J. Ind. Geophys. Union (July 2018)
v.22, no.4, pp: 389-398

Probabilistic Seismic Hazard Analysis for Jabalpur area, Madhya Pradesh, India

G. Dhanunjaya Naidu*, S. Selvan, G.R.Tripathy and L.R.Pattanur

Central Water and Power Research Station, Khadakwasla, Pune-411024
*Corresponding Author: dhanugeo@gmail.com

ABSTRACT

The Jabalpur city, situated in seismically active Central Indian Tectonic Zone (CITZ), witnessed a major earthquake of M_w 5.8 on 21st May, 1997. It caused significant damage to the structures and loss of human lives in Jabalpur city and surrounding areas. This necessitated the estimation and quantification of future ground motion in the Jabalpur area for protecting the buildings, life line and other sensitive structures. State-of-art probabilistic seismic hazard analysis study was carried out, covering the Jabalpur city on a grid size of 0.01° x 0.01° to develop seismic hazard maps of the city. Suitable Ground Motion Prediction Equation (GMPE) is used for reliable estimation of seismic hazard by considering the effects of all the earthquakes of different magnitudes and their spatial distribution. Seismic events of different magnitudes within the radius of 300 km from the Jabalpur city as center are considered for analysis. Peak Ground Acceleration (PGA) and spectral amplitudes at 0.2 sec and 1sec are estimated at each grid point, thereby, generating seismic hazard maps for Jabalpur city for the return periods of 2475 (~2500) and 475 (~500) years with 5% damping. The results highlight the surface level seismic hazard within the city.

Key words: Seismic hazard, probabilistic seismic hazard analysis, attenuation, Peak ground acceleration, ground motion prediction equation.

INTRODUCTION

It is well known that most of the earthquakes in the continents occur along the tectonic plate boundaries. However, it is also widely accepted that some of the significant seismic events occur within the rigid tectonic plate or stable continental region (Sykes, 1978). The peninsular India is considered to be seismically stable continental region, away from the seismically active Himalayan belt. However, several parts of the Peninsular India have witnessed significant seismic activity in the recent past (Khan, 2009). For instance, 1938 Satpura earthquake, 1967 Koyna earthquake, 1993 Killari earthquake, 1970 Broach earthquake, 1997 Jabalpur earthquake, and the 2001 Bhuj earthquake are some of the major devastating earthquakes that occurred in the so-called stable continental crust. Indian region is seismically divided into four zones based on intensity of the past earthquakes i.e. Zone- II, III, IV, V (IS:1893(2002). Urban areas, which are located in seismically active zones, are more vulnerable to seismic hazards due to poor land use, improper planning, lack of awareness on seismic hazard, dense population and substandard construction practices.

Jabalpur city in Madhya Pradesh is one of the major cities of India, located in seismically active Central Indian Tectonic Zone (CITZ). It lies in seismic zone-III (IS:1893(2002). Narmada South fault (NSF), which is considered to be one of the active faults in CITZ, passes close to Jabalpur city and it was assumed to be the causative source of 1997 Jabalpur earthquake with M_w 5.8 (Mandal et al., 2000). Jabalpur earthquake, apart from other earthquakes in peninsular India, has left many lessons, which are essential to be learnt in planning and design of the important structures. During Jabalpur earthquake, no strong motion records were available in the nearby affected area. The strong motion records obtained from Bhopal, about 275 km away from the earthquake affected area, are inadequate for the ground motion characterization in the Jabalpur area (EERI Special Earthquake Report, 1997). Hence, it is essential to estimate the future ground motion of the forthcoming earthquake events to mitigate the seismic risk. In the present study, the Maximum Credible Earthquake (MCE) and Design Basis Earthquake (DBE) level of ground motions, are estimated using suitable Ground Motion Prediction Equation (GMPE).

Many researchers have studied the occurrence of Jabalpur earthquake and its consequences. A study, soon after the Jabalpur earthquake by Gupta et al. (1997), revealed that it is a thrust type faulting along ENE-WSW trending by focal mechanism solutions and isoseismal map. A multi-disciplinary project on seismic microzonation study of Jabalpur urban area was initiated by Department of Science and Technology (DST). Several national nodal agencies viz. Geological survey of India (GSI), Central Region Nagpur, Indian Meteorology Department (IMD), New Delhi, CSIR-National Geophysical Research Institute, Hyderabad, Central Building Research Institute (CBRI), Roorkee and Government Engineering College, Jabalpur were involved in carrying out this study to prepare a seismic microzonation map of Jabalpur city (PCRSMJUA, 2005).

