PROBABILISTIC SEISMIC HAZARD ANALYSIS OF WARANGAL REGION

Submitted in partial fulfilment of the requirements

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Doctor of Philosophy

by

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CERTIFICATE

This is to certify that the thesis entitled “PROBABILISTIC SEISMIC HAZARD ANALYSIS OF WARANGAL REGION” being submitted by Mr. MOHAMMAD MUZZAFFAR KHAN for the award of the degree of DOCTOR OF PHILOSOPHY to the faculty of Civil Engineering of NATIONAL INSTITUTE OF TECHNOLOGY WARANGAL is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for award of any degree.

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DECLARATION

This is to certify that the work presented in the thesis entitled “Probabilistic Seismic Hazard Analysis of Warangal region” is a bonafide work done by me under the supervision of Dr. G. Kalyan Kumar and was not submitted elsewhere for the award of any degree.

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Abstract

Earthquakes are the natural geophysical hazards that have an adverse effect on humans and the environment. Earthquakes were initially assumed to occur only at the tectonic plate boundaries, but some of the earthquakes at Koyna (10^{th} December 1967), Bhadrachalam (13^{th} April 1969), Ongole (3^{rd} December 1987), Jabalpur (21^{st} May 1997), Latur (29^{th} September 1993) and Bhuj (26^{th} January 2001) emphasized that the intra-plate region is also prone to deadly earthquakes. The devastating effect of any seismic event can be decreased considerably by evaluating the seismic hazard at the area of interest and designing the buildings accordingly. It is noteworthy that the peninsular India (PI) region is vulnerable to moderate magnitude earthquakes and it is suggested that there be the site-specific hazard studies considering the local seismicity. Though Peninsular India has witnessed some of the catastrophic earthquakes, understanding of seismic hazard seems limited. In the present work, a probabilistic seismic hazard analysis including site characterization and site effects have been performed for the newly formed Warangal Urban District, Telangana, India.

Earthquakes are caused by the release of energy from the stressed faults in the Earth's interior which causes huge damage to property and life. The dynamic response of soil has an immense effect on the extent of damage to occur by an earthquake. The seismic waves at a particular site are affected by the medium within which they propagate. Therefore, a comprehensive understanding of soil properties up-to a depth of 30 m is necessary since the seismic waves generated by a sledgehammer effectively travels up-to a depth of 30 m only. The sites considered in the study was characterized based on the geotechnical properties obtained by conducting the Multi-channel analysis of surface wave (MASW) method. MASW uses the shear wave velocity of soil as a proxy for site characterization. The MASW

test was carried out at two major locations within Warangal. The sites were characterized based on the recommendation provided by National Earthquake Hazard Reduction Program.

Probabilistic seismic hazard analysis for Warangal district was performed by incorporating the logic tree approach. The standard Cornell-McGuire method has been adopted considering different seismic zones. The area of influence chosen has a radius of 500 km with NIT Warangal at its centre. An earthquake catalogue for the period 1800 AD to 2016 AD has been compiled and homogenized using global empirical relationships. Alternative models have been considered for seismic zoning scenario, completeness analysis of earthquake catalogue, maximum magnitude and ground-motion prediction equations (GMPEs) in the logic tree approach by assigning normalized weights to each model, thereby reducing the epistemic uncertainty. Seismic hazard has been calculated using the CRISIS software, and presented as the peak ground acceleration (PGA) and pseudo-spectral acceleration (PSA) maps at 5% damping for spectral periods T=0.05, 0.1, 0.5 and 1 s at 2% and 10% probability of exceedance in 50 years period. The results obtained were compared with IS: 1893-1 (2016) and NDMA (2011) and they were found to be in good agreement.

The soil strata above the bedrock alter the frequency content of the seismic waves (i.e. amplification or attenuation) depending on the arrangement of soil layers, their depth and geotechnical properties. Estimation of earthquake response for local site conditions is an important aspect of building design. The effect of localized soil strata on bedrock motion has been addressed by conducting ground response analysis. 1D ground response analysis is carried out at different sites within Warangal using DEEPSOIL software. A higher PGA has been observed at surface level when compared with PGA values obtained at bedrock level suggesting seismic wave amplification in Warangal due to subsoil condition.

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PGA	Peak Ground Acceleration
PSA	Pseudo-Spectral Acceleration
V_S	Shear wave velocity of soil
V_{S30}	Average shear wave velocity of top 30 m soil
PSHA	Probabilistic Seismic Hazard Analysis
DSHA	Deterministic Seismic Hazard Analysis
GMPE	Ground Motion Prediction Equation
MASW	Multichannel Analysis of Surface Wave
MCE	Maximum Credible Earthquake
DBE	Design Basis Earthquake
NEHRP	National Earthquake Hazard Response Program
SPT	Standard Penetration Test
Hz	Hertz
NITW	National Institute of Technology Warangal
M_w	Moment Magnitude scale
M_L	Local magnitude scale
M_S	Surwave magnitude scale
m_b	Body wave magnitude scale
CUVI	Cumulative Visual Inspection method
m_{max}	Maximum magnitude
PI	Peninsular India
UHS	Uniform Hazard Spectrum
1D	One dimensional

CHAPTER 1

INTRODUCTION

1.1 General

Earthquakes are one of the natural disasters that result in multilevel hazards like ground shaking, liquefaction, ground displacement, tsunamis and fire. The urban regions are more vulnerable to earthquakes due to poor land use, improper planning, substandard construction material and a high population density, which results in mass casualties, big economic losses and business disruption. Some of the earthquakes triggered in peninsular India (PI) that have caused large destruction and economic loss are the 1967 Koyna earthquake, the 1993 Latur earthquake, the 1997 Jabalpur earthquake and 2001 Bhuj earthquake (Bendick *et al.*, 2001; Gupta *et al.*, 1998).

Earthquakes are generally triggered by a sudden movement of ground to release the strain energy stored within the Earth's crust. The triggering of earthquakes is due to the movement of a large seismotectonic plates against one another. The occurrence of earthquakes at tectonic plate boundaries is due to active tectonic plate movement. Structures responding to earthquake ground shaking deform in a highly complex way and the design of structures to resist earthquake loading as desired is not a simple problem. Earthquake engineers need broad knowledge and a thorough understanding of all the facets of the problem. Earthquake-resistant design is adopted to protect against possible structural failures during earthquakes. The purpose of earthquake-resistant design is to build a foundation and structure that can resist a certain amount of shaking without much damage. The amount of shaking is most conveniently defined in terms of ground motion parameters.

The ground motion parameters such as peak ground acceleration, peak ground velocity and peak ground displacement are used in building codes that consider a return period of 475 years and 2475 years. A 475-years return period corresponds to 10% probability of exceedance in 50 years whereas the 2475-year return period corresponds to 2% probability of exceedance in 50 years.

One of the difficult parameters in earthquake geotechnics is to estimate the design specification of ground motion parameters. The seismic hazard assessment using the probabilistic approach presents a framework in which the uncertainties associated with location, size, effects of earthquakes and rate of recurrence are acknowledged in the evaluation of seismic hazard (Kramer, 1996; McGuire, 2001). All the uncertainties associated with probabilistic seismic hazard assessment (PSHA) are rationally quantified and integrated in a consistent way. The outcomes of PSHA are the assessment of ground motion parameters such as Peak Ground Acceleration (PGA), for a particular probability of occurrence, for a specific region or site. Seismic hazard studies are necessary for regions where no codes exist, for big infrastructure projects requiring special analysis, for developing earthquake loading regulations, and for different seismic risk management purposes.

The intensity of earthquake damage increases when soft sediments cover bedrock. The shear wave velocity up-to a depth of 30 m (V_{S30}) is an essential criterion used for site classification. The 30 m soil profile has been considered for site characterization since most of the engineering site investigation ranges upto a depth of 30m. Moreover, the seismic waves generated by sledgehammer effectively travels upto a depth of 30m. The seismic waves generated at a site are modified by the ground characteristics in which the earthquake motion progresses. Estimation of earthquake response for the local site conditions is an essential aspect of building design. The dynamic response of the soil present at a site can substantially affect seismic waves by modifying their amplitude, duration and frequency.

Seismic hazard analysis considers two approaches; the probabilistic approach and the deterministic approach. The approach should be selected by considering the sensitivity of the area and the availability of earthquake data. In the present investigation, a comprehensive seismic hazard analysis was carried out for deriving design ground motions of Warangal district, Telangana of Southern India. The subsurface dynamic site characteristics were evaluated to understand the effect of local site conditions on seismic waves. The results of the hazard analysis are presented in the form of maps showing spatial variation of peak ground acceleration and uniform hazard spectrum. The sites were characterized as per National Earthquake Hazard Reduction Program (NEHRP) classification. The variation of shear wave velocity (V_S) with depth is also presented. The outcome of the present study will benefit local authorities and policymakers in developing risk mitigation strategies during earthquake events.

1.2 Seismic Hazard Analysis

Seismic hazard analysis presents qualitative and quantitative evaluations of ground shaking risk at a particular site. The methodology for carrying out PSHA was proposed by Cornell (1968). Cornell’s approach (or method) consists of four stages in seismic hazard assessment of a particular site. The first stage is the identification of aerial seismic sources and active faults within the study area. The second stage is to identify the recurrence interval of earthquakes for different magnitude ranges in each source. The third stage is the selection of suitable ground motion prediction equations (GMPEs) for the study region based on site-specific parameters. The GMPEs predict the level of ground shaking by relating the ground-motion parameters to distance from site to source, magnitude, type of faulting and site conditions. Finally, the fourth stage is computing the seismic hazard curve considering all the data generated from the first three stages.

In the present investigation, PSHA was carried out for the Warangal district located in Telangana state, peninsular India. Warangal is an ancient city that was ruled by Kakatiya rulers from 1163 AD. The Kakatiyas have constructed many historical structures like Thousand Pillar Temple, Warangal Fort, Ramalingeswara temple. The presence of such historical structures in Warangal favoured its inclusion in the National Heritage City Development and Augmentation Yojana (HRIDAY) scheme by the Government of India with the aim of bringing together heritage conservation, urban planning and economic growth. Warangal was also selected for the Smart City Mission (2016) program by the Government of India to make it a citizen-friendly and sustainable city. It is the second-most populous city after the capital city, Hyderabad, which is at a distance of about 130 km from Warangal, Telangana. As per seismic zonation map of India (IS: 1893-1, 2016), Warangal comes under Zone III, which is a moderate seismic zone. Peninsular India comprises many active faults and lineaments. Some of the faults and lineaments present in the study region are Kaddam fault, Kinnerasani-Godavari fault and Musi lineament. Conservation of ancient historical structures from earthquake hazards is essential for future generations to understand the culture and history of the region. Any seismic activity in such a historical and populous city will have an adverse impact on the tourism industry, employment and rapid development of the area. These aspects do justify the need for seismic hazard studies of the Warangal region.

1.3 Motivation and Scope of the Present Study

The probabilistic seismic hazard analysis (PSHA) is an interesting topic both from practical and theoretical perspectives. It has drawn the attention of researches and scholars in different domains such as geotechnical engineering, structural engineering, engineering geology and engineering seismology. Some disastrous earthquakes in India like those of Uttarkashi (M_w = 6.8, 1991), Killari (M_w = 6.2, 1993), Jabalpur (M_w = 5.8, 1997), Chamoli (M_w = 6.8, 1999), Bhuj (M_w = 7.7, 2001), Kashmir (M_w = 7.6, 2005), Imphal (M_w = 6.7, 2016) and Tripura (M_w = 5.7, 2017) have exposed the vulnerability of buildings / structures to earthquakes. The seismic regulations for India have been recently upgraded by the Bureau of Indian Standards (IS: 1893-1, 2016). The country has been categorized into four seismic zones; the lowest earthquake-prone zone is zone II and the most severe earthquake-prone zone is zone V. A major portion of India falls in zone II and zone III with a PGA value of 0.1 and 0.16 respectively for maximum credible earthquake (MCE). As per Indian seismic standards, Warangal is classified as zone III for the seismic hazard of MCE with an expected ground motion of 0.16g. The area has significant stocks of important structures and valuable heritage structures.

The widespread damage sustained by buildings and structures in Bhuj after the earthquake in 2001 and in Andaman and Nicobar Islands after the Sumatra earthquake in 2004, has highlighted the deficiencies in earthquake-resistant buildings in seismically active regions of India. The intensity of earthquake damage increases when soft sediment layers overlie bedrock. The average shear wave velocity (V_{S30}) upto a depth of 30 m is an essential criteria used for site classification. V_{S30} has been analysed by many researchers to propose the amplification or attenuation of the waves. The 2001 Bhuj earthquake occurred at Bhuj but some multistory/high-rise buildings collapsed at a distance of 225 km away at Ahmedabad city (Rastogi *et al*., 2001). When seismic waves travel they get amplified by the soil properties, thereby causing large destruction. So, there is always a potential threat even from distant earthquakes if the area was built over soft soil deposits. South Indian cities like Warangal, Hyderabad, Chennai, Bangalore and Trivendrum are thus prone to future earthquakes. This fact has been evidenced by the tremors felt in Warangal during the recent Latur earthquake. Since then, the issue of seismic safety of cities and important archaeological sites has attracted considerable attention. A regional earthquake catalogue dates back to 1800 A.D. with the largest earthquake (M=6.3) that occurred at Bellary in 1843, about 417 km from Warangal. An earthquake occurred in 1969 of magnitude 5.8 at Bhadrachalam, which is at a distance of 113 km from Warangal. The tectonic features in the Warangal region (e.g., Kaddam fault, Kolleru lake fault and Godavari valley fault) are capable of generating moderate earthquakes that can cause structural damage to buildings and heritage sites which are not earthquake resistant. In this regard, the estimation of dynamic characteristics of the ground/soil using MASW will help understand the behaviour of structures from distant earthquakes.

Hence, there is an urgent need for carrying out hazard analysis for the Warangal region to develop strategies for mitigating seismic risk from future seismic events. This is accomplished by developing quantitative design ground motions for different levels of ground shaking in a more comprehensive way using a probabilistic approach. In view of the uncertainties involved in seismic hazard analysis, precise prediction of the hazard on a deterministic basis is mostly difficult. It is, therefore, preferable to perform probabilistic seismic hazard analysis where the uncertainties are considered as distributions rather than as constants. In the present study, aleatory uncertainties are handled in hazard analysis using probability theory and the logic tree approach is adopted to reduce epistemic uncertainties. The dynamic soil properties were estimated using the average shear wave velocity of top 30 m soil depth (V_{S30}). The site was characterized based on V_{S30} values recommended by NEHRP. The output from probabilistic seismic hazard analysis includes PGA values for different return periods and uniform hazard spectra. The PGA, uniform hazard spectra and spectrum compatible natural ground motion records are used as an input for site response analysis to evaluate the realistic impedance functions for seismic soil-structure interaction studies. The present thesis addresses these issues in a more comprehensive way with reference to the Warangal region.

1.4 Aim and Objectives

The main aim of the present investigation is to assess the seismic hazard for the archaeological region in South India named Warangal in Telangana State. In particular, the objectives of the present investigation are as follows:

- To study the seismic activity of Warangal region, a historical town of South India, in Telangana and to develop a homogenous earthquake catalogue.
- To evaluate a comprehensive seismic hazard assessment of Warangal city using a logic tree approach for safety evaluation of existing and future buildings.
- To develop hazard curves, and uniform hazard spectra at bedrock level, which are intended to be inputs for local site response analysis to derive surface ground motion.
- To evaluate dynamic soil properties and site characterization using shear wave velocity profile for different sites in Warangal region.
- To study local site effect and site response behaviour of soil in Warangal region.

1.5 Organization of the Thesis

The present investigation is undertaken with the idea of making a meaningful contribution to the area of development of design ground motions for seismic safety evaluation of existing structures and historical monuments and earthquake-resistant design for structures to be built in future at Warangal. This is accomplished by the following sequence of presentations:

- A brief introduction to the present investigation, scope of the present study, aim and objectives of the investigation are given in this chapter.
- In Chapter 2, a critical review of literature relevant to the area of present investigation is given. A brief overview of seismological aspects of peninsular India is presented at the beginning. A critical review of the available literature associated with PSHA is presented in later sections. Based on the critical appraisal of the reviewed literature, a procedure for the present study is identified and presented.
- Chapter 3 presents the site characterization using Multichannel Analysis of Surface Wave method and the sites have been classified as per NEHRP provisions.
- A comprehensive PSHA is carried out for Warangal district by incorporating logic tree approach. The results of this study are given in Chapter 4. Uniform hazard spectra and hazard maps were presented for the study region.
- Chapter 5 presents the 1-D site response study using the equivalent linear approach in DEEPSOIL.
- Conclusions obtained from the study are presented in Chapter 6.
- Appendix A gives a composite earthquake catalogue used for PSHA of Warangal region. A list of references is given at the end.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

Earthquakes are one of the natural hazards that are capable of causing the most extensive damage to infrastructure and human life. Every year, numerous earthquakes occur all over the world. Natural hazards can neither be predicted nor prevented. The only possible way is to take adequate mitigation steps so that the damage caused by theses calamities can be reduced. The high causalities caused by most earthquakes are due to the lack of preparedness rather than the magnitude of earthquakes. The amount of destruction caused by an earthquake depends on several factors like soil profile, density of population, magnitude and epicentre of earthquake etc. The catastrophic damage of an earthquake can be reduced significantly by accurately estimating the seismic hazard. One of the main aspects of seismic hazard mitigation is the zonation of the country or area into different seismic zones. The hazard levels in these zones are used in the formulation of regulations that have to be implemented for new building construction and retrofitting of existing buildings. The main objective of an earthquake-resistant design is to build a facility or structure such that it can tolerate a certain magnitude of earthquake without much damage (Kramer, 1996). Seismic hazard analysis is the estimation of possible failure of a structure due to an earthquake-related event which occurs during its lifetime. A probabilistic seismic hazard analysis consists of determining the site-specific earthquake characteristics (eg. peak ground acceleration) for future earthquakes considering a fixed time period (say, 50 years). Probabilistic seismic hazard analysis (PSHA) presents a framework for evaluation of seismic hazard by considering the uncertainties pertaining to location, size, recurrence relation and effects of earthquakes (Kramer, 1996; McGuire, 2001).

In this chapter, a brief review of the available literature on the seismotectonic setting of Peninsular India is presented at the beginning. A review of the relevant literature on the characterization of regional seismicity is also discussed. Subsequently, a note on uncertainties in seismic hazard assessment is outlined. A critical review of the literature associated with the probabilistic seismic hazard analysis of moderate seismicity region is given in the later part of the chapter. In the end, a critical appraisal of the reviewed literature is presented.

2.2 Seismotectonic setting of Peninsular India

Understanding earthquake hazards requires knowledge about the origin of earthquakes, characteristics of ground motion and amount of energy release and their effect on structures. All potential sources accountable for any seismic activity in the area must be evaluated. The various aspects of a historical earthquake can be studied to a great extent based on the data available and duration since the event has occurred. In the pre-instrumental era, only large magnitude earthquake events were reported. Lower magnitude events were reported with the advent of seismograph network of high sensitivity. An earthquake occurring in any part of the world is now being recorded by a number of seismograph networks installed and maintained by earthquake reporting organizations. The fact that no earthquake motions were reported by the seismograph network of a particular region does not assure that no earthquakes have occurred earlier or no earthquakes may occur in future. In the absence of a seismograph network or instrumental seismic record for a particular region, the geologic and tectonic evidence or historical seismicity must be used to uncover earthquake activity.

2.2.1 Overview of Seismotectonics of Peninsular India

The Indian peninsula is a plateau representing rivers, hills, mountain ranges, deep valleys and plains with varying elevations. The continental shelf is a Pre-Cambrian platform formed by Archaean gneisses, schists and metamorphosed rocks (Arora *et al*., 1970).

The peninsular region is considered to be a seismically stable region since very few earthquakes were recorded before the year 1965; moreover, there was no seismograph network available to record small magnitude earthquakes. After the installation of Gauribidanur array, frequent seismic activity has been recorded in different parts of Andhra Pradesh, Mysore and Madras. Some of the disastrous earthquakes recorded are the 1967 Koynanagar earthquake, 1969 Bhadrachalam earthquake, 1993 Latur earthquake and 2001 Bhuj earthquake were observed in peninsular India.

The Indian tectonic plate collides with the Eurasian plate at a velocity of 45 mm/year and rotates in anti-clockwise direction (Bilham, 2004). As shown in Figure 2.1, lines with triangles describe the active thrust zones with the northern and northeastern boundaries of the Indian plate. The hatch lines depict the trend of the mountain and the wrench movement is shown as lines with a sense of shear. The movement of the Indian plate is represented as a large arrow (Biswas and Mujumdar, 1997).

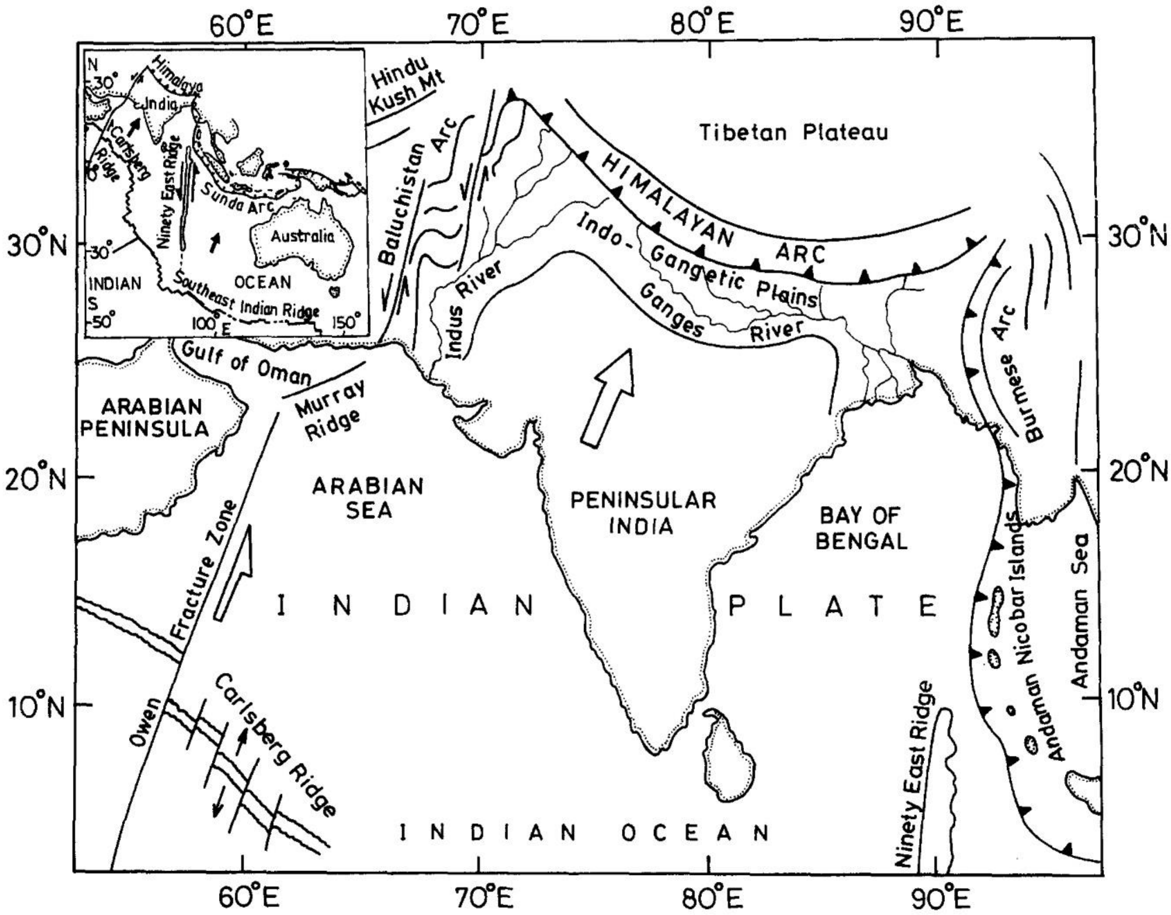


Figure 2.1 Tectonic plate of northern India representing direction of movement of Indian plate (Biswas and Mujumdar, 1997)

Wang *et al*. (2001) reported that the Himalayas move with a velocity of 37 ± 1 mm/year in northward direction relative to the stable Eurasian plate and southern India moves in the direction N26.9° ± 1.7°E at a rate of 36 ± 1 mm/year. The Indian plate indicates no significant deformation since the Himalayas and southern India show similar velocity.

An explanation for the Indian intraplate seismicity is the high stress within the Indian plate due to the collision of Indian plate with Eurasian plate. The intraplate earthquakes are observed to occur at rheologically weak areas (Gowd *et al*., 1992). Biswas and Majumdar (1997) studied the intraplate deformation, tectonic activity of Indian plate, and concluded that earthquakes show thrust faulting mechanism with north-dipping fault plane in N-S direction. The stress study concluded that the Indian plate is under N-S compression stress due to its northward movement. The flexural bending in the northern region of the Indian plate generates heterogeneous stresses within the Indian plate that results in intraplate earthquakes (Bilham *et al*., 2003).

Chandra (1977) stated that some of the past earthquakes in Peninsular India were observed over a larger area compared to earthquakes of an equivalent magnitude observed in other areas of the world. The seismic activity of the Indian plate is generally characterized by the triggering of mild and shallow-depth earthquakes. He attributed the intraplate seismicity in Peninsular India to different processes such as (a) the effect of continental margin (b) differential crustal movement (c) hot spots and (d) continental collision.

Rao and Rao (1984) describe the Indian peninsula, geologically, as the oldest landmass of the earth's crust, supposed to be a Precambrian shield confronted with tectonic and seismic activities from its geological history. The Precambrian rocks form the basement of the Cuddapah sediments considered to be the heaviest, in central Peninsular India, that has experienced uplift and volcanic activity. The eastern and western edges of the peninsula have undergone orogenic activity that results in the formation of the Ghats. The study observed the seismicity in Peninsular India from 1341 to 1983 A.D. and led to the hypothesis of a three-fold regional distribution of earthquake epicentres in conformity with three protocontinents, namely, Dharwar, Aravali and Singhbhum, and with low intracontinental seismicity.

An investigation of the source parameters of nineteen damaging earthquakes in India during the 1980s provided an opportunity for understanding the seismotectonics of PI and the Himalayas (Rastogi, 1992). The type of faulting and the orientation of fault for individual earthquakes and movement along the fault has been discussed for earthquakes that occurred in peninsular India. In Peninsular India, strike-slip faulting for earthquakes (Bhatsa, Idukki, Osmansagar, Hyderabad and Bangalore) indicates that compressional stress (N-NE) exists in the peninsula. Normal faulting (Valsad, Koyna and Sriramsagar) indicates the possibility that tension still prevails across Narmada, Godavari and Koyna rifts. In some parts of the southern peninsula, the stress is in NW-NNW direction.

Mandal (1999) observed that the earthquakes in peninsular India have focal depths within upper-crustal layers, while the Moho depth in the south Indian shield varies from 34 km to 41 km. It is concluded that the earthquakes in South India, i.e., intraplate earthquakes are due to the E-W trending weak zone movement in addition to the localized stress perturbation due to compressional ridge push, crustal density inhomogeneities and topography. It is predicted that the south Indian granulite terrain and western Dharwar may experience seismic activity in future.

Gangrade and Arora (2000) studied the seismicity of peninsular India and concluded that the region is vulnerable to earthquakes of magnitudes upto 6. It is also observed that some of the earthquakes occurred on unknown and fresh faults that had not been ruptured previously. It has been suggested that there is a possibility of future seismic activities on the tectonic lineaments in peninsular India.

Bilham *et al*. (2003) reported the collision of the Indian plate with the Tibetan plateau generated a flexural bulge on the Indian plate. The flexural bending in the northern part of India resulted in the development of heterogeneous stresses within the intraplate region, which triggered the Bhuj and Latur earthquakes in peninsular India.

Gangopadhyay and Talwani (2003) claimed that the occurrence of intraplate seismicity is due to the stress concentrators like rift pillows, buried plutons and intersecting faults within the pre-existing weak zones that build stresses and trigger earthquakes. It is also concluded that the recurrence interval for large intraplate earthquakes is longer compared with the large earthquakes at plate boundaries.

The GPS stations located at Hyderabad and Bangalore were used to study the motion of Indian plate (Catherine, 2004). The GPS station at Hyderabad shows a velocity of 37.09 ± 1.4 mm/yr, whereas the Bangalore GPS station moves at a velocity of 35.68 ± 1.7 mm/yr. The variation in velocities between two GPS stations suggests an ongoing internal deformation in peninsular India.

