PROBABILISTIC EVALUATION OF SEISMIC HAZARD IN AND AROUND KERALA

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ABSTRACT: In view of the major advancement made in understanding the seismicity and seismotectonics of the region, an updated probabilistic seismic hazard map of Kerala and its vicinity covering 5°-16°N and 72°-81°E was prepared. The earthquake catalogue was prepared by compiling the data from different national and international agencies. The seismotectonic map of the study area was prepared by considering the faults, lineaments and the shear zones which are associated with earthquakes of magnitude 3 and above. The seismicity parameters were estimated for the region and the hazard parameters (Rock level Peak Horizontal Acceleration (PHA) and spectral accelerations for periods 0.1s and 1s) were calculated considering all the seismic sources within a radius of 300 km. Epistemic uncertainty in hazard has been tackled within a logic-tree framework considering three types of source models and three attenuation models. The contour maps showing spatial variation of spectral acceleration values both at bed rock and surface level are presented in the paper.

INTRODUCTION
Kerala is a state in Southern India which is considered as a region with low to moderate seismic activity. Entire Kerala has been placed in zone III, the moderate level of seismic hazard potential, according to the seismic zonation map of India (BIS 2002). In view of the major advancement made in understanding the seismicity and seismotectonics of the region, an updated probabilistic seismic hazard map of Kerala and its vicinity covering 5°-16°N and 72°-81°E was prepared and presented in this paper. The earthquake catalogue was prepared by compiling the data from different national and international agencies. The duplicate events were removed and the homogenization of the catalogue was done to make it uniform in moment magnitude (Mw) scale. The seismotectonic map of the study area was prepared by considering the faults, lineaments and the shear zones which are associated with earthquakes of magnitude 3 and above.

The seismicity parameters were estimated for the region and the evaluation of spectral acceleration was done by considering the uncertainties in earthquake recurrence rate, hypocentral location and attenuation characteristics. Epistemic uncertainty in hazard has been tackled within a logic-tree framework considering three types of source models (Linear, areal and grided seismicity model) and three attenuation models. The contour maps showing spatial variation of spectral acceleration values at bed rock level are presented in the paper.

PREPARATION OF EARTHQUAKE CATALOGUE
Earthquake Database
Data sets provided by various national and international agencies were used in preparing the earthquake catalogue. The national agencies include Guaribidanur Array (GBA), Indian Meteorological Department (IMD) and National Geophysical Research Institute (NGRI) Hyderabad. International agencies include International Seismological Center (ISC) data file and USGS/NEIC catalog. The earthquakes which are occurring outside the study area will also add to the seismic hazard of the study area [1]. Hence the details of the past earthquakes and seismic sources were collected from an area which extend up to 300 km from the boundary of India.

Homogenization of earthquake magnitudes
The earthquake data obtained from different agencies were in different magnitude scales and it necessitates the conversion of these magnitude scales to a single magnitude scale for the analysis purposes. The original magnitudes of earthquakes in different time periods have been converted to unified Mw magnitudes. Existing Relations [2] were used for the conversion and a consistent catalog with unified magnitude scale was developed for the entire study area.

Fig.1 Distribution of Earthquake events in and around Kerala
Removal of dependent events

The instrumental catalogs report not only the main shocks but also foreshocks and aftershocks. Deleting aftershocks and other dependent events leads approximately to a Poisson, or random data set for a better estimation of return periods of randomly occurring events which is an important goal of seismic hazard studies. Declustering is the separation of the dependent events from the background seismicity [3]. For seismicity rate studies as well as hazard related studies, declustering is often considered necessary to achieve better results [4, 5]. In the present study, dependent shocks as those falls within the space and time intervals of the mainshock are eliminated to obtain a data set of mainshocks which are assumed to show a Poisson distribution [6,7]. 1592 mainshocks were identified in the area among which 423 events were of $M_W \geq 3$. The distribution of earthquake events in the declustered catalog is shown in Fig. 1.

SEISMICITY ANALYSIS

The Seismic activity of a region is given by earthquake recurrence law [8].

$$LogN = a - bM \tag{1}$$

Where $N$ is the total number of earthquakes with magnitude $M$ and above which will occur in a year and $a$ and $b$ are the seismicity parameters of the region. The values of seismicity parameters were evaluated using the maximum likelihood estimation technique [9, 10]. The parameter ‘$a$’ describes the productivity of a volume, and $b$, the slope of the frequency- magnitude distribution (FMD), describes the relative size distribution of events. The ample, high-quality earthquake catalogs collected primarily over the past two decades, and the availability of increased computing power, have enabled researchers to investigate spatial variations in $b$ with high precision. The strong difference in $b$ is simply a reflection of the heterogeneity of the earth that emerges on all scales, once suitable datasets become available [11]. The maximum likelihood method was used in the estimation of seismicity parameters.

For evaluating the seismicity parameter, the completeness of the catalogue has to be analyzed and the data in the complete part of the catalogue need to be used for the analysis. The magnitude of completeness is the lowest magnitude above which the earthquake recording is assumed to be complete. The evaluation of $b$ value was done based on the maximum likelihood method [11]. The uncertainties involved in evaluating $b$ value were calculated using the bootstrap method with 100 bootstraps [12].

