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Seismic Zoning for Nepal

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Abstract

Nepal is exposed to high seismic risk from local and distant earthquakes and it is one of the well-identified earthquake-prone countries in the world. It has experienced two great seismic events with magnitudes equal to 8.1 and above (Mw = 8.1, 1505 and Mw = 8.4, 1934 Bihar-Nepal) during the past six centuries with huge economic losses, material damage and human casualties. In addition to these two historical great earthquakes, Nepal has often suffered extensive material damage and enormous economic losses by numerous instrumental strong seismic events, including the September 18, 2011 (M = 6.8) seismic event. The area in and around Nepal is seismically active and such damaging events are likely to continue in the future, therefore, it is essential to identify earthquake-prone areas and prepare the seismic zonation maps of Nepal that provide strong seismic ground motion parameters for the government, engineers, scientists and others for planning and design of anti-seismic key infrastructures and emergency management in order to reduce the casualties and economic losses from future earthquake disasters in this region.

The aim of this dissertation is to prepare a set of seismic zonation maps for Nepal. This dissertation primarily composed of three studies. The first study is specifically devoted to the analysis of earthquake catalogue. All the available historical and instrumental earthquakes with magnitudes equal to or greater than 4.0 that occurred in the region defined between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E from 1255 to 2011 were compiled. The analysis of compiled earthquake database was carried out very carefully reviewing published literatures and duplicated seismic events, aftershocks and foreshocks were removed. By using the published empirical relations, different magnitudes (M_s, M_b, and M_L) and intensity scales were converted into the surface-wave magnitude and finally, an unified and homogeneous catalogue of earthquakes (in terms of surface-wave magnitude, $M_s \geq 4.0$) was prepared.

The analysis of seismic catalogue ($M_s \geq 4.0$) spanning the period 1255-2011 shows that earthquakes are unevenly distributed in the study area with the strongest earthquake activity

in the far-western and eastern parts of the country and the weakest seismic activity in southern Nepal. Furthermore, the spatial association of earthquakes with major faults demonstrates that the epicenters of the overwhelming number of seismic events are situated near the surface trace of Main Central Thrust (MCT) and epicenters of a few earthquakes are situated at small distances from the surface traces of the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) in this study area.

In the second study, earthquake-prone areas in the Nepal Himalaya and the surrounding regions were determined using the morphostructural zoning (MSZ) and pattern recognition techniques (PRT). The determination of location of future seismically dangerous areas using PRT in this dissertation shows that the majority of earthquake-prone areas are located on second rank lineaments than on the first and third rank lineaments in the investigation region. These identified potential earthquake-prone areas are also located in our study area where no records of strong seismic events ($M \geq 6.0$) have been reported in the past.

The third study is focused on defining potential seismic source zones and developing the seismic zonation maps of Nepal. Based on the distribution of catalogued earthquakes, distribution of faults and tectonic information, as well as earthquake-prone areas identified from the pattern recognition techniques, twenty-three potential seismic source zones were established for the study area. Integrating potential seismic source zone information and probabilistic earthquake hazard parameters (minimum magnitude, maximum magnitude and earthquake spatial distribution function for individual source zone, and *b*-value, average annual occurrence rate of earthquakes, hypocenter depth for the whole region) in conjunction with a selected PGA attenuation relationship, seismic ground motion hazard at bedrock level were calculated over a grid of 0.2° × 0.2° covering the entire territory of Nepal with 63%, 10%, and 2% probability of exceedance in 50 years. The resulting seismic zonation maps address earthquake ground motion hazard in terms of PGA at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years. These seismic zoning maps prepared at three different exceedance probabilities (63%, 10%, and 2%) generally reveal the high seismic ground motion hazard in the eastern and far-western segements of the country, and low seismic ground motion hazard in southern Nepal. In addition, the probabilistic seismic

zonation maps prepared in this dissertation are compared with the seismic zoning maps of China and India. This comparison of our seismic zonation maps with the seismic zonation maps of neighboring countries indicate that the PGA values obtained in the present analysis well-match with those of PGA values shown in the seismic zonation map of India only in a particular area of high seismic ground motion hazard in the far-western part of Nepal.

Key Words：Seismic Zonation; Potential Seismic Source Zone; Seismicity; Seismic Hazard Analysis; Peak Ground Acceleration; Pattern Recognition; Nepal

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1 INTRODUCTION

1.1 Background

Nepal is an earthquake prone country situated between two giant Asian nations, namely, China in the north and India to the east, south, and west (Fig. 1.1) encompassing a total area of 147,181 km^2 (average north-south span~193 km and east-west span~800 km) between latitudes 26˚22’N-30˚27’N and longitudes 80˚4’E-88˚12’E. It is a developing nation with a total population exceeding 26 million people according to the National Population and Housing Census (Government of Nepal) Central Bureau of Statistics (CBS, 2011) [1] and covers the ~800-km-long central-segment (80˚4’-88˚12’E) of the Himalayan seismic belt.

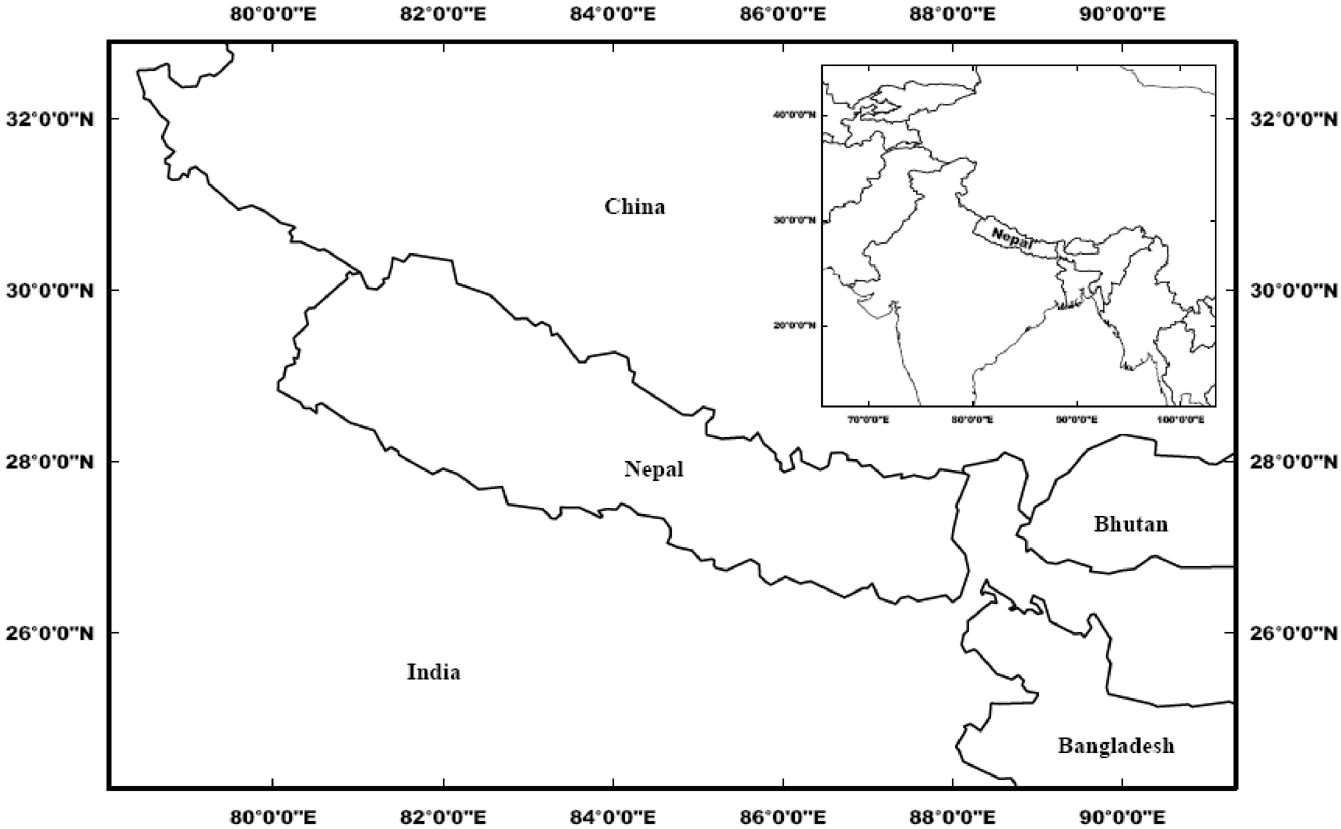

Fig. 1.1 Map showing the location of Nepal

During the seismic history of Nepal, the country has been frequently rattled by several disastrous earthquakes that occurred in the Nepal Himalaya and its nearby region. Table 1 lists the dates, magnitudes, epicenter areas and casualties of major earthquakes with surface-wave magnitude equal to or greater than 6.0 that occurred in Nepal from 1255 onwards. In fact, the date, records and the descriptions of damage of past several earthquakes that occurred in this region are probably missing and incomplete. As shown in Table 1, Nepal has experienced many strong earthquakes and has been intensively shaken by five destructive earthquakes (1255, 1408, 1505, 1833, and 1934) with magnitudes 7.6 and above since 1255 and suffered huge human casualties and countless economic losses. Among which, the earthquake of 1255 (M_s = 7.6) is the ever oldest documented destructive seismic event that caused a death of one third of a total accommodated population of Kathmandu including the King "Abhaya Malla" of the Kathmandu valley and severe damage to the buildings and temples with countless economic losses in Nepal [1]. The 1408 (M_s = 7.6) earthquake killed numerous people and caused damages to the several buildings and temples in the country. The 1505 earthquake (M_w = 8.1) occurred in the sparsely populated area in the northwestern part of Nepal [2]. This event is the second largest earthquake that was felt in several parts of the country but the death and damage from the great 1505 earthquake was scanty. The 1833 earthquake (M_s = 7.6) killed 414 people and caused damage of 18,000 buildings [4]. The 1934 earthquake (M_w = 8.4) is better known as the 1934 Bihar-Nepal great earthquake because it was not only widely felt and destroyed buildings, temples and houses throughout the territory of Nepal, but also felt and caused extensive destruction in Bihar of northern India. The 1934 Bihar-Nepal great earthquake is the most catastrophic historical great seismic event that caused huge casualties (> 8000 deaths) with tremendous material damage and countless economic losses in Nepal.

In addition to the aforementioned historical earthquakes, there are few accounts of some instrumentally recorded damaging strong earthquakes (M_s = 6.6, 1980, M_s = 6.8, 1988, and M_s = 6.8, 2011) that have caused significant loss of life and economy, and serious material damage in the country. The July 29, 1980 Bajhang earthquake (M_s = 6.6) was located in the far western segment of Nepal that resulted hundreds of deaths and damage accounted tens of thousands of buildings throughout the country. The August 20, 1988 Udayapur earthquake (M_s = 6.8) was located in the southeastern section of Nepal causing a few hundreds of deaths and damage amounted more than 60, 000 of buildings. The most recent strong damaging earthquake (M = 6.8, September 18, 2011) occurred around 270 kilometers to the east of Kathmandu (the capital of Nepal), near the Nepal-India boundary, caused the death of 6 people in Nepal, including the death of 3 people by a collapse of wall in Kathmandu. The earthquake of September 18, 2011 was felt over a wide area encompassing five Asian countries (Bangladesh, Bhutan, China, India, and Nepal), where it caused the death of more than 100 people. The September 18, 2011 earthquake badly affected chiefly in eastern Nepal and neighboring areas and damaged several houses and caused significant human casualties and economic loss in Nepal.

Most of the fatalities and damages from the past and recent earthquakes are associated with the vulnerable structures in the country. It is manifested by the death of 3 people from a collapsing wall in Kathmandu, approximately 270 kilometers far from the epicenter of the most recent strong September 18, 2011 (M = 6.8) earthquake that is located in the northeastern segment of Nepal near the Nepal-India border. In addition, there is a large annual growth of population, continued rapid urbanization, construction and expansion of infrastructures in Nepal. This high rate of population growth, fast urbanization coupled with the construction of infrastructures without considering seismic loading, in fact, increasing earthquake risk in Nepal. The reduction of seismic risk and consequent extensive damage or destruction from potential strong earthquakes is possible to a great extent in Nepal through the most effective and efficient earthquake disaster mitigation, protection planning and aseismic design of new structures in the country. Disaster mitigation, emergency planning, and aseismic design of new structures in Nepal require identifying earthquake-prone areas and quantification of reliable seismic hazard at the national scale utilizing updated seismological, geological and tectonic information of the country and surrounding regions.

Tab. 1.1 Major earthquakes with their associated casualties in Nepal (1255-2011)

YY/MM/DD	Magnitude (M_s)	Epicenter Area	Casualty	
			Death	Damage
1255	7.6	Near Kathmandu	~1/3 of the total citizens of Kathmandu including the King (Abhaya Malla) of Kathmandu Valley	Several Buildings and Temples
1408	7.6	Near Kathmandu	Several people	Several Buildings and Temples
1505/6/6	8.1	Lower Mustang	Not Available	Not Available
1681	7.0	Near Kathmandu	Several people	Several Buildings
1810	7.0	Near Kathmandu	Several people	Several Buildings and Temples
1833/8/26	7.6	Northeast of Kathmandu	414	18,000 Buildings
1866/5/23	6.3	Near Kathmandu	Not Available	Not Available
1916/8/28	7.3	Far-Western Nepal	Not Available	Not Available
1934/1/15	8.3	Northeastern Nepal	8,519	More than 200,000 Buildings and Temples
1936/5/27	7.0	Near Pokhara	Not Available	Not Available
1953/2/23	6.0	Far-Western Nepal	Not Available	Not Available
1954/9/4	6.5	Pokhara	Not Available	Not Available
1966/6/25	6.5	Far-Western Nepal	24	6,544 Houses
1967	6.0	Southwestern Nepal	Not Available	Not Available
1980/7/29	6.6	Far-Western Nepal	103	25,086 Buildings
1988/8/20	6.8	Southeastern Nepal	721	66,382 Buildings
2011/9/18	6.8	Northeastern Nepal	6	14, 544 Houses

(Notes: Casualty modified after [5-8]. YY, MM, and DD correspond to Year, Month, and Day, respectively).

The available both historical account of seismic events and instrumental earthquake database indicate the uneven distribution pattern of earthquakes in various parts of the country. The combination of uneven distribution of earthquakes and high seismic potential of the investigated region pose a major threat to people, cities, infrastructures and environment in Nepal and its neighboring nations. Thus, it is essential to recognize potential earthquake-prone areas and systematically develop a set of seismic zonation maps for Nepal at a national scale distinguishing seismically high hazardous areas that provide valuable ground motion information to the government for the long term economic planning, land use planning, construction and development planning of new cities, making decisions for locating and designing major infrastructures, and for effective seismic disaster prevention, mitigation and protection planning in this region.

In this dissertation, seismic zonation study of Nepal has been carried out at a national scale using a probabilistic method, after carefully compiling a detailed homogenous earthquake catalogue, defining potential seismic source zones, determining seismicity parameters for each potential seismic source zone and choosing an appropriate ground motion attenuation relationship for this region. The resulting seismic zonation maps address earthquake ground motion hazard in terms of peak ground accelerations (PGAs) at bedrock level estimated over a grid of 0.2° × 0.2° (longitude and latitude) covering the whole area of the country for 63%, 10%, and 2% probability of exceedance in 50 years. These probabilistic seismic zoning maps exhibit the distribution of PGA at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years that provide fundamental and valuable ground motion information for the civil engineers to design and evaluate the seismic performance of key engineering structures (e.g., buildings, hospitals, schools, pipelines, long-span bridges, dams, powerhouses, tunnels), and for the government to establish future city development plans in Nepal. Moreover, these seismic zonation maps constructed at bedrock level in this dissertation provide valuable information for the seismic microzonation and seismic site response studies in urban areas, major cities and many other locations in Nepal.

1.2 Topographic and Tectonic Setting

Nepal is a south Asian mountainous land locked nation surrounded by the world’s highest Tibetan plateau (with mean elevation > 5000 m above sea level) to the north and Gangatic plain of India to the south (Fig. 1.2) and has complicated topography and complex tectonics. It has a remarkably diverse topographical setting with a wide range of altitude varying from 70 m in the southern part up to 8,848 m in the northern segment of the country and the entire country can be divided into three distinct topographic regions from north to south: the mountain, the hill and the plain.

The mountains region is located in the northern part of the country representing the complex terrain which accounts for one third (35%) of the whole territory of Nepal (Fig. 1.2). The complex mountain terrain consisting of eight of the world-highest mountain peaks with elevation exceeding 8000 m (Mount Everest: 8,848 m; Kanchanjunga: 8,586 m; Lhoste: 8,516 m; Makalu: 8,462 m; Cho Oyu: 8,201 m; Dhaulagiri: 8,167 m; Manaslu: 8,156 m; and Annapurna: 8,091 m) and a large number of peaks having elevation ranging between 5000 and 8000 m. The hill region is located between the tall mountain region in the north and the flat low lying plain region in the south and consists of numerous east to west trending ridges and hills with the elevation varies from 600 to 5000 m (Fig. 1.2) that accounts the largest proportion (42%) of the total area of Nepal. The plain region lies entirely in the southern part of Nepal covering the smallest proportion (23%) of the total area of the country and has smooth topography with altitude as low as 70 m covered by thick pile of soft sediments. Overall, the altitudes increase from south to north in Nepal and the differences in topography is high between the plain region and the mountainous region.

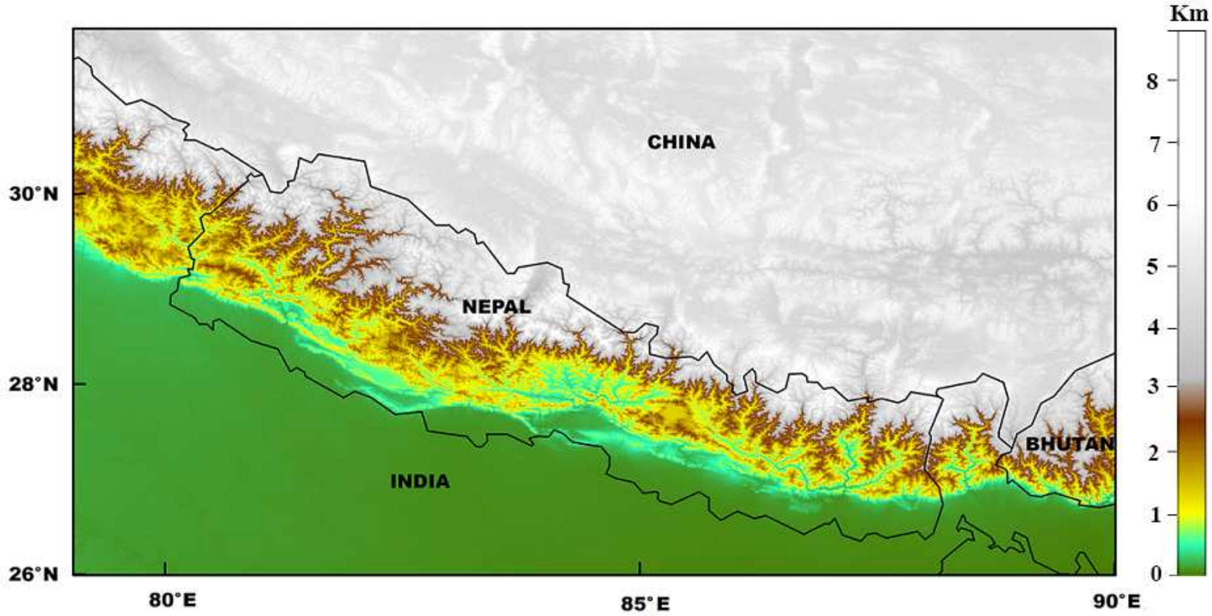

Fig. 1.2 Map showing the topography of Nepal and the surrounding regions (Shuttle Radar Topography Mission (SRTM) 30-meter Digital Elevation Model (DEM))

Tectonically, Nepal is an active and the most deformed segment in the Himalaya. The complex terrain of the Himalaya of Nepal which is active today was created by the ongoing continent-continent collision between the Indian and Eurasian plates that began about 50-55 million years ago [9-11] and is continuously colliding each other at present time. Tectonic evolution and geological investigations in the Nepal Himalaya and vicinity regions by several earth scientists such as Harrison et al. [12], Hodges [10], Molnar and Tapponnier [13] and Tapponnier et al. [14] confirmed that the collision between these two plates (India/Eurasia) has formed the considerably thickest crustal layer, lateral escape and the world's highest topographic features.

Additionally, the surface deformation of the Nepal Himalaya investigated using Global Positioning System (GPS) observations conjunction with spirit-leveling measurement in 1997 by Bilham et al. [15] demonstrated that the Indian plate is converging about 50 mm/year with Eurasian plate in which approximately 18-20 mm/year of the total convergence is absorbed in the Nepal Himalaya. Likewise, geodetic studies by Jouanne et al. [16-17], Larson et al. [18] and Bettinelli et al. [19] have addressed the more or less similar rate of convergence in the

Himalaya of Nepal. More recently, Ader et al. [20] obtained differential rate of convergence in the Himalaya of Nepal with approximately 20 mm/year geodetic convergence rate in western Nepal and approximately 18 mm/year rate of geodetic convergence in eastern and central Nepal.

Based on the tectono-stratigraphy and geological history of the country, some earth scientists such as Gansser [21] and Upreti [22] divided the territory of Nepal into five distinct tectonic domains from south to north namely, the Terai Zone which is also called as the Gangetic Plain, the Sub-Himalaya Zone which is also referred as the Siwalik Zone, the Lesser Himalaya Zone, the Higher Himalaya Zone, and the Tibetan-Tethys Himalaya Zone. These five major tectonic domains of the country from south to north are separated by four longitudinal major geological structures the Main Frontal Thrust fault (MFT), the Main Boundary Thrust fault (MBT), and the Main Central Thrust fault (MCT) and the South Tibetan Detachment System (STDS). In addition to these four major faults, a series of publications devoted to numerous intensive faults investigations, i.e., by Nakata [23-25], Nakata et al. [26-27], Dasgupta et al. [28] and Upreti et al. [29] indicate that there exist the Barigad fault, the Thakkhola Graben, several transverse faults and lineaments in the country. In fact, the MFT, MBT and MCT are regional thrust faults extending east-west throughout the entire length of Nepal, situated at small distance from each other in the ground surface in eastern Nepal, and interconnected along the sole thrust or a decollement zone at depth that is regarded as the Main Himalayan Thrust (MHT) [10] [30]. Deep seismic reflection investigations carried out by Zhao et al. [31] and Nelson et al. [32] have well recognized the geometry of the MHT. The MHT which represent the networks of major thrust faulting is a prominent regional seismogenic structure primarily contributing for the accommodation of the present day high heterogeneous topographic features, significant crustal shortening and consequence seismic activity in Nepal and the vicinity region [15-20] [30] [33-37].

1.3 Seismic Zonation

Seismic zonation in general is the division of the targeted region or the country into smaller hazardous areas associated with seismic hazard. The seismic zonation studies can be categorized into two main scales: macroseismic zonation and microseismic zonation studies. Furthermore, the seismic zoning study of a whole targeted region or the country could be conducted at the local, regional and national scales according to the purpose of the investigation. The seismic subdivision of the any targeted region or the country account the levels of seismic hazard that are expressed usually in terms of intensity, and strong ground motion parameters such as the peak ground acceleration (PGA) or spectral acceleration (Sa).

There were extensive seismic zonation studies in many countries of the globe using various zoning criteria and input parameters since the first half of the 20th century. For instance, the seismic zonation study of the former Soviet Union has been carried out by the Seismological Institutes of the Academy of Sciences of the former Union of Soviet Socialist Republics (U.S.S.R.) and developed the seismic zonation map of the former U.S.S.R. in 1937. The seismic zoning study of the contiguous United States (North America) was carried out by the United States Coast and Geodetic Survey (USCGS) and published in 1950 [38]. Likewise, the seismic zonation studies have been performed in China and India and have produced the seismic zoning map of China in 1957 by Lee [39] and the seismic zonation map for India in 1962 by the Bureau of Indian Standards [40].

Most of the seismic zonation studies conducted in various countries or the different regions before the 1960s have expressed the levels of seismic hazard in terms of intensity scales rather than strong ground motion parameters. With the development of science particularly in methodology of the seismic hazard, Cornell [41] developed PSHA method for the seismic risk analysis in the four and half decades ago. The introduction of the probabilistic seismic zonation method by Cornell [41] in 1968 has added a new dimension in seismic hazard assessment and afterward the seismic zonation study entered a new stage around the world.

PSHA method of Cornell [41] has received the great attention of earthquake scientists and engineers and has become the most extensively used and the most popular approach for the seismic zonation studies in many countries of the globe over the past 45 years. In fact, PSHA has becoming a most commonly used methodology not only for seismic zonation studies but also widely applied for earthquake engineering practices around the world. Presently, many nations in the world have been more intensifying the seismic zoning studies and replacing their previously prepared seismic zoning maps by updating the probabilistic strong ground motion zonation maps of their counties over time. As a result, most of the seismic zonation studies in many countries have shifted their estimate of seismic hazard in terms of intensity of ground shaking to strong ground motion parameters such as peak ground acceleration (PGA), peak ground velocity (PGV) or spectral acceleration (Sa). For example, Algermissen and Perkins [42] applied PSHA in North America in 1976 and prepared the seismic zonation map of the contiguous United States. Thereafter, the seismic zonation map of the United States was updated time to time such as by Algermissen et al. [43] in 1990, Frankel [44] in 1995, Frankel et al. [45] in 1996, Frankel et al. [46] in 2002, and Petersen et al. [47] in 2008.

Likewise, Basham et al. [48-49] applied PSHA in Canada in the 1980s and produced probabilistic strong seismic ground motion zonation maps of Canada. Subsequently, Adams et al. [50], and Adams and Halchuk [51] updated seismic ground motion zonation maps of Canada in 1999 and 2003, respectively. Interestingly, there is a dramatic increase in country level seismic zonation investigations in several nations by the national agencies as well as individual researchers in the first decade of the 21st century using the probabilistic approach: China [52], India [53], New Zealand [54], France [55], Thailand [56], and many other countries of the world.

As stated above, two giant neighboring countries of Nepal, China and India, have very good records of historical earthquakes and have intensively carried out the seismic zoning studies since the middle of the 20th century and produced their respective countries seismic zoning maps in the late fifties 1957 [39] and early sixties 1962 [40] of the last century. From time to time, these two giant Asian countries updated their own seismic zonation maps integrating new observations. Over time, China has updated the national seismic zoning maps in 1977, 1990, 2001, and the newest 5^{th} generation seismic zoning map will be available for China soon [57]. Moreover, at present, there exist seismic zoning maps at both provincial and national levels in China. Similarly, many seismic zonation research works have been carried out in India. More recently, Nath and Thingbaijam [58] have produced the seismic hazard maps of India in 2012. There is a gap in seismic zonation study in a total area of 147,181 km^2 occupied by Nepal lying between two seismically well mapped countries China in the north and India in the west, south and east. Unlike two giant neighboring countries of Nepal, China and India where intensive seismic zonation studies have been carried out in the past several decades, there is no such intensive seismic zoning research in Nepal. In other words, the seismic zonation research in Nepal is still in an infant stage and there is an urgent need to construct seismic zonation maps for Nepal. Hence the seismic zoning field of research has becoming the most active new areas of study in recent years in the country. Notably, only a very few number of investigators [59-60] have attempted to quantify the seismic hazard in Nepal over the first decade of the 21^{st} century. Indeed, these studies are important steps towards the quantification of seismic hazard in the country. However, these hazard analyses have not well established potential seismic source zones in Nepal and its surrounding region in detail. Moreover, future major earthquakes that occur in and around the surrounding regions of Nepal could cause serious damage to vulnerable structures in the country and thus it is essential to systematically establish the potential seismic source zones in Nepal and its vicinity in order to proper quantification of earthquake hazard in the country. This dissertation specifically incorporates an updated earthquake catalogue, the best available geological as well as tectonic information with identified earthquake-prone areas by the pattern recognition method to delineate twenty-three potential seismic source zones in Nepal and the neighboring areas for the purpose of developing reliable seismic zonation maps for Nepal.

1.4 Objectives of the Study

The overall objective of the present investigation is to estimate a reliable earthquake hazard for Nepal and construct the probabilistic seismic zonation maps of Nepal. This dissertation focus on probabilistic seismic zonation study, for which an earthquake catalogue for Nepal and the surrounding regions (latitudes 26°N and 31.7°N and longitudes 79°E and 90°E) covering the period from 1255 to 2011 has been compiled and twenty-three potential seismic source zones in this region were delineated by incorporating information from the distribution of catalogued earthquakes, and available geological and tectonic features as well as quantitative analysis by the pattern recognition method. The specific objectives of this dissertation are as follows:

(1) To compile and analyze the available all historically documented seismic events with instrumentally recorded earthquakes in modern times for the region spanning between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E during the period 1255-2011.

(2) To identify earthquake-prone areas in the Nepal Himalaya and its surrounding regions using morphostructural zoning and pattern recognition techniques.

(3) To establish potential seismic source zones in Nepal and its adjacent regions based on the available seismological, geological, and tectonic information as well as quantitative analysis by the pattern recognition techniques.

(4) To specify the probabilistic seismic hazard parameters for individual potential seismic source zone as well as the whole study region.

(5) To prepare seismic zonation maps for Nepal at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years using a probabilistic approach.

(6) To create earthquakes catalogue and seismic ground motion datasets for the detailed seismic microzonation studies in major cities, urban areas and risk analysis of the study region.

1.5 Organization of this Dissertation

This dissertation is divided into six chapters. Chapter 1 presents the introduction, objectives, and organization of the dissertation and the subsequent five chapters of the present dissertation are organized and briefly described as follows.

Chapter 2 describes the general methodology of earthquake hazard analyses. It presents a short description and basic steps of both deterministic and probabilistic seismic hazard analysis methods. This chapter also briefly outlines the probabilistic seismic hazard analysis approach that we used to construct the seismic ground motion zoning maps for Nepal.

Chapter 3 describes the general tectonics, geology and seismicity of Nepal and its surrounding regions. It presents an analysis of the earthquake catalogue encompassing the area between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E during the period from 1255 to 2011. This includes the merging of the best available historically documented seismic events with instrumentally recorded earthquakes and removing foreshocks, aftershocks, duplicated entries and repeated events in order to make homogeneous and reliable earthquake database. It further discusses the relationship between geological structures and seismicity of the study area by superimposing the spatial distribution of earthquakes with known surface faults and their importance for defining potential seismic sources in Nepal and its surrounding regions.

Chapter 4 focuses on the pattern recognition method used to identify the potential earthquake-prone areas in the Nepal Himalaya and its vicinity. This chapter deals with morphostructural zoning method and pattern recognition technique. The first section describes the morphostructural zoning map of the Nepal Himalaya and its surrounding areas produced from compiled geological, topographical, tectonic maps and satellite images. The second section presents the pattern recognition method and the results of the study. The results of pattern recognition is presented by circles (representing dangerous (D) nodes) and discussed their importance for the seismic zonation studies and choosing locations for key engineering infrastructures in this region.

Chapter 5 describes the study of probabilistic seismic zonation for Nepal. It discusses data incorporated in chapters 3 and 4 that form a basis for defining potential seismic source zones. The probabilistic earthquake hazard parameters assigned for individual potential seismic source zone as well as the whole region and an appropriate selected ground motion attenuation relationship for the study region are discussed in this chapter. It also presents the resulting probabilistic seismic zonation maps of Nepal in terms of PGA at bedrock level calculated over a grid of 0.2° × 0.2° (longitude and latitude) covering the whole area of the country with 63%, 10%, and 2% probability of exceedance in 50 years. These resulting probabilistic seismic zonation maps are compared with some recent earthquake zonation maps of China and India and its adjacent regions.

Chapter 6 presents the summaries of the whole study. This chapter discusses the main conclusions, innovations points, limitations, and highlights the importance of probabilistic seismic zonation maps prepared in this dissertation for earthquake scientists, engineers and others for further research, engineering practice and earthquake risk mitigation planning in the country. It also discusses additional interesting research topics that can be extended, enhanced and incorporated in future.

2 SEISMIC HAZARD ANALYSIS APPROACHES

In this chapter we briefly present an overview of the two commonly used methodologies for seismic zonation studies. First, we present here a general introduction of the four steps methodology of the deterministic seismic hazard analysis (DSHA) approach. Second, we mainly focus on presenting the general four major steps of the probabilistic seismic hazard analysis (PSHA) approach. We also introduce the probability method that we used to construct the seismic zonation maps of Nepal in this study. Finally, we give a short summary.

2.1 Introduction

The estimation of seismic ground motion hazard of the any targeted region is particularly important for planners, earthquake engineers, scientists and others because the predicted ground motion could be used as basis information to select the sites for major engineering projects or cities, as well as to design the earthquake-resistant structures with modern practice or to evaluate the seismic performance of engineering structures for that region. The design earthquake ground motion or input earthquake ground motion parameters of the site of interest or the major engineering structures can be essentially estimated by using the seismic hazard assessment methods [61].

Over the second half of the last century, several methods have been developed to best estimate the design earthquake ground motion parameters (quantify seismic hazard) for a particular region or the major structures at different scales among which the deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA) are typically used methods for the assessment of seismic hazard at the global, regional and local scales. These two seismic ground motion hazard estimation methods commonly aim to quantify the earthquake ground motion parameters, but they are fundamentally distinct and their basic steps of analysis are shown below in Figs. 2.1 and 2.2.

2.2 Seismic Hazard Analysis Methods

2.2.1 Deterministic Seismic Hazard Analysis (DSHA）

Assessing earthquake ground motion hazard using a deterministic seismic hazard analysis (DSHA) approach mainly includes the determination of the maximum credible earthquake magnitude and shortest source-to-site distance, and the ground motion attenuation relationship [62]. Fig. 2.1 depicts the four basic steps of a deterministic seismic hazard analysis framework. These four main steps of the deterministic seismic hazard analysis framework are briefly summarized in the following points.

1 Step I: Recognition of potential seismic sources

In this step, the seismic sources that could affect the area of investigation need to be defined for seismic zonation studies. The delineation of potential seismic sources of the targeted region in general is based on the best available seismological, tectonic, geological, geodetic, geomorphologic, geophysical and paleo-seismological information etc. The potential seismic sources can be defined as points, lines and area sources [62] according to the seismotectonic environment and associated seismic behavior of the targeted region.

2 Step II: Selection of the maximum credible earthquakes

After defining the potential seismic sources of the investigated region, the second step of DSHA is to define a maximum credible earthquake for each potential seismic source. The selected maximum credible earthquake for each potential seismic source is infrequent large damaging seismic event which is referred as various names: a controlling earthquake or a certain earthquake or a worse case seismic event. Generally, a controlling earthquake for each potential seismic source to construct the seismic zonation maps is selected based on the largest historically documented or instrumentally recorded seismic events or paleo-seismological studies of large earthquakes and geological structures of the study area.

3 Step III: Selection of a ground motion prediction relationship

In the third step, it is necessary to select a suitable earthquake ground motion attenuation relation for the area of investigation in order to compute ground motion parameters of the investigated site of interest. The best way is to first derive empirically ground motion model suitable for the study area if there is availability of sufficient updated recorded strong motions of earthquakes and then use it for seismic zoning studies. Alternatively, the region where there is a paucity of recorded strong motion data, the ground motion prediction relation can be developed by numerical simulation. For the seismic zonation studies, the ground motion attenuation relationship already developed by previous investigators for other seismic regions of the world has to be used for the area of interest where there is neither the availability of sufficient updated recorded strong motions of earthquakes nor simulated ground motion.

4 Step IV: Quantification of design strong ground motion parameters

The final step of DSHA is to quantify the seismic hazard in terms of ground motion parameters (e.g., peak ground acceleration, peak ground velocity, peak ground displacement and spectral acceleration) using the appropriate ground motion prediction relationship (step III) and the maximum credible earthquakes or a worst-case seismic events (step II) related to the individual recognized potential seismic source (step I).

