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KERNEL DENSITY ESTIMATION TECHNIQUES FOR SEISMIC HAZARD ANALYSIS OF SOUTH INDIA

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Abstract. *Peninsular India is known for its complex intraplate seismicity and the southern part of it is characterized by diffused and distributed seismicity. In such cases the most commonly adopted seismic source is the area source zone. The formation of seismic area source zone is subjective for regions such as south India and hence zonefree techniques to probabilistic hazard analysis have been carried out in the past. The zonefree technique specifically the kernel technique is still new and has been applied to specific sites in south India such as Chennai and Kanchipuram. In this study the fixed and adaptive kernel techniques have been applied to the whole of south India to obtain the hazard value. The most influencing parameter affecting the kernel technique has been varied in two ways - the bandwidth parameters determined for the whole earthquake catalogue of south India and the other by determining the bandwidth parameters for the earthquakes lying in an influence area of 300 km radius around a particular site. It was observed that the adaptive kernel technique yielded slightly higher hazard values in regions of high seismic activity and lower values in regions of low seismic activity. However both the techniques yielded similar results in regions of spatial uniform seismicity. A significant difference was observed in the uniform hazard spectra obtained for specific sites in south India when the bandwidth parameters were estimated considering whole of south India (regional) and an influence area of 300 km radius (local).*

1 INTRODUCTION

Seismic Hazard Analysis (SHA) is carried out to provide ground shaking values in the form of acceleration, velocity or displacement to determine the seismic input to be considered in the design of buildings. SHA is carried out in two ways – probabilistic or deterministic. In probabilistic seismic hazard analysis (PSHA), uncertainties in the earthquake location, magnitude and path of travel are considered. In deterministic seismic hazard analysis (DSHA), the ground shaking value is determined considering the worst case for location, magnitude and path of travel of the earthquake. This form of analysis is usually carried out for very important structures e.g. nuclear power plant facilities. However PSHA is the most commonly used form of hazard analysis; and the most widely used technique is the Cornell-McGuire approach [1, 2]. The first step in the conventional PSHA is the identification and characterization of the seismic sources. These sources may be in the form of point, line or area seismic source zone. The low to moderate seismicity regions are often characterized by diffused and distributed seismicity and hence the most common form of seismic source adopted is the area source zone.

The Cornell-McGuire approach to PSHA has been found to have several drawbacks when applied to some specific site conditions. These drawbacks are as follows:

1. Insufficient data to fit the G-R recurrence relation for low seismicity regions [3].
2. Difficulty in satisfying the homogeneity condition (*b* value constant) within an area source zone [4].
3. Areal extent of applicability of G-R recurrence law not known [5, 6].
4. Sudden change of seismicity at the zonal boundaries [7].
5. Expert knowledge of geology, seismology and tectonics required to form source zones [8, 9].

Probability theory provides several latest techniques of estimating the probability density function (PDF) for a given set of data viz. kernels, splines and wavelets. Hence, it is important to adopt new and also the most appropriate techniques available in probability theory in determining the density. Such techniques need to be implemented in seismic hazard analysis to help overcome some of the drawbacks of the conventional methodology.

2 KERNELS

Density estimation techniques can be broadly classified as parametric and nonparametric techniques. In the nonparametric techniques no prior assumption regarding the distribution is made, but is derived from the data in hand. The simplest technique under this category is the histogram and some latest techniques such as kernels, splines and wavelets can be found. Among the newer techniques, the kernel density estimation technique is the simplest one which consists of placing standard curves such as uniform, triangular, normal or quartic on each of the data point and the density is determined as the normalized sum of each of these individual kernels (Fig. 1).

Kernel density estimation technique has been popular in many areas of earthquake engineering such as hazard analysis [10], seismic occurrence rate determination [11], determination of influence area of an earthquake [12] and source size characterization to name a few. The kernel technique to seismic hazard analysis has already been applied to a few sites in south India such as Chennai [13, 14] and Kanchipuram [15] where the results matched well with the Cornell-McGuire approach.

