ESTIMATING SEISMIC HAZARD FOR CENTRAL AND SOUTHERN INDIA

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ABSTRACT :

This paper present probabilistic seismic hazard estimation of south central India (south of 28° N) which is characterized by crustal intra-plate seismic activity in its cratonic and rifting zones. It also brings several updates including: 1) hazard estimation in Central India 2) estimating source zone-specific seismicity parameters, 3) application of several newly available GMPEs both in terms of PGA and SA at different frequencies for incorporating the variability in the ground motion for seismic hazard associated with different zones in central and southern India.

KEYWORDS: Seismic hazard, Probability, Logic Tree, Gridded Seismicity

1. INTRODUCTION

In a previous study, the authors have developed probabilistic seismic hazard map in terms of peak ground accelerations incorporating spatial characteristics of seismic source zones of peninsular India (south of 28° N). Several combination models that are uniform, background, geo-based and reservoir induced seismicity to capture epistemic uncertainties in the seismic hazard (Jaiswal 2006, Jaiswal and Sinha, 2007). In the present investigation we estimate seismic hazard extending source zones further to North India (south of 32° N) but excluding foothills and Himalayan belt in north, highly seismic northeastern part and Hindukush region in northwest as most of these belongs to either inter-plate or continental-continental thrust, extended margins or plate boundary regions. Such regions need to be modeled with additional constraints such as knowledge of tectonic domain, accurate delineation of faults, paleoseismic and geologic investigation to understand active faults and their mechanism slip rates and rupture properties and is beyond the scope of this investigation. Central and southern India covers more than 50% of the country and approximately 50% of country's 1.1 billion population lives in this region. The most recent version of seismic zoning map of India available in building design codes (IS 1893: 2002) has not considered detailed seismic hazard analysis of the region using either deterministic or probabilistic approaches, rather it is based on limited earthquake catalog data, iso-seismals of large historical earthquakes and limited analysis (Krishna, 1992). Several researchers have highlighted the issue of urgent upgrade of existing seismic zoning map of India (Jain and Nigam, 2000, and Khattri, 2006) in the wake of recent earthquake disasters (Latur 1993, Jabalpur 1997, Chamoli 1999, Bhuj 2001 and Kashmir 2005) which has resulted in the death of over 20,000 people in India and left millions homeless and causing enormous impact on regional and country's economy.

2. METHODOLOGY

We use gridded or smoothed seismicity approach proposed by Frankel (1995) and has been used commonly for the estimation of seismic hazard in Central and Eastern United States (CEUS) region as a part of national seismic hazard maps in 1996, 2002 and the most recent 2008 revision (Petersen et al., 2008). The approach is especially suitable for modeling cratonic and rift zone specific seismicity in stable continental regions of peninsular India (Jaiswal, 2006). Probabilistic seismic hazard estimation consists of: a) establishing earthquake recurrence activity in each grid cell or source using earthquake catalog data and developing magnitude-frequency relationships (Gutenberg-Richter parameters *a* and *b*-values), and estimating seismicity rates for each grid cell or source, b) determining source-specific (grid cell, fault or area source) maximum magnitude potential, c) estimating ground shaking at site or grid cell from each of the earthquake source-specific earthquake along with its associated rate and developing hazard curve, d) estimating ground motion at a site or grid cell for certain predefined exceedance levels (e.g., 10% or 2% probability of exceedance in 50 years, corresponding to an average recurrence of ~475 or ~2500 years, respectively), and e) developing seismic hazard map in terms of peak ground parameters (accelerations, velocities) and pseudo spectral accelerations at different frequencies (3 and 5 Hz). More details about probabilistic seismic hazard estimation can be found at other literature (for example, Cornell, 1968, Frankel, 1995, McGuire, 2004).

