The occurrences of significant damaging earthquakes viz. 1819 Kutch, 1900 Coimbatore, 1927 Son Valley, 1938 Paliyad, 1938 Satpura, 1956 Anjar, 1964 Midnapur, 1967 Koyna, 1967 Ongole, 1969 Bhadrachalam, 1969 Mount Abu, 1970 Broach, 1975 Shimoga, 1993 Latur, 1997 Jabalpur, and 2001 Bhuj in the peninsular India signify its profound seismic instability, and argue the long-term view of stable continent. Gupta et al. (1969), Banghar (1972), Gupta et al. (1972), Chandra (1976, 1977, 1979), Gupta (1985, 1992), Rastogi (1992), Chung and Gao (1995), Gupta et al. (1997), Vita-Finzi (2004) interpreted the historical earthquake events based on focal mechanism solutions. Their studies revealed that the pre-existing tectonic lineaments are the weak zones where increasing stress concentration leads to the occasional occurrences of damaging earthquakes in the peninsular India. The Central India Tectonic Zone (CITZ) collocated with the peninsular India, experienced vertical tectonics and was re-activated several times since the Precambrian (West, 1962; Choubey, 1971; Kailasam, 1979; Ravi Shankar, 1988). Further, the CITZ is slightly different from other regions due to the fact that in its western part, earthquake hypocentres are located at shallower depth-levels (< 20 km) as opposed to deep-seated (close to the Moho) hypocentres in the eastern parts. We thus may propose that the eastward increasing depths of earthquake events (e.g., 1927 Son Valley, 1938 Satpura, 1964 Midnapore and the recent 1997 Jabalpur) in CITZ (Chandra, 1977; Purnachandra Rao et al., 2002) obviously demonstrate more deformation of the regions near Moho. Triggering of earthquakes was also noted in the lower crust in rift regions elsewhere (e.g., the Reelfoot rift, the Kenya rift, the Amazon rift, Zoback and Richardson, 1996; Pollitz et al., 2001).

Stress is likely being accommodated and amplified across plutons (Campbell, 1978; Stevenson et al., 2006), lithospheric flexure (Bilham et al., 2003), mid-lower crust (Zoback et al., 1985), around regional gravity lows (Chandrasekhar et al., 2005), intersecting faults (Talwani, 1988). Sykes (1978) and Hinze et al. (1988) interpreted the strong earthquakes in the peninsular shield are usually caused by loading of plate
boundary stress into the old rift systems. Rao et al. (1969) and Rao and Rao (1984) explained the continental cratonic nuclei (e.g., Dharwar, Aravalli, Bastar, Singhbhum) are the sources of seismic activities in the peninsular India. Geophysical studies reveal that the sub-surface medium along CITZ documented extensive tectonic underplating (Verma and Banerjee, 1992; Singh and Meissner, 1995), re-activation of pre-existing faults at deeper levels (near Moho, Rao et al., 2002), upwelling of fluid-induced very low resistive body through emplacement of magma in the shallower crust (Gokarn et al., 2001; Rao et al., 2004; Patro et al., 2005). Our present study of 26-mechanism solutions of events including 16-solutions of historical earthquakes indicates all types of strike-slip, over-thrusting, normal faulting, and also two events of compensated moment tensor dipole (CLVD) mechanisms. We, therefore, may conclude that the repeated occurrences of deep crustal (depth > 30 km) earthquakes might be associated with deeper-level reactivation process near Jabalpur and further towards east.

We further propose that the SONATA zone has a regional sinistral bend near Jabalpur. The regional stress field induced by the India-Asian collision on the north is associated with the development of maximum shear (first-order shear) along E-W direction, and development of Riedel and conjugate Reidel shear planes. The partitioned component of maximum compression normal and parallel to the Riedel shear is responsible for the development of thrust dominated movement. This is substantiated by the above 26-focal mechanism solution data with maximum compressive stress axis aligned along ~ N-S, which is different from the direction of Indian plate motion. The orientation close to the conjugate Riedel shear is subjected to transtension deformation with development of pull-apart opening and normal faults. Such opening facilitates mantle upwells and occurrence of mafic plutons at shallow level, which are also detected in geophysical studies. The model presented here accounts for association of thrust, normal as well as strike-slip fault related motions in the region.