There are two variables to be considered in kernel density estimation – shape of the kernel to be used and the spread of the kernel also known as the bandwidth or window width. Figure

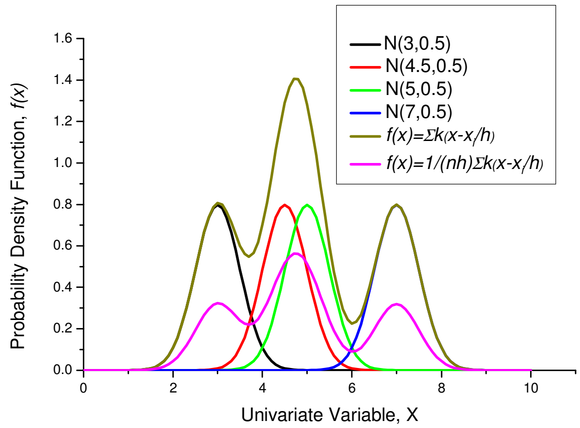

Figure 1: Kernel density estimation concept.

2 shows the various forms of kernels being placed on individual data points (say 7, 8, 9, 12 and 14) and the final form of the PDF obtained. It can be concluded that the shape of the kernel does not play an important role as the final PDF obtained is insensitive to the form of kernels used. However there are several works by previous researchers [16, 17, 18] stressing the importance of the bandwidth. The optimal bandwidth to be used for a data set can be fixed across the data or can be varied. The former is called the fixed kernel density estimation technique while the latter is called the variable or adaptive kernel density estimation technique.

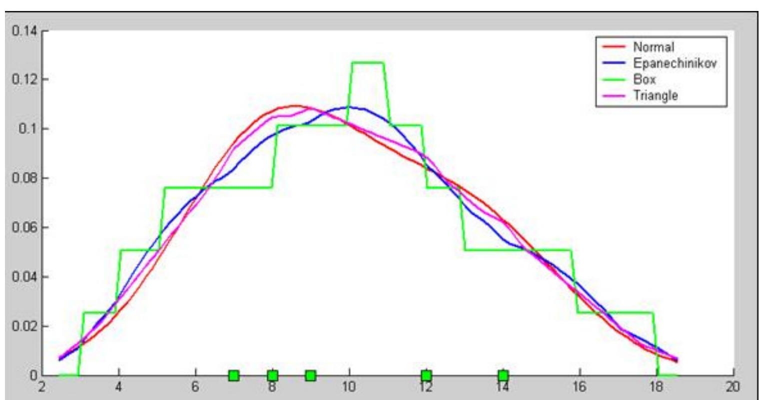

Figure 2: Various forms of kernels [de SMITH et al.[19]]

2.1 Fixed kernel density estimation technique

In the fixed kernel density estimation technique, the bandwidth or spread of the kernel function placed on the data are same across all the data. Consider the probability distribution of a random variable X given as

$$P(a \le X \le b) = \int_a^b f(x)\, dx \qquad (1)$$

where $f(x)$ is the PDF, a and b are the selected lower and upper bounds. A univariate PDF from the fixed kernel technique is given as

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{2}$$

where n is the number of data or observation, h is the fixed bandwidth which controls the variance of the symmetric function $K((x\text{-}x_i)/h)$, x is any point and x_i is the data. A multivariate PDF in d-dimensional space from the fixed kernel technique is given as

$$f(x) = \frac{1}{nh^d}\sum_{i=1}^{n} K\left\{\frac{1}{h}(\mathbf{x} - \mathbf{x}_i)\right\} \tag{3}$$

The kernel K considered must satisfy the following conditions

$$\int_{R^d} K(t)dt = 1, \ \int_{R^d} tK(t)dt = 0, \ \text{and} \ \int t^2 K(t)dt = k_2 \neq 0$$

and the unknown density f has a continuous derivatives of all orders required and the constant k_2 is the variance of K.