Roy (2006) studied the seismicity of peninsular Indian shield and suggested that the rupture process in the stress build-up region is due to the presence of fluid such as water leakage from a reservoir or during dehydration metamorphism or hydrothermal fluids from igneous intrusion. Patro *et al*. (2006) reported that fluids played an important role in intraplate earthquakes like the Latur earthquake and the Koyna earthquake.

Valdiya (2011) studied the geodynamic hotspots in India and highlighted the fact that the movement of the Indian plate is affecting peninsular India by developing elastic strain in the landmass. The non-active faults have been reactivated and some new faults have been developed as a result of the accumulated strains. There are blind faults which do not have any surface expression, yet reach the surface. An active fault generated earthquake poses low hazard due to the release of stored strain energy. Whereas in, in-locked faults, the strain energy in build-up gradually then released as high-magnitude earthquake.

Mahesh *et al*. (2012) studied the deformation rate of the Godavari rift region from GPS measurements. It has been concluded that the intraplate region has localized deformation of very low value (< 1.5 mm/yr) compared to the neighbouring regions (≤ 3.3 ± 0.5 mm/yr).

Ramkumar *et al*. (2017) reported an increase of crustal thickness from south to north in peninsular India, which itself indicates a tilt-uplift due to thrust in the Indian plate. It is considered that the Indian plate is experiencing tilt and thrust towards the north due to the difference in pressure, temperature and density beneath the tectonic plate. The drift in the Indian plate is accelerated due to the heavier lithosphere from the lava of Deccan volcanism.

2.3 Different types of magnitude scale

The earthquake magnitude is an essential parameter in seismic hazard analysis. Different earthquake reporting organisation report the earthquake magnitude in different scales. The magnitude scales generally used to determine the severity of earthquake are discussed below.

2.3.1 Intensity scale:

This is the oldest magnitude scale. Earthquake intensity is a qualitative description of the effects of the earthquake in any particular region. Some of the commonly used intensity scales are Rossi-Forel Intensity scale, Japanese Meteorological Agency (JMA) seismic Intensity scale, Medvedev-Sponheuer-Karnik (MSK) scale and Modified Mercalli Intensity scale (MMI). Of these, the MMI scale is the most commonly used intensity scale and the intensity level ranges from I (less damage) to XII (maximum damage) depending on the destruction caused by earthquakes.

2.3.2 Local Magnitude (M_L)

This scale was proposed by Richter (1935) to measure shallow local earthquakes (epicentral distance less than 600km) in southern California. The local magnitude scale is the best magnitude scale but it is not always the most appropriate scale (Kramer, 1996). It is observed that this scale will become saturated at higher magnitudes.

2.3.3 Surface wave magnitude (M_S):

This scale was based on the amplitude of the Rayleigh wave with a period of 20 sec. Surface wave magnitude scale was proposed by Gutenberg and Richter (1936) to estimate the size of distant (farther than 1000 km) and shallow (focal depth less than 70 km) earthquakes. Seismograph of any type can be used to estimate the surface wave magnitude since it is based on the maximum ground displacement amplitude (Kramer, 1996).

2.3.4 Body wave magnitude (m_b):

The deep-focus earthquakes have little amplitude of the surface to estimate the earthquake magnitude accurately using surface wave magnitude scale. The magnitude of an earthquake is, therefore, calculated using the maximum amplitude of the first few cycles of P wave motion with a period of 1 second (Guternberg, 1945) which is least influenced by the focal depth.

2.3.5 Moment magnitude (M_W):

The above magnitude scales (M_L, M_S, m_b) measure the earthquake magnitude considering the amplitude of motion. The main drawback of these magnitude scales is the magnitude saturation for earthquakes of large magnitude. To overcome the magnitude saturation effect, the moment magnitude scale was formulated. In this scale, the earthquake magnitude is measured with respect to the energy released. The rupture along the fault, during an earthquake, creates an equal and opposite force that produces a force couple. The seismic moment thus created will be calculated using the equation 2.1.

$$M_o = \mu A D \tag{2.1}$$

Where, M_o is the seismic moment, μ is the modulus of rigidity of the rocks involved in the earthquake, A is the area of the fault along the fault, D is the average displacement. The moment magnitude can be calculated using equation 2.2

$$M_W = \frac{2}{3} log_{10} M_o - 10.7 \tag{2.2}$$

The units of M_o is in dyne-cm. Nowadays, moment magnitude is the widely used magnitude scale in seismic hazard analysis.

2.4 Magnitude conversion

The relations between various magnitude scales depend on the observation errors, source characters such as fault geometry, stress drop etc. (Heaton *et al*., 1986). It is preferable to use the magnitude conversion relationships that have been developed from the earthquakes which occurred in that particular region. Due to the unavailability of sufficient data required for the development of a satisfactory relationship existing magnitude conversion equations are used instead. One of the most widely used magnitude scales for defining the size of an earthquake is the moment magnitude (M_w) scale because at higher magnitudes this scale doesn't saturate. (Scordilis, 2006). Several relationships were developed to convert other magnitude scales to M_w (Heaton *et al*., 1986; Johnston, 1996; Shedlock, 1999; Papazachos *et al*., 2002; Scordilis, 2006).

2.5 Plate tectonics

Earth's crust includes seven major plates and other minor plates and these plates move relative to each other. The plate boundaries are classified into three types depending on the relative movement of the plates i.e., spreading ridge boundaries, subduction zone boundaries and transform fault boundaries. High seismic activity was observed along the subduction and transforms plate boundaries. The earthquakes are divided into two types based on the location of epicentre. Earthquakes at the plate boundaries are named interplate earthquakes whereas earthquakes triggering within the plate are termed intraplate earthquakes. The difference between interplate and intraplate earthquakes is the recurrence time, fault visibility, energy release and energy dissipation. In intraplate earthquakes, the recurrence time is comparatively more, the faults visibility is less, the energy release is low and energy dissipation is very slow.

As the study area is far away from the plate boundaries, the earthquakes considered in the present study fall under the category of intraplate earthquakes. The magnitude and frequency of the intraplate earthquakes are less than that of interplate earthquakes. It is estimated that 10 % of the earthquakes occurring worldwide are intraplate earthquakes.

2.6 Magnitude recurrence relationship

The fundamental element in the analysis of the seismic hazard of a particular area is the evaluation of the recurrence interval for earthquakes of various magnitudes. The recurrence relationship reported by Gutenberg and Richter (1944) was adopted to predict the annual earthquake occurrence rate and the relationship is given in equation 2.3.

$$\log_{10}(\lambda_M) = a - bM \qquad (2.3)$$

where, a and b are region-specific constants that can be estimated using least square regression analysis; m_0 and m_u are the lower and upper bound magnitudes respectively, specific for seismic source. When the data available is not complete for a sufficiently long period of time to get statistically appropriate values of a and b, these parameters can be obtained from the maximum likelihood method (Kijko and Sellevoll, 1989; 1992) using mixed data files comprising of complete parts of the earthquake catalogue and extreme part for a very long historical period. The frequency-magnitude relationship is assessed based on the consideration of an extreme event. The ratio of *a/b* is a better description of seismicity of an area compared to *a* or *b* values.

The lower limit of earthquake magnitude “m_0” in seismic hazard analyisis is defined as the minimum magnitude that generates ground motions capable of damaging engineering structures. The lower limit of earthquake magnitude changes depending on the types of structures. The other reason to consider the lower limit of earthquake magnitude is the statistical data of smaller magnitude earthquakes is usually not reliable. The appropriate minimum magnitude value to be considered in PSHA has not been clearly defined, however, a m_0 = 4.0 seems to be usually regarded as lower limit in hazard analsis. Nevertheless, for sensitive structures like petroleum storage buildings, nuclear power plants that are responsive to low magnitude earthquakes, m_0 value can further be decreased. There is also an upper limit, “m_1”, for earthquake magnitude. The largest possible earthquake likely to occur in the considered region is termed as the upper limit of earthquake magnitude. The upper limit can be determined by using statistical methods or increasing the maximum observed magnitude by some margin.

2.7 Ground Motion Prediction Equations (GMPEs)

Ground motion prediction equations estimate the ground motion parameters, like peak ground acceleration, at the site of interest located at a distance from the epicenter. The seismic waves generated during an earthquake will propagate in all directions and attenuate with respect to distance depending on the soil properties. The GMPE gives an estimate of ground motion parameter as a function of distance from source to site, magnitude, type of fault and subsoil properties. Most of the GMPEs are developed from the statistical analysis of strong ground motion records and are updated when additional records are available with time. The parameters which are used to measure the ground motion amplitude are peak horizontal displacement (PHD), peak horizontal velocity (PHV) and peak horizontal acceleration (PHA). The PHA values are most generally used to define the strong ground motion because of their direct association with the inertial forces (Kramer, 1996). The PHV parameter is preferable to characterize strong ground motion with intermediate frequencies for flexible structures like bridges and tall buildings.

GMPEs are widely classified into two categories i.e., intraplate or stable continental shield regions and interplate earthquake regions. The classification of GMPEs is based on the dissipation of seismic energy. It is noted that plate boundaries dissipate seismic energy at a faster rate compared to mid-plate regions. Some important GMPEs developed for active tectonic regions (interplate) are Joyner and Boore (1981), Sadigh *et al*. (1997), Sharma (1998), Campbell and Bozorgnia (2003), Boore and Atkinson (2008), Abrahamson *et al*. (2013), and Chiou and Youngs (2014). The GMPEs suggested for the stable continental shield regions are Atkinson and Boore (1995), Toro *et al*. (1997), Atkinson and Boore (2006), Raghu Kanth and Iyengar (2007), Pezeshk *et al*. (2011) and Graizer (2016) that are helpful for seismic hazard analysis of low seismic regions.

One of the first GMPE proposed for India was developed by Sharma (1998). He proposed a GMPE for the Himalayan region. Subsequently, more GMPEs were developed for the Himalayan region by Jain *et al*. (2000) and Saini *et al*. (2002). For the microzonation of Delhi, Iyengar and Ghosh (2004) have modified the relation suggested by Sharma (1998) by including the standard deviation of the error term. Raghu Kanth and Iyengar (2007) and NDMA (2011) proposed the GMPE for peninsular India. Cramer and Kumar (2003) analysed the attenuation aspect of seismic waves at peninsular India (PI) during the 2001 Bhuj earthquake and concluded that the attenuation characteristics of PI are comparable to that of Eastern North America. Therefore, the attenuation relations developed for the ENA region can also be used for peninsular India region.

2.8 Seismic Hazard Analysis

The seismic hazard analysis is based on two alternative approaches – probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA). Even though the methodology adopted in these two approaches are entirely different, they can complement each other in estimating the seismic hazard. Most of the research and discussions are focused on identifying the appropriate method for seismic hazard analysis. The following subsections give a brief overview of two approaches.

2.8.1 Deterministic Seismic Hazard Analysis (DSHA)

Deterministic approach considers the maximum earthquake hazard event, either assumed or realistic. DSHA approach considers the seismic data, geological features and seismic sources that are closest to the site to estimate the ground motion at the site. DSHA comprises four steps; defining sources of earthquake, estimating the potential of each source of generating earthquakes, selection of appropriate GMPE and determining the ground motion parameter. The methodology involved in DSHA is presented as a schematic diagram in Figure 2.2. The limitation of DSHA is that, it doesn't consider uncertainties involved in location or magnitude of earthquake. The governing earthquake in DSHA is anticipated to act at the source nearest to the site thereby yields upper-bound values for ground motion. Hence, DSHA approach is considered in the estimation of seismic hazard for important and sensitive structures like hazardous waste contaminant facilities, bridges, big dams, nuclear power plants etc.

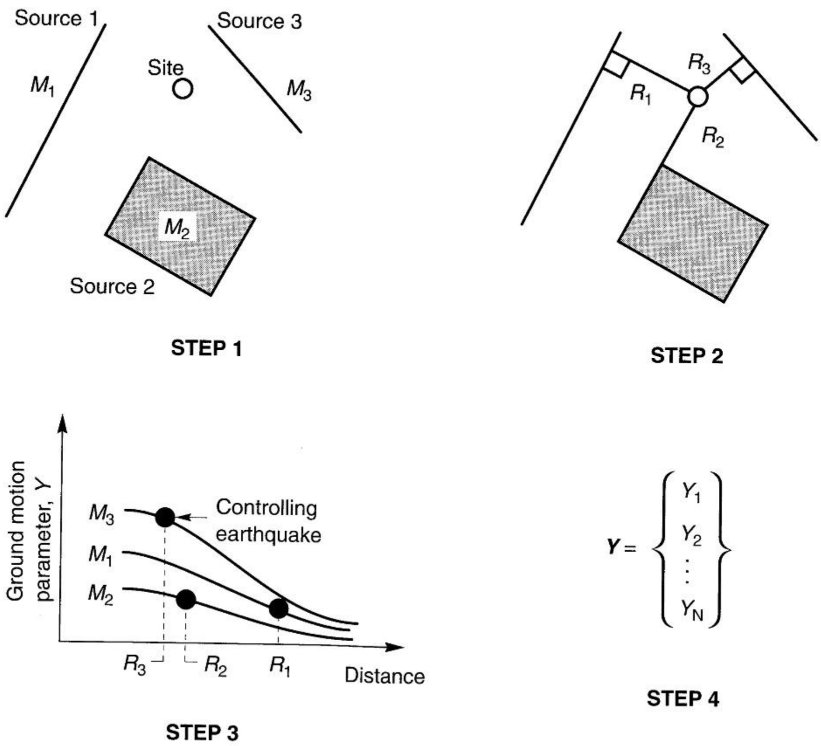


Figure 2.2 Different steps involved in DSHA (Kramer, 1996)

The first attempt in India to perform DSHA was by Parvez *et al*. (2003). He developed seismic hazard map of India by classifying 40 seismic zones based on geodynamics, tectonics and seismicity (Parvez *et al*., 2003). A maximum PGA value of 0.08g was reported for peninsular India. Sitharam and Anbazhagan (2007) adopted deterministic approach to evaluated seismic hazard for Bangalore using the GMPE suggested by Iyengar and Raghu Kanth (2004). The deterministic approach of seismic hazard was considered to develop hazard maps for North East India by Joshi *et al*. (2007). Mohan *et al*. (2008) assessed the Himalayas, a seismically active region, for seismic hazard assessment using the deterministic approach. DSHA for Chennai was performed by Boominathan *et al*. (2008) by incorporating the local site effects and reported the values of spectral acceleration ratio and for characteristic site period Chennai city. Kolathayar *et al*. (2012) analysed the seismic hazard of India with the deterministic approach using a code written in MATLAB. The PHA was calculated by dividing the region into grids of size 0.1°

× 0.1°. It was concluded that the seismic hazard at plate boundaries is higher compared to interplate regions. Haryana state was studied for seismic hazard by Puri and Jain (2016) using the deterministic approach. The region was divided into 12 seismic zones. Ground motion parameters were predicted using the attenuation relation proposed by NDMA (2011).

2.8.2 Probabilistic Seismic Hazard Analysis (PSHA)

The assessment of seismic hazard involves quantification of uncertainties in magnitude, location of earthquake, recurrence rate, and attenuation characteristics of seismic waves. The adoption of probabilistic approaches in seismic hazard analysis provides a framework for identifying, quantifying and combining these uncertainties in a rational way (Kramer, 1996). PSHA quantifies the rate of exceeding various ground motion levels at a particular site considering all possible earthquakes. In this section, a brief review of the previous work attempted by investigators as relevant to the topic of investigation is presented.

The numerical/analytical approach to PSHA was first formalized by Cornell (1968). The study of earthquakes and methodologies for earthquake hazard analysis in the last few decades were developed primarily to assess seismic hazards of tectonically active areas. Of late, researchers have begun exploring seismic characteristics of stable continental regions which were once considered to be free from seismic hazard. This was true before the last few decades but some catastrophic earthquakes like the 1997 Jabalpur earthquake and the 2001 Bhuj earthquake in the stable continental regions changed this perception.

The seismic hazard analysis using the probabilistic approach was adopted for many Indian cities like Delhi (Iyengar and Ghosh, 2004), Bangalore (Anbazhagan *et al.*, 2009), Mumbai (Desai and Choudhury, 2014) and West Bengal (Maiti *et al.*, 2017).

The basic steps in PSHA are presented in Figure 2.3. The important steps in PSHA method are:

(i) Identifying and characterizing potential seismic sources

(ii) Characterizing earthquake recurrence rate

(iii) Evaluation of ground motion using GMPEs

(iv) Determination of mean annual rate of exceedance of ground motion parameter by considering uncertainties in magnitude, location and attenuation relation.

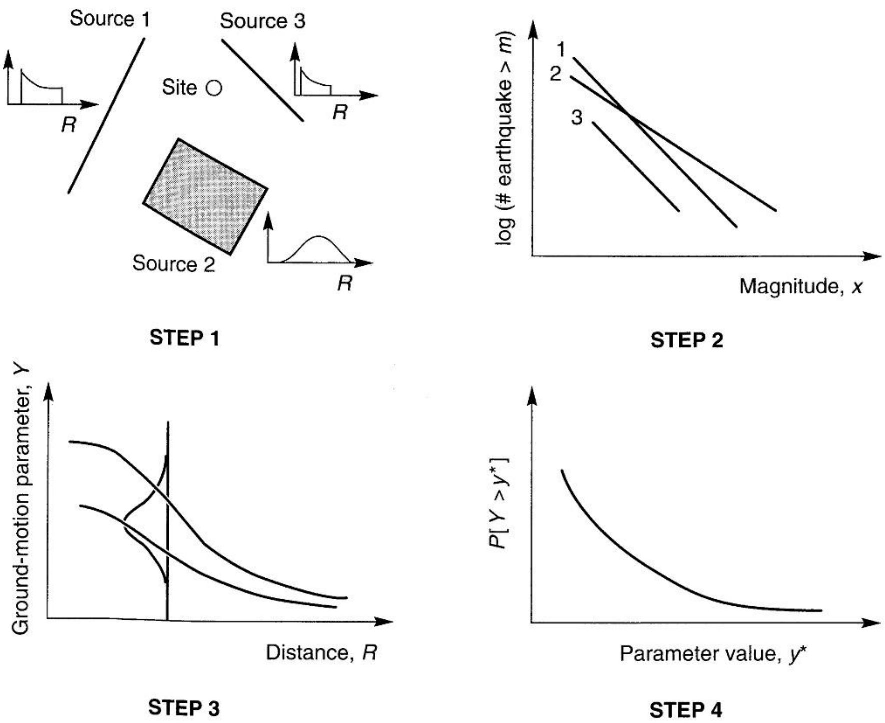


Figure 2.3 Steps involved in PSHA (Kramer, 1996)

Although the deterministic approach of seismic hazard analysis is based on maximum earthquake hazard scenarios regardless of how unlikely they may be, in PSHA, uncertainties in location of earthquake, magnitude and time are taken into account by considering all probable earthquake scenarios in terms of location and magnitude that may affect the structures at the site of interest and frequency of their occurrences. In PSHA, the uncertainties in attenuation of ground motion by distance, the spatial location of faults or boundaries of area sources are described by a probability distribution and systematically integrated into the results via probability theory. Therefore, contrary to the result obtained from DSHA i.e., a single ground motion value, PSHA provides the possibilities of different ground motion values that may occur at the site. PSHA takes into account the effect of all significant distances from the site and all possible earthquake magnitudes that may occur in the region. Considering the unpredictability in the occurrence of earthquakes with respect to magnitude, space, time and other sources of uncertainties, the probabilistic approach is the suitable tool for assessment of seismic hazard.

2.9 Consideration of Uncertainties

PSHA takes into account the uncertainties related to randomness in input parameters characterizing seismicity and selection of GMPEs. The types of uncertainties associated in PSHA studies are categorised as aleatory and epistemic uncertainties. The aleatory uncertainty relates to the uncertainty in the data used and accounts for the randomness associated with the result given by a particular model. The epistemic uncertainties is due to the incomplete knowledge in the predictive models and variability in the interpretations of the data used to develop the models. Epistemic uncertainty can be reduced with increase in data and information about the model.

In PSHA, aleatory uncertainties in the parameters are described by suitable probability distributions and are included directly in the calculations by quantifying the appropriate statistical parameters (i.e., standard deviation, coefficient of variation). In GMPE, the aleatory variability is given by the standard deviation of the mean ground motion. The incomplete knowledge of predictive models causes epistemic uncertainty. Epistemic uncertainty is considered by including alternative models and aggregating them through logic tree methodology.

2.10 Logic Tree Approach

As discussed in the previous section, different models and input parameters generate different seismic hazard curves. A simple and systematic way to reduce the epistemic uncertainties is to make use of the logic tree approach. The logic tree in PSHA comprises several nodes and branches that reflect the uncertainty in the selection of different models and input parameters assigned to each model. The node represents an uncertain assumption such as, a model or input parameter. The nodes must be arranged such that the dependent nodes are located to the right while independent ones are placed to the left. Branches spreading from each node are discrete alternatives for that assumption, model or input parameter. A subjective weight is assigned to each of these branches based on the confidence of one model over another. The combined weight for all branches at a particular node should add up to unity. For each seismic hazard curve, a subjective weight (discrete probability) which is equal to the product of weights on the branches leading to its corresponding end branch is assigned. The logic tree approach allows a formal characterization of epistemic uncertainty by including alternative models in the analysis (Bommer *et al*., 2005; Phung *et al*., 2018). The different models incorporated in PSHA using logic tree approach are source parameters, magnitude recurrence rate, evaluation of maximum probable earthquake, attenuation relations etc. The logic tree in PSHA can be arranged with as many branches as possible but it will make the hazard computation tedious. It should be noted that the logic tree approach is used in almost all PSHA studies to reduce epistemic uncertainties.

2.11 Site characterization and Ground Response Analysis

Analysis of the past earthquake damages shows that the severity of damage is affected by local geological characteristics and geotechnical parameters, earthquake source and path characteristics, structural design and construction features. The information of the geotechnical, geomorphological and geological data along with seismotectonic details are necessary to evaluate the ground response. In order to get a better estimate of ground response, details of the soil profile have to be collated using geotechnical or geomorphological methods. The three important features which affect the ground motion are the site, source and path characteristics.

The severe effects of site amplification were reported during the Bhuj earthquake in 2001. The damage was observed upto 250 km away from the epicentre (Rastogi *et al*., 2001). The main cause of damage at such faraway regions is the amplification of seismic waves due to subsoil characteristics. The subsoil characteristics can be identified by various in-situ geotechnical tests such as standard penetration test, cone penetration test, dilatometer test and pressuremeter test. In recent years, geophysical tests such as MASW (Multichannel Analysis of Surface Waves) and SASW (Spectral Analysis of Surface Waves) have become the preferred practitioner tools, as they yield more accurate data at a much faster rate, and allow for the measurement of soil characteristics at a much deeper level.

The GMPEs predict the ground motion parameters that provide the acceleration values at bedrock level. The surface level acceleration values will vary considerably from that of bedrock acceleration values due to the effect of seismic waves on basins and sediment-filled valleys. The methods proposed by Field (2000) and Steidl (2000) modify GMPEs to include the site effects in the estimation of surface level PGA values.

Seismic site classification based on top 30 m average shear strength is a standard practice (IBC, 2009). The site characterization for Chennai was performed using MASW and SPT data by Boominathan *et al*. (2008). 1-D equivalent linear ground response analysis were performed using SHAKE91 software for 38 representative sites and obtain the ground motion parameters. The site characterization for Bangalore was also performed by

Anbazhagan *et al*. (2009) using MASW and SPT values and 1D ground response analysis in SHAKE2000 was carried out to determine the local site effects. The region was classified as Class C and D based on the recommendations of NEHRP. Sil and Sitharam (2016) conducting MASW test to obtain the dynamic behaviour of soil and developed site-specific design response spectrum as per NEHRP procedure for the Agartala city. The ground response analysis and field tests were conducted at waste landfills in India that indicated the soil has less shear stiffness and high amplification of seismic waves due to the loose filling (Naveen *et al*., 2019).

2.12 A critical appraisal of the reviewed literature

Peninsular India (PI) is one of the oldest and seismically stable landmasses of the Indian plate. However, a recent study of seismicity divulges that the region has encountered devastating earthquakes of magnitude greater than 6.0, emphasising the necessity of seismic hazard assessment of PI. The collapse of numerous buildings and the large number of fatalities generated by the Bhuj earthquake point to a relatively high probability that similar powerful earthquakes may occur, especially along the frontal fault system. The south Indian peninsular is no more an exception in this regard.

Seismic activity is generally low within the interior of continents except in regions close to some of their boundaries. A few such areas of lower seismic activity called shield regions are located in Australia, Peninsula India and Africa (Srivastava and Ramachandran, 1985). A substantial amount of literature and earthquake data are available for the northern part of the Indian plate, whereas, very little information is available regarding the seismological aspects of peninsular India. In order to suggest mitigation strategies for an earthquake scenario, it is a prerequisite that the seismic hazard of the site is realistically estimated. Seismic hazard studies are required for areas where no codes exist, for determining the earthquake loading for sensitive projects like dams and power projects, for revising existing loading regulations, or for other earthquake risk management purposes. Data on historical seismicity of southern India is rather incomplete, and records on fault movement are currently not available, thereby requiring data compilation for a comprehensive understanding of the seismotectonic regime and seismogenic zones of the southern peninsular shield. Nevertheless, the recent network of seismographic stations, remote sensing facilities and advances in paleoseismology have helped to address these problems to some extent. Several sequences in the processing of the raw earthquake catalogue, aimed at estimating different parameters characterizing the seismicity of the seismogenic zones to be utilized in the hazard computations, are explained in detail in the literature. These sequences include the declustering of the catalogue, estimation of completeness periods for different magnitude classes and determination of magnitude-frequency recurrence relationships for different seismogenic zones.

The process of evaluating seismic hazard has undergone a considerable amount of improvement and its utilization since being introduced by Cornell (1968). Along with big magnitude earthquakes, smaller magnitude earthquakes are also influential in hazard analysis due to high occurrence rates. It is noted from the literature review that the deterministic approach is practised differently in various regions of the world and even in diverse applications. PSHA provides results with consistency and the practice is almost the same throughout the world. PSHA can be performed using different methods depending on how one defines the seismicity model.

It is to be noted that whether PSHA or DSHA is used in seismic hazard assessment, the primary input data are basically the same (the data of all previous earthquakes around the site of interest, the geological data of the region, the seismotectonic map, local site conditions and the ground motion attenuation behaviour).

Seismic hazard analysis performs a significant role in the design of earthquake-resistant structures by determining hazard parameters such as the peak ground acceleration and uniform hazard spectrum. Over the last few decades, a large amount of research work has been undertaken in the area of PSHA of low to moderate seismicity areas and tectonically active territories around the world. In the case of the South India peninsula, very few studies have been attempted with regard to seismic hazard assessment. Recently, major emphasis has been given for seismic microzonation of most of the Indian cities; in view of this; further in-depth studies are warranted in the form of a quantitative assessment of seismic hazard expected at a particular site for future seismic events of the region.

2.13 Summary

This chapter presents an overview of different methodologies and studies carried out in the field of seismic hazard analysis. Critical facilities and structures such as nuclear and thermal power plants, dams and heritage structures, as well as the setting of new industries, require design ground motion data which are as accurate, homogeneous and complete as possible so that hidden tectonic features may be revealed and seismic hazard assessed. Hazard assessments are invariably a blend of an expert's appraisal and interpretations of seismic events and statistical descriptions of these events. Analyses of the frequency of occurrence and magnitude of events, their spatial density and their potential effects are essential components of hazard assessment for buildings and heritage structures. This chapter has explored a systematic approach to studying the seismotectonic and regional seismicity of the study area based on a thorough review of previous studies and presented a brief review of the available literature on PSHA of low to moderate seismicity areas of the world.

The information presented in the chapter is related to the overall seismotectonic setting of Peninsular India in general and regional seismicity of Warangal region in particular. A few studies related to these aspects are briefly reviewed in the chapter. A review of the current state-of-the-art in PSHA was carried out for the other regions which have similar tectonic features and seismicity to that of Peninsular India.

Seismic site characterization conducted for the study region is outlined in the next chapter followed by the results obtained thereof.

CHAPTER 3

SITE CHARACTERIZATION OF WARANGAL

3.1 Introduction

Earthquakes are one of the natural geophysical hazards that have an adverse effect on humans and the environment. They are caused by the release of energy from the stressed faults in the Earth's crust. The dynamic response of soil during a seismic event depends on strength characteristic and cyclic nonlinear behaviour of the ground. The seismic waves generated at the source are modified by the medium in which the earthquake motion progresses. The dynamic response of the soil present at a site can substantially affect seismic waves by varying its amplitude, frequency and duration.