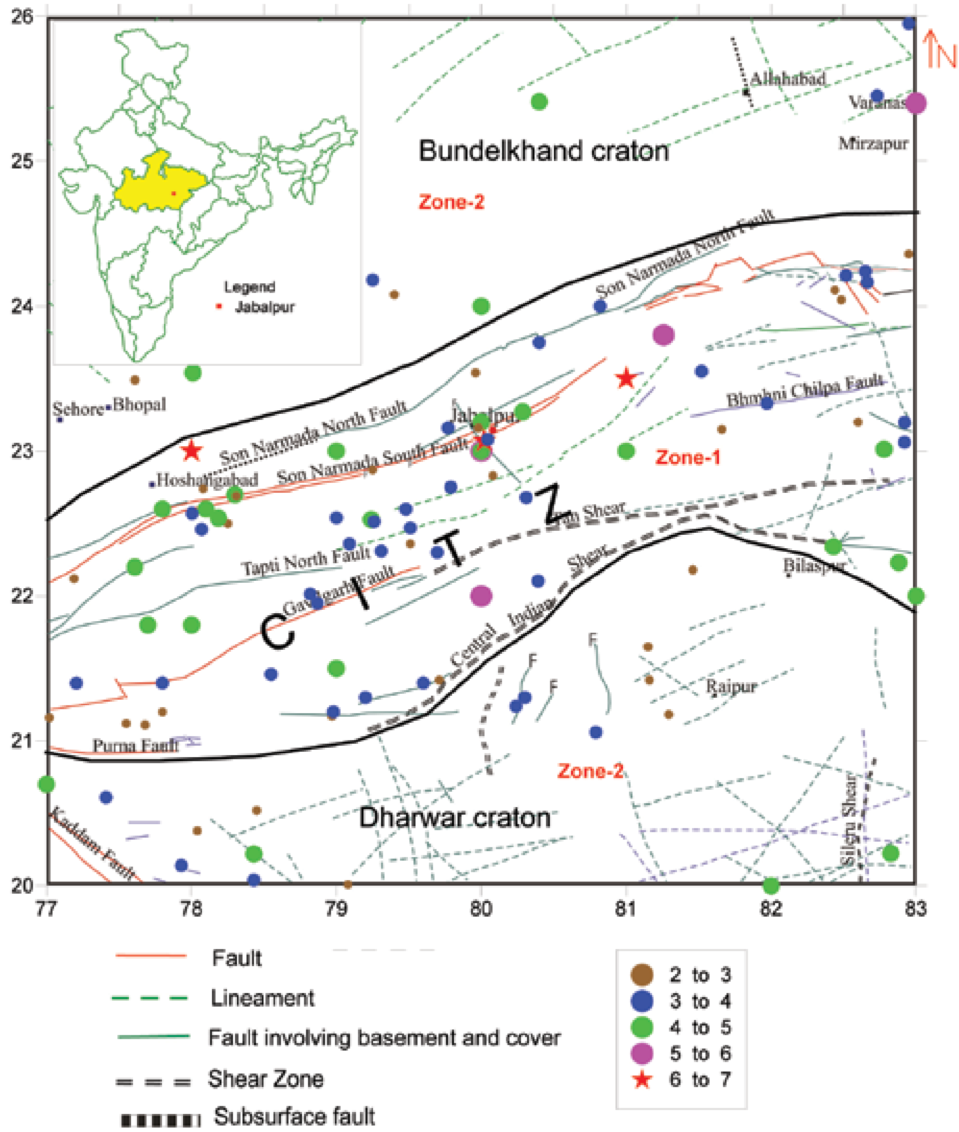

Figure 1. Seismotectonic map of Jabalpur and its surrounding area (modified after GSI, 2000) with past seismic events of different magnitudes (1846-2012).

Site amplification study, carried out by Purnachandra Rao et al. (2011) using Nakamura technique, has provided the site amplification values over different geological formations in the Jabalpur city. Another study by Grover et al., 2013 estimated the Peak ground acceleration of 0.15g for Jabalpur city. Probabilistic seismic hazard analysis study was also carried for whole India by National Disaster Management Authority (NDMA), Govt. of India (2010) and reported the Peak Ground Acceleration (PGA) values for major cities in India for different return periods. The PGA values reported from this study are 0.18 and 0.08 for Jabalpur city with 2500 and 500 return periods respectively for rock site.

The present study has an advantage of estimation of site specific seismic hazard at very close interval within the Jabalpur city. The Jabalpur city area is divided into 384 grid points with an interval of 0.01°x0.01° and assumed each corner of the grid as a site. Spectral amplitude values are computed at each grid point and thereby, seismic hazard contour maps are generated for Jabalpur city at selected periods by considering both rock and soil site conditions.

SEISMOTECTONIC SETTING AND GEOLOGY

Jabalpur earthquake epicenter lies in the ENE-WSW trending CITZ. CITZ is a mega geo-fracture of about 1200 km long extending from west to east in central India. This feature separates the Bundelkhand protocontinent towards north and Dharwar protocontinent towards south (Roy and Bandopadhyay, 1990) (Figure 1). Tectonically, CITZ is highly disturbed and reactivation is believed to

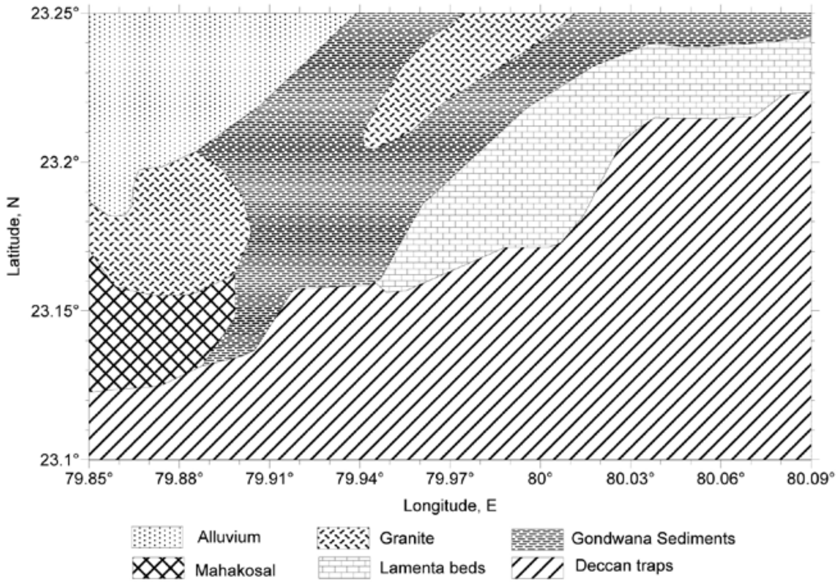

Figure 2. Geological map of the Jabalpur area consisting of various surface geological formations (modified after GSI, 2000).

be due to collision of Indian and Eurasian plates (Jain et al., 1984). Reactivation of CITZ took place throughout its evolution in different phases (Fermor, 1936; Auden, 1949; West, 1962). A total of ~25 earthquakes have occurred in Peninsular India with M>5.0 and intensity >VII (MM scale) (Purnachandra Rao et al., 2011). Out of twenty five, six are along the CITZ, indicates the level of seismic activity in this region. Jabalpur earthquake (1997) is one of them with M_w5.8.

Geologically, Jabalpur city and its surrounding region comprises a wide variety of rocks of different age ranging from Archean-Proterozoic to Tertiary-Quaternary (Matley, 1921; Jha et al., 1984). Jabalpur area mainly consists of Alluvium, Deccan traps, Vindhyan sediments, Gondwana sediments, Mahakoshal group and Madanmahal granites of different age (see Figure 2). The exposed Deccan traps in the region are considered one of the largest volcanic lava flows in the world belongs to Paleocene-Cretaceous boundary age. The Mahakosal group of rocks in the region are the oldest exposed rocks of Archean to Paleoproterozoic age. The NW of Jabalpur area is characterized by a thick layer of alluvial sediments of Tertiary and Quaternary age (Fermor, 1936; Auden, 1949; West, 1962).

