Chapter 1
Introduction

“It is a bitter and humiliating thing to see works, which have cost men so much time and labour, overthrown in one minute; yet compassion for the inhabitants is almost instantly forgotten, from the interest excited in finding that state of things produced in a moment of time, which one is accustomed to attribute to a succession of ages.”

- Charles Darwin, March 1835

1.1 Statement of the problem

Amongst all the natural calamities, earthquakes are the most destructive in terms of loss of lives and destruction of property as they occur without any warning but gives us a few minutes, at the most. It is believed that a death toll from only earthquakes across the globe is more than death toll by all other natural calamities. On an average, one earthquakes of magnitude 8 is reported to occur globally every year and about 1,30,000 earthquakes of magnitude more than three hit the earth every year (USGS, 2012; earthquake.usgs.gov/earthquakes/eqinthenews/2012). Earthquake can occur at any instance of time, in any season and in any part of the world. Honshu, Japan (M ~ 9.0, 2011) and Kamchatka (M ~ 9.0, 1952) at margins of Pacific Ocean, Sumatra (M ~ 9.1, 2004) and Sumatra (M ~ 8.6, 2012) at Mediterranean - Alpine region on Eurasian Plate; Shillong (M ~ 8.7, 1897) and Assam-Tibet (M ~ 8.6, 1950) at Himalaya range on Indo-Australiia plate are the deadliest earthquakes across the globe. As an approximate estimation, it is believed that 15 million human lives have been lost and damage worth hundred billions of dollars has been inflicted in the recorded history. The history of the earthquakes is as old as the history of civilization of mankind. By any means we cannot avoid earthquakes like other disastrous natural phenomena but only can minimize its effects by preparedness and mitigation measures. To achieve this, researchers from different fields are engaged to understand; why it happens; what happens when it occurs; where and when it may occur and finally what can be done to mitigate it. Seismology-the science of earthquakes can answer these questions up to certain extend. It helps to enhance scientific understanding of
their nature, causes, frequency, magnitude and area of influence. Like other natural processes, earthquake processes also follow its natural cycle. Each earthquake has unique characteristic of its own on different locations of the world. We can assemble our knowledge and understanding by piecing together observations of different parts of the earthquake cycle from different locations.

By improving our understanding of the earthquake processes, we can gain important insight into the physics of earthquakes in general. Earthquakes are complex phenomena as they are an expression of the forces driving tectonic plate motions, the state of temperature, stress and pore pressure within the earth, structural heterogeneities, material properties of rocks and existing faults zones under the surface and at the same time they have complex interactions with lithosphere-hydrosphere-atmosphere. Many physical, geological, geodetic, geothermal and geochemical processes are involved in the occurrence of the earthquake. In this scenario, the physics of earthquakes can explain complicated earthquake mechanism and contribute a lot to understand the earthquake processes.

As we know, earthquake is a sudden and sometimes catastrophic movement of a part of the earth's surface. It is caused by the release of stress accumulated along geologic faults or by volcanic activity hence the earthquakes are the earth's natural means of releasing stresses. When the earth's plates move against each other, stress is put on the lithosphere. When this stress is large enough, the lithosphere breaks or shifts. As the plates move they put forces on themselves and each other. When the force is large enough, the crust is forced to break and when the break occurs, the stress is released as energy which moves through the earth in the form of waves, which we feel and call an earthquake.

Many scientists from different field of earth sciences and from different regions of the world are engaged to solve this mystifying puzzle of earthquake. Some geologists try to understand tectonic movements of the plates and are engaged to calculate their relative motion, some geophysicists do study of earth’s interior and physicists are busy to understand physical processes involved with earthquake, while statistician and mathematicians try to analyze large dataset of earthquake sequences and to solve the
problem with the complicated mathematical formula. Structural engineers are busy to
design earthquake resistant buildings. They all contribute small piece of information about
earthquakes and thus we do enhance our knowledge about earthquake. We understand
earthquakes a lot better than we did even 50 years ago and a lot is yet to be done as many
important aspects of the physics of earthquakes themselves remain a mystery.

India has long history of earthquakes. In India, the study of earthquake is great practical
importance in the region of strong seismic activity like Himalaya, Assam and adjoining
area and Kutch. Numerous strong earthquakes in the history and recent past years have
taken many victims and many weaker shocks are often felt in various parts of the country.
For a dense populated area, like the country of India, it is important to know about
expected earthquake effects, no matter where the respective epicenters are. A weak but
nearly earthquake may have the same effect as the strong one whose epicenter is farther
away.

