ABSTRACT

India frequently experiences threats from a variety of natural hazards such as floods, droughts, landslides, cyclones, earthquakes, tsunamis, etc. Among these, the earthquake caused extensive damage in the past and heightened the sensitivity of administrators, engineers and general public to the looming hazard due to future earthquakes occurring near densely populated Indian cities. Earthquakes have occurred sometimes more or less in the same regions from pre-historic times, where they are presently felt. Many earthquakes in the past have left many lessons to be learned. These are essential to plan infrastructure and even to mitigate such calamities in future. In the last three decades, large earthquakes have caused massive loss of lives and extensive physical destruction in India.

The Central India (CI), concern of the present study, also suffered both financial as well as human lives losses during incidences of five historical damaging earthquakes (i.e., 1927 Mw 6.5 Son valley, 1938 Mw 6.3 Satpura, 1957 Mw 5.5 Balaghat, 1970 Mw 5.4 Broach and 1997 Mw 5.8 Jabalpur) along the SONATA and adjacent regions. Although the seismicity of this region is broadly sporadic in nature with few events occurring within the Central India Tectonic Zone (CITZ), occasionally, earthquakes with magnitudes more than 4.0 are still continued in different parts of this region. In line with these evidences, the following works were attempted under the present study. Here, we aim to understand the subsurface earthquake-source processes, related hazards, and their assessment over the CI. The entire present thesis has been divided into seven distinct chapters for attending the above tasks sequentially.

Chapter I introduces the study area that extends between latitudes 18° and 26°N and longitudes 73° and 86°E, and covers Madhya Pradesh, a part of Rajasthan, Gujarat, Maharashtra, Chhattisgarh and Uttar Pradesh. The area broadly falls under seismic zones II and III, and several tectonic features viz. Bundelkhand craton, Bastar craton, part of Dharwar and Singhbhum cratons, Son-Narmada-Tapi (SONATA) lineament, Central India Tectonic Zone (CITZ), and Mahakoshal, Satpura, Sakoli and Dongargarh fold belts are broadly distributed over the area. This chapter briefly also discusses the earlier geophysical works and a concise outline of the present work.
Chapter II summarizes the geology and tectonic setup of the region. A high resolution tectonic map has reconstructed for discussing the above.

Chapter III deals with the source mechanisms of small to moderate magnitude local earthquakes recorded by broadband stations under national seismic network.

Chapter IV demonstrates the detailed analysis and understanding of frequency dependent shear wave attenuation characteristics for the study area. The $Q_S(f)$ has been estimated using Double Spectral Ratio (DSR) method considering waveforms of 25 local earthquakes with magnitude ($M_L$) ranging from 3.0 - 4.7.

The analysis of deterministic seismic hazard carried out using five historical damaging earthquakes along the SONATA is explained in Chapter V.

Probabilistic of Seismic Hazard assessment (PSHA) carried out using all possible tectonic sources along the CITZ is discussed in Chapter VI.

Chapter VII summarizes the entire works including the conclusions of the thesis.

We have analyzed the seismic hazard for the study region based on updated seismotectonic database. Historical earthquake data since 1842 are compiled using catalogues of IMD, GSI, USGS, ISC, EMSC, etc, and 231 events of magnitude ($M_w$) between 3.0 and 6.5 are selected for the present study. Faults, lineaments and other neotectonic features have been identified using the seismotectonic Atlas of GSI and the recent seismicity pattern over the area. It is worth mentioning that small to moderate magnitude (up to 5.2) earthquakes are still occurring along such local crustal discontinuities. A high resolution tectonics map is generated using the Generic Mapping Tools (GMT). This map contains the information of topography, major cratons, active faults, lineaments, major rivers and few bench mark cities.