2. GEOLOGIC ZONING AND SEISMICITY

Stable continental regions are often characterized by short history of macro or micro seismic data and limited knowledge in terms of active faults/tectonic features and thus remain regions of wonders in terms of future seismic activity. Reactivation of quiescent seismic source or generation of earthquakes from new untraced seismic source in stable shield masses has often caused surprise earthquakes (for example, Latur earthquake of 1993). Nevertheless, it is apparent that seismic hazard associated with SCRs is substantially lower than active tectonic regions such as Himalayas in the north, Hindukush northwest and Andaman region in the eastern part (Figure 1). Seeber et al. (1999) proposed seismic zonation scheme for peninsular India while estimating the seismic hazard for the state of Maharashtra in India.

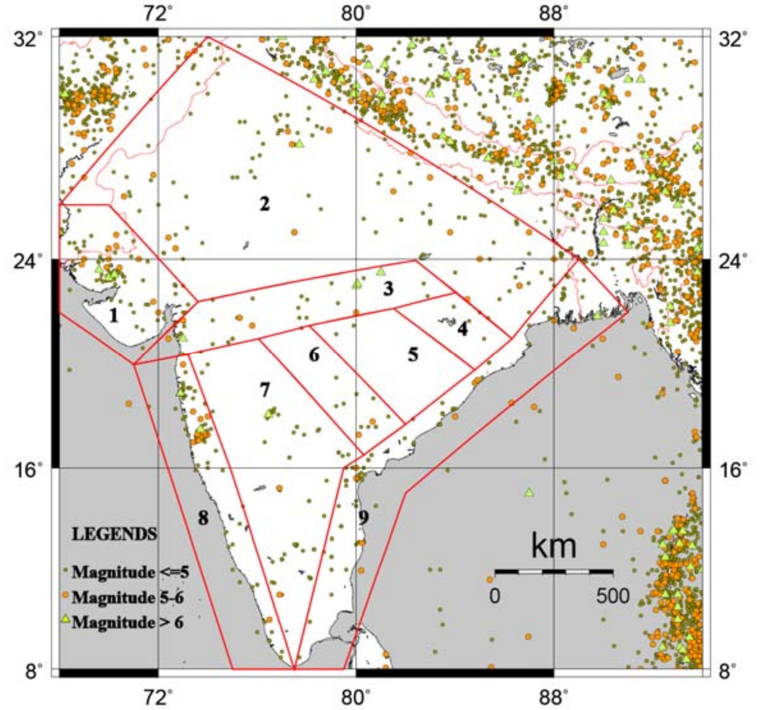
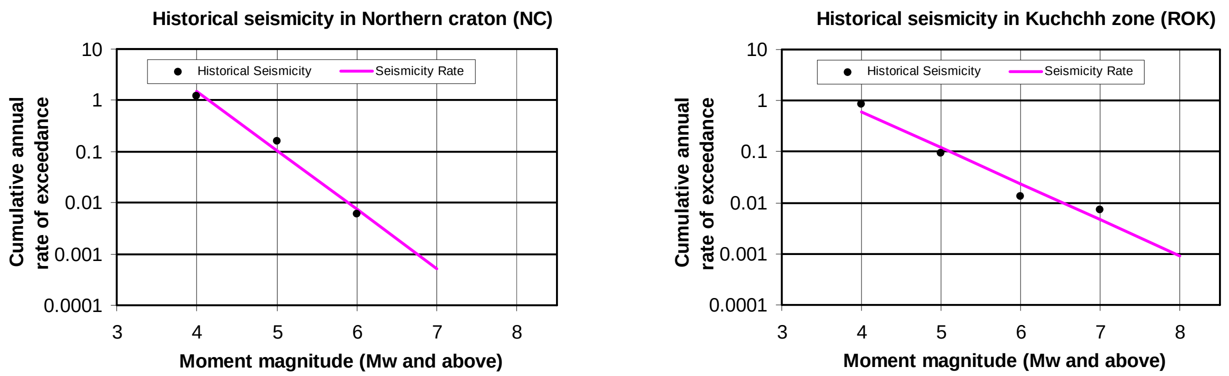


Figure 1. Seismic activity in India and adjoining regions (between 1600-2004) along with proposed new seismic zoning for central and southern India. The nine broad seismic zone are: 1) Runn of Kuchchh (ROK), 2) Northern Craton (NC), 3) Narmada Lineament (NL), 4) Mahanadi Graben (MG), 5) Eastern Craton (EC), 6) Godavari Graben (GG), 7) Southern Craton (SC), 8) Western Passive Margin (WPM), and 9) Eastern Passive Margin (EPM).

