curves) are similar to site response using geotechnical data.

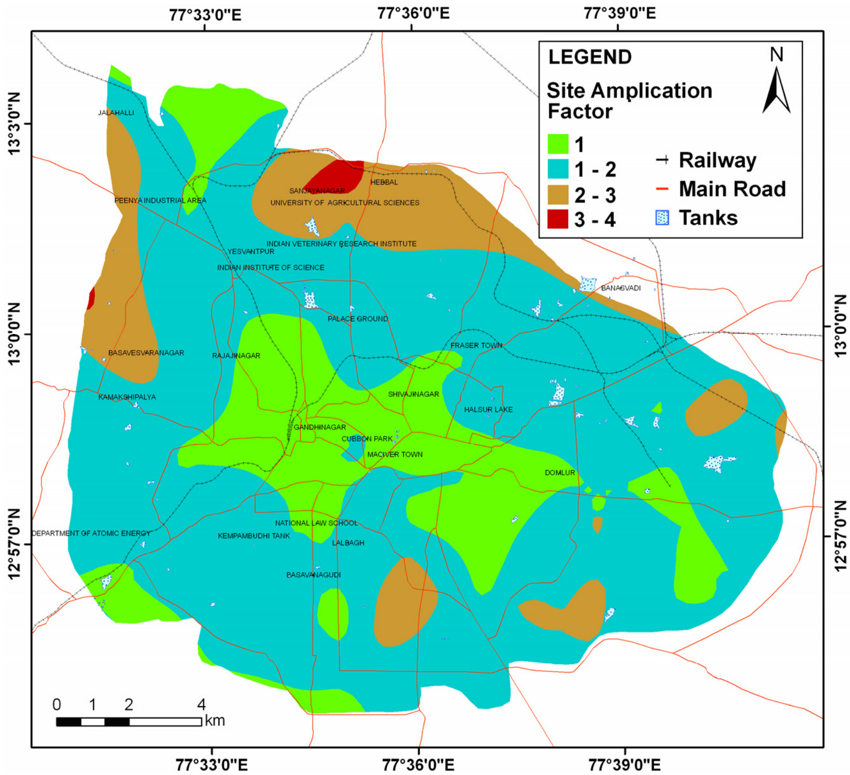


Figure 18: Site response amplification factor

Ground response analysis using shear wave velocity

The peak horizontal acceleration obtained using shear wave velocity ranges from 0.188g to 0.475g. This is comparable to peak horizontal acceleration values obtained using SPT data. The ground acceleration is considerably large in the areas of tank beds, resulting from the thick layers of silty sand with clay mixture. The shape of variation of peak acceleration with depth is similar to the SPT data, typical one is shown in Figure 19. Figure 19 shows the variation of peak acceleration of each layer for 18m soil overburden. Peak acceleration using SPT data is higher when compared to the MASW data and also these variation is large for shallow overburden (with in 12m) thickness. Peak acceleration using SPT data is higher when compared to the MASW data and also these variations are large for shallow overburden (with in 12m) thickness. The amplification factor thus calculated using MASW data ranges from 1 to about 4 which are comparable with the values calculated using SPT data. The dense sand soil, where average shear wave velocity is more than 350 m/s, has less amplification. Spectral values at different frequency using MASW data do not vary much from the values obtained using SPT data. The shape of the amplification spectrum obtained using both data matches well, however values of amplification ratio from MASW data is lower than the SPT data. Typical plot amplification ratio versus frequency is shown in Figure 20. Figure 20 clearly shows that both data gives same amplification ratio with different frequency. SPT data gives 5.5 Hz and MASW data gives 4 Hz corresponding to peak amplification ratio. Also amplification spectrum from both data shows the double peak but at different frequency.

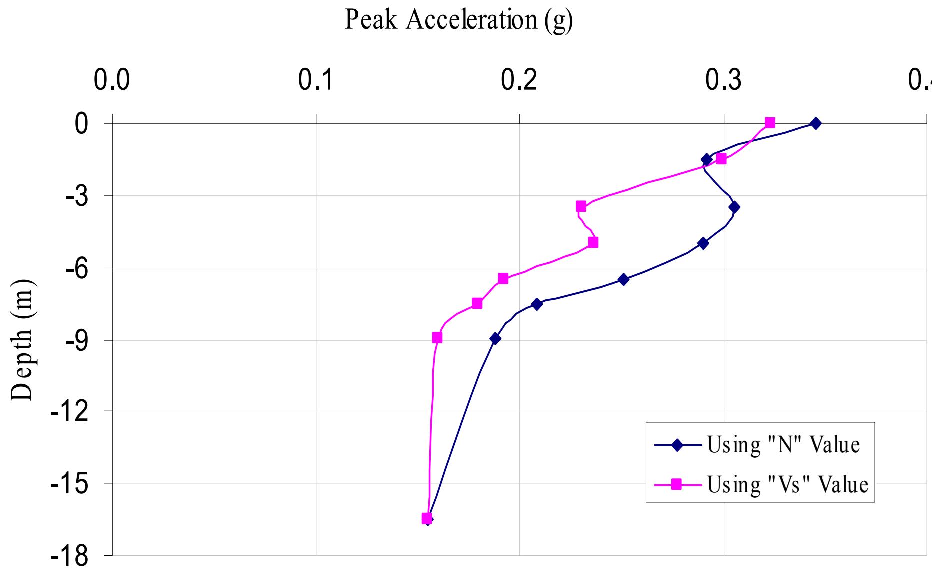


Figure 19: Typical peak ground acceleration with soil column thickness

Site response using micro tremor studies

In assessing the seismic hazard of any urban centre, ambient noise measurements are quite popular in estimating the amplification and the dominant frequencies. In this study predominant frequency of soil column has been estimated by carried out using experimental microtremor method. The method requires a seismic broad band station with three components. In estimating the site response, Nakamura technique has been widely used and the resonance frequency is obtained by evaluating the horizontal to vertical spectral ratios (Nakamura, 1989). The main consideration of this technique is the micro tremors which are primarily composed of Rayleigh waves, produced by local sources. These waves propagate in a surface layer over a half space, considering the motion at the interface of the surface layer and half space is not affected by the

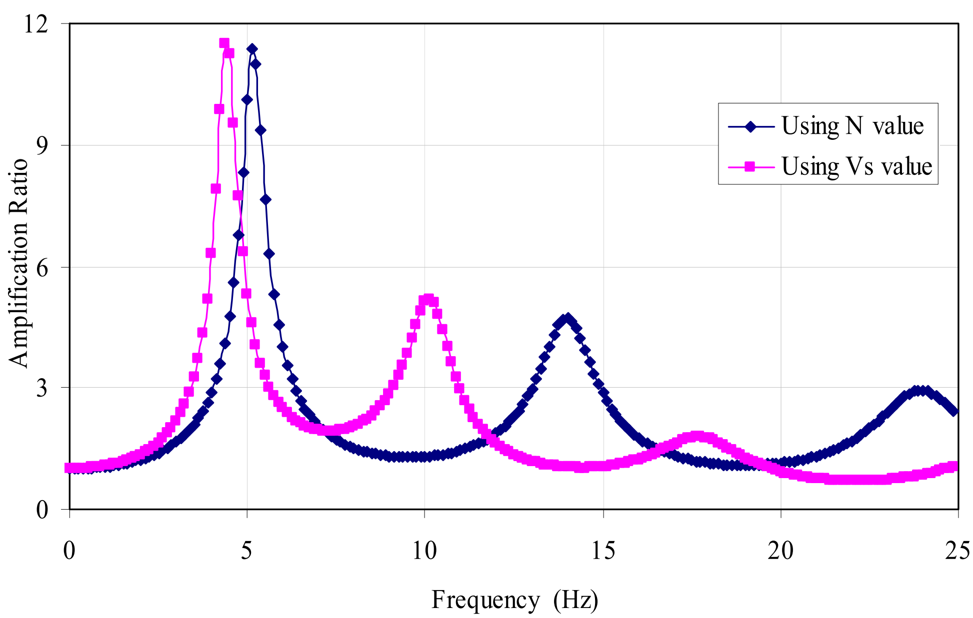


Figure 20: Typical amplification ratio using MASW and SPT

source effect and the horizontal and vertical motion at this interface are approximately equal. Site response studies mainly deal with the determination of peak frequency (f_0) of soft soil, amplification and the nature of response curve defines the transfer function at the site which forms an important input for evaluating and characterizing the ground motion for seismic hazard quantification. Use of ambient noise in the determination of the above parameters has been extensively used globally in trying to quantify the seismic hazard for a given region (Field and Jacob, 1993; Bindi et al, 2000; Parolai et al, 2001).

The instruments used in this experiment are L4-3D short period sensors equipped with digital acquisition system. The sites were selected based on the soil overburden thickness available in geotechnical data base. The duration of recording was for a minimum of 3 hours and a maximum of 26 hrs. In this study Nakamura method was adopted for obtaining the transfer function at various sites in Bangalore. The general layout of the horizontal to vertical spectral ratio technique (HVAR) is shown in Figure 21. The testing locations are selected based on the overburden soil distribution in Bangalore and also close to the available boreholes. Most of the sites were located with the overburden thickness greater than 5 meters. At about 54 locations testing was carried out through out the study area. Among these 54 locations, more than 30 seismological stations are located in important places like schools and colleges. This work was carried out jointly National geophysical research Institute (NGRI) Hyderabad. Dominant frequency and amplitude have been estimated at 54 sites. H/V spectral ratios at different sites located in Bangalore are shown in Figure 22a-b. The predominant frequencies observed in Bangalore ranges between 1.2 Hz -11 Hz.