These sediments are more vulnerable and cause seismic hazard during earthquake due to site amplification. Lameta group rocks of upper Cretaceous age are found towards NE of Jabalpur in the study region. These are basically sedimentary rocks overlying the Gondwana rocks. There is an abundance of Gondwana rocks found towards North and Northeast of Jabalpur. These sedimentary rocks consists of sandstones, shales and clays. In addition, there are intrusives of Madanmahal granites of late Proterozoic age at places within the Mahakoshal group.

SEISMICITY

CITZ in central India is seismically second most active tectonic zone after the Himalayas. This region had witnessed six seismic events of M>5. Out of these, two seismic events namely 1938 Satpura earthquake and 1997 Jabalpur earthquake, have occurred at lower crustal depths at 40km and 35 km depth respectively. The seismicity is mainly concentrated along the CITZ belt and also along some of the transverse features, which have been activated from time to time, as a result of the stresses accumulated by NNE movement of the Indian plate. Seismicity map has been prepared from the data on past earthquakes in a region of 6° Lat. × 6° Long. around the Jabalpur city, as compiled by different published sources. In order to study the seismicity of the region, a total of 112 earthquakes for the period from 1846 to 2012, with magnitudes greater than or equal to 2.0, are considered in the present study.

The epicenters of past earthquakes are plotted in seismotectonic map to decipher the association of past earthquakes with various tectonic features in the region (Figure 1). Though, the epicenters are seen to be dispersed widely, definite clustering along the CITZ longitudinal trend and along some of the transverse features is discernible. Epicentral concentrations are seen to occur along the Narmada South Fault, Narmada North Fault and lineaments and faults within the CITZ. Low level of seismicity observed in the Bundelkhand craton in the north and Dharwar craton in the south of CITZ may be related to the various lineaments/subsurface tectonic features. The earthquakes with magnitude M>4.0, and their epicenters are seen to be concentrated within the CITZ. The observed distribution of epicenters within the CITZ is explained

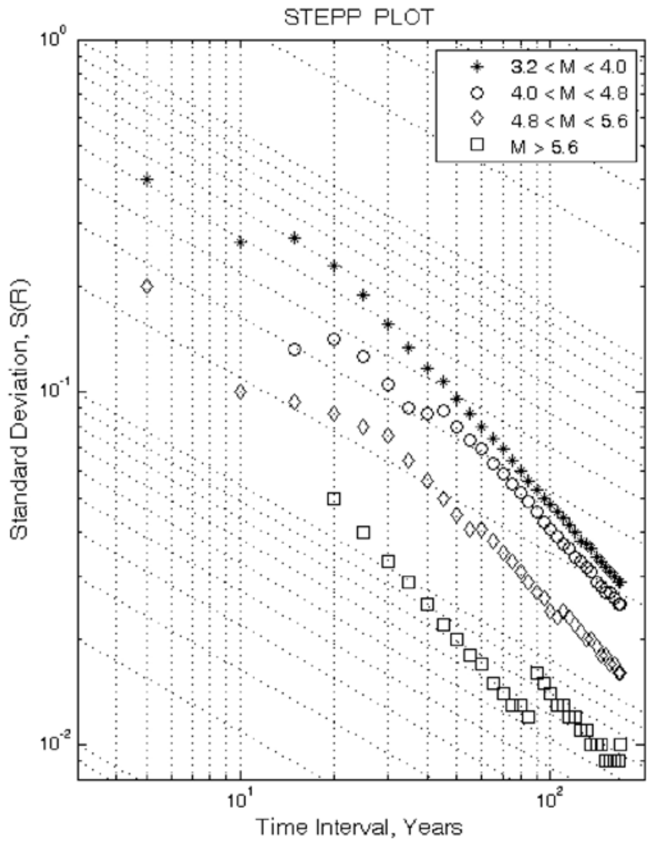

Figure 3. Stepp's completeness plot for the standard deviation S(R) as a function of time interval (T) for zone-1.

by reactivation of the crustal blocks due to subduction and collision tectonics along the Mesoproterozoic suture (Naganjaneyulu and Santosh, 2010b). This indicates neo-tectonic activity in this region. The recent seismicity in the CITZ reveals that reactivation process is still going on and suggests that this region is associated with mantle reaching faults (deep seated faults) since Precambrian to early Quaternary age (Mall et al., 2005; Mall and Sharma 2009; Choubey, 1971).

The study area is divided into two seismic source zones based on the trend of lineaments/faults and location of the past earthquake epicenters in the study region (Figure 1). Majority of the seismic events have been found to occur in the seismic source zone-1 i.e. CITZ and remaining events have occurred on either side of it, which is considered as seismic source zone-2. A total of 79 earthquake events have been observed in seismic zone-1with a maximum observed magnitude (M_{obs}) of M_w 6.5, where as 33 events were found in zone-2 with a maximum observed magnitude (M_{obs}) of M_w 5.5. The data completeness and annual recurrence rate of earthquakes using Gutenberg-Richter (G-R) recurrence relation are estimated for each zone in the following section.

Data completeness and G-R recurrence relationship

Based on available past earthquake data, the seismic activity of each source zone is characterized by the following recurrence relationship, as suggested by Gutenberg and Richter (1944).

$$\mathrm{Log}_{10}N\ (M) = a - bM \qquad \text{................} \ (1)$$

where, N is number of earthquakes with magnitude M or greater per year and 'a' and 'b' are statistical parameters estimated by least square analysis of past earthquake data. Parameter 'a' indicates the number of events per year with M=0. The value of 'b' is close to 1 and is tectonic parameter. A higher 'b' value indicates the large number of smaller magnitude seismic events in the catalogue whereas, lower 'b' value implies the small number of large magnitude seismic events in the catalogue (Tsapanos, 1990). The seismic hazard at any seismic zone is controlled by these two parameters. The annual recurrence rate of earthquakes can be assessed correctly from analysis of past seismic data, only when the available earthquake data are complete. However, in most of the cases data on past earthquakes are incomplete due to various reasons.