We slightly modify the original zonation scheme by spatially mapping the various tectonic settings in the region, covering broad geologic feature within zone (for example, extending Narmada Lineament further to the west, straightening and broadening of western passive margin to east, extending eastern passive margin zone further northeast, etc.) and including additional northwestern regions to better characterize seismic hazard associated with western part of northern craton (NC) zone. It is evident that the high seismic activity associated with northern part of India further north to the boundary of Northern Craton is not included in estimating seismicity parameters potentially due to different tectonic domain and settings. Clearly it will result in underestimation of seismic hazard for Northern Craton. Seismic hazard associated with Himalayan belt will most likely dominate in this region. The information specific to the geologic and tectonic characteristics of each seismic zone, their historic and recent seismic activity can be found at Jaiswal (2006). We extend our existing earthquake catalog in terms of moment magnitude (Jaiswal and Sinha, 2004) complete until 2002 for peninsular India to include earthquakes in northern part of India (south of 32° N) and extending it until the year 1600 using Bapat et al. (1983) which covers data from 1458, GSHAP earthquake catalog by Bhatia et al. (1999) and adding the most recent activity until the year 2005, from NEIC Preliminary Determination of Epicenters (PDE) data (NEIC 2007). The raw data has been processed by removing foreshock and aftershock data and then converting it into moment magnitude using the procedure described in Jaiswal (2006). Figure 1 illustrates the epicenters of historical seismic activity associated with India and adjoining regions between the years 1600 to 2005.

3. SEISMICITY RATES AND MAXIMUM MAGNITUDE

While evaluating seismic activity in different geologic zones, it was important to establish completeness of earthquake catalog in different magnitude intervals. Jaiswal and Sinha (2007) discuss the completeness analysis of catalog data and derivation of completeness intervals. With the addition of new data, modifications of some geologic zones and extending the catalog data upto the year 1600, we use new completeness interval as $M_w \geq 4.0$ and above since 1960, $M_w \geq 5.0$ and above to be complete since 1900, $M_w \geq 6.0$ and above since 1840 and $M_w \geq 7.0$ and above to be complete since the year 1600. Unlike previous hazard estimation, we estimate zone specific seismicity parameters rather than considering various source models. In our previous map, we used uniform background, reservoir induced source models; however, in present analysis we directly model the effective seismicity rate in each geologic zone by estimating zone-specific Gutenberg-Richter (1944) seismicity parameters. Figure 2 illustrates plot of cumulative annual rate of exceedance obtained using the completeness criteria for Northern Craton and Runn of Kuchchh regions.



(a) (b)

Figure 2. Modeling historical seismic activity using magnitude frequency relationship in a) Northern Craton (NC) and b) Runn of Kuchchh (ROK) zone.

The *b*-value estimated for different regions are: Runn of Kuchchh, 0.7; Narmada Lineament, 0.64; Western Passive Margin, 1.09; Southern Craton, 1.0; Northern Craton, 1.15; Eastern Craton, 0.67; Eastern Passive Margin, 0.9; Godavari Graben, 0.65; and Mahanadi Graben, 0.9. The *b*-value estimated for each geologic zone is then used to estimate seismic activity rate λ for each grid-cell using gridded seismicity approach. The seismicity parameters obtained for each geologic zones can be used to estimate average recurrence interval of earthquakes of different magnitude and is shown in Figure 3. The average recurrence of magnitude 5.5 in the Runn of Kuchchh zone is ~25 years; magnitude 6.5 to be ~125 years and magnitude 7.5 to be ~625 years. Such estimates are not only important for understanding the seismic activity pattern for each geologic zone but also provides opportunity to estimate earthquakes with certain predefined exceedance rates using Poissonian assumption, e.g., an earthquake of average recurrence rate of 475 years represent design basis earthquake (DBE) of that zone. Obviously, the rates estimated for large size earthquakes ($M_w > 7.0$) in each zone does not provide the complete and correct interpretation of their recurrence pattern (especially when catalog data is limited, about 400 years in this case), however further geological and paleoseismic investigations could significantly benefit constraining these rates.