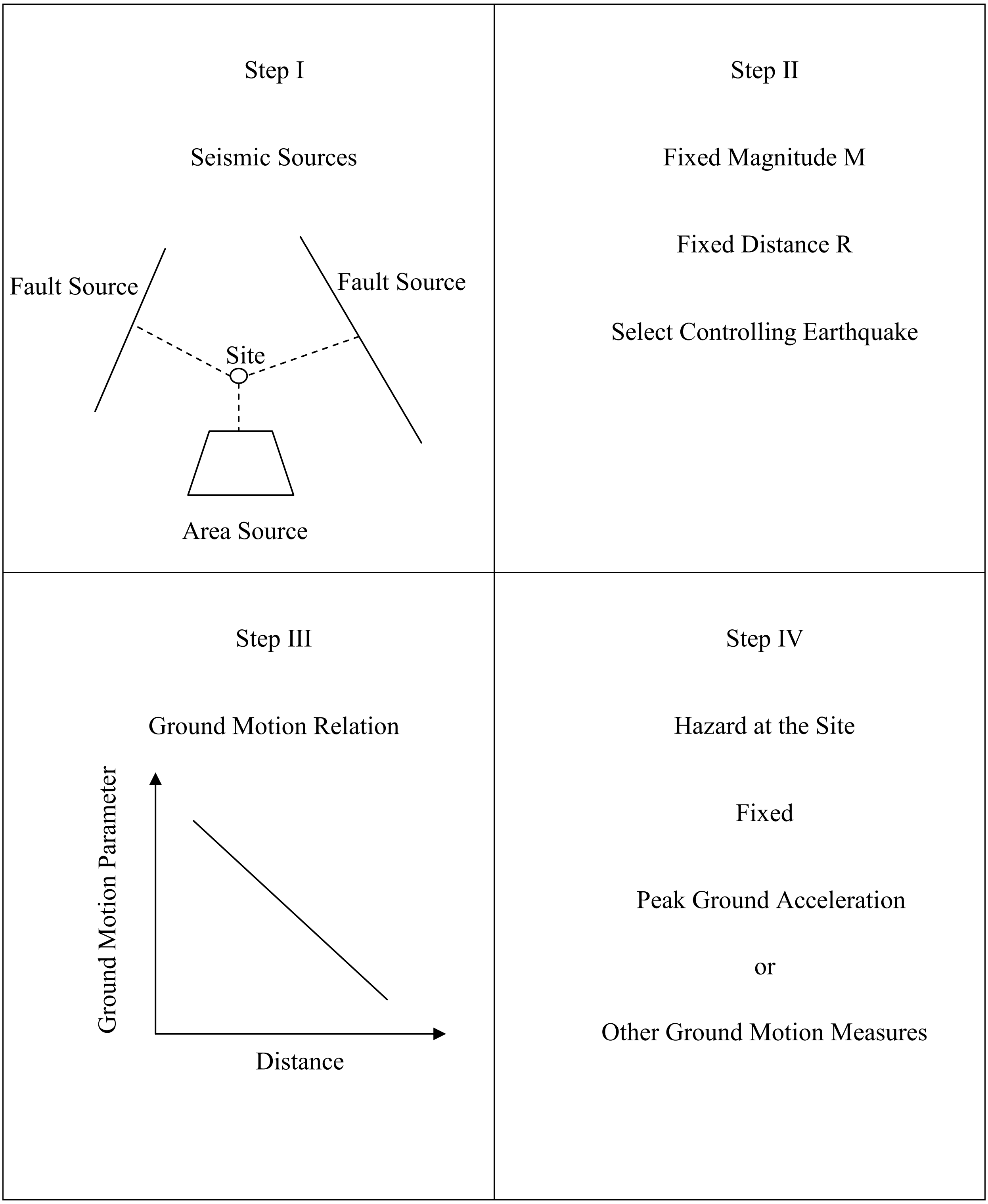

Fig. 2.1 Four basic steps of the deterministic earthquake hazard analysis [62]

DSHA method can be used to quantify the absolute earthquake ground motion parameters resulting from the controlling earthquake [62]. In other words, DSHA only takes account of the computed earthquake ground motion parameters from the worse-case referred as the controlling earthquake and does not consider frequency of all possible seismic events as well as occurrence of seismic events in time and it generally overestimates the seismic ground motion hazard in low seismic environments rather than in high seismic regions. In order to overcome such highlighted problems in DSHA framework, PSHA approach should be applied to estimate the various levels of seismic ground motion hazard for a particular region that incorporates the seismic activity in time, space, uncertainty of ground motion parameters.

2.2.2 Probabilistic Seismic Hazard Analysis (PSHA)

Quantitative evaluation of earthquake ground motion using PSHA framework which of course is quite complicated and less straightforward than that of DSHA [63-64]. In addition, PSHA essentially integrates the effects of all defined potential seismic sources with all considered earthquakes with different sizes (magnitudes, intensities) and variability of seismic ground motion attenuation characteristics. As known, the use of probabilistic earthquake hazard assessment approach allows us to estimate the various levels of earthquake ground motion hazard for a particular region of interest by using different exceedance probabilities. The theoretical elements of PSHA was introduced in the second half of the last century (45 years ago) by Cornell [41] and since then many investigators have adopted PSHA that has became a customarily method for seismic zonation studies around the world over the past four and half decades. Fig. 2.2 systematically illustrates the four basic steps of PSHA approach [62]. These four basic steps [62] of PSHA approach are described in the following points below.

1 Step I: Recognition of potential seismic sources

Delineation of potential seismic sources in PSHA is similar to DSHA method that utilizes the best available seismological, tectonic, geological, geodetic, geomorphologic, geophysical and paleo-seismological information of the targeted region. Nevertheless, the identified earthquake potential source in PSHA is regarded to have a uniform distribution of seismic events in space, so that there is an equal possibility of future earthquake occurrence throughout the defined seismic source in the study area.

2 Step II: Recurrence relationship, average annual occurrence rate and magnitudes

Once all the potential seismic sources are delineated, the next step of PSHA is to determine the seismicity parameters (e.g., average annual occurrence rate of earthquakes, *b* value, depth of earthquakes, minimum magnitudes, and maximum magnitudes) for each potential seismic source as well as for the whole region using the homogenous and complete earthquake catalogue of the study area as far as possible.

3 Step III: Selection of the ground motion prediction equation

The third step of PSHA is identical to DSHA in which a suitable ground motion prediction relationship for the study area should be selected in order to assess the ground motion for seismic zonation. In contrast to DSHA, PSHA consider ground motion attenuation relationship that takes into account the uncertainty of seismic ground motion, so that PSHA can assess the future levels of earthquake ground motion hazard of the targeted region from various earthquake magnitudes.

4 Step IV: Probabilistic earthquake hazard analysis

The final step of PSHA is to assess the levels of strong earthquake ground motion parameters (peak ground acceleration, peak ground velocity or spectral acceleration) integrating the aforementioned three steps of the PSHA (Steps I, II and III) by applying the total probability theorem.

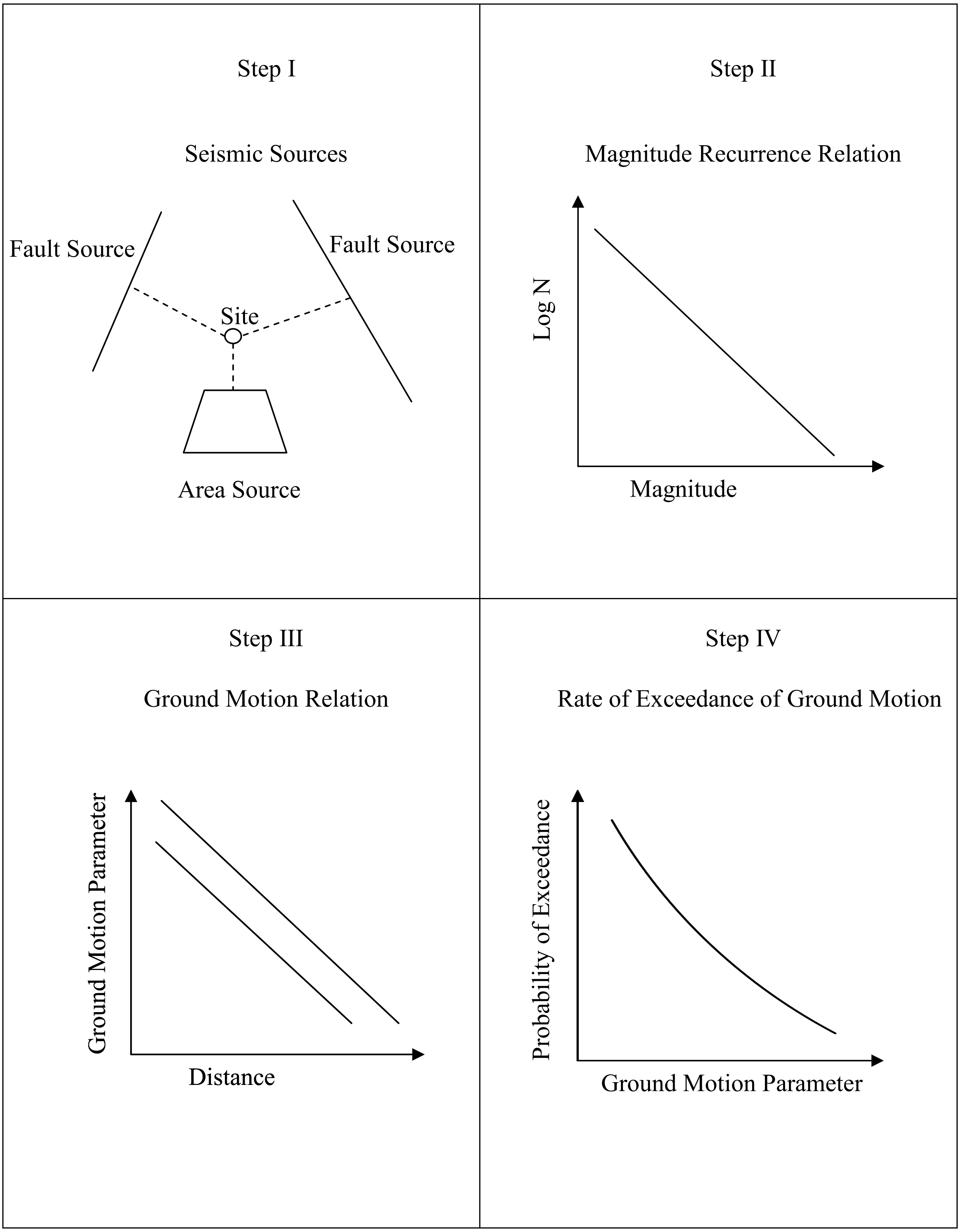

Fig. 2.2 Four basic steps of the probabilistic earthquake hazard analysis [62].

In this dissertation, we follow the procedure developed by the China Earthquake Administration (CEA) [65] that is based on the probabilistic method firstly established 45 years ago in the late sixties of the last century by Cornell [41] in 1968 which assumes the occurrence of earthquakes is a Poisson process. The steps regarding the probabilistic earthquake hazard assessment approach applied in this dissertation has been thoroughly described in the training material on earthquake hazard analysis for engineering sites [65] and here we only introduced the underlying equations relevant with this seismic hazard analysis approach. The probability, *P*, of occurrence of seismic events greater than a threshold magnitude (*M*) in a time for a particular area can be given in equation (2.1) below:

$$P(n) = \frac{(\nu)^n}{n!} e^{-\nu} \qquad \text{for } n = 0,1,2,3................. \tag{2.1}$$

where *P(n)* is the probability of event, *v* is the annual average rate of occurrence earthquake with magnitude greater than a threshold magnitude. The recurrence of earthquake is described by a Gutenberg-Richter frequency magnitude relation [66] shown in equation (2.2) below:

$$logN = a - bM \tag{2.2}$$

where *N(m)* is the cumulative number of earthquakes equal to or greater than the specified magnitude (*M)*, and constant parameters *a* and *b* characterize the Gutenberg and Richter (G-R) parameters for a particular targeted region. The parameter *a* describes the earthquake activity of the targeted region and the parameter *b* describes the ratio of small to large magnitude seismic events which is called as the *b*-value that can be approximately equal to 1.0.

It is known that small magnitude earthquakes have weak damaging power and have very little impact on engineering structures, thus earthquakes with magnitudes lower than the threshold magnitude were neglected to determine the cumulative (probability) distribution function (CDF). The cumulative distribution function, F_M *(m),* for earthquake with magnitude (m) is given by:

$$F_M(m) = P(M > m/m_0 \le m \le m_u) = \frac{N(m_0) - N(M)}{N(m_0) - N(m_u)} \tag{2.3}$$

where m_0 is the threshold magnitude, m_u is the upper limit magnitude.

With $\beta = b \times ln10$, inserting equation (2.2) into equation (2.3), the CDF then becomes:

$$F_M(m) = \frac{1 - \exp[-\beta(m - m_0)]}{1 - \exp[-\beta(m_u - m_0)]} \qquad m_0 \le m \le m_u \tag{2.4}$$

Subsequently, the corresponding probability density function (PDF) for earthquake with magnitude (m) is denoted by $f_M(m)$ can be expressed as follows:

$$f_M(m) = \begin{cases} \dfrac{\beta exp[-\beta(m - m_0)]}{1 - exp[-\beta(m_u - m_0)]} & m_0 \le m \le m_u \\ 0 & \text{otherwise} \end{cases} \tag{2.5}$$

In PSHA, the probability that a seismic ground motion (A) equal to or greater than a specified acceleration value (a) at a targeted site is denoted by $P\ (A \ge a)$ can be computed using the total probability theorem and that is presented in the following equation [65]:

$$P(A \ge a) = 1 - exp(-\sum_{j=1}^{N_m}\sum_{k=1}^{N_r}\sum_{i=1}^{N_{ks}}\iint \frac{2v_k}{A_{ki}} \cdot P(A \ge a | m_j, (x,y)_{ki}) \cdot f_{ki,m_j} \cdot \frac{exp[-\beta_k(m_j - m_0)]}{1 - exp[-\beta_k(m_{uk} - m_0)]} \cdot Sh(-\tfrac{1}{2}\beta_k \Delta m)dxdy) \tag{2. 6}$$

In equation (2.6), v_k denotes the average annual rates of occurrence of seismic events in the *k-th* potential earthquake source zone, A_{ki} denotes the area of the *k-th* potential source zone, $P(A \ge a | m_j, (x,y)_{ki})$ denotes the conditional probability of strong ground motion (A) equal to or greater than the specified ground motion (a) associated at a site or an area from an earthquake with *j-th* magnitude interval in the *k-th* potential seismic source zone and location (x, y), f_{ki,m_j} denotes the earthquake spatial distribution function, and Δm denotes the change in earthquake magnitude values.

2.3 Summary

In this chapter, we described here the brief introduction of two most commonly used methodology of seismic hazard analysis namely, the deterministic and probabilistic approaches. In the first section we discussed four fundamental steps of the deterministic earthquake hazard assessment approach. In the second part of this chapter we presented the short description of the four basic elements of the probabilistic earthquake hazard assessment framework and introduced the method used here to prepare the seismic zonation maps in this dissertation.

3 TECTONIC, GEOLOGICAL AND SEISMOLOGICAL FEATURES OF NEPAL

This chapter presents the regional tectonic and geological setting of Nepal, and seismicity of the area encompassing between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E for the period 1255-2011. The first section briefly describes the general tectonic and geological features of Nepal. The second section presents the earthquake database compiled from available sources in order to make a homogenous and reliable earthquake catalogue as possible. It addresses the spatiotemporal patterns of the updated earthquake catalogue for Nepal and the surrounding regions from 1255 to 2011. The chapter also presents the distribution of earthquakes and their spatial association with the surface traces of known major faults in the study area. The final section of this chapter summarizes the major geological structures and the analysis of earthquake catalogue of Nepal and its vicinity region.

3.1 Tectonic and Geological Features of Nepal

Nepal is a well identified active tectonic region in the Himalayan seismic belt. A large number of tectonic and geological studies have been carried out in different segments of Nepal: eastern Nepal [67], central Nepal [68-76], western Nepal [77-80], and far-western Nepal [81-82] and have yielded tectonic and geological characteristics of different sections of the country. The territory of Nepal and its vicinity regions consist of numerous major longitudinal faults and transverse faults, as well as their associated minor faults. e.g. [11] [21-29] [83-84]. The major tectonic structural features of the study area is plotted in Fig. 3.1, which displays the distribution of a set of longitudinal faults (Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Bari Gad Fault (BGF), Main Central Thrust (MCT), and South Tibetan Detachment System (STDS)) in Nepal, and the Indus-Tsangpo Suture Zone (ITSZ) and some transverse faults in southern Tibet. From Fig. 3.1, it can be seen that the STDS is located in a section between longitudes 82.5°E and 85.0°E in Nepal and the MFT, MBT, and MCT are running east-west throughout Nepal and have lengths larger than the entire length of the country (~800 km) that extending (further east and west) outside the border of Nepal. In the territory of Nepal, the surface traces of MFT, MBT, and MCT are sub-parallel (Fig. 3.1) and trending east-west in the eastern section of Nepal and north 120° in the western segment of Nepal [85], and these thrust faults (MFT/ MBT/MCT) linked together at depth along the sole thrust or a decollement zone referred as the Main Himalayan Thrust (MHT) [31-32]. The MHT which is an east to west extending longitudinal thrust fault system coincides with the MFT in the near ground surface [25], and has been regarded as a major regional longitudinal seismogenic structural element that is primarily controlling the modern-day tectonic deformation pattern in Nepal and its surrounding areas [35-36] [86].

The whole territory of Nepal is dissected by the above mentioned four major east-west trending longitudinal faults, namely, the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), and the South Tibetan Detachment System (STDS), which divide the country into five distinct longitudinal tectonic domains [21-22] from south to north:

(1) Terai (Gangetic Plain) Zone

(2) Sub-Himalaya (Siwalik) Zone

(3) Lesser Himalaya Zone

(4) Higher Himalaya Zone

(5) Tibetan-Tethys Himalaya Zone

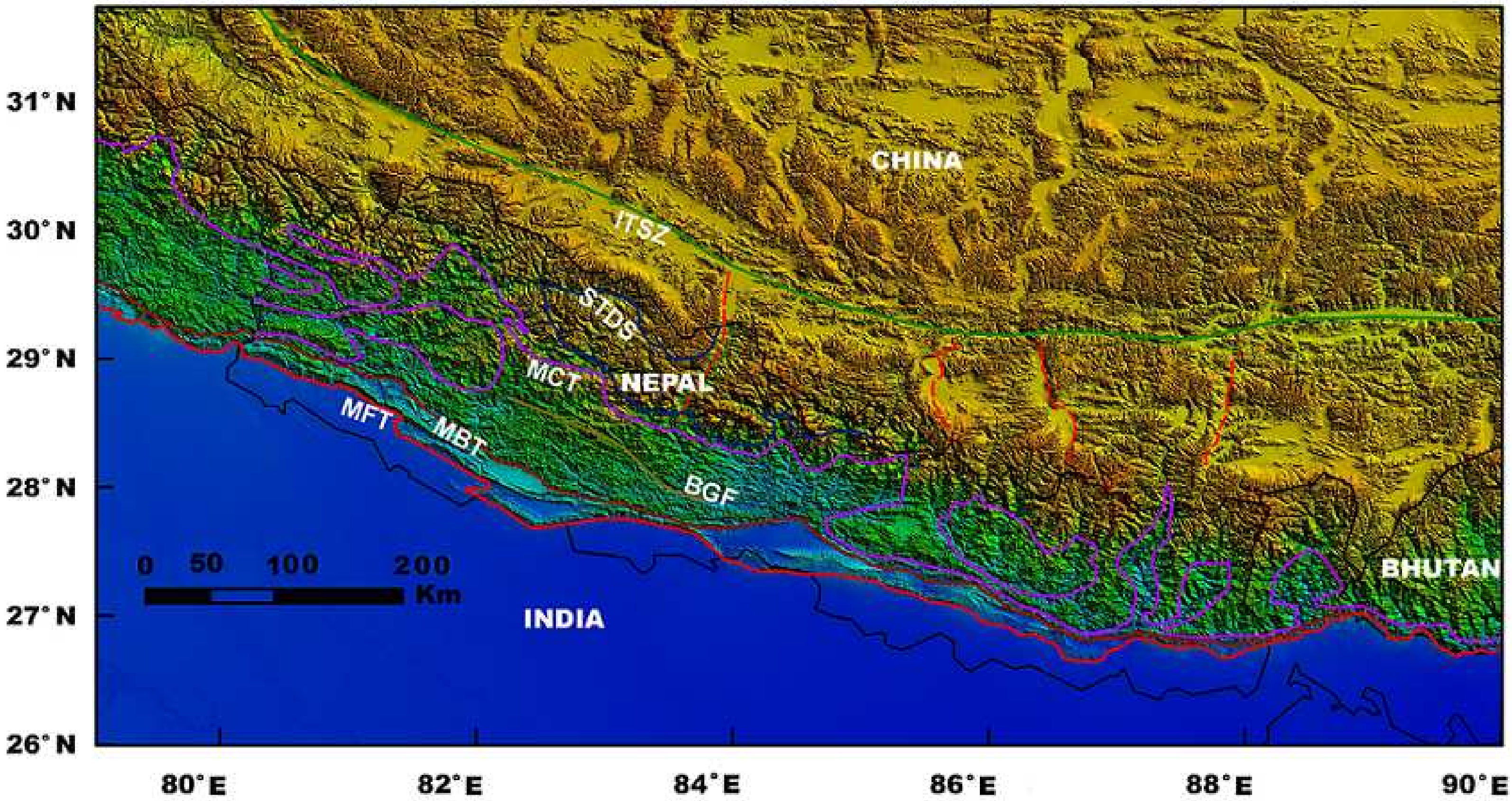

Fig. 3.1 Major faults in the Nepal Himalaya and surrounding regions (ITSZ = Indus-Tsangpo Suture Zone; STDS = South Tibetan Detachment System; MCT = Main Central Thrust; MBT = Main Boundary Thrust; MFT = Main Frontal Thrust; and BGF = Bari Gad Fault). STDS; MCT; MBT; MFT and BGF in Nepal modified from Amatya and Gnawali [87], ITSZ and active normal faults (Red discontinuous lines) in southern Tibet modified from Taylor and Yin [84]

Each tectonic domain differs from one another in dimension, stratigraphy, topography and geological history. The brief introduction of each tectonic domain is described below in the following subsections.

3.1.1 Terai (Gangetic Plain) Zone

The Terai domain is the southernmost lowland geological domain of Nepal and is located in three selected areas (80.14°E-81.98°E, 82.7°E-83.921°E, and 84.63°E-84.2°E) extending up to a 50-km wide belt (Fig. 3.1). The average altitude of this Terai domain ranges from 70 m to 200 m and mainly consists of more than one thousand meters thick Quaternary aged alluvial loose sedimentary deposits. The thick pile of loose sedimentary deposits of the Terai zone extremely vary in grain size (such as gravel, sand, silt, and clay from north to south) and cover the thrusted and folded Sub-Himalayan bedrocks [88-89]. On the basis of grain size variation of the soft sedimentary deposits, the Terai domain has been subdivided into three parts from south to north, namely, the southern Terai, middle Terai and northern Terai (Bhabar zone) [90]. The southern Terai zone is largely composed of finely grained alluvial sediments (silts and clay) and reaches up to the national boundary of India in the south. The middle Terai domain is composed primarily of coarsely grained sands and medium grained gravels deposits. The northern portion of the Terai domain is also referred as a Bhabar zone which is basically consisted of extremely coarse grained alluvial sediments like gravels and boulders and is separated from the Sub-Himalaya domain to the north by the MFT [25].

3.1.2 Sub-Himalaya (Siwalik) Zone

The Sub-Himalaya domain lies between the MFT in the south and the MBT in the North and extending east-west throughout the entire length of Nepal. The average altitude across this domain ranging from 200 m to 1500 m and consist of numerous nearly east-west striking ridges. The Sub-Himalaya domain extends east-west continuously in a zone of about 3-40 km wide (north-south) in Nepal and is composed of Tertiary-Quaternary aged sedimentary rocks (e.g., mudstones, siltstones, sandstones and conglomerates) [12] [91]. The Sub-Himalaya domain is classically subdivided into the following three units: lower, middle and upper Siwaliks [12] [76] [92-94] according to the lithostratigraphy. The lower Sub-Himalaya domain is made up of alternate sequence of fine grained predominantly mudstones with layers of shales, siltstones and sandstones. The middle Sub-Himalaya domain is mainly characterized by coarse grained thickly bedded sandstones with alternating sequence of thinly bedded mudstones. The upper Sub-Himalaya domain is primarily composed of thickly bedded conglomerates and boulders with some very thinly inter-bedded mudstones.

3.1.3 Lesser Himalaya Zone

The Lesser Himalaya domain is running longitudinally throughout the entire middle section of Nepal and is separated from the underlying completely un-metamorphosed to weakly metamorphosed Sub-Himalaya domain in the south by the MBT to the overlying strongly metamorphosed crystalline Higher Himalaya domain in the north by the MCT [21]. The north-south span of the entire succession of the Lesser Himalayan zone varies enormously from about 3 km-narrow belt in eastern Nepal to more than 70 km-wide belt in the western part of the country. The Lesser Himalaya domain is mostly composed of Precambrian-Paleozoic aged sedimentary and weakly metamorphosed rocks such as limestones, dolomites, quartzites, phyllites, and slates [68-70].

3.1.4 Higher Himalaya Zone

The higher Himalaya domain is separated from the Lesser Himalaya domain in the south by the MCT and from the Tibetan-Tethys Himalaya domain in the north by the STDS. This domain is extending east to west in the entire territory of Nepal and encompasses the high topographic terrain consisting dominantly of tall mountain peaks with average altitudes greater than 5000 m. The north-south width of the entire succession of the Higher Himalayan zone varies enormously in Nepal like the Lesser Himalayan domain. However, the north-south width of the Higher Himalayan zone ranges from about 5-km narrow belt in the western extent of the country to more than 115-km-wide belt in the eastern portion of Nepal. The Higher Himalayan domain basically composed of Proterozoic-Cretaceous aged strongly metamorphosed crystalline rocks such as paragneisses, orthogneisses, marbles, schists as well as leucogranites, and migmatites [95-97]. These strongly metamorphosed crystalline rocks lie below the several tall mountain peaks in the Nepal Himalaya and its surrounding regions.

3.1.5 Tibetan-Tethys Himalaya Zone

The Tibetan-Tethys Himalaya zone is the northernmost geological domain of Nepal and is separated from the strongly metamorphosed more resistant crystallized Higher Himalaya regime in the south by a normal fault system called as the South Tibetan Detachment System (STDS) [98]. This zone is mainly situated in the selected region between 82.5°E and 85.1°E as well as small patches in the northern parts of Nepal. The maximum north-south width of the Tibetan-Tethys Himalaya zone spanning up to 100 km-wide near the 84°E longitude in Nepal at the border with China. The Tibetan-Tethys Himalaya domain is chiefly characterized by Cambrian-Cretaceous fossiliferous sedimentary rocks and slightly metamorphosed rocks such as limestones, sandstones, shales and phyllites [21] [99].

3.2 Seismological Setting of Nepal

Although Nepal has a long history of frequent damaging earthquakes, there is no complete, reliable, homogenous published earthquake catalogue available hitherto for Nepal and its vicinity region. In order to create an homogenous and complete earthquake datasets as possible, we have assembled available earthquakes with surface-wave magnitudes equal to and greater than M_s 4.0 that occurred in the location encompassing between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E for the period from 1255 to 2011 from previous seismicity studies [3] [6-7] [60] [100-108] as well as earthquake datasets from three agencies, namely, the International Seismological Centre (ISC) [109], the United States National Earthquake Information Centre (NEIC) [110], and the National Seismological Center (NSC) [111].

These assembled best available earthquake database were very carefully analyzed and aftershock and foreshock clusters, as well as duplicated events have been removed. The quality of our seismicity datasets has been enhanced, especially from 1994 onwards when the substantial instrumental local magnitudes (M_L) and epicenter locations of seismicity data recorded by the National Seismological Center (NSC) of Nepal (the national seismographic networks operating under the ministry of industry, Nepal) became available. It is important to note that earthquake data assembled from a variety of data sources (authors and agencies) documented the seismicity parameters (locations and magnitudes) and time differently for the same seismic event.

In order to get reliable seismicity parameters (locations, magnitudes) and origin time of these assembled earthquakes as possible, we reviewed more recently available published literatures for historical and strong instrumental seismic events in this analysis. By considering the existing literatures as the main and more reliable sources of earthquakes information, we choose the seismicity parameters (locations and magnitudes) for historical and strong instrumental seismic events in our catalogue. For instance, the 1934 Bihar-Nepal (Mw = 8.4) was located here in this study as documented in the literature by Pandey and Molnar [107]. Likewise, the magnitude and epicenter location of the 1505 great earthquake (Mw = 8.1) was taken in the present study based on the study of Ambraseys and Douglas [3].

In addition, the pre-instrumental and modern instrumental seismicity data assembled for the study region reported by three agencies namely, ISC [109], NEIC [110], and NSC [111] consist of different magnitude scales (local magnitudes, body-wave magnitudes and surface-wave magnitudes) and locations for the same seismic events. In order to choose the single magnitude size and location of each seismic event, we mainly choose the available body-wave magnitudes (M_b) and locations as reported in ISC [109] and NEIC [110] catalogues by giving the high priority information available in NEIC [110] catalogue for the period before 1993 and local magnitudes (M_L) and locations reported by NSC [111] covering the period from 1994 to 2011.

As discussed above, the aggregated seismic catalogue after careful analysis in this study consists of different scales of estimated magnitudes (local magnitudes, body-wave magnitudes and surface-wave magnitudes) for some of the seismic events recorded post-1900 and only intensity values (I), particularly for some of the seismic events that occurred before-1900. We need to convert these various estimated earthquake magnitude scales and intensity values to a common magnitude type to assign the seismicity parameters and perform the seismic zonation in this dissertation. Thus, the available various estimated magnitude scales and intensity values have been converted to a common surface-wave magnitude in the present analysis by using the following published different empirical relationships as below:

The intensity values (I) of 28 seismic events in this study have been first converted to moment magnitudes (M_w) by using the following empirical relationship [112]:

$$M_w = (2/3)\ I + 1 \tag{3.1}$$

After the moment-magnitudes (M_w) of 28 earthquakes were obtained by applying the equation (3.1), these moment-magnitudes have been converted to the scalar seismic moment (Nm), M_0, by using the empirical relationship of Hanks and Kanamori [113]:

$$M_w = (2/3)\ log\ M_0 - 10.63 \tag{3.2}$$

Subsequently, the values of seismic moment (M_0) were converted to the surface-wave magnitude (M_s) by using the following set of empirical relations [3]:

$$log\ M_0 = 16.03 + 1.5\ M_s\ (\text{For } M_s > 5.94) \tag{3.3}$$

and

$$log\ M_0 = 19.38 + 0.93\ M_s\ (\text{For } M_s \leq 5.94) \tag{3.4}$$

Similarly, the local magnitudes (M_L) of 273 earthquakes have been converted to M_s using the empirical relationship of Wang et al. [114]:

$$M_s = 0.98\ M_L + 0.03 \tag{3.5}$$

Additionally, the body-wave magnitudes (M_b) of 507 seismic events have been converted to M_s using the following empirical relationship of Liu et al. [115]:

$$M_s = 1.07\ M_b - 0.63 \tag{3.6}$$

The resulting updated homogeneous earthquake datasets after the catalogue analysis and magnitude conversion contains a total of 883 earthquakes with surface-wave magnitude equal to or greater than 4.0. The resulting datasets consists of 709 (80.29%) earthquakes magnitude ranging from 4.0 to 4.9, 121 (13.70%) earthquakes magnitude ranging from 5.0 to 5.9, 42 (4.75%) earthquakes magnitude ranging from 6.0 to 6.9, 9 (1.01%) earthquakes magnitude ranging from 7.0 to 7.9, and 2 (0.02%) earthquakes with magnitudes equal to or greater than 8.0. The date, epicenter location (latitude, longitude), and size (magnitude) of each earthquake that occurred in Nepal and the surrounding regions are listed in Appendix.

In order to observe patterns of seismicity in time and space, we separately analyzed the entire earthquakes catalogue both temporally and spatially. The analyzed temporal and spatial distributions of earthquake in the present study are briefly described in the following subsections.

3.2.1 Temporal Distribution of Earthquakes

The available entire updated earthquake database of the investigated region from 1255 to 2011 shows the strong heterogeneity in both quantity and quality. Because of the inhomogeneous quality and quantity of earthquake datasets, the entire earthquake database can be broadly subdivided into three different period windows:

(1) Earthquakes before 1800

(2) Earthquakes during 1801-1963

(3) Earthquakes during 1964-2011

Each period window specified here is characterized by its distinctive temporal pattern of earthquakes. Fig. 3.2 shows the temporal distribution of seismic events of the study area covering the time period 1255-2011.

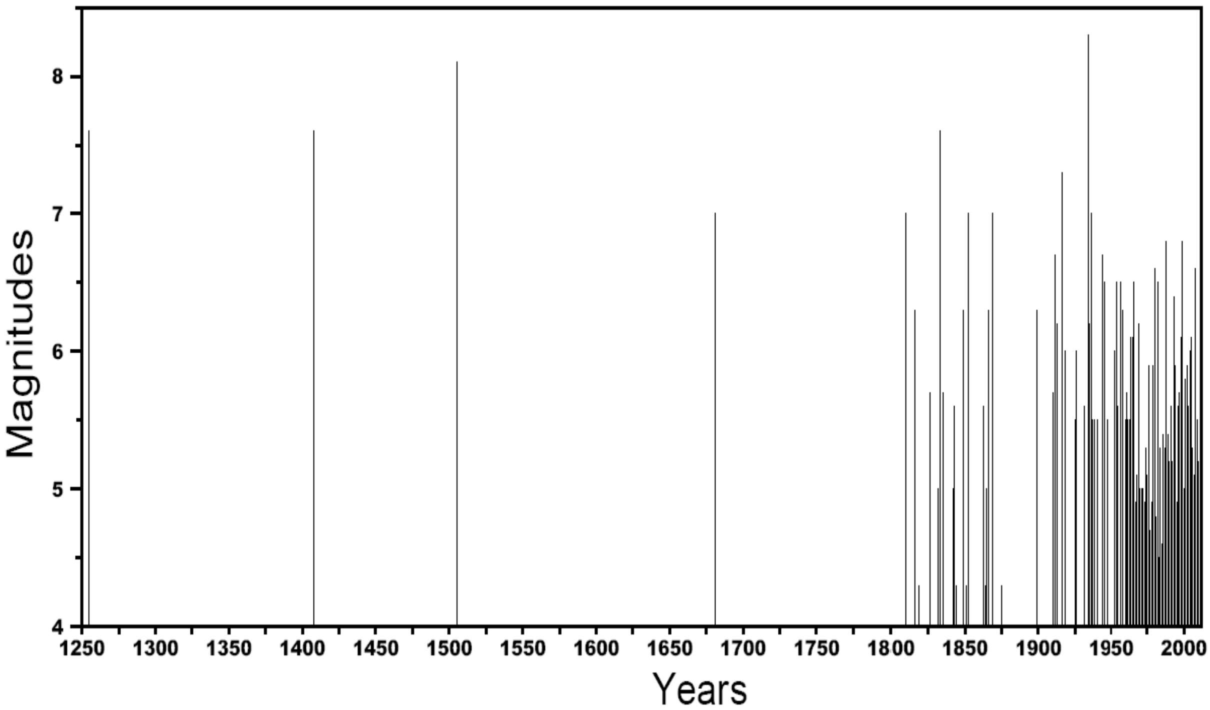

Fig. 3.2 Temporal distribution of earthquakes with surface-wave magnitude equal to or greater than 4.0 that occurred in the Nepal Himalaya and surrounding regions during the period 1255 to 2011.

1 Earthquakes Before 1800

There are very few accounts of historically documented damaging earthquakes in Nepal during the time period window before 1800. An updated earthquake catalogue consists of four historically documented catastrophic seismic events (M = 7.6, 1255; M = 7.6, 1408; M = 8.1, 1505; and M =7.0, 1681) with magnitudes exceeding 7.0 during this period. This period widow does not contains moderate to strong magnitude seismic events and cannot be considered for seismic activity analysis, but catastrophic earthquakes reported in the present study before 1800 are quite informative to define potential seismic source zones as well as determining representative maximum earthquake magnitudes for the seismic hazard assessment in Nepal and its adjacent regions.

2 Earthquakes During 1801-1963

The available earthquake datasets during the interval 1801-1963 is much more informative than that of seismic events reported in the time period before 1800. There is a significant increase in the total number and quality of reported earthquake datasets over this 163 years period window. Seismicity datasets covering the period between 1801 and 1963 consist of 74 earthquakes ($Ms \geq 4$) including two damaging earthquakes occurred in 1833, and 1934. It consists of 10, 35, 22, and 7 earthquakes in the magnitude range of 4.0-4.9, 5.0-5.9, 6.0-6.9, and 7.0-7.9, respectively. Earthquake database from 1803 to 1963 is particularly complete for strong seismic events. In contrast, medium magnitude earthquakes reported during the same time period window is incomplete. Due to the incomplete records of medium magnitude earthquakes in the period 1801-1963, we do not include these earthquake datasets to characterize seismicity parameters in this study.

3 Earthquakes During 1964-2011

There has been a significant increase in the quality and number of earthquake datasets during the past 48 years period window (1964-2011) particularly since 1964 when a large amount of detected earthquake datasets became available in the globe from the worldwide extensively spread seismic instrumentation. The substantial increase in earthquakes imply that our aggregated earthquake catalogue is complete from 1964 to 2011 and it contain a total of 805 events with surface-wave magnitude equal to or greater than 4.0 (699 earthquakes between magnitude 4.0 and 4.9, 86 earthquakes between magnitude 5.0 and 5.9, and 20 earthquakes between magnitude 6.0 and 6.9). Thus, earthquake datasets for the period between 1964 and 2011 have been used to assign seismicity parameters for assessing the seismic hazard in this analysis (in Chapter 5).