Table 1. The period of completeness of different magnitude intervals for seismic zone-1 and zone-2.

S.no	Earthquake magnitude interval	Period of completeness	Earthquake magnitude interval	Period of completeness
		Zone-1		Zone-2
1	$3.2 \le M_w \le 4.4$	20	$3.2 \le M_w \le 4.4$	20
2	$4.4 \le M_w \le 4.8$	50	$4.4 \le M_w \le 4.8$	50
3	≥ 4.8	160	$4.8 \le M_w \le 5.6$	110
4	--	--	≥ 5.6	170

Table 2. The seismic parameters a, b and observed and assigned upper bound magnitudes (M_{obs} and M_{max}) for source zone 1 and zone-2.

S. No.	Seismic Source zone	*a*	*b*	M_{obs}	M_{max}
1.	Zone -1	2.56	0.75	6.5	7.0
2.	Zone-2	1.55	0.59	5.5	6.2

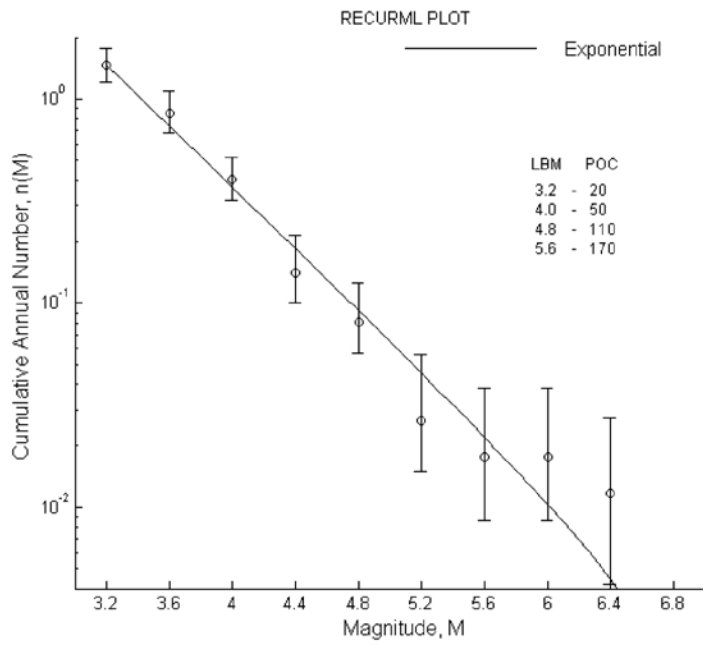

Figure 4. A typical exponential decay curve for annual recurrence rate versus magnitude for the source zone-1.

The effect of incompleteness in the available data set can be minimized by adopting statistical method suggested by Stepp (1972). In this method, the available earthquake catalogue is grouped into magnitude intervals with a time interval of about 5-10 years to calculate the completeness period. The completeness plot for the standard deviation S(R) as a function of time interval (T) is plotted in Figure 3 for zone-1. The estimated completeness period for source zones 1 and 2 are given in Table-1. The parameters 'a' and 'b' are evaluated by maximum likelihood method (Weichert, 1980) and given in Table-2.

The exponential decay of the recurrence relation using the parameters β, M_{min} and M_{max} is described by Cornell and VanMarcke (1969) as below.

$$N(M) = N(M_{min})\frac{\exp(-\beta(M-M_{min})) - \exp(-\beta(M_{max}-M_{min}))}{1-\exp(-\beta(M_{max}-M_{min}))} \qquad ....(2)$$

In the above expression, threshold magnitude (M_{min}) is taken as 3.8 for the present study. The upper bound magnitude (M_{max}) used for each source zone is given in the Table 2. The upper bound magnitude (M_{max}) is obtained by incremental approach by adding some increment to the observed magnitude. The maximum magnitude (M_{max}), by definition, is no earthquakes are possible with magnitude exceeding M_{max} (Kijko, 2003). When the available data is lacking to apply a formal method for estimation of M_{max}, the observed magnitude is enhanced by a suitable amount (0.5 to 1 units), depending on the available largest magnitude and expected regional potential of the study area. The estimation of M_{max} in probabilistic procedures is merely depends on seismological history of the area such as using seismic event catalogs and appropriate statistical estimation procedures (Kijko, 2003). The most commonly used probabilistic procedure for estimation of M_{max}, based on extrapolation of the classic, log-linear, frequency-magnitude Gutenberg-Richter relation, was developed in late sixties (Kijko, 2003). The incremental method of M_{max} has also been estimated by conventional approach of M_{obs} with an increment of 0.5, which considers Gutenberg-Richter b-value (Wheeler, 2009). This method may be used according to the regional b-value since 0.5 increment equals to one increment of equal intensity value. An increment value of 0.5 is used to the M_{obs} when b-value is close to 1 (Anbazhagan et al., 2014). The b-value of seismic zone-I is close to 1 (i.e.0.75) compared to zone-II (i.e.0.59) in the study area. Hence, increment of 0.5 is added to the observed magnitude (M_{obs}) M.6.5 for zone-I and accordingly M_{max} is fixed as M7.0 (M_{obs} + 0.5). Whereas, 0.7 units added to zone-II conservatively as its b-value and M_{obs} are less. The parameter β is related to b-value and is expressed as β = bln10. A typical exponential decay curve for annual recurrence rate versus magnitude for the source zone-1 is shown in Figure 4. The annual occurrence rate of earthquakes with a specified magnitude interval and spatial distribution is considered in the probabilistic approach to estimate the MCE and DBE level of ground motion.