The intensity of earthquake damage increases when bedrock is overlain by soft soil. The average shear wave velocity (V_{S30}) upto a depth of 30 m is an essential criterion used for site classification. The soil profile upto a depth 30 m has been considered for site characterization since most of engineering site investigations, like boring, cover a depth up to 30m. V_{S30} can be analyzed to propose the amplification or deamplification of the region (Liu *et al*., 2017). The best example of site amplification is the 1985 Michoacán earthquake in Mexico City which sustained catastrophic damage even though the fault rupture was 350 km away. The amplification of earthquake motion in Mexico City was primarily due to the presence of soft deposits (Singh *et al*, 1988). The 2001 Bhuj earthquake witnessed the damage of high-rise buildings at Ahmedabad, located at a distance of 225 km from source (Rastogi *et al*., 2001). Furthermore, the recent 2015 Hindu Kush earthquake recorded tremors at New Delhi which is nearly 1300 km away from the epicenter. This is due to low shear wave velocity (V_{S30}) of soil at New Delhi which is varying from 185 m/s to 495 m/s (Satyam and Rao, 2008). Peninsular India was considered to be aseismic in nature, but some of the historical evidence such as the 1993 Killari earthquake, the 1997 Jabalpur earthquake and the 2001 Bhuj earthquake show that peninsular India is also prone to strong earthquakes. There is always a potential threat even from distant earthquakes if the area was built over soft soil deposits. Therefore, there is a need for characterization of the site to understand the behaviour of seismic waves.

Subsurface properties of a site can be determined by laboratory and / or field tests. Accurate measurements of soil properties in the laboratory can only be achieved by replicating similar field conditions. In-situ tests are field tests where the soil properties are measured in their existing state which allow for the complex effects like structural, thermal and chemical conditions to be taken into account. The various field tests are Steady-state vibration (Rayleigh Wave) test, Seismic refraction test, Seismic reflection test, Suspension logging test, Dilatometer test, Multi-channel analysis of surface wave (MASW) test, spectral analysis of surface wave (SAWS) test, Seismic downhole test, Seismic cone test, Seismic cross-hole test, Standard penetration test, Cone penetration test and Pressuremeter test.

Several seismic hazard studies were started in India after the Bhuj earthquake in 2001. Seshunarayana and Sundararajan (2004) studied the subsurface layers of Jabalpur region using MASW method. Satyam and Rao (2008) conducted MASW tests at 118 sites in Delhi and observed that the V_{S30} ranges between 400 to 480 m/s at rocky locations and 120 to 250 m/s in trans Yamuna area. Anbazhagan *et al*. (2009) conducted MASW tests at 58 sites in Bangalore and classified the region according to NEHRP provision. A major portion of the city was categorized as class C and class D whereas a smaller portion was classified as class B. Sairam *et al*. (2011) conducted MASW test at 63 sites within

Gandhinagar, Gujrat and classified the soil according to NEHRP provision. The site amplification was also studied using microtremor records that suggests buildings more than three stories require careful design. Sil and Sitharam (2014) proposed a relation between V_S and SPT-N for Agartala region by conducting 27 MASW test across the city. Kirar *et al*. (2016) conducted 10 MASW tests and 10 SPT tests for Roorkee region and developed an empirical relationship between V_S and SPT-N values. Singh and Singh (2019) estimated V_S profile for the Assam basin and concluded that the V_S value ranges from 200 m/s to 450 m/s.

The study area Warangal is classified as Zone III according to IS: 1893-1 (2016) zonation map of India, which is a moderate seismic area. To study the amplification or de-amplification effect of seismic waves for Warangal sites, seismic site characterization is a prerequisite. Therefore, an attempt has been made to study the subsurface characteristics of the Warangal sites.

In this chapter, Multi-channel analysis of surface wave method (MASW) (Park *et al*. 1999) is used for site characterization. MASW uses shear wave velocity as a proxy for site characterization and evaluation of site amplification (Borcherdt, 1994). This method is more cost-effective compared to other geophysical techniques, considering the overall cost, field operation and data analysis. The shear wave velocity obtained from MASW and the density of soil are used to calculate the shear modulus of soil. Shear modulus is one of the most critical engineering parameters associated with material stiffness. The parameters obtained from MASW test can be used in the ground response analysis. The average shear wave velocity of top 30 m is considered for seismic design procedures by NEHRP to categorize a region/area into different classes. NEHRP classification systems are acknowledged by seismologists all over the globe as the basis for seismic design manuals (BSSC, 2003; Cox *et al*., 2011).

Seismic site characterization of any study area can be carried out using different non-invasive methods which include microtremor array method, horizontal to vertical spectral ratio (HVSR), refraction microtremor (ReMi), spatial autocorrelation (SPAC), reflection/refraction, surface wave (SW), frequency-wavenumber (f-k), spectral analysis of surface waves (SASW) and MASW. In this study, the MASW method is used to study the site characterization owing to simplicity of data collection and analysis.

3.2 Multi-channel Analysis of Surface Wave (MASW)

MASW is a universally accepted technique adopted for analysis of spatial variations of V_S, classification of subsurface material, and calculation of dynamic soil properties. The MASW test uses Rayleigh waves in the determination of shear wave velocity profile. Many investigations have been carried out to explore the application of V_S in different areas such as geological, geophysical, geotechnical and environmental engineering. The seismic waves were used to identify the presence of oil/gas using reflection seismology (Mendel, 1981). MASW technique can be used to identify weak spots in bedrock (Miller *et al*., 1999), underground anomalies and fracture zones (Parker and Hawman, 2012). Ivanov *et al*. (2006) identified an existing fault by mapping a known shallow depth fault zone using MASW. Bitri *et al*. (2013) assessed the extent and quality of ground compaction at a construction site using MASW and cone penetration test. Park *et al*. (2018) undertook periodic checks of the subsurface profile beneath a built road using MASW.

MASW test measures the velocity from the time taken to travel the surface waves from the source to the receiver. The source of surface waves can be an active source or a passive source. The passive source is the source of seismic waves created by wind, cultural noise, moving traffic, etc. at some distance from the geophone. The active source is the source where vibrations are created intentionally at a definite location. Seismic energy for active source surface wave surveys can be created by a sledgehammer (impulsive source). In this study, a sledgehammer is used to strike the ground since it is a low-cost, readily available item and tends to be energetic enough for most near-surface investigations. The sledgehammer which is hit on the ground generates seismic waves that are recorded by the seismograph. The recorded seismogram is used in the analysis of shear wave velocity. A typical schematic setup for active MASW survey is shown in Figure 3.1.

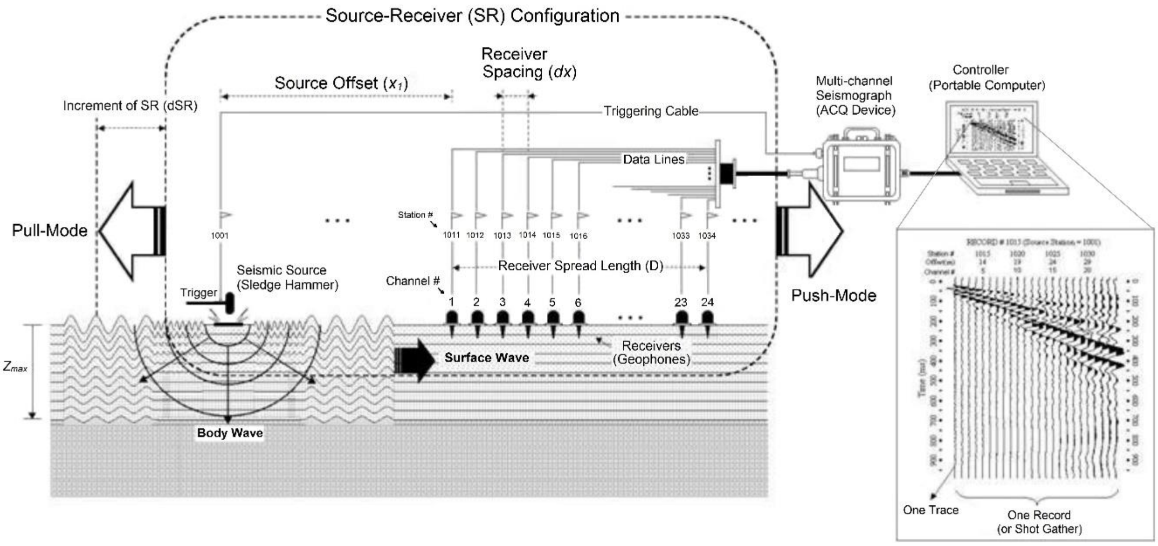


Figure 3.1 A schematic view of active MASW survey

3.3 Seismic Site Characterization

Catastrophes such as landslides, excessive ground shaking, foundation failure and liquefaction during an earthquake depend on local subsoil properties. The reason for such catastrophic damages is due to the characteristics of seismic waves that modify due to the local soil properties, which are termed Local site effects. Seismic site characterization is an important part of hazard studies that defines the safety against earthquake hazards such as liquefaction, ground shaking and lateral spreading based on the strength of the subsurface soil at the site. Geophysical tests such as MASW have become popular for soil classification owing to its accuracy, low time and subsoil stratification details till the deepest depths.

Seismic site classification is based on the average shear strength of top 30 m of soil. The estimation of top 30 m average of shear wave velocity of soil (V_{S30}) is given in equation 3.1.

$$V_{S30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n}\left({d_1}/{V_s^i} \right)} \tag{3.1}$$

Where, d_i is the thickness of each layer below ground level, Σd_i is the total depth of interest which is 30 m as per IBC (International Building Code, 2009) and NEHRP (National Earthquake Hazard Reduction Program; BSSC, 2003) site classification scheme, V_s^i is shear wave velocity at depth d_i. V_{S30} is the 30 m average shear wave velocity.

Seismic site classification chart as per Eurocode-8 (EC8, 2004) and NEHRP (BSSC, 2003) have been presented in Table 3.1 and 3.2 respectively.

Table 3.1 Seismic Site Classification as per Eurocode 8 (EC8, 2004)

Site Class	**Soil Description**	**V_{S30} (m/s)**
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180

E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.	-
S_1	"Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content.	< 100
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1	-

Table 3.2 Site classification as per NEHRP (BSSC, 2003)

NEHRP site class	Material description	V_{S30} (m/s)
A	Hard Rock	> 1500
B	Firm and hard rock	760 – 1500
C	Dense soil, soft rock	360 – 760
D	Stiff soil	180 – 360
E	Soft clays	< 180
F	Special sandy soils, e.g. liquefiable soils, sensitive clays, organic soils, soft clays > 3m thickness, PI > 20	-

3.4 Data Acquisition

MASW test was performed using 24 channel seismic Geode recorder (Geometrics make) with single geode operating software. The seismic waves generated by active source were captured by 4.5 Hz frequency geophones. The spacing of geophones (24 nos.) was maintained at 2 m interval along the linear line survey such that the total length extends upto 48 m. The nearest geophone from the source was also at 2 m interval. The receivers were connected to a multichannel recording device. The seismic waves were generated by hitting a thick iron plate (30 cm × 30 cm × 2 cm) with a sledgehammer of 6.5 kg weight. This process was repeated for 5 shots at different locations along the geophone array as shown in Figure 3.2.

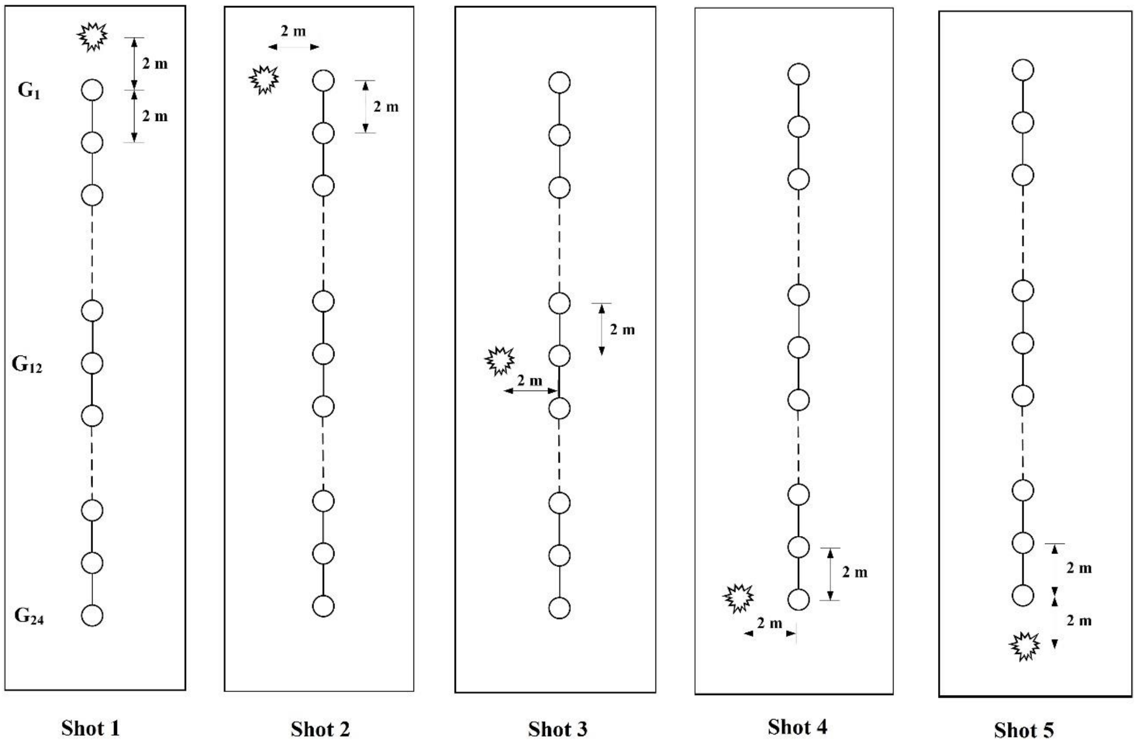
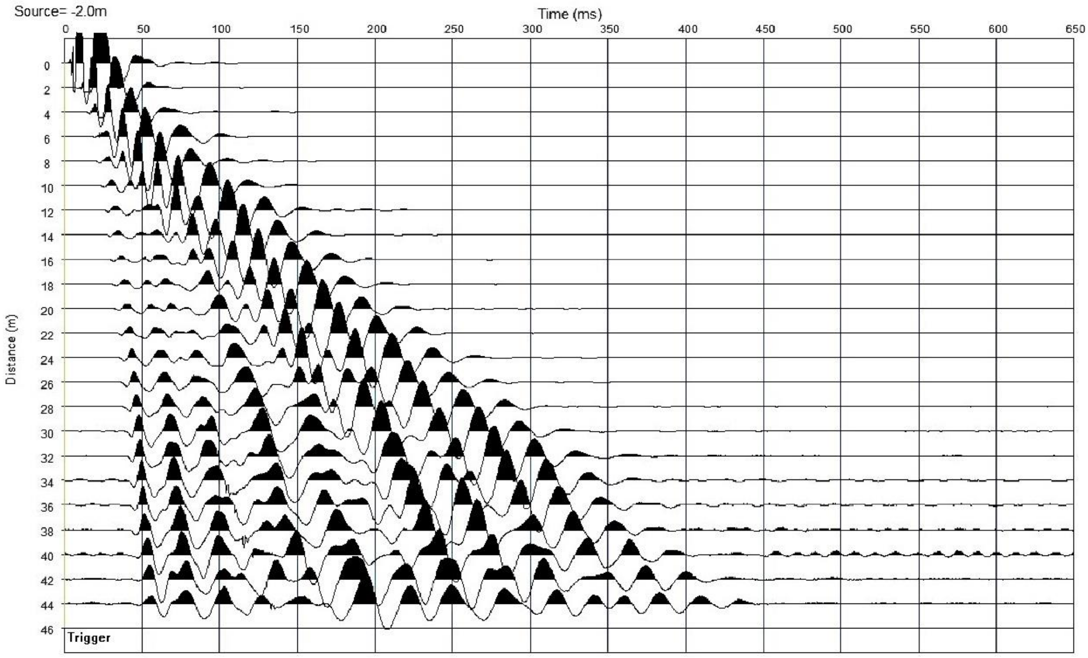


Figure 3.2 The 5 shot locations adopted at each test site

The test setup for MASW along with the arrangement of geophones is shown in Figure 3.3 (a) and (b). The generated seismic wave was recorded for a time of 1000 millisecond with an interval of 0.5 millisecond. A typical wave recorded by a geode seismograph is shown in Figure 3.3c. The geophone arrays attached to the data acquisition unit was used to record the signals for post-processing.

(a) (b)



(c)

Figure 3.3 (a) Geode seismograph (b) Linear array of geophones

(c) A typical wiggle plot

3.5 Data Analysis

Seismic waves of smaller wavelengths are regulated by the ground characteristics of shallow depth whereas; the seismic waves of larger wavelengths are affected by the deeper parts of the earth. This phenomenon known as dispersion, causes waves of different wavelengths to travel at different speeds with respect to depth. As a result, different wavelengths arrive at different times on a seismic record. The process of producing a V_S profile comprises three phases, namely generation of seismic waves, development of phase velocity vs. frequency plot (dispersion curve) and inverse computation of the developed dispersion curve.

The obtained input was analyzed using SeisImager/SW package which consists of Pickwin, WaveEq and GeoPlot modules. The Pickwin Module identifies the first break of generated seismic waves (s- and p-waves) and develops Phase velocity-Frequency plot, for extraction of dispersion curve. A typical phase velocity-frequency plot and dispersion curve are shown in Figure 3.4 and 3.5 respectively. The dispersion curve should be extracted very carefully since inaccurate estimation of dispersion curve could cause inversion to generate an imprecise shear wave velocity profile. Moreover, airwaves, guided waves, refracted waves, and surface wave of higher modes can emerge as noise and prevent accurate extraction of the dispersion curve. WaveEq module uses the dispersion curve as an input to generate the first V_S model. Later, an iterative inversion process is used to develop the final V_S profile. Inversion is a statistical technique based on the least-square method that changes the first model to reduce the difference from the observed data. Observed and estimated dispersion curves were compared and the Root Mean Square (RMS) error was monitored. The iteration is stopped when the RMS error between the observed and estimated dispersion curve is found to be less than 5%. The shear wave velocity profile is obtained from the GeoPlot module.

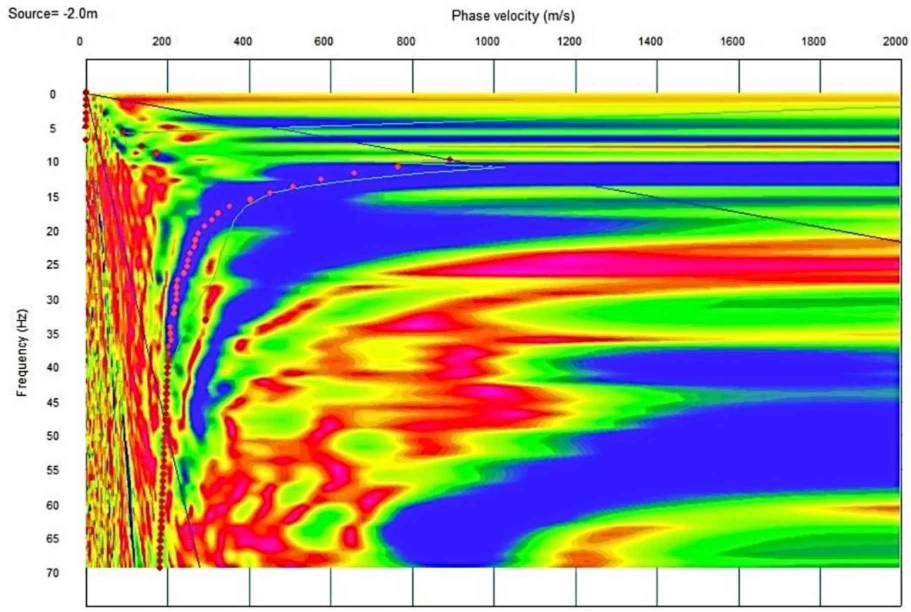


Figure 3.4 A typical plot of Phase velocity vs. Frequency (b) Dispersion curve

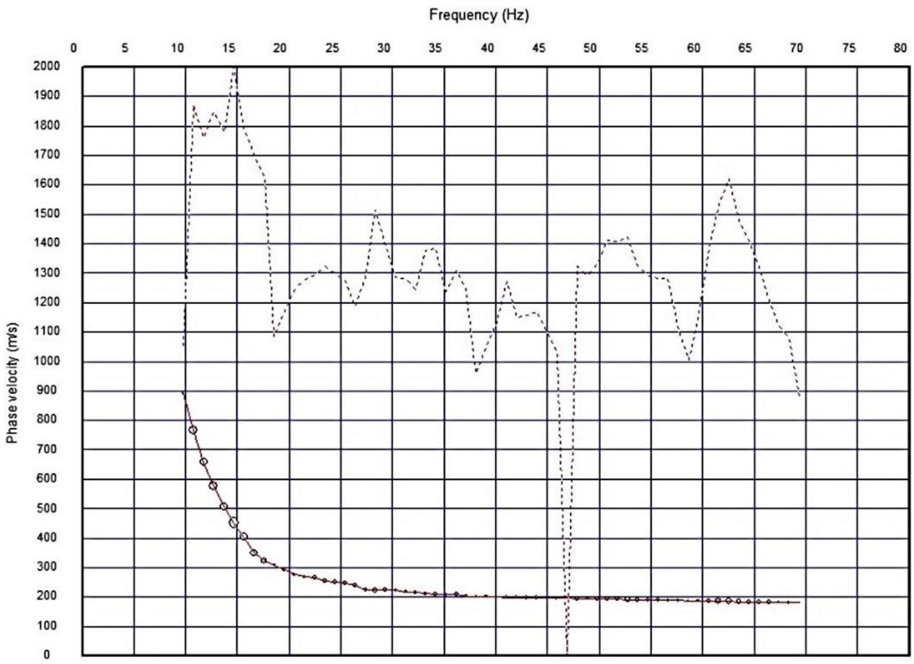


Figure 3.5 A typical plot of Dispersion curve

3.6 Results

The frequency of vibration and amplification of seismic waves is affected by the properties of soil upto a depth of 30 m. The shear wave velocity profile for NITW site is shown in Figure 3.6. The shear wave velocity varies from 138 m/s at the upper level to 1127 m/s at the bottom level for NITW site. The average shear wave velocity for the top 30 m depth at NITW is 446.3 m/s. The site is classified as Class C (dense soil / soft rock) according to NEHRP based on the average value of V_{S30}. The classification of subsoil at NIT Warangal according to NEHRP classification based on the shear wave velocity is shown in Table 3.3.

The shear wave velocity at Thousand Pillar temple varies from 196 m/s at the top level to 859 m/s at the lower level of the soil. The average shear wave velocity for the top 30 m depth is 433.6 m/s. The shear wave velocity profile at Thousand Pillar temple is shown in Figure 3.7. The site is classified as Class C (dense soil / soft rock) as per NEHRP based on the average value of V_{S30}. The classification of subsoil at Thousand Pillar temple according to NEHRP classification based on the shear wave velocity is shown in Table 3.4.

Table 3.3 Classification of subsoil at NIT Warangal based on the shear wave velocity

Depth (m)	Range of shear wave velocity (m/s)	Type of soil
0 – 1.0	$V_S < 180$	Soft Clay
1.0 – 7.0	$180 > V_S > 360$	Stiff Clay
7.1 – 13.2	$360 > V_S > 560$	Dense Sand
13.3 – 26.8	$560 > V_S > 760$	Soft Rock
> 26.8	$760 > V_S > 1500$	Firm Rock

Table 3.4 Classification of subsoil at Thousand Pillar temple based on the shear wave velocity

Depth (m)	Range of shear wave velocity (m/s)	Type of soil
0 – 2.3	$V_S < 180$	Soft Clay
2.4 – 7.0	$180 > V_S > 360$	Stiff Clay
7.1 – 18.1	$360 > V_S > 560$	Dense Sand
18.2 – 26.8	$560 > V_S > 760$	Soft Rock
> 26.8	$760 > V_S > 1500$	Firm Rock

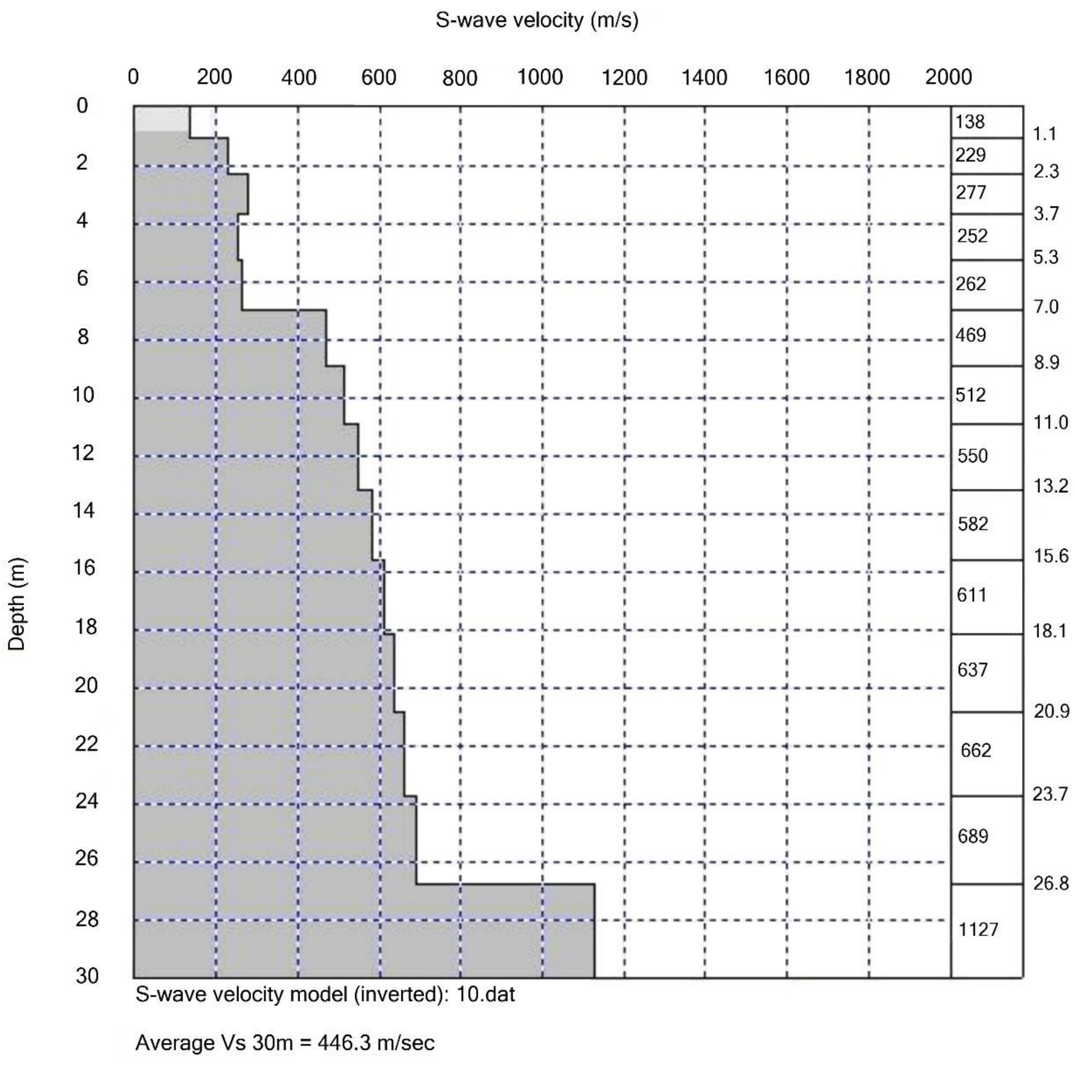


Figure 3.6 Shear wave velocity profile at NIT Warangal

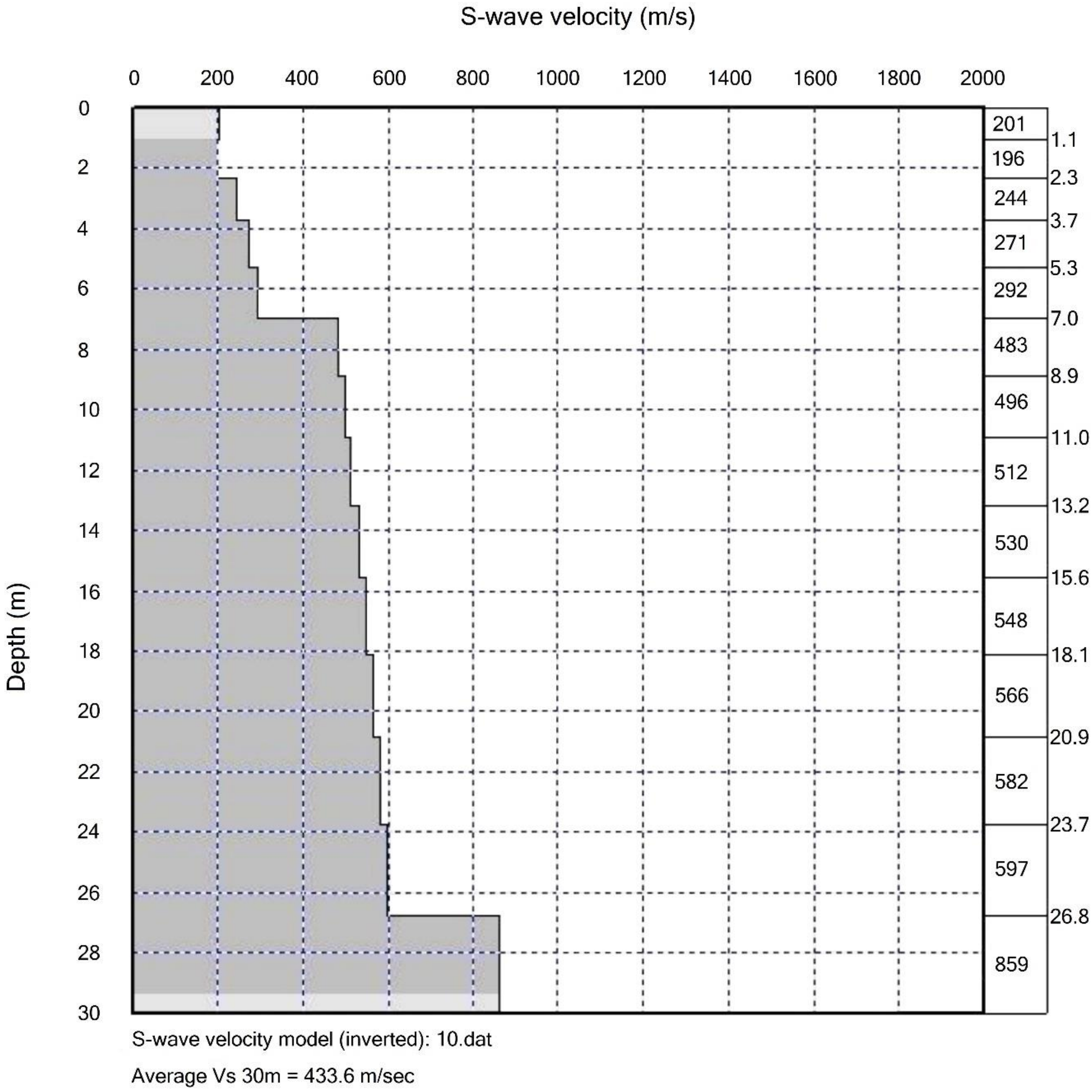


Figure 3.7 Shear wave velocity profile at Thousand Pillar temple

3.7 Summary

This chapter mainly dealt with site characterization which included determination of V_{S30} profiles for selected sites in Warangal. The V_{S30} profiles were obtained from MASW test performed at NIT Warangal and Thousand Pillar temple. MASW technique is based on seismic refraction method which is a non-destructive geophysical method that's well suited for subsoil investigations. The dispersion curve was developed from the generated active seismic waves. The seismic refraction method was used to obtain V_S variation profile after post-processing (inversion of dispersion curve) of MASW data using SeisImager/SW software. Based on average shear wave velocity of 30 m depth (V_{S30}), the site was classified as class C as per NEHRP.