Ideally, the estimation of the maximum magnitude potential in different geologic zones of central and southern India should be based on: a) identifying the underlying structure and its seismic activity dating back to thousands of years, b) geologic archiving of source-specific data about largest historical earthquakes, c) detailed paleoseismic and geodetic studies following by identifying style of faulting, mechanism, associated slip or strain rates etc. The development of such database is extremely difficult and requires enormous resources and efforts. Rajendran and Rajendran (2003) describe the state of existing data and necessity of further research while discussing the seismogenesis of two recent large earthquakes in peninsular India. Due to limited data, the maximum magnitude is chosen based on the tectonic settings of the region e.g., cratonic regions such as Eastern, Southern and Northern Cratons alongwith inactive grabens such as Godavari and Mahanadi graben have been assigned with M_w 7.0 which is higher than our previous assignment of M_w 6.5 in our earlier zoning map (Jaiswal and Sinha 2007), passive margins such as Eastern and Western marginal areas have been assigned with M_w 7.5, and also M_w 7.5 for

Naramada rift system (Narmada Lineament, NL).

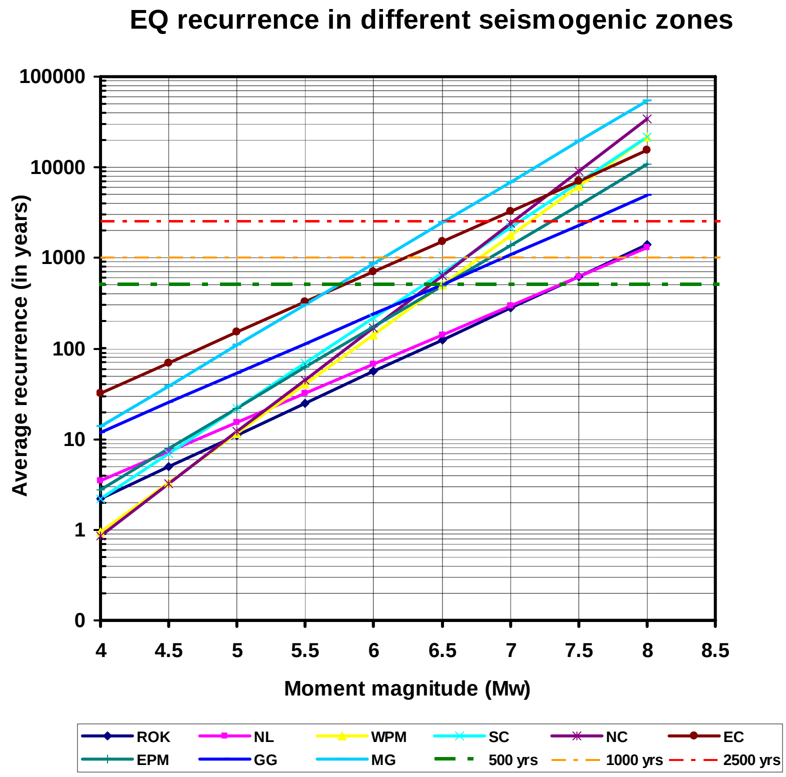


Figure 3. Average recurrence rate of seismic activity modeled in different zones of central and southern India.