Probabilistic Seismic Hazard Analysis

The probabilistic seismic hazard analysis (PSHA) approach is used to get a reliable estimation of the seismic hazard by considering the effects of total expected seismicity with suitable spatial distribution of the site of interest. The PSHA approach provides the 5 % damped target response spectra for a given area with a specified confidence level. This will not be exceeded due to any of the earthquakes expected to occur anywhere in the region during a specified exposure time. The Maximum Credible Earthquake (MCE) level of ground motion is commonly specified with a 2% of exceedence during 50 years of exposure time for 2475 (~2500) years return period (FEMA, 2004). The composite probability distribution of the spectral amplitude at a given natural period is expressed in the PSHA approach as given below (Cornell, 1968; McGuire, 1977; Anderson and Trifunac, 1978; Gupta, 2002a).

$$P[SA(T)] = \exp\left\{-Y\sum_{i,j} q[SA(T)\mid M_j, R_i]\cdot \upsilon(M_j, R_i)\right\} \quad \text{......(3)}$$

In the above equation, Y is the considered exposure period and $\upsilon(M_j,R_i)$ is the annual occurrence rate of earthquakes within a small magnitude range (M_j–δM_j, $M_j+\delta M_j$) and a small distance range ($R_i - \delta R_i$, $R_i+\delta R_i$) from the site of interest. Quantity $q[SA(T)|M_j, R_i]$ represents the probability of exceeding the spectral amplitude $SA(T)$ due to an earthquake of magnitude M_j at distance R_i. In the present study, the 5 % damped probabilistic response spectra are obtained for both MCE and DBE levels of ground motion. This is estimated by the spectral amplitudes at all the natural periods with 96 % and 81% probability of not exceeding in the exposure period of 100 years. The MCE and DBE levels of ground motion are estimated for the Jabalpur area using a suitable Ground Motion Prediction Equation (GMPEs).

Ground motion prediction equations (GMPEs)

There are several ground motion prediction equations developed by many authors (Ambrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozognia, 2008; Chiou and Youngs, 2008a; Idriss, 2008) as a part of Next Generation Attenuation (NGA) of ground motions for seismically active tectonic regions worldwide. In addition, there are several attenuation relations developed for Himalayan region by many authors (Anbazhagan et al., 2015). However, no attenuation model is developed for intra-plate regions based on recorded instrumental data as the strong motion data available for the region are sparse. Since the Jabalpur area in CITZ lies in intra-plate region and selecting the suitable ground motion prediction equation is difficult. In light of this problem, the attenuation models for seismically active regions based on only instrumental recordings are adopted to find out the suitable relation for the present study area. Except Boore and Atkinson, 2008 (BA08), the NGA relations need the exact information on fault directivity, fault rupture geometry and site effects more comprehensively, which are not available in most cases. Hence, the NGA attenuation relations cannot be used without making some subjective assumptions leading to biased results (NCSDP guidelines, 2011). Hence, three different GMPEs, AS97 (Abrahamson and Silva, 1997); LEE87 (Lee, 1987) and BA08 (Boore and Atkinson, 2008) are identified for the study region, which needs less number of fault parameters.

The seismic hazard level is specified in terms of standard response spectrum shape, which is scaled by the zone factor (Raghukanth, 2010). The zone factor in Indian Standard IS:1893 (2002) is assumed to be the expected Peak Ground Acceleration (PGA). On the other hand, Zero Period Acceleration (ZPA) value obtained from the resultant spectral amplitude values by any GMPE is also considered as PGA. In this context, the terms Zero Period Acceleration (ZPA), Peak ground acceleration (PGA) and Zone factor are considered to be same. Since AS97, LEE87 and BA08 are meant for seismically active tectonic environments and the study area falls in seismically active tectonic region too i.e. CITZ in peninsular India, these three models are adopted for comparison. The response

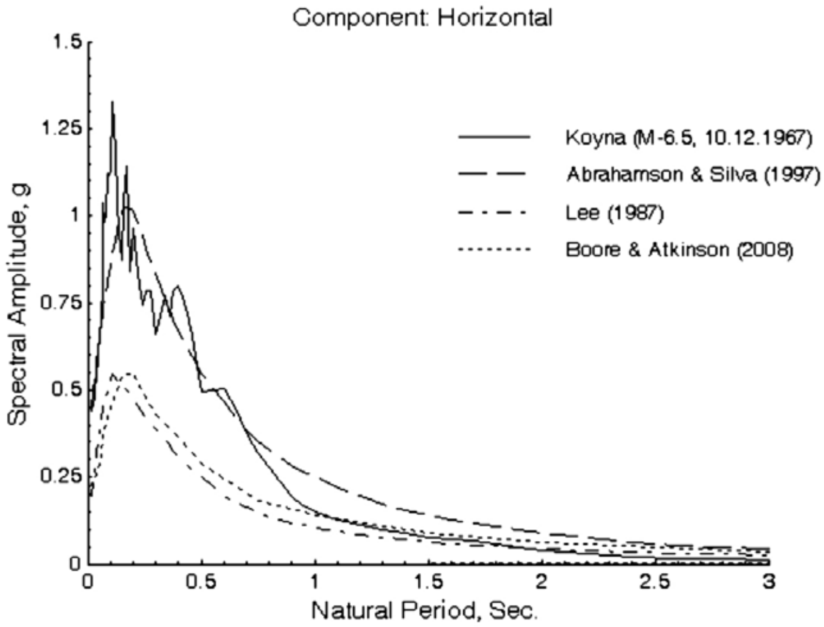

Figure 5. Comparison of mean Response spectra of two horizontal components of the accelerograms recorded from Koyna earthquake of 10 Dec, 1967 with those predicted by three selected empirical attenuation relations at bedrock level.

Table 3. The estimated ZPA/PGA values from three GMPEs (AS97, LEE87 and BA08) for both rock and soil site conditions.

S.No	Geology	Hazard parameter	GMPE		
			AS97	LEE87	BA08
1	Soil	ZPA/PGA	0.17g	0.09g	0.13g
2	Rock		0.15g	0.08g	0.07g

spectra obtained from these three GMPEs are plotted in Figure 5 for bedrock level. From the figure, it is discerned that the spectral amplitude values obtained by AS97 are found to be higher than the spectral values due to other two GMPEs for both rock and soil site conditions (table 3). To show the suitability of the AS97 attenuation relation for peninsular India, mean response spectra of two horizontal components of the Koyna earthquake of 10 December, 1967 along with the mean estimation of the predicted response spectra of other three empirical attenuation relations at bedrock level is compared. It is observed that AS97 is more compatible to the Koyna spectrum in terms of shape, amplitude and it's PGA (Figure 5). In addition, results obtained using the attenuation relations of Iyengar and Raghukanth (2004) and NDMA (2010) by Grover et al., (2003) and NDMA, 2010 for the same region, are well correlated with the values obtained in the present study. Hence, the use of GMPE of AS97 is justifiable for the study region and considered conservatively to be MCE level of target response spectra. The same has been discussed in detail in the results and discussion section. The ZPA value obtained by AS97 is also observed to be close to the zone factor value given in IS:1983(2002) i.e. 0.16 for seismic zone-III. Hence, the GMPE by AS97 is adopted for the present study to determine the spectral amplitude values for different natural periods.