In this thesis, main focus is to look one piece of this giant puzzle of earthquake for one of
the most seismically active corner of the world i.e. Kutch region of western peninsular
India. The problem “Study of seismicity over Kutch region using multiparametric
observations: 2001 to 2011” is addressed. I accomplished this aim by studying previously
recorded moderate and large earthquakes in the region and long ongoing aftershock
sequences of 2001 Bhuj earthquake in Kutch region of Gujarat province of western
peninsular India. As we know, on January 26, 2001; a devastating earthquake struck the
Kutch region. The earthquake lasted for 85 seconds and death toll reached to more than
1,30,000. Here, an attempt is made to study seismicity over the Kutch region by means of
dynamic characteristics of earthquakes under the surface and its consequence above the
surface using multiparametric observations. The entire study has three dimensions,
comprising study of source parameters; study of interrelation between seismic events and
meteorological parameters and seismic hazards analysis of Gujarat region.

1.2 Review of literature
There are references about earthquakes in ancient Indian literature like Rigveda around
5000BCE (Lele et al., 2006) and Chinese literature of Ying dynasty (16-11 century BCE)
and Qin dynasty (221-206 BCE) (Wang, 2004). In historical times also we found references of earthquakes in Greek and British literature. Later as a result of scientific revolution during 16 to 19th century, many inventions and new thought came into vogue and Seismology- the science of earthquake born in early 19th century with the introduction of P-wave and S-wave in 1830s. In view of studying causes of earthquake, systematic field studies after earthquakes were started during second half of 19th century. First attempt to relate them with tectonic processes were made by Mallet for Naples–Italy ($M \sim 6.9, 1857$); Koto for Mino-Owari–Japan, ($M \sim 8.0, 1891$) and Oldham for Assam-India,($M \sim 8.3, 1897$) among other researchers. In 1886, John Milne explained the fracturing of the earth’s crust by kinematic and dynamic models. In 1911, elastic rebound theory proposed by Reid and in 1912 Alfred Wegener proposed hypothesis of ‘continental drift’, later in 1929, Arthur Homes supported the hypothesis which is later known as ‘plate tectonic theory’, since 1960. According to elastic rebound and plate tectonic theory, elastic strain and tectonic stress are related to relative motion of plates. There are a variety of scientific literatures available on earthquakes today. According to the thesis title and the study undertaken here, the scientific literature could be basically grouped in three sections:
(a) The scientific literature on evaluation of the source parameters, their studies and empirical relations between them,
(b) The scientific literature on interrelation between earthquake and meteorological parameters,
(c) The scientific literature on Seismic hazard assessment, its two approaches and its considerations in a particular region of the world.
Let us now go through literature for each section. Now once the causes of earthquakes well understood by theory of elastic rebound and plate tectonic, researchers then emphasized on characteristics of earthquake which explains earthquake mechanism. Earthquake mechanism can be explained by kinematic and dynamic source model. Milne (1886) was the first to present kinematic kind of model to explain earthquake processes. Later, Haskell (1964) and Brune (1970) presented kinematic models and explained earthquake dislocation, wave propagation and shaking on the free-surface. It provides fault dimensions, rupture velocity and details on slip. This model has simple and straightforward application for macro-scale earthquake simulation. Graves et al. (2006) and Olsen et al. (2008) used this model to understand geological effects on ground motion based on
waveguides and wave-propagation recorded by broadband instruments. But these models cannot explain rupture processes and have limitations for predicting source-oriented ground motion phenomena. Earthquake is such a complex phenomenon and only kinematic source models are not enough to explain it. Dynamic models help to understand the physical processes involved in the fault rupture, incorporating conservation laws of quantum mechanics, constitutive behavior of rocks under interface sliding and state of stress in the crust. Many different models of fault dynamics are currently being investigated and presented by researchers. These include quasi-static three-dimensional continuum elastic models, one and two dimensional continuum models with inertial dynamics and cellular automata. Das and Aki (1977) for fault planes and Day (1982) for fault dynamics studies used this model. Dalguer et al. (2001, 2003) and Dalguer and Irikura (2003) studied earthquake dynamics of 1999 Chi-Chi ($M_w \sim 7.5$, Taiwan), 2000 Tottori ($M \sim 7.3$, Japan) and 1999 Kocaely ($M_w \sim 7.4$, Turkey) earthquakes respectively. The only disadvantage in the dynamic modeling is that we cannot exactly know the frictional strength on the fault and the stress condition in the crust. In this scenario, earthquake dynamics by physical processes