We assign a higher expected earthquake size of M_w 8.0 for highly active rift system of Runn of Kuchchh (ROK) which has produced two largest earthquakes (M_w 7.6 in 1819 and M_w 7.7 in 2001) on two independent sources. Our assignment is in many ways similar to M_{max} assigned for cratonic and extended margin areas of Central and Eastern United States (CEUS), a region which shares geologic and seismotectonic characteristics with Indian shield (Cramer and Kumar 2003). The 2008 version CEUS map uses the weighting scheme for assigning the maximum magnitude potential as $0.1\times 7.1 + 0.2\times7.3 + 0.5\times7.5 + 0.2\times7.7$ which is $\cong 7.5$ for extended margins, and it is $0.1\times6.6 + 0.2\times6.8 + 0.5\times7.0 + 0.2\times7.2 \cong 7.0$ for cratons, as used in the present investigation. Although the M_{max} used in the present investigation appears to be largely consistent with other regions of tectonic similarities and also in terms of historical seismic activity during last few centuries in these regions, further investigations are necessary to validate some of these assignments and use latest available scientific knowledge for developing future seismic hazard map of the region.

4. GROUND MOTION EQUATIONS

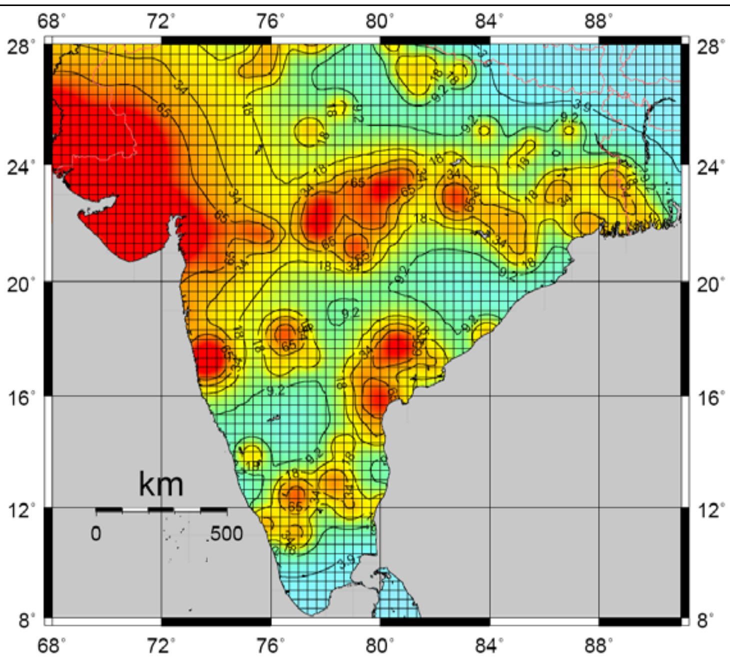
Due to the lack of well-defined ground motion prediction equations for the region, we used four crustal intra-plate relationships, which include two simulation-based relationships for Central and Eastern United States (CEUS). Both Eastern North America and Peninsular India regions share similar features in terms of observed seismogenic activities and known seismotectonics, as discussed by Schweig et al. (2003) and Cramer and Kumar (2003). We have used newly developed ground motion equations for Central and Eastern North America and weighted them based on the categories as explained below: We used Frankel et al. (1996) single corner model along with the new model developed by Toro et al. (2005) which is a single corner, extended source model, and Atkinson and Boore (2006), a dynamic corner frequency source model which accounts for magnitude saturation and variable stress drop and Silva et al. (2002), a constant stress drop with magnitude saturation model. The weights are assigned to single corner finite fault model (accounts for magnitude saturation; wt 0.25), single corner point source (accounts for Moho bounce and 1/r geometric spreading; wt 0.25), dynamic corner frequency models (accounts for magnitude saturation and variable stress drop, i.e., 140 and 200 bar; wt 0.125 each) and the remaining weight for a constant stress drop model by Silva et al. (2002). We have converted hard-rock attenuation relations to approximate ground motions for a site with shear velocity on the NEHRP B/C boundary using kappa (typically assumes value of 0.01). It is a single key parameter that defines the high frequency near-surface site attenuation of the ground motion. Information specific to the ground motion predictions equation used in this investigation, its distance metric and uncertainties in ground motions are discussed in detail by Petersen et al. (2008).