Twenty six earthquake events those occurred during the period from May, 1997 to October, 2012 and recorded at eleven three-component permanent broadband seismic stations in Central India are used to understand the subsurface geological processes along the CITZ. The preliminary parameters of the 26-events computed using SEISAN software have been improved through Moment Tensor Inversion (MTI). Revised 5-layered velocity model up to lower crust has been obtained using VELEST program for the study area. The moment tensor inversion of the 1997 Jabalpur earthquake reveals a seismic moment of $0.41 \times 10^{19}$ N-m, moment magnitude ($M_w$) of 6.3, and a focal depth
of 38 km, while fault parameters suggest a fault plane with strike 62.1°N, dip 67.9°, rake 68.2° and an auxiliary plane with strike 288.8°N, dip 30.6°, rake 132.4°. Similar task has also been extended for other 26-events. The minimum and maximum depths of 5 and 38 km are estimated for events occurring towards west and east of the study area. Besides, a general trend on increasing depth-levels of events is noted towards east and becomes maximum near Jabalpur, Rewa and Mandla. Apart from thrust dominated movements, normal and strike-slip motions are also apparently active in the area. Further, two events are dominated by compensated linear vector dipole (CLVD) mechanism. We propose here that the Central Indian region being curviplanar with sinistral curvature is subjected to compression along the longer ~ E-W segments and transtension along shorter segments with ~ NE-SW segments. The occurrences of normal faulting, intrusion of mafic plutons and CLVD mechanism for earthquakes are interpreted to be related with transtension zones and reverse mechanism earthquakes are associated with the compressions along ~ E-W segments.

The frequency-dependent shear wave quality factor ($Q_s$) has been estimated over the CITZ and its surrounding regions using Double Spectral Ratio (DSR) method considering 25 local earthquakes with magnitude ($M_L$) varying from 3.0 - 4.7 recorded at 11 stations operating under the national seismic network. The Fast Fourier Transform (FFT) spectra are computed from the recorded waveform having time-window from onset of S-phase to 1.0 sec and for a frequency-band of 0.1 – 10 Hz. Three different average shear wave velocities (i.e., 3.87, 3.39 and 3.96 km/sec) for northern, central and southern part have been obtained over the study area using a pair of earthquakes recorded at pair of stations. Three well-defined zones are identified based on $Q_s$ values i.e. 51 to 96 for the SONATA region ($Q_s = 51f^{0.49}$; $Q_s = 90f^{0.488}$ and $Q_s = 96f^{0.53}$), 204 to 277 ($Q_s = 204f^{0.56}$ and $Q_s = 277f^{0.55}$) for both sides of the SONATA area, and 391 to 628 ($Q_s = 391f^{0.49}$, $Q_s = 409f^{0.48}$, $Q_s = 417f^{0.48}$, $Q_s = 500f^{0.66}$, $Q_s = 585f^{0.65}$ and $Q_s = 628f^{0.69}$) for areas little away from the CITZ area.

The very low $Q_s$ values between 72 and 325 at frequencies from 2 to 10 Hz along the SONATA region might be associated with the fractures, alluvium and deep sheeted heterogeneous medium. While the moderate $Q_s$ values between 301 and 1006 at frequencies from 2 to 10 Hz possibly accounts for the stronger formation of Deccan.
Trap and cratonic areas (e.g., Bundelkhand in the north and Bastar in the south). The estimated high Qs values between 549 and 3076 at frequencies from 2 to 10 Hz might be indicating the higher seismic stability of the south Indian shield region. The low Qs values might be attributed to the more heterogeneous SONATA rift system. Low Qs values further may presumably be associated with lower-level of seismicity and apparently account for higher tectonic stress accumulation over long duration. The long-term accumulated stress is generally released through occasional triggering of moderate magnitude earthquakes in the CITZ zone. Surrounding the SONATA region, the higher Qs values possibly accounts for a more homogeneous subsurface structure.