Comparison of Predominant Frequency from Site Response Study using Vs and Microtremor

Even though the Microtremor and MASW tests were carried out separately, about 43 locations are comparatively closer to each other. The results at these locations are further used to compare the predominant frequency of Bangalore soil. Site response studies using SPT and MASW data shows that the predominate frequency of Bangalore soil varies from 3Hz to 12Hz. But microtremor studies show that the predominant frequency of Bangalore soil varies from 1.5Hz to 12Hz. The predominant frequency estimated from Microtremor and site response using MASW is shown in Figure 23. In Figure 23, the values above the symbol are obtained using MASW site response study and values below the symbols are obtained using microtremor. Figure 23 also clearly shows that in most of the locations predominant frequency from both the methods match well. Only at few points the low predominant frequency is not matching and still close to these frequencies points no site response analysis are carried out. Most of the study area has predominant frequency of 3 Hz to 12 Hz (except at 7 locations in microtremor studies from site response using SHAKE and microtremor studies (See Table 2).

Table 2: Predominant frequency using site response study and microtremor

Predominant Frequency Range (Hz)	Symbols	Numbers	
		Using	Using
3.0 to 5.0	▲	7	16
5.1 to 7.0	■	15	10
7.1 to 9.0	✚	11	5
9.0 to 11.0	×	6	2
11.1 to 12.5	●	4	3
1.5 to 2.9	✶	-	7

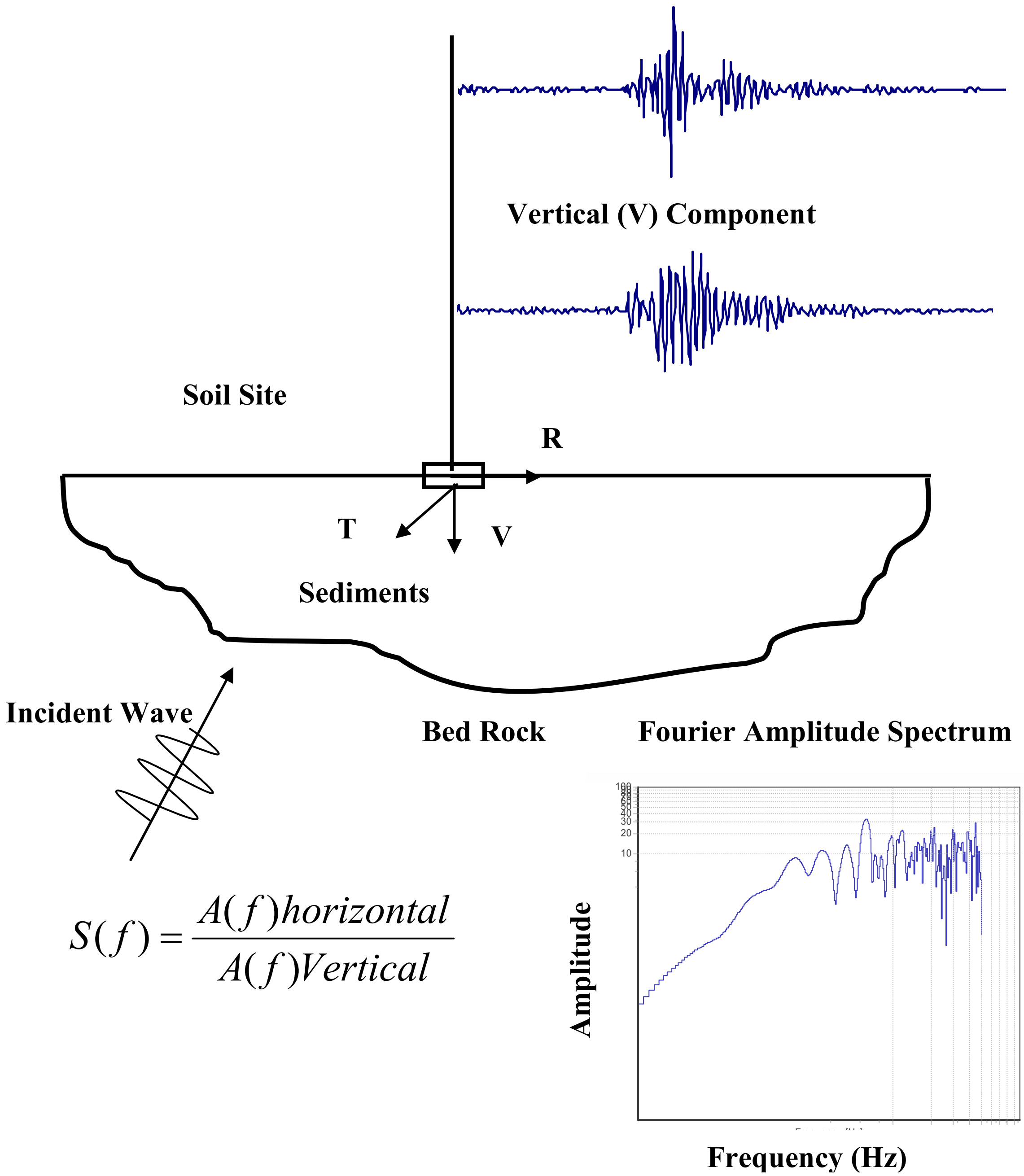
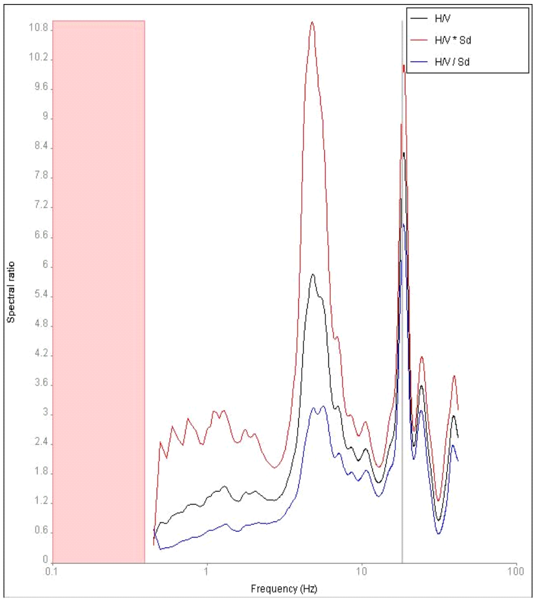


Figure 21: Horizontal to vertical spectral ratio technique – Layout



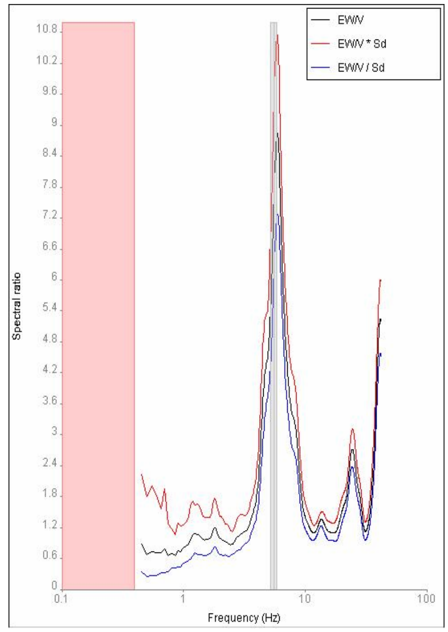


Figure 22a: Typical predominant frequency at IISc **Figure 22b:** at National Dairy Research Institute:(Black line depicts the computed spectral ratio whilst the red and blue show the standard deviation of $\pm 1\sigma$).