The average shear wave velocity (V_{S30}) value was used for seismic site classification which can be suggested as a prerequisite for the seismic design manual suggested by NEHRP. The sites classified as class C are subjected to less intense shaking and therefore the structures must be designed for seismic resistance. The design for structures in class C region is comparatively economical than other classes. These values can be used for site response analysis and seismic microzonation studies.

CHAPTER 4

PROBABILISTIC SEISMIC HAZARD ANALYSIS

4.1 Introduction

Earthquakes are one of the main causes of destruction all over the world. Every year millions of earthquakes occur at several places with different magnitudes. Some of the earthquakes are so small that they can only be detected by sensitive seismographs while others are so massive that a whole region is shattered from ground shaking, landslides, floods and tsunamis. The amount of destruction caused by an earthquake in a certain area depends on its magnitude, epicentral distance, focus, soil properties and structural design of infrastructures. The main reason for the large amount of destruction is due to the lack of building code enforcement (Das and Sharma 2016) and poor construction practice in earthquake-prone areas (Humar *et al*. 2001). IS: 1893-1 (2016) broadly classified India into 4 zones depending on the earthquake intensity. The localized site behaviour within a zone cannot be predicted accurately since the effect of an earthquake depends on the site geology and variation of soil properties and site effects. Some of the earthquakes that caused severe damage in the last decade within peninsular India, indicating the negligence in the implementation of risk reduction programs. Seismic hazard assessments are a prerequisite to mitigate the effects of destructive earthquakes on human life. Seismic hazard assessment is useful for earthquake resistant design in the construction industry and risk analysis studies. Many researchers have undertaken seismic hazard studies at regional level (Anbazhagan *et al*. 2017), national level (Nath and Thingbaijam, 2012) and global level (Ordaz *et al*., 2014). Some of the recent seismic studies initiated for important cities in India are Delhi (Mohanty *et al*., 2007), Krishnagar (Chowdhuri *et al*. 2008), Bangalore (Anbazhagan *et al*., 2009), Kachchh (Singh *et al*., 2011), Gandhinagar (Sairam *et al*., 2011), Agartala (Chowdhuri *et al*., 2012), Kolkata (Nath *et al*., 2014), Mumbai (Desai and Choudhury, 2014), Jaipur (Chakrabortty *et al*., 2018) and Vishakhapatnam (Putti *et al*., 2019).

The dynamic response of soil has a marked effect on the extent of damage caused by earthquakes. The strength characteristics and cyclic nonlinear behaviour of the ground regulate the dynamic response during a seismic event. The generated seismic waves at a particular site are modified by the medium in which the earthquake motion progresses and the site characteristics. Estimation of earthquake response for the local site conditions is an important aspect of building design. The dynamic response of the soil present at a site can substantially affect seismic waves by changing its amplitude, frequency content and duration. The intensity of earthquake damage increases when soft sediments cover bedrock. The best example of site amplification is the 1985 Michoacán earthquake in Mexico City that experienced catastrophic damage even though the fault rupture was 350 km away from the city. The amplification of earthquake motion in Mexico was primarily due to the presence of soft deposits (Singh et.al, 1988). The 2001 Bhuj earthquake occurred at Bhuj but some multistory/high-rise buildings collapsed at a distance of 225 km in Ahmedabad (Rastogi *et al*., 2001). Furthermore, in the recent 2015 Hindu Kush earthquake whose epicentre was 82 km southeast of Feyzabad, Afghanistan, the tremors were felt even at New Delhi which is nearly 1300 km away from the epicentre. It's because the average shear wave value (V_{S30}) of New Delhi is varying from 185 m/s to 495 m/s (Satyam and Rao, 2008). Therefore, it is always recommended to consider local soil aspects and shear wave velocity for assessing site-specific seismic hazard (Mandal *et al*., 2013). When seismic waves travel, they are amplified by soil properties thereby causing huge destruction. So, there is always a potential threat even from far away earthquakes if the area was built over soft soil deposits.

The main objective of the present chapter is to carry out the probabilistic seismic hazard assessment of Warangal Urban district at surface level considering the local site effects. Warangal is the second-largest city in Telangana with a moderate climate, which favours agricultural activity as well as industrial and social development. The study region is located in Peninsular India which includes many active faults and lineaments such as the Kaddam fault, Kinnerasani-Godavari fault and Musi lineament etc. In addition, the region comes under Zone III with a PGA value of 0.08g (IS: 1893-1, 2016). Although the seismic activity in the study region is moderate, compared to the northern regions, there is high seismic risk due to poor construction of buildings and dilapidated structures without earthquake resisting design, the presence of archaeological sites and high population density. Any seismic activity in such a densely populated region will have an adverse impact on the economic development of the region. These aspects necessitate the need for an appreciation of seismic hazard studies of Warangal region.

The basic requirement in seismic hazard study is to recognize the earthquake magnitude recurrence pattern and the identification of the seismic sources. Accordinlgy, a homogeneous earthquake catalogue was compiled from the available sources that provide valuable data required to understand the seismicity of the study region. A seismotectonic map has been developed using ArcGIS software that provides information required to identify potential seismic zones. In this study, two seismic zoning scenarios have been considered. The seismic zones help in identifying vulnerable areas that assist in providing the necessary earthquake resistant design corresponding to hazard level in each zone. In the first scenario, the whole study region is considered as a single seismic zone, whereas, in the second scenario, the region is divided into four zones based on the geology and spatial variation of past seismicity. The completeness analysis of earthquake catalogue and the maximum magnitude were assessed by considering two alternative methods. A total of four ground-motion prediction equations (GMPEs) were considered to calculate the peak ground acceleration (PGA) and pseudo-spectral acceleration (PSA) values. Different alternative models of each input parameter i.e., the zoning scenario, completeness analysis, maximum magnitude and GMPE were assigned normalized weights and were incorporated in hazard analysis through the logic tree approach. The seismic hazard has been estimated and presented in the form of maps showing the spatial variation of PGA and PSA maps at 5% damping for spectral periods T=0.05, 0.1, 0.5 and 1 second. The shear wave velocity explained in the previous chapter was further used to study the ground response analysis using DEEPSOIL software.

4.2 Study Region and Tectonics

The study region considered for seismic hazard assessment is the newly formed Warangal Urban district in Telangana state, India. Warangal is the second-largest city in Telangana after the capital city, Hyderabad, with many ancient monuments like the Thousand Pillar Temple, Warangal Fort, Kush Mahal and Bhadrakali Temple that make it a historic city. The presence of ancient structures favoured Warangal to be chosen for "National Heritage City Development and Augmentation Yojana (HRIDAY)" scheme by the Government of India with the aim of bringing together heritage conservation, urban planning and economic growth thereby emphasizing a holistic development. Warangal has also been selected in the Smart City Mission (2016) program by the Government of India to make it a citizen-friendly and sustainable city.

A number of sedimentary basins are present in peninsular India (PI). The sedimentary basins present in the influence region are Godavari Graben, Cuddapah basin and some parts of Eastern Ghats. These areas are well-known and can be classified as moderate seismic regions from the history of past seismicity (Gupta, 2006). Peninsular India, an intra-plate region of Indian plate, was considered to be aseismic in nature but the unexpected earthquakes at Koyna (10th December 1967), Latur (29th September 1993), Jabalpur (21st May 1997) and Bhuj (26th January 2001) emphasized that the intra-plate region is also prone to deadly earthquakes. The Indian plate collides with the Eurasian plate at a velocity of 50 mm per year (Kumar *et al*., 2007) that results in the development of flexural bulge at central India thereby triggering intraplate earthquakes (Bilham *et al*., 2003). The seismological and geological data identifies the presence of many active faults and lineaments in different locations in the study region. The location and orientation of linear seismic sources i.e., lineaments and faults were identified from Seismotectonic Atlas of India (Geological Survey of India, 2000). These lineaments and faults were digitized using ArcGIS software to develop the seismotectonic map. The majority of the earthquake epicentres are close to the active faults and major lineaments. In the study region, a total of seventeen active faults and six major lineaments have been identified with varying lengths.

4.3 Database

An earthquake catalogue of a particular area includes details of past earthquakes such as the location, depth and magnitude, which helps in identifying the seismic activity of that region. The earthquake catalogue compiled for the current research covers historical and instrumental seismic events that have happened in a circular area of 500 km radius, with NIT Warangal as centre. The geographical coordinates of NIT Warangal are 17.98N latitude and 79.53E longitude. Many researchers have attempted to compile an earthquake catalogue of peninsular India; Chandra (1977) compiled data for the period 1594-1975, Rao and Rao (1984) for the period 1341-1984, Srivastava and Ramachandran (1985) for the time span 1839-1900, while Guha and Basu (1993) collected earthquake data of magnitude greater than 3.0 for Peninsular India. Recently, Nath *et al*., (2017) compiled the earthquake data for the period 1900-2014 for South Asia, which includes Peninsular India. Along with the published sources, internationally recognized databases of earthquakes stored in digital format by the India Meteorological Department (IMD), International Seismological Centre (ISC) and the United States Geological Survey (USGS) have been accessed to compile the earthquake catalogue. A total of 325 earthquake events consisting of foreshocks, aftershocks and mainshocks which occurred in the period 1800 AD to 2016 AD were compiled.

Before the installation of the global seismic network, seismic understanding of the region was limited due to a limited number of seismographs. In India, the first seismograph station was established at Alipore, Calcutta in 1898 AD. Some stations were started at Bombay and Kodaikanal in 1899 AD (Srivastava and Das, 1988). Presently, there are 84 seismological observatories situated at various locations in India that are monitored by IMD. Before the installation of seismograph network in India, small to medium magnitude earthquakes and large earthquakes in rural areas were not reported accurately. In the modern era of sophisticated instruments and high sensitivity seismographs, smaller magnitude earthquakes even in rural areas are also being reported accurately but on different magnitude scales.

4.4 Catalogue Homogenization

The instrumental and historical data obtained from the above-mentioned sources were in different magnitude scales. Before measurements by instruments became popular, earthquake damage was measured by observing the severity of the damage using Rossi-Forel intensity scale (I) with values ranging from I to X and modified Mercalli intensity (MMI) scale ranging from I to XII (Kramer, 1996). After the development of seismographs, earthquakes are being reported in local magnitude (M_L), surface-wave magnitude (M_s), body-wave magnitude (m_b) and moment magnitude (M_w) based on the type of seismograph.

Except for moment magnitude, all other magnitude scales saturate at certain higher magnitudes. Therefore it seems essential to convert various magnitude scales to a convenient scale. The earthquake magnitude reported in various scales were changed to a moment magnitude scale (M_w) since it does not have magnitude saturation (Kanamori, 1983) and depends on physical parameters of the fault (Das *et al*., 2012). The body wave magnitude and the surface wave magnitude are changed to M_w scale using Scordilis (2006) equations. The local magnitude scale was converted using the relationship proposed by Heaton *et al*. (1986). Gutenberg and Richter (1956) equation was used to convert the Intensity scale to M_w scale. The empirical equations were considered to obtain a homogeneous magnitude rather than developing their own site-specific relationship because of the fewer number of events in the study region that make it difficult to obtain a satisfying relationship (Sawires *et al*., 2016). In this study, the earthquake catalogue was compiled for the period 1800 AD to 2016 AD, considering seismic events with M_w greater than 3.0. The seismic events are digitized on the previously generated fault map using ArcGIS software to obtain the seismotectonic map of the study region, as shown in Figure 4.1. The seismotectonic map obtained provides the basic information required to perform the seismic hazard analysis for the study region.

4.5 Declustering of Events

The main earthquake shocks are independent events that follow a Poisson distribution (Gardner and Knopoff, 1974). The foreshocks and aftershocks depend on the main earthquake event and follow a different probability distribution than the main earthquake event. The earthquake catalogue should be entirely independent of foreshocks and aftershocks for accurate assessment of seismicity parameters. Therefore, the foreshock and aftershock earthquakes are discarded from the earthquake catalogue to have a Poisson distribution. Several methods have been proposed to decluster an earthquake catalogue by adopting different approaches (Reasenberg, 1985; Molchan and Dmitrieva, 1992; Gardner and Knopoff, 1974). Gardner and Knopoff (1974) proposed a dynamic windowing method to decluster an earthquake catalogue. The windowing method is a simple technique extensively used in declustering of aftershock and foreshock events. In this study, the earthquake catalogue was declustered by utilizing the windowing method of Uhrhammer (1986). In windowing technique, the spatial and temporal windows depend on earthquake magnitude. Equation (4.1) is used to identify the spatial and temporal window for declustering earthquake catalogue.

Distance, R (km.) = $e^{-1.024+0.804M}$ and Time, t (days) = $e^{-2.87+1.235M}$ (4.1)

After declustering, the study region had 288 events with $M_w \geq 3.0$ from 1800 to 2016.

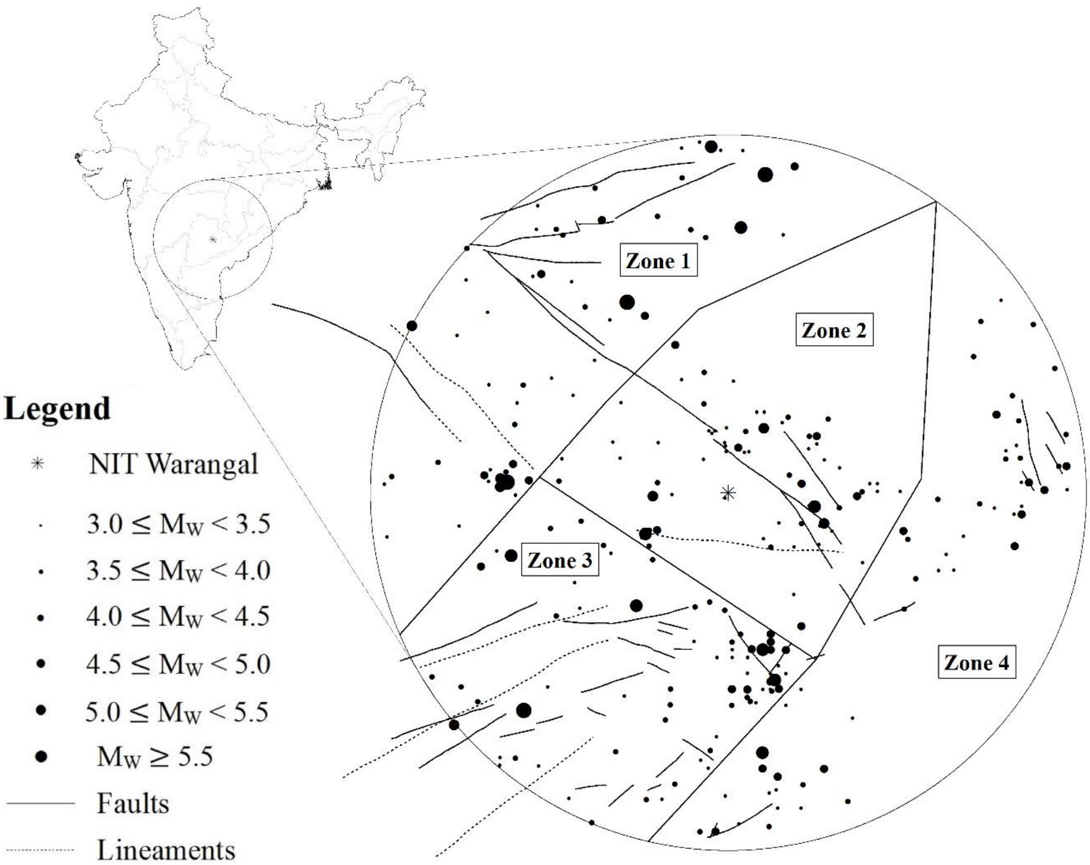


Figure 4.1 Seismic zonation along with digitized faults and epicentres of earthquakes

4.6 Catalogue Completeness

Statistical analysis of earthquake catalogue using incomplete data will result in unsatisfactory outcomes. The completeness analysis of an earthquake catalogue is essential for hazard assessment. The catalogue completeness is investigated for seismic scenario I (single seismic zone) as well as for seismic scenario II (four seismic zones) individually. The catalogue completeness was analysed by adopting Stepp's (1972) and the Cumulative Visual Inspection methods (Mulargia and Tinti, 1985).

The Cumulative Visual Inspection (CUVI) is a graphical method to analyse the catalogue completeness proposed by Mulargia and Tinti (1985). This method is based on the constant average slope. In this method, a graph is plotted between the cumulative number of earthquakes and time duration. The catalogue is considered to be complete for the time period in which the rate of earthquake events is constant. In the present study, completeness analysis was performed after the earthquake catalogue was divided into magnitude intervals starting from magnitude 3.0 with an increment of 0.5. The plots of completeness analysis for the single-zone model are shown in Figure 4.2. The results of the completeness period for scenario I are provided in Table 4.1. Similarly, the completeness analysis for the four seismic zones (scenario II) has also been performed individually and the completeness time period is listed in Table 4.2.

Table 4.1 Completeness period for the scenario I

Magnitude interval	CUVI method	Stepp's method
$3.0 \leq M_w < 3.5$	1972 – 2016	1967 – 2016
$3.5 \leq M_w < 4.0$	1969 – 2016	1967 – 2016
$4.0 \leq M_w < 4.5$	1968 – 2016	1957 – 2016
$4.5 \leq M_w < 5.0$	1968 – 2016	1957 – 2016
$5.0 \leq M_w < 5.5$	1876 – 2016	1837 – 2016
$M_W \geq 5.5$	1843 – 2016	1817 – 2016

Table 4.2 Completeness period for the scenario II by CUVI method

Magnitude interval	Zone 1	Zone 2	Zone 3	Zone 4
$3.0 \leq M_w < 3.5$	1995 – 2016	1972 – 2016	1968 – 2016	1967 – 2016
$3.5 \leq M_w < 4.0$	1975 – 2016	1939 – 2016	1948 – 2016	1959 – 2016
$4.0 \leq M_w < 5.0$	1968 – 2016	1936 – 2016	1946 – 2016	1927 – 2016
$M_w \geq 5.0$	1862 – 2016	1876 – 2016	1843 – 2016	1850 – 2016

In Stepp's (1972) method, the earthquakes were grouped into a magnitude range of 0.5 starting from a magnitude of 3.0. The complete time interval for a particular magnitude class is the period (T) in which the mean rate of occurrence remains constant. The standard deviation of the mean, σ_v, ($=\sqrt{\nu/T}$) follows the $1/\sqrt{T}$ behaviour for the complete time interval. The completeness period plot for seismic scenario I is shown in Figure 4.3 and completeness interval is listed in Table 4.1. The completeness period for seismic scenario II has also been assessed and the results are given in Table 4.3.

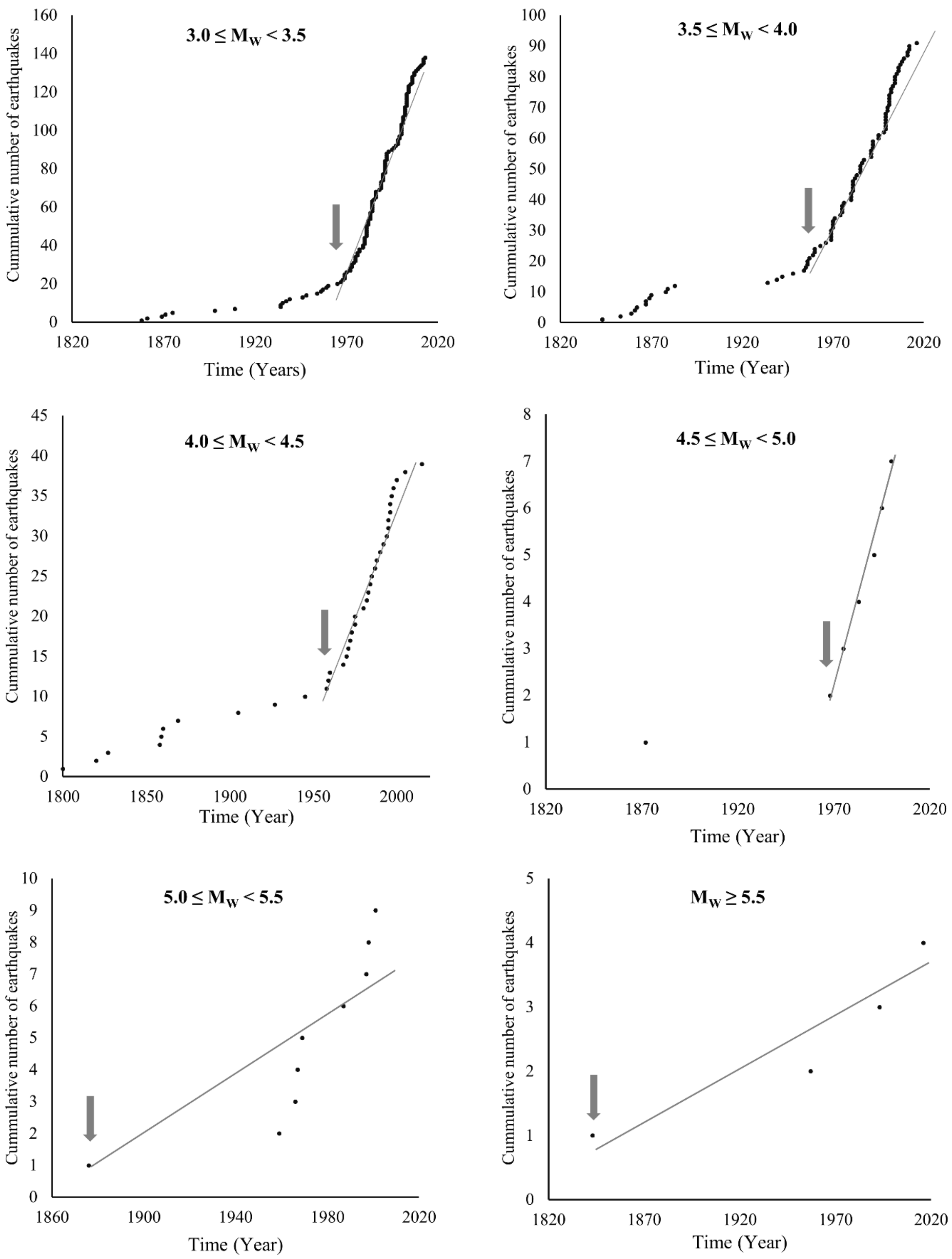


Figure 4.2 Completeness analysis for earthquake data using CUVI method

Table 4.3 Completeness period for scenario II by Stepp's method

Magnitude interval	Zone 1	Zone 2	Zone 3	Zone 4
$3.0 \leq M_w < 3.5$	1987 – 2016	1967 – 2016	1957 – 2016	1967 – 2016
$3.5 \leq M_w < 4.0$	1967 – 2016	1937 – 2016	1947 – 2016	1957 – 2016
$4.0 \leq M_w < 5.0$	1967 – 2016	1937 – 2016	1947 – 2016	1927 – 2016
$M_w \geq 5.0$	1837 – 2016	1837 – 2016	1837 – 2016	1837 – 2016

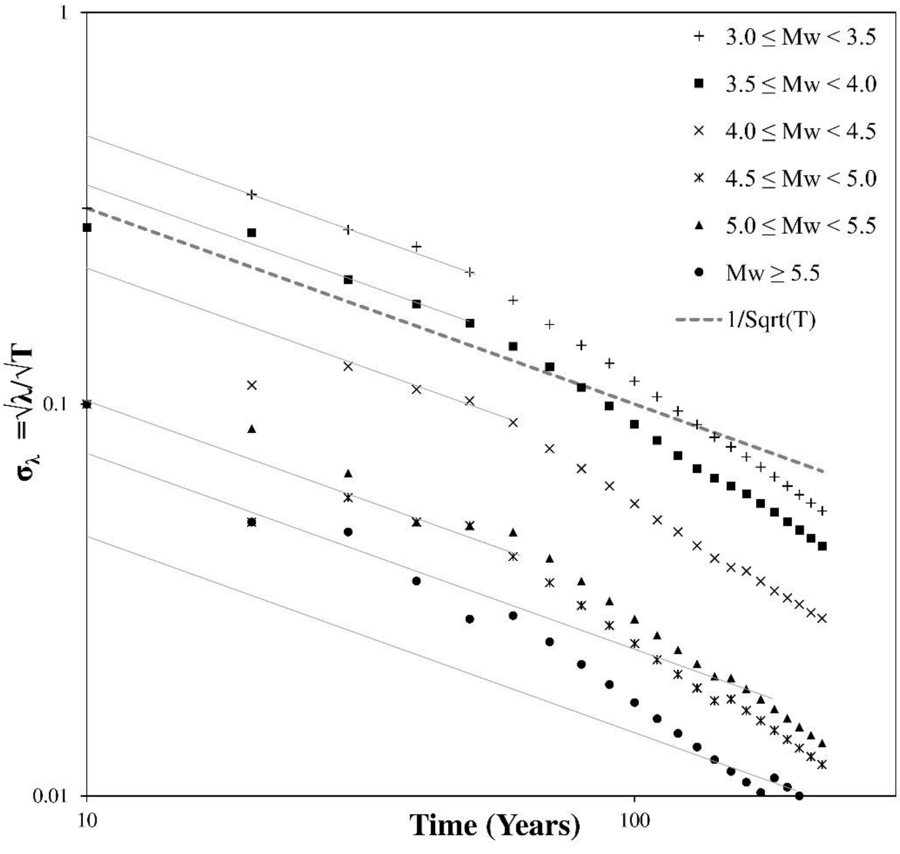


Figure 4.3 Completeness analysis for earthquake data using Stepp's method

In old practice, only large earthquake events were reported; subsequently, with the increase in seismograph network and its sensitivity, smaller earthquakes were also being reported implying that the completeness level of small to moderate magnitude earthquakes has been attained in the era of instruments, which can be observed from the completeness period.