There are several methods of determining the optimal bandwidth in the literature [16, 17, 18] and are summarized as the least-square cross validation, biased cross validation, plug-in bandwidth selection, smoothened cross validation, root-n bandwidth selection and the contrast methods [20].

2.2 Adaptive kernel density estimation technique

In adaptive kernel density estimation technique the bandwidth is varied depending on the spatial location of the data. It follows the principle that smaller bandwidth is more appropriate in regions of high density since a larger number of samples enable a more accurate estimation of density in these regions. From Fig. 3a it can be observed that larger bandwidth leads to over smoothing whereas smaller bandwidth leads to spiky PDF (Fig. 3b). A larger bandwidth is more appropriate in low density areas where a few sample points are available.

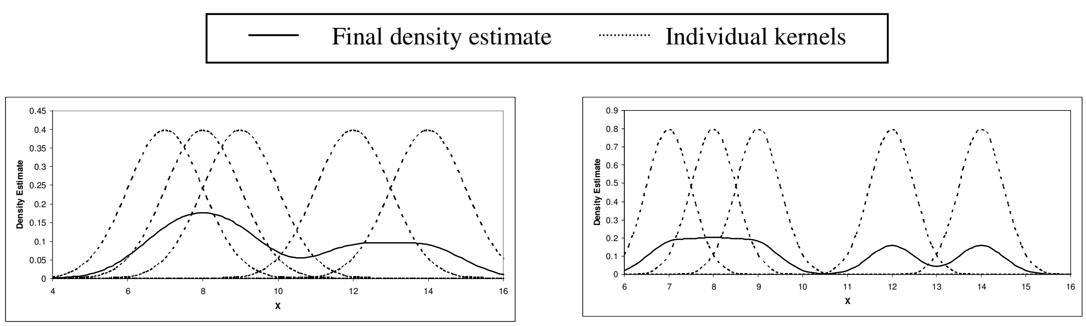

Figure 3a: Large bandwidth kernels

Figure 3b: Small bandwidth kernels

The PDF from the adaptive kernel technique is determined as

$$f(\mathbf{x}) = \frac{1}{n}\sum_{i=1}^{n} \frac{1}{[h(\mathbf{x}_i)]^d} K\left\{\frac{1}{h(\mathbf{x}_i)}(\mathbf{x} - \mathbf{x}_i)\right\} \tag{4}$$

There are several techniques of varying the bandwidth, however in the present study, a three step procedure has been adopted [16] and is given as

1. Find a pilot estimate of $f(\mathbf{x})$ that satisfies $f(\mathbf{x}_i) > 0$ for all i
2. Define local bandwidth factor λ_i by

$$\lambda_i = \{f(\mathbf{x}_i)/g\}^{-\alpha} \tag{5}$$

where g is the geometric mean of $f(\mathbf{x}_i)$ given as

$$\log g = n^{-1}\sum \log f(\mathbf{x}_i) \tag{6}$$

and α is the sensitivity parameter ($0 \leq \alpha \geq 1$).

3. Define the adaptive kernel estimate $f(\mathbf{x})$ by

$$f(\mathbf{x}) = n^{-1}\sum_{i=1}^{n} h^{-d}\lambda_i^{-d} K\left\{h^{-1}\lambda_i^{-1}(\mathbf{x}-\mathbf{x}_i)\right\} \tag{7}$$

where h is the global bandwidth.

When α is 0, the estimate reduces to fixed kernel and a value closer to 1 causes the estimate to become more sensitive to the variation in bandwidth from point to point. A value of α = 0.5 has been proven to give good results [16, 21]. The above three step procedure has been used to arrive at the earthquake occurrence model by smoothing the annual activity for Australia and New Zealand [11].