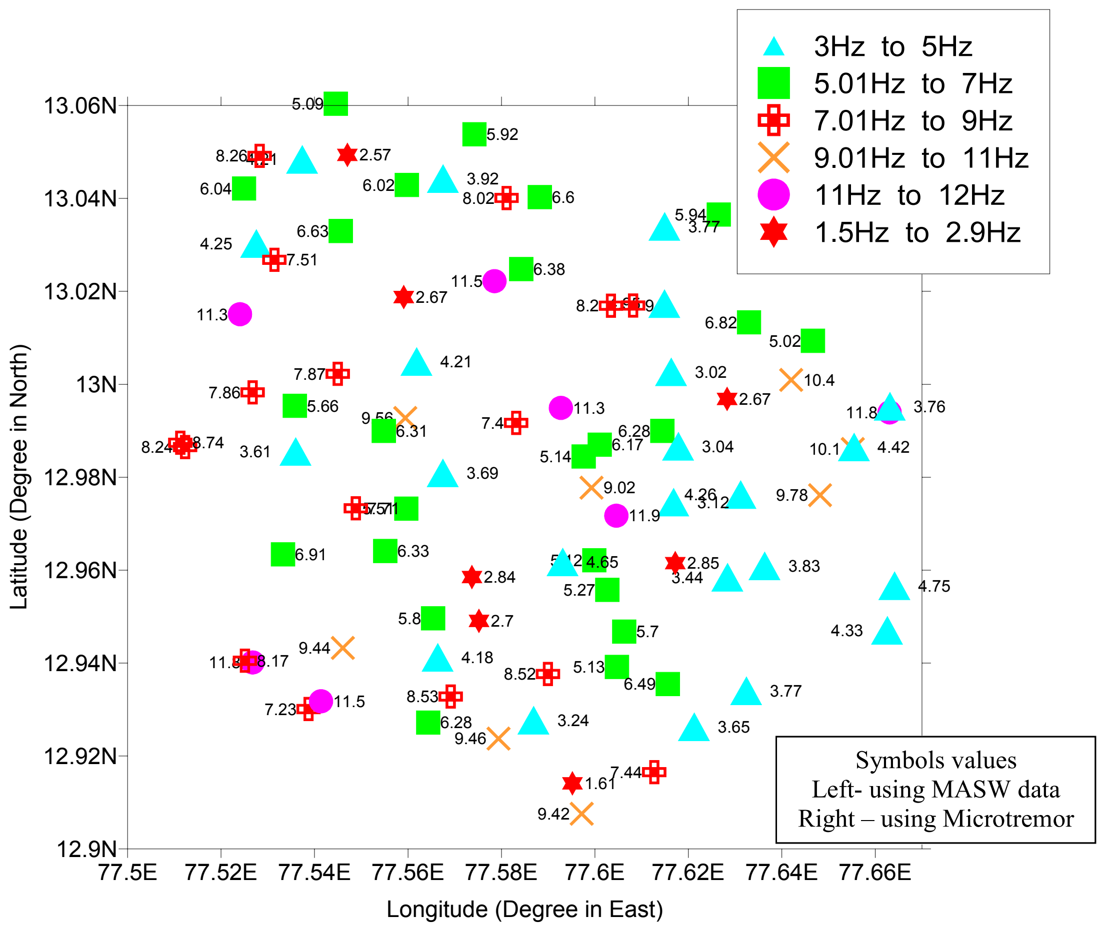


Figure 23: Predominant frequency from microtremor and site response using shear wave velocity

PROBABILISTIC SEISMIC HAZARD ANALYSIS WITH LOCAL SITE EFFECTS

From the extensive field investigation carried out using MASW survey (at 58 locations in the study area) it has been observed that the shear wave velocity for the Bangalore region falls in the range of 0.18 km/sec ≤ Vs ≤ 0.36 km/sec (Site Class D). Keeping this in mind surface level response spectrum has been developed based on PSHA considering Bangalore as “Site Class D”. To evaluate the spectral acceleration at ground surface with probabilistic considerations, the spectral acceleration relation developed for southern India by RaghuKanth and Iyengar (2007) has been used. The hazard curve and spectral acceleration spectrum has been evaluated as discussed in PSHA. The mean spectral acceleration mean annual rate of exceedance versus spectral acceleration for a period of 1s and 5% damping considering the “Site class D” has been evaluated. From rock level and surface level spectral acceleration, it is very clear that the spectral acceleration from each source due to the local soil condition get modified (increased), resulting in an increase in the cumulative spectral acceleration. Figure 24 presents the variation of mean annual rate of exceedance versus cumulative spectral acceleration for a period of 1s and 5% damping for rock site and soil with site class D. Figure 25 presents the plot of UHRS for 10% probability of exceedance in 50 years considering local site conditions. A value of PGA (ZPA = PGA) 0.33g is obtained when local site effect is taken into account. The observed PGA value at considering the local soil conditions is higher than bed rock level, shows an amplification of 2.73 due to local soil condition. This amplification factor is with in the range observed by other methods as described earlier.

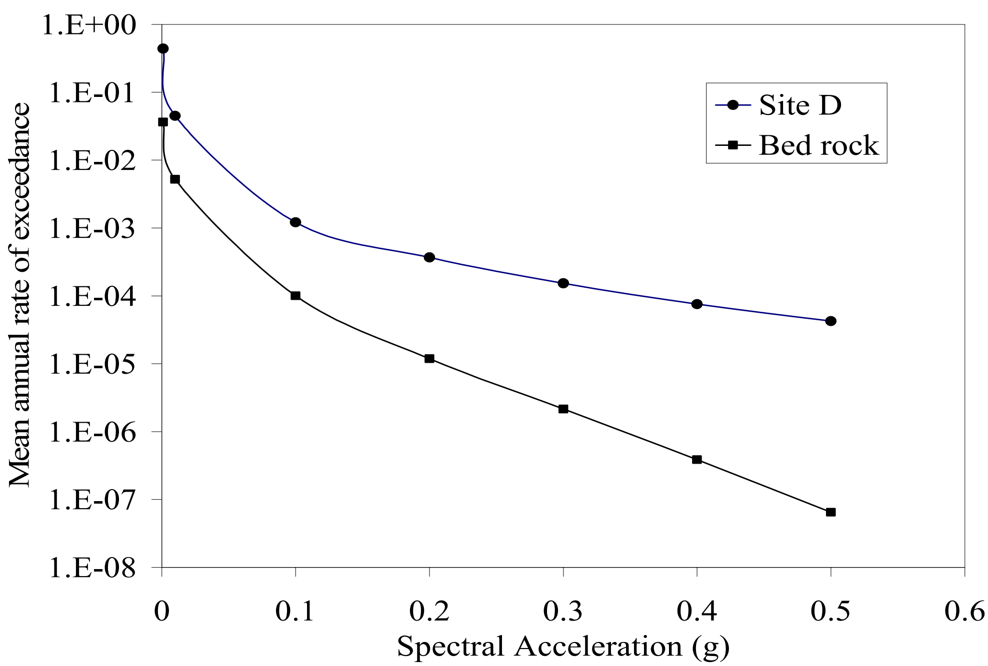


Figure 24: Spectral acceleration at bed rock and site D corresponding to period of 1s and 5% damping for Bangalore.

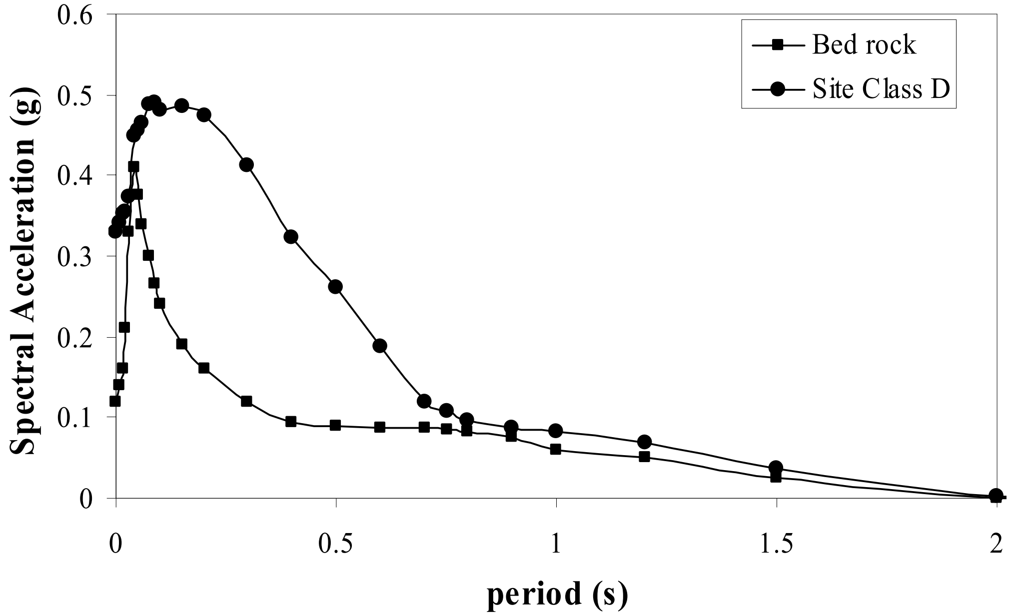


Figure 25: Uniform hazard response spectrum for bed rock and site class D with 10% probability of exceedance in 50 years (5% damping) for Bangalore.

LIQUEFACTION HAZARD ASSESSMENT

The response of soil due to seismic hazards producing a significant amount of cumulative deformation or liquefaction has been one of the major concerns for geotechnical engineers working in the seismically active regions. Liquefaction can occur in moderate to major earthquakes, which can cause severe damage to structures. Transformation of a granular material from solid state to liquid sate due to increased pore pressure and reduced effective stress is defined as liquefaction (Marcuson 1978). When this happens, the sand grains loose its effective shear strength and will behave more like a fluid. The grain size distribution of soil, duration of earthquake, amplitude and frequency of shaking, distance from epicenter, location of water table, cohesion of the soil and permeability of the layer affects liquefaction potential of soil. The liquefaction hazards are associated with saturated sandy and silty soils of low plasticity and density.