5. HAZARD ESTIMATION

For the application of gridded seismicity approach, the entire region is divided into smaller grid cells of size 0.1° × 0.1° i.e. approx. 11 km × 11 km area. A minimum magnitude $M_w = 4.5$ has been chosen for the hazard estimation based on the observation that earthquakes of that magnitude can be damaging to the existing vulnerable building stock (Sinha et al. 2001). In case of gridded seismicity approach, we estimate number of earthquakes greater than minimum cutoff magnitude in each grid cell and then estimate the incremental rate for each grid cell. Spatial smoothening of 50 km incorporates errors associated with epicentral locations of pre-instrumental earthquake events, catalog incompleteness in low magnitude ranges and variability in grid patterns. The mean rate of hazard at the centre of each grid is evaluated using all the *a*-values associated with all grid cells that are within the smoothening distance range (Frankel, 1995). The estimated ground motions are typically quantified in terms of a median value (a function of magnitude, distance, site condition, and other factors) and a probability density function of peak horizontal ground accelerations or spectral accelerations (McGuire, 2004). Ground motion maps have been produced by considering the ground motion distribution from each of the potential earthquakes that can affect the site and that have 2% probability of exceedance in 50 years. The seismic hazard maps have been prepared using a reference site condition that is specified to be the boundary between NEHRP classes B and C, with an average shear-wave velocity in the upper 30 m of the crust of 760 m/s.

6. DEVELOPMENT OF SEISMIC HAZARD MAP

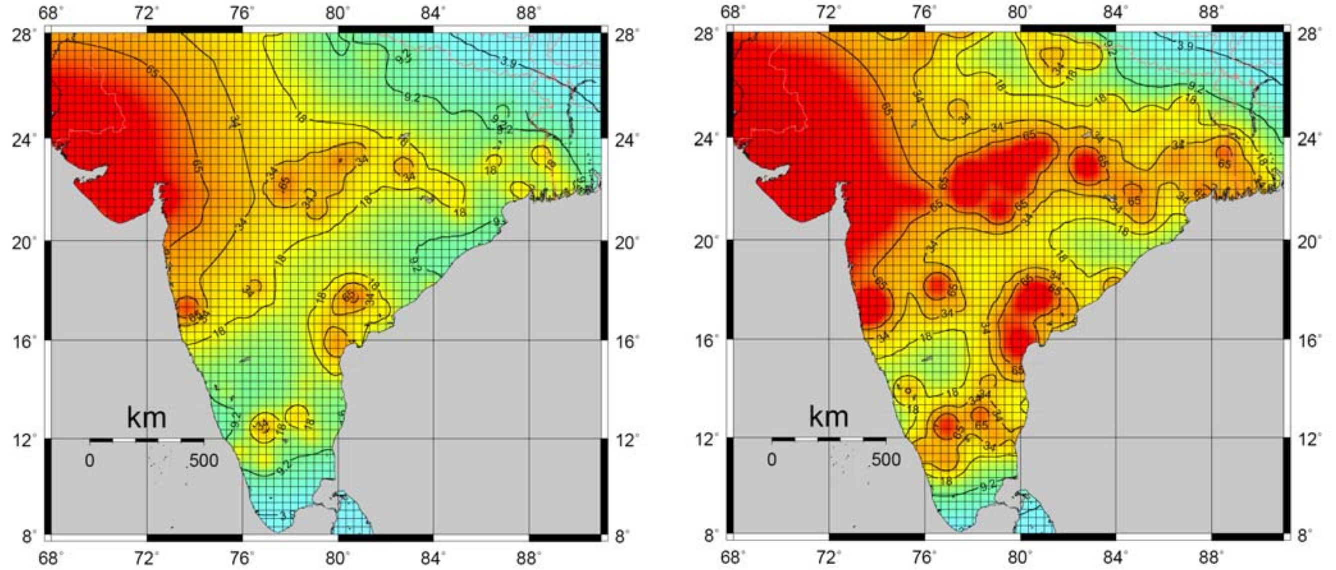
The authors have earlier presented hazard map in terms of 10% probability of exceedance of peak ground accelerations in 50 years for peninsular India (Jaiswal and Sinha 2007). The seismicity model consisted of uniform, geo-based, reservoir induced and background seismicity with equal weights. We observed that the background seismicity model with 25% weight considerably reduced the ground motion associated with Runn of Kuchchh and Naramda lineament zone. In this investigation we derive the seismicity rates for each zone independently (Figure 3) from the catalog data and then model the Gaussian smoothed seismicity for each zone in such a way that the overall modeled seismicity of the zone directly reflects the historical seismicity rates. We used higher Gaussian smoothening distance of 50 km to spread the recorded seismicity at larger distance to account for errors in the epicentral location, uncertainties in the source characterization (for example, lack of data on active vs. inactive faults within each zone). The source of the Bhuj earthquake of 2001 was not associated with any previous large historical earthquakes (Rajendran and Rajendran, 2003), and similarly the occurrence of Killari earthquake of 1993 in a region that had not experienced notable seismicity in the past.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