2.3 Implementation of kernels in seismic hazard analysis

In PSHA, the mean annual rate of exceedance λ_{y*} of the selected ground motion parameter Y (acceleration, velocity or displacement) exceeding a particular value $y*$ is given by

$$\lambda_{y^*} = \sum_{i=1}^{N_S}\sum_{j=1}^{N_M}\sum_{k=1}^{N_R} \upsilon_i\, P\left[Y > y^* \mid m_j, r_k\right] P\left[M = m_j\right] P\left[R = r_k\right] \tag{8}$$

where N_s is the number of sources, N_M is the range of magnitudes, N_R is all the possible range of distances from site to source, υ_i is the seismicity rate for each source defined by the G-R recurrence law, $P[Y>y^* \mid m_j,r_k]$ is obtained from the attenuation relationship, $P[M = m_j]$ and $P[R = r_k]$ are obtained from the probability density function of magnitude and distance respectively. In kernel approach, the seismicity rate υ_i is replaced by the spatial activity rate density function given as

$$\upsilon(M,x) = \sum_{i=1}^{N} \frac{K(M, x-x_i)}{T_i} \tag{9}$$

where N is the number of earthquake events, x is the observation/estimation point and T_i is the effective return period evaluated using the following expression:

$$T_i = Timeperiod \sum_i p_i \tag{10}$$

where p_i is the detection probability of the event in a particular time period and a numerical value is assigned to it based on the seismicity of the region.

An anisotropic kernel form used for earthquakes [22] is given as

$$K(M,r) = \frac{n-1}{\pi h^2(M)} \frac{1+\delta\cos^2\phi}{1+(\delta/2)} \left(1+\left(\frac{r}{h(M)}\right)^2\right)^{-n} \tag{11}$$

where n is the exponent of the power law or fractal scaling index taking value between 1.5 and 2, h is the bandwidth and is a function of magnitude, r is the distance to the epicentre, the parameter ϕ is the angle subtended at r between the intersection of the fault plane with the earth's surface and the epicentre location and δ is the degree of anisotropy taking value between 0 and 2. A value of zero indicates isotropy and higher value signifies anisotropy. Anisotropic kernel is useful when the activity rate associated with a fault needs to be determined. However in this study, isotropic kernel was used since most parts of south India are known for distributed seismicity.

The most important step in kernel technique is to arrive at an optimal bandwidth keeping in mind the earthquake phenomenon. For this the power law which takes into consideration the fractal behaviour of the earthquakes is used [10] and is given as

$$h(M) = ce^{(dM)} \tag{12}$$

where parameters c and d depend on the spatial distribution of earthquake epicentres. These parameters are calculated by forming various magnitude bins and for each earthquake event within the bin, the distance to the nearest epicentre is determined. The mean nearest distance for each bin is obtained and through a least-square fit between the magnitude and bandwidth, the parameters c and d are obtained.

It has been observed by previous studies [23, 24] that the fixed kernel technique yields similar results for low to moderate seismicity regions and lower values in high seismicity regions when compared to the Cornell-McGuire approach. The adaptive kernel technique has been used to determine the seismic hazard for Chennai City [14]. It is concluded that the adaptive technique yielded similar results to the fixed kernel technique since Chennai city lies in low to moderate seismicity region and it needs to be tested for other regions. Hence in this study an attempt has been made to evaluate the suitability of the kernel techniques to the other regions of south India and on a much larger scale.

3 GEOLOGY, SEISMOLOGY AND TECTONIC SETTINGS OF SOUTH INDIA

South India mainly consists of four states – Andhra Pradesh, Karnataka, Kerala and Tamil Nadu lie on Deccan Trap which is a part of Peninsular India. The movement of the Indian plate northward from rest of the Gondwana over geologic hotspots caused the melting of the Indian craton underneath. The melting broke out on the surface of the craton creating the Deccan Trap. Hence the Deccan Trap was formed as a result of sub-aerial volcanic activity during the Mesozoic era. Peninsular India is one of the oldest land masses of the earth's crust and is the most stable Precambrian Shield subjected to tectonic and orogenic activities in its subsequent geological history. The region is bounded by Western Ghats (WG) along the coast line and similarly the Eastern Ghats (EG) on the eastern coast line.