involved with earthquakes can be best explained by source parameters. The idea of measuring size of an earthquake is given by Richter (1935). The magnitude $M$ was instrumental measurements of the ground motion adjusted for epicentral distance and source depth. It was based on maximum amplitudes measured in displacement records. Later, Gutenberg (1945) extended the magnitude concept to applicable to ground motion measurements from medium-and-long-period seismographic recordings of both surface wave ($M_S$ or $M_L$) and different types of body waves ($mB$ or $m_B$). In 1956, Gutenberg and Richter introduced local magnitude $M_L$ or $M_b$. In 1975, Herrmann proposed a duration magnitude $M_d$. All these magnitude scale have one or another kind of advantage and suffering from saturation. In 1977, Kanamori prodposed a moment magnitude ($M_w$) scale which was tied to $M_s$ but do not get saturate. Choy and Boatwright (1986) established energy magnitude $Me$ which direct relates energy to magnitude. This scale is also closely related to the seismic potential for damage. Okal and Taladier (1989, 1990) introduced mantle magnitude $M_m$ for very long-period mantle surface waves. The scale $M_m$ is extensively useful to reassess moment of shallow, intermediate and deep historical earthquakes. All these magnitude scales have one or another type of limitation and useful
for particular application. While moment magnitude-\(M_w\) scale is directly determined from seismic moment and would not get saturate even at larger earthquakes. Moment magnitude scale is more accurate and widely used today for seismic hazard program. Kanamori (1983) summarized the relationship between the various magnitude scales which is useful to prepare long period catalog for the region where one or another kind of magnitude record is available. First time Hanks and Kanamori (1979) established relation between seismic moment to rupture area and displacement. This relationship is still in use for most of source measurement. In 1885, Bassani first time proposed about earthquake energy. Later Reid (1911) and Gallitzin (1915) estimated energy by different method. Finally, Gutenberg defined radiated seismic energy as a fundamental parameter describing earthquake (Gutenberg, 1942, 1956; Gutenberg and Richter, 1956a, 1956b) and established the first empirical relation between magnitude and energy. Boatwright and Choy (1986), directly determined radiated energy as an integral of seismic velocity data with the advent of broadband seismometers. To specify dynamic behavior of earthquake, rupture and stress drop is being used for a long. Eshelby (1957) and Keilis-Borok (1959) represented static stress drop as difference between final stress and initial stress at the faulting. They determined stress drop from moment and radius of circular fault area. Afterwards, Brune in 1970 suggested a forth source parameter i.e. corner frequency to calculate stress drop. Later Madariaga (1976, 1977); Chery et al. (1976) and Archuleta and Frazier (1976) presented stress drop model. Amongst all these models, Brune’s (1970) stress drop model is widely used. The model introduced by Brune (1970) was developed specifically for the ground motion associated with far-field shear waves. Brune (1970) developed the relationship between the corner frequency and the radius of the circular crack by assuming that the final stress was equal to the frictional stress. Brune (1971) later corrected equations corresponding to the approximate solution to the near-field displacement.

The problem of source study is addressed by several researchers for different earthquake of different zone and for many aftershock sequences of the world. Japan, Parkfield, Africa and Taiwan are few examples of them. Valle (2007) estimated source parameters for 2004 Sumatra (\(M_w \sim 9.1\)) giant earthquake by Rayleigh wave using EGF-Empirical Green’s function. He found seismic moment of \(5.6 \times 10^{22}\) N.m. Baltay et al. (2011) studied source
parameter for four aftershock sequences in Honsu region in Japan for $M_w$ ranging from 1.8-6.9. $E_R$ for Chuetsu-Oki main shock was of $10^{15}\text{J}$ and for Kameishi stress drop is 28.72 MPa. They concluded that there is no systematic dependence of apparent stress or stress drop on seismic moment for these sequences; they both are log normally distributed. Parkfield region of America experiences moderate earthquakes frequently. Abercrombie (2000) estimated source parameters for Parkfield region. Later Imanishi et al. (2004) determined source parameters for Parkfield region and found moment of $10^{10}\text{N.m}$, source radius of 35.6 m and stress drop of 8 bars respectively. Their results are matching with Abercrombie (2000) for the same region but results from empirical relations given by Nadeau and Johnson (1998) are far away from the reality. They concluded that small repeating earthquakes in Parkfield region have typical tectonic stress drop. Allmann and Shearer (2007) studied stress drop variation near Parkfield and came to the conclusion that no dependency of stress drop observed on Magnitude and depth. In the Parkfield, middle mountains show significantly lower stress drop value than the rupture area of 2004 earthquake.