The liquefaction potential of soil is generally estimated from laboratory tests or field tests. Among the field in-situ tests, the SPT test has been widely used for this purpose. Corrected 'N' values from large number of SPT test data in Bangalore have been used for direct assessment of ground's liquefaction resistance in this work. An attempt has been made to prepare the susceptibility and liquefaction hazard maps. The simple spread sheet has been generated for applying corrections to 'N' field values and calculation of factor of safety against liquefaction. About 620 bore hole information are used for this purpose and the factor of safety against liquefaction are estimated. Based on the factor of safety, the regional liquefaction hazard maps are generated for the estimated peak ground acceleration at the ground surface. At few locations the undisturbed soil samples has been collected and laboratory cyclic triaxial tests have been carried out to validate the liquefaction resistance of soil.

Liquefaction evaluation using SPT data

Liquefaction susceptibility was evaluated based on the primary relevant soil properties such as grain size, fine content, and density, degree of saturation, SPT "N" values and age of the soil deposit in each of the borelogs. These susceptible areas have been identified by considering the approach of Pearce and Baldwin (2005). Soil is susceptible for liquefaction if (1) presence of sand layers at depths less than 20m, (2) encounter water table depth less than 10m, and (3) SPT field "N" blow counts less than 20. By interpolation, susceptibility of map has been prepared. From susceptibility of map, only susceptible areas are further considered for the evaluation of factor of safety against liquefaction.

Factor of Safety against liquefaction of soil layer has been evaluated based on the simplified procedure (Seed and Idriss, 1971) and subsequent revisions of the simplified procedures (Seed et al., 1983, 1985; Youd et al., 2001; Cetin et al., 2004). In this study, the earthquake induced loading is expressed in terms of cyclic shear stress and this is compared with the liquefaction resistance of the soil. The cyclic stress ratio caused by the earthquake is greater than the cyclic resistance ratio of in situ soil, then liquefaction could occur during an earthquake. Detailed procedures and calculation with example are presented in Sitharam et al, (2007). The earthquake loading is represented in terms of cyclic shear stresses. The earthquake loading has been evaluated by using Seed and Idriss (1971) simplified approach by using amplified peak ground acceleration from site response study. The liquefaction resistance can be calculated based on laboratory tests and in situ tests. Here, liquefaction resistance using in situ test based on SPT 'N' values are attempted. Cyclic resistance ratio (CRR) is evaluated based on corrected "N" value as per Seed et al. (1985), Youd et al., (2001); Cetin et al., (2004). The corrected 'N' values are used to calculate the CRR for the magnitude of 7.5 earthquakes using the equation proposed by Idriss and Boulanger (2005). For the present study, for the earthquake moment magnitude of 5.1 has been considered, hence Magnitude Scaling Factor (MSF) has been evaluated using revised Idriss scaling factors (1995) and considered for factor of safety evaluation. After applying necessary corrections to SPT 'N' values corrected "N" [$(N_1)60_{cs}$] values were obtained. A simple excel spread sheet has been developed to automate these calculations for all the 620 borelogs with depth. The factor of safety for each layer of soil was arrived by considering corresponding "$(N_1)60_{cs}$" values. The liquefaction hazard map is prepared for the moment magnitude of 5.1. The minimum factor of safety from each bore log has been considered to represent the factor of safety against liquefaction at that location, which are used for the mapping. Figure 26 shows the map of factor of safety against liquefaction (FS) for Bangalore city to the local magnitude of 5.1. Figure 26 shows that factor of safety against liquefaction locations is more than unity for a local magnitude of 5.1 except in northwestern part (area in and around Kurubahalli) and southern part (in and around Venkatapura, Jakasandra, Sri Narashimaraj colony, Basaveshwara nagar and Kethamaranahalli) of Bangalore.

Out of 620 locations liquefaction analyses indicates that the factor of safety is less than one in only for 4.2% of total locations. Factor of safety of 1 to 2 and 2 to 3 each having 14.7% and 12.5% of the total locations, factor of safety of more than 3 is about 68% of the total locations. At 33% of total locations detailed study is needed using laboratory tests according to Idriss and Boulanger (2005). Where these soil (silty clay having PI>12) can cause the stress reduction in soil during earthquake. Because in these locations the liquid limit is more than 32 and plasticity index are more than 12 due to presence of silty clay soil. Most of the data points having PI>12 fall in the area of factor of safety more than 3. Areas close to water bodies and streams have the factor of safety less than unity, however, the areas having FS less than 1 is very less. Typical borelogs having a factor of safety of less than 1 is shown in Figure 27. Figure 27 clearly shows that, up to a depth of about 6 m, very loose silty sand with clay and sand are found in these locations which are classified as medium to fine sand having very low field 'N' values.

Also in this location shallow water table has been met, ground water has been found at 1.2m from the ground level. These factors may attribute to the low factor of safety in these locations. Borelogs corresponding to a factor safety 1 to 2 show that, these location having moderate field 'N' values. Also ground water has been reported at about 2m from the ground level. These locations have the filled up soil, sandy soil and clayey silt up to depth of 5 m. Area covered by this range of factor safety is lager than area having factor of safety less than 1. Typical borelog for these locations is shown in Figure 28.

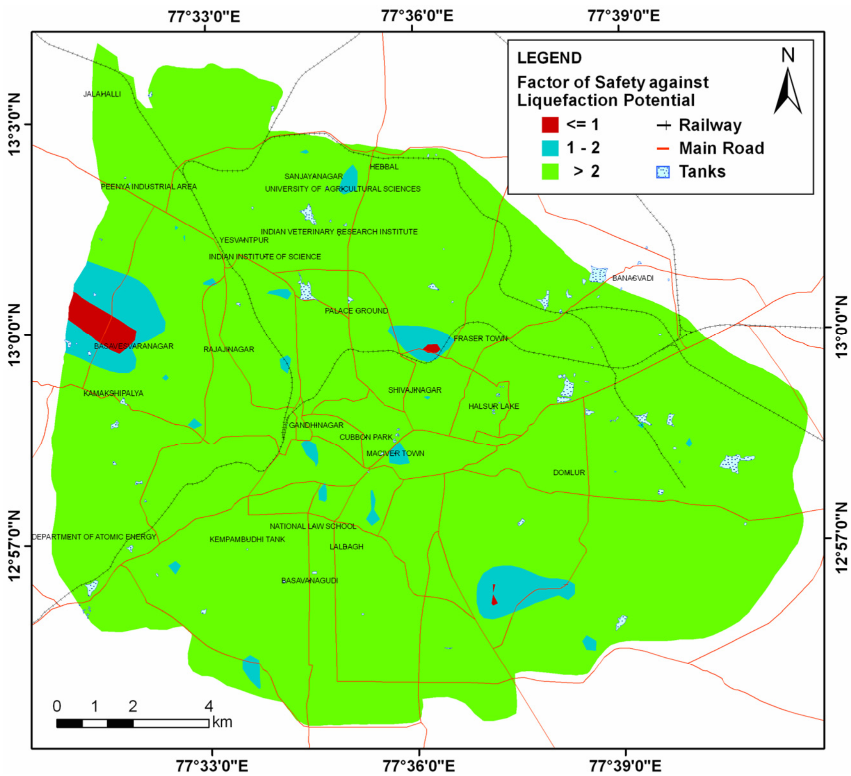


Figure 26: Factor of safety against liquefaction

BORE LOG

Location	Palace Guttahalli Road,Bangalore	Date of commencement	4.12.1996
BH No	2	Date of completion	5.12.1996
		Ground Water Table	1.2m

Depth Below GL(m)	Soil Description	Thickness of Strata (m)	Legend	Details of Sampling: Depth (m)	Details of Sampling: Type	SPT N' Value
0.5	Filled Up Soil	0.5				
	Yellowish					
1.0						
2.0	Sandy Silt	1.5		1.5	SPT*	N=1
	Greyish/Blackish					
	Soft Clay			2	UDS*	
3				2.8	DS	
3.5		1.5				
4	Greyish/Brownish			4	SPT	N=1
	Sand(medium to fine)					
				5.3	DS	
5.0				5.5	SPT	8/9/12
		2.3				N=21
	Whitish Sand with Gravel					
6				6.6	SPT	8/8/09
						N=17
7						
				8	SPT	10/11/22
8		2.2				N=33
	Greyish/Whitish Silty Clayey					
	Sand(medium to fine)			9.2	SPT	27/29/32
9						N=61
10		2				
	Borehole terminated at 10m					

Bore hole Terminated at 10m		**Note**	
* Sample not retrived		SPT	Standard Penetration Test
R	Rebound	UDS	Undisturbed Sample

Figure 27: Typical bore log corresponding to location which has factor of safety less than 1

BORE LOG

Location	koramangakla, Bangalore	Date of commencement	23.1.1997
BH No	4	Date of completion	24.1.1997
		Ground Water Table	2m

Depth below Ground level (m)	Soil Description	Thickness of Strata (m)	Legend	Details of Sampling		SPT 'N' Value
				Depth (m)	Type	
	Filled Up Soil					
1.0		1				
1.5	Greyish/Yellowish Sandy			1.5	SPT	5/7/09
				3	UDS	N=16
3.0	Clayey Silt			4.5	SPT	8/11/17
5.0		4				N=28
6.0	Yellowish/Greyish			6	SPT	10/13/19
						N=32
	Clayey Sand			7	SPT	12/18/20
7.0						N=38
				9	SPT	15/22/26
9.0.						N=48
10.5		5.5				

* Sample not retrived

Note
Standard Penetration Test
Undisturbed Sample

Figure 28: Typical bore log corresponding to locations which has factor of safety between 1 to 2

Cyclic Triaxial experiments on undisturbed soil samples

Undisturbed samples were collected from few locations in (south east region) Bangalore city to verify the liquefaction potential of the soil. Cyclic triaxial tests have been carried out in the laboratory on the undisturbed soil samples collected from Boreholes. The tests have been carried out as per ASTM: D 3999 (1991) in strain controlled mode. Cyclic triaxial tests are carried out with double amplitude axial strains of 0.5%, 1% and 2% with a frequency of 1Hz. Figure 29 shows the pore pressure ratio versus number of cycles. From these plots it is clear that even after 120 cycles, the average pore pressure ratio is about 0.94 and deviatoric stresses vs. strain plots have not become flat, indicating no liquefaction. The resistance to liquefaction of these soils is very high. The calculated factor of safety against liquefaction results for this borehole is also very high indicating no liquefaction and results matches well with the lab test results. This study shows that Bangalore is safe against liquefaction except at few locations where the overburden is sandy silt with shallow water table. Strain controlled cyclic triaxial tests on undisturbed soil samples collected from south west region of Bangalore city indicates that soils are non liquefiable.