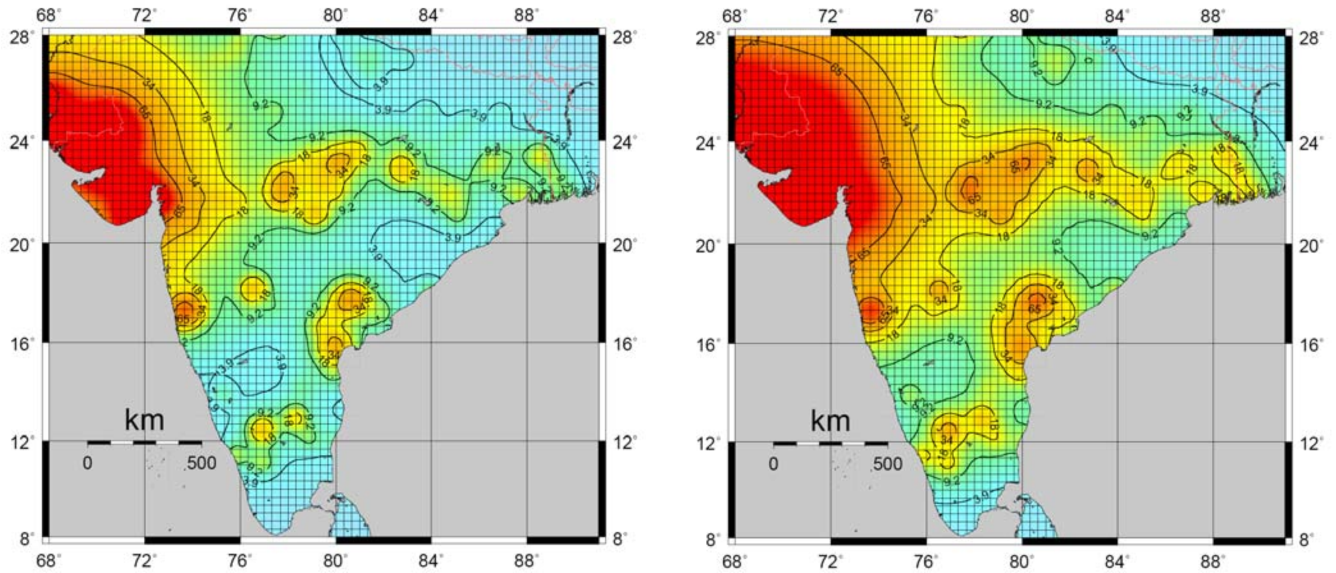
Figure 4. Probabilistic seismic hazard map showing peak ground acceleration hazard in different zones of central and southern India for 2 % probability of exceedance in 50 years using ShakeMap style color palette (Wald et al., 1999).

Figure 4 provides seismic hazard map for 2% probability of exceedance in 50 years, i.e., corresponding to estimation of ground motion at a site in terms peak ground acceleration that have an average recurrence of 2500 years or also termed as maximum considered earthquake (MCE) ground motion. Most of the building code uses this hazard value to define the seismic hazard and then reduce it by correction factors to estimate design basis earthquake (DBE) ground motion (i.e., ground motion corresponding to 10% of probability of exceedance in 50 years or return period of ~475 years). The map shown in Figure 4 indicates peak ground acceleration estimates shown using Shakemap color palette scheme that provides an interpretation from peak ground motion parameters to shaking intensity. In case of Runn of Kuchch, we estimate ground motion to be much higher than rest of peninsular India and in general it reaches beyond 0.65 g for most of the zone or MMI IX shaking intensity.