4.7 Seismicity Parameters

The key element in the assessment of the seismic hazard is the estimation of the recurrence interval for earthquakes of different magnitudes. The spatial variation of seismicity parameters has been investigated for various regions across the globe (Amaro-Mellado *et al.*, 2017; Ali, 2016). Schorlemmer and Wiemer (2005) proposed that the seismicity parameter (*b*-value) can be used as stressmeters for Earth's crust to predict the location of the rupture area and magnitude of the earthquake event. In this study, the control region is divided into zones and the seismicity parameters are assumed to be uniform within each zone. The annual earthquake occurrence rate of magnitude greater than or equal to M in a given region has been described by Gutenberg - Richter (1944) recurrence relationship given in equation (4.2):

$$\log_{10}(\lambda_M) = a - b\,M \tag{4.2}$$

where, λ_M is the mean annual rate of exceedance of magnitude M, 'a' and 'b' are the constants specific to the source zone. The constants 'a' and 'b' have been estimated by the least square regression analysis using past seismic data. The 'b' value is sometimes thought of as a measure of the brittleness of the crust; it defines the relative proportion of small and large earthquakes. The values of 'a' and 'b' vary from region to region. The following are the steps to calculate 'a' and 'b' values: The catalogue was grouped into magnitude bin of ΔM_w = 0.5 starting from magnitude 3.0, then the annual rate of earthquake occurrence was calculated for each magnitude range (number of earthquakes occurred in the completeness interval by the completeness period, in years). A regression analysis between the cumulative annual rate of earthquake occurrence and the mean of the magnitude range was used to obtain '*a*' and '*b*' values. The recurrence relationship plot for the seismic scenario I is shown in Figure 4.4 and the seismicity values are listed in Table 4.4.

For seismic scenario II, the Gutenberg-Richter activity parameters '*a*' and '*b*' for each of the seismic zones were evaluated after sorting out events falling within each zone using the established catalogue. The G-R recurrence relationship for the seismic scenario II (Zone 1, Zone 2, Zone 3 and Zone 4) has been evaluated in a way similar to that adopted for seismic scenario I and the seismicity parameters are listed in Table 4.4.

Table 4.4 Gutenberg - Richter Recurrence parameter for different zone scenarios

Zone Scenario	**Seismicity parameter**	**CUVI method**	**Stepp's method**
Single Zone	*b*-value	0.82	0.85
	a-value	3.33	3.40
Zone 1	*b*-value	0.73	0.71
	a-value	2.56	2.43
Zone 2	*b*-value	0.82	0.85
	a-value	2.68	2.78
Zone 3	*b*-value	0.72	0.72
	a-value	2.45	2.44
Zone 4	*b*-value	0.97	0.98
	a-value	3.20	3.23

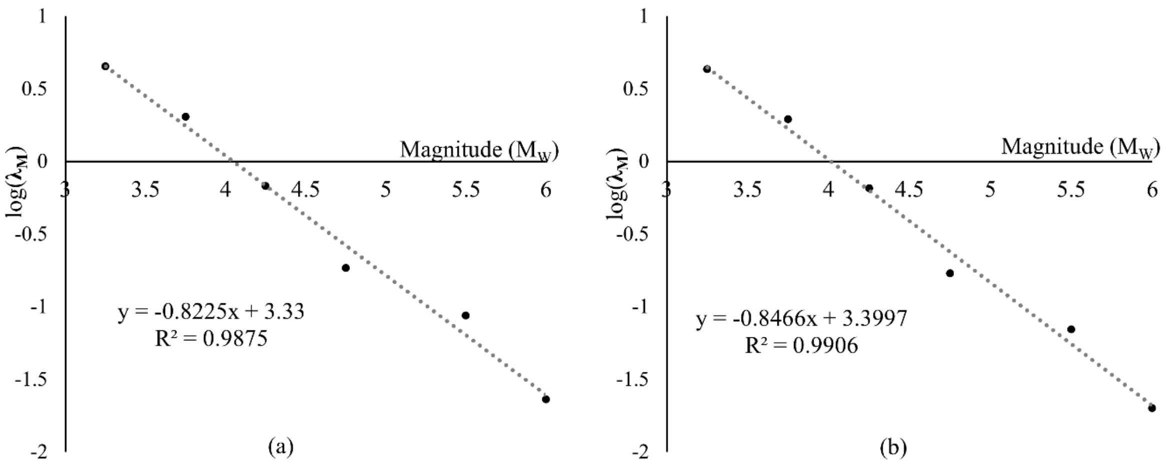


Figure 4.4 Gutenberg-Richter recurrence relationship for single-zone scenario (a) CUVI method (b) Stepp's method

4.8 Maximum Magnitude (m_{max})

The maximum magnitude (m_{max}) is an important parameter for the insurance industry, disaster management agencies and for seismologists. Kijko (2004) defined m_{max} as "the upper limit of earthquake magnitude i.e., the maximum possible earthquake in the area or zone." In the present study, m_{max} value has been estimated considering two methods. The first method to estimate the maximum magnitude (m_{max}) is the Kijko-Sellevoll-Bayes (K-S-B; Kijko and Graham, 1998) method which was first proposed by Kijko and Sellevoll (1989, 1992), and later enhanced by Kijko *et al.* (2016). This method considers the incompleteness of the earthquake catalogue, the uncertainty in earthquake magnitude and earthquake-occurrence model. The determination of earthquake magnitude without error is not possible. Usually, the magnitude determined using a good-quality instrument has an uncertainty of up to 0.2 magnitude units (Musson, 2012). The uncertainty of historical earthquake events can be up to 0.5 magnitude units. The uncertainty of the magnitude is considered by assuming that the observed magnitude is the true magnitude subjected to a random error, which follows the Gaussian distribution with a known standard deviation at zero mean. The procedure considers the complete part as well as the incomplete part of the earthquake catalogue and the uncertainty of *b*-value in the estimation of the maximum magnitude (m_{max}). The earthquake events are considered to follow Poisson law. The equation used for the estimation of m_{max} is as follows.

$$m_{max} = m_{max}^{obs} + \frac{\delta^{1/q+2}\exp[n.r^q/(1-r^q)}{\beta}[\Gamma(-1/q\,,\delta.r^q) - \Gamma(-1/q\,,\delta)] \tag{4.3}$$

where, m_{max}^{obs} = maximum observed magnitude, $\delta = nC_\beta$, $\beta = b\ln(10)$, C_β = normalizing coefficient of β, $\Gamma(.,.)$ = complementary incomplete gamma function, n = number of recorded magnitudes, $r = p/(p+m_{max}-m_{min})$, $p = \bar{\beta}/(\sigma_\beta)^2$, σ_β = standard deviation, $\bar{\beta}$ = mean value, $q = (\bar{\beta}/\sigma_\beta)^2$.

In the present study, the earthquake catalogue was divided into two parts: historical part (1800 AD – 1967 AD) and instrumental part (1968 AD – 2016 AD). The uncertainty of the magnitude in the incomplete historical part is assumed to be 0.3 magnitude while the instrumental part is assigned 0.2 magnitude (Thingbaijam and Nath, 2008). The uncertainty in the earthquake-occurrence model parameters is considered to be 25%. A MATLAB program (HA3) written by Kijko *et al.* (2016) has been utilised to estimate the maximum magnitude. The m_{max} values obtained for different seismic zones are listed in Table 4.5.

The second method to estimate m_{max} value as proposed by Gupta (2002), was considered. In this method, the largest earthquake magnitude observed in a particular region was increased by 0.5 magnitude. It is a simple method that has been adopted by Bahuguna and Sil (2018) and Bashir and Basu (2018) for seismic hazard analysis of Assam and Gujarat regions respectively. The m_{max} values obtained using Gupta (2002) method for the considered seismic zones are listed in Table 4.5.

Table 4.5 Maximum magnitude (m_{max}) for different zone scenarios using Gupta (2002) and Kijko (2016) method

Zone Scenario	$\mathbf{m_{max}^{obs}}$	Gupta method	Kijko method
Single Zone	6.23	6.73	6.64 ± 0.46
Zone 1	6.23	6.73	6.65 ± 0.46
Zone 2	5.23	5.73	5.50 ± 0.34
Zone 3	5.67	6.17	6.02 ± 0.40
Zone 4	5.00	5.50	5.18 ± 0.27

4.9 Ground Motion Prediction Equation

Ground motion prediction equation (GMPE) is the basic component in seismic hazard analysis of a specific region. GMPE predicts the ground motion parameter at the site of interest by relating it to the magnitude of an earthquake, the distance between site and source and other variables like local soil conditions. Generally, Peak Ground Acceleration (PGA) and Pseudo-Spectral Acceleration (PSA) at different structural periods are considered as parameters to define strong ground motion. The selection of an appropriate GMPE for a particular region is a critical task in PSHA (Anbazhagan *et al.*, 2016). It is generally preferable to choose region-specific GMPEs in seismic hazard analysis (Muthuganeisan and Raghukanth, 2016). In the absence of region-specific GMPEs, the GMPEs developed for other regions with similar seismotectonic features can be adopted (Patil *et al.*, 2018). The GMPEs developed for shallow crustal earthquakes have been selected, considering the tectonic setting of the study region, where most of the seismic activities occur at shallow depths. In the present study, four GMPEs have been selected, these being: (i) Abrahamson *et al*. (2014) (abbreviated as 'ASK14'), (ii) Boore *et al*. (2014), 'BSSA14', (iii) Campbell and Bozorgnia (2014), 'CB14' and (iv) National Disaster Management Authority (2011), 'NDMA11'.

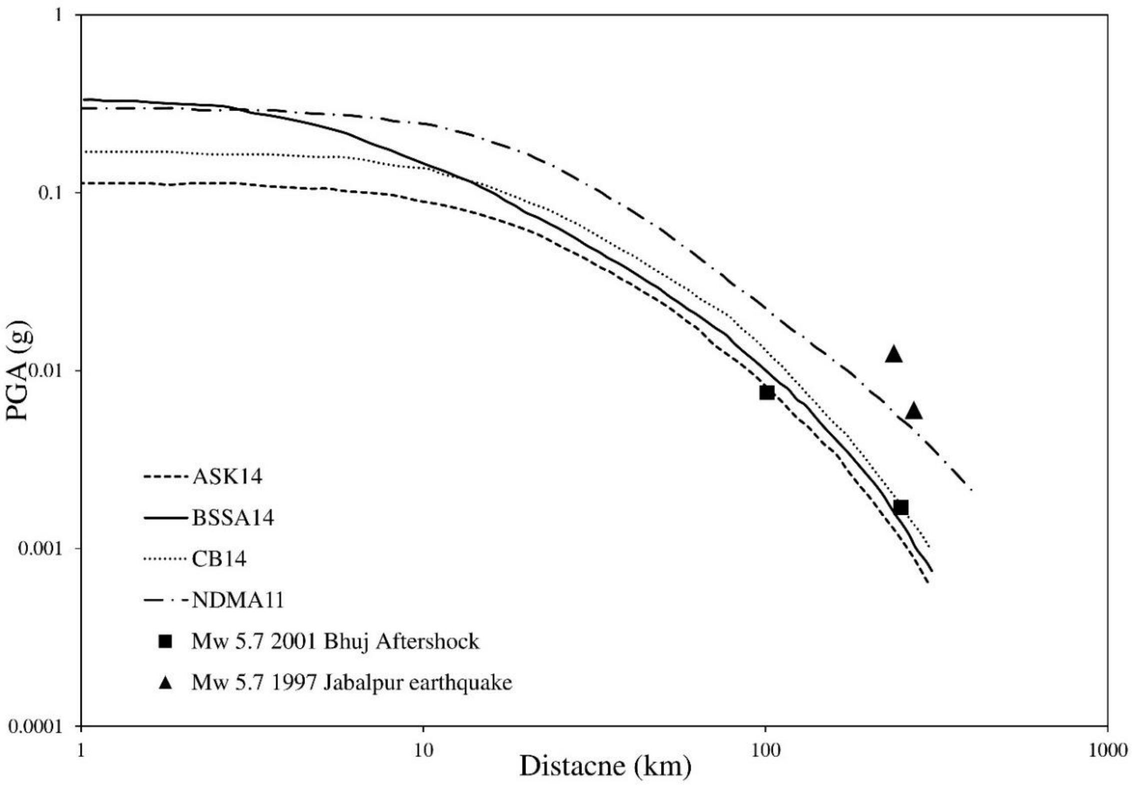


Figure 4.5 Comparison of GMPEs with strong motion data of the 1997 Jabalpur earthquake and the 2001 Bhuj aftershock

The compatibility of the selected GMPEs for the study region has been assessed by comparing it with strong-ground motion records available for the earthquake which occurred in PI, i.e., the 2001 Bhuj aftershock and the 1997 Jabalpur earthquake both of magnitude M_w 5.7 (Singh *et al*., 2003). The strong-ground motion records at different stations for the Bhuj aftershock and Jabalpur earthquake are listed in Table 4.6. The comparison of the selected GMPEs with the strong motion record is shown in Figure 4.5. ASK14, BSSA14 and CB14 match well with the 2001 Bhuj aftershock values whereas NDMA11 matches the 1997 Jabalpur earthquake strong motion records. Four GMPEs were used in the seismic hazard computation using the logic tree approach by assigning normalized weights to each GMPE.

Table 4.6 Strong-ground motion records for earthquakes that occurred in Peninsular India (Singh *et al.*, 2003)

Station	Distance (km)	a_{max} (g)		
		N	E	z
The 2001 Bhuj Aftershock				
BHUJ	101	0.0075	0.0079	0.0042
DGA	249	0.0017	0.0013	0.0011
BOM	576	0.0003	0.0002	0.0002
PUNE	654	0.0001	0.0001	0.0002
The 1997 Jabalpur Earthquake				
BLSP	237	0.0125	0.0116	0.0042
BHPL	271	0.006	0.0086	0.0048
BOKR	600	0.0007	0.0009	0.0004
AJMR	665	0.0006	0.0006	0.0005

4.10 Seismic Hazard Computation

The seismic zones, recurrence parameters, maximum magnitude and GMPE that have been discussed previously were incorporated in the analysis of seismic hazard by adopting the logic tree approach. The alternative models for different input parameters were branched and normalized weights assigned to each input parameter based on the confidence level of each model. The normalized weights of alternative models for each input parameter should add up to unity. The normalized weights assigned to different alternative models based on the confidence of a particular model are shown in Figure 4.6. The alternative models considered for seismic zoning scenario, completeness analysis, maximum magnitude and GMPEs built a total of 32 branches in the logic tree. The ground motions have been estimated by considering all 32 branches.

The alternative model for seismic scenario i.e., single zone scenario and four zone scenario was allotted an equal weight of 0.5 since there in no supremacy of one over the other. The completeness analysis by CUVI method was given a weighting of 0.6 whereas Stepp's method was given a weighting of 0.4. The CUVI method was given a higher weightage since it gives a specific value for completeness period whereas Stepp's method gives the completeness period at an interval of 10 years. The Kijko method and Gupta method for estimation of maximum magnitude was given equal weightage of 0.5 since both the methods has given a nearly same value even though they a different approach. The GMPE suggested by NDMA11 was given a weighting of 0.4 whereas ASK14, BSSA14 and CB14 were assigned a weighting of 0.2 each. NDMA11 was given a higher weighting since it was developed exclusively for the Peninsular India region whereas ASK14, BSSA14 and CB14 were developed using global strong motion data.

The classical Cornell-McGuire approach which was first proposed by Cornell (1968) and later enhanced by McGuire (1976) was used in the seismic hazard analysis. The Probability of Exceedance (PoE) of ground motion in a given time period of 50 years has been evaluated for Warangal district, Telangana, India. Most of the earthquakes in Peninsular India occur at a shallow depth of 10 to 20 km (Ashish *et al.*, 2016). The focal depth was assumed to be 10 km considering the worst-case scenario. The numerical calculations for seismic hazard were performed by considering the area source model in CRISIS2015 (Aguilar-Meléndez *et al.*, 2017) software. The peak ground acceleration (PGA) and Psuedo spectral acceleration (PSA) have been estimated at the bedrock level considering the shear wave velocity as 1500 m/s.

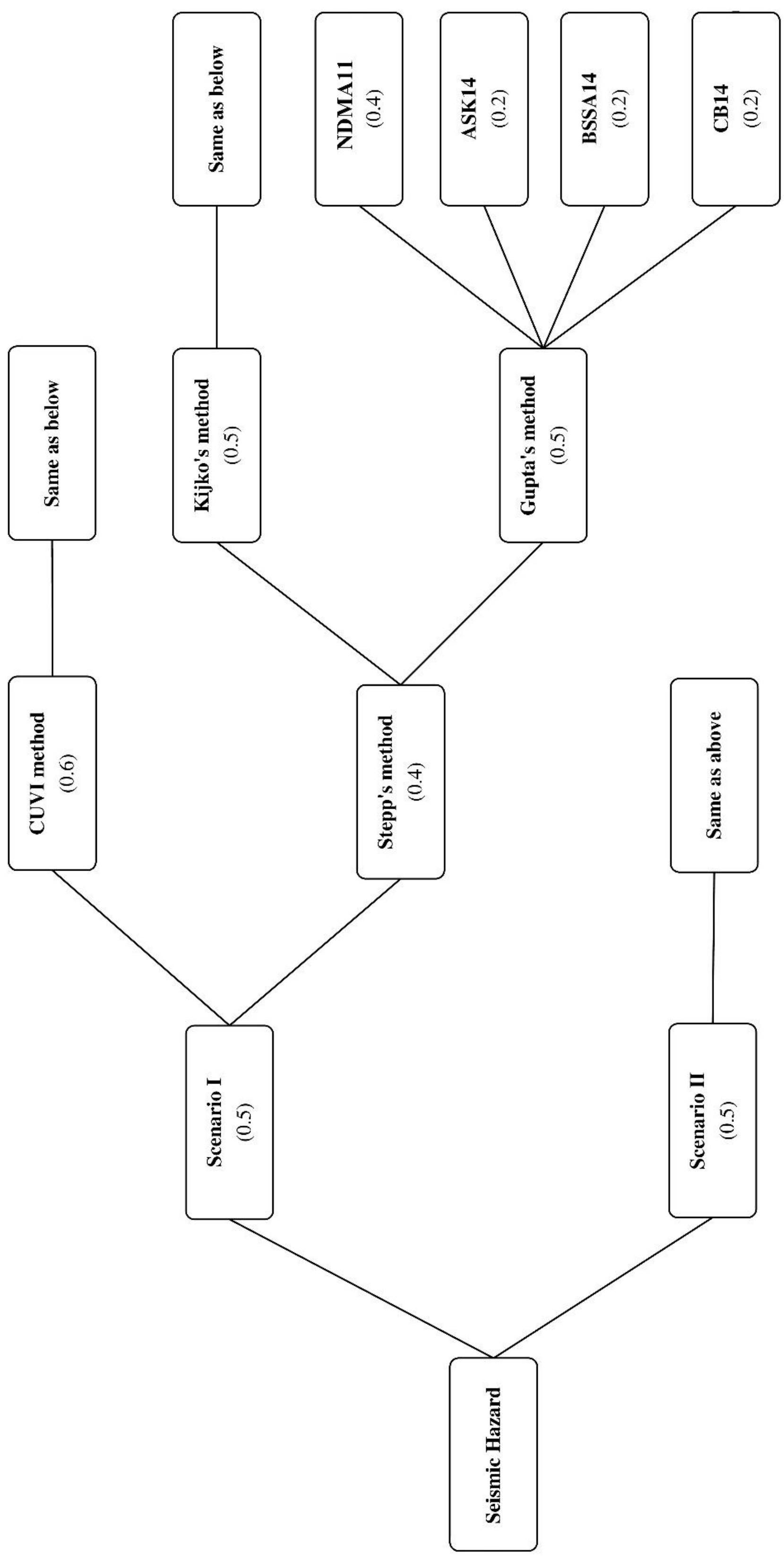


Figure 4.6 Logic tree branches with different models and their respective weighting adopted for seismic hazard computation

4.11 Results and Discussion

The output in the probabilistic seismic hazard analysis involves developing hazard maps and hazard curves of peak ground acceleration (PGA) or pseudo-spectral acceleration (PSA) against the mean annual rate of exceedance. The hazard values were calculated at the centre of the grid of size 0.05° × 0.05° stretching all over the study region. The hazard maps for PGA and PSA for 5 % damping at spectral period, T=0.05, 0.1, 0.5 and 1 s were developed to understand the seismic hazard intensity at different structural periods. The spatial variation of PGA at hard stratum for 475 and 2475 years return period for Warangal district is shown in Figures 4.7 and 4.8 respectively. The pseudo-spectral acceleration map at 5 % damping for spectral periods of 0.05, 0.1, 0.5 and 1 s for 10% in 50 years are shown in Figures 4.9, 4.10, 4.11 and 4.12 respectively, whereas maps for 2% PoE in 50 years are shown in Figures 4.13. 4.14, 4.15 and 4.16 respectively

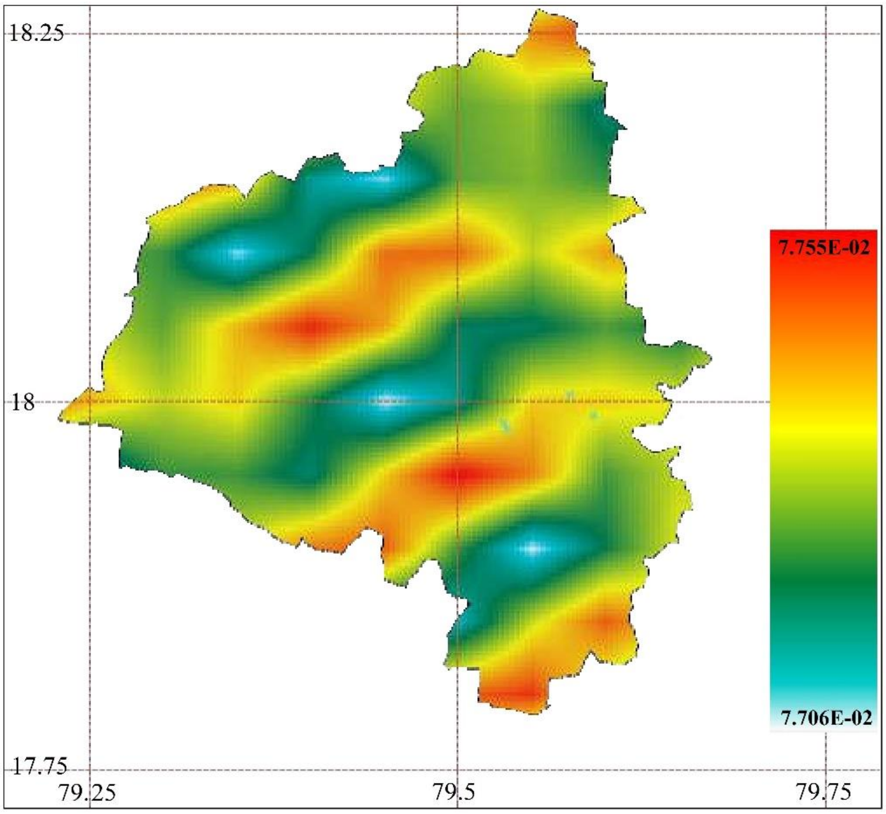


Figure 4.7 Spatial variation of PGA at bedrock level for 475 years return period

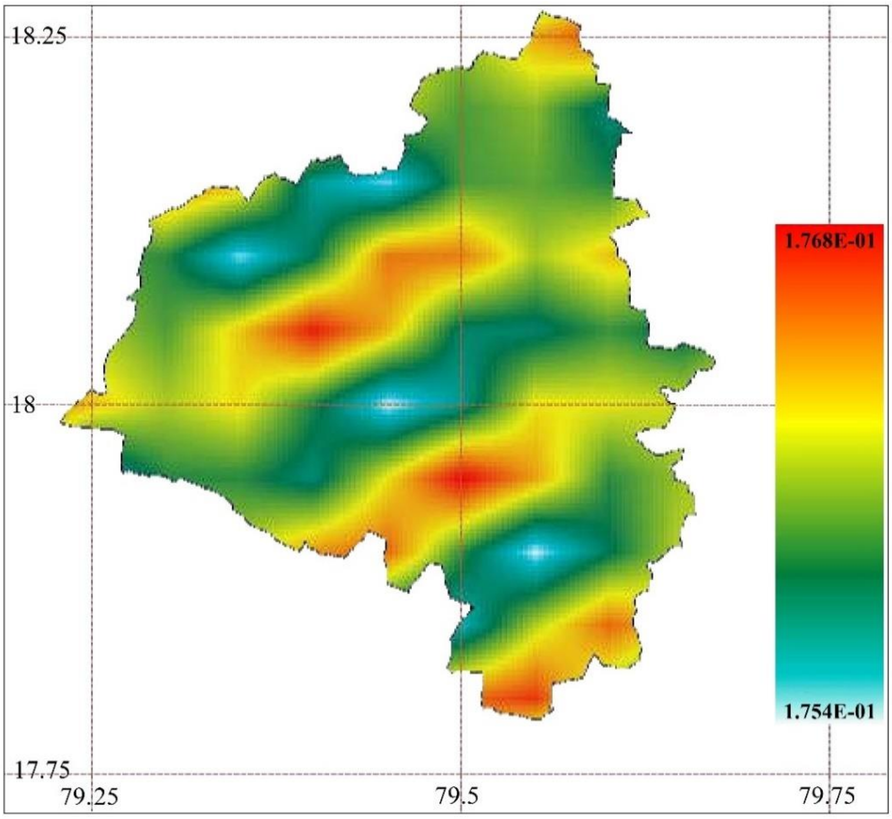


Figure 4.8 Spatial variation of PGA at bedrock level for 2475 years return period

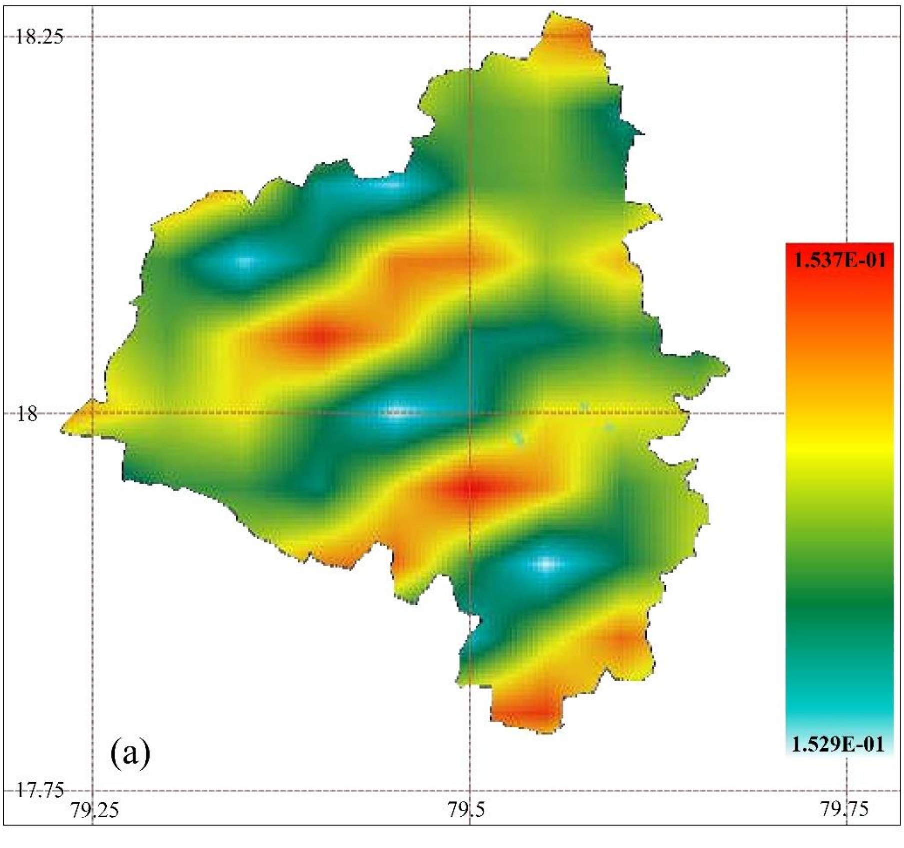


Figure 4.9 Spatial variation of PSA at bedrock level for 475 years return period at T=0.05s