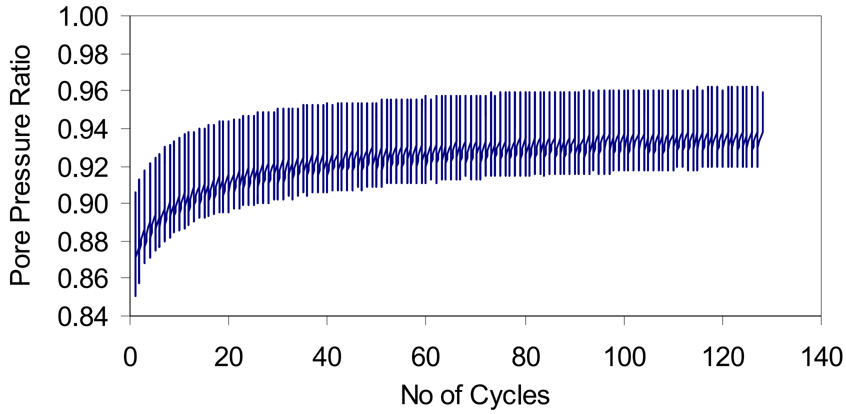


Figure 29: Typical pore pressure ratio plots with no of cycles

INTEGRATION OF HAZARD MAPS ON GIS PLATFORM

Geographical Information System (GIS) provides a perfect environment for accomplishing comprehensive regional information including seismic damage assessment. GIS has the capability to store, manipulate, analyze and display a large amount of required spatial and tabular data. One of the most important features of a geographic information system is the data analyses of both spatial (graphic) and tabular (non-graphic) data. A final hazard index map for BMP area is developed using Analytic Hierarchy Process (AHP) on GIS platform. AHP is a multi-criteria decision method that uses hierarchical structures to represent a problem and then develop priorities for the alternatives based on the judgment of the user (Saaty, 1980).Application of GIS for microzonation mapping is amply demonstrated by many researchers all over the world. Nath (2006) used GIS as integration tool to map seismic ground motion hazard for Sikkim Himalaya in India. In this study, similar approach of Nath (2006) is used to develop a hazard index map where in the seismic hazard parameters are integrated and coupled with ground information. The hazard index maps are prepared using both deterministic and probabilistic approaches.

Saaty's Analytical Hierarchy process constructs a matrix of pair-wise comparisons (ratios) between the factors of earthquake hazard parameters (EHP). The constructed matrix shows the relative importance of the EHP based on their weights. If 9 earthquake hazard parameters are scaled as 1 to 9, 1 meaning that the two factors are equally important, and 9 indicating that one factor is more important than the other. Reciprocals of 1 to 9 (i.e., 1/1 to 1/9) show that one is less important than others. The allocation of weights for the identical EHP depends on the relative importance of factors and participatory group of decision makers. Then the individual normalized weights of each EHP are derived from the matrix developed by pair-wise comparisons between the factors of EHP. This operation is performed by calculating the principal Eigen vector of the matrix. The results are in the range of 0 to 1 and their sum adds up to '1' in each column. The weights for each attribute can be calculated by averaging the values in each row of the matrix. These weights will also sum to '1' and can be used in deriving the weighted sums of rating or scores for each region of cells or polygon of the mapped layers.

Since EHP vary significantly and depends on several factors, they need to be classified into various ranges or types, which are known as the features of a layer. Hence each EHP features are rated or scored within EHP and then this rate is normalized to ensure that no layer exerts an influence beyond its determined weight. Therefore, a raw rating for each feature of EHP is allocated initially on a standard scale such as 1 to 10 and then normalized using the relation,

$$X_i = \frac{R_i - R_{\min}}{R_{\max} - R_{\min}} \quad (9)$$

Where, R_i is the rating assigned for features with single EHP, R_{min} and R_{max} is minimum and maximum rate of particular EHP.

Earthquake hazard parameters

Seismic microzonation is subdividing a region into smaller areas having different potential for hazardous earthquake effects. The earthquake effects depend on ground geomorphological attributes consisting of geological, geomorphology and geotechnical information. The parameters of geology and geomorphology, soil coverage/thickness, and rock outcrop/depth are some of the important geomorphological attributes. Other attributes are the earthquake parameters, which are estimated by hazard analysis and effects of local soil for a hazard. The Peak Ground Acceleration (PGA) [from deterministic or probabilistic approach], amplification/ site response, predominant frequency, liquefaction and land slide due to earthquakes are some of the important seismological attributes. Weight of the attributes depends on the region and decision maker, for example flat terrain has weight of "0" value for land slide and deep soil terrain has highest weight for site response or liquefaction. Different attributes considered for Bangalore microzonation are presented below;

Geomorphological Attributes

The geomorphological attributes (here after called as themes) considered in this study are the geology and geomorphology (GG), rock depth/ soil thickness (RD/ST), soil type and strength (represented in terms of average shear wave velocity) (SS), drainage pattern (DP) and elevation level (EL). In the previous sections important attributes of rock depth/ (RD), and soil type and strength (represented in terms of average shear wave velocity) (SS) are discussed, in this section discusses the other geomorphological attributes.

Geology and Geomorphology (GG)

As the study area is densely covered by buildings, it is very difficult to obtain the detailed geological/geomorphological maps. A simple geological and geomorphology map of Bangalore is prepared based on the available literature and presented in Figure 30 for the study area. Bangalore lies on top of the south Karnataka Plateau (Mysore Plateau) and its topology is almost flat with the highest point being at Doddabettahalli (954 m above Mean Sea Level) in the direction of a NNE-SSW trending ridge lies east of the Vrishabhavathi river. The study area falls under the expanse of the Peninsular Gneissic Complex. The main rock types in the regions are Gneissic country rock and as well as intrusions of Granites and Migmatites. Bangalore city lies over a hard and moderately dense Gneissic basement dated back to the Archean era (2500-3500mya). A large granitic intrusion in the south-central part of the city extends from the Golf Course in the north central to Vasantpur VV Nagar in the south of the city (almost 13 km in length) and on an average 4 km from east to west along the way. A magmatite intrusion formed within the granitic one extends for approximately 7.3 kms running parallel with Krishna Rajendra Road/ Kanakpura Road from Puttanna Chetty Road in Chamrajpet till Bikaspura Road in the south. A 2.25km Quatrzite formation is found in Jalahalli East (see Figure 30).

Dike swarms are seen around the western outskirts of the city (west of the Outer Ring Road) majority striking approximately oriented on N15°E. However random east west trending ones are also seen. They appear to strike parallel to the strike of the vertical foliation of the country rock. These basic intrusions dated back to the close of the Archean era (Lower Proterozoic; 1600-2500 mya) mainly constitute of hard massive rocks such as Gabbro, Dolerite, Norite and Pyroxenite. Bangalore city is subjected to a moderate annual soil erosion rate of 10 Mg/ha. The basic geomorphology of the city comprises of a central Denudational Plateau and Pediment (towards the west) with flat valleys that are formed by the present drainage patterns. The central Denudational Plateau is almost void of any topology and the erosion and transportation of sediments carried out by the drainage network gives rise to the lateritic clayey alluvium seen throughout the central area of the city. The pediment/pediplain is a low relief area that abruptly joins the plateau.

Drainage pattern (DP) and Elevation Level (EL)

The geotechnical attributes presented above are based on large number of geotechnical data and experiments. But the geological and geomorphologic information is presented as one map (Figure 30) based on available information. This map does not have sufficient information and account for other factors such as impedance contrast, 3-dimensional basin and topographical effects. Hence to account the above parameters, the other important parameters of drainage pattern (DP) and elevation level (EL) are considered as separate themes based on the recent available information. Figure 31 shows the drainage pattern of study area with water bodies and Figure 32 shows the elevation levels in the form of contours at 10m intervals.