There are two distinct methodologies for the seismic hazard analysis viz. the deterministic seismic hazard analysis (DSHA) and the probabilistic seismic hazard analysis (PSHA). In the present study, we have used both the methods. Seismic hazard map is generated in the backdrop of Modified Mercalli (MM) intensity scale along the SONATA zone and its surrounding regions in CI following the DSHA. First, the whole area is divided into 2665 square grids of 20×20 sq. km dimension. Next, we assign the soil amplification factor (ratio of the surface to the bedrock ground motion) at the centre of each grid. Finally, we estimate the soil amplification factors and its responses for 30 m depth of soil at very close spacing of ~1 km interval for 25 sites in Delhi region using a local acceleration time history of duration ~ 41 sec which is recorded at the Delhi Ridge Observatory in the rock site. Then, these soil parameters are used for similar types of soils in the present study. The soil amplification factors (e.g., 1.10, 1.50, 2.50 and 3.00 for hard rock, soft rock, medium soil, and soft soils) are chosen on the basis of the geology and geomorphological features crossing the grids. Five historical damaging earthquakes (i.e., 1927 Mw 6.5 Son valley, 1938 Mw 6.3 Satpura, 1957 Mw 5.5 Balaghat, 1970 Mw 5.4 Broach and 1997 Mw 5.8 Jabalpur earthquakes) which have occurred along the SONATA and adjacent regions, have been chosen for DSHA. Seismic wave attenuation relation is used for estimating the peak ground acceleration (PGA) and then the estimated PGA values are transformed into intensities on MMI scale and hence hazard maps are evolved at the surface level for the study area. It is apparent from the hazard maps that the quantified intensities are somehow correlated with respective magnitudes of earthquakes. The more or less elliptical patterns of intensity contours might be caused by soft to medium soil covers associated with the
weak SONATA zone. A wider intensity contours towards south are also noted for events located either to the south of the SONATA lineament (e.g., 1957 Balaghat and 1938 Satpura) or in the deeper part of the lithosphere (e.g., 1997 Jabalpur). This study though provides important information related to damages, precise seismic hazard assessment is yet to be carried out for proper sustainable development and disaster managements for well-developed cities in CI.

PSHA thus is carried out for CI using new dataset. Seventeen significant faults and lineaments, those having considerable influence on ground motion, are identified from the seismotectonic map. Regional recurrence relation has been developed using historic and instrumental database because of lack of slip rate for individual fault. Based on derived robust relationship between ZPA and Vs, uniform hazard response spectra are reconstructed for 10% and 2% probability of ground motion exceedances in 50 years and found to be well-compatible with earlier studies. The designed spectra developed in this study incorporate uncertainties in location, magnitude and recurrence of earthquakes, and hence are superior to spectra recommended by IS 1893-2002. Influence of local site condition has been accounted for providing designed spectra for A-, B-, C-, D- and E/F-type sites (NEHRP soil class) separately. Many workers reconstructed regression equations to generate the response spectra for soil types A, B, C and D except E/F type. They also opined that rigorous nonlinear site response analysis would be needed for E- and F-type sites with specific local parameters. It is internationally accepted for building coding that E/F-type soil can only be liquefiable and hence the responses for such soil are not available. In the present study an attempt has been made to carry out the soil response analysis for A, B, C, and D and E/F-type soils on the basis soil amplification data for the Delhi Ridge and surrounding regions. We estimate the frequency-dependent soil amplification factor at the surface ($F_s$) from a recoded acceleration-time series at the rock site using equivalent linear method, and generate the response spectra for E/F-type soil.