We obtain the average shear wave velocities of 3.87, 3.96 and 3.37 km/sec for the constituent crust in northern, southern and central part of the study area, and those corroborate with studies of Dube et al. (1973), Bhattacharya (1981) and Singh et al. (1999). Our estimates of low Q in the SONATA region are well-correlated with the attenuation relationships of the four Indian regions i.e. the Garhwal Himalaya (Gupta et al., 1995), Koyna, Northeast India (Gupta, 1999) and Kumaun Himalaya (Paul et al.,
2003). However, the frequency exponent derived by them is relatively higher than the present computed values. Although the derived exponent of frequency for Q is corroborating with those of Singh et al. (1999), Singh et al. (2004), Mitra et al. (2006) for the peninsular India and other shield region around the world. The moderate value of Qs might be associated with regions of moderate-level seismic activity. A comparison between Qs values estimated by these workers (Singh et al., 1999, Singh et al., 2004; Mitra et al., 2006) and present analysis shows a poor correlation, and this might be caused by consideration of distant earthquakes during the estimation of a single Q value.

Mandal and Yokoi (2006) reported very low Qs (i.e., 8 at 1 Hz) values in the central part of graven and high Qs values (i.e., 31 and 40 at 1 Hz) in north and south of the 44 km long Ohchigata fault and surroundings in the Ishikawa prefecture in Japan. Low Q values between 7 and 16 were also reported by Khan et al. (2011) for the Eastern Indian Shield Region. Izutani and Ikegaya (2003) reported low Qs of 40 and higher Qs of 100 on both side across the central median tectonics lines in south-west Japan. It was also reported that Q for shear waves in the upper mantle seems to vary from about 50 to about 150 (Anderson et al., 1965). Low Qs value obtained may be due to the presence of deep sheeted faults, formation of rift and graven and the thick alluvium soil deposit area and vice versa for Dry, hard and compact rocks (Aki, 1980; Aki, 1982, Aki and Chouet, 1975; Izutani and Ikegaya, 2003; Mandal and Yokoi, 2006). Present study has delineated three well-defined zones based on Qs values of 51 to 96 for the SONATA region, 204 to 277 for both sides of the SONATA area, and 391 to 628 for areas little away from the CITZ area. The very low Qs values along the SONATA region might be associated with the fractures, alluvium and deep sheeted heterogeneous medium. While the moderate Qs values 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 highest Qs values might be indicating the higher seismic stability of the south Indian shield region. The similar higher values were also noted for the different parts of stable continental regions on the globe (Canadian shield, Hasegawa, 1985; Eastern Canada, Shin and Herrmann, 1987; Chun et al., 1987; Eastern United States, Gupta and McLaughlin, 1987; Central Appalachia, Shi et al., 1996; Adirondack Mountain, Shi et al., 1996). The computed frequency dependent average Qs value was also observed
elsewhere (Aki, 1980; Sato and Matsumura, 1980; Bennet and Banku, 1982; Masuda, 1988; Kato et al., 1992; Scherbaum and Sato, 1991; Takemura et al., 1991; Feheler et al., 1992; Yoshimoto et al., 1993; Kinoshita, 1994; Yoshimoto et al., 1998). The results thus obtained through the present study will have more significance to the geoscientist and civil engineers for their various modeling purposes, and moreover, the attenuation data will be more useful for future disaster preparedness, designing buildings, and nuclear power plants development activities.

Deterministic seismic hazard analysis using 1927 Son valley, 1938 Satpura, 1957 Balaghat, 1970 Broach, and 1997 Jabalpur earthquakes shows that the intensity (on MMI scale) distributions are more or less elliptical. It is apparent from the reconstructed 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 soils 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 or in the deeper part of the lithosphere.