Seismically south India has experienced less seismic activity and the earthquakes are due to intraplate seismicity and hence are very complex. Although several faults have been identified in the region [25, 26], there movement has not been recorded. Hence the seismicity is distributed in nature and also diffused. There are several anomalies regarding the seismicity of this region. Wang et al.[27] noted that there is no major deformation of the Peninsular region based on the velocity reading observed at two stations – one located in the northern Ganges plain and the other in Bengaluru located in Karnataka state and hence no major seismic activity. Bilham[28] on the other hand noted that the Indian plate has undergone sufficient flexure (Fig. 4) resulting in major earthquakes such as Koyna (M_w = 6.3, 1967), Latur (M_w = 6.1,1993), Jabalpur (M_w = 5.8,1997) and Bhuj (M_w = 7.7,2001) in Peninsular India. However most of the earthquakes that have occurred in south India are mild and shallow-depth earthquakes. The average focal depths of the earthquakes in these regions are within the upper-crustal (0-12 km) layers complying with the depth of the Moho varying from 34 to 41 km beneath the region of southern India [27].

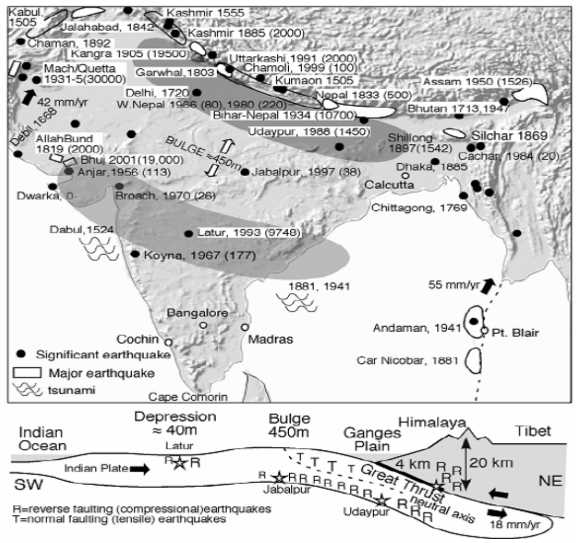

Figure 4: Schematic views of Indian tectonics [Bilham[28]]

The India tectonic plate is currently penetrating into the Eurasian plate at a rate of approximately 45 mm/year along with an anticlockwise rotation in the Indian plate (Fig. 5).

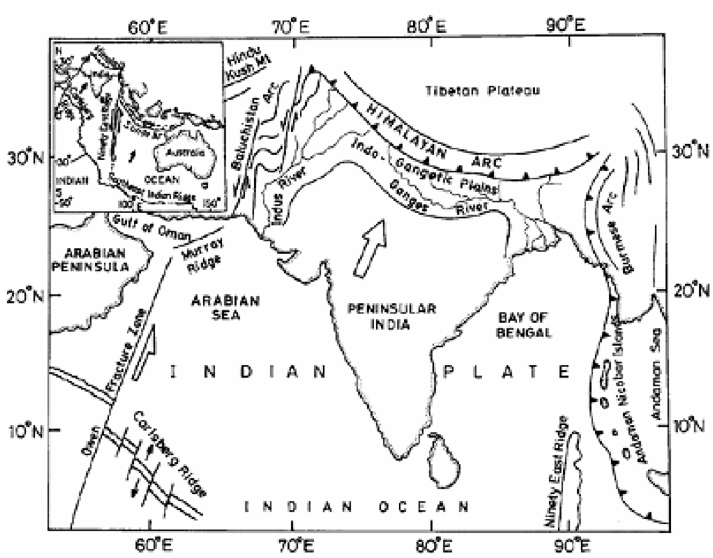

Figure 5: Tectonic map of the northern Indian plate [Biswas and Majumdar[30]]

South India’s major tectonic features are seen in Fig. 6. A major compression zone lying over the transition zone running from Mulki in the west to Pulicat late located on the east has been observed [31]. It has been formed due to the continuous spreading of the sea floor in the Indian Ocean. This zone acts has a major block and hence numerous earthquakes of smaller magnitude are observed around this region. However major earthquakes are observed north of this zone (Latur, Jabalpur). The Southern Granulite Terrain (SGT) Craton has several lineaments and notable earthquakes have occurred in this region (Coimbatore and Pondicherry). The Caddapah Basin forms part of the extended stable continental region and consists of the Pampar lineament and the east-west trending Tiruttani swarms of lineaments.