3.2.2 Spatial Distribution of Earthquakes

The spatial distribution of all catalogued earthquakes for the location between latitudes 26°N-31.7°N and longitudes 79°E-90°E spanning the period from 1255 to 2011 is shown in Fig. 3.3. It can be seen that earthquakes are not evenly distributed and illustrates roughly east-northwest trend in Nepal and its surrounding regions. In general, an uneven spatial distribution of seismicity shows the strongest earthquake activity in the far-western and eastern parts of Nepal, and the weakest seismic activity in the southern part of the country. We pointed out that the catalogued seismicity is mainly distributed in a continuous east-northwest trending 50-150 km-wide belt throughout Nepal. The width of the seismic belt varies remarkably in the north-south portion with about 50-km wide in the central section and about 150 km in the eastern and far-western segments of the country.

In order to study the spatial distribution of seismicity and the surface traces of main fault structures in the investigated region, we superimposed the epicenter map of all updated catalogued earthquakes with major known faults in the Himalaya of Nepal and the adjoining areas. Fig. 3.4 displays the epicenter distribution of catalogued earthquakes for the period 1255-2011 and major known geological structures in the Nepal Himalaya and its vicinity regions. In general, earthquakes are aligned parallel to the surface traces of the previously identified major faults (STDS, MCT, MBT, and MFT) in Nepal and its nearby region. It can be seen that the overwhelming majority of the seismic events that occurred in Nepal and the surrounding region are roughly aligned in east-northwest direction and concentrated near the surface trace of Main Central Thrust (MCT). Moreover, epicenters of strong earthquakes ($M_s \geq 6.0$) are spatially situated at small distance from the known major faults in Nepal and its surrounding areas.

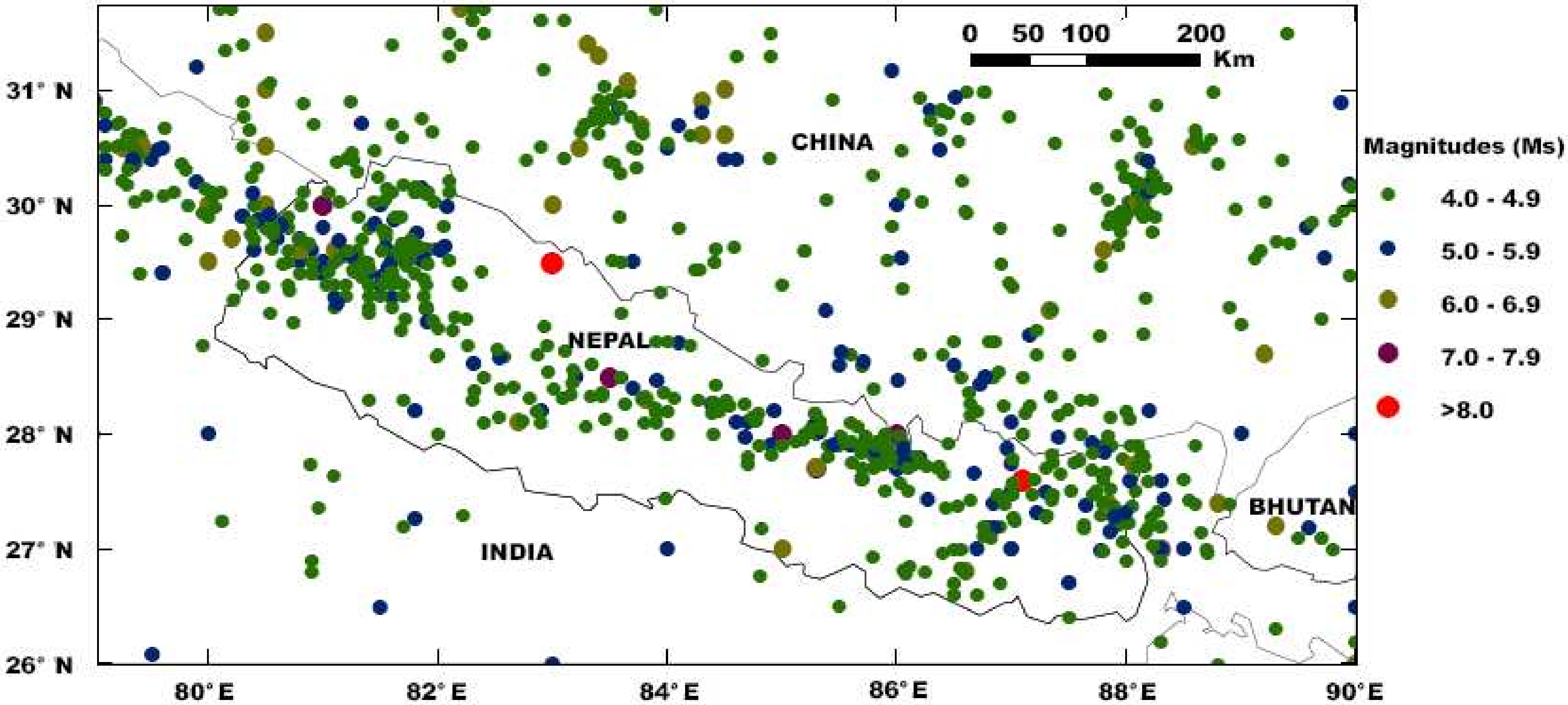

Fig. 3.3 Epicenters of earthquakes of surface-wave magnitude equal to or greater than 4.0 occurred in Nepal and its surrounding regions for the period 1255-2011

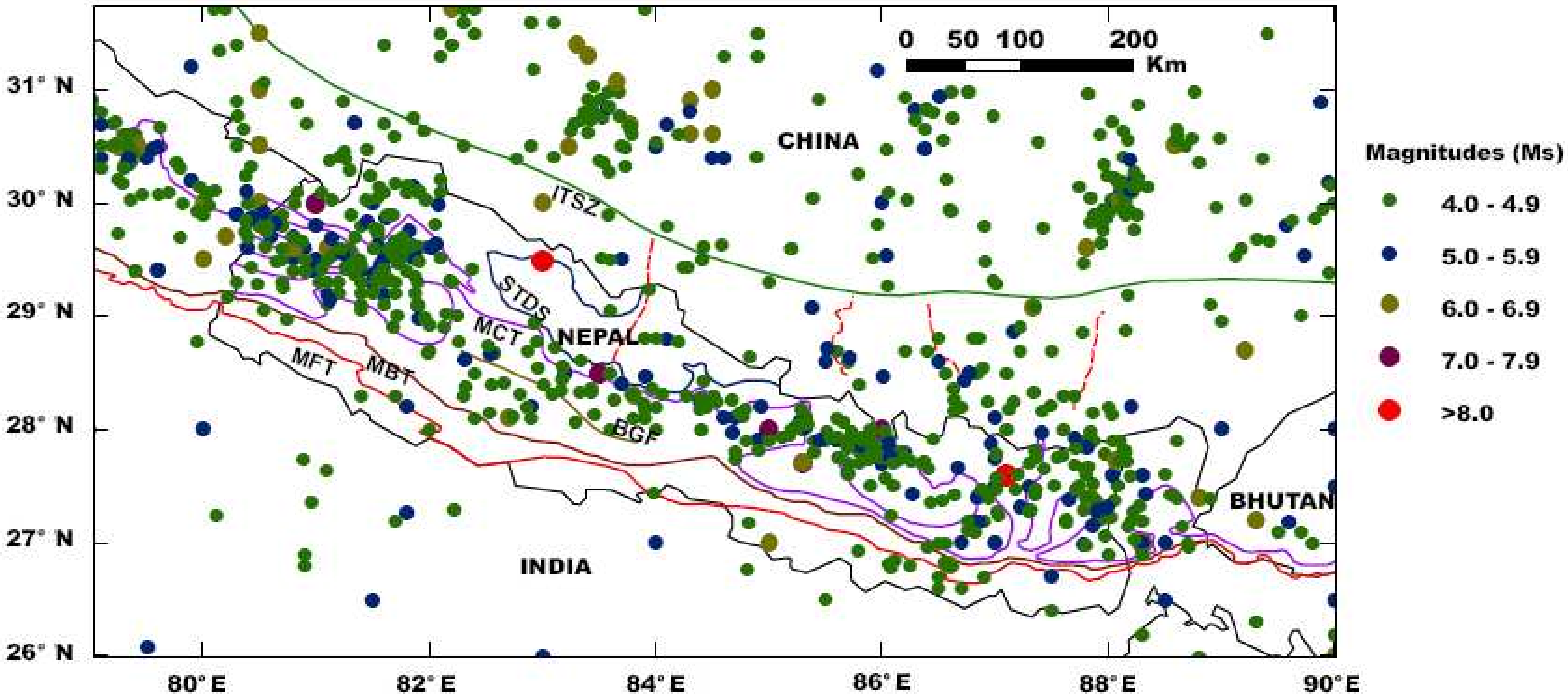

Fig. 3.4 Major faults and epicenters of earthquakes with surface-wave magnitude equal to or greater than 4.0 occurred in the Nepal Himalaya and surrounding regions for the period 1255-2011. Faults legend is the same as in Fig. 3.1

3.3 Summary

In this chapter, the general tectonics and geological settings of Nepal and analyses of seismicity covering the area extending between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E for the period 1255-2011 has been presented. First, the general tectonic and geologic features of Nepal have been discussed here. Second, the available documented historical seismic events and instrumentally recorded earthquake data covering the area between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E for the period 1255-2011 were compiled to determine the locations, and sizes (magnitudes) of earthquakes, and seismological features of this region were presented after removing, foreshocks, aftershocks, and duplicated as well as repeated events. The resulting updated seismicity database after the catalogue analysis consists of a total of 883 earthquakes with surface-wave magnitude equal to or greater than 4.0. The following conclusions can be drawn from the general review of tectonic and geological settings, and the analysis of earthquake catalogue of the investigated area:

(1) The study area represents a well identified active tectonic region and the most complex segment of the Himalaya consisting of four main longitudinal faults (Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT), and South Tibetan Detachment System (STDS)) and their associated minor faults and a Barigad fault in Nepal, and several transverse faults and the Indus-Tsangpo Suture Zone (ITSZ) in southern Tibet.

(2) The temporal distribution of available seismicity data for the period 1255-2011 shows that there are a very few accounts of significant earthquakes prior to 1800. The temporal trend of our seismic catalogue indicates gradual increase in earthquake data during the period from 1800 to 1963 and significant increase in number of seismic events particularly from 1964 onwards. The substantially increase in both quantity and quality of earthquake data in the last five decades suggests that our earthquake catalogue is complete from 1964 to 2011.

(3) The epicenters of the overwhelming numbers of catalogued earthquakes from 1255 to 2011 mainly aligned in a continuous east-northwest trending 50-150 km-wide belt in Nepal and its adjacent region.

(4) The spatial distribution of catalogued earthquakes for the period from 1255 to 2011

show the uneven distribution of earthquakes in Nepal with the strongest earthquake activity in the far-western and eastern parts of the country and the weakest seismic activity in southern Nepal.

(5) The superimposed seismicity map with major known faults in Nepal and the vicinity region demonstrates that the epicenters of overwhelming predominance of seismic events are situated near the surface trace of Main Central Thrust (MCT) and epicenters of a few number of earthquakes are situated at small distances from the surface traces of Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) in Nepal and its adjacent areas.

4 IDENTIFICATION OF POTENTIAL EARTHQUAKE-PRONE AREAS IN THE NEPAL HIMALAYA AND ITS SURROUNDING REGIONS

The main purpose of this chapter is to recognize potential earthquake-prone areas in the Himalaya of Nepal and its adjacent regions using the pattern recognition method. The first section briefly discusses the morphostructural zoning of the Nepal Himalaya and its surrounding regions by combining best available topographic, morphological, geological and tectonic information and satellite images. The second section describes the pattern recognition method and presents the determined potential earthquake-prone areas of the study region. It further discusses recognized seismic-prone areas and their association with past strong earthquakes that occurred in the investigation region. The last section summarizes the locations of identified potential seismic areas and discusses its importance to define potential seismic source zones for quantifying the seismic hazard in Nepal and its vicinity regions.

4.1 Introduction

The Himalaya of Nepal represents a structurally active tectonic regime extended with an approximate 800 km long-section in the central segment of the overall 2500 km long Himalayan mountain terrain. This region consists of the highest topography in the world (elevation up to 8,848 m above sea level) and has a complex tectonic setting developed by the collision of the Indian plate with the Eurasian plate that began around 50-55 million years ago [9-11] and this collision is still ongoing at present as a result mountain building process is continuing. The ongoing north-south continental collision of two tectonic plates (India/Eurasia) making the Nepal Himalaya one of the seismo-tectonically active regime in the world that is demonstrated by the existence of active faults [11] [23-28] [83-84] and the occurrence of strong seismic events in this region [15-18] [30] [33-35].

Although the database of earthquakes that occurred in the historical times are very scanty, the analysis of earthquake catalogue of Nepal described in chapter 3 shows the Himalaya of Nepal has been strongly rattled by five earthquakes of magnitudes 7.6 and above

(Ms = 7.6, 1255; Ms = 7.6, 1408; Ms = 8.1, 1505; Ms = 7.6, 1833; and Ms = 8.3, 1934) and facing huge casualties and economic losses in the past few centuries. In addition to these five large to great earthquakes, Nepal has often been suffering heavy material damage and enormous economic losses by several strong earthquakes including the September 18, 2011 (M = 6.8) earthquake. Owing to the structurally active tectonic region, such damaging seismic events are likely to continue in the future, therefore, it is extremely important to identify earthquake-prone areas in the Nepal Himalaya and its vicinity in order to prepare for reducing the casualties and economic losses from future earthquake disasters in this region.

It is well known that identification of locations of future seismic events is crucial not only to define proper potential seismic source zones for the seismic hazard assessment and seismic zonation studies in particular but also to select suitable sites for developing new cities and designing specific engineering structures in general. In fact, the best available historical and instrumental seismicity data combining with recent outcomes of various studies such as geological, geomorphological, geodetic, geophysical, plaeoseismological, tectonics, and neo-tectonics can be utilized to determine the likely locations of future events in the area of interests. However, list of historical earthquakes that occurred in Nepal is incomplete and the seismic instrumentation history of the country is less than a half century old. Using these insufficient earthquake datasets together with recently available outcomes of various studies may not provide proper locations of future seismic events in the Nepal Himalaya and its surrounding regions. Therefore, an alternative way of determining possible locations of future earthquakes is to evaluate the seismic potential of intersecting lineaments by using the pattern recognition techniques [116]. The pattern recognition is one of the most popular approaches [116] and useful tool that have been used by many researchers to determine earthquake-prone-areas in diverse seismic regions of the world over the last four decades: Adria Margin in Peninsular Italy and Sicily [117], Alborz Region [118], California [119], Himalaya [120], Iberian Peninsula [121], Tien Shan and Pamirs [116], and Western Alps [122]. Bhatia et al. [120] applied this pattern recognition methodology to determine the earthquake-prone areas in the Himalaya and recognized 48 earthquakes-prone nodes ($M \geq 6.5$) in which a few of them are located in the Nepal Himalaya. However, they paid less attention to transverse structures, particularly in the Nepal Himalaya. Here we attempt to outline the available transverse lineaments in Nepal and the adjacent areas by combining the best available topographic, geological and tectonic information with the aim to determine more detailed representation of potential earthquake-prone areas ($M \geq 6.0$) in the Himalaya of Nepal and its adjoining regions.

In this study we first prepared a morphostructural map of the Nepal Himalaya and its surrounding regions by combining information from geological, topographical, tectonic maps and satellite images. In a second step, we evaluated the seismic potential of all mapped morphostructual nodes in the Himalaya of Nepal and its adjoining regions using the pattern recognition techniques [119]. We finally discussed the locations of identified seismic potential-areas and their association with past strong earthquakes and highlighted their importance as basis information to delineate potential seismic source zones for the scientific quantification of seismic hazard and microseismic zonation studies in the Nepal Himalaya and its surrounding regions.

4.2 Methods

The method we utilized in the present study to determine the potential seismic-prone areas consists of two steps: morphostructural zoning [123] and classification of the morphostructural nodes applying the algorithm CORA-3 pattern recognition [119]. The former one method was used to map the morphostructural nodes of the investigated area, whereas the later technique was applied to classify the all the mapped morphostructural nodes in this dissertation into two distinct categories: Dangerous (D) nodes and Non dangerous (N) nodes. Class D comprise the nodes potential to earthquakes of magnitude (M) greater than or equal to a specified magnitude threshold (M_0 = 6.0 in this study), whereas class N consist of nodes capable of generating only seismic events with magnitude (M) less than a specified magnitude threshold ($M_0 <$ 6.0 in this study). Furthermore, the pattern recognition technique used in the present study consists of two stages: a learning stage selecting the distinctive features for each class according to the training sets comprised of subset D_0 of class D and subset N_0 of class N with regard to priori known epicenter locations of strong seismic events from the mapped morphostructural nodes, and a recognition stage classifying all the mapped nodes of the area of interests into either potential to strong earthquakes or only potential to smaller than strong seismic events. We briefly introduce these two stages below.

1 Learning Stage

The purpose of the learning stage of pattern recognition [119] used in this study is to choose the distinguishing features (characteristics traits) for class D and class N of mapped nodes. For the number of components ($1 \le i_1 \le i_2 \le i_3 \le L$), let the binary vectors of the node of interest be denoted by L. The trait can be represented by a following matrix A [119]:

$$A = \begin{vmatrix} i_1 & i_2 & i_3 \\ \delta_1 & \delta_2 & \delta_3 \end{vmatrix} \tag{4.1}$$

In the above expression, i_1, i_2, i_3 are integers, and values of $\delta_1, \delta_2, \delta_3$ should be 0 or 1.

Gelfand et al. [119] also demonstrated that for i node each binary vector is denoted by $\omega^i = (\omega^i_1, \omega^i_2, \ldots\ldots\ldots\ldots\ldots\ldots, \omega^i_L)$ which consists of trait, A, when:

$$\omega^i_{i_1} = \delta_1, \omega^i_{i_2} = \delta_2, \omega^i_{i_3} = \delta_3 \tag{4.2}$$

Let the set of given nodes be denoted by W and let $K\ (W, A)$ represent the number of nodes of the trait A for $\omega^i \varepsilon W$. Considering here the characteristic of traits, parameters $(k_1, \bar{k}_1, k_2, \bar{k}_2)$ of the algorithm should be chosen as positive integer. Then, for each node, the corresponding features can be distinguished as follows [119]:

(1.1) The trait A is said to be a characteristic trait of class D as:

$$K(D_0, A) \ge k_1 \text{ and } K(N_0, A) \le \bar{k}_1 \tag{4.3}$$

(1.2) The trait A is said to be a characteristic trait of class N as:

$$K(N_0, A) \geq k_2 \text{ and } K(D_0, A) \leq \bar{k}_2 \tag{4.4}$$

2 Classification Stage

After choosing the characteristic traits of all nodes, each targeted node of the investigated area needs to be identified whether earthquake prone or not utilizing the classification stage. In this second stage, two numbers n_D^i of the characteristic traits D and n_N^i of the characteristic traits N for each node of interest are first calculated using the algorithm CORA-3 [119]. The difference between n_D^i and n_N^i for a given node is denoted by Δ_i which can then be determined as follows [119]:

$$\Delta_i = n_D^i - n_N^i \tag{4.5}$$

Finally, each given node can be identified whether earthquake prone or not for a specific magnitude threshold from the difference between above two numbers. Thus, a given node is recognized to be the D node as:

$$\Delta_i \geq \Delta \tag{4.6}$$

Similarly, a given node is recognized to be the N node as:

$$\Delta_i \leq \Delta \tag{4.7}$$

where Δ denotes the parameter of the CORA-3 algorithm in both equations (4.6) and (4.7).

4.2.1 Morphostructural Zoning of the Nepal Himalaya and its Surrounding Regions

The morphostructural zoning carried out in this dissertation covers a wide area that encompasses the whole territory of Nepal and some parts of northern India, western Bhutan and south-western China. Detailed geological, tectonic structures and evolution history of this region have been well documented by many geoscientists [9] [11] [21-22] [25] [28] [79] [83-84] [124-129]. These several lines of investigations identified that the study region consists of five major regional longitudinal faults (ITSZ, STDS, MCT, MBT, and MFT) and numerous transverse faults and their associated minor faults and lineaments. Moreover, the locations and strike directions of these major regional longitudinal faults have been already described in chapter 3. As described in chapter 3, the STDS, MCT, MBT, and MFT marks the boundary lines of five tectonic domains of Nepal, where as the ITSZ is located to the north of Nepal (Fig. 3.1) in southern Tibet, in the world highest topographic Tibet plateau, that is considered as the initial boundary line between Indian plate and Eurasian plate [11][21]. Moreover, the study region demonstrates strong topographic contrast with the world highest point in the globe as shown in Fig. 1.2 in chapter 1.

In this study, we used the morphostructural zoning method of Alexeevskaya et al. [123] to prepare a morphostructural map of the Nepal Himalaya and its surrounding regions by combining information from geological, topographical, tectonic maps and satellite images. It is worthwhile to mention that the morphostructural zoning method used in this dissertation does not include earthquakes located in this investigation region, but requires defining a hierarchical structure with associated ranks: areas of different rank (blocks), linear boundary zones of blocks (morphostructural lineaments) and intersection of lineaments (morphostructural nodes). It also needs to be mentioned here that the morphostructural lineaments defined in this study do not represent the actual trace of previously known fault zones, but coincide with the surface expressions of previously identified faults and lineaments in Nepal and its vicinity regions.

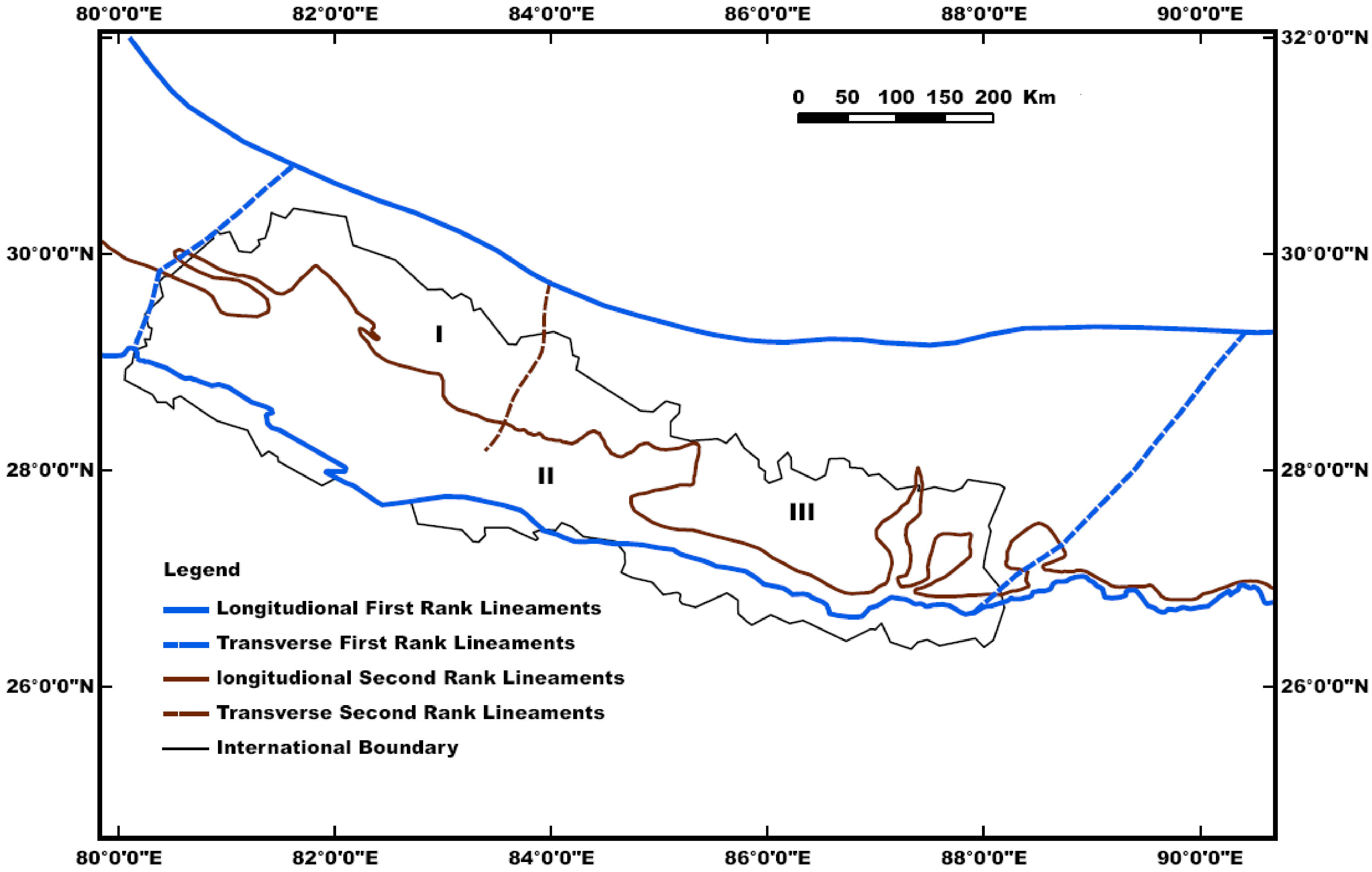

Fig. 4.1 First and second rank lineaments map of the Nepal Himalaya and its surrounding regions. Roman numbers denote the megablocks

We first treat here the Nepal Himalaya and surrounding regions as a single first rank area because the present day architecture of the whole study area was formed by the Himalayan orogenic process [9] [21] [124]. We mapped two first rank longitudinal lineaments following the surface expression of the Main Frontal Thrust (MFT) in the south and the Indus-Tsangpo Suture Zone (ITSZ) in the north as well as two first rank transverse lineaments along the Mahakali River in the west and following the Yadong lineament in the east. These delineated first rank lineaments in this study are shown in Fig. 4.1.

The study area shows the extreme topographic variation in the north-south direction and slight change in orientation of the mountain range in the east-west direction that is clearly visible in the topographic map of Nepal (Fig. 1.2). Based on the topographic characteristics and the general orientation of the mountain chain, we next divided the whole examined morphostructural area into three megablocks (Megablock I, Megablock II, and Megablock III) that are separated by second rank lineaments. We traced the second rank longitudinal lineament coinciding with the surface expression of the MCT which separate the Megablocks I and III in the north from the Megablock II in the south, and the second-rank transverse lineament following the western boundary of the Thakkhola Graben [126] that separates the Megablock I and Megablock III (Fig. 4.1).

We further subdivided these three megablocks (I, II and, III) into blocks separated by third rank lineaments. We mapped third rank lineaments primarily following the surface trace of previously identified both longitudinal and transverse faults as well as lineaments available in the existing literatures [25] [28] [83]. The third rank longitudinal lineaments corresponds to the nearly east-west oriented Bari Gad fault [25], the boundaries of tectonic zones such as the MBT and some segments of the STDS as shown on the geological map of Nepal [87], third rank transverse lineaments following the surface trace of previously identified transverse faults and lineaments in Nepal [28] and approximately north-south trending grabens in southern Tibet [83]. In addition, we mapped some transverse lineaments along the long linear segments of river valleys, topographic transition along the slope of the ridges visible in the topography map of Nepal and the surrounding region (Fig. 1.2).

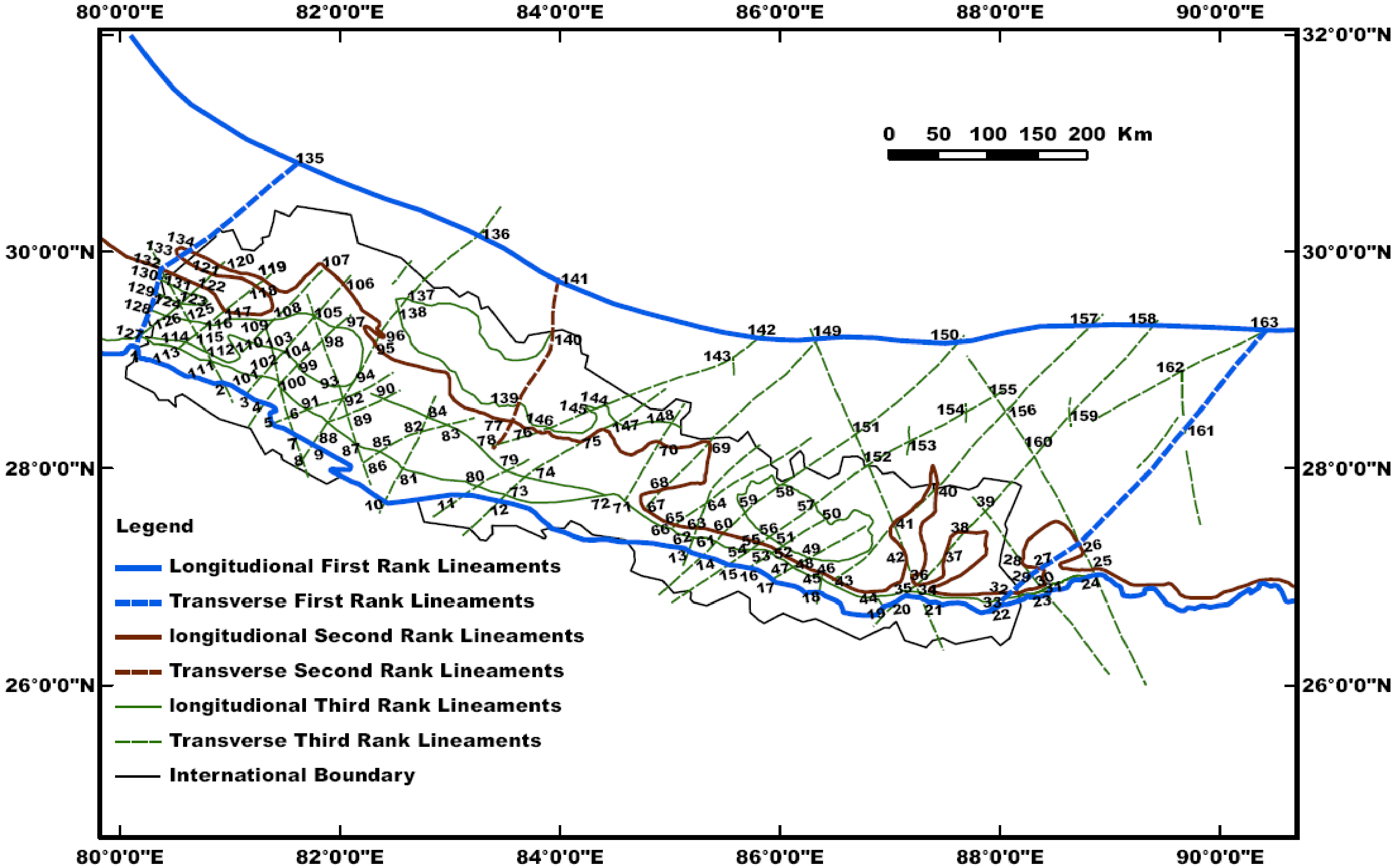

Fig. 4.2 Morphostructural map of the Nepal Himalaya and its surrounding regions showing lineaments. Numbers denote the intersection of lineaments

All the lineaments mapped in this study are displayed in Fig. 4.2. It can be seen from Fig. 4.2 the distribution of the first rank lineaments, second rank lineaments and third rank lineaments, and their intersection points in the Nepal Himalaya and its surrounding regions. The resulting morphostructural map of the entire investigation region contains a total of 163 intersections of lineaments. We considered all 163 points formed by intersecting lineaments as morphostructural nodes and subsequently used as recognition patterns in the present study.

4.2.2 Input parameters for Earthquake-prone Areas Determination in the Nepal Himalaya and its Surrounding Regions

The main parameters utilized in this research to identify seismic-prone areas using the pattern recognition technique were extracted at each node over a 25-km radius circular window of the intersections of lineaments after properly compiling the best available information from topographic, geological, and morphological along with the morphostructural map of the Himalaya of Nepal and its adjacent regions (Fig. 4.2). These four input parameters (Table 4.1) used to evaluate potential earthquake-prone areas reflect fundamental characteristics relevant to the existing seismic behavior of the examined area. Additionally, two parameters namely the region of soft quaternary-recent sedimentary deposits and topography (slope and relief energy) indicate the indirect manifestation of the level of ongoing tectonic movements, and the parameter relating to the lineaments density is primarily associated with the level of crustal-fracturing of the studied area.

We measured the values of topographic parameters (maximum elevation, minimum elevation, relief energy, distance between the maximum and minimum elevation points, and slope), geological parameters (fraction of the node region covered by soft quaternary-recent sedimentary deposits), lineaments-blocks geometry related parameters (the highest rank of lineament, number of lineaments forming a node, distance from the nearest first rank lineament, distance from the nearest second rank lineament, and distance from the nearest node) and morphological parameters (one value with respect to morphology: mountain and plain, mountain and piedmont, mountain and mountain, piedmont and plain, piedmont and piedmont, plain and plain) at each node over a radius of 25-km from the intersections of lineaments. The measured values of these parameters in this investigation are essentially needed to convert into binary vectors when applying the CORA-3 algorithm. In this regard, we first converted all these measured values into binary vectors using discretization and coding [119]. We then choose one-threshold of discretization (for the distance between maximum altitude and minimum altitude points, and number of lineaments forming a node) to divide the measured values into two binary components (1 for small value and 0 for large value), and two-threshold of discretization (for all the parameters listed in Table 4.1 other than the distance between maximum and minimum altitude points, and number of lineaments forming a node) to divide the measured values into three binary components (11 for small value, 01 for medium value, and 00 for large value). All input parameters (topographic, geological, lineaments-blocks geometry, and morphological) and thresholds of discretization used in the present study are listed in Table 4.1.

Tab. 4.1 Input parameters and thresholds of discretization values used in this study

Input parameters	Thresholds of discretization		
(1) **Topographic Parameters**			
Maximum Topographic Elevation H_{max} (m)	2552		4556
Minimum Topographic Elevation H_{min} (m)	194		632
Relief Energy *DH* $(H_{max} - H_{min})$ (m)	2121		3142
Distance between the points H_{max} and H_{min} *L* (km)		40	
Slope *DH/L*	56.87		86.57
(2) **Geological Parameters**			
The fraction of the node region covered by soft quaternary to recent sedimentary deposits *Q* (%)	2		34
(3) **Parameters of Lineaments and Blocks Geometry**			
The Highest Rank of Lineament in a Node *HR*	1		2
Number of Lineaments Forming a Node *NL*		2	
Distance from the Nearest First Rank Lineament D_1 (km)	9		48
Distance from the Nearest Second Rank Lineament D_2 (km)	7		51
Distance from the Nearest Node D_n (km)			
(4) **Morphological Parameters**			

Tab. 4.1 (Continued)

A value of Morphological Parameters is used for Recognition to Each Node from six values given below: 1. Mountain and Plain (m/p) 2. Mountain and Piedmont (m/pd) 3. Mountain and Mountain (m/m) 4. Piedmont and Plain (pd/p) 5. Piedmont and Piedmont (pd/pd) 6. Plain and Plain (p/p)	2	3

Notes: Discretizations were carried out with two thresholds. One value and two values indicate one-threshold of discretization and two-threshold of discretization, respectively.

4.3 Morphostructural Nodes and Earthquakes in the Nepal Himalaya and its Surrounding Regions

As mentioned above, we mapped the spatial distribution of morphostructural nodes in the Nepal Himalaya and its adjacent regions using information from geological, topographical, tectonic maps and satellite images. It is worthwhile to note that we performed the morphostructural mapping of the study area without field observations and specified the geometry of the morphostructural node by a circle of 25-km radius from the point of intersection. The purpose of specifying dimension of the node (radius = 25-km in this study) is to incorporate the source zones for earthquakes with magnitudes equal to or greater than 6.0, which is basically larger than that of seismic source dimension (about length = 20 km and width = 10 km) for an earthquake of magnitude M = 6.0 [130].