Source parameters in African region (eastern rift and Kenya rift) are studies by several researchers. Shudofsky (1985) for East African earthquakes, Ambraseys (1991a and 1991b) for Rukwa earthquake of 1910 in East Africa and Subukia earthquake of 1928 in Kenya rift, Ayele and Kulhanek (2000) for moderate earthquakes from 1900 to 1990 are important. They concluded that seismic moment of these earthquakes of $M_w$ 6.0 to 7.0 is around $10^{19}\text{N.m}$ and western part of the Ethiopian rift is more active than the eastern. Huang et al. (2001, 2002) estimated source parameter of two large aftershocks of 1999 Chi-Chi, Taiwan earth quake. They found higher values of stress drop $\sim$ 991 and 831bars, apparent stress of 402 and 337 and $E/M_0 \sim 10^{-3}$ for $M_L$ 6.4 & 6.0 respectively. They suggested larger aftershock transformed higher percentage of strain energy into the seismic wave energy.

Some researchers have studied this problem in broad aspect of global view. Wells and Copersmith (1994) compiled source parameters for historical earth quake worldwide and developed a series of empirical relationship. They found strong correlation between
magnitude and various rapture parameters. They found different results for regions having different tectonics and concluded that tectonic setting play an important role for multiple estimates of magnitudes. Choy and Boatwright (1995) studied global pattern of radiated seismic energy and apparent stress. They concluded that correlation between energy and moment varies systematically with faulting type seismic region and tectonic environment. Venkatraman et al. (2006) estimated radiated seismic energy for large earthquake worldwide. She concluded understanding of variation in energy budget of earth quakes with sizes will immerge with better constrains on static stress drop and rupture velocity. At the regional level, Bhattacharya et al. (1997) and Singh et al. (1999) studied source parameters for Jabalpur earthquake ($M_w \sim 6.0$) and studied crustal and upper mantle structure of peninsular India and derived for Jabalpur earthquake using regional broadband data. Mandal (1998) estimated source parameters for Koyna earthquake ($M_w \sim 6.3$) and B. Ajay et al. (2006) estimated source parameters for 2005 Koyna-Warna region. They found seismic moment, source radius, stress drop and moment magnitude of $3.1 \times 10^{16}$N.m, 875m, 19MPa and 5.1 respectively. They found near-surface attenuation factor $k=0.01$ and suggested thin low-velocity sediments beneath the region. Pandey et al. (2001) estimated source parameters of 1999, Chamoli earthquake ($M_w \sim 6.8$) in Garhwal-Himalays region of North India from strong motion data. They observed seismic moment of order of $10^{25}$dyne.cm and moment magnitude in the range of 6.53-6.69 for different stations. Earlier occurrence of low stress drop earthquakes in Garhwal Himalaya regions were studied by Sharma et al. (1994). Source parameters were also studied previously using body wave for Himalaya and adjoining region by Singh et al. (1979). Wason and Sharma (2000) presented source parameters for local earthquakes of Garhwal-Himalaya region using digital broadband data. They found seismic moment ranges from $10^{18}$ to $10^{20}$ dyne.cm and stress drop less than 100bars for magnitude range 2.4 to 3.3. Nath et al. (2008) estimated source parameter for Gauhati region from geotechnical analysis. They found higher values of moment of the order of $10^{23}$ dyne.cm and stress drop as high as 442bars for $4.5 \leq M_w \leq 4.8$. 2001 Bhuj earthquake ($M_w \sim 7.7$) shook the western peninsula of India and its effect experienced far away as 2000 km. The source study for this devastating event was carried out by Singh et al. (2004) using EGF-empirical green’s function for Bhuj Main shock. They estimated $M_0=3.4\times10^{27}$ dyne.cm, effective stress drop $\sim 300$ bars and $E_R=2.1\times10^{23}$
erg. They suggested that rupture propagation was essentially radial and ratio of rupture to shears wave velocity ~ 0.5 is reasonable agreement with duration of source time function. Mandal and Johnston (2006) estimated source parameter for 2001 Bhuj aftershocks. The value ranges from $10^{11}$ to $10^{17}$ N.m, 239-285 m, 0.63-20.7 MPa for seismic moment, source radius and stress drop respectively for $M_w$ ranging from 2.16 to 5.71. They found high stress drop values are more scatter towards the larger seismic moment. They concluded that they observed size dependency of stress drop from estimated seismic moment and source radius which is not observed for other SCR earthquakes in India and globally. Later Saha et al. (2012) found $M_0$ from $10^{12}$ to $10^{16}$ N.m, Stress drop ~ 0.12-20 MPa and source radius 132-513m for the same sequence. Recently, Source parameters for Talala region of Saurashtra, West India are determined by S. Kumar et al. (2012). They found seismic moment of $10^{16}$N.m, stress drop of 16bars and source radius of 2.3km for the 2011 Talala earthquake of $M_w$ ~5.1. We hypothesize that the results from the individual studies, noted above, indicate that the source parameters do depend on the seismic moment and that the scaling relationship appears to differ between the various seismogenic environments.