Three recurrence relationships with seismic b-values ranging from 0.68 to 0.76 are established under the present study. The predictive response spectra generated at the bedrock level for $Vs = 3.5\ km/sec$ using the analyzed hazard curves for 10% and 2% probability of exceedance of ground motion at a site for 50 years corresponds to the earthquake of return period 475 and 2475 years, respectively. Variation of mean annual
rate of exceedance with PGA and $S_a$ at $t = 0.1$ sec for 5% damping are obtained according to the prescribed designed force of BSSC (2001) for bedrock A-, B-, C-, D- and E/F-type soils. The uniform hazard response spectra for CI are obtained at different site conditions according to National Earthquake Hazard Reduction Program (NEHRP) site classifications for A-, B-, C-, D- and E/F-type soil’s criteria for average shear wave velocity $V_s(30)$ up to 30 m depth. However, in recent times, the $S_a$ is more useful parameters for designing the short period (0.2 - 0.5 sec) for residential normal buildings and long period (1.0 sec) for monuments like structures. The Uniform Hazard Reduction Spectra (UHRS) are generated for probability of 10% exceedance of ground motion at a site for 5% structure damping in 50 years and probability of 2% exceedance of ground motion at a site for 5% structural damping in 50 years over the study area, respectively. A comparison is made between the normalized designed response spectra for maximum considered earthquake of soil type A, B, C, D and E/F and the IS 1893-2002 code involves only three soil types used by Indian designers. Type I: Rock or Hard soil, Type II: Medium soils and Type III: soft soils are classified on the basis of N-values of Standard Penetration Test (SPT). It may be stated that the normalized design spectral shapes for Type-I, Type-II and Type-III soils (IS 1893-2002) are similar with C-, D- and E/F-type soils in the present study. Further, as per IS 1893-2002 code, the normalized response spectra for Type I site corroborates with the C-type site’s design response spectra of NEHRP instead of its A- or B-type soil, and that essentially overestimates the analysis of design. The zero peak acceleration (ZPA) is 0.08 g and 0.15 g for return period of earthquake $T = 475$ years and $T = 2475$ years at the rock-level. The common practices in the study of dynamic soil responses are confined within 30 m soil to solve the engineering purposes for site characterization. In line with this understanding, the different levels of the Indian Government are encouraging to carryout seismic microzonation study, and accordingly, any structure are designed to reduce the disaster in cities of highest seismic risk on priority basis and so on. Based on this inference, the present PSHA is very important to evaluate the exact soil response at a site with due consideration of the NEHRP soil classifications. The generated response spectra for A-, B-, C-, D- and E/F-type sites will thus have immense use to the engineers for designing structures for specific soil types. The design spectra developed here incorporate uncertainties in location, magnitude and or recurrence of earthquakes;
hence, these are superior to spectra recommended by IS - 1893. Influence of local site condition has been accounted by providing design spectra for A-, B-, C-, D-, E/F-type sites separately. The result shows that the frequency content of the UHRS varies with local site condition. The present work has provided requisite parameters for building designers and engineers. The results presented here can be directly used to create a microzonation map for Bhopal (BHPL), Jabalpur (JBP), Nagpur (NGP), Akola (AKL) and other cities of CI region after getting the detailed shear wave profile for the upper 30 m layer. A micro-level seismic hazard map of Bhopal and cities surrounding SONATA region in CI on a finer grid will create the needs of city-level disaster management.

Empirical power law relationships for ZPA against shear wave velocity at bedrock, A-, B-, C-, D-, E/F-types of soils for the return period of 475 and 2475 years as 
\[ Z_{PA_{T=475}} = 0.1146V_s(30)^{-0.2924} \text{ and } Z_{PA_{T=2475}} = 0.2053V_s(30)^{0.2053} \] are established. These two equations for ZPA will be much useful to the engineers for estimating the base-shear of a structure using the \( V_s(30) \) at top 30 m layers, and moreover, the equations will reduce the uncertainty for categorizing the site class in complex areas for designing purposes. The total design seismic base-shear for the buildings (\( V_B \)) along each direction due to earthquake is equal to the product of design horizontal seismic coefficient (\( A_h \)), total weight of the building (\( W \)). Further, the horizontal seismic coefficient (\( A_h \)) is a function of zone factor (\( Z \)), the periodic variation of \( S_a/g \), importance factor (\( I \)) and response reduction factor (\( R \)) as per IS: 1893-2002. Here, we equate the parameter \( Z \) as ZPA. As per the IS 1893-2002 code, \( Z \) varies from 0.10 to 0.16g for seismic zones II and III for all soil Types-I, II and III, respectively. Instead, in the present study, we suggest to estimate the \( Z \) value from the empirical relations for ZPA using \( V_s(30) \) values prior to the assessment for new sites. Interestingly, we found ZPA as 0.18, 0.23, 0.27, 0.31, 0.35g for sites A, B, C, D, and E/F, respectively for MCE of \( T = 2475 \) years. The estimated ZPA and the normalized designed response spectra are helpful to the engineers for selection of useful designed periods of normal residential buildings or tall structures (multistoried buildings, tower, etc.) and lateral long structures such as bridges, moreover, the building code for the study area can be modified accordingly.