We superimposed the morphostructural map with the seismicity map of the Nepal Himalaya and its vicinity regions to understand the relationship between morphostructural nodes and earthquakes. For this purpose, we utilized here an earthquake catalogue compiled and analyzed in chapter 3. The earthquake catalogue analyzed and prepared in chapter 3 encompassing the region (26°N-31.7°N latitudes, 79°E-90°E longitudes) for the period from 1255 to 2011. The updated homogenous earthquake catalogue prepared for the present study

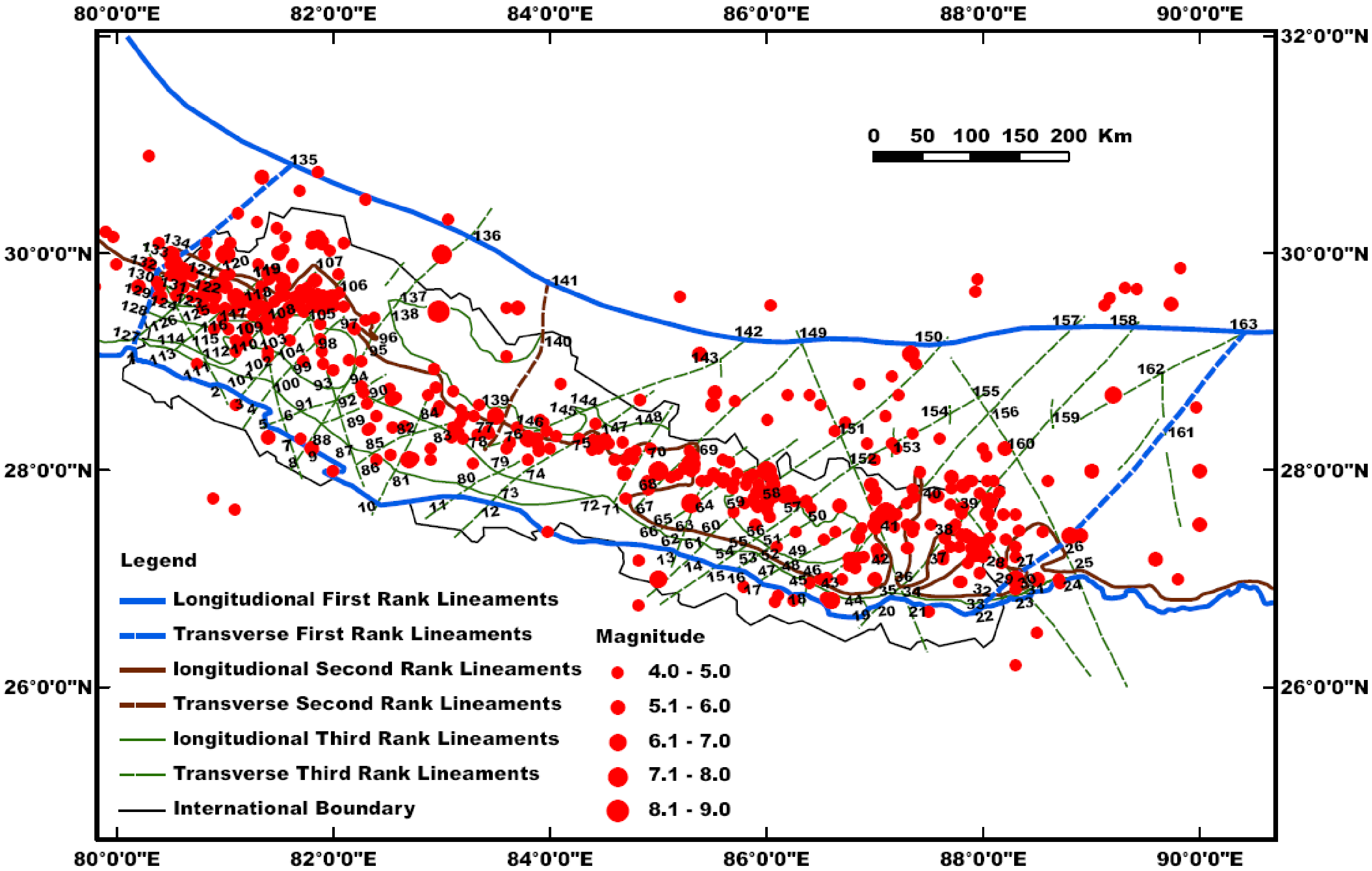

Fig. 4.3 Map showing intersection of lineaments and epicenters of earthquakes in the Nepal Himalaya and surrounding regions

area consists of 883 earthquakes with surface-wave magnitudes equal to or greater 4.0.

Fig. 4.3 shows the lineaments and spatial distribution of earthquakes ($Ms \geq 4.0$) that occurred in Nepal and its vicinity areas for the period 1255-2011. The spatial distribution pattern of earthquakes ($Ms \geq 4.0$) shows the majority of strong size earthquakes clustered along the second rank longitudinal lineament and third rank transverse lineaments. It can be clearly seen from Fig. 4.3 that earthquakes with magnitudes less than 6.0 are more scattered, thus, it is difficult to associate mapped morphostructural nodes with these moderate size earthquakes in the study region. In other words, morphostructural nodes are well associated with strong earthquakes rather than moderate size earthquakes. In addition, our earthquake database (described more detailed in chapter 3) consists of 30 shallow depth (less than 70 km) seismic events with surface-wave magnitudes equal to or greater than 6.0. Seismicity parameters (locations and magnitudes) of these strong earthquakes ($Ms \geq 6.0$) are listed in Table 4.2 and their epicenter locations are displayed in Fig. 4.4.

Tab. 4.2 List of strong earthquakes that occurred in the Nepal Himalaya and its vicinity regions

Year	Month	Day	Longitude (E)	Latitude (N)	Magnitude (M_s)
1255			85.3	27.7	7.6
1408			85.3	27.7	7.6
1505	6	6	83	29.5	8.1
1681			85.3	27.7	7
1810			85.3	27.7	7
1833	4	10	85	27	7
1833	4	10	85	27	6.3
1833	8	26	86	28	7.6
1849	2	27	88.3	27	6.3
1852	5	1	88.3	27	7
1866	5	23	85.3	27.7	6.3
1899	9	25	88.3	27	6.3
1913	3	6	83	30	6.2

Tab. 4.2 (Continued)

1916	8	28	81	30	7.3
1934	1	15	87.1	27.6	8.3
1935	3	5	80.2	29.7	6
1935	5	21	89.2	28.7	6.2
1936	5	27	83.5	28.5	7
1953	2	23	81.3	29.5	6
1954	9	4	83.8	28.3	6.5
1964	9	26	80.5	30	6.2
1966	6	27	81	29.7	6.2
1967	2	11	82.7	28.1	6
1969	2	22	88.58	30.51	6.2
1980	7	29	81.1	29.6	6.6
1980	11	19	88.8	27.4	6.1
1988	8	20	86.6	26.8	6.8
1993	3	20	87.33	29.08	6.4
2008	1	28	81.86	30.15	6
2011	9	18	88.06	27.72	6.8

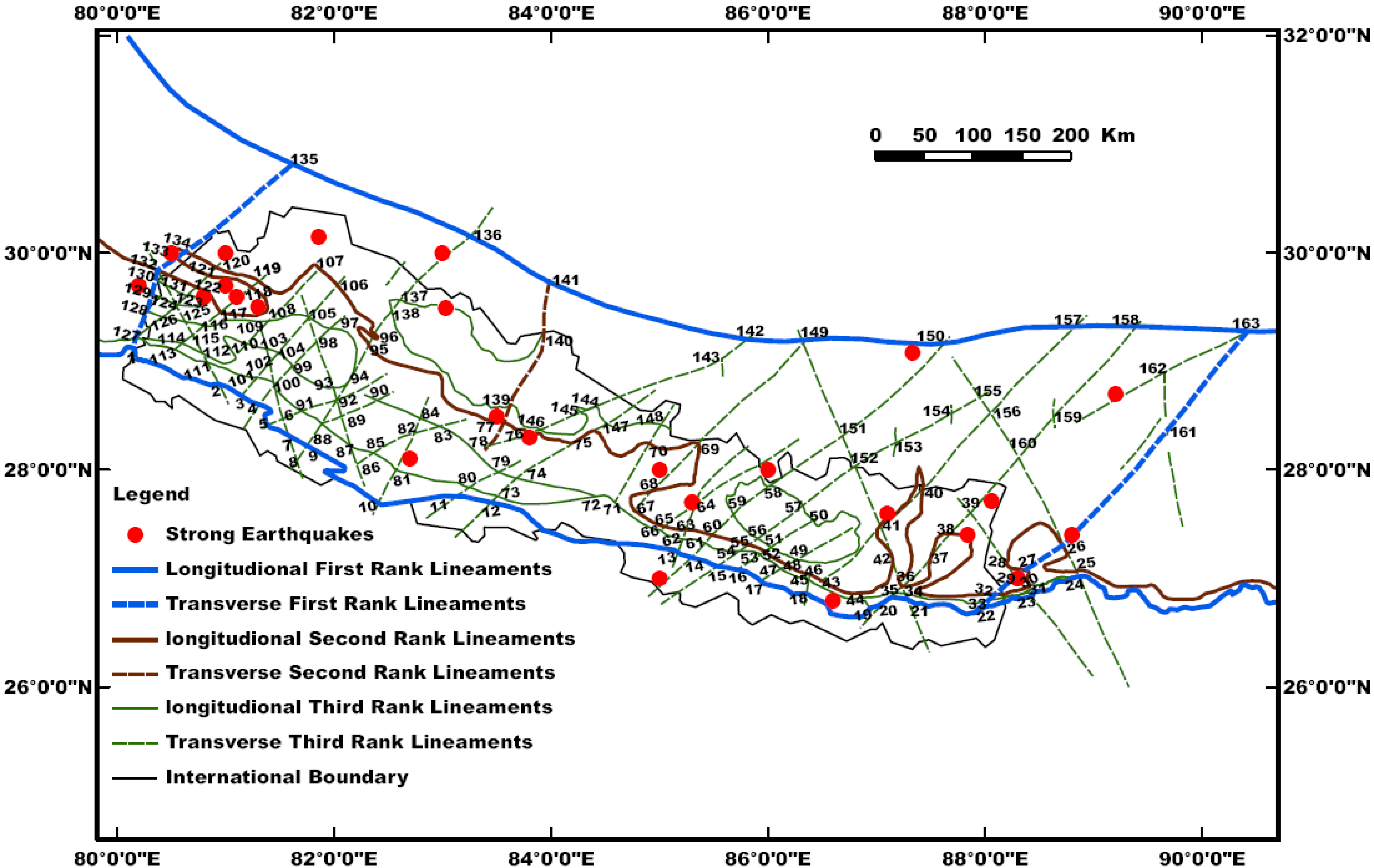

Fig. 4.4 Map showing intersection of lineaments and epicenters of strong earthquakes in the Nepal Himalaya and its surrounding regions

Fig. 4.4 displays the morphostructural map superimposed with the epicenters distribution of strong earthquakes ($Ms \geq 6.0$) that occurred in the Himalaya of Nepal and its vicinity regions for the period 1255-2011. It can be seen that the epicenters of the majority predominance of strong seismic events are located near the second rank longitudinal lineament in the study region. In addition, the association of intersection of morphostructural lineaments (nodes) and strong earthquake (Fig. 4.4) exhibits a more or less similar pattern to that of moderate size earthquakes and nodes as shown in Fig. 4.3. The spatial association of intersection of morphostructural lineaments (nodes) and strong earthquakes in Nepal and the surrounding region shows a casual relation.

In sum, 30 shallow strong seismic events were reported in our catalogue of which only six earthquakes of magnitudes greater than 6.0 (M = 8.1, 1505; M = 6.2, 1913; M = 6.2, 1935; M = 6.3, 1833; M = 6.0, 2008; and M = 6.8, 2011) are located at distances greater than 25 km from the intersections of lineaments (morphostructural nodes). Of these six strong catalogued earthquakes, five events (M = 8.1, 1505; M = 6.2, 1913; M = 6.2, 1935; M = 6.3, 1833, and M = 6.8, 2011) are located along the lineaments and one event (M = 6.0, December 12, 2008) is situated far from the mapped lineaments. The December 12, 2008 earthquake is located at a distance of more than 25 km from the nearest node 107 and generally does not shows obvious association with lineaments in the Nepal Himalaya and its vicinity areas.

The distance between morphostructural nodes and epicenters of all strong earthquakes as well as the general seismological condition of the Nepal Himalayan and its adjoining region are utilized in the learning step of the pattern recognition that are presented below in the subsection 4.4.1.

4.4 Identification of Earthquake-prone Nodes ($M \geq 6.0$) in the Himalaya of Nepal and its Surrounding Regions

4.4.1 Training Sets Selection

In order to identify the earthquake-prone areas in the Himalaya of Nepal and its adjacent regions, we selected the training sets of the outlined nodes on the basis of the epicenter distances of strong seismic events from the mapped morphostructural nodes in the

Nepal Himalaya and its surrounding regions and subsequently divided all 163 morphostructural nodes into three different training sets:

(1) Set D_0 consisting of morphostructural nodes which are located at distances less than or equal to 25 km from the epicenters of strong earthquakes in Nepal and the surrounding regions (Fig. 4.4). The set D_0 contains 36 morphostructural nodes (23, 26, 27, 28, 29, 30, 31, 38, 41, 43, 44, 58, 64, 68, 76, 77, 81, 108, 109, 116, 117, 118, 120, 121, 122, 123, 124, 125, 129, 130, 131, 132, 133, 134, 139, and 146).

(2) Set N_0 consisting of morphostructural nodes that are situated over distances of 50 km from the epicenters of strong earthquakes in the study area (Fig. 4.4). The set N_0 includes 85 morphostructural nodes: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 21, 25, 34, 35, 36, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 71, 72, 73, 79, 80, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 111, 112, 113, 114, 115, 127, 135, 137, 138, 140, 141, 142, 143, 144, 145, 147, 148, 149, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, and 163.

(3) Set X consisting of those morphostructural nodes which are located at the distances of 25-50 km from the epicenters of strong earthquakes as shown in the Nepal Himalaya and its vicinity regions (Fig. 4.4). The set X comprise of 42 morphostructural nodes: 13, 14, 18, 19, 20, 22, 24, 32, 33, 37, 39, 40, 42, 45, 46, 57, 59, 60, 61, 62, 63, 65, 66, 67, 69, 70, 74, 75, 78, 82, 83, 84, 85, 86, 107, 110, 119, 126, 128, 136, 150, and 162.

4.4.2 Recognition of Earthquake-prone Areas and Discussions

We identified earthquake-prone sites in the Nepal Himalaya and its surrounding regions by applying the CORA-3 algorithm pattern recognition [119]. In this study, we set the threshold values of four parameters $k_1, \bar{k}_1, k_2,$ and $\bar{k}_2$ of the algorithm to 1, 2, 27, and 1, respectively, when $\Delta = 0$ and the best results were obtained selecting twelve D traits and five N traits. The identified earthquake-prone nodes of the whole examined region are plotted in Fig. 5 and the selected twelve D and five N characteristics traits are presented in Table 4.3.

Tab. 4.3 Characteristics traits of D and N nodes in the Nepal Himalaya and its surrounding regions

Number	Parameters					
	H_{min} (m)	DH (m)	DH/L	HR	D_2 (km)	Morphology
			D traits			
1			≥ 86.57		≥ 7	
2	≤ 632		≥ 86.57			
3						m/m or m/pd
4					≥ 7	m/m or m/pd
5					≤ 51	
6	≥ 194				≤ 51	m/m or m/pd
7	≤ 632					
8				1^{st} or 2nd		
9					≥ 7	
10	≤ 632				≥ 7	
11	≥632				≤ 51	
12	≤ 632	≥ 3142				
			N traits			
1			≤ 86.57			Other than m/m or m/pd
2	≤ 194		≤ 86.57		≥ 51	
3	≥632					
4		≤3142		1^{st} or 2nd	≥ 51	
5		≤3142				

The characteristic traits of D nodes in this study indicate the large difference in elevation ($DH \geq 3142$ m) and high gradient ($DH/L \geq 86.57$), whereas the characteristic traits of N nodes have small values of elevation difference ($DH \leq 3142$ m) and low gradient ($DH/L \leq 86.57$). These characteristic traits (elevation difference and gradient) suggest that the level of tectonic movements near the recognized D nodes is generally more pronounced than that of the vicinity of N nodes in the investigation region. It can also be seen that the D nodes are located at small distance from the second rank lineament ($D_2 \leq 51$ km) and the N nodes are lying at relatively more distant from the second rank lineaments ($D_2 \geq 51$ km), which suggest the high crustal-fragmentation near the D nodes rather than the vicinity of N nodes in the Himalaya of Nepal and its nearby regions.

The D nodes contain 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 35, 36, 37, 38, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 51, 52, 53, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 74, 75, 76, 77, 78, 79, 80, 93, 95, 96, 101, 106, 107, 108, 109, 112, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 129,130, 131, 132, 133, 134, 139, 140, 145, 146, 151, and 152.

The N nodes consist of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17,18, 19, 20, 21, 22, 34, 39, 50, 54, 71, 72, 73, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 94, 97, 98, 99, 100, 102, 103, 104, 105, 110, 111, 113, 114, 127, 128, 135, 136, 137, 138, 141, 142, 143, 144, 147, 148, 149, 150, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, and 163.

In total, we identified 84 earthquake-prone areas (D nodes) which includes 35 from set D_0 (23, 26, 27, 28, 29, 30, 31, 38, 41, 43, 44, 58, 64, 68, 76, 77, 108, 109, 116, 117, 118, 120, 121, 122, 123, 124, 125, 129, 130, 131, 132, 133, 134, 139, and 146), 24 from set N_0 (25, 35, 36, 47, 48, 49, 51, 52, 53, 55, 56, 79, 80, 93, 95, 96, 101, 106, 112, 115, 140, 145, 151, and 152) and 25 from set X (24, 32, 33, 37, 40, 42, 45, 46, 57, 59, 60, 61, 62, 63, 65, 66, 67, 69, 70, 74, 75, 78, 107, 119, and 126). Approximately 52 % of the mapped morphostructural nodes in the present study were identified potential earthquake-prone areas (D Nodes) in the Nepal Himalaya and its vicinity regions.

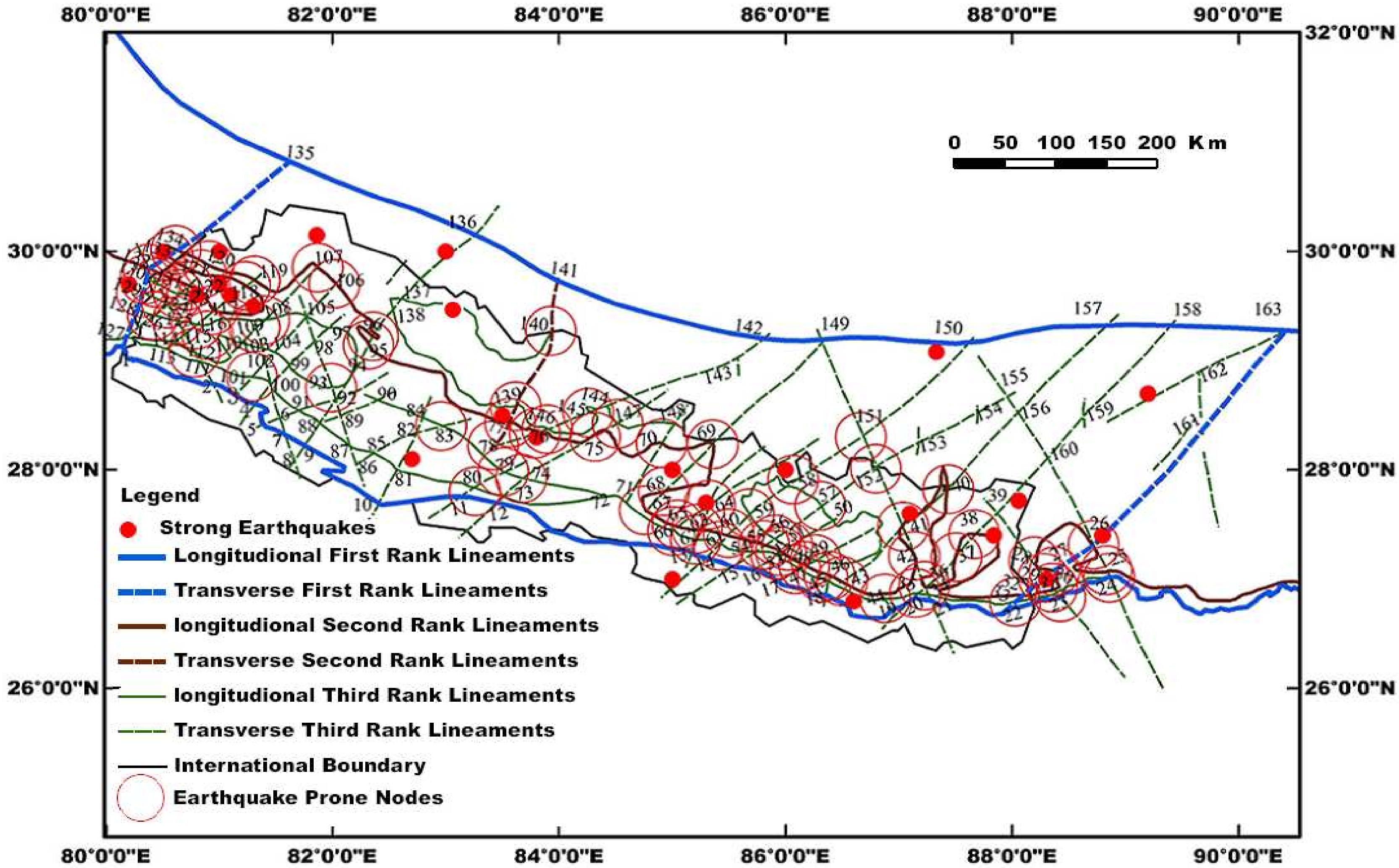

Fig. 4.5 Map showing morphostructural nodes prone to earthquakes with M ≥ 6.0 (open red circles) in the Nepal Himalaya and surrounding regions

Fig. 4.5 shows the locations of recognized potential earthquake-prone areas (D nodes) in the study area. The spatial distribution of identified potential earthquake-prone areas (D nodes) demonstrates that a large number of earthquake-prone areas ($M \geq 6.0$) are located in the far-western and south-eastern portions of Nepal. These identified earthquake-prone nodes (D nodes) presented herein mainly lie on the second rank lineament in the Himalaya of Nepal and its vicinity regions. The epicenter locations of most of the strong past seismic events that occurred in the investigation area coincide with identified earthquake-prone sites (D nodes) in this study.

This study further demonstrates that several identified earthquake-prone sites are located in places where no earthquakes with magnitudes equal to or greater than 6.0 have been reported in both recent and historical times in the Nepal Himalaya and its vicinity regions. These identified 84 earthquake-prone areas have potential to generate strong earthquakes that could cause extensive damage in Nepal and its neighboring countries. Moreover, these identified potential earthquake prone-areas (D nodes) presented here provide useful information for earthquake scientists and engineers to delineating potential seismic source zones for quantifying seismic hazard and earthquake zonation studies, and for the government making important decision for choosing the locations of key infrastructures, develop new cities in several parts of the country and strategy to reduce earthquake risk in Nepal and its adjacent regions.

4.5 Summary

In this chapter, the pattern recognition technique has been applied to identify the potential earthquake-prone areas in the Nepal Himalaya and its adjoining regions. First, a morphostructural map of the Nepal Himalaya and its surrounding regions has been prepared using information from geological, topographical, tectonic maps and satellite images. Second, seismic potential of each mapped morphostructural nodes of the study area were evaluated using the pattern recognition algorithm. These identified potential earthquake-prone areas (D nodes) presented here provide useful information for earthquake scientists and engineers to delineating potential seismic source zones for assessing seismic hazard and earthquake zonation studies, and for the government making important decision for choosing the locations of major engineering structures, develop new cities and strategy to minimize seismic risk in Nepal and the surrounding regions. The primary features drawn from the present study are concluded in the following points:

(1) A morphostructural map produced here by combining information from geological, topographical, tectonic maps and satellite images and the resulting map consists of in total 163 morphostructural nodes in the Himalaya of Nepal and its adjoining areas.

(2) The results obtained from pattern recognition found that approximately 52 percent (84 out of 163) of delineated morphostructural nodes recognized prone to strong seismic events ($M \geq 6.0$) in the Himalaya of Nepal and its adjoining areas. These identified earthquake-prone areas (D nodes) are mostly situated in the far-western and southeastern portions of central Nepal, while the N nodes are mainly located in southwestern Nepal and southern Tibet.

(3) The spatial distribution of potential earthquake-prone areas displays that the majority of the determined earthquake-prone areas (D nodes) are mostly localized along the longitudinal second rank lineament in the Nepal Himalaya and its surrounding area.

(4) There are remarkable difference observed between the characteristic traits of D nodes and N nodes in this study. The large variations in elevation ($DH \geq 3142$ m) and high gradient ($DH/L \geq 86.57$), indicating that these recognized D nodes are situated near to the areas of contrast tectonic movements in Nepal and its adjacent regions. Additionally, the relatively small distance ($D_2 \leq 51$ km) between D nodes and second rank lineaments suggesting the densely crustal-fragmentation in the vicinity of the D nodes in the study region. In contrast, small values of elevation difference ($DH \leq 3142$ m), low gradient ($DH/L \leq 86.57$) and relatively more distant from the second rank lineaments ($D_2 \geq 51$ km) obtained here in the characteristics traits of the N nodes suggest the less pronounced tectonic movements and crustal fractures in the vicinity of the N nodes in the Himalaya of Nepal and its nearby regions.

(5) The epicenter locations of most of the seismic events with magnitudes equal to or greater than 6.0 that occurred in Nepal its vicinity areas coincide well with the recognized potential earthquake-prone areas (D nodes) in this study. The present study further reveals

that several recognized potential earthquake-prone areas (D nodes) are located in sites where no seismic events with magnitudes equal to or greater than 6.0 have been reported in both historical and recent times in Nepal and the surrounding region.

5 PROBABILISTIC SEISMIC ZONATION FOR NEPAL

This chapter presents an analysis of the seismic hazard in Nepal using a probabilistic method, after defining potential seismic source zones by integrating information described in chapters 3 and 4, determining seismicity parameters for each potential seismic source zone as well as the entire study region and choosing a ground motion attenuation relationship. The first section introduces the major earthquakes and reviews of previous studies related to earthquakes, crustal deformation, faults and earthquake hazard in Nepal. The second section deals with the delineation of twenty-three potential seismic source zones by integrating information described in chapters 3 and 4, and the determination of seismicity parameters for each potential seismic source zone as well as for the whole area of study. The third section discusses the analyses of earthquake ground motion hazard in Nepal at bedrock level with three different exceedance probabilities (63%, 10%, and 2% in 50 years) and highlights the importance of these seismic zonation maps to the engineers for designing and evaluating the seismic performance of key infrastructures, and to the government for making future city development plans, as well as effective earthquake disaster mitigation, prevention and protection plans in the country. This section also present a comparison of probabilistic seismic zonation maps prepared in the present study with the seismic zoning maps of China and India. The final section presents the summary of potential seismic source zones and seismic zonation study for Nepal.

5.1 Introduction

Nepal is a well-identified earthquake-prone country extending between latitudes 26˚22’N-30˚27’N and longitudes 80˚4’E-88˚12’E in the central section of the Himalayan seismic belt with a total population exceeding 26 million residents [1]. It has a prolonged history of disastrous earthquakes and previously shaken by five seismic events (1255, 1408, 1505, 1833, and 1934) with magnitudes greater than 7.5 over the past nine centuries. Additionally, the country has been frequently suffering huge casualties and countless economic losses by the numerous strong to great historical and recent damaging earthquakes among which the historical 1255 seismic event represents the oldest documented damaging earthquake that occurred in Nepal and killed around one third citizens of Kathmandu (including King Abahya Malla of the Kathmandu valley) and badly-damaged several temples and buildings in Kathmandu [2]. The great earthquake of 1934 (M_w = 8.4, Bihar-Nepal earthquake) is so far the largest and the most catastrophic historical event that caused tremendous material damage, countless economic losses and casualties exceeding tens of thousands in the country. In addition to those of 1255, 1408, 1505, 1833, and 1934 historical earthquakes, Nepal has often been suffering widespread material damage and economic losses from many instrumental recorded strong seismic events, including the most recent strong earthquake of September 18, 2011 (M = 6.8). The most recent instrumentally recorded strong earthquake (M = 6.8, September 18, 2011) that occurred near the eastern border between Nepal and India about 270 kilometers east of Kathmandu (the capital city of Nepal) caused the considerable damage to houses especially in the eastern portion of the country and death of a total 6 people in Nepal including the death of 3 people (by a collapsing wall) in Kathmandu.

In fact, the region in and around Nepal has a long history of damaging earthquakes and a less than a half century old history of instrumental seismicity. Hence this region has captured the great attention of local and foreigner scientists and investigated in detail mainly devoting on a variety of disciplines such as seismic monitoring, geodetic measurements, and fault investigations particularly in the last three decades. The seismicity of Nepal has been started to monitor instrumentally since 1978 when the first local seismic station of Nepal was installed at the Phulchoki, southeast of Kathmandu and presently there are about two dozen of seismograph stations within the country that are well monitoring seismic events by the National Seismological Centre (Ministry of Industry, Nepal). These seismic stations detect earthquakes with local magnitude equal to or greater than 2.0 that occurred in Nepal and its vicinity and enabled more accurately determine the locations and magnitudes of seismic events. Pandey et al. [131] analyzed the microseismic data ($M_L \geq 2.0$) recorded between May 1994 and January 1998 by the national seismological network of Nepal and showed that the epicenters of the majority of these instrumental microseismic events ($M_L \geq 2.0$) are primarily concentrated along the topographic front of the Higher Himalaya zone where the level of stress accumulation is high over the inter seismic period [34]. Crustal deformation estimation of Nepal using GPS measurements over the last two decades by several geoscientists [15-20] [33] revealed the Main Himalayan Thrust (MHT) is locked and the significant deformation occurs in the north of the Main Frontal Thrust (MFT) that encloses the region of the high level of microseismic activity identified by Pandey et al. [131]. Moreover, the study of faults by several investigators, e.g. [21] [23-26] [28] [74] [82-84] [86] [126] [128] have well documented many active geological structures that are capable of producing earthquakes in Nepal and the surrounding regions.

The combination of above mentioned seismic monitoring, geodetic measurements, faults studies have significantly improved the understanding of present day seismicity, crustal deformation and geological structures and have inferred earthquake potential of this region, but the seismic hazard of this region has not yet understood. Furthermore, the distribution pattern of earthquakes (described in Chapter 3) as well as identified potential earthquake-prone areas (described in Chapter 4) in the study region clearly demonstrating strong earthquakes could occur in future and pose serious threat to people, cities and infrastructures in Nepal and nearby areas. The material damage and losses in the country could rise tremendously in the years to come from future earthquakes owing to the high annual rate of population growth, rapid urbanization, construction and expansion of infrastructures in Nepal. Disastrous effects from future earthquakes that originate in the Himalaya of Nepal and its vicinity region can effectively be reduced to a large extent only through the proper recognition of seismically hazardous zones and subsequent improvement in construction methods with aseismic design of structures and effective protection and mitigation planning in Nepal. Therefore, it is necessary to systematically develop a set of seismic zoning maps for Nepal at a national level that aid the government for future city development plans, making decisions on locating and aseismic design of civil infrastructures, as well as for seismic disaster mitigation, prevention and protection planning in this region.

A number of approaches can be applied for recognizing seismically hazardous areas at various scales (local, national and global), in which the probabilistic seismic hazard analysis (PSHA) method developed 45 five years ago firstly by Cornell [41] is one of the most widely used methods in assessing the seismic hazard and earthquake zonation researches. The well-defined PSHA has been becoming a highly popular in the last four and half decades and many organizations and investigators from different parts of the globe, e.g. [61-62] [65] [132-141] have often adopted the method and widely applied for the hazard assessment of a specific project, site, city, country as well as seismic zonation researches, and provided the design guidelines of large civil infrastructures in many different seismic regions in the world.

The present study aims to develop a set of seismic zonation maps for Nepal at a national scale using a probabilistic approach. We first presented delineated twenty-three potential seismic source zones by integrating information described in chapters 3 and 4, determined seismicity parameters for each potential seismic source zone and selected a ground motion attenuation relationship for this region. We then discussed the analysis of seismic hazard for Nepal and resulting probabilistic seismic zoning maps that represent earthquake ground motion hazard in terms of PGAs at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years. We finally compared these probabilistic seismic zonation maps with the seismic zoning maps of China and India.

5.2 Potential Seismic Source Zones and Earthquake Hazard Parameters

5.2.1 Delineation of Potential Seismic Source Zone

In this section, we focused on delineating potential seismic source zones in a wide region that primarily covers the entire territory of Nepal and some portions of south western China, northern India, northern Bangladesh, and western Bhutan (Fig. 5.1). The general tectonic features, geological structures and seismological features of Nepal and the surrounding region have been described in chapter 3 and the potential earthquake-prone areas in the Nepal Himalaya and its vicinity have been identified in chapter 4. Based on the distribution of seismic events from 1255 to 2011, available information on faults and tectonic features described in Chapter 3 as well as quantitative analysis by the pattern recognition method [119] described in Chapter 4, we divided the investigation region into twenty-three potential seismic source zones. Fig. 5.1 shows the twenty-three potential seismic source zones in Nepal and the surrounding regions.

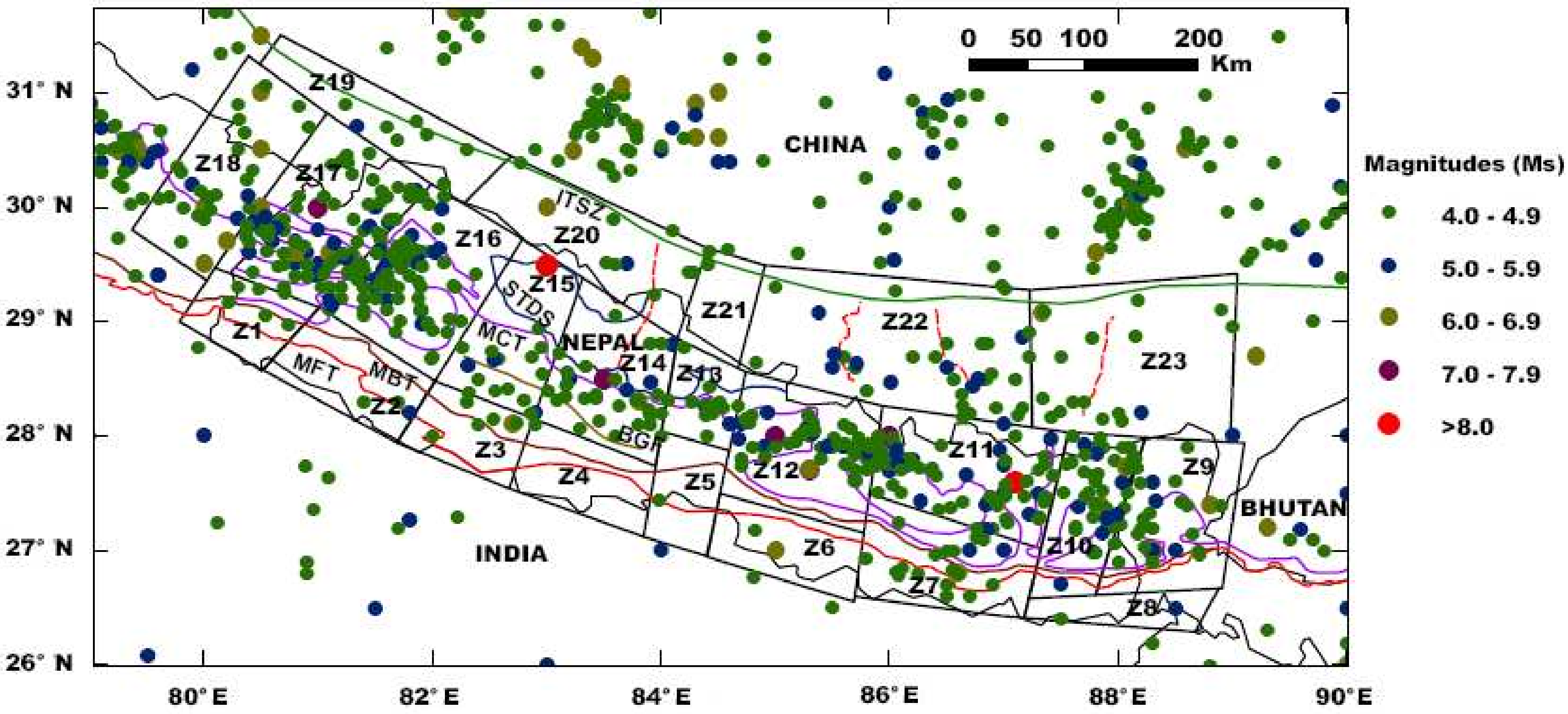

Fig. 5.1 Potential seismic source zones in Nepal and the surrounding areas. Faults legend is the same as in Fig. 3.1

The southern part of Nepal and its nearby areas have experienced relatively less earthquakes than the northern segment of Nepal. In this study, we delineated potential seismic source zones 1-8 that are located in southern Nepal and span to some segments of northern India and northwestern Bangladesh. Seismic source zones from 1 to 5 are primarily related to the MFT and MBT and are characterized by their weaker level of earthquake activity. There are no reports of occurrence of strong earthquakes in source zones 1, 2, 4, and 5, whereas a strong seismic event (M = 6.2, 1969) has occurred in the source zone 3 during the last 50 years. In seismic zone 4 the MFT and MBT are located close to each other (less than 7 km apart), whereas in seismic zone 5 they (MFT/MBT) are situated quite far from each other (more than 45 km apart). The source zone 6 has produced a strong seismic event (M = 6.3, 1833) in the last 200 years and this zone is primarily associated with the MFT. The seismic source zone 7 which is chiefly related to the closely spaced MFT, MBT, and MCT in Nepal and the earthquake activity in this zone is found to be relatively higher than those of the other seismic zones lying in the southern portion of the country. Medium size earthquakes are frequent in zone 7 and this zone has produced a strong seismic event (M = 6.8, 1988) within the past 30 years. The seismic source zone 8 is the southernmost zone in the study region which occupies the southeastern segment of Nepal and some portions of northeastern India and northwestern Bangladesh and there are very few accounts of medium size earthquakes.