For Section-II of this thesis, i.e., the study of interrelation between seismic event and meteorological parameters, we have references from the ancient histories of Herodotus (484-425 BCE) to the modern writings of David Lance Goines and from Indian literature; from Rigveda to Rajatrangini we found narrations describing relation between earthquake and weather parameters. In Brihat Samhita, great Indian scholar Varahmihira (505–587 CE) discussed a number of signs warning of earthquakes. In this section, three meteorological parameters are studies i.e. temperatures, barometric pressure and rainfall. Use of thermal data in seismic studies was first put into application in Russia in 1985. Grony et al. (1988) studied outgoing IR radiation as an indicator of seismic activity. Afterwards Qiang et al. (1991, 1997, 1999) studied thermal anomaly during impending earthquake for China. They proposed earth-degassing theory for temperature increasing mechanism and suggested temperature increase as an earthquake precursor. Later, Tronin (2000) supported Qiang by his studies on satellite thermal survey as a new tool for the study of seismo-active regions. At the same time Freund (2000, 2002, 2003) proposed ‘$p$-
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Hole activation’ theory as a pre-earthquake phenomenon. Ouzounев and Freund (2004) found infrared emission prior to strong earthquake. Pulinets and Dunajecka (2007) studied previous meteorological data around the time of 1985 Mxico ($M \sim 8.1$) earthquake. They found specific variation of air temperature and relative humidity at the region close to the tectonic plates. They suggested before an earthquake increased radon emanation provides Lithosphere-Atmosphere-Ionosphere coupling to vary air temperature and humidity through the air ionization. Corvone et al. (2006) also found anomalous behavior of surface latent heat flux-SLHF in the epicentral region during Tokachi-Oki ($M \sim 8.3$), Japan earthquake. At the regional level Dey and Singh (2003) studied surface latent heat flux-SLHF as an earthquake precursor. They studied five earthquakes in Indian continent, Taiwan ($M_w \sim 7.7$, 1999) and Mexico ($M_w \sim 7.3$, 2003) during 1993 to 2003. They found maximum increased of SLHF 2 to 7 days prior to the main earthquake. They concluded that systematic pattern of SLHF shows a potential precursor to provide information about earthquake and high resolution remote sensing data may provide more reliable information. In 2004, Dey et al. (2004) extended the study and found anomalous changes in water vapor around epicentral region. They concluded that water vapor increases over the land before an earthquake and it increases over ocean after the earthquake. Thermal anomaly also studied by Saraf (2003) and Saraf and Choudhary (2005a) for 2001 Bhuj earthquake by NOAA-AVHRR sensor. Satellite based IR anomaly studied by Saraf (2005b) for 2003 Algerian earthquake and by Saraf et al. (2007) for other major earthquakes. Swapnamita et al. (2006a) studied other earthquakes of Kalet, Pakistan ($M \sim 6.1$, 1990); Zhangkei, China ($M \sim 6.2$, 1998); Izmit, Turkey ($M \sim 7.6$, 1999); Bhuj, India($M \sim 7.7$, 2001); Double Hindukush-Afghanistan ($M \sim 6.2$ and $M \sim 7.4$, 2001); Hindukush-Afghanistan ($M \sim 6.1$, 2002); Xinjiang, China ($M \sim 6.4$, 2003) and found temperature anomaly from $2^\circ$C - $10^\circ$C and Swapnamita et al. (2006) studied Bam-Iran ($M_w \sim 6.6$, 2003) and Dahoeieh-Zarand, Iran ($M_w \sim 6.4$, 2005 ) earthquakes by remote sensing methods. She also found temperature changes of $6^\circ$C-$8^\circ$C for both the earthquakes. Panda et al. (2007) studied Kashmir earthquake ($M \sim 7.6$, 2005) by space borne sensors like Advanced Very High Resolution Radiometer-AVHRR and MODIS-Moderate Resolution Imaging Spectro-radiometer from Terra satellite of NASA. They found $4^\circ$C-$8^\circ$C rise in land surface temperature (LST) to the south of the earthquake epicentre.
We have very few references for study of barometric pressure change during earthquakes. Mukumo (1968) observed atmospheric pressure disturbances recorded by microbarographs along Pacific coast in Alaska after the great 1964 Alaskan earthquake of $M \sim 8.7$. Their studies of phase and group velocity of pressure disturbances suggest that the pressure disturbances might have been caused by rapid vertical ground displacement due to surface tectonic deformation. Ohtake and Nakahara (1999) studied seasonality of great earthquake occurrence at north-west margin of the Philippine Sea plate. During their study, they checked the possibility of stress change cause by annual variation of the atmospheric pressure. They suggested that atmospheric pressure hardly accounts for the seasonality of the great earthquake. John Ebel (2002) studied weather and seismograph pattern in Boston area of west UK. He found different observation then Mukumo (1968) and Ohtake (1999). He observed that low pressure systems have their impression on seismogram at highest amplitude in microseism. While other found exact reverse result that whenever seismic event occurs, it generates atmospheric pressure changes. Wadata et al. (2006) confirmed barometric pressure changes with respect to 2003 Tokachi-Oki, Japan earthquake. They observed that pressure change starts at the arrived of seismic waves and reaches its maximum amplitude at the arrival of Rayleigh waves. They compute the seismic-to-pressure transfer function and concluded that observed pressure change was driven by the ground motion of seismic waves passing by the site.