The Ground motion prediction Equation (GMPE) due to Abrahamson and Silva (1997) has been used to obtain the 5 % damped acceleration response spectra for horizontal component of the ground motion.

This relation is developed using a strong motion database of 655 recordings from 58 shallow crustal events in seismically active tectonic regions worldwide. Abrahamson and Silva (1997) have presented their attenuation relation for spectral acceleration (*SA (T)*), as given below.

$$\ln Sa(g) = f_1(M,R) + F \cdot f_3(M) + HW \cdot f_4(M,R) + S \cdot f_5(a_{\max}) \quad .....(4)$$

where Sa (g) is the spectral acceleration in g, M is moment magnitude and R is the closest distance to the fault rupture plane in km. Parameter F defines the type of faulting (1 for reverse fault, 0.5 for reverse/oblique, 0 for otherwise), HW is the variable, which specifies the location of site on hanging or footwall side of dipping faults (1 for hanging wall, 0 for otherwise) and S defines the site class (0 for rock or shallow soil, 1 for deep soil). Functions f_1, f_3, f_4 and f_5 in eqn. (2) are expressed in terms of 12 regression coefficients, $a_1(T)$, $a_2(T)$, ……, $a_{12}(T)$, evaluated by Abrahamson and

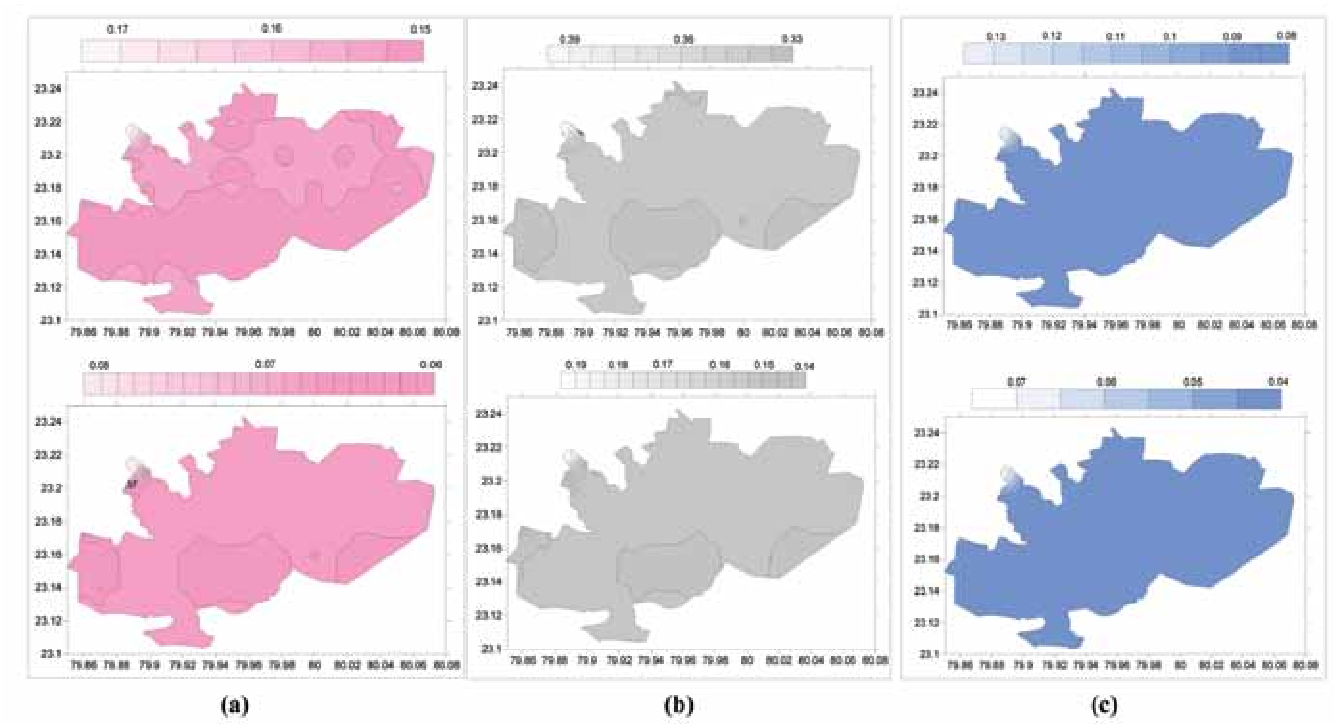

Figure 6. (a) Peak Ground Acceleration (PGA) contours for 2500 years (top) and 500 years (bottom) of return periods with an exposure period of 100 years. (b) Short period spectral acceleration values at 0.2 sec for return period of 2500 (top) and 500 (bottom) years with 5% damping for both rock and soil site conditions. (c) Long period spectral acceleration values at 1sec for return period of 2500 (top) and 500 (bottom) years with 5% damping for both rock and soil site conditions.

Silva (1997) at 28 natural periods between 0.02 sec and 5.0 sec. The expression of eqn. (2) gives the least squares median value, $\langle Sa(g) \rangle$, of the spectral amplitudes.