The vulnerability analysis for built environment covering dwellings, community structures, industries, support system, supply lines and heritage structures is focused to ascertain characteristic natural periods and provide prognosis of damage scenario considering the ground motion model of the area. In this regard the Rapid Screening Procedure (FEMA ATC-21 1988 and ATC-21-1, 1988) and quantitative approach of demand capacity computations (FEMA ATC-40, 1996) as outlined by FEMA provide comprehensive methods. However, Codal provisions by Bureau of Indian Standards (BIS) on the building structures required to be considered for evaluating the vulnerability. The intensity maps so reconstructed are much helpful to calculate the earthquake Risk (Risk = Hazard × Vulnerability) over the region. The present study thus provides a reconnection survey to the researchers and engineers and the policy maker to prepare against the incidences of damaging earthquakes. The evaluations of seismic risk are a dynamic process and needs organized interaction between multiple participating disciplines/agencies and the end user of the results needs to be establishing suitable institutional mechanism.

The Indian Standard Criteria for earthquake resistant design of structures (cf. IS: 1893-2002) is basically guided by the characteristics of four seismic zones defined on
the seismic zonation map of India. The present study area lies in seismic zones II and III. The zonation map of India provides base value of PGA and seismic coefficients for earthquake resistance designs. However, the zonation map is a conceptual document and detailed factors for high resolution site condition with seismic parameters are still waiting. Thus, the IS code does not provide a detailed guidelines for localized hazard and risk evaluation. The study for seismic hazard thus needs to be focused on source characterization, wave path characterization, ground characterization and vulnerability analysis. The model enunciates studies on two parallel streams (i) the main stream of geoscientific characterization and (ii) parallel stream of engineering seismological studies. The geoscientific studies are focused to constrain ground condition map with rationalized existing seismic hazards and the geological conditions. The geological map would provide the base for evaluating ground motion on seismic loading where as vulnerability analysis would target the understanding of response of the built–in environment.

The Probabilistic Seismic Hazard Analysis (PSHA) carried out over the area with a radius of ~ 300 km encircling Bhopal yielded an important relationship between earthquake return period (T) and peak ground acceleration (PGA). Analyses of T and PGA shows that PGA value at bedrock varies from 0.08 to 0.15 g for 10% (T = 475 years) and 2% (T = 2475 years) probabilities of exceedance in 50 years, respectively. We establish the empirical relationships $ZPA_{T=475} = 0.1146[V_s(30)]^{0.2924}$ and $ZPA_{T=2475} = 0.2053[V_s(30)]^{0.2426}$ between Zero Period Acceleration (ZPA) and shear wave velocity up to a depth of 30 m [$V_s(30)$] for the two different return periods. These demonstrate that the ZPA values decrease with increasing shear wave velocity, suggesting a diagnostic indicator for designing the structures at a specific site of interest. Based on these robust relationships between ZPA and $V_s$, the uniform hazard response spectra derived for 10% and 2% probability of exceedances in 50 years are assimilated and found to be well-compatible with earlier study reported by Seeber et al. (1999) and Raghukanth and Iyengar (2006). The designed spectra developed in this study incorporate uncertainties in location, magnitude and recurrent earthquakes, and hence are superior to spectra recommended by IS - 1893. Influence of local site condition has been accounted for providing designed spectra for A-, B-, C-, D- and E/F-type sites separately. The result presented here can be directly used to reconstruct microzonation.
map for CI through detailed geotechnical investigations. A seismic hazard map covering CI and its environment on a finer grid will cater to the needs of precise disaster management.

We infer from this study that seismic hazard assessment is dictated by several seismological factors, including the type of soil and nature of response at the bedrock site. The effort of estimating seismic hazard by evaluating the likelihood of an earthquake occurrence and its magnitude in and around the site of interest is bearing the severity of strong ground motions expected for a certain return period. The effect of local site condition plays a vital role for local enhancement of strong ground motion with PGA and spectral acceleration. Seismic hazard assessment is a procedure to indicate on a small scale map in a geographical distribution to estimate strong ground motion parameters. The assimilated basic seismic hazard information may be useful for improving structural design/building codes for earthquake resistance structures. Such scientific endeavor may provide a set of guidelines for calculating earthquake insurance premium rate under disaster risk transfer plan of the area under study. We found that the empirical relationships between ZPA and $V_S$ for given return period of earthquakes have effective implications for construction of a structure in a region devoid of observed seismic ground motion parameters. These established relationships are equally important where the occurrence of earthquake is irregular and sporadic, and moreover, no proper guidelines. We suggest for exercising this approach in other parts of central India as well as elsewhere in the world having analogous seismotectonic settings.