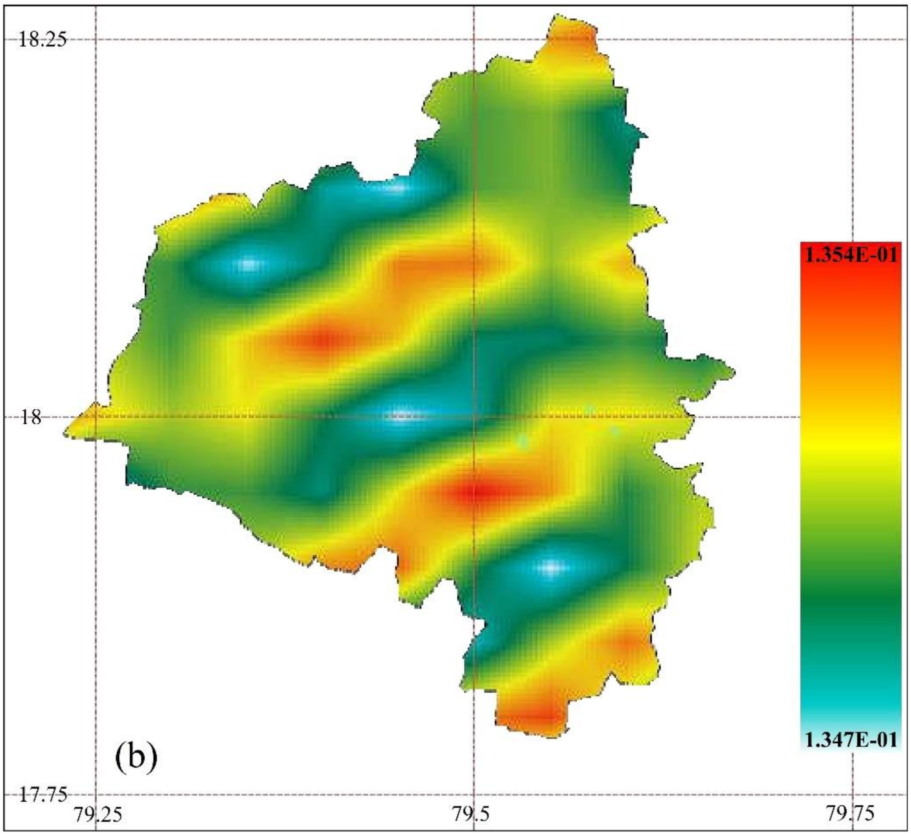


Figure 4.10 Spatial variation of PSA at bedrock level for 475 years return period at T=0.1s

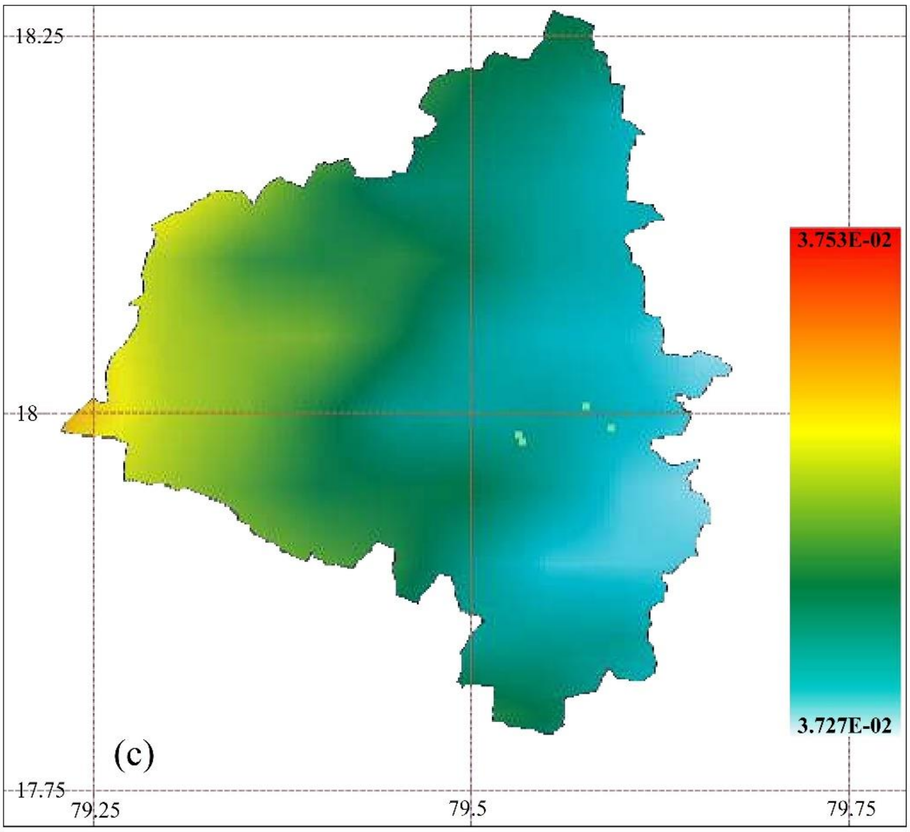


Figure 4.11 Spatial variation of PSA at bedrock level for 475 years return period at T=0.5s

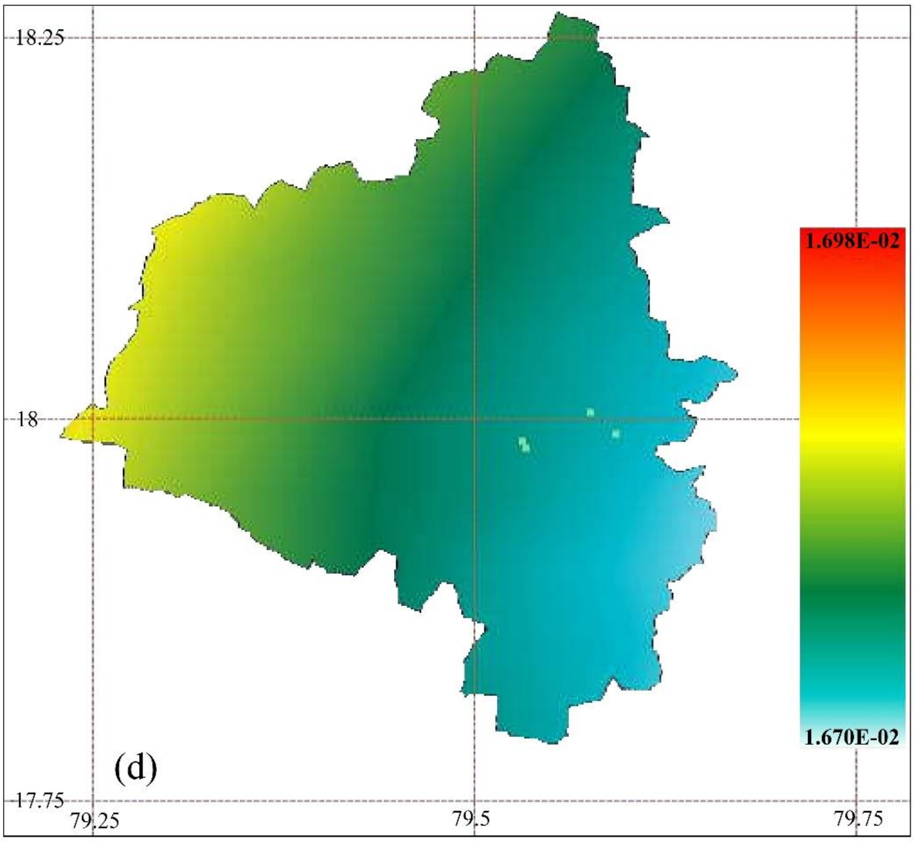


Figure 4.12 Spatial variation of PSA at bedrock level for 475 years return period at T=15s

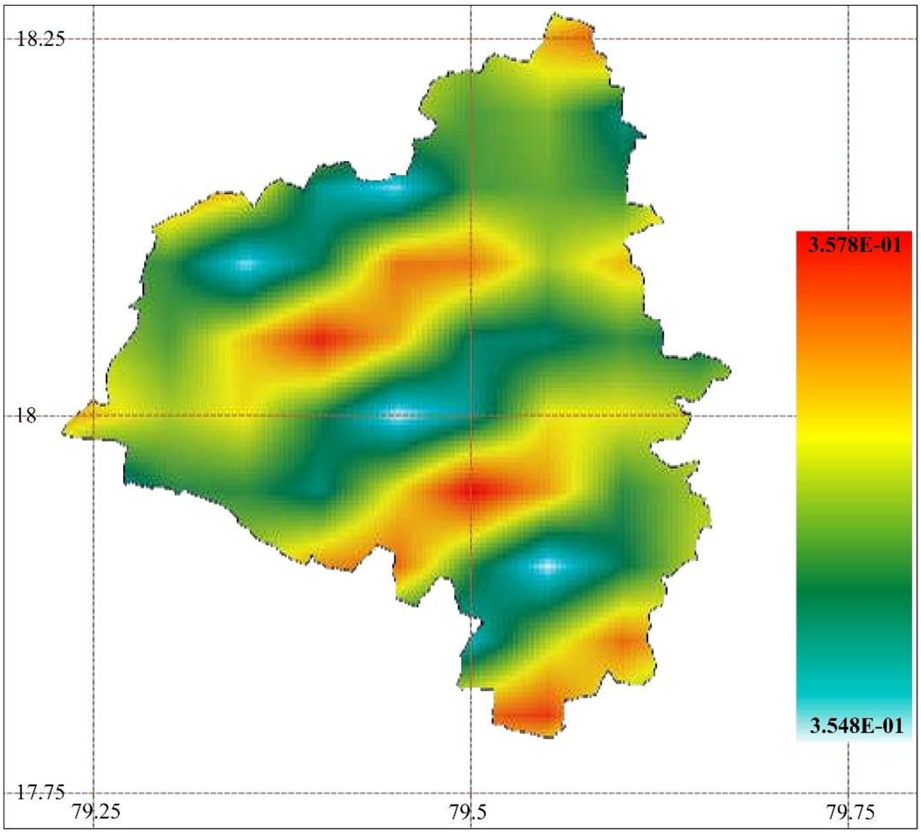


Figure 4.13 Spatial variation of PSA at bedrock level for 2475 years return period at T=0.05s

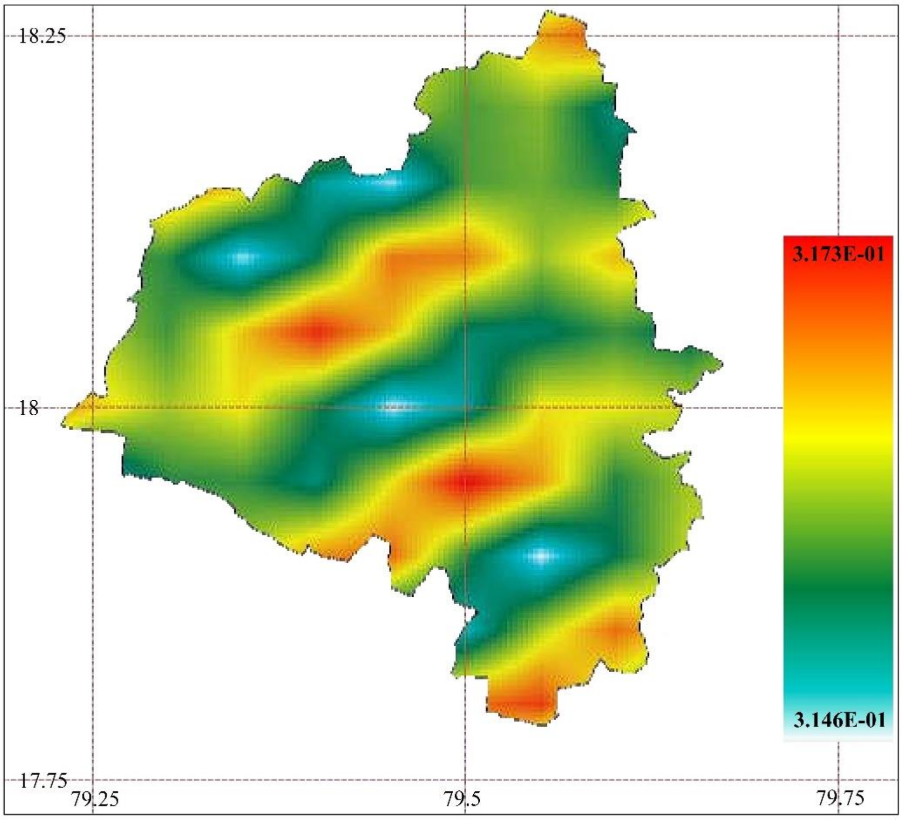


Figure 4.14 Spatial variation of PSA at bedrock level for 2475 years return period at T=0.1s

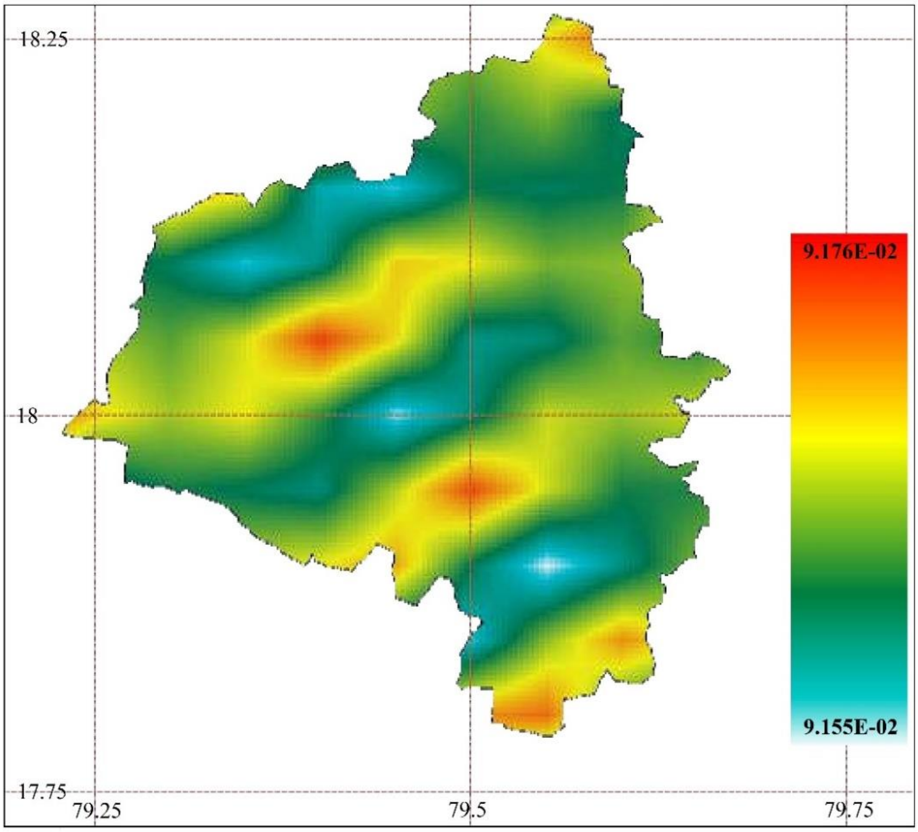


Figure 4.15 Spatial variation of PSA at bedrock level for 2475 years return period at T=0.5s

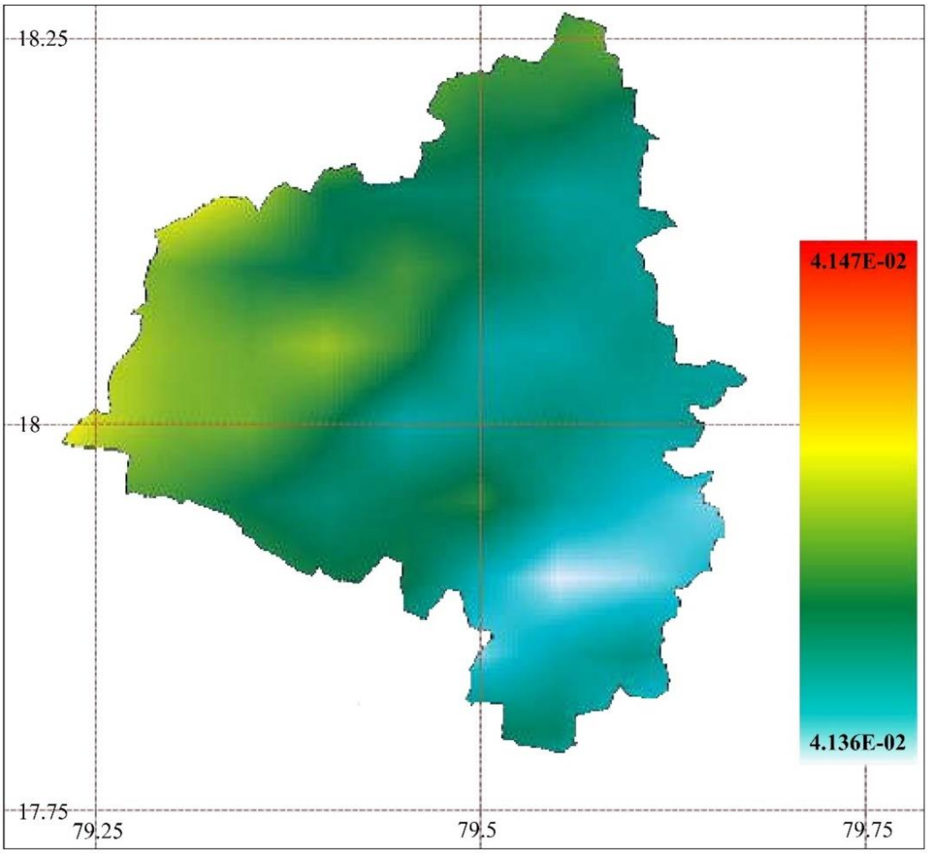


Figure 4.16 Spatial variation of PSA at bedrock level for 2475 years return period at T=1s

The uniform hazard spectrum (UHS) is generally used in the response spectrum analysis of structures. The UHS was generated for hard stratum at NIT Warangal, bearing coordinates 17.98N and 79.53E for the return periods of 475 and 2475 years. The UHS with structural period ranging from 0 to 2 s is shown in Figure 4.17. The PGA and PSA values for 10% and 2% PoE in 50 years for NIT Warangal site are compared with NDMA (2011) and IS: 1893-1 (2016) in Table 4.7. As per IS: 1893-1 (2016), Warangal comes under Zone III with expected PGA for design basis earthquake (DBE) being 0.08g and maximum credible earthquake (MCE) being 0.16g. The PGA values obtained are in accordance with IS: 1893-1 (2016) whereas the NDMA (2011) suggests slightly lower values. The obtained PSA values (T=0.05, 0.1, 0.5 and 0.1 s) match well with the NDMA (2011), whereas the IS: 1893-1 (2016) suggests higher values. The reason for lower PSA values compared to IS: 1893-1 (2016) may be on account of the consideration of probabilistic approach in hazard analysis. Moreover, the hazard curves suggested by IS: 1893-1 (2016) is based on past seismicity, not on a probabilistic approach which makes it difficult to analyse the probability of occurrence for a certain level of ground shaking.

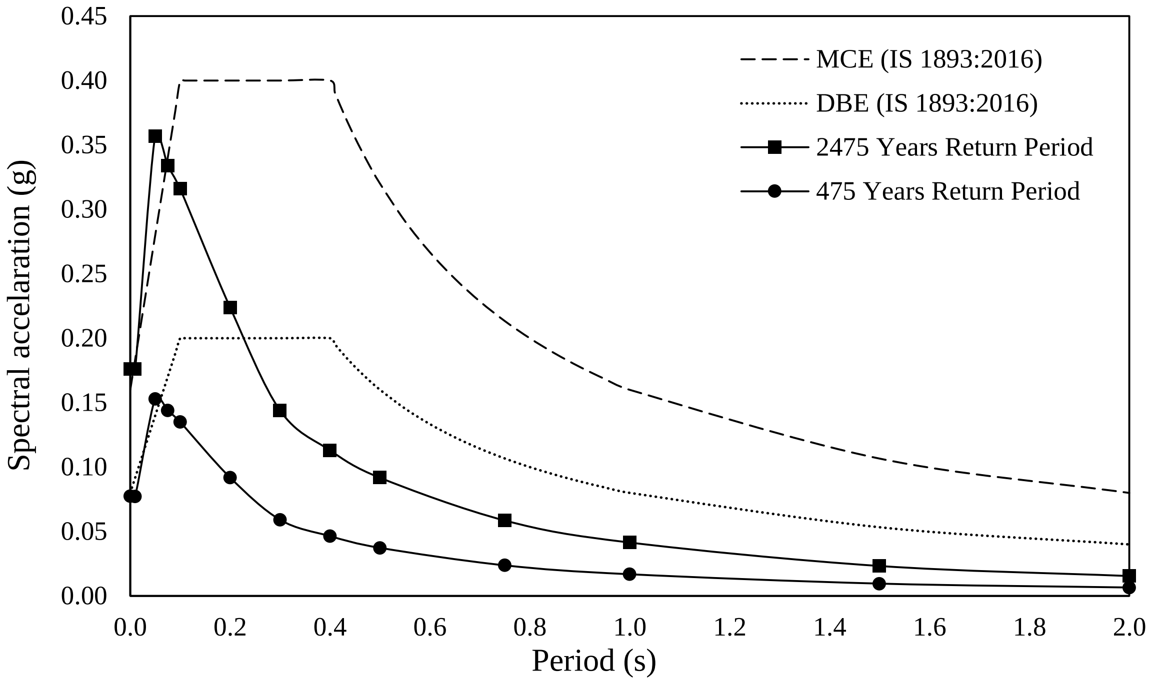


Figure 4.17 Uniform Hazard Spectrum (UHS) for different return periods

Table 4.7 Comparison of PGA and PSA values with NDMA (2011) and IS 1893 (2016)

	Present study				NDMA (2011)				IS 1893-1 (2016)			
	PGA	PSA	PSA	PSA	PGA	PSA	PSA	PSA	PGA	PSA	PSA	PSA
Return Period	T=0	0.2	0.5	1	T=0	0.2	0.5	1	T=0	0.2	0.5	1
475	0.077	0.092	0.037	0.017	0.06	-	0.025	-	0.08	0.2	0.16	0.08
2475	0.176	0.224	0.092	0.041	0.12	0.13	0.06	0.01	0.16	0.4	0.32	0.16

The results obtained are comparable to previous seismic hazard studies carried out for Peninsular India by Jaiswal and Sinha (2007), Sitharam and Vipin (2011) and Ashish *et al*. (2016).

4.12 Summary

The primary objective of this chapter was to estimate the seismic hazard for the newly formed Warangal district in the state of Telangana, India by adopting the probabilistic method of analysis incorporating the logic tree approach. An earthquake events catalogue was developed for the study area of 500 km. radius with NIT Warangal as centre from the period 1800 AD to 2016 AD. The earthquake data was collated from available national and international earthquake reporting organisations and published catalogues. The catalogue contains the time of origin, location coordinates, epicentral depth and moment magnitude. Temporal heterogeneity of the earthquake data was observed until 1966 AD. Stable earthquake records were seen from the year 1967 AD. The earthquake catalogue was standardized in terms of magnitude by using global empirical equations. A total of 288 intraplate earthquakes at shallow depths with $M_w \geq 3.0$ were identified after declustering for foreshocks and aftershocks. To quantify the seismic activity, two scenarios were considered. In scenario I, the whole study region was taken as a single zone. On the other hand, in scenario II, the study area was divided into four zones taking into account the geology and seismicity. The completeness analysis of earthquake catalogue was performed for two seismic scenarios using CUVI and Stepp's method. The maximum magnitude has been determined using incremental and statistical methods for each seismotectonic zone. The m_{max} value for different seismic zones suggests that all the zones in the considered area are capable of triggering moderate magnitude earthquakes. The lowest and highest m_{max} values were observed in zone 4 and zone 1 respectively. A total of four GMPEs have been considered to predict the ground motion parameters; three GMPEs were developed using worldwide shallow crustal earthquake data whereas one GMPE was developed using earthquake data of Peninsular India. The GMPEs considered are checked with the strong motion records of earthquakes which happened in Peninsular India. The input parameters for alternative models were used by adopting the logic tree approach and assigning a normalized weight to each model. Seismic hazard calculations were performed and the output was generated in terms of hazard maps at different spectral periods.

The outcomes of this study can be used in civil engineering construction and design. Important structural projects can be selected based on the results obtained. It may not be possible to control or predict an earthquake accurately, but these studies help in reducing the impact on human life. The seismic hazard assessment and the hazard maps need to be updated periodically with the development of new methodology and the addition of seismotectonic data of a region.

CHAPTER 5

GROUND RESPONSE ANALYSIS

5.1 Introduction

The amplification of seismic waves has been observed from the previous earthquakes that occurred around the globe. The seismic wave amplification is very much dependent on site-specific geotechnical conditions, topography and geology. The damages due to earthquakes are tsunamis, landslides and soil liquefaction induced by ground shaking. Considerable research has been carried out on the estimation of local site effects and it was observed that catastrophic damage in a particular area during an earthquake is due to the local subsoil that transforms the seismic waves. In general, the bedrock earthquake motion amplifies or attenuates depending on the arrangement and depth of soil layers, and geotechnical characteristics. The presence of locally available geology at a site can modify the bedrock ground motions from the seismic source. As a result, it will cause outright modification in the ground motion characteristics, such as duration of motion, frequency content and amplitude at surface level in comparison to bedrock. Thus, the scenario will get completely changed compared to seismic hazard values obtained at bedrock. These modified motions are called surface motions and are the actual ground motions initial phenomena such as liquefaction and landslides produced by ground shaking. Hence, the effects due to local soil should be addressed thoroughly while performing hazard studies for any region. Performing the ground response analysis helps a geotechnical engineer calculate the natural frequencies of the locally available soils and predict ground motion amplification and assess the acceleration response. The evaluated parameters can additionally be used in earthquake resistant design of structures.

The local site effect is accountable for increasing the damages of an earthquake. Heterogeneity in the soil media of different layers causes the disparity in the characteristics of seismic waves as they propagate from bedrock to the surface from one site to another. Also, the attenuation of these waves and trapping of body waves augment the damping scenario. The influence of near-surface geological conditions in the form of sediment amplification or site response is apparent from the damage distribution of many destructive earthquakes. Some of the classical examples of site-specific damages due the local soil playing a major role are the 1985 Mexico earthquake, the 1999 Chamoli earthquake in India, the 2001 Bhuj earthquake in India, the 2011 Sendai earthquake in Japan, the 2011 Sikkim earthquake in India and 2015 Nepal earthquake. It is observed from the earthquakes that the damages were seen as far as 500 km away from the epicentre. In order to minimize the catastrophic damage during an earthquake, the local site effects should be effectively determined. Site-specific ground motion studies aim at addressing these effects considering local subsoil conditions.

The amplification is usually seen in younger softer soils compared to older competent bedrock or soils. The density of soil increases with depth. The earthquake is generated at the bedrock and the seismic waves travel from bedrock to the ground surface. Therefore, the waves travel from higher density to lower density media. The velocity of seismic waves depends on the density of soil and shear modulus. The velocity of the seismic wave decreases as it propagates from bedrock to ground surface due to the decrease in soil stiffness. The decrease in velocity causes an increase in the amplitude of motion due to the conservation of energy principle.

Understanding and estimation of the response of different subsoil layers for the given seismic input motion at bedrock is called site response study. This is the second step in understanding the role of local geology in surface-induced seismic hazard. The seismic waves that travels away and when spread over a large province might attenuate or amplify depending on the soil profile. The degree of shaking of ground relies on the matching of the fundamental frequency of the ground and the building and the degree of structural damage is in turn influenced by the properties and type of rock, soil deposits, tectonic and geomorphologic features. Hence, it is essential to perform a ground response analysis to find out the ground motion parameters at the ground surface.

In this chapter, an attempt has been made to determine the change in bedrock motion due to local subsurface soil characteristics. Data presented in previous chapters are coupled together and detailed site response study was performed. Equivalent linear site response programme of DEEPSOIL has been used for the analysis. The measured shear wave velocity using MASW has been considered for the subsoil profile. The input motion is selected based on the seismic hazard analysis results discussed in Chapter 4. The selected ground motion has been imparted at the bedrock level. Site response parameters such as surface PGA, amplification, peak spectral acceleration, period corresponding to peak spectral accelerations and frequencies have been estimated. The detailed methodology adopted for site response analysis is presented in this chapter.