In this study, the seismically active Narmada South Fault (NSF) passing approximately in E-W direction and intersecting the southern part of Jabalpur city. Since this fault is southerly dipping reverse (thrust) type of fault (Mandal et al., 2000), the same is considered in the AS97 GMPE. Both hanging wall and foot wall conditions are considered based on location of the grid point, with respect to the fault line and its dip direction. Jabalpur area consists of various surface geological formations such as Basalt, Gondwana sedimemnts, lameta formation, Granite, Mahakoshal group of rocks and alluvial sediments as per Seismotectonic atlas map of India published by Geological Survey of India (GSI, 2000). However, all these rocks are broadly classified into rock and soil, based on shear wave velocities. Alluvial sediments are considered as soil, whereas all other type of rocks are considered as rock in the AS97 ground motion prediction equation. Spectral amplitudes are calculated at 28 natural periods from 0.02 sec to 5 sec.

RESULTS AND DISCUSSION

The Jabalpur city is divided into smaller grid interval of 0.01° x 0.01° (approximately 1 km x 1km) and Seismic hazard contour maps have been prepared by performing the seismic hazard computations at 384 grid points. The 5% damped spectral amplitudes are estimated at each corner of the grid for both MCE and DBE level of the ground motions. The Zero Period Acceleration (ZPA) of spectral amplitudes at each corner of the grid are assumed to be Peak ground acceleration values and plotted in contours (Figure 6a).

The PGA values are varying from 0.15g to 0.17g for MCE condition and 0.06g to 0.08g for DBE condition. In addition, Spectral amplitudes at selected natural periods of 0.2 sec and 1 sec are computed for the design response spectrum and presented in contours as shown in Figures 6 (b) and (c) respectively. The spectral amplitude values at 0.2 sec are varying between 0.33g to 0.39g for MCE condition, whereas it is varying from 0.14g to 0.19g for DBE level of ground motion. The spectral amplitude values at 1sec for MCE condition are varying from 0.08g to 0.13g and for DBE condition; it is 0.04g to 0.07g. These maps are prepared for the return period of 2500 years and 500 years with an exposure period of 100 years.

The results obtained from the study in terms of PGA for the return period of 2500 years is close to the study results carried out for Jabalpur area by several authors. A site amplification study carried out for seismic microzonation in Jabalpur area obtained the maximum site amplification in the north-western part of the Jabalpur area (Purnachandra Rao et al., 2011) where highest PGA value of 0.17g is obtained by the present study for the return period of 2500 years as shown in Figure 6 (a) top. The maximum site amplification and higher PGA values represents the presence of thick alluvial sediments in north-western part of Jabalpur area. The highest PGA value of 0.15g obtained at bedrock level using GMPE of AS97 from the present study is well correlated with the same value i.e. 0.15g at bedrock level by Grover et al. (2003) using GMPE of Iyengar and RaghuKanth (2004, 2006). Another PSHA study carried out by National Disaster Management Authority (NDMA), Govt. of India (2010) reported the Peak Ground Acceleration (PGA) value of 0.18g at bedrock level with 2500 years return period. This value is almost close to the value obtained from the present study. Moreover, The PGA value obtained in the present study is comparable to zone factor value reported in the IS code i.e. 0.16 (IS:1893 (2002)) for seismic zone-III.

CONCLUSION

Probabilistic seismic hazard analysis is carried out for the Jabalpur city to quantify the ground motion and thereby to estimate seismic hazard for the forthcoming earthquakes. An earthquake catalogue starting from 1846 to 2010 is compiled from several resources within a radius of 300 km from the Jabalpur city. Data completeness is calculated and annual recurrence rate is estimated for available data set. Three ground motion prediction equations are tested for the study region i.e. AS97; LEE87 and BA08; and AS97 is found suitable after comparing the predicted response spectra by these three attenuation relations with the response spectra of recorded accelerogram of Koyna earthquake (10 Dec, 1967). Existing soil/rock formations, footwall/hanging wall and reverse (thrust) type of faulting are considered in the selected GMPE to determine the 5% damped spectral amplitudes for different natural periods. Seismic hazard contour maps in terms of PGA and spectral amplitudes have been generated for 2475 (~2500) and 475 (~500) years return periods, which is equal to 96% and 81% probability of not exceeding in 100 years. As per International building code IBC-2009, spectral acceleration values are also computed at 0.2 sec and 1 sec for developing the design response spectrum for any major sensitive structures/buildings in Jabalpur area. It is observed that the seismic hazard in terms of PGA is varying from 0.15g to 0.17g for MCE and 0.06 to 0.08 for DBE levels of ground motion within the Jabalpur city. The spectral acceleration and PGA values estimated from the present study are based on broad classification of site geology (Rock and soil). The maximum peak ground acceleration 0.17g is observed towards NW of Jabalpur city over the thick alluvial sediments, which is most prone for site amplifications.

ACKNOWLEDGEMENTS

Authors are thankful to Dr.M.K.Sinha, Director for providing permission to publish this work. Our sincere thanks to Shri.M.D.Kudale, Additional Director for his encouragement to carry out this study. Authors are also thankful to the anonymous reviewer for his critical comments and valuable suggestions to improve the manuscript.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

REFERENCES

Abrahamson, N.A. and Silva, W.J., 1997. Empirical response spectral attenuation relations for shallow crustal earthquakes. Seism. Res. Lett., 68(1), 94–127.

Anbazhagan, P., Dutta, N., Bajaj, K., Moustafa, S.S.R. and Al-Arifi, N.S., 2014. Earthquake maximum magnitude estimation considering regional seismotectonic parameters, in ST Smith (ed.), 23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23), Byron Bay, NSW, 9-12 December, Southern Cross University, Lismore, NSW, II, 979-984. ISBN: 9780994152008.

Anbazhagan, P., Bajaj, K. and Patel, S., 2015. Seismic hazard maps and spectrum for Patna considering region-specific seismotectonic parameters, Nat. Hazards., 78, 1163–1195.

Anderson, J.G. and Trifunac, M.D., 1978. "Uniform risk functionals for characterization of strong earthquake ground motion", Bull. Seismol. Soc. Am., 68(1), 205–218.

Auden, J.B., 1949**.** Geological discussion of the Satpura hypothesis, Proc. Natl. Inst. Sci. India., 15, 315–340.

Boore, D.M. and Atkinson, G.M., 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV and 5% damped PSA at spectral periods between 0.01 and 10.0 s, Earthq. Spectra., 24(1), 99–138.