(a) (b)

Figure 5. Probabilistic seismic hazard map showing pseudo spectral acceleration at a) 3 Hz, and b) 5 Hz in different zones of central and southern India for 2% probability of exceedance in 50 years.



(a) (b)

Figure 6. Probabilistic seismic hazard map showing a) peak ground accelerations, and b) pseudo spectral accelerations at 5 Hz in different zones of central and southern India for 10 % probability of exceedance in 50 years.

The higher seismic hazard estimates appear to be consistent with the three devastating earthquakes (M ≥ 7.5, shaking intensity IX and above) in this region during relatively shorter catalog duration (e.g., 1668 earthquake that destroyed the town of Samaji; 1819 earthquake of M_w 7.7 that killed 1500 people in Bhuj and 500 in Ahmedabad;

Bhuj earthquake of 2001 that killed over 13000 people). We also develop hazard map in terms of pseudo spectral acceleration at 3 and 5 Hz frequencies (figure 5a and 5b, respectively), which is generally very useful to structural engineers for earthquake resistant design. The MCE level ground motion associated with Koyna region appears to be in the range of 0.65 g in terms of PGA, that corresponds to instrumental shaking intensity VIII and above, whereas the spectral acceleration at 3 Hz ranges from 0.35 to 0.65 g. Seismic hazard map developed in terms of peak ground acceleration for 10% probability at 50 years (see Figure 6a) in general, indicates higher hazard for Runn of Kuchchh which corresponds to shaking intensity IX and above. Similarly the hazard associated with Narmada lineament zone and eastern passive margin ranges from 0.18 g to 0.3 g corresponding to instrumental shaking intensity VII as shown in figure 6a. This matches the shaking intensity associated with recent 1997 Jabalpur earthquake in NL zone of Madhya Pradesh and 1969 Bhadrachalam earthquake in eastern Andhra Pradesh respectively. The design basis ground motion increases by 1 intensity unit for the 5 Hz spectral acceleration map as shown figure 6b in these zones.

6. CONCLUSIONS

The paper presents probabilistic seismic hazard map of central and southern India in terms of peak ground accelerations and spectral accelerations at different frequencies. Some of the important features of this study are use of several newly developed ground motion prediction equations for hazard assessment, re-assignments of maximum magnitude potentials to the zones, re-alignment of zonal boundaries, estimation of zone specific seismicity parameters and development of a hazard map in terms of spectral acceleration parameters at different frequencies which would be useful for engineering applications. It is important to note some of assumptions and idealization that are inherent with this assessment, such as a) estimated historical rate of seismicity will represent future seismicity, b) geo-based maximum magnitude potential is applicable, c) similarity of ground motion characteristics between CEUS and peninsular India, and finally d) earthquake occurrence in peninsular India is Poisson process. Although, the investigation utilizes the 400+ years of earthquake data along with similarity hypothesis of seismotectonic characteristics elsewhere to deduce the recurrence characteristics of future earthquakes and zone-specific maximum magnitude potential, rigorous geological and paleoseismic studies are necessary in this area before such data could be used to constrain these parameters for future updates of the map. The newly developed seismic hazard map shows higher design seismic forces than currently used in earthquake zoning map of India of IS code. The authors feel that it is possible to carry out further improvements in the zoning map presented in the paper based on emerging multi-disciplinary research before a definitive zoning map can be developed.

ACKNOWLEDGMENTS

We dedicate this paper to late Prof. Kailash Nath Khattri (1934-2007), a well known Indian scientist who contributed significantly in the area of seismic hazard estimation especially by developing one of the early versions of probabilistic seismic hazard map for Indian region. The authors also thank Dr. Mark Petersen of USGS for inspiring for this work and for useful discussion during this investigation. The first author also thanks Dr. David Wald of USGS allowing contributing to this research effort.

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