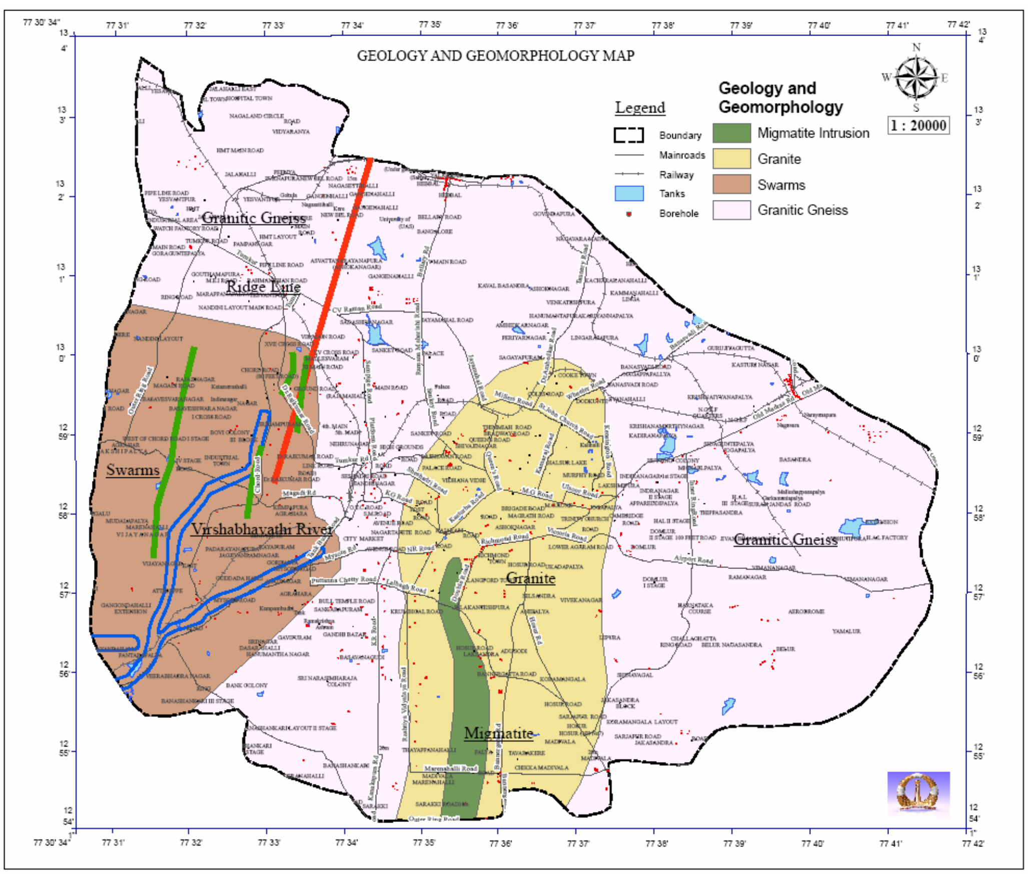


Figure 30: Geology and Geomorphology of the study area

Seismological Attributes

The seismological thematic maps have been generated based on detailed studies of seismic hazard analysis, site response studies and liquefaction analysis. From these studies different earthquake hazard parameters are mapped. But for final Index map preparation and GIS integration only selected maps presented earlier are considered as themes:

- Peak ground acceleration (PGA) at rock level based on synthetic ground motions from MCE based on DSHA.
- PGA at rock level at 10 % probability in 50 years exceedance based on PSHA.
- Amplification factor based on ground response analysis using SHAKE2000.
- Predominant frequency based on site response and experimental studies.
- Factor of safety against Liquefaction potential.

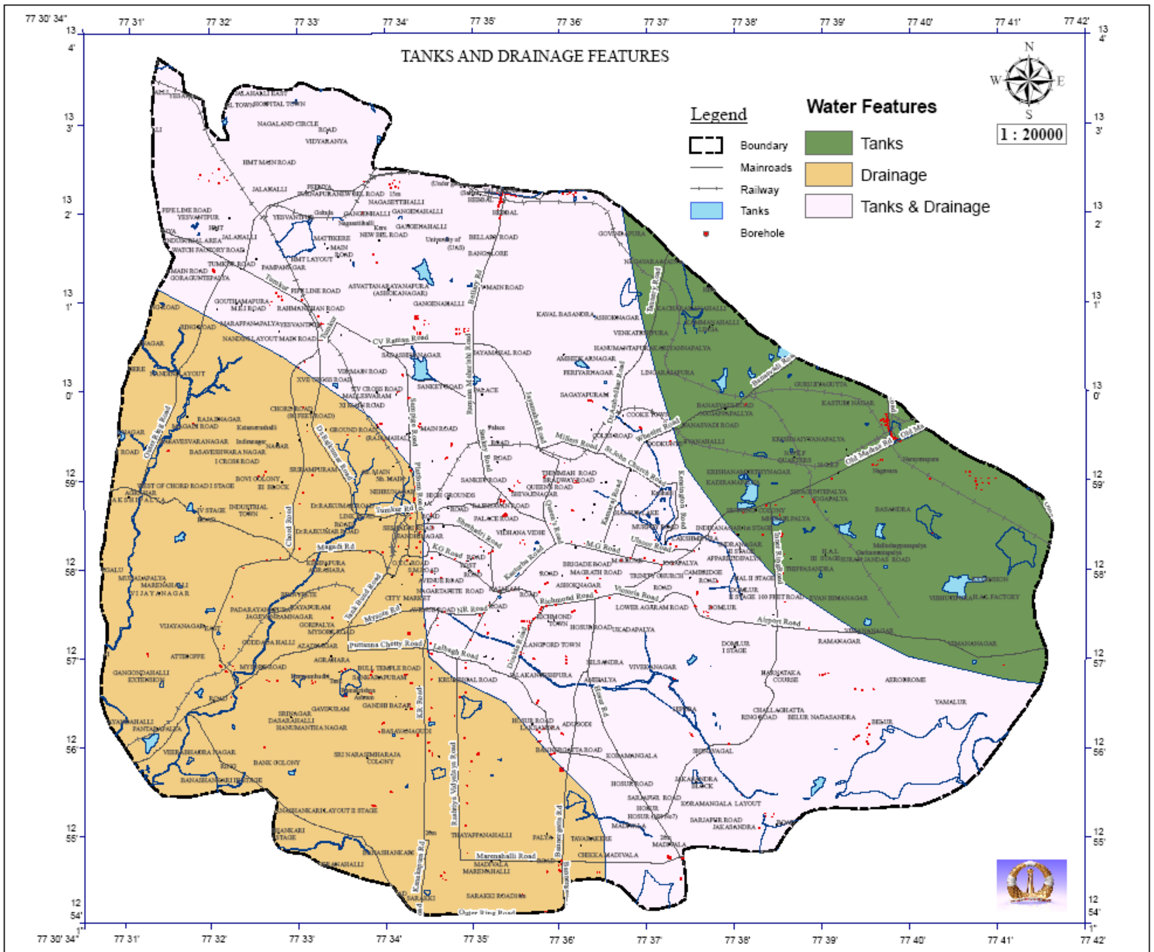


Figure 31: Tanks and drainage Features in the study area

INTEGRATION OF DIFFERENT LAYERS (THEMES)

For seismic microzonation and hazard delineation the different themes as presented above, considering both geomorphological and seismological are integrated to generate seismic microzonation maps. The final microzonation maps can be represented in three forms, 1) hazard map, 2) vulnerability map, and 3) risk map. Because earthquake loss not only depends on the hazard caused by earthquakes, but also on exposure (social wealth) and its vulnerability. Usually hazard map gives the hazard index (HI) based on hazard calculation and site conditions. Vulnerability map gives us the expected degree of losses within a defined area resulting from the occurrence of earthquakes and often expressed on a scale from 0 (no damage) to 1 (full damage). Vulnerability study includes all the exposure such as man-made facilities that may be impacted in an earthquake. It includes all residential, commercial, and industrial buildings, schools, hospitals, roads and railroads, bridges, pipelines, power plants, communication systems, and so on. Risk map will be combination of hazard classes and vulnerability classes an output risk classes. At present only hazard maps have been prepared and presented for BMP area.

Hazard index is the integrated factor, depends on weights and ranks of the seismological and geomorphological themes. Theme weight can be assigned based on their contribution to the seismic hazard. Rank can be assigned with in theme based on their values closer to hazards.