5.2 Study Area

Warangal is the second-largest and second-fastest growing city after Hyderabad in Telangana, India. Warangal, also known as Orugallu, was included in HRIDAY scheme (Heritage City Development and Augmentation Yojana) by the Government of India. The city was also selected in the Smart City Mission (2016) program by the Government of India to make a citizen-friendly and sustainable city. The city is known for its historic monuments built by Kakatiya Dynasty.

Generally, the soil profile consists of: a few meters of topsoil is black cotton soil, followed by morrum type of soils. In some places, instead of morrum, sandy type soils are present followed by soft rock. Seismically, the region falls under Zone III as per IS: 1893-1 (2016), which is a moderately seismic zone with a PGA value of 0.08g. Predicting the amplification factor for a moderately seismic region with layered soil is a difficult task when no previous earthquake motion data is available for a particular region like Warangal. Many tall buildings are proposed within the Warangal region owing to the growing needs of people. It is, therefore, necessary to understand the response of subsoil during an earthquake event for designing earthquake resistant structures and retrofitting techniques for existing structures.

5.3 Methodology

The local site conditions play an important role in modifying the ground motion parameters during the propagation of seismic waves from bedrock to the ground surface. The degree of modification is dependent on the characteristics of input motion, properties and thickness of soil profile, modulus reduction curve and damping ratio curve. Different methods are available for the analysis of local site effects (i) linear analysis, (ii) equivalent-linear analysis and (iii) nonlinear analysis. The difference in these methods is the techniques used to integrate the equation of motion and the simplifying assumptions considered in the stress-strain relationships of soil. The effect of local soil properties on ground motion is generally assessed by performing one-dimension ground response analysis using equivalent linear or non-linear methods. It is desirable to conduct non-linear analysis using the site-specific modulus reduction and damping curves. However, the unavailability of site-specific curves was a constraining factor in carrying out equivalent linear approach. The equivalent linear approach is a simple method with sufficient accuracy yielding conservative results compared to nonlinear analysis (Rayhani *et al*., 2008). Consequently, the ground response analysis was carried out for two sites, i.e., National Institute of Technology Warangal (NITW) and Thousand Pillar temple. The input data include shear wave velocity profile, modulus reduction and damping curves for different soil strata and acceleration time history at bedrock.

The shear wave velocity profile was obtained by performing the MASW test at NIT Warangal and Thousand Pillar temple. The detailed procedure and methodology of MASW test have been discussed in Chapter 3. The subsoil stratification at the sites is given in Table 5.1.

Table 5.1 Soil stratification at NIT Warangal and Thousand Pillar temple

Site	**Depth (m)**	**Soil type**	**Unit wt. (kN/m^3)**	**Shear wave velocity (m/s)**
NIT Warangal	0.0 – 1.1	Soft clay	16	138
	1.2 – 7.0	Stiff clay	17	256
	7.1 – 13.2	Dense sand	19	498
	13.3 – 26.8	Soft rock	22	640
Thousand Pillar Temple	0.0 – 2.3	Soft clay	16	198
	2.4 – 7.0	Stiff clay	17	271
	7.1 – 18.1	Dense sand	19	516
	18.2 – 26.8	Soft rock	22	582

The soil properties are modelled using the modulus reduction and damping curves. This method is deemed preferable to developing site-specific curves by conducting cyclic triaxial and resonant column test. In the absence of site-specific modulus reduction and damping curves, alternative curves given by Vucetic and Dobry (1991) and Seed and Idriss (1970) for sand and clay respectively were used in the ground response analysis.

5.3.1 Selection of input acceleration time history

For the input ground motion, array recording or rock outcrop records are used to simulate field response. The necessary components of the bedrock motion are duration content, frequency and acceleration amplitude. In locations where recorded strong motion data are not available such as Warangal region, a recorded time history of another region is usually selected as input acceleration time history. In the present study, a recorded time history from the database is selected and scaled to suit the requirements.

Input ground motion has to be selected in such a way that it represents the regional seismicity and must incorporate information about anticipated earthquakes. The selection of ground motion can be done based on expected magnitude and distance, soil profile, strong motion duration, seismotectonic environment etc. In this study, the time history of the Coyote earthquake (M_w = 5.7) was considered as input ground motion for the analysis. Figure 5.1 shows the time history of Coyote earthquake after scaling to 0.08 g i.e., the design basis earthquake value given for Warangal region by IS: 1893-1 (2016). The reason for selecting the time history of Coyote earthquake as input motion is the magnitude i.e., M_w 5.7, which is a moderate size event. The tectonic setting of the study area can likewise trigger moderate magnitude earthquakes under seismic Zone III of IS: 1893-1 (2016).

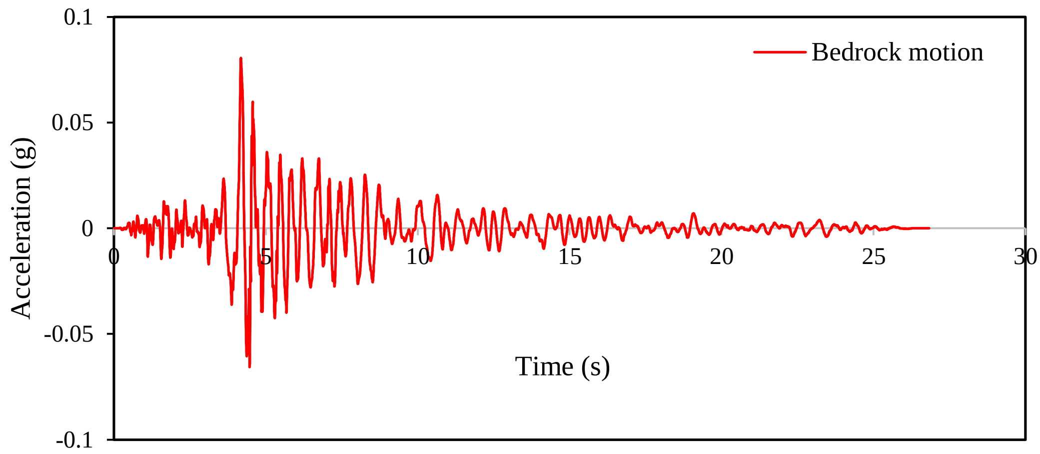


Figure 5.1 Time history of Coyote Earthquake after scaling

The most general method of site response analysis is one dimensional analysis. The 1D analysis considers the propagation of seismic waves in one dimension. The assumption in 1D analysis is the consideration of horizontal boundaries and the response of soil is reliant on vertical propagation of SH wave (shear wave component in the horizontal direction) from the bedrock below. The bedrock and soil are assumed to be infinite in the horizontal direction since the variation of soil properties in the vertical direction is comparatively greater than in the horizontal direction. The assumptions are justified as the velocity of wave generally decreases as the wave reaches the surface as a nearly vertical path after successive refraction from the earth's interior. Moreover, the horizontal motion is the most important aspect for structural engineers than vertical motion. Therefore, 1D ground response analysis has been performed considering an equivalent linear approach in DEEPSOIL (Hashash *et al.*, 2016).

5.4 Results

Ground response analysis which is also termed soil amplification study comprises the calculation of ground motion amplification and site natural periods. The surface level peak spectral acceleration at NIT Warangal and Thousand Pillar temple is 0.131g and 0.124g for 5% of damping to a bedrock peak acceleration of 0.08 g showing amplification of 1.64 and 1.55 respectively. A comparison of acceleration time history at bedrock and ground surface at NIT Warangal site and Thousand Pillar temple are shown in Figures 5.2 and 5.3 respectively. The variation of PGA along the depth is shown in Figure 5.4. It is observed that the seismic waves are amplified as it reaches the surface level due to the presence of soft clay in top layers.

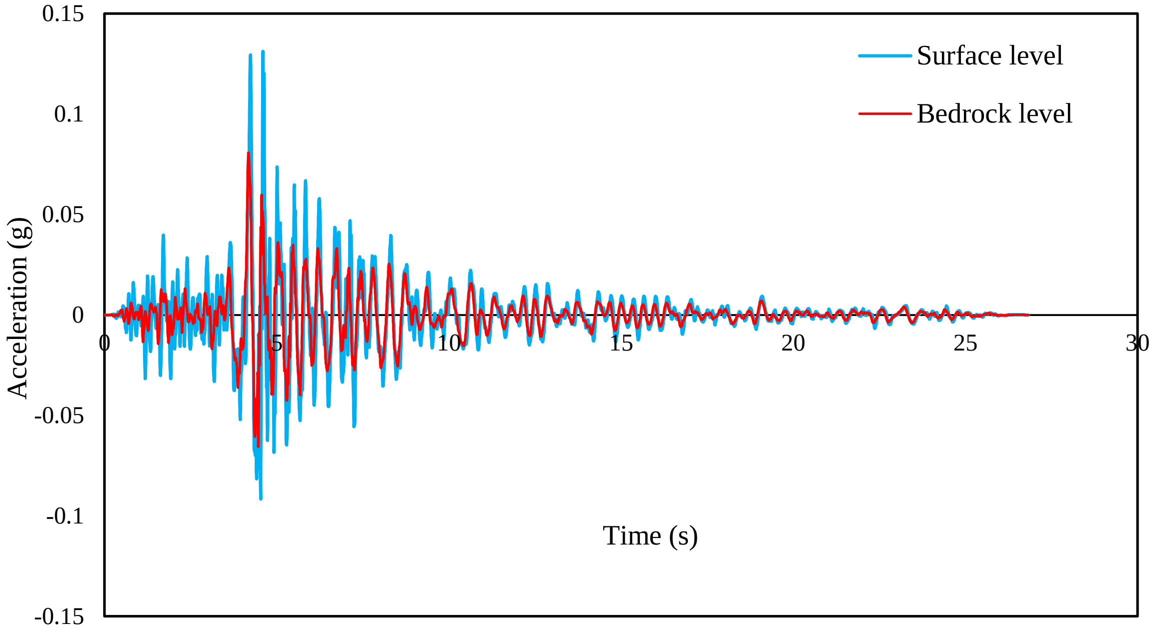


Figure 5.2 Comparison of acceleration time history at bedrock and ground surface at NIT Warangal site

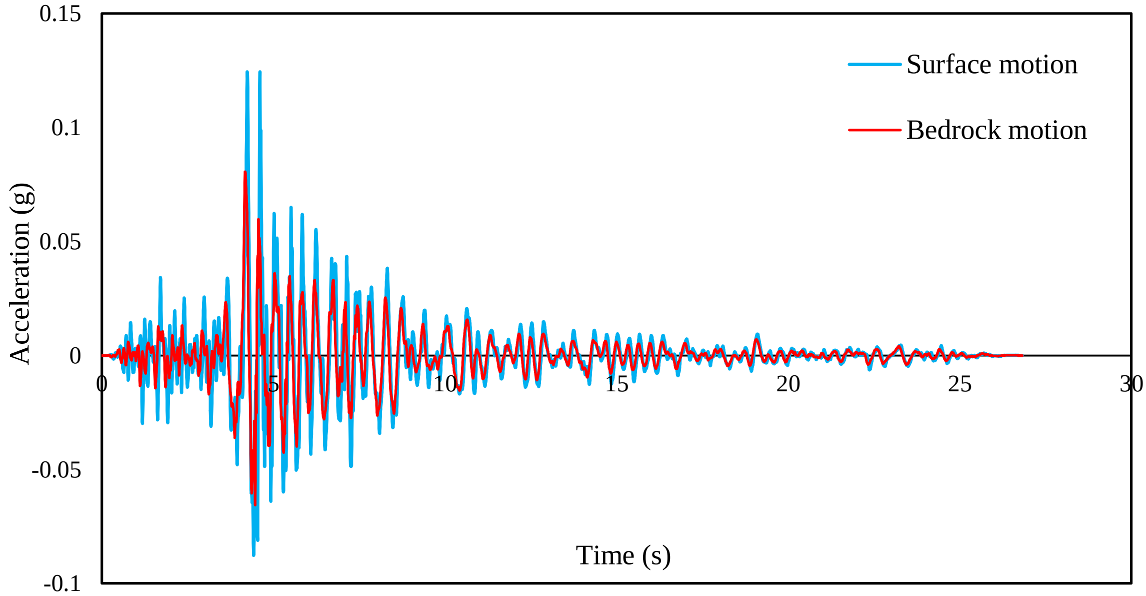


Figure 5.3 Comparison of acceleration time history at bedrock and ground surface at Thousand Pillar temple site

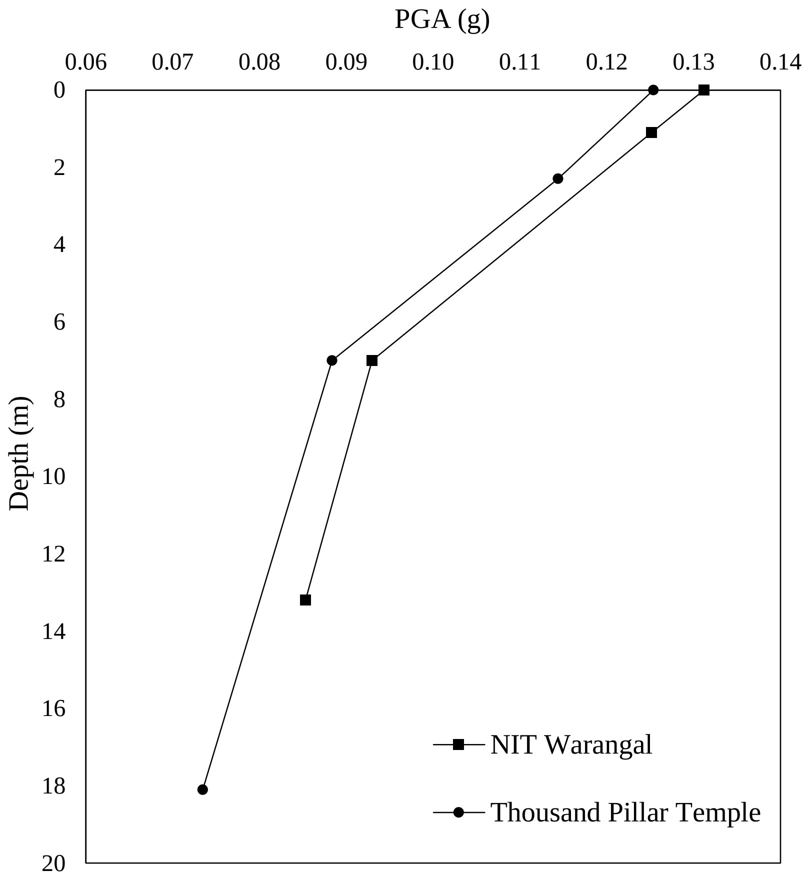


Figure 5.4 Variation of PGA along the depth

The frequency content of an earthquake motion will strongly influence the impact on structures and hence only peak acceleration PGA value cannot characterize ground surface motion. The frequency of the dynamic loads plays an important role in the response of soil deposits. The ground motion in time domain is converted into frequency domain using a Fourier transformation to understand the behaviour of ground motion in terms of amplitude at different frequencies. Figures 5.5 and 5.6 show the comparison of Fourier amplitude spectrum for bedrock and surface-level motion at NIT Warangal and Thousand Pillar temple, respectively.

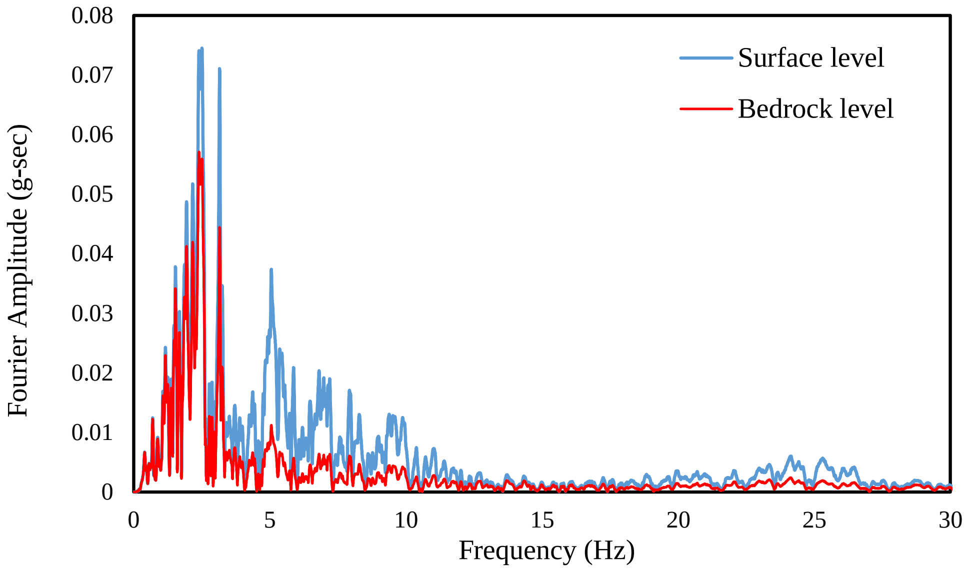


Figure 5.5 Fourier Amplitude Spectra at NIT Warangal

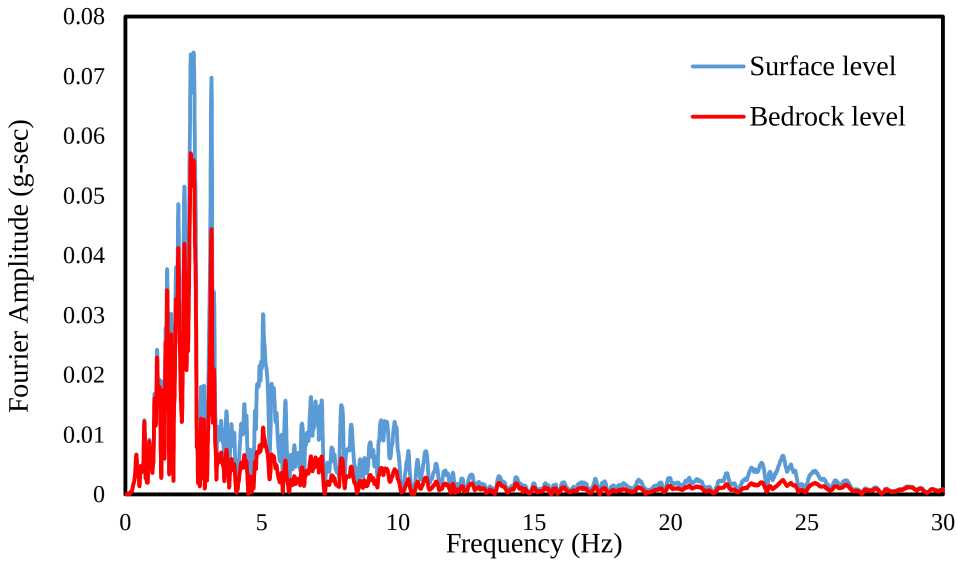


Figure 5.6 Fourier Amplitude Spectra at Thousand Pillar Temple

Response spectrum is another way of representing a ground motion. A response spectrum represents the maximum response of a single degree of freedom (SDOF) system to a particular input motion as a function of the natural frequency and damping ratio. It represents in a single graph the combined influences of terrain acceleration amplitudes and frequency components of the movement. A response spectrum is widely used in earthquake engineering to identify the frequency content of earthquake motion. The response spectra help in the assessment of spectral acceleration on the structure characterized by its natural period of vibration. The response spectra were plotted with 5% damping value, which is a pertinent value from the point of view of structural engineering. The response spectra for 5% damping at bedrock level and surface-level for NIT Warangal and Thousand Pillar temple are shown in Figures 5.7 and 5.8 respectively. The surface peak spectral acceleration value at NIT Warangal and Thousand Pillar temple is 0.349g and 0.337g observed at a period of 0.197s and 0.416s respectively. Therefore, during any seismic activity within Warangal region, the structures with a fundamental period in the range of 0.197 s to 0.416 s may exhibit substantial ground shaking compared to structures with fundamental period greater than 0.416s.

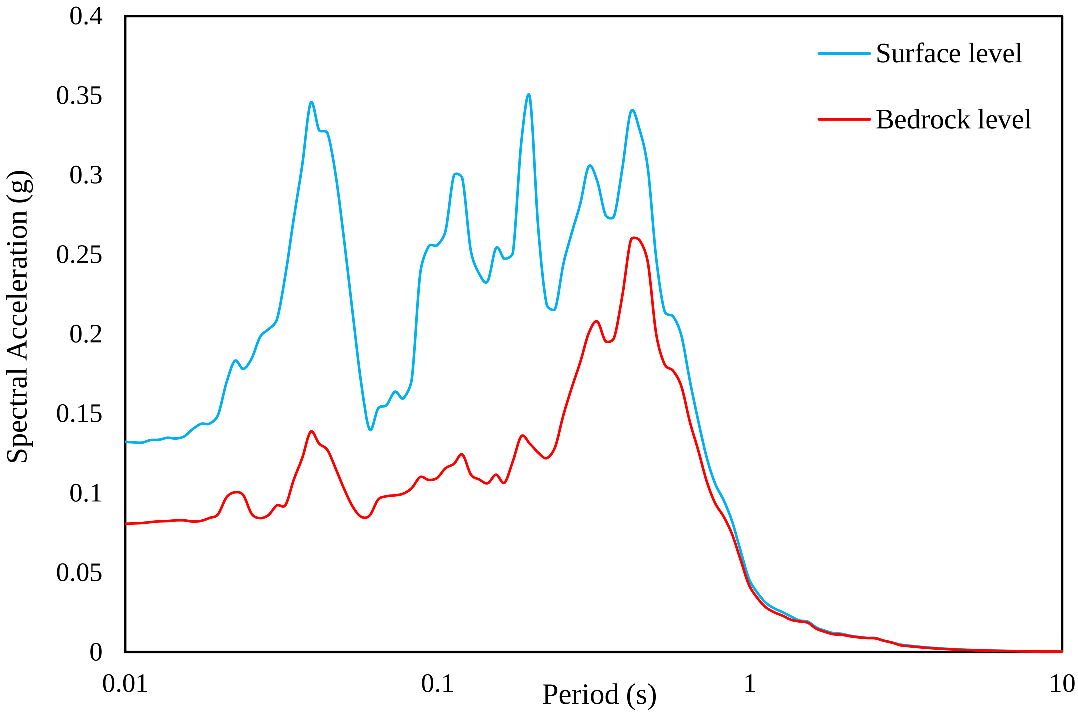


Figure 5.7 Response Spectra at NIT Warangal

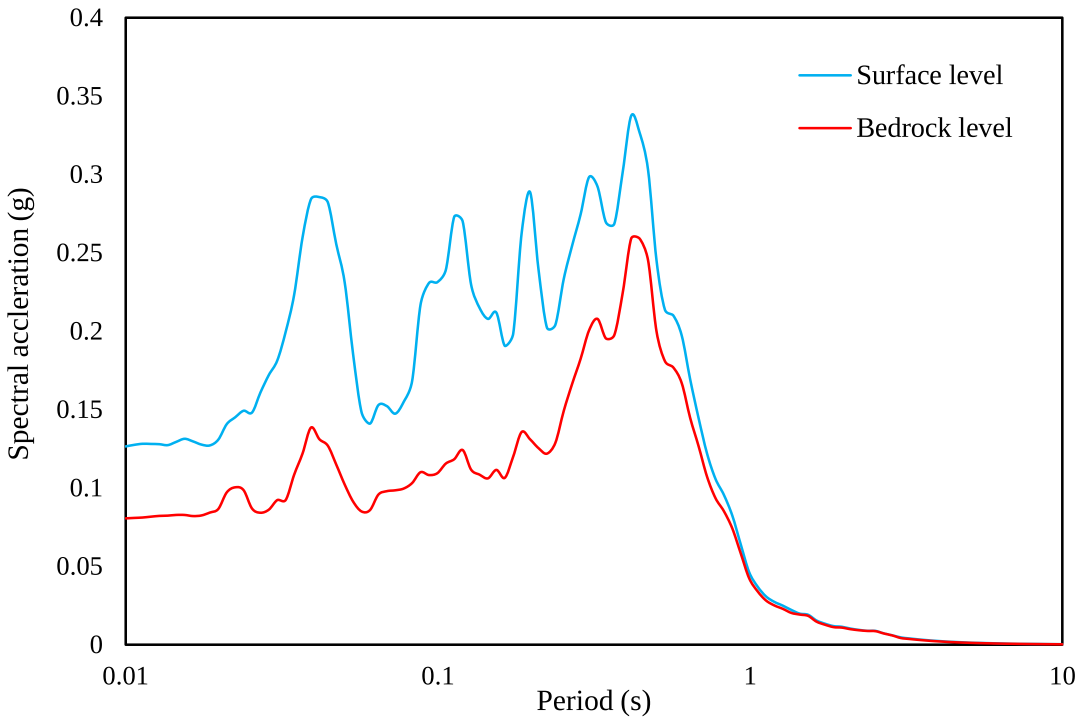


Figure 5.8 Response spectra at Thousand Pillar Temple

5.5 Summary

Ground response analysis is one of the crucial steps in the seismic hazard assessment of any area. Response of a site to seismic shaking is required to evaluate and remediate structural as well as geotechnical hazards. To evaluate the effects of the topsoil properties and to estimate the dynamic effects, site-specific ground response analysis was carried out. The essential input parameters were bedrock motion, variation in shear wave velocity along the depth and dynamic soil characteristics. Equivalent linear analysis in frequency domain was the form of analysis selected to obtain free field response. Coyote earthquake of magnitude M_W 5.7 was considered as input ground motion due to the unavailability of recorded earthquake data for earthquake occurring in the study area. The dynamic soil properties were estimated using shear wave velocity profile by performing MASW tests at NIT Warangal and Thousand Pillar temple. The peak ground acceleration at the ground surface was estimated by performing one-dimensional equivalent linear analysis. Peak acceleration at the ground surface for the given sites is 0.131 g and 0.124 g at NIT Warangal and Thousand pillar temple respectively to a peak acceleration of 0.08 g at bedrock level, indicating that the site is amplifying in nature. The amplification of ground motion is due to the presence of a soft layer of low shear wave velocities near the ground surface.

CHAPTER 6

SUMMARY AND CONCLUSTIONS

6.1 Summary

Seismic hazard is the potential of earthquakes to cause damages; this could be in terms of ground shaking, liquefaction, tsunamis, landslides, etc. Seismic hazard studies are desired for earthquake sensitive projects, as well as for developing earthquake loading regulations and various earthquake risk management purposes. Probabilistic seismic hazard assessment is ideally suited for compilation of seismic hazard maps. The seismic hazard assessment of a specific region is generally performed by a specialist in engineering seismology and earthquake engineering. Nevertheless, the user of hazard analysis results should have a proper understanding of the accuracy and reliability of data presented. The present study has examined the use of the standard probabilistic seismic hazard analysis (PSHA) procedure of Cornell-McGuire approach for defining the seismic input for Warangal district.

In probabilistic hazard analysis, the location, size, recurrence rates and ground motion that may result from a future earthquake at a site of interest are uncertain and require careful consideration. In order to check the completeness period of earthquake catalogue, the occurrence rate for several magnitude thresholds is examined in the present study. Great care must be taken in using published earthquake catalogues for low seismicity areas such as Warangal region. Completeness thresholds have been determined using CUVI and Stepp's methods. The regional recurrence relations are obtained based on nearly 217 years (1800-2016) of past data and the same is used in PSHA. The maps of PGA are very useful in determining the earthquake hazard susceptible areas, thereby facilitating the design, planning and construction as well as the strengthening of new and existing structures in Warangal region. Based on the results obtained in this study, the following conclusions can be drawn:

1. The estimated values of *a* and *b*-value for Waragnal region are 3.40 and 0.85 respectively, which are the important input parameters of the Gutenberg-Richter recurrence relationship.
2. Due to the absence of well-established GMPEs for the study region, three attenuation relationships developed for areas similar in tectonic features and seismicity to that of southern India are used in the study along with the one developed for peninsular India. It has been found that there is a slight variation in the predicted earthquake hazard in terms of the PGA values using the four attenuation relationships.
3. The PGA expected in Warangal region on stiff ground, with a 10% probability of exceedance in 50 years (which corresponds to a return period of 475 years) is 0.077 g, whereas, that with a 2% probability of exceedance in 50 years (return period = 2475 years) is 0.176 g.
4. The code specified spectra (IS: 1893-1, 2016) tend to overestimate the acceleration at higher structural periods for horizontal component of ground motion at Warangal, vis-à-vis the uniform hazard spectral from PSHA. On the other hand, the PGA is comparable and the acceleration at higher periods is significantly lower.
5. The hazard maps developed as part of the study show that the variation of PGA at the bedrock level is not very large. However, the PGA values are amplified at the surface when combined with the amplifying effects of the subsoil deposits of NIT Warangal and Thousand Pillar temple.