Campbell, K.W. and Bozorgnia, Y., 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, Earthquake Spectra, 24, 139–171

Chiou, B.S.J. and Youngs, R.R., 2008a. An NGA model for the average horizontal component of peak ground motion and response spectra, Earthquake Spectra, 24, 173–215.

Choubey, V.D., 1971. Narmada-Son linement, India, Nature. Phys. Sci., 232, 38-40.

Cornell, C.A. and Vanmarcke, E.H., 1969. The major influences on seismic risk, Proc. Fourth World Conf. Earthq. Eng., Santiago, Chile, 1, 69–93.

Cornell, C.A., 1968. Engineering seismic risk analysis, Bull. Seism. Soc. Am., 58(5), 1583-1606.

EERI Special Earthquake Report., 1997. Some observations on engineering aspects of the Jabalpur earthquake of 22 May 1997, EERI Newsletter, 32(2).

FEMA, 2004. NEHRP recommended provisions for seismic regulations for new buildings and other structures (FEMA 450), Part 1: Provisions", 2003 Edition.

Fermor, L.L., 1936. An attempt at the correlation of the ancient schistose formation of Peninsular India, Mem. Geol. Surv. Ind., 70(I), 217.

Grover, R.K., Vishwakarma, A., Jain, R. and Mishra, K.H., 2013. Estimation of peak ground acceleration for Jabalpur city, Int. J. Eng. Res. Appl., 3(1), 1777-1780.

GSI, 2000. Seismotectonic Atlas of India and its environs, Geological Survey of India, India.

Gupta, H.K., Chadha, R.K., Rao, M.N., Narayana, B.L., Mandal, P., Ravikumar, M. and Kumar, N., 1997. The Jabalpur earthquake of May 22, 1997, J. Geol. Soc. India, 50, 85-91.

Gupta, I.D., 2002a. State of the art in seismic hazard analysis, ISET Jour. Earthq. Eng., 39(4), 311-346.

Gutenberg, B. and Richter, C.F., 1944. Frequency of earthquakes in California, Bull. Seismol. Soc. Am., 34, 185-188.

IBC, 2009. International building code, International code council.

Idriss, I.M., 2008. An NGA empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes, Earthq. Spectra, 24, 217–242.

IS:1893., 2002. Indian standard criteria for earthquake resistant design of structures, part 1-general provisions and buildings, Bureau of Indian Standards, New Delhi.

Iyengar, R.N. and Raghukanth, S.T.G., 2004. Attenuation of strong ground motion in peninsular India, Seism. Res. Lett., 79, 530 – 540.

Iyengar, R.N. and RaghuKanth, S.T.G., 2006. Seismic hazard estimation for Mumbai city, Curr. Sci., 91(11, 10), 1486-1494.

Jain, A.K., Annup, N. and Singhal, D.C., 1984. Crustal evolution of the Narmada- Son lineament and associated shear zones of the Indian lithosphere, J. Earth. Sci., CEISM Seminar, 125–148.

Jha, D.K. et al., 1984. Systematic geological mapping from Barmanghat to Tilwarghat in parts of Narsingpur and Jabalpur district of M.P GSI unpub. Report.

Khan, 2009. Why Tectonically stable Indian shield becomes seismically unstable? J. South Asia Disast. Studies, 2, 129-138.

Kijko, A., 2003. Estimation of the maximum earthquake magnitude, $M_{max.}$ Pure. Appl. Geophys., 1-29.

Mall, D.M. and Sharma, S.R., 2009. Tectonics and thermal structure of western Satpura, India, J. Asian earth sci., 34, 450-457.

Mall, D.M., Singh, A.P. and Sarkar, D., 2005. Structure and seismotectonics of Satpura central India, Curr. Sci., 88, 1621–1627.

Mandal, P., Rastogi, B.K. and Gupta, H.K., 2000. Recent Indian earthquakes, Curr. Sci., 79, 1334–1346.

Matley, C.E., 1921. Stratigraphy, fossil and of the lameta beds of Jabalpur, Geol. surv. India, 53,142-169.

McGuire, R.K., 1977. Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response, Earthq. Eng.Struct. Dyn., 5(3), 211–234.

Naganjaneyulu, K., and Santosh, M., 2010b. The central India tectonic zone: a geophysical perspective on continental amalgamation along a Mesoproterozoic suture, Gond. Res., 18, 547–564.

NDMA, 2010. National disaster management authority Govt. of India. Development of probabilistic seismic hazard map of India.

NCSDP, 2011 (revised 2014). Guidelines for preparation and submission of site specific seismic study report of river valley project.

PCRSMJUA, 2005. Project completion report of seismic microzonation of Jabalpur urban area, Department of Science and Technology, Government of India, India.2 volumes.

Purnachandra Rao et al., 2011. Site amplification studies towards seismic microzonation in Jabalpur urban area, Central India, Phys. Chem. Earth, 36, 1247-1258.

Raghukanth, S.T.G., 2010. Estimation of seismicity parameters for India, Seism. Res. Lett., 81(2), 207-217.

Roy, A., and Bandyopadhyay, B.K., 1990. Tectonic and structural pattern of the Mahakoshal belt of central India: A discussion, GSI spl. publ. no.28, workshop of Precambrian of central India, 226-240.

Stepp, J.C., 1972. Analysis of completeness of the earthquake sample in the Puget Sound area and its effect on statistical estimates of earthquake hazard, Proc. Int. conf. microzonation, 2, 897–910.

Sykes, L.R., 1978. Intraplate seismicity, reactivation of preexisting zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation, Rev. Geophys. Space Phys., 16, 621–688.

Tsapanos, T.M., 1990. b-Values of two tectonic parts in the Circum–Pacific belt, Pure. Appl. Geophys., 134(2), 229–242.

Weichert, D.H., 1980. Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes, Bull. Seismol. Soc. Am., 70(4), 1337–1346.

West, W.D., 1962. The line of the Narmada and Son valleys, Cur. Sci., 31, 143–144.

Wheeler, R.L., 2009. Methods of Mmax estimation east of the Rocky Mountains U.S. Geol. Surv., Open-File Report 2009-1018.

Received on: 24.1.18; Revised on: 19.2.18; Accepted on: 25.3.18