On the accountability of rainfall, Huang et al. (1979) performed a detailed study to check relationship between precipitation and earthquake in South–California. They compare seasonal rainfall data for 90-years with occurrence of 12 events of $M \geq 6.0$ earthquakes near San Andreas fault in southern California. They found that most of these earthquakes occurred after drought years pattern terminated by one or two consecutive heavy rainfall seasons. Thus drought-heavy rainfall cycle can be observed prior to major earthquake. Costain et al. (1987) proposed a hydroseismicity hypothesis in generation of intraplate seismicity. He suggested that in crustal volumes with a combination of connected fractures and adequate groundwater, natural transient increases in hydraulic head in recharge area of ground water basins can be transmitted to depth of 10-20km and thereby trigger earthquakes. Further, in extended study Costain (1996), confirmed that long-term increase
and decrease in rainfall cause periodic regional and temporal variations in the elevation of
the water table that results in small changes in fluid pressure by pore pressure diffusion at
any given depth in the crust. The chemical effects of small changes in fluid pressure lead
mechanical processes resulting in a ‘hydraulically induced seismicity’. Liritzis and
Petropoulos (1992) studied rainfall data of Athens for 119 years and compared with the
occurrence of large \( M \geq 6 \) earthquakes along the fault and thrust systems in Athens. The
preliminary investigation suggested the possible occurrence of a large earthquake as a
triggering factor of precipitation. Betim Mü (1995) studied earthquake of Albania from
1901 to 1990. During the period the region experienced 211 earthquakes with \( M_s \sim 4.5 \).
They attempted to cross-correlate rainfall and seismic activity and concluded that changing
groundwater can act as a valve allowing accumulated seismic energy to be released earlier
without groundwater change in Albania region. Furthermore, he studied seismic activity
and rainfall induced earthquake in Balkan area. (Betim Mü, 1999) and found
interconnection between these two parameters in Balkan region. Later, Kraft et al. (2006)
studied earthquake swarms, a result from the interactions of subsurface fluids and earth’s
crust. They observed two rainfall-induced swarm sequences and concluded seismicity in
Hochstaufen region is induced hydraulically. In India, first time I have studied impact of
2001 strong earthquake and its aftershock sequence on rainfall pattern and presented the
results in this thesis.