The delineated potential seismic source zones herein from 9 to 18 occupy northern Nepal and span to some areas of western Bhutan, south western China, and northern India. These ten seismic source zones are primarily associated with the MCT (Fig. 5.1). The occurrence of medium size earthquakes are common in source zones 9, 10, 11, 12, 14, 15, 17, and 18, and these eight zones have been struck by at least one strong seismic event in the seismic history. The source zone 9 is related to the MFT, MBT and MCT which is located in eastern Nepal and nearby areas (northern India, western Bhutan, and south western China) represents the one of the active zones in the whole study region that is manifested by the occurrence of three strong earthquakes (M = 6.3, 1849; M = 7.0, 1852; and M = 6.1, 1980) within the past 200 years. The seismic source zone 10 is also related to the MFT, MBT and MCT that lies in the eastern section of Nepal and has generated two strong seismic events (M

= 6.1, 1965; and *M* = 6.8, 2011) in the last 50 years. The seismic source zone 11 is also represent the seismically active zone in this study area that has produced numerous moderate size and two seismic events of magnitudes equal to and greater than 7.6 (*M* = 7.6, 1833; and *M* = 8.4, 1934) within the past 200 years. The seismic source zone 12 lying in the central part of Nepal that is associated with the MBT, MCT, and STDS and has produced four earthquakes with magnitudes greater than 7.0 (*M* = 7.6, 1255; *M* = 7.6, 1408; *M* = 7.0, 1681; and *M* = 7.6, 1810). The seismic source zone 13 is associated with the MCT and STDS, which has generated moderate sized seismic events in the past. The seismic source zone 14 is associated with the eastern section of the Bari Gad fault, the southern part of the Thakkhola graben, the MCT and STDS (where MCT and STDS are located less than 5 km apart) and has produced two strong earthquakes (*M* = 7, 1936; and *M* = 6.7, 1954) in the last 80 years. The seismic source zone 15 is related to the western section of the Bari Gad fault, and some portions of the MCT and STDS and has been an epicenter zone of the second largest seismic event (*M* = 8.1, 1505) that occurred in Nepal. The seismic source zone 16 lies in the western section of Nepal, which is associated with the westernmost margin of the STDS and MCT, has produced moderate size earthquakes in the past. The seismic source zone 17 is mostly located in the far-western segment of Nepal and encompasses some areas of northern India and south western China, which represent the zone of pronounced level of earthquake activity in the study region, and has generated five earthquakes with magnitudes equal to and greater than 6.0 (*M* = 7.3, 1916; *M* = 6.0, 1953; *M* = 6.0, 1964; *M* = 6.0, 1966; and *M* = 6.6, 1980) within the past 100 years. The seismic source zone 18 is the westernmost zone in the study region occupying some segments of south western China and northern India, which has also produced several moderate and five seismic events with magnitudes equal to 6 .0 and above (*M* = 6.7, 1911; *M* = 6.0, 1926; *M* = 6.0, 1935; *M* = 6.5, 1945; and *M* = 6.3, 1958) during the last 110 years.

The outlined potential seismic source zones 19-23 lie in the south western part of China and nearby areas of northern Nepal and northern India and are primarily associated with the Indus-Tsangpo Suture Zone (ITSZ) and north-south directed grabens. The seismic source zone 19 mostly occupies south western China and some parts of northern Nepal that is mainly associated with the ITSZ and defines the northwestern source zone outlined in this study where numerous moderate sized seismic events have occurred in the past. The potential seismic source zone 20 is related to the ITSZ and northern section of the Thakkhola graben and has generated a strong seismic event (M = 6.2, 1913) during the last 100 years. The seismic source zone 21 is associated with the ITSZ and indicates less earthquake activity in comparison with other seismic zones of the southern western part of China and no strong seismic events had been reported in this zone. The seismic source zone 22 is related to the ITSZ, Kung Ko graben and Gyirong graben and has produced several moderate sized seismic events. The seismic source zone 23 is associated with the ITSZ and Pum Qu graben and this zone has produced several moderate sized and a strong earthquake (M = 6.4, 1993) in the last 20 years.

5.2.2 Determination of Probabilistic Earthquake Hazard Parameters

After defining the twenty-three potential seismic source zones, the earthquake hazard parameters were determined for the study area from the best available earthquake datasets. In the following subsections, we briefly describe the earthquake hazard parameters (minimum earthquake magnitude, maximum earthquake magnitude, hypocenter depth, b-value, average annual seismicity rate, and earthquake spatial distribution function) used in this seismic zonation study.

1 Minimum Magnitude

It is common that small and medium earthquakes occur frequently rather than strong to large earthquakes in the region in and around Nepal, but these more frequently occurring small magnitude earthquakes are generally less damaging and have obviously little impact on engineering structures. The majority of the existing buildings and structures in Nepal and the surrounding region chiefly lack aseismic design criteria, so that future seismic events with a surface-wave magnitude of 4.0 could be normally hazardous for engineering structures. Therefore, we set a minimum earthquake with surface-wave magnitude of 4.0 for all the potential seismic source zones delineated in this study (Table 5.2).

2 Maximum Magnitude

The earthquake datasets discussed in Chapter 3 and presented in Appendix shows the Himalaya of Nepal was struck by two great historical earthquakes in 1505 (M_w = 8.1) and 1934 (M_w = 8.4, Bihar-Nepal). The size of these two great historical earthquakes that occurred in Nepal enabled us to determine the anticipated largest magnitudes of seismic events in the segment of the Nepal Himalaya. We determined the anticipated maximum earthquake size (magnitude) for each outlined potential seismic source zone in this dissertation based on both historically-documented and instrumentally-recorded earthquakes as well as the largest earthquake that struck in neighboring delineated potential seismic source zones that have a similar tectonic and geological environment. Table 5.2 lists the anticipated maximum magnitude earthquakes for all delineated twenty-three potential source zones.

3 Average Annual Occurrence Rate and *b* Value

The entire seismic catalogue of Nepal (Appendix) suggests that the earthquake database is available since year 1255, but it consists of only four large-great sized earthquakes (1255, 1408, 1505, and 1681) before 1800 and a small fraction of small-medium sized earthquakes during the period from 1801 to 1963. Overall, the catalogue is incomplete covering the period 1255-1963 for earthquakes with surface-wave magnitudes equal to or greater than 4.0. In fact, our updated homogeneous earthquake catalogue is more complete since 1964 when the abundant earthquake data are available from modern seismic instruments as well as seismicity data from the NSC of Nepal since 1994. Our updated detailed earthquake catalogue for the investigated region during the period from 1964 to 2011 consisted of a total of 805 seismic events with surface-wave magnitude equal to or greater than 4.0. The magnitudes range and frequencies of all 805 earthquakes that occurred in Nepal and the adjacent area for the period 1964-2011 are listed below in Table 5.1.

Tab. 5.1 Frequency of earthquakes that occurred in Nepal and the surrounding region during the period 1964-2011

Surface Wave Magnitude	$M \geq 4.0$	$M \geq 4.5$	$M \geq 5.0$	$M \geq 5.5$	$M \geq 6.0$	$M \geq 6.5$
Number of Earthquakes	805	366	106	40	20	7

It is observed that the seismicity data of Nepal and its adjacent region from 1964 to 2011 consists of 54.53% earthquakes between magnitude 4.0 and 4.4, 32.29% earthquakes between magnitude 4.5 and 4.9, 8.19% earthquakes between magnitude 5.0 and 5.4, 2.48% earthquakes between magnitude 5.5 and 5.9, 1.61% earthquakes between magnitude 6.0 and 6.4 and 0.08% earthquakes between magnitude 6.5 and 6.9.

As described above, seismicity datasets prepared in this study consisting of more complete information of instrumentally recorded earthquakes with surface-wave magnitude equal to or greater than 4.0 in the last four and half decades particularly between 1964 and 2011. Thus, we utilized earthquake datasets between 1964 and 2011 here in this study to determine the seismicity parameters (average annual occurrence rate of earthquakes and *b* value) for Nepal and the adjoining region. The *b* value from earthquake data for the period 1964-2011 was determined for the whole region by applying the frequency magnitude relation of Gutenberg and Richter [66] that is already presented by equation (2.2) in chapter 2.

Fig. 5.2 shows the frequency magnitude distribution of seismic events with surface-wave magnitude equal to or greater than 4.0 that occurred in Nepal and the surrounding region and the *b* value that was calculated here using the Gutenberg and Richter relation [66]. In this dissertation, we determined the *b* value of 0.85 for the whole study area using data from 1964 to 2011.

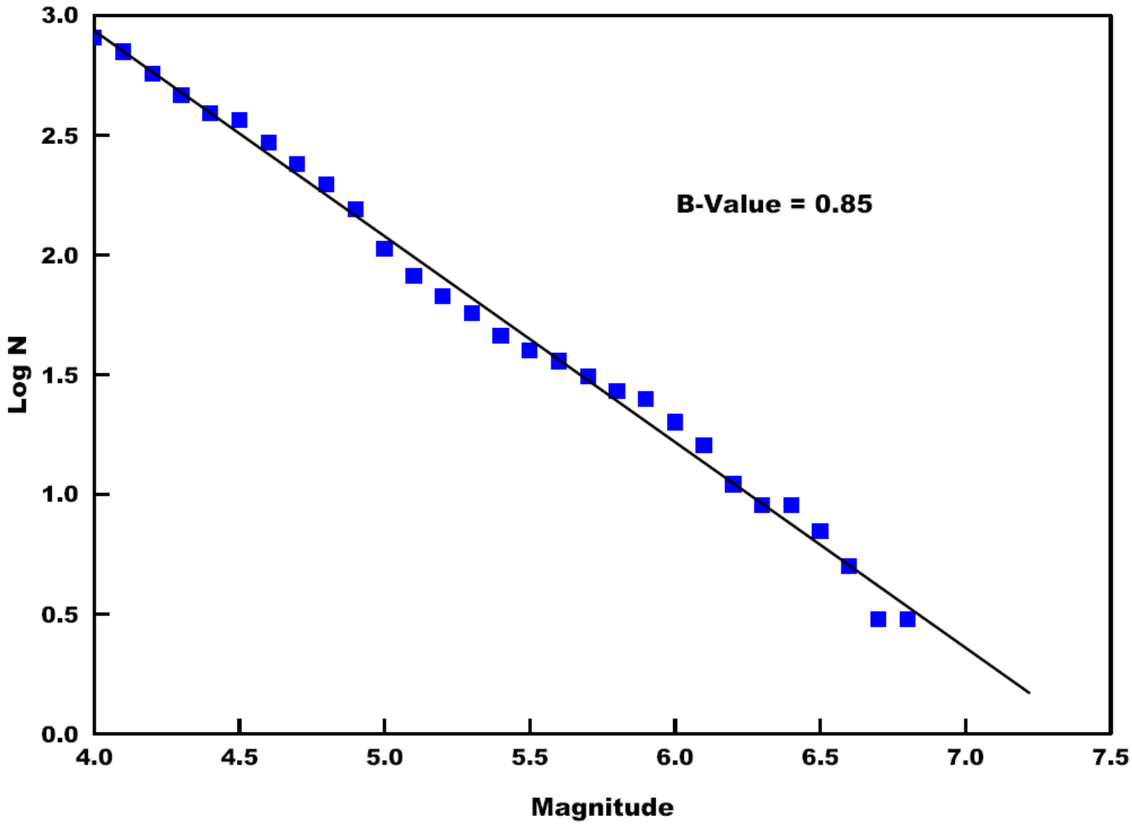

Fig. 5.2 Frequency-magnitude relation of earthquakes with surface-wave magnitudes greater than or equal to 4.0 that occurred in Nepal and the surrounding regions (1964-2011)

4 Hypocenter Depth

As discussed in Chapter 3, the hypocenter depth distribution of seismic events that occurred in Nepal and the adjoining region is poorly identified for historically documented earthquakes. Moreover, available depths information of instrumentally recorded earthquakes in our study area is not hitherto adequately quantified for the purpose of well constraining the hypocenter depths of earthquakes in Nepal and the hypocenter depth distribution of present day instrumentally recorded earthquakes that occurred in Nepal reveal that a large amount of seismic events are located in the upper layer of the crust, and only a very small fraction of seismic events have deep origin occurring in the lower section of the crust and upper section of the mantle. In this dissertation, we set 10-km hypocenter depth for the entire area as this depth is a typical focal depth of earthquakes in our study area.

5 Earthquake Spatial Distribution Function

The earthquake spatial distribution function can be used to take accounts the effect of potential seismic source zone dimension in earthquake generation in the study region. We determined the spatial distribution function for five specified ranges of magnitudes (4.0-6.4, 6.5-6.9, 7.0-7.4, 7.5-7.9, and 8.0-8.4) in individual potential seismic source zone by following the criterion regarding the spatial distribution function thoroughly described in the training material on seismic hazard analysis for engineering sites by the China Earthquake Administration [65]. The earthquake spatial distribution function, f_{j,m_j}, can be defined [65] in equation (5.1) as follows:

$$f_{j,m_j} = \frac{s_i}{\sum s_i} \tag{5.1}$$

In the above equation (5.1), m_j represents the earthquake magnitude within the *j-th* interval, and S_i represents the area of the potential seismic source zone *i*. In order to capture the density of faults and its association with the background earthquake activity and the spatial distribution of seismicity within individual potential seismic source zone, we have made adjustments in values of the spatial distribution functions for earthquakes with magnitude equal to 7.5 or larger according to the existence of faults and locations of the past earthquakes of 7.5 or greater in the adjacent zones with similar geological domain. We considered zones which lies in the region of high seismic potential and enclose closely spaced faults but have not been generated large to great earthquakes during the last 500 years are most likely areas of occurrence of a large seismic event in this study and we slightly increased the spatial distribution function for these zones. On the contrary, we slightly reduced the spatial distribution function for zones which encompass less faults and have produced large/great earthquakes in the past 100 years. Table 5.2 gives the earthquake spatial distribution functions determined here for five magnitude ranges (4.0-6.4, 6.5-6.9, 7.0-7.4, 7.5-7.9, and 8.0-8.4) in twenty-three potential seismic source zones.

Tab. 5.2 Minimum earthquake magnitude, expected maximum earthquake magnitude and spatial distribution function of each potential seismic source zone

Potential Source Zone	Minimum Magnitude	Maximum Magnitude	Spatial Distribution Function				
			M= 4.0-6.4	M= 6.5-6.9	M=7.0-7.4	M= 7.5-7.9	M= 8.0-8.4
Z_1	4.0	6.5	0.0220	0	0	0	0
Z_2	4.0	6.5	0.0332	0	0	0	0
Z_3	4.0	6.5	0.0243	0	0	0	0
Z_4	4.0	6.5	0.0292	0	0	0	0
Z_5	4.0	6.5	0.0215	0	0	0	0
Z_6	4.0	6.5	0.0299	0	0	0	0
Z_7	4.0	7.0	0.0452	0.0873	0	0	0
Z_8	4.0	6.5	0.0169	0	0	0	0
Z_9	4.0	8.0	0.0506	0.0977	0.1071	0.1113	0
Z_{10}	4.0	8.5	0.0344	0.0664	0.0727	0.0756	0.1166
Z_{11}	4.0	8.5	0.0562	0.1086	0.1190	0.1237	0.1909
Z_{12}	4.0	8.0	0.0537	0.1038	0.1137	0.1182	0
Z_{13}	4.0	7.5	0.0179	0.0346	0.0379	0	0
Z_{14}	4.0	8.5	0.0464	0.0896	0.0982	0.0251	0.0750
Z_{15}	4.0	8.5	0.0400	0.0772	0.0846	0.0479	0.0557
Z_{16}	4.0	8.5	0.0579	0.1118	0.1225	0.1073	0.0564
Z_{17}	4.0	8.5	0.0597	0.1153	0.1263	0.1313	0.2026
Z_{18}	4.0	8.0	0.0555	0.1073	0.1175	0.1222	0
Z_{19}	4.0	6.5	0.0368	0	0	0	0
Z_{20}	4.0	6.5	0.0541	0	0	0	0
Z_{21}	4.0	6.5	0.0191	0	0	0	0
Z_{22}	4.0	6.5	0.1035	0	0	0	0
Z_{23}	4.0	6.5	0.0914	0	0	0	0

5.3 Ground Motion Prediction Relationship

Once the potential seismic sources were delineated and seismic hazard parameters were determined, a single or a set of appropriate ground motion attenuation relationship for the targeted region or country should be selected to estimate the earthquake ground motion hazard and seismic zonation studies. In particular, the suitable ground motion prediction relationship for a targeted region or country is developed by performing the statistical regression analyses of best available sets of well-recorded ground motion database of earthquakes [142]. In the context of Nepal, the recorded strong ground motion datasets is lacking for deriving a ground motion attenuation relationship appropriate for Nepal and the adjacent region. Due to this reason, it is necessary to use the ground motion attenuation model developed for other regions or countries in order to develop seismic zonation maps of Nepal in this dissertation.

As known, the geological continuity, tectonic structures and earthquakes do not limit political boundary. As discussed in Chapter 3, the northernmost geological domain of Nepal extends to nearby Tibet in the southwestern part of China. The geographic areas occupied by Nepal and nearby region of the southwestern part of China represent the world's highest topography with complex geology formed by the Himalayan orogenic process [9] [21] [124] and hence the seismotectonics of the northernmost region of Nepal is not completely different to that of nearby region of China. The earthquake originates in one country obviously affects the adjacent region of another country and the resulting ground motion may has similar attenuation characteristics. Therefore, we believe that the ground motion model developed for the western part of China is reasonable to use for seismic zonation study in Nepal. In order to estimate the seismic ground motion hazard for Nepal in the current analysis, we used the ground motion attenuation relationship developed by CEA [65] for western China and this attenuation relation was used to prepare for the 4th generation seismic zoning map in China. The elliptical attenuation relationship of PGA for the major axis and minor axis [65] are respectively expressed by equations (5.2) and (5.3) as follow:

$$\ln a_{Ra} = 5.912025 + 1.836588\ M - 2.84658\ \ln(R_{Ra} + 3.400 Exp(0.451M)) \tag{5.2}$$

and

$$ln\, a_{Rb} = 2.509012 + 1.360759\ M - 1.79151\ ln(R_{Rb} + 1.046\, Exp(0.451M)) \quad (5.3)$$

where a_{Ra} and R_{Ra} in equation (5.2) are the peak ground acceleration (in units of cm/sec^2) and hypocenter distance (in units of kilometers) along the major axis, respectively, a_{Rb} and R_{Rb} in equation (5.3) are the peak ground acceleration (in units of cm/sec^2) and hypocenter distance (in units of kilometers) for the minor axis, respectively, and M is the surface-wave magnitude in both equations (5.2) and (5.3).

5.4 Probabilistic Seismic Zonation for Nepal

In this study we applied a probabilistic approach to prepare a set of seismic zonation maps for Nepal. The seismic zonation for Nepal has been conducted here following the steps developed by CEA [65] that is based on the probabilistic method firstly established 45 years ago in the late sixties of the last century by Cornell [41] and the total probability used in this study has been presented in equation (2.6) in chapter 2. First, twenty-three potential seismic source zones have been delineated in Nepal and nearby region on the basis of available epicenter distribution of earthquakes, faults distribution and tectonic information. Second, the probabilistic earthquake hazard parameters were assigned and set a hypocenter depth of 10 km as this depth is the most common hypocenter depth of earthquakes in the whole study region, and a spatial distribution function, maximum expected earthquake magnitude and minimum earthquake magnitude were assigned for each delineated potential seismic source zone. Third, a suitable PGA attenuation relationship has been selected in this analysis. Finally, PGAs at bedrock level were calculated over a grid of 0.2° × 0.2° covering the entire area of the country with 63%, 10%, and 2% probability of exceedance in 50 years by integrating potential seismic source zones information and probabilistic earthquake hazard parameters in conjunction with a selected PGA attenuation relationship and prepared the seismic zoning maps for Nepal with three different exceedance probabilities (63%, 10%, and 2% probability of exceedance in 50 years).

The resulting probabilistic seismic zonation maps prepared in this dissertation address earthquake ground motion hazard in terms of PGA at bedrock level for Nepal with three different exceedance probabilities (63%, 10%, and 2% in 50 years). Figs. 5.3, 5.4, and 5.5 show probabilistic seismic zoning maps of Nepal developed in this dissertation at bedrock level for 63%, 10%, and 2% probability of exceedance in 50 years are, respectively.

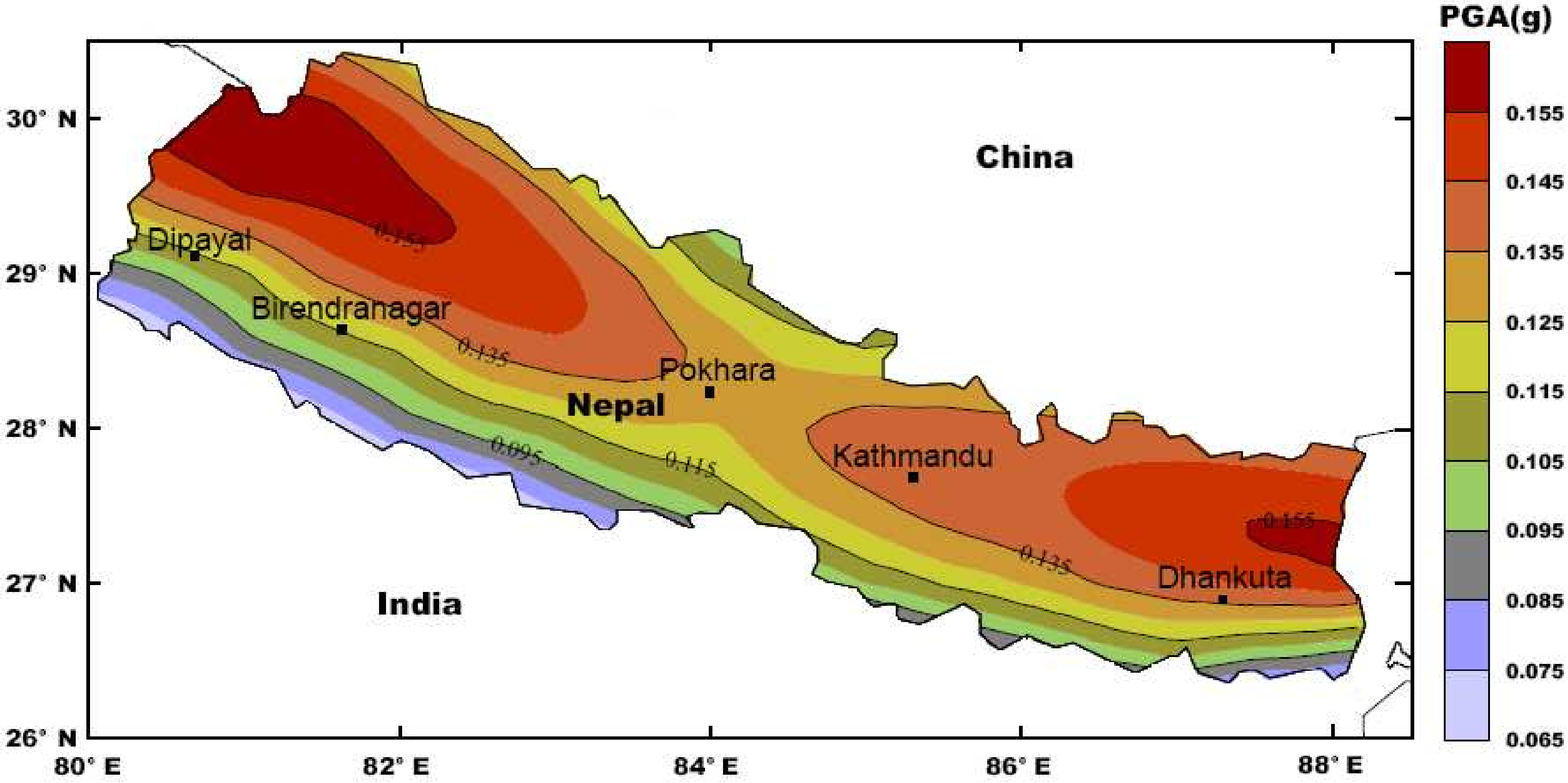

Fig. 5.3 Seismic zonation map of Nepal showing peak ground accelerations for 63 % probability of exceedance in 50 years

Fig. 5.3 depicts the probabilistic seismic zonation map of Nepal with PGA distribution for the 63% probability of exceedance in 50 years. The values of PGA estimated here over the entire territory of Nepal with the 63% probability of exceedance in 50 years at bedrock level vary between 0.07 and 0.16g. The highest seismic ground motions hazard are obtained in the eastern and far-western sections of Nepal where the value of PGA exceeded 0.15g. These two high seismic hazard areas where the values of PGA exceeding 0.15g are located between latitudes 27.09°N-27.41°N and longitudes 87.43°E-88.03°E in the eastern part of Nepal, and enclosed between latitudes 29.19°N-30.18°N and longitudes 80.49°E-83.34°E in the far-western portion of Nepal. It is seen that the PGA values decreases in an approximately symmetrical pattern from these two high hazard zones primarily towards the north-south directions and attain the minimum seismic hazard in the southern part of the country near the political boundary with India. The lowest seismic hazard is found in the region situated at the west of 83.34°E longitude where the PGA value reached as low as 0.07g. The minimum value of PGA (0.07g) in southern Nepal estimated in this dissertation is noticeably lower than in any other sections of Nepal.

Additionally, there is no recorded peak ground accelerations of strong earthquakes that occurred in Nepal to compare with our estimated values of PGA presented in the probabilistic seismic zonation map of Nepal (Fig. 5.3). Nevertheless, the distribution of PGA obtained in this dissertation well correlated with the available spatial distribution of seismic activity. The high seismic ground motion hazard regions are located in eastern and far-western Nepal that are corresponding to the high level of earthquake activity, while the observed minimum seismic hazard in the southern part of the country lying in an area where the rate of earthquakes occurrence is lower than in the eastern and far-western segments of Nepal.

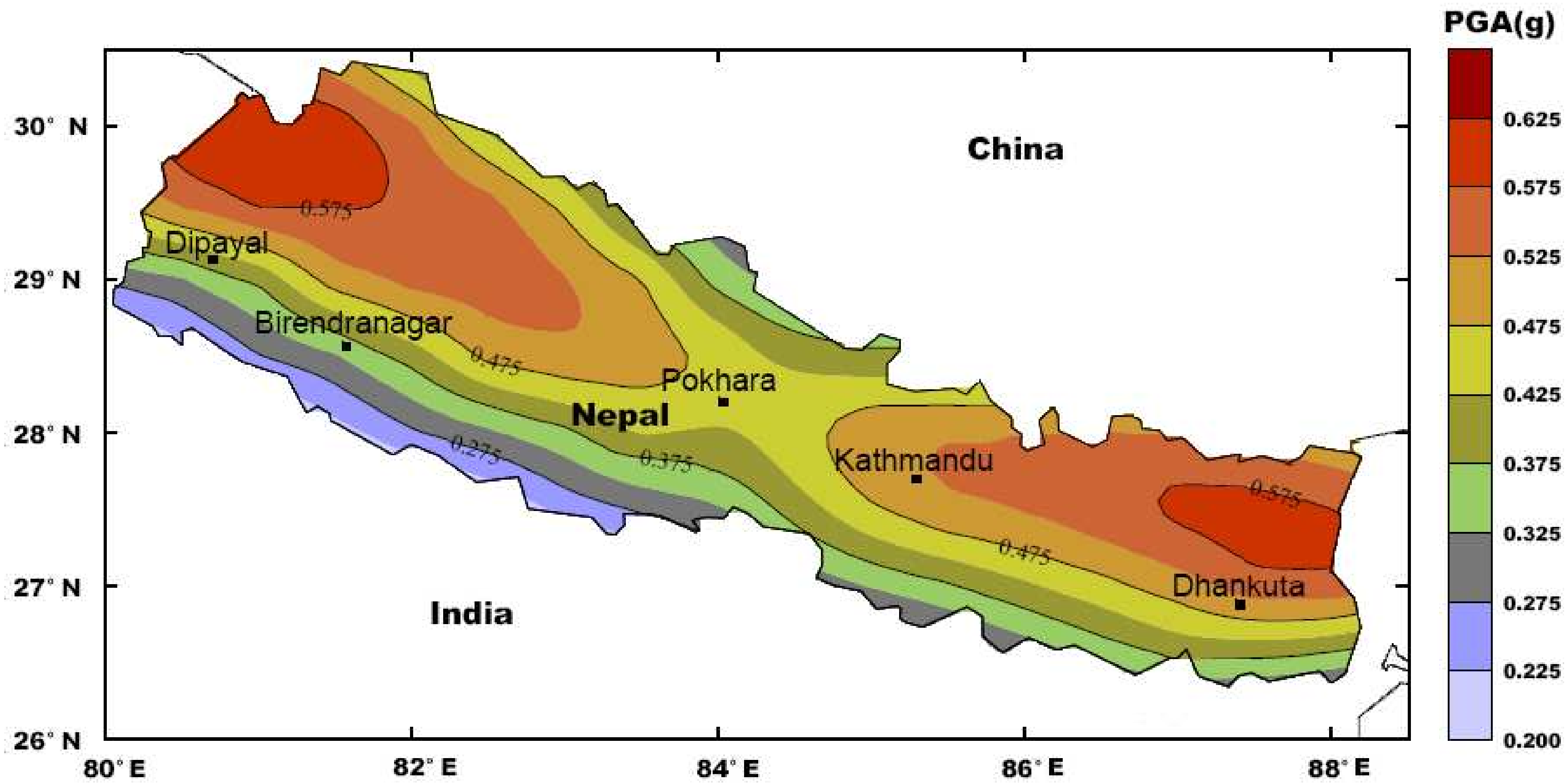

Fig. 5.4 Seismic zonation map of Nepal showing peak ground accelerations for 10% probability of exceedance in 50 years

Fig. 5.4 displays the probabilistic seismic zonation map of Nepal with PGA distribution for the 10% probability of exceedance in 50 years. The values of PGA obtained in this dissertation for Nepal at the 10% probability of exceedance in 50 years are of the order of 0.21 to 0.62g. The PGA value is observed as high as 0.62g in the eastern region of the country bounded between latitudes 27.17°N-27.66°N and longitudes 86.88°E-88.07°E, and the far-western portion in the country enclosed between latitudes 29.19°N-30.18°N and longitudes 80.49°E-83.34°E, which represent the highest seismic hazard areas in Nepal. It is observed that the PGA values decreases from these two high hazard regions mainly towards the north-south directions and attain the minimum seismic ground motion hazard in the southern part of the country particularly near the political boundary of Nepal with India. The lowest seismic ground motion hazard obtained in the area lying at the west of 83.50°E longitude where the values of PGA reaching less than 0.22g. Furthermore, the estimated values of PGA in southern Nepal from the west of 83.50°E longitude is significantly lower than in any other parts of the country as shown in Fig. 5.4.

The probabilistic seismic zonation maps presented in Figs. 5.3 and 5.4 generally show the similar pattern of distribution of PGA values in Nepal for both 10% probability of exceedance in 50 years and 63% probability of exceedance in 50 years. Moreover, the PGA values estimated for the 10% probability of exceedance in 50 years in this dissertation are obviously higher than those of PGA values calculated for the 63% probability of exceedance in 50 years.

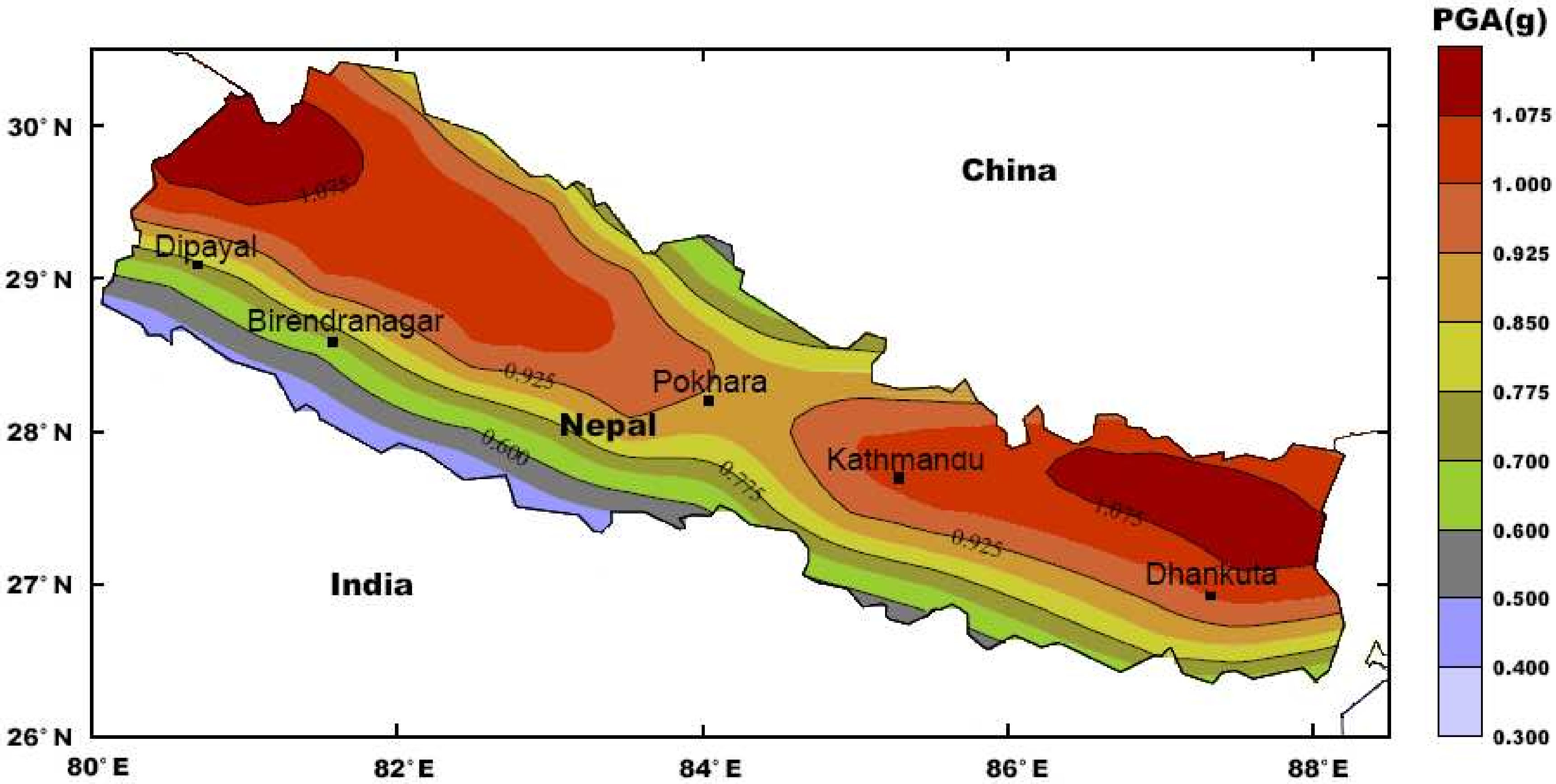

Fig. 5.5 Seismic zonation map of Nepal showing peak ground accelerations for 2 % probability of exceedance in 50 years

Fig. 5.5 depicts the probabilistic seismic zonation map of Nepal with PGA distribution for the 2% probability of exceedance in 50 years. The PGA values obtained for Nepal range from 0.38 to 1.1g at the 2% probability of exceedance in 50 years. The highest seismic ground motions hazard is concentrated in the eastern region of the country bounded between latitudes 27.08°N-27.90°N and longitudes 86.26°E-88.07°E, and in the far-western region of the country enclosed between latitudes 29.47°N-30.18°N and longitudes 80.38°E-81.73°E, where we obtained the PGA value exceeded 1.0g. It can be viewed that the PGA values decreases basically to the northward and southward directions from these high hazard regions and appears to have the lowest seismic hazard in the southern part of the country particularly in the region near the southern boundary of Nepal with India. The lowest seismic hazard observed in the region west of 84.40°E longitude where the minimum value of PGA reached less than 0.4g.

The probabilistic seismic zonation maps presented in Figs. 5.3, 5.4 and 5.5 generally indicate a similar pattern of PGA distribution in Nepal for 63%, 10%, and 2% probability of exceedance in 50 years. In contrast, the estimated values of PGA with 2% probability of exceedance in 50 years in this dissertation are around 1.7-2.0 times higher than the values of PGA with 10% probability of exceedance in 50 years and around 6.0-7.0 times higher than the values of PGA with 63% probability of exceedance in 50 years. The lowest and the highest earthquake ground motion hazard are observed here in the southern part of Nepal, and the far-western as well as the eastern parts of the country, respectively. Moreover, the distribution of the highest seismic ground motion regions generally occurs in the same region in the eastern section with both 2% and 10% probability of exceedance in 50 years, whereas the highest seismic ground motion occupies a smaller region in the eastern segment of the country with 63% probability of exceedance in 50 years.