SEISMIC SOURCE MODELS

Another important step in the seismic hazard analysis is the identification of vulnerable seismic sources. One of the best documents listing the linear seismic sources in India and adjoining areas is the Seismotectonic Atlas [13] published by the Geological Survey of India (GSI). The Seismotectonic Atlas was prepared after extensive studies using remote sensing technique and by geological explorations. The SEISAT maps are available in A0 size sheets with 1:1,000,000 scale and each maps covers an area of $3^\circ \times 4^\circ$. SEISAT contains the details of the faults, lineaments and shear zones in addition to the geological features in India and adjoining areas. Required sheets of SEISAT were scanned, georeferenced and were combined together to form a complete map of study area with linear seismic sources. From this map the tectonic features were carefully extracted which consist of all the linear seismic sources identified by SEISAT.

SEISAT does not include sources in the ocean beds and also, it was seen that there are few events which are not associated with any of the identified linear seismic sources. When the seismic hazard analysis is done using the identified linear seismic sources alone, the effects of such earthquake events will not be considered. In those cases the modeling of seismic sources which are spread over an area, will be a better option. For this smoothed Gridded seismicity model [5] is used which is one of the most widely adopted methods to model seismic sources for the regions in the absence of clearly identified sources. While considering the areal sources, the first step is the selection of grid size and the cutoff magnitude ($M_{max}$). After selecting a suitable grid size, the number of earthquake events of magnitude greater than or equal to $M_{cut}$ has to be calculated for each grid cell and this represents the maximum likelihood estimate of the total number of earthquakes (equal to or greater than $M_{max}$) for that grid cell. In the present study the value of $M_{max}$ was taken as 4.0 to eliminate the effect of rock bursts and blasting. More over seismic events with magnitude less than 4.0 may not cause much damage also. Based on this value the recurrence rates for different magnitude intervals were calculated. These values were smoothed using a Gaussian function to get the final corrected values for each grid. This smoothing is done to account for the uncertainty associated with location of earthquake events.

EVALUATION OF GROUND MOTION

Ground motion prediction equations

In India, there is lack of strong motion data and this in turn has resulted in the development of only very few region specific GMPEs. Hence, in the present study we have used some of the well accepted GMPEs which were developed for other regions of the world which are having similar seismic attenuation characteristics.

Kerala is a stable continental region with low to moderate seismicity. Three different attenuation relations were used in the present study [14, 15, 16]. Out of these the relation by Raghu Kanth and Iyengar (2007) was developed for the Peninsular Indian Shield regions. Raghu Kanth and Iyengar (2007) observed that their model have predictions similar to those of the available models for other intraplate regions. Attenuation relations given by Campbell and Bozorgnia (2003) and Atkinson and Boore (2006) were developed for
the Eastern North America (ENA). Ground motion attenuation in ENA and Peninsular Indian shield are comparable due to similar regional tectonics of both the regions [17, 18].

![Logic Tree Structure](image)

**RESULTS AND DISCUSSIONS**

The seismic hazard analysis of Kerala was done by dividing the entire study area into grids of size $0.1^\circ \times 0.1^\circ$ (about 11km$\times$11km). For each grid point the peak horizontal acceleration (PHA) and spectral acceleration (Sa) (for periods of 0.1 s and 1 s) values were evaluated for bed rock level corresponding to probability of exceedance (PE) of 10 % and 2 % in 50 years. These exceedance values correspond to return periods of 475 and 2475 years respectively. While evaluating the seismic hazard using PSHA method, the hypocentral and magnitude uncertainties were considered. This was done by deaggregating the hypocentral distance into small intervals of 2 km and the magnitude range (between minimum and maximum magnitude) into small incremental values of 0.2 (a lower value of the hypocentral incremental distance (less than 2 km) and magnitude interval (0.2) was not improving the accuracy of the results significantly and it was increasing the computational time). For each grid point all the sources which are within a radius of 300 km were considered for evaluation of PHA and Sa values. The spatial variation of PHA values obtained for 10 % and 2 % PE in 50 years are shown in Figs 3&4. The spectral acceleration values for the periods 0.1s and 1s obtained for 10 % probability of exceedance in 50 years are shown in Fig. 5. For 475 years return period, The PHA value goes upto to 0.15g whereas for 2475 years return period, it goes upto 0.3g.

![Fig.3. PHA values (g) for a return period of 475 years](image)

![Fig.4. PHA values (g) for return period of 2475 years](image)
CONCLUSIONS

The seismic hazard evaluation of the Kerala based on a state-of-the-art PSHA study has been performed using the classical Cornell–McGuire approach with different source models and attenuation relations. The most recent knowledge on seismic activity in the region has been used to evaluate the hazard incorporating uncertainty associated with different modeling parameters. The PSHA has been performed with currently available data and their best possible scientific interpretation using an appropriate instrument such as the logic tree to explicitly account for epistemic uncertainty by considering alternative models.

The hazard maps have been produced for horizontal ground motion at bed rock level. The present study shows that the seismic hazard is less in North Kerala and moderate in South and Central Kerala except few spots where PGA value goes up to 0.1g for a return period of 475 years. The ground motion predicted from the present study will not only aid in safe design of structures, but also will help in deciding the locations of important structures. Reliable information on the active faults and geodetic measurements of fault movement rates will help in redefining seismogenic sources which need to be carried out. Strong ground-motion records for earthquakes in the region would be essential to develop region specific attenuation relations. The updated and reliable information on these factors would go a long way in redefining the seismic hazard of the region in a better way.

REFERENCES