6. The surface level PGA value expected in Warangal region, with a 10% probability of exceedance in 50 years (which corresponds to a return period of 475 years) is 0.131g, which corresponds to an amplification factor of 1.64.
7. The established acceleration time-histories of ground motions can be of great use in earthquake-resistant design of new structures and also for assessing seismic performance of existing structures in Warangal region. When performed properly, an adequate PSHA will be valid for a number of years and will not be invalidated by new theories or data that result from the occurrence of a single earthquake.

6.2 Scope for further research

Good design measures based on experience, judgement and careful probabilistic seismic hazard analysis offer an adequate protection against the failure of structures, damages to infrastructure and potential threat to human lives. The main aim of the present study was to contribute to the area of seismic hazard analysis, for low to moderate seismic regions wherein the available information about seismic events is scarce, within the framework of probability theory. The considerable challenge of providing hazard estimates for the long return periods relevant to cultural heritage structures cannot be overstated. The cultural heritage structures need to be preserved to accommodate natural hazards that will occur over time periods of 5000 years, yet the present data sets collectively are incomplete. In addition, data quality and quantity are variable in space and time, and the standard methods of probability hazard analysis are very basic and generalized. The methods simplistically base future hazards on past seismic events, so only limited allowance is made for totally unanticipated hazardous events in previously inactive areas or low-activity areas.

Having explored the performance of the PSHA, a few more aspects need further study. The PSHA can be supplemented with the following aspects:

1. In the present study, PSHA was performed using the seismic zonation approach. Even though the zonation is based on the seismicity, geological data and tectonics of the region under study; but the demarcation of the seismic source zones is based on subjectivity of the analyst. In future studies, zone free approach could be used. To some extent, the zone free approach eliminates the subjectivity in the zonation.
2. It is possible to include the information about the mechanics of seismic sources directly in the PSHA procedure for realistic estimation of ground shaking hazards expected at a specific site.
3. For low to moderate seismic regions, the use of Gutenberg-Richter recurrence relation may not give reliable estimates of ground motion expected at a site. In such cases, recurrence models based on distributed seismicity may be more reliable and hence these models could be used in PSHA for estimating ground-shaking hazards.

The continued accumulation of high-quality data sets, improving methods of earthquake source modelling and current research revealing the limited validity of the ergodic assumption in probabilistic hazard analysis can only contribute positively to the reliability of future hazard estimates and engineering design.

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APPENDIX A

Earthquake catalogue compiled for the study region

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IMD – India Meteorological Department

ISC – International Seismological Centre

USGS – United States Geological Survey

S.No	Year	Mon	Day	Hour	Min	Sec	LAT	LON	Depth	M_w	Ref
1	1800	10	18	0	0	0	15.6	80.1	0	4.3	Rao
2	1820	12	31	0	0	0	14.5	80	0	4.3	Rao
3	1827	1	6	0	0	0	17.7	83.4	0	4.3	Iyenger
4	1843	3	12	0	0	0	15.2	76	0	4.7	Iyenger
5	1843	3	12	0	0	0	17.5	78.5	0	3.7	Rao
6	1843	3	31	0	0	0	15.2	76.9	0	5.7	Rao
7	1853	2	21	0	0	0	17.7	83.4	0	3.7	Rao
8	1858	8	24	0	0	0	17.8	83.4	0	3.3	Nath
9	1858	10	12	0	0	0	18.3	84	0	4.3	Rao
10	1859	7	21	0	0	0	16.3	80.5	0	4.3	Rao
11	1859	8	2	0	0	0	16.3	80.5	0	3.7	Rao
12	1859	8	9	0	0	0	16.3	80.5	0	3.7	Rao

13	1859	8	24	0	0	0	18.1	83.5	0	3.7	Rao
14	1860	2	2	0	0	0	13.7	79.4	0	4.3	Rao
15	1861	7	24	0	0	0	16.4	77.3	0	3.7	Rao
16	1861	11	13	0	0	0	18.1	83.4	0	3.3	Nath
17	1862	1	13	0	0	0	16.4	77.3	0	3.7	Rao
18	1867	1	3	0	0	0	16.1	79.6	0	3.8	Nath
19	1867	1	6	0	0	0	16.1	79.8	0	3.0	Rao
20	1867	3	11	0	0	0	16	80.3	0	3.7	Rao
21	1869	9	1	0	0	0	14.5	80.8	0	4.3	Rao
22	1869	9	2	0	0	0	14.5	80	0	3.0	Rao
23	1869	12	19	0	0	0	17.9	82.3	0	3.7	Rao
24	1870	12	19	0	0	0	17.7	83.4	0	3.7	Rao
25	1871	9	27	0	0	0	18.3	84	0	3.3	Nath
26	1872	11	22	0	0	0	18.8	80	0	4.7	Iyenger
27	1875	1	2	0	0	0	15.5	80	0	3.3	Nath
28	1876	10	1	0	0	0	17.45	78.45	0	5.0	Rao
29	1876	11	1	0	0	0	17.5	78.5	0	4.7	Iyenger
30	1878	12	1	0	0	0	18.3	84	0	3.8	Nath
31	1879	4	28	0	0	0	13.8	77.8	0	3.8	Nath
32	1883	7	27	0	0	0	21.2	79.2	0	3.8	Nath
33	1898	6	1	0	0	0	17	82.3	0	3.3	Nath
34	1905	4	2	0	0	0	16	80.1	0	4.1	Iyenger
35	1909	9	1	0	0	0	16.2	80.1	0	3.2	Nath
36	1917	4	17	0	0	0	18	84	0	5.2	Nath
37	1917	4	18	0	0	0	18.1	83.5	0	3.2	Nath
38	1918	5	19	0	25	22	15.9	83.7	0	5.4	IMD
39	1927	1	1	0	0	0	17.7	83.4	0	4.1	Nath
40	1934	1	1	0	0	0	17.5	77.2	0	3.7	Nath
41	1934	2	20	0	0	0	18.5	83.2	0	3.2	Nath
42	1934	10	15	0	0	0	17.5	76	0	3.2	Nath
43	1935	1	1	0	0	0	18.4	78.1	0	3.4	Nath
44	1937	8	22	0	0	0	15.4	78.2	0	3.4	Nath
45	1939	4	19	0	0	0	17.3	78.5	0	3.7	Nath
46	1939	11	5	0	0	0	21.4	77.8	0	3.2	Nath
47	1942	1	1	0	0	0	19.1	79.2	0	3.7	Nath

48	1945	6	6	0	0	0	17.7	83.4	0	4.1	Nath
49	1946	11	2	0	0	0	15.4	78.2	0	3.2	Nath
50	1948	2	6	0	0	0	14.6	76.8	0	3.7	Nath
51	1948	7	9	0	0	0	18.3	84	0	3.2	Nath
52	1954	1	5	0	0	0	18	81.3	0	3.9	Rao
53	1954	3	11	0	0	0	18.1	83.5	0	3.2	Nath
54	1955	1	1	0	0	0	18.8	76.7	0	3.7	Nath
55	1956	2	18	0	0	0	15.6	80.1	0	3.7	Nath
56	1956	10	1	0	0	0	18.1	77.3	0	3.7	Nath
57	1956	11	5	0	0	0	17.2	76.5	0	3.2	Nath
58	1957	4	20	0	0	0	15.6	80.1	0	3.2	Nath
59	1957	8	25	21	4	50	22	80		5.5	ISC
60	1957	10	17	0	0	0	21.3	79	0	3.7	Nath
61	1958	1	13	0	0	0	16.1	80.1	0	4.1	Nath
62	1959	6	15	0	0	0	16.1	80.1	0	3.2	Nath
63	1959	8	9	0	0	0	18.1	83.5	0	3.7	Rao
64	1959	8	21	0	0	0	15.8	80.2	0	3.7	Rao
65	1959	10	12	19	26	0	16	80	0	5.4	IMD
66	1959	10	13	0	0	0	15.6	80.1	0	5.0	Rao
67	1959	12	23	0	0	0	18.1	83.5	0	4.3	Rao
68	1960	1	19	0	0	0	15.7	80.1	0	3.2	Nath
69	1960	1	28	0	0	0	13.7	79.4	0	3.7	Nath
70	1960	10	8	0	0	0	16	80.3	0	4.3	Rao
71	1960	10	19	0	0	0	18.3	83.9	0	3.7	Nath
72	1963	12	5	0	0	0	17.3	80.1	0	3.6	Rao
73	1965	7	8	0	0	0	22.4	79.1	0	3.2	Nath
74	1966	4	10	0	0	0	14.7	80	0	5.0	Rao
75	1966	12	1	0	0	0	19.3	76.8	0	3.7	Nath
76	1967	3	27	8	9	45.7	15.62	80.16	15	5.1	IMD
77	1967	7	28	0	0	0	18.1	83.5	0	3.2	Nath
78	1968	6	20	0	0	0	16	79.6	0	3.2	Rao
79	1968	7	21	0	0	0	21.4	77.8	0	4.5	Rao
80	1968	7	27	0	0	0	17.6	80.8	0	4.5	Rao
81	1968	11	14	0	0	0	21.8	78	0	4.0	Nath
82	1969	1	16	0	0	0	14.1	78.7	0	3.4	Nath

83	1969	2	5	0	0	0	14.1	77.5	0	3.4	Nath
84	1969	3	16	0	0	0	14.6	76.6	0	3.4	Nath
85	1969	4	1	0	0	0	16.6	79.3	0	3.5	Rao
86	1969	4	7	0	0	0	16.6	79.3	0	3.7	Rao
87	1969	4	13	15	24	54.7	17.81	80.67	25	5.2	IMD
88	1969	4	15	17	58	39	18	80.7	33	4.9	ISC
89	1969	7	1	0	0	0	14.1	78.5	0	3.9	Nath
90	1969	9	15	0	0	0	17.6	80.5	0	3.7	Rao
91	1969	11	10	0	0	0	13.7	79.2	0	3.9	Nath
92	1970	1	12	0	0	0	15.5	79.6	0	4.0	Rao
93	1970	1	16	0	0	0	15.3	79.6	0	3.9	Rao
94	1970	4	3	0	0	0	14.7	78.1	0	3.2	Nath
95	1970	5	13	0	0	0	13.7	79.2	0	3.9	Nath
96	1970	10	27	0	0	0	15.5	79.6	0	3.8	Rao
97	1970	12	6	0	0	0	14.7	78.1	0	3.9	Nath
98	1971	5	22	0	0	0	17.6	77.6	0	3.5	Rao
99	1971	5	27	0	0	0	17.6	77.6	0	3.8	Rao
100	1971	7	28	0	0	0	15.5	79.6	0	4.2	Rao
101	1972	4	21	0	0	0	20.7	77	0	4.1	Nath
102	1972	6	11	0	0	0	17.6	80.2	0	3.2	Nath
103	1972	11	10	0	0	0	13.7	79.2	0	3.2	Nath
104	1973	1	2	0	0	0	13.8	79.7	0	3.2	Nath
105	1973	3	16	0	0	0	14.9	79.4	0	3.1	Nath
106	1973	11	15	0	0	0	17	76.3	0	4.1	Nath
107	1974	11	28	0	0	0	15.6	80.2	0	3.8	Nath
108	1974	12	9	0	0	0	14.5	77.1	0	3.2	Nath
109	1975	2	25	0	0	0	15.3	79.6	0	3.8	Nath
110	1975	3	28	0	0	0	14.5	79.3	0	3.2	Nath
111	1975	4	24	0	0	0	18.7	80.7	0	4.1	Rao
112	1975	5	12	0	0	0	15	76	0	4.6	Nath
113	1975	7	3	0	0	0	18.5	79.5	0	3.1	Nath
114	1975	7	27	0	0	0	15.5	79.6	0	4.0	Rao
115	1975	8	13	0	0	0	21.8	77.7	0	3.9	Nath
116	1975	9	2	0	0	0	17.3	77.9	0	3.7	Rao
117	1975	9	15	0	0	0	18.4	79.2	0	3.1	Nath

118	1976	1	20	0	0	0	19.5	79.2	0	3.9	Rao
119	1976	2	9	0	0	0	14.7	78.1	0	3.4	Nath
120	1976	10	25	0	0	0	15.5	78.8	0	3.4	Nath
121	1977	5	25	0	0	0	15.5	79.6	0	3.4	Nath
122	1977	9	30	0	0	0	18	81.5	0	3.1	Nath
123	1979	4	22	0	0	0	18.4	80.8	0	3.4	Nath
124	1979	10	10	0	0	0	16.1	79.1	0	3.4	Nath
125	1980	2	3	0	0	0	15.3	80.3	0	3.2	Nath
126	1980	3	30	13	31	53.4	17.5	81.84	54	4.3	IMD
127	1980	3	31	0	0	0	20.6	76	0	3.1	Nath
128	1980	5	1	0	0	0	21	76	0	3.9	Nath
129	1980	9	3	0	0	0	14.5	76.6	0	3.1	Nath
130	1980	10	2	0	0	0	16.9	82	0	3.9	Nath
131	1980	11	13	0	0	0	15.3	76.3	0	3.7	Nath
132	1980	12	31	0	0	0	18	75	0	3.4	Nath
133	1981	2	13	0	0	0	16.5	79.5	0	3.5	Rao
134	1981	2	18	0	0	0	15.3	78.8	0	3.5	Rao
135	1981	3	21	0	0	0	16	79.6	0	3.2	Nath
136	1981	3	30	0	0	0	17.4	81.9	0	3.9	Nath
137	1981	7	22	0	0	0	15.3	79.6	0	3.2	Nath
138	1981	9	20	0	0	0	15.5	78.8	0	3.5	Rao
139	1981	11	2	0	0	0	15.5	78.8	0	3.4	Nath
140	1981	12	4	0	0	0	18.1	81.4	0	3.2	Nath
141	1981	12	8	0	0	0	16.3	80.5	0	3.2	Nath
142	1981	12	16	0	0	0	18.6	80.7	0	3.1	Nath
143	1982	1	14	0	0	0	17.4	78.4	0	3.4	Nath
144	1982	2	24	0	0	0	17.5	78.6	0	4.0	Rao
145	1982	5	10	0	0	0	18	75	0	3.4	Nath
146	1982	6	13	0	0	0	15.9	79.8	0	3.2	Nath
147	1982	9	11	0	0	0	18.1	75.1	0	3.9	Nath
148	1983	4	24	0	0	0	15.5	79.8	0	3.2	Nath
149	1983	5	20	0	0	0	15.5	79.8	0	4.1	Rao
150	1983	6	30	6	59	31.1	17.93	78.54	33	4.8	IMD
151	1983	8	14	0	0	0	15.6	80.2	0	3.2	Nath
152	1983	9	7	0	0	0	17.8	81	0	3.2	Nath

153	1983	9	15	0	0	0	15.5	79.6	0	3.1	Nath
154	1983	12	14	0	0	0	18.7	80.6	0	3.7	Nath
155	1984	3	28	0	0	0	17.3	83.3	0	4.0	Nath
156	1984	3	28	0	0	0	20.2	76.3	0	3.4	Nath
157	1984	4	24	0	0	0	18.8	79.5	0	3.4	Nath
158	1984	6	27	0	0	0	16.7	80.4	0	3.3	Nath
159	1984	7	21	0	0	0	19.1	78.1	0	3.1	Nath
160	1984	7	31	0	0	0	15.9	79.6	0	3.2	Nath
161	1984	8	23	0	0	0	17.7	83.3	0	3.4	Nath
162	1985	1	6	0	0	0	20.2	78.4	0	4.0	Nath
163	1985	5	12	0	0	0	18.7	84	0	3.7	Nath
164	1985	6	1	0	0	0	22	80	0	3.9	Nath
165	1985	9	7	0	0	0	17.8	81	0	3.7	Nath
166	1985	9	27	0	0	0	19.4	78.9	0	3.2	Nath
167	1986	2	7	0	0	0	15.7	80.3	0	3.2	Nath
168	1986	3	31	0	0	0	15.9	79.4	0	3.1	Nath
169	1986	5	22	0	0	0	20.3	77.6	0	3.9	Nath
170	1986	6	2	0	0	0	18	81.8	0	3.2	Nath
171	1986	8	18	0	0	0	15.5	80.5	0	3.4	Nath
172	1987	3	12	0	0	0	15.5	80.2	0	3.9	Nath
173	1987	4	18	16	59	48	22.346	79.259	33	5.2	USGS
174	1987	12	3	18	15	50.1	15.51	80.21	70	4.4	IMD
175	1988	2	4	0	0	0	15.7	79.8	0	3.2	Nath
176	1988	3	21	21	23	1	14.4	80.2	33	4.0	IMD
177	1989	3	11	0	0	0	18.3	81	0	3.2	Nath
178	1989	4	21	0	0	0	17.3	80.4	0	3.3	Nath
179	1989	7	15	0	0	0	18.6	78	0	3.1	Nath
180	1989	10	24	0	0	0	17.5	80.9	0	3.4	Nath
181	1990	6	9	0	0	0	18.1	80.5	0	4.4	Nath
182	1990	7	24	0	0	0	17.1	81.3	0	3.4	Nath
183	1990	9	29	0	0	0	15.5	77.2	0	3.2	Nath
184	1990	10	9	0	0	0	14	80.2	0	3.4	Nath
185	1990	12	18	0	0	0	14	80.5	0	3.2	Nath
186	1991	1	4	0	0	0	18.1	81.5	0	3.2	Nath
187	1991	1	28	0	0	0	17.4	80	0	3.2	Nath

188	1991	2	3	0	0	0	16.52	81.85	0	3.7	Nath
189	1991	2	25	0	0	0	19	80	0	3.3	Nath
190	1991	3	18	0	0	0	17	82.5	0	3.2	Nath
191	1991	4	30	0	0	0	20	75.3	0	4.7	Nath
192	1991	5	5	0	0	0	17.2	82.4	0	3.1	Nath
193	1991	7	12	17	31	24	18.1	78.6	9	3.9	ISC
194	1991	10	13	0	0	0	18.3	75.7	0	3.7	Nath
195	1991	12	6	0	0	0	19	79.9	0	3.1	Nath
196	1991	12	15	0	0	0	18.6	78.6	0	3.2	Nath
197	1992	4	30	0	0	0	14.6	79.2	0	3.1	Nath
198	1992	5	16	0	0	0	17.2	78	0	3.1	Nath
199	1992	5	22	6	30	34	18.4	83.2	0	3.9	IMD
200	1992	10	6	0	0	0	21.2	77.28	0	3.7	Nath
201	1992	10	18	17	33	3.2	18.1	76.9	33	4.3	IMD
202	1992	10	21	0	0	0	18.5	79.8	0	3.2	Nath
203	1992	11	2	0	7	0.5	18.2	76.6	33	3.8	IMD
204	1992	11	14	0	0	0	15.5	80.1	0	3.4	Nath
205	1993	9	25	0	0	0	16.5	77.6	0	3.1	Nath
206	1993	9	29	22	25	47.5	18.07	76.62	12	6.2	IMD
207	1993	9	29	23	10	57.5	18	76.4	10	4.9	IMD
208	1993	9	30	0	53	13	18	76.5	12	4.6	IMD
209	1993	9	30	2	16	56.3	18.1	76.6	12	4.4	IMD
210	1993	10	1	17	1	16.8	17.9	76.6	12	4.3	IMD
211	1993	10	2	23	15	30.5	17.9	76.6	12	3.5	IMD
212	1993	10	4	21	19	34.8	18	76.6	12	3.8	IMD
213	1993	10	8	20	45	7.3	18	76.7	33	4.5	IMD
214	1993	10	16	8	58	11.6	18	76.5	15	3.2	IMD
215	1993	10	17	0	7	12.3	17.9	77.2	1	3.7	IMD
216	1993	10	18	18	9	39.9	17.9	76.6	2	3.4	IMD
217	1993	10	28	19	21	17.4	18	76.5	1	3.1	IMD
218	1993	10	29	23	45	7	17.369	77.468	10	5.3	USGS
219	1993	11	1	6	28	44.3	18	76.6	21	3.3	IMD
220	1993	11	12	13	27	31	18	76.5	3	4.9	IMD
221	1993	11	13	4	21	2.2	18.1	76.5	4	3.3	IMD
222	1993	11	18	0	0	0	18.37	76.88	0	3.7	Nath

223	1993	11	24	14	46	1.6	18	76.6	1	4.3	IMD
224	1994	6	23	22	3	11	18.1517	76.3119	10	4.1	ISC
225	1995	5	24	13	46	37	16.2	80.1	33	4.3	IMD
226	1995	5	26	13	58	23	19.2	83.3	33	3.7	IMD
227	1995	10	21	0	0	0	15.4	79.8	0	3.8	Nath
228	1995	11	7	6	18	30	19.9	75.9	33	3.3	IMD
229	1995	12	14	4	9	32	18.1149	76.528	10	4.5	ISC
230	1995	12	18	11	28	4	18	83.7	33	4.4	IMD
231	1996	5	14	0	0	0	15.8	80.2	0	3.3	Nath
232	1996	8	4	21	51	55	16.01	79.85	0	4.0	IMD
233	1996	11	10	9	0	4.1	18.3	76.69	33	4.0	IMD
234	1997	1	23	2	34	50	17.1421	76.6916	33	5.0	ISC
235	1997	2	21	9	37	39	18	76.6	0	3.1	IMD
236	1997	11	23	1	34	44	22.104	80.3924	33	4.3	ISC
237	1998	3	29	18	54	20	22.5138	79.2597	33	4.3	ISC
238	1998	4	9	6	22	18.4	16.54	78.34	0	5.4	IMD
239	1998	4	17	22	9	17.2	21.26	76.92	15	3.0	IMD
240	1998	6	29	6	58	2	18.55	79.66	15	4.3	IMD
241	1998	7	19	22	38	0	15.6	75.7	0	3.9	Iyenger
242	1998	8	10	17	20	29.7	18.08	76.68	10	3.3	IMD
243	1998	12	2	9	57	43.9	18.76	79.27	5	3.1	IMD
244	1999	2	3	23	8	44.5	18.21	80.34	17	3.5	IMD
245	1999	2	20	11	20	6.8	18.03	76.5	10	3.7	IMD
246	1999	2	26	22	7	37.9	21.46	78.55	34	3.7	IMD
247	1999	3	25	5	45	51.5	18.76	79.76	10	3.8	IMD
248	1999	3	30	9	47	25.5	18.61	79.48	5	3.2	IMD
249	1999	4	2	10	19	25.7	17.13	78.55	28	3.6	IMD
250	1999	5	2	19	21	0.6	14.3	78.87	33	3.5	IMD
251	1999	10	9	5	58	50.7	19.18	77.46	15	3.2	IMD
252	2000	1	24	4	50	27.5	18.94	80.32	10	3.7	IMD
253	2000	3	27	9	59	14.1	19.63	77.74	15	3.1	IMD
254	2000	4	5	6	47	47	17.91	79.49	10	3.1	IMD
255	2000	6	19	8	22	5.3	18.01	76.53	15	4.5	IMD
256	2000	6	22	10	10	41.2	19.84	78.81	5	4.1	IMD
257	2000	6	30	13	57	32.4	21.95	78.87	15	3.5	IMD

258	2000	8	15	11	57	26.2	17.43	82.63	5	3.2	IMD
259	2000	8	19	8	22	0	18.01	76.53	15	4.5	Iyenger
260	2000	10	9	2	47	15.8	19.29	76.34	15	3.0	IMD
261	2000	11	2	5	34	34	17.82	80.6	33	3.1	IMD
262	2000	12	9	22	22	7.3	15.33	79.91	15	3.3	IMD
263	2001	3	26	18	55	6.3	18.88	83.38	15	3.9	IMD
264	2001	3	26	19	9	9.3	18.74	83.29	15	3.5	IMD
265	2001	5	15	17	5	7.9	18.07	76.37	9	3.2	IMD
266	2001	6	8	2	38	31.5	13.77	80.09	15	3.5	IMD
267	2001	6	15	7	48	47.2	15.11	78.74	15	3.9	IMD
268	2001	7	26	10	5	23	21.327	79.671	10	5.3	ISC
269	2001	9	9	9	54	1.3	18.49	79.74	33	3.0	IMD
270	2001	11	3	15	2	26.7	19.7	82.79	15	3.6	IMD
271	2001	11	5	22	31	5.4	19.07	76.72	15	3.0	IMD
272	2001	11	8	6	36	20.5	19.39	77.17	15	3.0	IMD
273	2002	1	11	3	34	59.5	17.57	80.74	22	3.0	IMD
274	2002	1	30	10	25	46.5	18.54	80.59	10	3.1	IMD
275	2002	5	15	9	52	23.7	18.57	79.49	5	3.3	IMD
276	2002	7	10	14	9	12.3	15.48	76.08	10	3.5	IMD
277	2002	9	21	10	26	16	19.536	83.866	15	3.6	ISC
278	2002	11	22	9	50	54	18.73	79.31	5	3.1	IMD
279	2002	11	29	10	15	53.5	17.95	78.79	10	3.3	IMD
280	2003	1	19	9	48	34.1	20.61	77.41	7	3.0	IMD
281	2003	3	10	22	45	7.5	21.27	77.19	9	3.7	IMD
282	2003	4	7	22	55	16.1	14.15	79.52	5	3.1	IMD
283	2003	4	8	3	1	37.8	14.19	80.09	27	3.3	IMD
284	2003	4	14	10	22	3.8	18	84	34	3.3	IMD
285	2003	5	7	8	21	46.5	15.64	82.48	38	3.3	IMD
286	2003	5	28	10	14	56.1	18.76	79.35	18	3.0	IMD
287	2003	11	29	7	5	21.4	21.24	80.24	13	3.0	IMD
288	2003	12	26	18	37	44.5	20.67	76.89	13	3.0	IMD
289	2004	1	17	10	40	45.5	18.38	77.33	49	3.0	IMD
290	2004	5	28	5	26	37.1	15.35	79.84	10	3.6	IMD
291	2004	7	6	2	7	2.4	18.92	80.85	17	3.5	IMD
292	2004	8	25	0	11	44	20.0927	83.5913	10	3.5	ISC

293	2004	8	26	6	56	30.1	18.57	83.34	39	3.3	IMD
294	2004	11	20	9	49	45.6	19.39	79.59	20	3.1	IMD
295	2004	12	2	9	48	10.5	20.14	77.93	19	3.0	IMD
296	2005	3	14	17	37	23.6	18.96	83.08	14	4.0	IMD
297	2005	4	13	6	7	3.2	18.06	76.62	5	3.4	IMD
298	2005	7	21	18	24	59.5	18.41	83.39	12	3.6	IMD
299	2006	1	4	23	17	1.3	15.48	80.12	11	3.5	IMD
300	2006	1	4	11	1	33.8	18.22	76.39	7	3.4	IMD
301	2006	1	12	13	58	43.7	17.91	76.73	10	3.1	IMD
302	2006	8	4	2	2	11.2	14.09	81.11	24	3.9	IMD
303	2006	8	5	2	57	29.1	22.3	79.39	10	3.3	IMD
304	2006	12	16	3	21	35.6	15.14	81.17	10	3.4	IMD
305	2007	1	28	17	4	20.3	18.87	80.24	10	3.4	IMD
306	2007	9	6	7	9	45	18.07	76.66	10	3.7	IMD
307	2007	9	14	22	6	18.8	17.34	75.06	15	3.3	IMD
308	2008	5	29	11	20	17.1	17.84	82.85	56	3.5	IMD
309	2008	12	17	9	13	30	20.4	83.16	10	3.0	IMD
310	2009	8	1	18	49	57.5	22.3	79.69	10	3.4	IMD
311	2009	12	11	14	3	10.9	14.3	80.53	28	3.5	IMD
312	2010	1	25	17	0	44.3	21.56	76.93	10	3.1	IMD
313	2011	9	19	0	52	4.6	18.02	76.6	10	3.8	IMD
314	2011	10	19	18	53	45.4	16.54	79.11	10	3.5	IMD
315	2011	11	26	18	34	51.4	16.82	77.53	10	3.0	IMD
316	2012	2	8	19	22	34.5	14.23	80.18	8	3.3	IMD
317	2012	6	9	8	14	40.9	20.14	82.89	8	3.8	IMD
318	2012	6	12	1	9	44	22.32	78.86	15	3.3	IMD
319	2012	8	16	22	15	56.7	17.33	80.73	10	3.2	IMD
320	2012	10	29	6	23	7.8	16.2	79.71	12	3.9	IMD
321	2012	12	19	6	23	24	15.6769	82.727	10	4.8	ISC
322	2013	11	4	13	8	38.4	17.78	83.04	15	3.2	IMD
323	2015	2	25	0	39	31	17.9425	81.2311	0	4.3	ISC
324	2016	2	12	10	11	14	20.37	78.16	10	5.6	ISC
325	2016	5	28	3	12	36	14.7281	79.3235	0	3.9	ISC

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