In this dissertation we systematically performed the seismic zonation study in Nepal with three different exceedance probabilities for the first time. The resulting probabilistic seismic zonation maps represent the earthquake ground motion hazard in terms of bedrock level PGA that provide fundamental valuable ground motion information for the city planners to establish city development plans, and for the civil and structural engineers to locate, design, and evaluate the seismic performance of important structures such as schools, hospitals, pipelines, long-span bridges, dams, powerhouses, and tunnels on bedrock foundations. Furthermore, the results of the estimated ground motions provide direct input for seismic microzonation studies in different locations and extremely useful for the seismic risk analysis in Nepal.

5.5 Comparison of Seismic Zonation Maps of Nepal with Seismic Zoning Maps of Neighboring Countries

A set of probabilistic seismic zonation maps developed with three different exceedance probabilities (63%, 10%, and 2% probability of exceedance in 50 years) in this study generally shows the pronounced seismic ground motion hazard in the eastern and far-western parts of the country and the lowest seismic ground motion hazard in southern Nepal. As discussed in section 1.3 in chapter 1, there are extensive probabilistic seismic zonation studies in neighboring countries of Nepal: the northern neighbor China and the southern neighbor India. These two neighboring countries have previously developed the several probabilistic seismic zonation maps of their respective countries.

In order to check the consistency of the seismic hazard quantified in this study with that of seismic hazard analysis of neighboring countries, it is very useful to compare our probabilistic seismic zonation maps with the recently available probabilistic seismic zonation maps of China and India. In this section, we compared our probabilistic seismic zonation maps of Nepal prepared at 10% and 2% probability of exceedance in 50 years with the national probabilistic seismic zonation map of China developed with a 10% probability of exceedance in 50 years [52] and probabilistic seismic zonation maps of India with 10% and 2% probability of exceedance in 50 years prepared by Nath and Thingbaijam [58] and discussed the similarities and differences among these probabilistic seismic zoning maps.

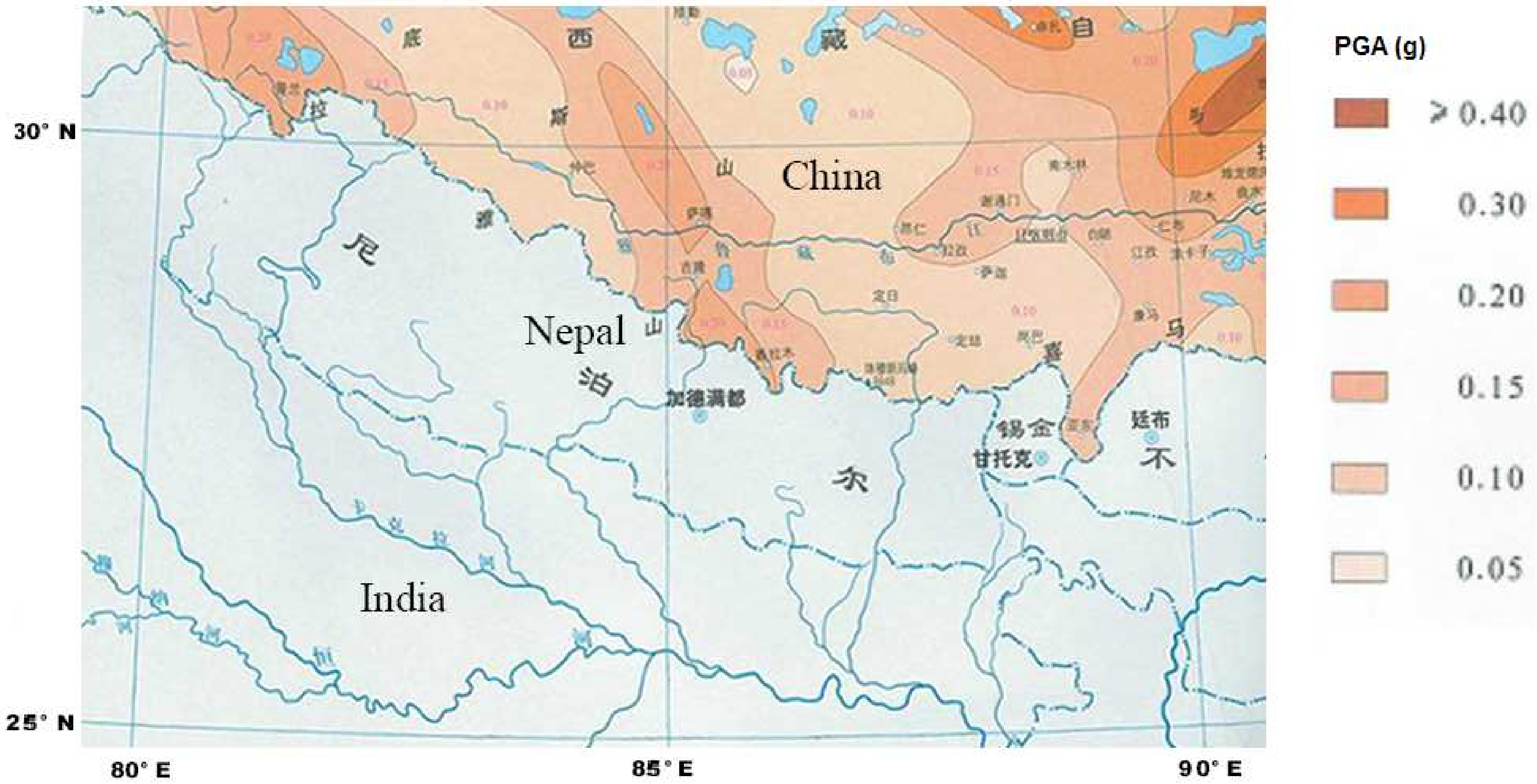

Fig. 5.6 Seismic zonation map of China showing peak ground accelerations for 10 % exceeding probability in 50 years [52]

The fourth generation national seismic zonation map for China with a 10% probability of exceedance in 50 years is shown in Fig. 5.6. The probabilistic seismic zonation map of China shows the PGA values ranging between 0.10 and 0.20g in the southwestern section of China particularly between longitudes 80.4°E and 88.12°E near the political boundary of China and Nepal. Fig. 5.6 displays the highest seismic ground motion hazard along the border with Nepal in two regions between longitudes 81°E and 81.76°E and between longitudes 84.96°E and 85.89°E where the estimated values of PGA reached 0.20g. The estimated values of PGA decrease in both eastward and westward directions from the region bounded between longitudes 84.96°E and 85.89°E. In the eastern part, 0.15g PGA is observed in the location from 85.89°E to 86.45°E. The PGA values further decreases from 86.45°E towards the eastward region that extends up to the border of China with India at 88.88°E. The PGA in the east of 85.89°E reached 0.10g. Similarly, in the western segment, 0.15g and 0.10g PGA are observed in the regions located between 84.49°E and 84.96°E and between 82.32°E and 84.49°E, respectively. However, further to the west, the seismic hazard found increases. The PGA values reached 0.15g in the region between longitudes 81.76°E and 82.32°E and observed as high as 0.20g in the area situated between longitudes 81°E and 81.76°E.

The calculated PGA values in our study near the Nepal-China boarder region differ than those of the probabilistic earthquake zonation map of China [52]. Our probabilistic earthquake zonation map reveals 0.30g in a much smaller region bounded between longitudes 83.95°E and 84.24°E. The PGA values calculated in our study increase in both eastward and westward directions from the region enclosed between longitudes 83.95°E and 84.24°E (Fig. 5.4). In addition, the PGA distribution pattern in our study near the Nepal-China boundary region differs than those of the pattern of PGA distribution demonstrated in the probabilistic earthquake zonation map of China [52]. In general, the PGA values (~0.10-0.20g) observed in the seismic zonation map of China near the border region of China with Nepal at a 10% probability of exceedance in 50 years is lower than that of our estimated PGA values (~0.27-0.50g) near the boundary area of China and Nepal for a 10% probability of exceedance in 50 years as displayed in the probabilistic earthquake zonation map of Nepal (Fig. 5.4).

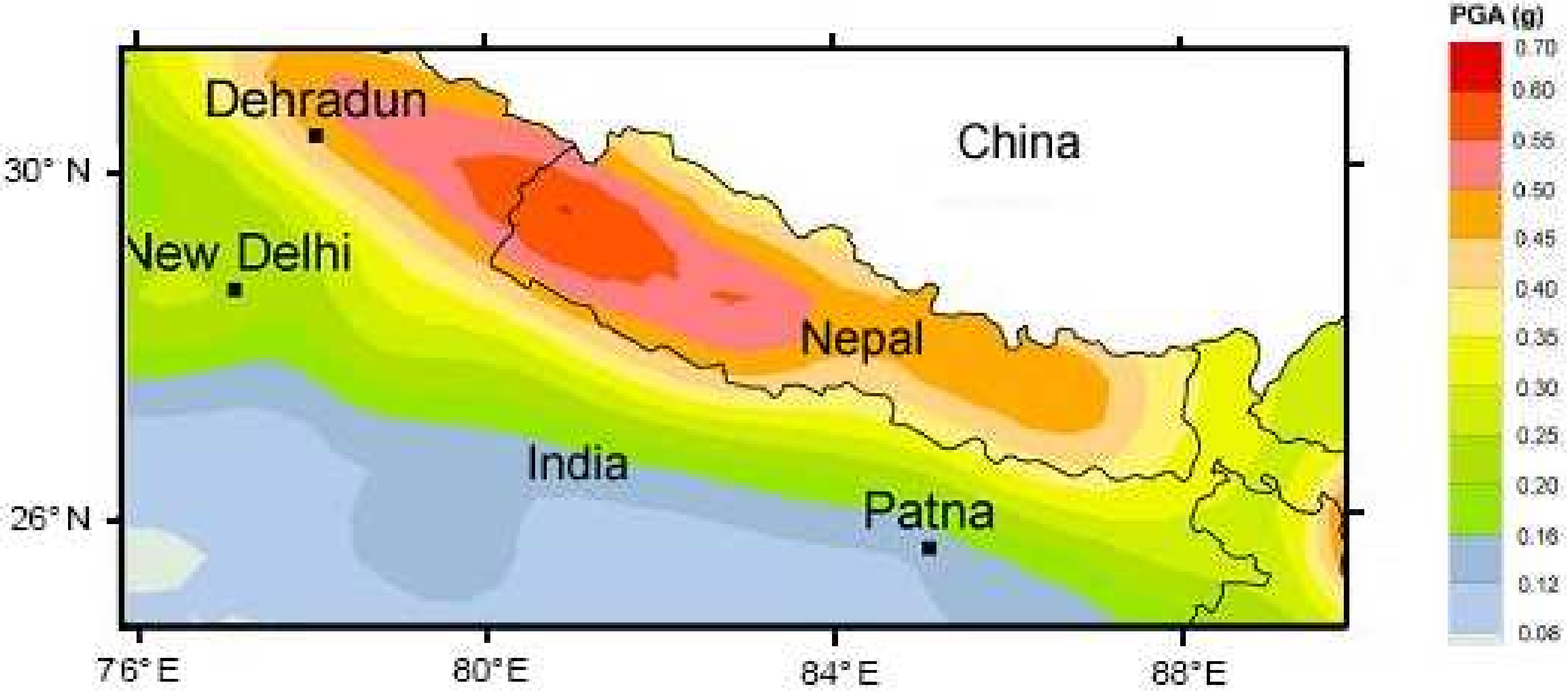

Fig. 5.7 Seismic zonation map of India showing peak ground accelerations for 10 % exceeding probability in 50 years [58]

Fig. 5.7 shows the probabilistic seismic zonation map of India and the surrounding region for a 10% probability of exceedance in 50 years prepared by Nath and Thingbaijam [58]. The probabilistic seismic zonation map of India displayed in Fig. 5.7 include the entire territory of Nepal where the values of PGA ranging between 0.30 and 0.60g. The highest seismic ground motion hazard in Nepal is mainly obtained in the far western section of the country in the region enclosed between latitudes 28.58°N-29.99°N and longitudes 80.25°E-82.20°E where the PGA values ranging between 0.55 and 0.60g. Similarly, the lowest seismic ground motion hazard in Nepal is observed in the southeastern segment in the country located east of longitude 87.74°E where the estimated values of PGA observed as low as 0.30g.

The PGA values estimated by Nath and Thingbaijam [58] at the 10% probability of exceedance in 50 years ranging between 0.55 and 0.60g in far-western Nepal is consistent with our estimated highest PGA values 0.57-0.62g in far-western Nepal at the 10% probability of exceedance in 50 years as shown in the probabilistic seismic zonation map of Nepal (Fig. 5.4). It is observed that these two hazard analysis agreed well particularly in far-western Nepal and while there are discrepancies in the levels of seismic ground motion hazard in the eastern and southern segments of the country.

The PGA values obtained by Nath and Thingbaijam [58] in the eastern part of Nepal ranging between 0.35 and 0.40g is lower than our estimated hazard level in the same region in eastern Nepal where our calculated PGA values of the order of 0.57 and 0.62g at 10% probability of exceedance in 50 years. On the contrary, the PGA values estimated by Nath and Thingbaijam [2012] in southern Nepal ranging between 0.32 and 0.52g is higher than that of our estimated hazard level in southern Nepal in which PGA values varies from 0.21 to 0.32g.

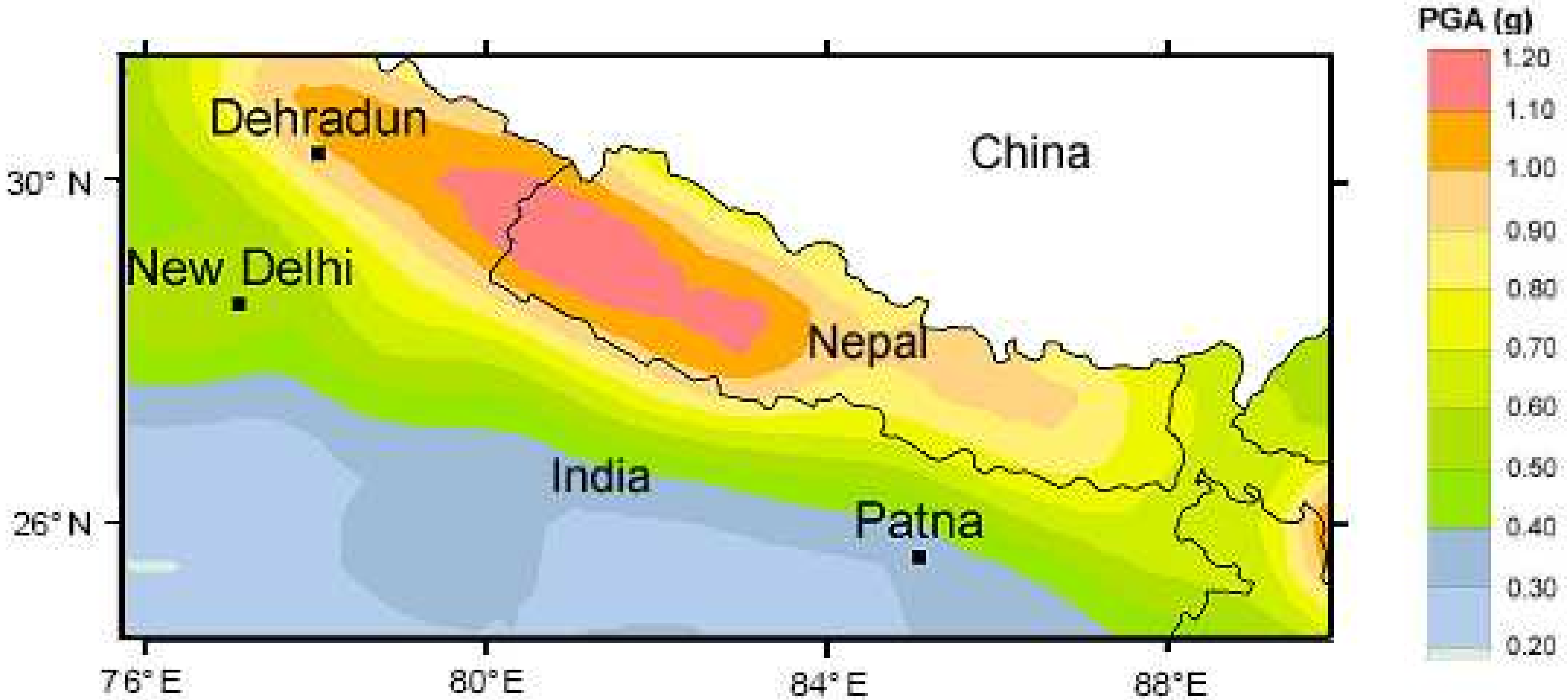

Fig. 5.8 Seismic zonation map of India showing peak ground accelerations for 2% exceeding probability in 50 years [58]

Fig. 5.8 displays the probabilistic seismic zonation map of India and the surrounding region for a 2% probability of exceedance in 50 years prepared by Nath and Thingbaijam [58]. The probabilistic seismic zonation map of India shown in Fig. 5.8 encloses the whole territory of Nepal where the values of PGA ranging between 0.65 and 1.2g. The highest earthquake ground motion hazard in Nepal is mostly concentrated in the far western portion of the country in an area bounded between latitudes 28.01°N-30.01°N and longitudes 80.25°E-83.35°E where the values of PGA ranging between 1.1 and 1.2g. Similarly, the lowest seismic ground motion hazard in Nepal is observed in the southeastern segment of Nepal located east of longitude 87.91°E where the values of PGA estimated as low as 0.65g.

The estimated PGA values around 1.1-1.2g in far-western Nepal for the 2% probability of exceedance in 50 years by Nath and Thingbaijam [58] is consistent well with our highest estimated PGA values around 1.0-1.1g in far-western Nepal at the 2% probability of exceedance in 50 years as shown in Fig. 5.5. It can be seen that the highest seismic hazard estimated in far-western Nepal by Nath and Thingbaijam [58] appears in a much wider area than that of our seismic zonation map (Fig. 5.5). Although the comparison displays similarities in seismic hazard levels only in far-western Nepal, there are substantial differences in the levels of seismic ground motion hazard in the other portions of Nepal.

The PGA values obtained by Nath and Thingbaijam [58] in the eastern section of Nepal ranging between 0.70 and 0.80g that is lower than our estimated hazard level in the same region where we obtained PGA values of the order of 1.0 and 1.1g in the eastern section of Nepal at 2% probability of exceedance in 50 years. In contrast, the PGA values estimated by Nath and Thingbaijam [58] in southern Nepal ranging between 0.65 and 1.0g that is higher than that of our estimated hazard level in southern Nepal in which our estimated values of PGA varies from 0.38 to 0.70g.

In summary, the comparison of our seismic zonation maps with the seismic zonation maps of China [52] and India [58] indicate that there is a reasonable match among the PGA values obtained in this study with those of seismic ground motion hazard estimated by Nath and Thingbaijam [58] only in a particular area of pronounced seismic hazard in the far-western portion of Nepal, whereas there are differences in the levels of estimated PGA in other parts of Nepal [58] and near the boundaries of Nepal with China [52]. The quantified values of PGA in the eastern section of Nepal in this dissertation are higher than that of estimated in the same area by Nath and Thingbaijam [58]. Similarly, the quantified values of PGA in the border of Nepal with China in this analysis are higher than those estimated in the adjacent region of China [52]. In contrast, the calculated PGA values in the southeastern segment of Nepal in this analysis are lower than those estimated by Nath and Thingbaijam [58] in the same area.

The PGA distribution pattern in the far-western Nepal in this study is similar to that of seismic zonation map of India prepared by Nath and Thingbaijam [58]. Both studies show pronounced earthquake hazard in the far western region of Nepal. However, the highest seismic ground motion hazard obtained here in a relatively smaller region in and around far-western Nepal compared to the hazard level estimated by Nath and Thingbaijam [58] in the same region. In other words, the width of the high hazard segment estimated by Nath and Thingbaijam [58] is larger rather than that of our analysis. Our estimated hazard is relatively lower in the periphery of India compared with the seismic zonation map of India [58]. However, our seismic zonation maps show the hazard values generally higher than that of the national seismic zonation map of China particularly near the political boundary of China and Nepal, as well as slightly higher in eastern Nepal and relatively lower in southern Nepal than on the earthquake hazard maps for India that covers the entire territory of Nepal.

The comparison of our seismic zonation maps with the seismic zoning maps of neighboring countries show that our estimated earthquake ground motion hazard levels are similar to those of PGA obtained by Nath and Thingbaijam [58] in the particular region mainly in the far-western segment of Nepal and the trend of ground motion generally differ in other regions of Nepal. The primary reason for such discrepancies in ground motion hazard estimated in this analysis for Nepal and seismic hazard assessment of neighboring countries namely, China [52] and India [58] is due to the use of different inputs (e.g., potential earthquake source models, earthquake catalogue of different time periods, probabilistic seismic hazard parameters for each potential seismic source as well as for the whole study area, and the ground motion prediction equation) for the probabilistic seismic hazard assessment in these three Asian nations. In other words, the general pattern of our estimated seismic ground motion in this study differs from ground motion obtained by previous studies of neighboring countries [52] [58]. This is probably associated with the fact that we carefully scrutinized seismicity data for the period 1255-2011 which combined the historically documented earthquakes with instrumentally recorded local seismic events and systematically defined seismic source zones based on available information on earthquake catalogue of past centuries, faults distribution, tectonic features as well as quantitative analysis by the pattern recognition approach and subsequently assigned seismicity parameters that are entirely different than those of earthquake catalogue, seismic source zones as well as the probabilistic seismic hazard parameters used to prepare seismic zonation maps of the surrounding countries [52] [58]. Due to the reason that we used more detailed and the most recent information existing in the literatures to prepare seismic zonation maps for Nepal in this study, we believed that our estimated seismic ground motion hazard in Nepal is more reliable that the seismic hazard calculated by Nath and Thingbaijam [58] that encompasses the whole territory of Nepal.

5.6 Summary

This chapter presents the study of seismic zoning of Nepal using a probabilistic approach. This is the first time the seismic zonation study has been carried out systematically for Nepal with a PGA distribution with three different exceedance probabilities (63%, 10%, and 2% probability of exceedance in 50 years) through the careful compilation and analysis of earthquake catalogues, establishing twenty-three potential seismic source zones, estimating probabilistic seismic hazard parameters, and selecting an appropriate PGA attenuation relationship for the area of study.

In this chapter, we primarily paid attention to establishing twenty-three potential seismic source zones in Nepal and its vicinity on the basis of catalogued seismic events, fault information and tectonic features (in chapter 3) as well as the distribution of identified earthquake-prone areas (in chapter 4). We assigned a spatial distribution function, maximum magnitude, and minimum magnitude for each potential seismic source zone. The *b*-value was determined and a hypocenter depth of 10 km was set for the whole region. We prepared a set of seismic zonation maps for Nepal at bedrock level over a grid of 0.2° × 0.2° (longitude and latitude) covering the whole territory of the country using twenty-three potential seismic source zones and probabilistic seismic hazard parameters in conjunction with a selected appropriate PGA attenuation relationship. These resulting seismic zonation maps represent earthquake ground motion hazard in terms of PGAs at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years that provide valuable information for the civil and structural engineers to design and evaluate the seismic performance of major infrastructures and for the government to establish future city development plans and earthquake disaster mitigation, prevention and protection planning in the country. The main conclusions drawn from the present seismic hazard analysis are summarized in the following points:

(1) The established twenty-three potential seismic source zones in this study shows that potential source zones from 9 to 18 located in northern Nepal and vicinity regions are relatively seismically more active than that of potential source zones from 1 to 8 lying in southern Nepal and the nearby region, and potential source zones from 19 to 23 situated in south western China and its nearby region (Fig. 5.1).

(2) A spatial distribution function, maximum expected earthquake magnitude and minimum earthquake magnitudes were assigned for each potential seismic source zone. The hypocenter depth of 10 km was set for the whole region and the *b*-value was determined for Nepal and the surrounding region utilizing earthquake datasets with magnitudes ranging from 4.0 to 6.9 during the period between 1964 and 2011.

(3) Probabilistic seismic zonation maps of Nepal display the distribution of PGA values ranging from 0.07 to 0.16g for 63% probability of exceedance in 50 years, 0.21 to 0.62g for 10% probability of exceedance in 50 years, and 0.38 to 1.1g for 2% probability of exceedance in 50 years.

(4) The values of PGA estimated here in this dissertation with 2% probability of exceedance in 50 years are around 1.7-2.0 times typically higher than those with 10% probability of exceedance in 50 years and around 6.0-7.0 times typically higher than those with 63% probability of exceedance in 50 years.

(5) The distribution of PGA values in probabilistic seismic zonation maps with three different exceedance probabilities (63%, 10%, and 2% probability of exceedance in 50 years)

generally indicate the pronounced seismic ground motion hazard in the eastern and far-western parts of the country and the lowest seismic ground motion hazard in southern Nepal.

(6) The pronounced seismic ground motion hazards in this study distributed nearly in the same region in the eastern section of Nepal for both 2% and 10% probability of exceedance in 50 years, while the highest seismic ground motion obtained in a smaller area in the eastern segment of Nepal for 63% probability of exceedance in 50 years.

(7) A set of probabilistic seismic zonation maps developed in this study were compared with some recent earthquake zonation maps of China [52] and India [58]. The ground motion hazard estimated in this study consistent well with those of seismic ground motion hazard calculated by Nath and Thingbaijam [58] only in a particular location of pronounced hazard in the far-western portion of Nepal, while there are quite discrepancies with the levels of seismic hazard in other parts of Nepal [58] and near the boundaries of Nepal with China. The estimated levels of seismic hazard in the eastern portion of Nepal in this analysis are higher than those calculated in the same region by Nath and Thingbaijam [58]. Similarly, the quantified seismic hazard in the border of Nepal with China in this analysis is higher than those estimated in the adjoining region of China [52]. In contrast, the quantified seismic ground motion hazard in the southeastern portion of Nepal in this analysis is lower than those estimated in the same region by Nath and Thingbaijam [58].

6 CONCLUSIONS, INNOVATION POINTS, LIMITATIONS AND FUTURE WORK

This dissertation focuses on seismic zonation study of Nepal using a probabilistic approach. Seismic zonation maps developed in this research represent the earthquake ground motion hazard in terms of PGA estimated over a grid of 0.2° longitude × 0.2° latitude covering Nepal at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years. The main scientific contributions have been made in updating a homogenous earthquake catalogue for Nepal and the surrounding regions after compiling and careful analysis of seismicity data spanning the period from 1255 to 2011, establishing potential seismic source zones and assessing the probabilistic seismic hazard for Nepal. The key findings, innovations, limitations and future possible research topics relevant to the present dissertation are briefly highlighted in the subsequent sections.

6.1 Conclusions

In this study seismic zoning maps for Nepal have been prepared using the probabilistic approach. This is the first time a set of probabilistic seismic zonation maps have been systematically developed for Nepal at a national scale that represent seismic ground motion hazard at bedrock level in terms of PGA distribution with three different exceedance probabilities through the compilation and detailed analysis of earthquake catalogues, establishing twenty-three potential seismic source zones, estimating seismic hazard parameters, and choosing a PGA attenuation relationship. The seismic zonation maps presented in this dissertation provide valuable ground motion information for the city planners to establish city development plans, for the civil and structural engineers to locate, design, and evaluate the seismic performance of important engineering structures such as schools, hospitals, long-span bridges, pipelines, dams, powerhouses, and tunnels on bedrock foundations, and for earth scientists and earthquake engineers to carryout seismic microzonation studies in different parts of the country. In addition, this seismic zonation study is a first step for earthquake disaster prevention, mitigation and reduction, which provides valuable ground motion information for formulating effective guidelines to the engineering, scientific and social community in Nepal. The key findings of the present study are summarized in the following points.

(1) Since a homogeneous and complete earthquake catalogue have not hitherto been updated for Nepal, all the available historical and instrumental earthquake data of the study region spanning between 26°N-31.7°N and 79°E-90°E for the period from 1255 to 2011 were compiled. All the available earthquake data were first analyzed very carefully and duplicated seismic events, foreshocks, aftershocks were removed and then converted into a common surface-wave magnitude. Our updated earthquake catalogue spanning the period 1255-2011 consists of a total of 883 seismic events with surface-wave magnitude equal to or greater than 4.0.

The temporal distribution of all the available earthquake data from 1255 to 2011 show that there are a few accounts of significant earthquakes during the pre-instrumental period and the quality and quantity of earthquake data has increased after 1900 and increased substantially both in quantity and quality of data since 1964.

The spatial distribution of seismicity data covering the period from 1255 to 2011 demonstrate that earthquakes are unevenly distributed in Nepal and the surrounding region with the strongest seismic activity in the far-western and eastern regions of the country and the weakest seismic activity in southern Nepal. Additionally, the spatial distribution of earthquakes map superimposed with major faults map displays that the epicenters of the overwhelming number of earthquakes are located near the Main Central Thrust (MCT) and epicenters of a few seismic events are located at small distances from the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) in Nepal and its adjacent area.

(2) A morphostructural map prepared in this study by integrating information from geological, topographical, tectonic maps and satellite images consists of in total 163 morphostructural nodes in the Nepal Himalaya and its surrounding regions. The evaluation of seismic potential of these mapped 163 morphostructural nodes using the pattern recognition techniques shows the approximately 52 percent (84 out of 163) delineated morphostructural nodes identified prone to strong earthquakes ($M \geq 6.0$) in the Nepal Himalaya and its adjoining regions. These recognized D nodes (earthquake-prone nodes) are mainly located in

the far-western and southeastern portions of central Nepal, while the N nodes are concentrated mostly in southwestern Nepal and southern Tibet. The majority of recognized D nodes here in this study are mostly localized along the longitudinal second rank lineament in Nepal and its vicinity. Furthermore, the identification of earthquake-prone areas shows the epicenters of a large number of reported strong seismic events coincide with identified D nodes in Nepal and its adjacent regions. This study also reveals that several identified D nodes are located in areas where no seismic events with magnitudes equal to and greater than 6.0 have been reported in both historical and recent times in the territory of Nepal and its surrounding areas.

(3) Twenty-three potential seismic source zones were established in Nepal and its vicinity regions on the basis of catalogued seismic events, faults information and tectonic features as well as the distribution of identified earthquake-prone areas and the probabilistic seismic hazard parameters have been assigned for each demarcated potential seismic source zone as well as for the entire region. The *b*-value was determined for the whole region utilizing complete earthquake datasets with magnitudes ranging between 4.0 and 6.9 from 1964 to 2011 and a hypocenter depth of 10 km has been set for the entire region as such depth is normal in the Nepal Himalaya and adjoining region. Furthermore, a spatial distribution function, maximum earthquake magnitude, and minimum earthquake magnitude have been assigned for each demarcated potential seismic source zone.

(4) A set of seismic zonation maps for Nepal were developed in this dissertation by using the probabilistic approach. These probabilistic seismic zonation maps presented in this study were prepared at a grid of 0.2° × 0.2° (longitude and latitude) covering the whole territory of Nepal by using seismic source information and seismicity parameters in conjunction with a selected ground motion prediction equation. These resulting seismic zonation maps represent earthquake ground motion hazard in terms of PGA at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years.

(5) Probabilistic seismic zoning maps for Nepal show the distribution of PGA values of the range of 0.07-0.16g for 63% probability of exceedance in 50 years, 0.21-0.62g for 10% probability of exceedance in 50 years, and 0.38-1.1g for 2% probability of exceedance in 50 years. The PGA values estimated in this dissertation at 2% probability of exceedance in 50

years are around 1.7-2.0 times typically higher than those at 10% probability of exceedance in 50 years and around 6.0-7.0 times typically higher than those at 63% probability of exceedance in 50 years. The set of probabilistic seismic zonation maps (63%, 10%, and 2% probability of exceedance in 50 years) in general indicate that the eastern and far-western parts of Nepal have the pronounced seismic ground motion hazard and the southern part of the country is subjected to the lowest hazard.

(6) The comparison of probabilistic seismic zonation maps (10%, and 2% probability of exceedance in 50 years) of Nepal prepared in the present study with the seismic zoning maps of China (10% probability of exceedance in 50 years) and India (10%, and 2% probability of exceedance in 50 years) shows similarities in the values of PGA obtained in the far-western portion of Nepal and differences in the levels of estimated PGA in other parts of Nepal as well as near the boundary with China and Nepal in the north and boundary with India and Nepal in the south.

(7) The highest PGA values calculated in this study for 10%, and 2% probability of exceedance in 50 years in the far-western portion of Nepal, respectively, match well with those of PGA values estimated by Nath and Thingbaijam [58] for 10%, and 2% probability of exceedance in 50 years in the same section of Nepal.

The estimated PGA values in the eastern portion of Nepal at 10%, and 2% probability of exceedance in 50 years in this analysis, respectively, are higher than those calculated in the same region by Nath and Thingbaijam [58] at 10%, and 2% probability of exceedance in 50 years. Likewise, the estimated values of PGA in the border of Nepal with China in this analysis at the 10% probability of exceedance in 50 years are higher than those calculated in the adjoining region of China at the 10% probability of exceedance in 50 years [52]. On the other hand, the estimated PGA values in the southeastern segment of Nepal at 10%, and 2% probability of exceedance in 50 years in this analysis, respectively, are relatively lower than that of calculated values of PGA in the same region by Nath and Thingbaijam [58] at 10%, and 2% probability of exceedance in 50 years.

6.2 Innovation Points

This dissertation presents the seismic zonation study of Nepal using a probabilistic approach. It is the first systematic seismic zoning study for Nepal together with the compilation of a catalogue of earthquakes with surface-wave magnitude equal to or greater than 4.0 that occurred in the region located between latitudes 26°N and 31.7°N and longitudes 79°E and 90°E covering the period from 1255 to 2011, establishing twenty-three potential seismic source zones, specifying seismic hazard parameters, and choosing a ground motion attenuation relationship. The probabilistic seismic zonation has been carried out and the following three principle innovation points can be drawn from this dissertation.

(1) Creation of an unified and homogeneous earthquake catalogue with more detailed and reliable information for Nepal and its surrounding regions by collecting and analyzing all the available catalogues from different sources.

In this study a catalogue of earthquakes (in terms of surface-wave magnitude, $M_s \geq 4.0$) for Nepal and its surrounding regions has been prepared by merging available seismic events that occurred in a geographical area bounded between latitudes 26° N and 31.7° N and longitudes 79° E and 90° E for the period from 1255 to 2011, carefully scrutinizing earthquake datasets after removing duplicated events and foreshocks as well as aftershocks and finally converting different heterogeneous magnitudes (M_s, M_b, M_L) and intensity scales of earthquakes into a common surface-wave magnitude scale (M_s). The unified and homogeneous earthquake catalogue updated for Nepal and the surrounding regions is the first detailed catalogue analysis in Nepal that improves the reliability and completeness of seismicity data and provides the reasonable estimates of seismic activity for this region. The newly prepared homogeneous earthquake catalogue of Nepal and its vicinity regions for the period 1255-2011 from the reliable sources of earthquake information that are very useful for future seismological studies, selecting the sites for specific engineering structures and properly define seismic sources to estimate the seismic hazard in this region.

(2) Established twenty-three potential seismic source zones by qualitative and quantitative methods for Nepal and the surrounding regions.

The potential seismic source zones that may generate damaging earthquakes in Nepal and the surrounding regions have been delineated in this dissertation. Twenty-three potential seismic source zones have been established in the present study for Nepal and its adjoining regions based on the spatial distribution of earthquakes, available faults information, tectonic features and quantitative analysis of intersections of morphostructural lineaments by using the pattern recognition techniques. In order to delineate seismic source zones more properly, the pattern recognition has been performed in this analysis after producing a morphostructural map by integrating the best available information from geological, topographical, tectonic maps and satellite images and have identified 84 earthquake-prone areas that can produce earthquakes of $M \geq 6.0$ in the Nepal Himalaya and its vicinity regions. It is first time twenty-three potential seismic source zones has been delineated for Nepal and the surrounding regions by combining spatial distribution of earthquakes, faults and tectonic information with the quantitative analysis of intersection of morphostructural lineaments. These delineated potential seismic source zones can be directly used as inputs for the assessment of earthquake hazard and microzonation studies in this region.

(3) Performed the seismic zonation study and established zoning maps with three exceedance probabilities in 50 years for Nepal using the probabilistic seismic hazard analysis (PSHA) method.