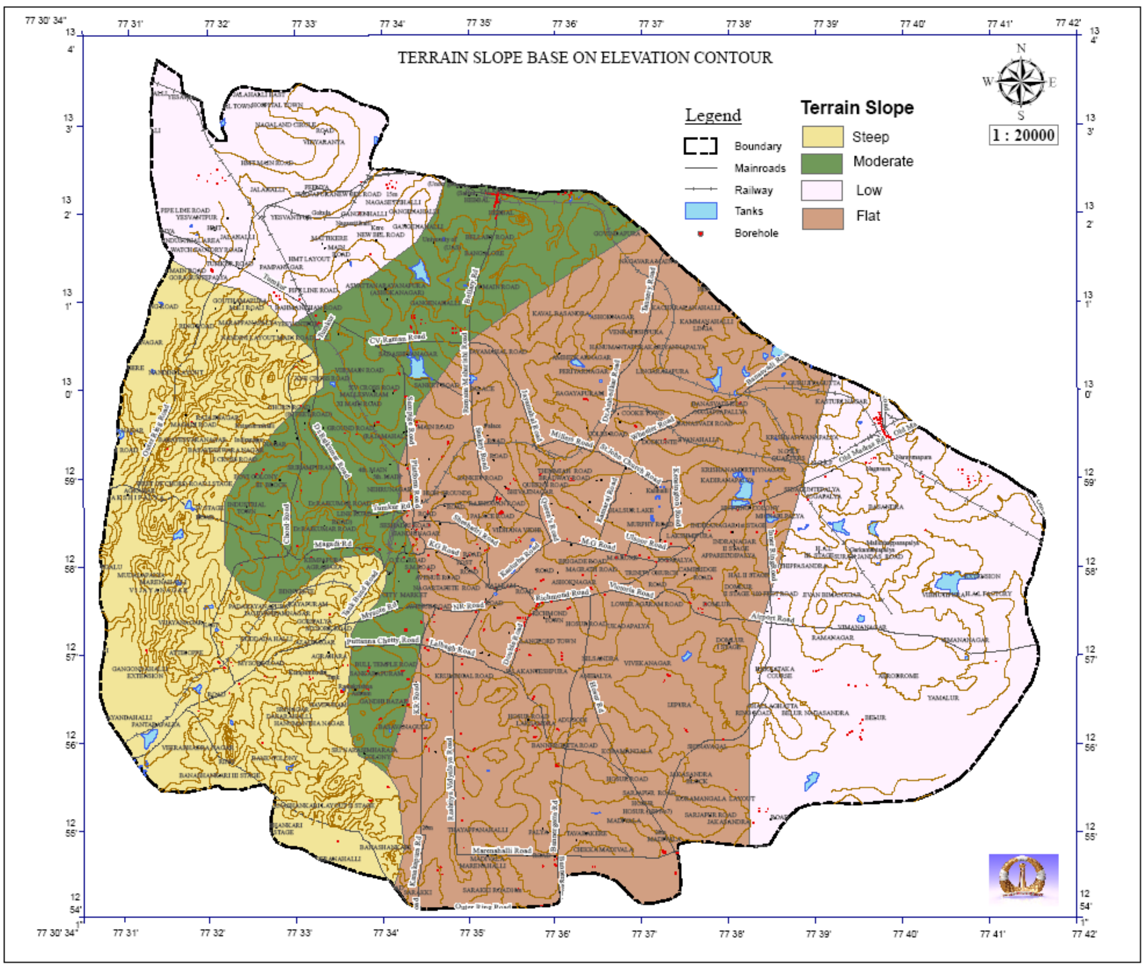


Figure 32: Terrain slope based on the elevation contour

Usually higher rank will be assigned to values, which is more hazardous in nature, for example larger PGA will have the higher rank. The contributing themes and their weights are listed below in Table 3. Once the identical weights are assigned then normalized weights can be calculated based on the pair-wise comparison matrix. Some of the attributes (like PGA and Vs) has two values for the same theme, hence both are given same weights with different percentage. The normalized weights are calculated using Saaty's Analytical Hierarchy Process (Nath, 2004).

Table 3: Themes and its weights for GIS integration

Index	Themes	Weights
PGA	Rock level PGA using DSHA-DPGA	9
	Rock level PGA using PSHA-PPGA	9
AF	Amplification factor	8
ST	Soil Thickness using borehole	7
SS	Equivalent Shear wave velocity for Soil	6
FS	Factor of safety against liquefaction	5
PF	Predominant period / frequency	4
EL	Elevation levels	3
DR	Drainage pattern	2
GG	Geology and geomorphology	1

In this method, a matrix of pair-wise comparisons (ratio) between the factors is built, which is used to derive the individual normalized weights of each factor. The pair-wise comparison is performed by calculating the principal Eigen vector of the matrix and the elements of the matrix are in the range of 0 to 1 summing to '1' in each column. The weights for each theme can be calculated by averaging the values in each row of the matrix. These weights will also sum to '1' and can be used in deriving the weighted sum of rating or scores of each region of cells or polygon of the mapped layers. Since the values within each thematic map/layer vary significantly, those are classified into various ranges or types known as the features of a layer. Table 4 shows the pair-wise comparison matrix of themes and the calculated of normalized

Table 4: Pair-wise comparison matrix of Themes and their normalized weights

Theme	PGA	AF	ST	Vs	FS	PF	EL	DR	GG	Weights
PGA	1	9/8	9/7	9/6	9/5	9/4	9/3	9/2	9/1	0.200
AF	8/9	1	8/7	8/6	8/5	8/4	8/3	8/2	8/1	0.178
ST	7/9	7/8	1	7/6	7/5	7/4	7/3	7/2	7/1	0.156
Vs	6/9	6/8	6/7	1	6/5	6/4	63	6/2	6/1	0.133
FS	5/9	5/8	5/7	5/6	1	5/4	5/3	5/2	5/1	0.111
PF	4/9	4/8	4/7	4/6	4/5	1	4/3	4/2	4/1	0.089
EL	3/9	3/8	3/7	3/6	3/5	3/4	1	3/2	3/1	0.067
DR	2/9	2/8	2/7	2/6	2/5	2/4	2/3	1	2/1	0.044
GG	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	0.022

weights. With in individual theme a grouping has been made according to their values. Then rank is assigned based on the values. Usually these ranks varies from 1 to 10, highest rank is assigned for values more hazard in nature. These rank are normalized to 0 -1 using the equation 9. The assigned ranks with normalized values are given in Table 5. Based on above attributes, two types of hazard index map are generated. One is deterministic seismic microzonation map (DSM), which is basically deterministic hazard index map using PGA from deterministic approach and other themes. Another map is the probabilistic seismic microzonation map (PSM). Probabilistic hazard index are calculated similar to DSM but PGA is obtained from probabilistic seismic hazard analysis.

Table 5: Normalized ranks of the themes

Themes	Values	Weight	Ranks	Normalized Ranks
	≤ 5.0		1	0
	5 - ≤10		2	0.25
SOT (m)	10- ≤ 15	0.2857	3	0.5
	15- ≤ 20		4	0.75
	>20		5	1
	≤ 100		4	1
EVS (m/s)	100- ≤ 200	0.2381	3	0.66
	200- ≤ 300		2	0.33
	>300		1	0
	< 1		3	1
FSL	1 - ≤ 2	0.1905	2	0.5
	> 2		1	0
	≤ 0.120		1	0
	0.12 - ≤ 0.13		2	0.25
DPGA (g)	0.13 - ≤0.14	0.1429	3	0.5
	0.14- ≤0.15		4	0.75
	>0.15		5	1
	1- ≤ 2		1	0
SRAF	2- ≤ 3	0.0952	2	0.66
	3- ≤ 4		3	0.33
	>4		4	1
	≤ 3.5		5	1
	3.5- ≤ 5.0		4	0.75
SPF (Hz)	5- ≤ 7.5	0.0476	3	0.5
	7.5- ≤9.5		2	0.25
	9.5- ≤11		1	1
	≤ 0.20	1		0
PPGA (g)	0.2- ≤ 0.22	2		0.66
	0.22- ≤ 0.24	3		0.33
	0.24- ≤ 0.26	4		1

Deterministic seismic microzonation map

Deterministic seismic microzonation map is hazard index map for worst scenario earthquake. Important factor of PGA (weight is 9) is estimated from synthetic ground motions, which are generated based on MCE of 5.1 in moment magnitude for closest vulnerable source of

Mandya- Channapatna- Bangalore lineament. Hazard index values are estimated based on normalized weights and ranks through the integration of all themes using the following equation:

$$DSM = \begin{pmatrix} \mathrm{DPGA}_W \mathrm{DPGA}_r + AF_W AF_r + ST_W ST_r + SS_W SS_r + \\ FS_W FS_r + PF_W PF_r + EL_W EL_r + DR_w DR_r + GG_w GG_r \end{pmatrix} / \sum W \qquad (10)$$

Using estimated values deterministic seismic microzonation map has been generated. Figure 33 shows the deterministic seismic microzonation map for Bangalore. Integrated GIS map shows that hazard index values vary from 0.10 to 0.66. These values are groped into four groups, <0.1, 0.10-0.15, 0.15-0.30, 0.3-0.45, 0.45-0.6 and 0.6 to 0.66. The maximum hazard is attached to the seismic hazard index greater than 0.6 at western part of Bangalore. Eastern part of city attached to a minimum hazard when compare to other areas. Western and southern part has mixed hazard and northern part has moderate hazard.