The Section-III of the thesis deals with seismic hazard analysis. The term seismic hazard
refers to the study of the effect of the ground motion at the earth’s surface due to expected
earthquake in the region. The first time this technique was introduced by joint efforts of
Allin Cornel and Luis Esteva (1966). They developed concept of designing of buildings for
earthquakes by accounting for the probabilities of earthquake occurrences. In 1968, Cornel
added ground motion equation and prepared maps for probabilistic hazard assessment for
South California for 50, 100 and 500 years return period during 1970s. McGuire developed
EQRISK and FRISK computer programs in 1976 and 1978 respectively. Seismic hazard
analysis can be achieved by two approaches. Deterministic seismic hazard analysis
(DSHA) is based on known seismic source available historical and geological data. After
Cornel (1968), many researchers have carried out detailed seismic hazards analysis for
seismically hazardous region around the globe. Auden (1959), Gaur and Chouhan (1968), Kaila and Rao (1979), Khattri et al. (1984), Parvez and Ram (1997, 1999), Parvez (2001, 2002, 2003) are some of examples. First attempt to evaluate seismic hazard for Indian subcontinent based on deterministic approach was done by Parvez (2003). DSHA for Bangalore city is done by Sitharam and Anbazhagan (2007) and for Chennai city by Boominathan et al. (2008). For Gujarat and adjoining area, DSHA is given by Shukla and Choudhary (2012). They presented DSHA for six major cities of Gujarat. Chopra et al. (2013) presented hazard analysis for Gujarat region for building design purpose. They estimated expected damage to buildings from future large earthquakes in Gujarat region. It has been observed that the seismic hazard of Kutch region is more in comparison with Saurashtra and mainland. All the cities of Kutch are expected peak acceleration in excess of 500 cm/s$^2$ at surface in case of future large earthquakes, while expected accelerations of 200 cm/s$^2$ for Saurashtra and 100 cm/s$^2$ for Gujarat mainland is estimated by them. DSHA is carried out using specio-temporal clustering over the region. Earlier Basab et al. (2010) used this method to estimate seismic hazard in Himalaya and Andaman-Burmese Arc.

Another approach of probabilistic seismic hazard analysis (PSHA) is widely used by researchers. After 1970s, PSHA maps became more popular. PSHA based analysis is carried out by Ferraes (1985) for Hellenic Arc, Ferraes (1986) for Mexico City, Gence Genc (2004) for Turkey, Atkinson (2006) for eastern North America, Raghukant and Iyenger (2006) for Mumbai city, Mahajan et al. (2009) for North-West Himalaya and Yadav et al. (2011) for Northeast India and adjoining region are the major contributions in seismic hazard analysis based on different models. In the present study, we used Bayesian model for probabilistic hazard analysis. Present model of Bayesian extreme-value distribution was initially introduced by Benjamin (1968). Later Campbell (1982, 1983) combined the Bayesian probability theory with a probabilistic model of extremes. Parvez (2007) first time presented seismic hazard analysis on the basis of Bayesian approach for Indian subcontinent, i.e. Northeast India. He calculated basic parameters and estimated prior seismicity and updated in terms of Bayes’ theorem. He found that central Himalaya, Indo-Burma border, Burmese arc and Burma region exhibits highest probability of earthquake occurrence than rest of the region.
Bayesian approach also applied to Circumpacific belt and Greece in view to derive seismic hazard parameters by Tsapanos et al. (2001, 2002). They estimated quintiles of the probabilistic distribution of $M_{\text{max}} > 6.0$ for different time-intervals. They found high probabilities for Ochrida, Samos and Chios region of Greece. For Greece probabilistic Bayesian prediction is given by Stavrakakis and Tselentis (1987) by seismic hazard maps for Greece. Galanis et al. (2001) presented the same for South America. They first studied temporal distribution and then magnitude distribution. On the basis of these studies, they estimated prior values and later posterior parameters for calculating probabilities. They found that probability of occurrence of earthquake of $M > 7.5$ for South Colombia is 68%, for southern Peru is 81%, for central Chile 63% and for South Chile is 60%.