Seismic hazard analysis and seismic zonation have been systematically performed in Nepal for the first time with a PGA distribution with three different exceedance probabilities (63%, 10%, and 2% probability of exceedance in 50 years). The seismic zonation was performed in the present study by calculating PGA at bedrock level over the grid of 0.2° × 0.2° (longitude and latitude) covering the entire territory of Nepal together with the compilation of homogeneous seismicity catalogues, establishing twenty-three potential seismic source zones, specifying the probabilistic seismic hazard parameters, and selecting a PGA attenuation relationship. These resulting seismic zonation maps prepared in this dissertation display the PGA distribution in Nepal at bedrock level that provide fundamental and valuable information which can be used as input for seismic design of major engineering structures (i.e., pipelines, long-span bridges, dams, powerhouses and tunnels) on bedrock foundations, and to carry out seismic microzonation studies in different in parts of the country.

6.3 Limitations and Future Work

6.3.1 Limitations

Although a suitable ground motion predication model for the area of interest is crucial for the seismic zonation studies, there is no recorded strong ground motion datasets of earthquakes in Nepal in order to derive an appropriate ground motion prediction relationship for this study area. Moreover, the ground motion attenuation model could be generated by simulating the seismic ground motions using modern advances in science and technology in such a region like Nepal. The simulation of strong ground motions for Nepal is beyond the scope of this dissertation. Owing to the lack of recorded strong motion datasets to derive a suitable ground motion prediction relationship for Nepal as well as the lack of simulated ground motion attenuation model for Nepal, we choose a PGA attenuation relationship developed for the neighboring region to calculate the earthquake ground motion in this study. The government and research institutions conducting earthquake studies in Nepal therefore should place high priority on seismic ground motions recording by installing more strong motion instruments throughout the country as well as developing a reliable ground motion prediction model for this investigation region. Hence the derivation of a suitable PGA attenuation relationship for Nepal from the recorded strong motion datasets in the future would extremely useful to improve the quantification of earthquake hazard and upgrade the seismic zonation maps of Nepal. We therefore suggest that earthquake research should be intensified in the areas of historical and instrumental seismicity, strong ground motion and more detailed seismic zonation in the country.

6.3.2 Future Work

This dissertation presents the systematically quantified seismic hazard with three different exceedance probabilities of Nepal for the first time at a national scale. It established twenty-three potential seismic source zones in Nepal and the surrounding areas on the basis of catalogued earthquakes, available geological information and tectonic features. The analysis of an updated detailed homogeneous catalogued earthquakes and obtained results of the present seismic zonation study provide a better understanding the seismicity and earthquake hazard and form the strong basis for the broad spectrum of future earthquake research directions ranging from establishing a casual relationship between earthquakes and individual fault to the seismic risk analysis in Nepal. In particular, the updated seismicity database and obtained results of this dissertation could be extended, enhanced and incorporated in the following additional possible interesting research areas in future:

(1) A casual relationship between earthquakes and individual geological structure and estimate recurrence rates of strong earthquakes on individual segment of faults in Nepal and the vicinity regions could be established by utilizing the detailed updated homogeneous earthquake catalogue created in this dissertation together with the available geological structures.

(2) The updated homogeneous seismicity data and identified potential earthquake-prone areas could be incorporated to define earthquake scenarios and perform the numerical simulation of earthquake ground motions for a wide range of magnitudes and distances for this region.

(3) The established potential twenty-three seismic source zones and determined maximum magnitude for each potential seismic source zone in this dissertation could be directly used to prepare the deterministic seismic zonation maps for Nepal. The results from the purposed deterministic seismic zonation mapping for Nepal could also comprehensively be compared with the results of probabilistic seismic zonation maps prepared in this dissertation.

(4) The obtained seismic ground motions hazard at bedrock level for Nepal in the present analysis could be used as direct input to carry out seismic microzonation studies in different locations, especially site specific seismic hazard assessment of major cities (e.g., Kathmandu, Pokhara, Biratnagar, Bharatpur, Birganj, and Nepalganj) and many other large urban areas which are built on thick sedimentary deposits in the country by taking into account the geotechnical and geological effect of soil conditions at a local scale.

(5) The systematically estimated seismic ground motion hazard with three different exceedance probabilities (63%, 10%, and 2% probability of exceedance in 50 years) in this dissertation could be used for the seismic risk analysis and vulnerability assessment for Nepal.

References

[1] Central Bureau of Statistics (CBS). National Population and Housing Census (NPHC) [R]. National Report Government of Nepal, 2011. (http://cbs.gov.np).

[2] Shava R. Ancient and Medieval Nepal [M]. Manohar Publications, New Delhi, 1992.

[3] Ambraseys N, Douglas J. Magnitude calibration of North Indian earthquakes [J]. Geophysical Journal International, 2004, 159(1): 165-206.

[4] Campbell A. Account of the earthquake at Kathmandu [J]. Journal of the Asiatic Society of Bengal, 1833, 2: 564-567.

[5] Building Code Development Project (BCDP). Seismic hazard mapping and risk assessment for Nepal [R]. UNDP/UNCHS subproject, Ministry of Housing and Physical Planning, Nepal, 1994.

[6] Bilham R, Bodin P, Jackson M. Entertaining a great earthquake in Western Nepal: Historic Activity and Geodetic Tests for the Development of Strain [J]. Journal of Nepal Geological Society, 1995, 11: 73-88.

[7] Bilham, R. Location and magnitude of the 1833 Nepal earthquake and its relation to the rupture zones of contiguous great Himalayan earthquakes [J]. Current Science, 1995, 69(2): 101-128.

[8] Upreti B N, Yoshida M. Seismic hazard and mitigation activities in Nepal-with emphasis on Kathmandu Valley [J]. Journal of South Asia Disaster Studies, 2009, 2(1): 1-19.

[9] Le Fort P. Himalayas: The collided range. Present knowledge of the continental arc [J]. American Journal of Science, 1975, 275: 1-44.

[10] Hodges K V. Tectonics of the Himalaya and southern Tibet from two perspectives [J]. Geological Society of America Bulletin, 2000, 112: 324-350.

[11] Yin A, Harrison T M. Geologic evolution of the Himalaya-Tibetan orogen [J]. Annual Review Earth and Planetary Science Letters, 2000, 28: 211-280.

[12] Harrison T M, Copeland P, Hall S A, Quade J, Burner S, Ojha T P, Kidd W S F. Isotopic preservation of Himalayan/Tibet uplift denudation, and climatic histories of two molasse deposits [J]. Journal of Geology, 1993, 101: 159-177.

[13] Molnar P, Tapponnier P. Cenozoic tectonics of Asia: Effects of a continental collision [J]. Science, 1975, 189: 419-426.

[14] Tapponnier P, Xu Z Q, Roger F, Meyer B, Arnaud N, Wittlinger G, Yang J S. Oblique stepwise rise and growth of the Tibet plateau [J]. Science, 2001, 294(5547): 1671-1677.

[15] Bilham R, Larson K, Freymueller J, Project Idylhim members. GPS measurements of present-day convergence across the Nepal Himalaya [J]. Nature, 1997, 386: 61-64.

[16] Jouanne F, Mugnier J, Pandey M, Gamond J, Le Fort P, Serrurier L, Vigny C, Avouac J P. Oblique convergence in the Himalayas of western Nepal deduced from preliminary results of GPS measurements [J]. Geophysical Research Letters, 1999, 26(13): 1933-1936.

[17] Jouanne F, Mugnier J, Gamond J, Le Fort P, Pandey M R, Bollinger L, Flouzat M, Avouac J P. Current shortening across the Himalayas of Nepal [J]. Geophysical Journal International, 2004, 157: 1-14.

[18] Larson K M, Bürgmann R, Bilham R, Freymueller J T. Kinematics of the India-Eurasia collision zone from GPS measurements [J]. Journal of Geophysical Research, 1999, 104: 1077-1093.

[19] Bettinelli P, Avouac J P, Flouzat M, Jouanne F, Bollinger L, Willis P, Chitrakar G. Plate motion of India and Interseismic strain in the Nepal Himalaya from GPS and DORIS measurements [J]. Journal of Geodesy, 2006, 80: 567-589.

[20] Ader T, Avouac J P, Zeng J L, Caen H L, Bollinger L, Galetzka J, Genrich J, Thomas M, Chanard K, Sapkota S N, Rajaure S, Shrestha P, Ding L, Flouzat M. Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust: Implications for seismic hazard [J]. Journal of Geophysical Research, 2012, 117: B04403, doi: 10.1029/2011JB009071.

[21] Gansser A. Geology of the Himalayas [M]. Interscience Publisher, New York, 1964.

[22] Upreti B N. An overview of the statigraphy and tectonics of the Nepal Himalaya [J]. Journal of Asian Earth Sciences, 1999, 17: 577-606.

[23] Nakata T. Geomorphic history and crustal movements of foothills of the Himalaya [R]. Tohoku University, Science Report, 1972, 22: 39-177.

[24] Nakata T. A photogrammetric study on active faults in the Nepal Himalayas [J]. Journal of Nepal Geological Society, 1982, 2: 67-80.

[25] Nakata T. Active faults of the Himalaya of India and Nepal [J]. Special paper-Geological Society of America, 1989, 232: 243-264.

[26] Nakata T, Iwata S, Yamanaka H, Yagi H, Maemoku H. Tectonic landforms of several active faults in the western Nepal Himalayas [J]. Journal of Nepal Geological Society, 1984, 4: 177-200.

[27] Nakata T, Otsuki K, Khan S H. Active faults, stress field and plate motion along the Indo-Eurasian plate boundary [J]. Tectonophysics, 1990, 181: 83-95.

[28] Dasgupta S, Mukhopadhaya M, Nandy D R. Active transverse features of the central portion of the Himalaya [J]. Tectonophysics, 1987, 136: 255-264.

[29] Upreti B N, Nakata T, Kumahara Y, Yagi H, Okumura K, Rockwell T K, Virdi N S, Maemoku H. The latest active faulting in southeast Nepal [C]. Proceedings of the Hokudan International symposium and School on active faulting, January 17-26, 2000, Japan, 533-536.

[30] Seeber L, Armbruster J G. Great detachment earthquakes along the Himalayan arc and long-term forecasting [C]. Earthquake Prediction, the American Geophysical Union, Maurice Ewing Series, 1981, 4: 259-277.

[31] Zhao W, Nelson K D, Che J, Quo J, Lu D, Wu C, Liu X. Deep seismic reflection evidence for continental underthrusting beneath southern Tibet [J]. Nature, 1993, 366: 555-559.

[32] Nelson K D, Zhao W, Brown L D, Kuo J, Che J, Liu X, Klemperer S L, Makovsky Y, Meissner R, Mechie J, Kind R, Wenzel F, Ni J, Nabelek J, Leshou C, Tan H, Wei W, Jones A G, Booker J, Unsworth M, Kidd W S F, Hauck M, Alsdorf D, Ross A, Cogan M, Wu C, Sandvol E, Edward M. Partially molten middle crust beneath southern Tibet: synthesis of project-INDEPTH results [J]. Science, 1996, 276: 1684-1686.

[33] Jackson M, Bilham R. Constraints on Himalaya deformation inferred from vertical velocity fields in Nepal and Tibet [J]. Journal of Geophysical Research, 1994, 99: 13897-13912.

[34] Pandey M R, Tandukar R P, Avouac J P, Lavé J, Massot J P. Interseismic Strain Accumulation on the Himalayan Crustal Ramp (Nepal) [J]. Geophysical Research Letters, 1995, 22(7): 751-754.

[35] Cattin R, Avouac J P. Modeling mountain building and the seismic cycle in the Himalaya of Nepal [J]. Journal of Geophysical Research, 2000, 105: 13389-13407.

[36] Lavé J, Avouac J P. Active folding of fluvial terraces across the Siwaliks Hills, Himalayas of central Nepal [J]. Journal of Geophysical Research, 2000, 105: 5735-5770.

[37] Bollinger L, Avouac J P, Cattin R, Pandey M R. Stress buildup in the Himalaya [J]. Journal of Geophysical Research, 2004, 109: doi: 10.129/2003JB002911.

[38] Roberts E B, Urich F P. Seismological activities of the US Coast and Geodetic Survey in 1948 [J]. Bulletin of the Seismological Society of America, 1950, 40(3): 195-216.

[39] Lee S P. The map of seismology of China [J]. Acta Geophysica Sinica, 1957, 6(2): 127-158.

[40] Bureau of Indian Standards (BIS). Indian standard recommendations for earthquake resistant design of structures [R]. IS-1893-1962, New Delhi, 1962.

[41] Cornell C A. Engineering seismic risk analysis [J]. Bulletin of the Seismological Society of America, 1968, 58: 1583-1606.

[42] Algermissen S T, Perkins D M. A probabilistic estimate of maximum acceleration in rock in the contiguous United States [R]. U.S. Geological Survey Open-File Report, 1976.

[43] Algermissen S T, Perkins D M, Thenhaus P C, Hanson S L, Bender B L. Probabilistic earthquake acceleration and velocity maps for the United States and Puerto Rico [R]. U.S. Geological Survey Miscellaneous Field Studies Map MF-2120, 1990.

[44] Frankel A. Mapping seismic hazard in the Central and Eastern United States [J]. Seismological Research Letters, 1995, 66: 8-21.

[45] Frankel A D, Mueller C, Barnhard T, Perkins D, Leyendecker E V, Dickman N, Hanson S, Hopper M. National seismic-hazard maps [R]. U. S. Geological Survey Open-File Report, 1996.

[46] Frankel A D, Petersen M D, Mueller C S, Haller K M, Wheeler R L, Leyendecker E V, Wesson R L, Harmsen S C, Cramer C H, Perkins D M, Rukstales K S. Documentation for the 2002 update of the National Seismic Hazard Maps [R]. U.S. Geological Survey Open-File Report, 420, 2002.

[47] Petersen M, Frankel A D, Harmsen S, Mueller C, Haller K, Wheeler R L, Wesson R L, Zeng Y, Boyd O S, Perkins D M, Luco N, Field E H, Wills C J, Rukstales K S. Documentation for the 2008 update of the United States National Seismic Hazard Maps [R]. US Geological Survey Open-File Report, 1128: 2008.

[48] Basham P, Weichert D, Anglin F, Berry M. New probabilistic strong seismic ground motion maps of Canada- A compilation of earthquake source zones, methods and results [R]. Earth Physics Branch Open-file Report Ottawa, 1982.

[49] Basham P, Weichert D, Anglin F, Berry M. New probabilistic strong seismic ground motion maps of Canada [J]. Bulletin of the Seismological Society of America, 1985, 75: 563-595.

[50] Adams J, Atkinson G. Development of seismic hazard maps for the 2003 National Building Code of Canada [J]. Canadian Journal of Civil Engineering, 2003, 30: 255-271.

[51] Adams J, Halchuk S. Fourth generation seismic hazard maps for the 2005 National Building. Code of Canada [C]. Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, 2004, Paper 2502.

[52] People's Republic of China National Standard (PRCNS) [R]. Seismic ground motion parameter zonation map of China. China Standard Press, 2001, GB 18306-2001.

[53] Bureau of Indian Standards (BIS). Indian standard criteria for earthquake resistant design of structures, general provisions and buildings [R]. IS-1893-2002, New Delhi, 2002.

[54] Stirling M W, McVerry G H, Berryman K R. A new seismic hazard model for New Zealand [J]. Bulletin of the Seismological Society of America, 2002, 92: 1878-1903.

[55] Marin S, Avouac J P, Nicolas M, Schlupp A. A probabilistic approach to seismic hazard in metropolitan France [J]. Bulletin of the Seismological Society of America, 2004, 94: 2137-2163.

[56] Ornthammarath T, Warnitchai P, Worakanchana K, Zaman S, Sigbjörnsson R, Lai C G. Probabilistic seismic hazard assessment for Thailand [J]. Bulletin of the Earthquake Engineering, 2010, DOI 10.1007/s10518-010-9197-3.

[57] Pan H, Gao M, Xie F. The earthquake activity model and seismicity parameters in the new seismic hazard map of China [J]. Technology for earthquake disaster prevention, 2013, 8(1): 11-23.

[58] Nath S K, Thingbaijam K K S. Probabilistic seismic hazard assessment of India [J]. Seismological Research Letters, 2012, 83: 135-149.

[59] Pandey M R, Chitrakar G R, Kafle B, Sapkota S N, Rajaure S, Gautam U P. Seismic hazard map of Nepal [R]. National Seismological Centre, Kathmandu, Nepal, 2002.

[60] Thapa D R. Seismic hazard and ground motion in Nepal [D]. The Abdus Salam International Centre for Theoretical Physics, 2008.

[61] Kramer S L. Geotechnical earthquake engineering [R]. Prentice Hall International Series in Civil Engineering and Engineering Mechanics, Washington, 1996, 106-129.

[62] Reiter L. Earthquake hazard analysis [M]. Columbia University Press, New York. 1990.

[63] Sokolov V Y, Wenzel F, Mohindra R. Probabilistic seismic hazard assessment for Romania and sensitivity analysis: a case of joint consideration of intermediate-depth (Vrancea) and shallow (crustal) seismicity [J]. Soil Dynamics and Earthquake Engineering, 2009, 29: 364-381.

[64] Stirling M, Litchfield N, Gerstenberger M, Clark D, Bradley B, Beavan J, McVerry G, Van Dissen R, Nicol A, Wallace L, Buxton R. Preliminary probabilistic seismic hazard analysis of the CO2CRC Otway Project Site, Victoria, Australia [J]. Bulletin of the Seismological Society of America 2011, 101: 2726-2736.

[65] China Earthquake Administration (CEA). GB17741-2005. Training material on seismic hazard analysis for engineering sites [S], 2005.

[66] Gutenberg B, Richter C F. Frequency of earthquakes in California [J]. Bulletin of the Seismological Society of America, 1944, 34: 185-188.

[67] Schelling D. The tectonostratigraphy and structure of the eastern Nepal Himalaya [J]. Tectonics, 1992. 11, 925-943.

[68] Stocklin J. Geology of Nepal and its regional frame [J]. Journal of the Geological Society London, 1980, 137: 1-34.

[69] Sakai H. Geology of the Tansen Group of the Lesser Himalaya in Nepal [J]. Memoirs of the Faculty of Science Kyushu University Series D Geology, 1983, 25: 27-74.

[70] Sakai H. Geology of the Kali Gandaki Supergroup of the Lesser Himalayas in Nepal [J]. Memoirs of the Faculty of Science Kyushu University Series D Geology, 1985, 25: 337-397.

[71] Hodges K V, Parrish R R, Searle M P. Tectonic evolution of the central Annapurna Range, Nepalese Himalayas [J]. Tectonics, 1996, 15: 1264-1291.

[72] Godin L. Structural evolution of the Tethyan sedimentary sequence in the Annapurna area, central Nepal Himalaya [J]. Journal of Asian Earth Sciences, 2003, 22: 307-328.

[73] Gehrels G E, DeCelles P G, Ojha T P, Upreti B N. Geologic and U-Pb geochronologic evidence for early Paleozoic tectonism in the Kathmandu thrust sheet, central Nepal Himalaya [J]. Geological Society of America Bulletin, 2006, 118: 185-198.

[74] Martin A J, DeCelles P G, Gehrels G E, Patchett P J, Isachsen C. Isotopic and structural constraints on the location of the Main Central thrust in the Annapurna Range, central Nepal Himalaya [J]. Geological Society of America Bulletin, 2005, 117:926-944.

[75] Martin A J, Gehrels G E, DeCelles P G. The tectonic significance of (U,Th)/Pb ages of monazite inclusions in garnet from the Himalaya of central Nepal [J]. Chemical Geology, 2007, 244: 1-24.

[76] Martin A J, Ganguly J, DeCelles P G. Metamorphism of Greater and Lesser Himalayan rocks exposed in the Modi Khola valley, central Nepal [J]. Contributions to Mineralogy and Petrology, 2009, 159: 203-223.

[77] DeCelles P G, Gehrels G E, Quade J, Ojha T P. Eocene-early Miocene foreland basin development and the history of Himalayan thrusting, western and central Nepal [J]. Tectonics, 1998, 17: 741-765.

[78] DeCelles P G, Gehrels G E, Quade J, Ojha T P, Kapp P A, Upreti B N. Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal [J]. Geological Society of America Bulletin, 1998, 110(1): 2-21.

[79] DeCelles P G, Robinson D M, Quade J, Ojha T P, Garzione C N, Copeland P, Upreti B N. Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal [J]. Tectonics, 2001, 20: 487-509.

[80] Robinson D M, DeCelles P G, Copeland P. Tectonic evolution of the Himalayan thrust belt in western Nepal: implications for channel flow models [J]. Geological Society of America Bulletin, 2006, 118: 865-885.

[81] Pearson O N, DeCelles P G. Structural geology and regional tectonic significance of the Ramgarh thrust, Himalayan fold-thrust belt of Nepal [J]. Tectonics, 2005, 24: 4, TC400810.1029/2003TC001617.

[82] Gehrels G E, DeCelles P G, Ojha T P, Upreti B N. Geologic and U-Pb geochronologic evidence for early Paleozoic tectonism in the Dadeldhura thrust sheet, far-west Nepal Himalaya [J]. Journal of Asian Earth Sciences, 2006, 28: 385-408.

[83] Armijo R, Tapponnier P, Mercier J L, Tonglin H. Quaternary extension in Southern Tibet [J]. Journal of Geophysical Research, 1986, 91: 13803-13872.

[84] Taylor M H, Yin A. Active structures of the Himalayan-Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism [J]. Geosphere, 2009, 5(3): 199-214.

[85] Upreti B N, Le Fort P. Lesser Himalayan crystalline nappes of Nepal: Problems of their origin [J]. Special Paper-Geological Society of America, 1999, 328: 225-238.

[86] Avouac J P. Mountain building, erosion and the seismic cycle in the Nepal Himalaya [J]. Advances in Geophysics, 2003, 46: 1-79.

[87] Amatya K M, Gnawali B N. Geological map of Nepal, 1:1000000 Scale [R]. Department of Mines and Geology, Kathmandu, ICIMOD, CDG, UNEP, 1994.

[88] Bashyal R P. Petroleum exploration in Nepal [J]. Journal of Nepal Geological Society, 1998, 18: 19-24.

[89] Mugnier J L, Leturmy P, Mascle G, Huyghe P, Chalaron E, Vidal G, Husson L, Delcaillau B. The Siwaliks of western Nepal I: Geometry and kinematics [J]. Journal of Asian Earth Sciences, 1999, 17: 629-642.

[90] Sharma C K. Geology of Nepal [M]. Educational Enterprises Limited, First Edition, 1977.

[91] Auden J B. Traverses in the Himalaya [R]. Records of the Geological Survey of India, 1935, 69: 123-167.

[92] Tokuoka T, Takayasu K, Yoshida M, Hisatomi K. The Churia (Siwalik) group of the Arung Khola area, west central Nepal [M]. Memoirs of the Faculty of Science Shimane University, 1986, 20: 135-210.

[93] Sah R B. Lithostratigraphy of Nepalese Siwalik: an appraisal for standardization [J]. Journal of Nepal Geological Society, 1998, 18: 217-226.

[94] Szulc A G, Najman Y, Sinclair H, Pringle M, Bickle M, Chapman H, Garzanti E, Ando S, Huyghe P, Mugnier J L, Ojha T P, DeCelles P G. Tectonic evolution of the Himalaya constrained by a detrital investigation of three Siwalik foreland basin successions, SW Nepal [J]. Basin Research, 2006, 18: 375-392.

[95] Pecher A. The metamorphism in the central Himalaya [J]. Journal of Metamorphic Geology, 1989, 7(1): 31-41.

[96] Searle M P, Godin L. The South Tibetan detachment and the Manaslu Leucogranite: a structural reinterpretation and restoration of the Annapurna-Manaslu Himalaya, Nepal [J]. Journal of Geology, 2003, 111(5): 505-523.

[97] Searle M P, Simpson R L, Law R D, Parrish R R, Waters D J. The structural geometry, metamorphic and magmatic evolution of the Everest Massif, High Himalaya of Nepal-South Tibet [J]. Journal of the Geological Society London, 2003, 160(3): 345-366.

[98] Le Fort P. Manaslu leucogranite: A collision signature of the Himalaya. A model for its genesis and emplacement [J]. Journal of Geophysical Research, 1981, 86: 10545-10568.

[99] Garzanti E. Stratigraphy and sedimentary history of the Nepal Tethys Himalaya passive margin [J]. Journal of Asian Earth Sciences, 1999, 17: 805-827.

[100] Oldham T. A catalogue of Indian earthquake from earliest time to the end 1869 [J]. Memoirs of the Geological Survey of India, 1883, 19: 163-215.

[101] Gutenberg B, Richter C F. Seismicity of the Earth and Associated phenomena [M]. Second Edition, Princeton University Press, 1954.

[102] Lee W H K, Wu F T, Jacobsen C. A catalog of historical earthquakes in China [J]. Bulletin of the Seismological Society of America, 1976, 66: 2003-2016.

[103] Chen W P, Molnar P. Seismic moments of major earthquakes and the average rate of slip in Central Asia [J]. Journal of Geophysical Research, 1977, 82(20): 2945-2969.

[104] Pandey M R. Seismicity of Nepal (A Preliminary Study) [R]. His Majestry's Government of Nepal, Ministry of Industry, Department of Mines and Geology, Kathmandu, Nepal,1983, 3-17.

[105] Srivastava N N, Ramachandram K. A new catalogue of earthquakes for Peninsular India during 1839-1900 [J]. Mausam, 1985, 36(30): 351-358.

[106] Chandra U. Seismotectonics of Himalaya [J]. Current Science, 1992, 62: 40-71.

[107] Pandey M R, Molnar P. The distribution of intensity of the Bihar-Nepal earthquake of 15 January 1934 and bounds on the extent of the rupture zone [J]. Journal of Nepal Geological Society, 1988, 5(1): 22-44.

[108] Thapa D R, Wang G. Spatial distribution of seismicity and possible disasters in the Nepal Himalaya and its surrounding region [C]. Proceedings of the 9th International Conference on Civil and Environmental Engineering, Advances in Civil and Environmental Engineering, China architecture and building press, 2010, Paper number 2.53.

[109] International Seismological Centre (ISC), Bulletin, Thatcham, UK, (http://www.isc.ac.uk/Bull).

[110] National Earthquake Information Center (NEIC), United States Geological Survey, U.S.A, (http://neic.usgs.gov).

[111] National Seismological Centre (NSC), Department of Mines and Geology, Nepal, (http://seismonepal.gov.np).

[112] Gutenberg B, Richter C R. Earthquake magnitude, intensity, energy and acceleration [J]. Bulletin of the Seismological Society of America, 1956, 46: 105-145.

[113] Hanks T C, Kanamori H. A moment magnitude scale [J]. Journal of Geophysical Research, 1994, 84: 2348-2350.

[114] Wang S, Wang J, Yu Y, Wu Q, Gao A, Gao M. The empirical relationship between M_L and M_S based on bulletin of seismological observations of Chinese stations [J]. Earthquake Research in China, 2010, 26(1): 14-22.

[115] Liu R, Chen Y, Ren X, Xu Z, Sun L, Yang H, Liang J, Ren K. Comparison between different earthquake magnitudes determined by China seismograph networks [J]. Acta Seismologica Sinica, 2007, 29: 467-476.

[116] Gelfand I, Guberman S h, Izvekova M, Keilis-Borok, V, Rantsman E. Criteria of high seismicity, determined by pattern recognition [J]. Tectonophysics, 1972, 13: 415-422.

[117] Gorshkov A I, Panza G F, Soloviev A A, Aoudia A. Morphostructural zoning and preliminary recognition of seismogenic nodes around the Adria margin in peninsular Italy and Sicily [J]. Journal of Seismology and Earthquake Engineering, 2002, 4(1): 1-24.

[118] Gorshkov A I, Mokhtari M, Piotrovskaya A A. The Alborz Region: Identification of seismogenic nodes with morphostructural zoning and pattern recognition [J]. Journal of Seismology and Earthquake Engineering, 2009, 11(1): 1-15.

[119] Gelfand I, Guberman Sh, Keilis-Borok V, Knopoff L, Press F, Rantsman E, Rotwain I, Sadovsky L. Pattern recognition applied to earthquake epicenters in California [J]. Physics of the Earth and Planetary Interiors, 1976, 11: 227-283.

[120] Bhatia S C, Chetty T R K, Filimonov M B, Gorshkov A I, Rantsman E Y, Rao M N. Identification of potential areas for the occurrence of strong earthquakes in Himalayan arc region [C]. Proceeding of Indian Academy of Science, Earth and Planetary Sciences, 1992, 101: 369-385.

[121] Gorshkov A I, Soloviev A A, Jimenez M J, Garcıa-Fernandez M, Panza G F. Recognition of earthquake-prone areas ($M \geq 5.0$) in the Iberian Peninsula [J]. Rendiconti Lincei Scienze Fisiche e Naturali, 2010, 21: 131-162.

[122] Cisternas A, Godefroy P, Gvishiani A, Gorshkov A, Kossobokov V, Lambert M, Rantsman E, Alantin J, Salado H, Soloviev A, Weber C. A dual approach to recognition of earthquake prone areas in the Western Alps [J]. Annales Geophysicae, 1985, 3(2): 249-270.

[123] Alekseevskaya M A, Gabrielov A M, Gvishiani A D, Gelfand I M, Ranzman E Y A. Formal morphostructural zoning of mountain territories [J]. Journal of Geophysics, 1977, 43: 227-233.

[124] Gansser A. Facts and theories on the Himalayas [J]. Eclogae Geologicae Helvetiae, 1991, 84: 33-59.

[125] Harrison T M, Copeland P, Kidd W S F, Yin A. Raising Tibet [J]. Science, 1992, 255: 1663-1670.

[126] Garzione C N, DeCelles P G, Hodkinson D G, Ojha T P, Upreti B N. East-west extension and Miocene environmental change in the southern Tibetan Plateau: Thakkhola Graben, central Nepal [J]. Geological Society of America Bulletin, 2003, 115(1): 3-20.

[127] Yoshida M, Upreti B N, DeCelles P G, Gehrels G E, Ojha T P. Basement history and provenance of the Tethys sediments of the Himalaya: an appraisal based on recent geochronologic and tectonic data [J]. Bulletin of the Tethys Geological Society, 2006, 1: 1-6.

[128] Yin A. Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation [J]. Earth-Science Reviews, 2006, 76:1-131.

[129] Gehrels G E, Kapp P, DeCelles P G, Pullen A, Blakey R, Weislogel A, Ding L, Guynn J, Martin A, McQuarrie N, Yin A. Detrital zircon geochronology of pre-Tertiary strata in the Tibetan-Himalayan orogen [J]. Tectonics, 2011, 30: doi:10.1029/2011TC002868.

[130] Wells D L, Coppersmith K J. New Empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement [J]. Bulletin of the Seismological Society of America, 1994, 84: 974-1002.

[131] Pandey M R, Tankudar R P, Avouac J P, Vergne J, Héritier T. Seismotectonics of the Nepal Himalaya from a local seismic network [J]. Journal of Asian Earth Sciences, 1999, 17:703-712.

[132] McGuire R K. FORTRAN computer program for seismic risk analysis [R]. U.S. Geological Survey, 76-67, 1976.

[133] McGuire R K. FRISK computer program for seismic risk analysis using faults as earthquake sources [R]. U.S. Geological Survey, 78-1007, 1978.

[134] McGuire R K. Computations of seismic hazard [J]. Annali Di Geofisica, 1993, XXXVI: 3-4.

[135] McGuire R K. Probabilistic seismic hazard analysis and design earthquakes: closing the loop [J]. Bulletin of the Seismological Society of America, 1995, 85: 1275-1284.

[136] McGuire R K. Seismic hazard and risk analysis [R]. Earthquake Engineering Research Institute Report MNO-10, 2004.

[137] McGuire R K, Shedlock K M. Statistical uncertainties in seismic hazard evaluations in the United States [J]. Bulletin of the Seismological Society of America, 1981, 71(4): 1287-1308.

[138] McGuire R K, Arabasz W J. An introduction to probabilistic seismic hazard analysis [J]. Geotechnical and Environmental Geophysics I: Review and Tutorial, 2000.

[139] Merz H A, Cornell C A. Seismic risk based on a quadratic magnitude-frequency law [J]. Bulletin of the Seismological Society of America, 1973, 69: 1209-1214.

[140] International Atomic Energy Agency (IAEA). Evaluation of seismic hazards for nuclear power plants [R]. Safety Guide NS-G-3.3, Vienna, 2002.

[141] US Nuclear Regulatory Commission. A performance-based approach to define the site-specific earthquake ground motion [R]. Regulatory Guide 1.208, Washington D.C, 2007.

[142] Douglas J. Earthquake ground motion estimation using strong-motion records: A review of equations for the estimation of peak ground acceleration and response spectral ordinates [J]. Earth-Science Reviews, 2003, 61: 43-104.

Appendix

The earthquake catalogue described in Chapter 3 were compiled from various sources and carefully analyzed and converted into an uniform magnitude scale ($Ms \geq 4.0$). The available date (year, month and day), location (latitude, longitude), and magnitudes of earthquakes that occurred in Nepal and its surrounding regions from 1255 to 2011 are presented here in Appendix.