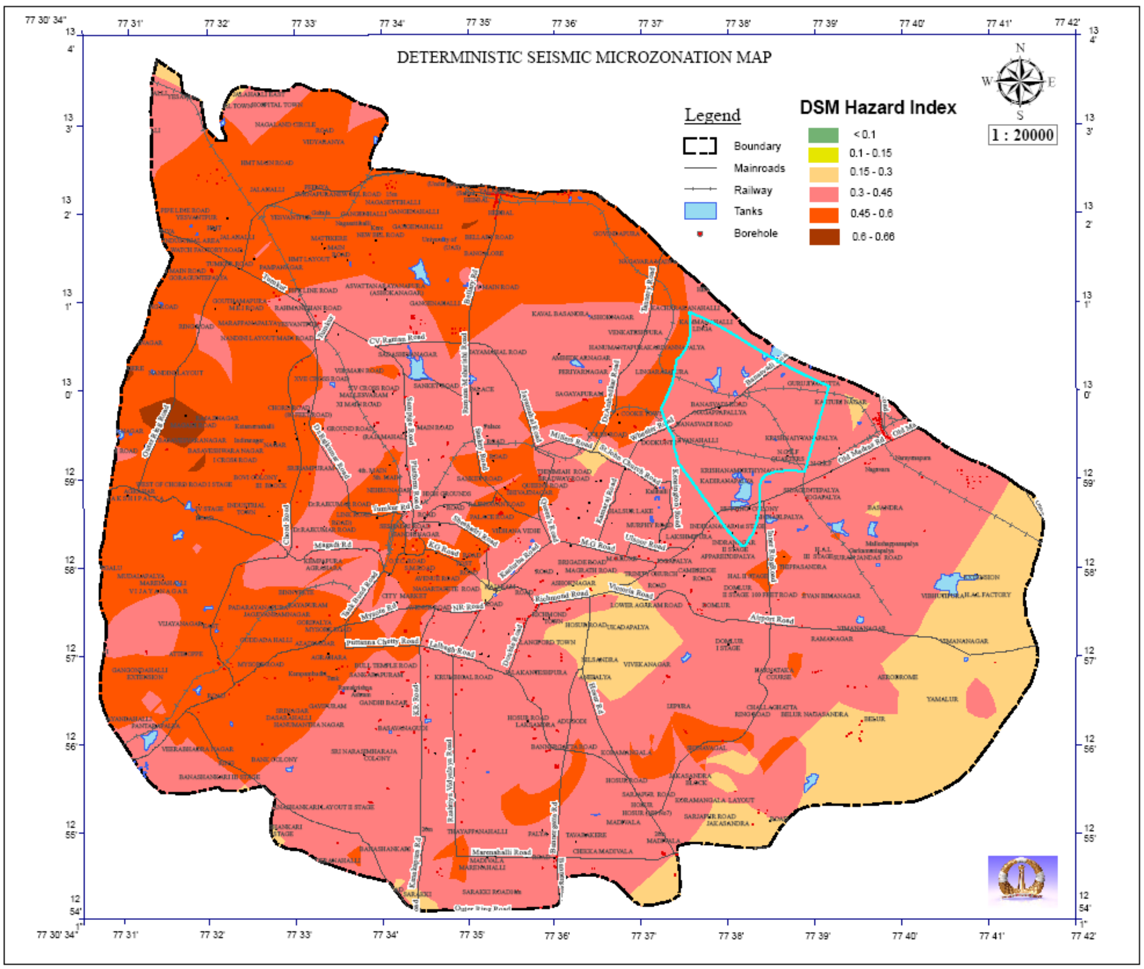


Figure 33: Deterministic seismic microzonation map

Probabilistic seismic microzonation map

Similar to DSM hazard index calculation, probabilistic hazard index has been estimated, but PGA values are taken from the probabilistic seismic hazard analysis. PGA at 10% probability of exceedance in 50 years has been estimated considering six seismogenic sources and regional recurrence relation. Based on probabilistic hazard index values probabilistic seismic microzonation map (PSM) has been generated. Probabilistic hazard index values are estimated based on normalized weights and ranks through the integration of all themes using the following equation:

$$PSM = \left(\begin{array}{l} \mathrm{PPGA}_W \mathrm{PPGA}_r + AF_W AF_r + ST_W ST_r + SS_W SS_r + \\ FS_W FS_r + PF_W PF_r + EL_W EL_r + DR_w DR_r + GG_w GG_r \end{array} \right) / \sum W \qquad (11)$$

Figure 34 shows the probabilistic seismic microzonation map based on calculated hazard index. Probabilistic hazard index values vary from 0.10 to 0.66 and has been grouped to four such as <0.1, 0.10-0.15, 0.15-0.30, 0.3-0.45, 0.45-0.6 and 0.6 to 0.66. These values are lesser that deterministic hazard index. The maximum hazard is attached to the seismic hazard index greater than 0.6 at south western part of Bangalore. Lower part (south) of Bangalore is identified as moderate to maximum hazard when compared to the northern part.

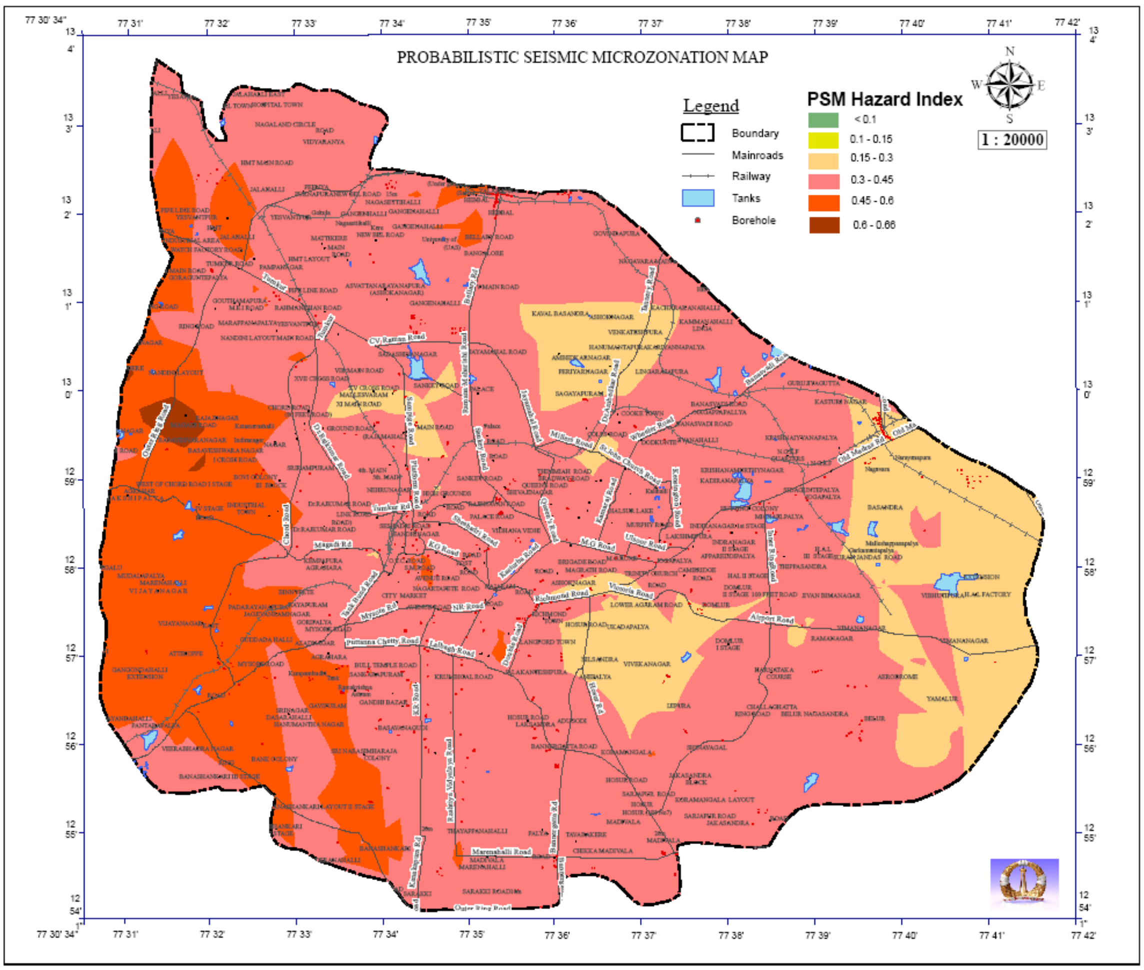


Figure 34: Probabilistic seismic microzonation map

CONCLUSIONS AND RECOMMENDATIONS

Case studies of seismic microzonation of Indian cities have been presented with brief introduction to seismic microzonation and their grade/level. Important issues related to seismic microzonation of Indian cities with reference to seismology, Grade and geological details, and geotechnical details are highlighted. For shallow overburden regions (region having engineering rock with in 30m) application of 30m average site class may not be appropriate. Such regions it is recommended to take average shear wave velocity of overburden thickness (up to the engineering rock depth). A summary of seismic microzonation of Bangalore with simple methodology is presented in this paper. Hazard maps are generated using both deterministic as well as probabilistic approaches. Probabilistic study generates the spectral acceleration map, which is essential component for building designs. It is recommended to generate surface level spectral acceleration maps using probabilistic approach. Probabilistic hazard map for particular return period will be more useful for vulnerability and risk analysis. Even though different hazard index maps are generated for Indian cities, these maps are developed considering different number of themes with weights and ranks. There is no global match in hazard index values. Hence, specification about number of themes, weights and ranks need to be recommended in near future. As a first level, several themes have been considered to generate hazard maps.

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