1.3 Objectives of the study

- To study distribution of earthquakes over the globe and to study characteristics of the deadliest earthquakes of the world.
- To study Jan 26, 2001 earthquake and its long ongoing aftershocks sequence in detail with multi-parametric approach.
- To estimate the source parameters for detailed understanding of the characteristic of source, dynamic behavior of earthquakes and earthquake mechanism using near and far-field waveforms and spectra of seismic waves with implication of Jan 26, 2001 Bhuj earthquake and aftershock sequence.
- To characterize and to establish empirical relations between different source parameters and to draw first order trends in relationships between source parameters for Kutch region for ongoing aftershocks sequence of Jan 26, 2001 Bhuj earthquake and for future large earthquakes.
- To study inter-relation between seismic events and variation in meteorological parameters like air temperatures, barometric pressure and rainfall pattern.
- To derive seismic hazard analysis for entire Gujarat state on the basis of two approaches i.e., Deterministic Seismic Hazard Analysis (DSHA) using specio-temporal clusters Probabilistic seismic hazard analysis (PSHA) on the basis of Bayesian extreme value model.
1.4 Study area and data used

The study area of present work is Kutch region, Gujarat province of western peninsular India. The Kutch region is located between latitude 22.44°N-24.41°N and longitude 68.89°E-71.45°E. It is on the Indo-Australian primary plate and on Indian sub plate. Figure 1.1 shows the study area-Kutch region of the present study.

![Figure 1.1 Location map of the study area-Kutch region.](image)

General geology and seismotectonic settings of the study area in detail are discussed in Chapter 3 under section 3.2. When we think about seismically most active region of India, Kutch region comes at the third, after Himalayas and Northeast Indian region. It is declared as Zone V of seismic zones by Bureau of Indian Standards. Three large earthquakes of
Kutch ($7.7 < M < 8.2$, 1819), Anjar ($M \sim 6.0$, 1956) and Bhuj ($M \sim 7.7$, 2001) has visited Kutch region in past and Jan 26, 2001 Bhuj earthquake ($M_w \sim 7.7$) and its long ongoing aftershock sequence is the main source of inspiration for this study. Seismic waveform data recorded by different seismological observatories of India Meteorological Department from immediate hour of Jan 26, 2001 Bhuj earthquake ($M_w \sim 7.7$) to Dec 2010 are used and catalog data of Indian Meteorological Department(IMD) from Jan 2001 to Dec 2012 and Institute of Seismological Research (ISR) from Jan 2007 to Dec 2012 are considered for the study. I also used published catalogue of United States of Geological Survey (USGS), International Seismological Centre (ISC), National Disaster Management Authority of India (NDMA) and Geological Survey of India (GSI). I used meteorological data recorded by three meteorological observatories namely Bhuj, Naliya and New Kandla of IMD network situated over Kutch region from Jan 1991 to Dec 2012 and normal climatological data from 1971 to 2000 latest available with IMD. Statistical data for Kutch region are collected from the state agencies, like Department of Relief, Departments of Statistics and Gujarat State Disaster Management Authority (GSDMA), Government of Gujarat. Secondary data are collected from scientific journals, periodicals, newspapers, websites and other reference materials; Nature Geoscience, Bulletins of Seismological Society of America, Journal of Geological Society of India, Mausam, Earth System Science, Times of India (Ahmedabad edition), Journal of Physics, Science Direct, Elsevier and Springer are some of them.

1.5 Outline of the thesis

As stated above, the entire thesis is divided into three sections of total eight chapters. The following organization chart in Figure 1.2 describes the outline of the study. Chapterization scheme can be discussed briefly here. Chapter 1 is general introduction of the problem which includes statement of the problem, literature review and study area along with description of data used. Chapter 2 deals with seismicity over the globe and at regional level as it is very much important to study worldwide and regional status of the seismicity before focusing on the local seismicity i.e. seismicity over Kutch region. Chapter 3 describes past and present scenario of seismicity over Kutch region. The description in Chapter 2 and Chapter 3 i.e., distribution of large destructive earthquakes
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and its characteristics at International, national and regional level helped me to keep the knowledge to the date. Chapter 4 deals with characterization and empirical relations between source parameters and Chapter 5 describes interrelations between meteorological parameters and seismic events. Finally, Chapter 6 finds results on seismic hazard analysis. Chapter 7 and Chapter 8 represent major conclusions of the study and scope of present work and future perspective respectively.

Figure 1.2 Organization chart for thesis layout.