Year	Month	Day	Long./°	Lat./°	*Ms*
1255	0	0	85.3	27.7	7.6
1408	0	0	85.3	27.7	7.6
1505	6	6	83	29.5	8.1
1681	0	0	85.3	27.7	7
1810	0	0	85.3	27.7	7
1816	5	26	79	30.9	6.3
1816	5	27	79	30.9	5.7
1816	5	28	79	30.9	5.7
1819	8	3	85.5	26.5	4.3
1826	10	29	85	28	5.7
1832	2	7	79.6	29.4	5
1832	7	2	79.6	29.4	5
1833	4	10	85	27	7
1833	5	30	79.6	29.4	5
1833	8	26	85.7	27.7	7.6
1833	8	30	85.3	27.7	4.3
1833	10	4	85	27	7
1833	10	18	84	27	6.3
1833	11	8	85.3	27.7	5
1835	1	14	79.6	29.4	5.7
1842	1	16	83	26	5
1843	8	10	88.3	27	5.6
1849	2	27	88.3	27	6.3
1849	2	28	88.5	26.5	5
1851	2	14	79.4	29.4	4.3
1852	5	0	88.3	27	7
1863	3	29	88.3	27	5.6
1863	7	8	88.3	27	5
1864	8	30	80.9	26.8	4.3
1865	12	16	88.3	27	5
1866	5	23	85.3	27.7	6.3
1869	1	10	90	26	6.3
1869	3	23	88.3	27	4.3
1869	7	7	85	28	7
1869	7	25	79.4	29.4	4.3
1869	8	9	88.3	27	5.6
1875	4	26	88.3	27	4.3
1899	9	25	88.3	27	6.3
1909	2	17	87	27	5.5
1910	8	13	90	28	5.7
1911	10	14	80.5	31	6.7
1913	3	6	83	30	6.2
1916	8	28	81	30	7.3
1918	2	4	87.8	29.6	6
1925	11	6	81.5	26.5	5.5
1926	7	27	80.5	30.5	6
1931	6	18	84	30.5	5.6
1934	1	15	87.1	27.6	8.3
1935	3	5	80.2	29.7	6
1935	3	15	80.4	29.6	5.5
1935	5	21	89.2	28.7	6.2
1936	2	11	87	27.5	5.6
1936	5	27	83.5	28.5	7
1937	4	30	81.5	30	5.5
1938	1	29	87	27.5	5.5
1940	4	10	81.5	30	5.5

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1944	10	17	83.3	31.4	6.7	1966	1	11	85.8	27.8	4.1
1944	10	29	83.4	31.3	6.7	1966	3	6	80.5	31.5	6.5
1945	6	4	80	30	6.5	1966	3	17	82.9	31.6	4.6
1947	8	19	79.9	31.2	5.5	1966	6	25	82.3	30.5	4.8
1953	2	23	81.3	29.5	6	1966	6	27	80.8	29.6	6
1954	9	4	83.8	28.3	6.5	1966	6	28	80.9	29.6	4.9
1955	4	17	90	26.5	4.5	1966	6	29	81	29.8	5
1955	9	20	90	27.5	5.6	1966	10	5	81.2	29.3	4.1
1955	11	23	90	26.5	5	1966	10	13	80.3	31.4	4.8
1957	4	14	84.3	30.6	6.5	1966	11	5	84	28.2	4.8
1957	4	14	84.5	31	6.2	1966	12	16	80.8	29.6	6
1957	4	22	84.3	30.9	6	1966	12	18	80.9	29.5	4.6
1958	1	23	84.1	30.7	5.8	1966	12	21	80.8	29.7	5.1
1958	10	28	84.5	30.6	6.2	1966	12	28	89	28	4.9
1958	12	28	80	29.5	6.3	1967	1	2	79.3	30.6	4.5
1960	8	21	88.5	27	5.5	1967	1	5	86	30	4.9
1961	12	24	80.8	29.5	5.7	1967	3	2	86.4	28.7	4.5
1962	1	11	84.9	27.9	5	1967	3	11	81.4	29.3	4.5
1962	7	13	79.6	30.5	5.5	1967	7	16	82	28	4.6
1962	7	14	79.5	30.4	5.5	1967	8	14	80	28	4.9
1963	1	30	80.6	29.7	5.5	1967	9	13	87	27	4.9
1963	11	27	79.1	30.8	4.8	1967	11	21	79	28	4.6
1964	1	25	86.64	28.27	4.1	1967	12	18	81.9	29.1	4.9
1964	1	25	86.8	28.5	4.1	1968	1	5	79.1	30.4	5.1
1964	2	1	87.78	27.3	4.5	1968	2	7	80.3	30.9	4.3
1964	2	1	87.8	27.4	4.5	1968	5	27	80.4	29.7	4.8
1964	3	27	89.3	27.2	6.1	1968	5	31	80	29.9	4.8
1964	5	24	82.1	30.1	4.8	1968	10	28	86.03	27.57	4.6
1964	8	30	88.3	27.6	4.9	1969	2	4	81.4	28.3	4.8
1964	9	26	80.5	30	6	1969	2	11	82.7	28.1	6.2
1964	10	6	80.98	29.4	5	1969	2	13	85.4	27.9	4.7
1964	10	25	88.6	27.9	4.5	1969	2	13	81.8	28.2	5
1964	11	9	86.04	29.53	4.8	1969	2	24	85.6	27.9	4.9
1964	12	2	81.3	29.5	4.8	1969	3	3	79.9	30.2	5
1964	12	3	89.4	31.49	4.1	1969	3	5	81.1	29.2	4.9
1964	12	20	81	29.5	4.9	1969	3	7	83.8	28.1	4.5
1965	1	12	87.84	27.4	6.1	1969	4	13	81.7	28.3	4.6
1965	3	18	80.3	29.9	4.9	1969	5	3	79.9	30.2	5
1965	5	13	80.5	29.8	4.8	1969	6	22	79.4	30.6	5
1965	6	1	83.2	28.5	5.1	1969	8	9	88.3	27	5.7

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1969	12	5	80.8	29.7	4.6	1976	9	12	85.8	27.7	4.5
1970	2	12	81.6	29.2	5	1976	9	14	89.57	29.81	5.2
1970	2	26	85.7	27.62	4.9	1976	9	29	81.4	29.8	4.7
1970	7	21	84.8	27.9	4.3	1976	10	23	86.2	28.7	4.8
1971	1	30	79.1	30.5	4.2	1977	4	20	79.4	30.5	4.5
1971	5	3	84.3	30.8	5	1977	6	5	88.3	26.2	4.5
1971	6	6	85.6	28.1	4.6	1977	9	20	81.1	29.5	4.7
1971	6	25	83.6	28	4	1977	11	4	81.3	29.6	4.6
1971	10	24	87.16	28.25	4.8	1978	1	1	81.14	30.02	4
1971	12	4	87.87	27.9	4.7	1977	1	7	79.4	30.6	4.3
1972	2	4	84.6	30.4	4.9	1978	2	4	81.4	29.3	4
1972	3	15	84.5	30.4	5	1978	2	10	85	27.9	4
1972	4	8	89.42	29.67	4.5	1978	2	10	84.6	28.1	4.9
1972	4	28	84.9	31.3	4.8	1978	2	19	85	29.3	4.3
1972	8	21	88.02	27.23	4.8	1978	2	28	80.7	29.3	4.3
1972	11	6	88.71	26.96	4.5	1978	8	13	85.2	28	4
1972	11	6	88.7	27	4.5	1978	8	15	84.6	31.3	4.5
1973	2	10	80.3	30.5	4.2	1978	10	4	86	27.8	4.9
1973	3	22	87	28.1	4.9	1978	10	14	87.3	27.7	4.5
1973	4	4	83.7	30.5	4.5	1978	10	23	86.8	28.8	4
1973	8	1	89.17	29.59	4.6	1978	12	25	83.9	28.1	4.1
1973	10	16	82.9	28.2	4.9	1979	4	11	88.8	26	4.5
1974	3	3	86.29	30.83	5	1979	5	20	80.3	29.9	5.9
1974	3	13	81.6	29.3	4.1	1979	6	19	87.5	26.7	5
1974	3	24	86	27.7	5.1	1979	10	17	87.6	28	4.2
1974	5	6	81.7	29.3	4.1	1979	11	16	88.2	27.2	4.2
1974	9	27	85.5	28.6	5.3	1980	2	22	88.58	30.51	6.2
1974	12	23	81.4	29.4	4.9	1980	2	28	88.98	30.57	4.2
1975	1	31	84.7	28.1	5.1	1980	3	4	88.68	30.51	4.3
1975	2	6	87.8	27.9	4.3	1980	6	3	88.6	30.66	4.8
1975	4	9	84.89	30.41	4.6	1980	6	10	88.6	30.56	4.6
1975	4	24	86.9	27.2	4.8	1980	6	22	81.8	30.1	4.8
1975	6	24	87.3	27.5	4.9	1980	7	29	81.1	29.6	6.6
1975	9	6	82.2	29.3	4.8	1980	7	30	80.7	29.6	4.8
1975	9	8	84.9	31.5	4.6	1980	7	31	80.9	29.4	4.1
1975	11	21	86.5	27	4.6	1980	8	4	80.8	29.4	4.1
1975	11	26	87.6	28.3	4.8	1980	9	8	80.4	30	4.1
1976	5	10	81.5	29.3	5.9	1980	10	10	81.2	29.2	4.7
1976	7	23	83.9	31.7	4.5	1980	11	18	85.2	29.6	4.3

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1980	11	19	88.8	27.4	6.1	1984	1	6	84.7	27.8	4.1
1980	11	20	85.2	29.6	4.5	1984	1	25	86.1	27.5	4.2
1980	12	22	89.3	26.3	4.1	1984	2	19	80.5	29.9	4.7
1980	12	26	88.9	29.1	4.1	1984	3	14	81.1	29.1	4.6
1981	2	8	88.61	30.6	4.5	1984	4	15	82.3	31.7	4.7
1981	2	9	89.8	27	4.8	1984	4	22	84.2	30.6	4.5
1981	3	6	80.7	29.8	4.6	1984	5	18	81.9	29.6	5.3
1981	4	9	84.4	28	4.1	1984	5	19	81.9	29.3	4.3
1981	5	15	81.9	29.5	4.8	1984	5	30	83.9	28.8	4.1
1981	6	19	79.2	30.5	4	1984	7	29	81.8	29.4	4.1
1981	7	1	80.31	30.77	4.2	1984	9	15	81.5	29.2	4.2
1981	9	10	81.1	29.3	4.2	1984	10	2	88.76	30.98	4
1981	11	21	89.12	29.53	4.5	1984	11	18	84.1	28.8	5
1982	1	22	89.87	30.89	5.7	1984	11	23	81.6	29.4	4
1982	1	23	82.2	31.7	6.5	1984	11	26	79.3	30.5	4.1
1982	1	24	82.4	31.5	4.2	1984	12	5	81.7	27.2	4.3
1982	1	25	82.3	31.6	4.8	1984	12	18	80.9	29.4	4.3
1982	2	4	82.2	31.4	4.2	1985	1	30	85.44	30.92	4.5
1982	2	20	85.7	27.7	4.1	1985	2	15	81.6	30.1	4
1982	3	24	88.74	30.57	4.2	1985	5	6	82.3	28.3	4.1
1982	4	5	88.9	27.4	4.8	1985	5	25	88.5	27.6	4.2
1982	5	2	81.7	29.2	4.1	1985	6	17	82.3	31.6	4.2
1982	5	29	83.6	28.5	4	1985	7	12	82.4	31.7	4.3
1982	6	10	82.1	31.5	4.6	1985	7	28	88.8	30.36	4.1
1982	6	20	90	26.2	4.1	1985	9	13	84.1	29.8	4.1
1982	8	3	85.5	27.9	4.2	1985	10	2	89.7	27.1	4
1982	8	18	89.5	27.1	4.2	1985	10	21	84	28.8	4.1
1982	9	9	81.99	28.68	4.3	1985	10	30	82.9	31.6	4.2
1982	9	9	82	28.7	4.1	1985	12	8	86.62	30.75	4.6
1982	10	16	79.1	30.3	4.1	1985	12	15	86.39	30.83	4.1
1982	12	21	81.4	29.2	4.3	1985	12	23	85.7	27.6	4.2
1982	12	29	79.8	30.3	4.5	1986	1	6	85.4	27.8	4.1
1983	1	6	82.1	31.3	4.3	1986	1	7	88.3	26.9	4.7
1983	1	27	81.4	29.1	4.5	1986	1	10	86.5	28.6	5.4
1983	5	20	79.77	30.36	4.1	1986	2	2	86.45	27.92	4.6
1983	7	5	80.7	29.5	4.2	1986	2	10	87.86	28.15	4.3
1983	11	23	83.1	30.4	4.2	1986	2	28	81.9	29.1	4.2

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1986	4	4	88.26	30.86	4.1	1989	3	8	84	28	4.1
1986	4	12	86.5	28.8	4	1989	4	19	89.96	30.16	4.1
1986	9	16	86.61	30.99	4.1	1989	5	22	87.9	27.2	4.7
1987	1	19	83.7	28.4	5.2	1989	10	10	87.5	28.7	4.2
1987	2	24	81.9	29.1	4	1989	11	19	89.7	29	4
1987	4	23	87.1	28	4.3	1990	1	9	88.2	28.2	5.2
1987	4	30	85.8	28.4	4.1	1990	1	10	86.7	26.6	4.3
1987	5	10	86.7	28.2	4.2	1990	1	30	85.7	28.6	4.1
1987	6	6	79.3	30.6	4.3	1990	2	9	80.7	29.9	4.2
1987	8	9	83.7	29.5	5.3	1990	2	18	89.95	29.39	4.1
1987	8	21	80.2	31.7	4.3	1990	2	21	82.4	28.1	4.5
1987	11	25	85.9	28	4.2	1990	5	6	89.98	29.99	4.1
1988	1	23	81.6	29.5	4.3	1990	5	20	83.16	28.35	4.6
1988	2	12	82.9	30.5	4.2	1990	7	13	86.93	28.25	4.1
1988	4	9	86.9	29.8	4.1	1990	9	21	79.8	29.7	4.8
1988	4	11	85.9	27.5	4.6	1990	10	14	86.39	30.82	4.6
1988	4	20	86.7	27	5.1	1990	10	28	81.6	30.7	4.1
1988	4	25	86.6	26.8	4.5	1990	11	9	86.29	30.73	4.6
1988	5	15	80.5	29.9	4.5	1990	12	18	79.1	30.3	4.6
1988	5	26	88.6	27.4	4.3	1990	12	20	82.9	28.1	4.5
1988	6	9	79.2	30.7	4.5	1991	2	15	84.24	29.43	4.1
1988	6	12	82.4	28.5	4.5	1991	3	15	87.7	28.3	4.2
1988	8	20	86.6	26.8	6.8	1991	4	22	79.7	30.1	4.2
1988	8	22	86.9	26.7	4.1	1991	5	18	80.1	31.7	4.2
1988	8	24	86.5	26.7	4.3	1991	5	20	86.77	30.99	4.2
1988	8	29	87.5	26.4	4.1	1991	5	26	80.3	29.3	4.1
1988	9	1	86.6	26.8	4.2	1991	5	27	80.3	29.3	4.2
1988	9	2	86.5	26.6	4.7	1991	6	10	80.3	29.3	4.2
1988	9	21	85.6	28.7	4.3	1991	9	14	80.92	30.7	4.3
1988	9	27	88.3	27.2	4.7	1991	10	15	79.3	30.6	4.1
1988	10	29	85.6	27.9	5.1	1991	12	9	81.6	29.5	5.6
1988	11	14	82.1	30.2	4.1	1991	12	21	88.1	27.9	4.6
1988	12	2	81.2	29.6	4.1	1992	1	30	81.2	29.2	4.1
1988	12	7	83.1	31.6	4.2	1992	3	7	89.31	29.68	4.5
1988	12	15	81.6	29.1	4.1	1992	3	14	79	30.4	4.6
1988	12	24	88	26.9	4	1992	3	24	81.6	31.4	4.6
1988	12	27	87.8	27.9	4.2	1992	4	1	87.2	27.6	4.8
1989	2	3	89.94	30.19	5.4	1992	4	2	87.84	27.98	4.1

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1992	4	4	88	28.2	4.6	1995	1	19	83.43	28.34	4.2
1992	6	2	81.91	28.98	5.2	1995	1	29	86.11	26.85	4.4
1992	6	13	82.93	28.94	4.7	1995	1	30	82.18	29.31	4.2
1993	1	2	81.12	29.15	4.9	1995	2	2	87.84	30.05	4
1993	1	13	86.56	28.5	4.1	1995	2	18	85.88	27.74	4.5
1993	3	4	86.91	29.48	4.2	1995	3	16	87.95	29.94	4
1993	3	20	87.33	29.08	6.4	1995	3	24	87.77	28.86	4.1
1993	3	25	80.55	29.62	4.2	1995	3	29	84.2	28.77	4.3
1993	3	31	87.35	29.09	4.8	1995	4	17	81.71	29.5	4.6
1993	4	12	82.8	28.31	4.3	1995	4	24	88.25	29.89	4.2
1993	7	3	86.63	28.36	4.3	1995	6	11	87.94	27.21	4.1
1993	7	5	85.12	27.94	4.3	1995	7	30	88.23	30.27	4.5
1993	7	9	86.06	26.81	4.2	1995	8	3	81.54	30.04	4.7
1993	8	19	80.04	30.08	4	1995	8	7	81.62	29.87	4.9
1993	9	5	87.31	27.29	4.1	1995	10	4	84.43	28.27	4.6
1993	9	12	83.58	30.99	4.1	1995	10	5	88.23	30.16	4.5
1993	9	13	83.67	30.98	4.5	1995	11	25	86.76	30.99	4.5
1993	10	20	82.26	28.78	4.7	1995	11	27	79.23	30.71	4.2
1993	11	14	80.36	30.66	4	1995	12	27	88.26	30.23	4
1993	11	22	82.86	28.2	4	1996	1	23	79.42	30.46	4.1
1993	12	14	86.84	28.49	4.2	1996	1	25	87.22	28.7	4.8
1994	1	31	81.79	29.55	4.3	1996	2	28	86.76	27.12	4.7
1994	5	10	83.94	29.23	4	1996	3	12	88.15	30.01	4.6
1994	5	25	87.79	27.65	4.2	1996	3	26	79.1	30.69	5
1994	6	25	86.15	27.75	5	1996	4	26	87.7	27.93	5.2
1994	7	17	81.51	29.37	5.4	1996	5	10	88.07	30	4.5
1994	8	31	79.51	26.08	5.9	1996	5	11	88.08	29.98	4.5
1994	9	25	87.34	28.34	4.7	1996	5	17	88.14	30.06	4.2
1994	10	22	82.25	29	4.5	1996	7	3	88.19	30.15	5.6
1994	10	24	82	28.92	4.6	1996	7	3	88.19	29.92	4.7
1994	11	21	81.14	29.53	4.1	1996	7	4	88.08	30.01	4.6
1994	11	27	81.55	29.72	4.4	1996	7	8	88.15	30.05	4.1
1994	12	8	79.62	30.67	4.6	1996	7	10	81.98	29.61	4.5
1994	12	12	80.69	29.83	4.5	1996	7	18	88.17	30.09	4.2
1994	12	13	82.87	28.69	4.5	1996	7	22	88.02	30.02	4.1
1995	1	1	87.59	27.77	4.6	1996	7	31	88.18	30.17	5.3
1995	1	12	88.21	30.21	4	1996	8	7	88.1	30.16	4

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1996	8	25	87.74	30.14	4.1	1997	10	30	89.73	29.54	5.2
1996	8	29	88.18	30.09	4.3	1997	11	3	85.38	29.08	5.3
1996	9	13	88.23	27.03	4.1	1997	11	26	86	27.75	4.2
1996	9	25	88.55	27.43	4.7	1997	11	27	87	27.74	5.4
1996	10	3	87.49	28.21	4.1	1997	12	8	86.85	27.19	4.9
1996	10	14	88.17	29.94	4	1997	12	8	87.18	27.48	4.7
1996	10	16	79.95	28.77	4.3	1998	2	1	87.12	28.19	4.1
1996	11	4	81.85	29.63	4.8	1998	2	12	88.19	27.59	4.5
1996	11	8	81.69	29.66	4.8	1998	2	22	85.52	28.72	5.4
1996	12	3	86.84	27.39	5.2	1998	2	22	88.05	30.22	4.2
1996	12	22	81.72	29.01	4.3	1998	2	28	87.86	27.15	4.9
1996	12	29	81.82	29.75	5.1	1998	3	15	86.89	28.55	4
1996	12	30	86.64	27.43	4.7	1998	5	1	79.46	30.07	4
1997	1	1	86.56	27	4.4	1998	5	10	82.38	29.41	4.6
1997	1	5	80.58	29.78	5.5	1998	5	16	84.81	26.76	4.7
1997	1	25	88.09	30.07	4	1998	6	6	89.36	30.39	4.8
1997	1	31	85.28	28.07	5.7	1998	6	27	85.81	27.86	4.9
1997	2	1	85.3	28	4.6	1998	7	15	81.24	29.55	5
1997	2	3	85.33	28.02	4.9	1998	7	20	88.17	30.13	5.5
1997	2	10	85.33	28.12	4.1	1998	7	21	88.19	30.38	4.9
1997	2	18	81.33	29.52	4.3	1998	7	23	88.09	30.18	4.2
1997	3	3	86.08	27.24	4.3	1998	8	16	87.95	29.77	4.5
1997	3	22	88.15	29.9	4	1998	8	25	88.11	30.08	5.8
1997	3	22	87.96	30.34	4.2	1998	8	25	87.91	29.83	4
1997	3	24	85.28	28.06	4.9	1998	8	28	88.07	29.99	4.9
1997	4	5	86.06	30.09	4.1	1998	8	30	88.08	30.01	4.7
1997	4	7	87.74	27.5	4.5	1998	9	3	86.96	27.87	5.5
1997	5	2	80.43	29.43	4.2	1998	9	3	88.1	30.02	6.1
1997	5	28	82.58	28.68	4.4	1998	9	6	87.01	27.79	4.6
1997	7	5	86.86	28.8	4	1998	9	6	88.13	30.06	4.2
1997	8	16	86.22	30.02	4	1998	9	7	88.14	30.06	4.3
1997	9	15	88.21	30.1	4.2	1998	9	8	88.15	30.07	4
1997	9	18	88.15	28.87	4.2	1998	9	10	88.33	27.44	4.9
1997	10	5	88.13	30.4	4	1998	9	26	88.18	30.1	4
1997	10	11	86.41	27.65	4.7	1998	9	30	88.19	30.11	5.1
1997	10	24	82.54	28.66	5.1	1998	10	5	88.21	30.13	4.9

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1998	10	16	85.66	28.07	4.8	2000	1	25	88.05	27.37	4.5
1998	10	24	88.23	30.15	4.3	2000	2	26	82.31	28.61	5
1998	11	19	88.24	30.15	4.1	2000	3	13	87.41	27.98	5
1998	11	26	87.81	27.85	5.3	2000	3	17	87.55	27.76	4.1
1998	11	26	88.24	30.16	4.8	2000	4	10	88.34	30.15	4.1
1998	12	1	88.25	30.17	4.5	2000	5	4	79.95	29.92	4.1
1998	12	25	88.25	30.17	4	2000	5	5	81.57	29.4	4
1999	2	11	83.34	28.61	4.6	2000	5	29	86.98	30.76	4
1999	2	19	80.61	29.86	4.5	2000	6	2	83.29	28.07	4.1
1999	2	28	79.31	30.34	4.1	2000	9	2	85.33	28.07	4.4
1999	3	19	85.83	27.93	4.7	2000	10	8	88.11	30.19	4.3
1999	3	28	79.25	30.49	6.4	2000	10	26	81.88	29.21	4.5
1999	3	19	85.61	27.75	4.1	2000	12	31	87.71	27.84	4
1999	3	28	79.42	30.51	6.8	2001	2	27	87.1	28.5	4.6
1999	3	29	79.25	30.21	4.2	2001	3	12	79.23	30.52	4.1
1999	3	30	79.35	30.34	5	2001	4	3	86.13	27.8	4.2
1999	4	1	79.34	30.5	4.1	2001	4	4	86.17	27.8	4.7
1999	4	6	79.56	30.48	5.2	2001	4	11	81.39	29.5	4.2
1999	4	7	81.22	29.59	4.3	2001	4	12	88.11	29.94	4.2
1999	4	7	79.37	30.45	4.3	2001	4	15	81.4	29.45	4.3
1999	4	14	79.37	30.38	4.8	2001	4	28	87.16	28.87	4.9
1999	4	18	79.34	30.4	4.9	2001	4	29	87.22	28.91	4.3
1999	4	22	82.13	28.91	4.3	2001	7	2	86.54	30.55	4.1
1999	5	7	79.29	30.18	4.1	2001	7	6	85.18	27.96	4.7
1999	5	14	79.3	30.31	4.2	2001	7	11	81.57	29.46	5.3
1999	5	28	81.03	29.3	4.5	2001	7	16	84.68	27.97	5.8
1999	6	13	86.64	28.16	4	2001	7	16	84.27	28.29	4.7
1999	8	1	86.73	28.44	4.9	2001	8	6	87.43	27.66	4
1999	8	10	86.2	27.79	5.6	2001	9	13	80.64	29.82	4.9
1999	8	25	84.74	28.15	4.4	2001	9	27	87.78	26.98	5
1999	9	5	87.41	28.16	4.1	2001	11	27	81.81	29.53	5.7
1999	9	5	80.83	30.89	4	2001	11	28	81.77	29.59	4.4
1999	9	20	87.89	27.38	4.4	2001	11	30	81.64	29.33	4.3
1999	11	16	82.77	30.39	4.2	2001	11	30	81.6	29.41	4.3
1999	12	1	81.44	30.02	4.1	2001	12	2	88.17	27.15	4.8
1999	12	11	81.56	30.15	4.5	2001	12	18	81.8	29.58	4.7
2000	1	20	86.06	27.92	4.7	2002	2	3	86.37	27.72	4

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2002	2	17	81.27	29.42	4.1	2003	5	27	86.38	30.65	4.2
2002	3	7	84.42	29.62	4.2	2003	6	3	88.13	30.63	4
2002	3	9	80.11	30.11	4.2	2003	6	23	87.97	27.79	4.7
2002	3	23	87.93	29.86	4.3	2003	7	8	82.22	27.29	4.2
2002	3	31	87.98	29.87	4	2003	7	28	82.52	28.75	4.4
2002	4	2	87.01	29.29	4.2	2003	8	2	82.1	29.51	4.3
2002	5	2	86.67	27.67	5.1	2003	8	5	86.03	27.99	4.1
2002	5	9	87.84	29.83	4.2	2003	8	20	81.7	30.17	4.2
2002	6	4	81.34	30.71	5.9	2003	9	3	81.69	30.58	4.5
2002	6	4	81.45	30.47	4.2	2003	9	24	81.96	28.99	4.2
2002	6	5	81.26	30.39	4	2003	9	29	87.86	27.52	4.5
2002	6	6	81.25	30.46	4.3	2003	9	29	86.43	27.36	4.2
2002	7	2	84.82	27.17	4	2003	11	5	86.16	27.78	4
2002	7	9	87.87	29.89	4.3	2003	11	22	83.91	28.47	4.9
2002	7	16	87.36	27.75	4.2	2003	12	10	86.04	30.47	4.1
2002	8	1	81.68	29.9	4	2003	12	11	80.54	29.85	4
2002	8	6	88	29.91	4.2	2003	12	19	87.97	27.06	4.1
2002	8	11	86.4	26.97	4	2004	1	3	86.06	27.87	5.4
2002	8	22	85.96	29.82	4.1	2004	1	3	80.89	27.74	4.6
2002	8	31	89.82	29.87	4.7	2004	1	6	87.38	30.54	4.2
2002	9	9	80.74	28.98	4	2004	2	14	80.88	29.67	4.2
2002	9	27	87.42	29.78	4	2004	2	18	87.8	27.61	4.6
2002	10	9	83.9	28.18	4	2004	2	18	80.96	27.36	4.3
2002	10	11	86.61	29.92	4	2004	2	22	81.53	29.32	4
2002	11	5	87.82	30.96	4.7	2004	2	27	88.03	28.13	4.5
2002	11	20	81.56	29.61	4.3	2004	3	1	81.12	30.37	4.5
2003	1	16	80.57	29.8	4.8	2004	3	17	87.82	27.67	4
2003	2	26	86.01	28.47	4.9	2004	3	31	87.63	27.18	4.5
2003	3	21	81.86	30.75	4.6	2004	4	3	89.62	29.85	4.2
2003	3	25	89.59	27.18	5.6	2004	5	29	82.96	28.55	4.8
2003	3	25	81.8	27.26	4.9	2004	6	5	87.93	29.86	4.1
2003	4	4	80.39	30.1	4.9	2004	7	11	83.77	30.69	6
2003	4	4	79.36	30.03	4.3	2004	7	12	83.53	30.75	4.2
2003	5	18	85.92	29.51	4	2004	7	16	84.06	28.32	4.5
2003	5	18	86.05	29.27	4	2004	7	20	85.88	27.96	4.4
2003	5	27	88.17	30.56	4.8	2004	7	23	88.09	30.17	4.5

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2004	7	28	88.03	30.71	4.8	2005	8	28	81.09	27.64	4.5
2004	8	22	85.24	28.03	4	2005	9	5	81.21	30.41	4.2
2004	8	25	83.5	30.37	4.1	2005	10	10	87.99	30.24	4
2004	8	25	86.57	30.21	4	2005	10	25	79.97	30.15	4.6
2004	9	2	85.93	27.87	4.1	2005	10	29	81.88	29.5	5
2004	9	9	87.78	29.47	4	2005	10	29	83.52	29.52	4.2
2004	9	12	81.84	29.51	4.3	2005	10	31	82.06	29.64	5
2004	9	12	84.41	29.5	4.1	2005	10	31	84.83	28.65	4.4
2004	10	5	86.55	26.83	4	2005	11	6	82.02	29.61	5
2004	10	27	81.24	30.9	4	2005	11	6	79.25	29.73	4.7
2004	11	9	82.95	28.77	4.3	2005	12	10	80.22	29.17	4.2
2004	11	17	84.67	28.26	4	2005	12	12	80.48	29.28	4.3
2004	12	26	81.63	29.9	4.2	2005	12	14	86.38	30.48	5
2004	12	27	86.2	27.76	4.1	2006	2	1	81.3	30.29	4.6
2005	1	15	84.28	29.44	4.2	2006	2	3	86.8	27.18	5.3
2005	1	16	81.14	29.68	4.9	2006	2	3	80.12	27.25	4.7
2005	1	16	87.93	29.65	4.5	2006	2	14	87.65	27.38	5.1
2005	2	8	86.07	27.76	4.9	2006	2	14	85.79	30.26	4.1
2005	2	8	84.7	27.74	4.6	2006	2	19	83.89	28.24	4.6
2005	3	5	84.39	28.27	4.9	2006	2	21	80.71	29.25	4
2005	3	6	83.4	30.62	4.2	2006	4	4	85.83	27.91	4.5
2005	3	19	84.39	28.25	5.3	2006	5	5	81.26	29.43	4.7
2005	3	19	83.46	28.13	4	2006	5	5	83.6	29.5	4.7
2005	3	26	83.63	28.26	4.6	2006	8	5	83.58	29.89	4.1
2005	3	29	84.77	28.11	4.3	2006	8	15	85.7	27.89	4.2
2005	4	4	83.18	28.56	4	2006	8	30	83.6	29.05	4.2
2005	4	7	81.88	29.35	4.1	2006	8	30	80.54	29.05	4.1
2005	4	7	83.23	30.49	6.1	2006	9	17	87.8	26.98	4.1
2005	4	8	83.59	30.28	4	2006	9	19	81.54	29.62	4.9
2005	4	8	84	30.53	4.8	2006	9	19	80.65	29.49	4.3
2005	4	9	83.73	30.49	4.1	2006	9	26	80.83	30.1	4.4
2005	4	10	83.54	30.36	4.2	2006	9	26	88.23	29.76	4.3
2005	4	15	85.71	27.92	4	2006	11	11	87.63	27.21	4.1
2005	5	5	87.7	27.69	4	2007	1	20	82.92	31.18	4.2
2005	5	11	87.92	30.6	4.2	2007	2	5	81.05	30.1	4.1
2005	6	14	87.89	27.28	4.4	2007	2	6	83.43	28.35	4
2005	7	27	86.88	27.47	4.2	2007	2	6	83.43	28.36	4.1
2005	8	8	85.51	27.98	4.1	2007	2	15	81.45	29.83	4.9
2005	8	28	87.22	27.31	5.2	2007	3	10	81.73	29.47	4.4

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2007	5	16	88.08	27.5	4.5	2008	8	29	83.37	30.8	4.3
2007	5	18	88.22	27.27	4.1	2008	8	30	83.45	30.76	4
2007	5	20	88.27	27.33	4.2	2008	9	1	83.47	30.78	4.1
2007	6	4	83.98	27.44	4.1	2008	9	4	80.38	30.24	4.7
2007	6	17	84.91	27.83	4.2	2008	9	10	83.01	28.4	4
2007	7	30	87.02	27.27	4	2008	9	10	83.43	30.85	4.7
2007	8	1	81.91	29.49	4.5	2008	9	25	83.58	30.84	5.1
2007	8	3	87.03	27.24	4.4	2008	9	25	83.59	30.85	4
2007	8	6	85.69	27.84	4	2008	10	7	87.71	27.47	4.4
2007	8	9	80.15	31.34	4.1	2008	11	17	88.17	29.19	4.2
2007	8	11	87.9	27.28	5.1	2008	11	18	83.73	30.32	4.1
2007	8	26	89.21	30.03	4.5	2008	11	25	83.68	30.76	4
2007	9	7	85.33	28.05	4.1	2008	12	1	85.29	28.18	4.7
2007	9	7	86.26	27.72	4	2008	12	2	87.99	27.32	5.3
2007	9	18	88.95	29.97	4.2	2008	12	8	82.08	29.98	5
2007	10	29	85.45	27.9	4.9	2008	12	8	81.86	30.15	5.9
2007	11	5	84.45	28.2	4.4	2008	12	19	81.91	30.1	4.3
2007	12	1	85.28	28.05	4	2008	12	23	84.39	28.19	4.3
2008	1	15	86.53	27.37	4	2008	12	25	88.65	27.15	4.1
2008	2	14	88.15	27.8	4	2008	12	26	81.9	30.09	4.4
2008	2	16	86.25	26.8	4.1	2009	1	10	88.04	27.9	4.1
2008	3	2	81.76	29.69	4.3	2009	1	23	81.4	29.05	4.1
2008	3	17	81.53	29.76	4.5	2009	2	18	83.78	30.63	4.2
2008	5	8	87.52	27.5	4.1	2009	3	8	87.8	27.41	4.4
2008	5	20	83.33	28.33	4.2	2009	3	12	84.42	28.43	4
2008	5	25	89	28.96	4	2009	4	13	84.54	28.25	4.2
2008	6	2	85.91	27.8	4	2009	5	14	87.36	27.48	4.5
2008	6	14	89.89	29.94	4.1	2009	5	14	87.35	27.43	4.1
2008	6	15	81.05	29.42	4.1	2009	6	6	86.2	30.93	4.2
2008	6	20	85.73	27.98	4.7	2009	7	12	86.36	27.71	4.2
2008	8	2	85.29	28.18	4.3	2009	7	24	85.96	31.16	5.5
2008	8	25	83.65	31.06	6.6	2009	9	21	79.02	30.83	4.3
2008	8	25	83.51	30.91	4.3	2009	9	26	82.05	29.81	4.2
2008	8	26	83.28	30.7	4.5	2009	9	29	83.4	30.91	4.3
2008	8	27	83.45	31.03	4.1	2009	10	3	79.82	30	4.1
2008	8	27	83.35	30.73	4.1	2009	10	29	83.11	28.73	4
2008	8	28	83.25	30.64	4	2009	10	30	84.58	29.64	4

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2009	11	1	81.81	30.1	4.4
2009	11	7	86.04	29.53	5.3
2009	11	8	81.91	30.11	4.2
2009	11	20	83.42	30.73	4.7
2009	11	22	82.15	29.02	4.4
2009	12	15	84.4	28.28	4
2009	12	16	81.51	29.6	4.5
2009	12	28	83.77	30.69	4
2010	1	1	83.79	30.61	4.6
2010	1	11	80.56	29.74	4.3
2010	1	18	83.97	28.37	4
2010	2	17	86.08	26.79	4
2010	2	22	80.06	29.98	4.2
2010	2	25	81.52	29.78	4.5
2010	2	26	86.77	28.5	5.2
2010	3	1	81.55	29.76	4.2
2010	3	15	81.95	30.64	4.6
2010	4	13	81.34	29.37	4.4
2010	4	14	83.09	28.31	4.1
2010	5	1	80.03	30.1	4.1
2010	5	13	84.51	28.3	4.1
2010	6	13	81.65	29.6	4.7
2010	6	22	80.43	29.87	4.9
2010	7	4	80.38	29.85	4.3
2010	7	5	80.54	31.06	4.5
2010	7	10	79.61	30.08	4.2
2010	7	10	86.98	29.32	4.2
2010	10	17	85.71	28.64	4.9
2010	11	25	83.17	28.44	4.6
2010	11	25	82.32	28.38	4.4
2010	11	30	85.79	26.93	4.3
2010	12	5	81.69	29.57	4.1
2010	12	18	84.79	28.18	4
2010	12	29	86.51	30.94	4.9
2010	12	29	86.45	30.8	4.6
2011	1	18	81.97	30.03	4
2011	1	18	85.94	27.8	4.2
2011	2	13	86.94	27.39	4.1
2011	2	13	87.01	27.47	4.6
2011	2	22	87.01	27.57	4.1
2011	3	10	85.24	28.02	4.2
2011	3	11	83.8	28.31	4.2
2011	3	12	83.78	28.31	4.3
2011	3	22	82.74	28.11	4.1
2011	4	4	80.54	29.92	5.6
2011	4	4	80.81	30	4
2011	4	5	80.37	29.74	4
2011	4	7	85.61	27.93	4
2011	5	4	80.43	30.32	4.2
2011	5	24	85.39	30.04	4.1
2011	6	3	88.03	27.6	5.1
2011	6	11	82.66	28.41	4.1
2011	6	11	82.55	28.4	4
2011	6	13	86.82	27.1	4.4
2011	6	17	81.48	30.24	4.1
2011	6	18	87.35	27.83	4.2
2011	6	20	79.34	30.61	4.6
2011	7	15	87.3	27.28	4.4
2011	7	29	86.76	27.19	4.1
2011	8	9	81.31	29.9	4.2
2011	8	15	86.27	27.44	4.9
2011	8	19	81.34	29.7	4.8
2011	8	25	82.53	28.15	4.3
2011	8	27	86.6	29.94	4.1
2011	9	18	88.03	27.78	6.8
2011	10	1	81.81	30.16	4.6
2011	10	2	81.68	29.55	4.1
2011	11	8	85.55	27.94	4
2011	11	13	84.93	28.2	4.9
2011	11	19	86.1	27.7	4
2011	11	23	81.68	28.91	4.1
2011	12	2	85.34	28.05	4.1
2011	12	9	88.13	27.83	4.1
2011	12	14	88.09	27.72	4.8
2011	12	18	88.16	27.73	4.5

Publications during PhD Program

[1] **Thapa Dilli Ram**, Wang Guoxin. Probabilistic Seismic Hazard Analysis in Nepal [J]. ***Earthquake Engineering and Engineering Vibration,*** 2013, 12 (4): 577-586 (***SCI***: doi: 10.1007/s11803-013-0191-z) (本博士学位论文第一,二,三,五章).

[2] **Thapa Dilli Ram**, Wang Guoxin. Seismic Zonation for Nepal. **Proceedings of the SE-50EEE International Conference on Earthquake Engineering,** May, 29-31 (2013), Skopje, Republic of Macedonia, 2013, Paper number: 574 (本博士学位论文第一,三,五章).

[3] **Thapa Dilli Ram**, Wang Guoxin. Spatial Distribution of Seismicity and Possible Disaster in the Nepal Himalaya and its Surrounding Region. **Proceedings of the 9th International Conference on Civil and Environmental Engineering, (ICCEE2010)**, November, 1-3 (2010), Dalian, P.R. China, Advances in Civil and Environmental Engineering, China architecture and building press, 2010, Paper number: 2.53 (本博士学位论文第三章).

[4] **Thapa Dilli Ram**, Wang Guoxin. Seismicity and Geological Structures in the Nepal Himalaya and its Surroundings. **Abstract of the 2011 conference of International Union of Geodesy and Geophysics (IUGG2011),** June 28-July 7 (2011), Melbourne, Australia.

[5] **Thapa Dilli Ram**, Wang Guoxin. Identification of Earthquake-prone Areas in the Nepal Himalaya and its Surrounding Regions Using Pattern Recognition Techniques. 2014, (to be submitted) (本博士学位论文第四章).

[6] **Thapa Dilli Ram**, Wang Guoxin. Deterministic seismic hazard map of Nepal. 2014, (to be submitted).

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