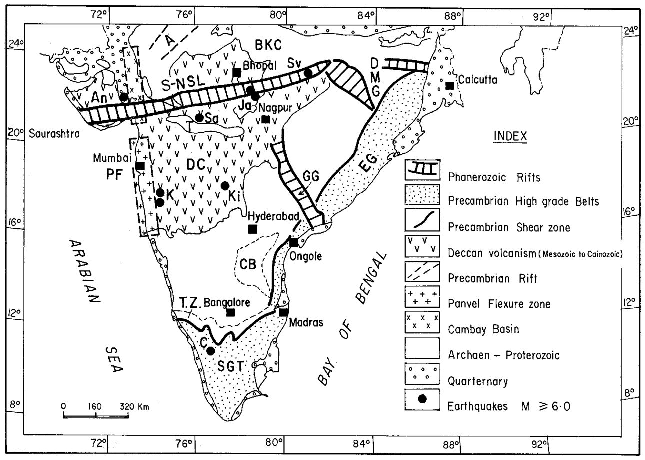

Figure 6: Broad tectonic units in Peninsular India along with significant earthquakes that occurred with M_w = 6.0 and above [Rao[32]]

4 SEISMIC HAZARD ANALYSIS

Seismic hazard analysis for south India (4.667°N to 17.889°N and 70.409°E to 85.687°E) was carried out using two approaches - the fixed and the adaptive kernel techniques. Peak ground acceleration (PGA) contour maps for 475 years return period (10% probability of exceedance in 50 years) were developed using both the kernel techniques by calculating the bandwidth parameters considering the whole south Indian region. The uniform hazard spectra (UHS) for four sites were determined – one by using the bandwidth parameters determined for the whole of south India (regional parameters) and the other by determining the bandwidth parameter for the influence area of 300 km radius around the site (local parameters). The sites chosen were: Site 1 (12.685°N 78.414°E) close to Bengaluru, Site 2 (15.597°N 80.032°E) close to Ongole, Site 3 (17.322°N 73.804°E) close to Koyna, Site 4 (13.0833°N 80.2833°E) Chennai city. Site 1 is characterized by numerous small earthquakes, Site 2 is a seismically active region in south India, Site 3 is characterized by reservoir induced seismicity and Site 4 is characterized by non uniform earthquake epicentre distribution. An average hypocentral depth of 17 km was considered for all the earthquakes.

4.1 Earthquake catalogue processing

A reliable earthquake catalogue fundamental in the estimation of regional seismicity rate is not readily available for south India due to various reasons ranging from lack of detailed historical records to probable seismic quiescence in the past. Hence in the present study, the earthquake catalogue compiled by Menon et al.[33] from 1063 A.D. to 2008 A.D. for 2°N to 20°N and 76.2°E to 80.4°E region was used for the analysis. This would also facilitate a one-to-one comparison of the results. The dependent events (foreshocks and aftershocks) were removed by using the dynamic windowing technique [34]. This resulted in a Poissonian earthquake catalogue with 750 events of $M_w \geq 3.5$ (Fig. 7).

The Poissonian earthquake catalogue was used in determining the bandwidth parameters for the whole region (4.667°N to 17.889°N and 70.409°E to 85.687°E) by forming various magnitude bins. In each bin the bandwidth was determined as the average of the minimum distances among the epicentre. Table 1 shows the average minimum distance determined for each magnitude bin.

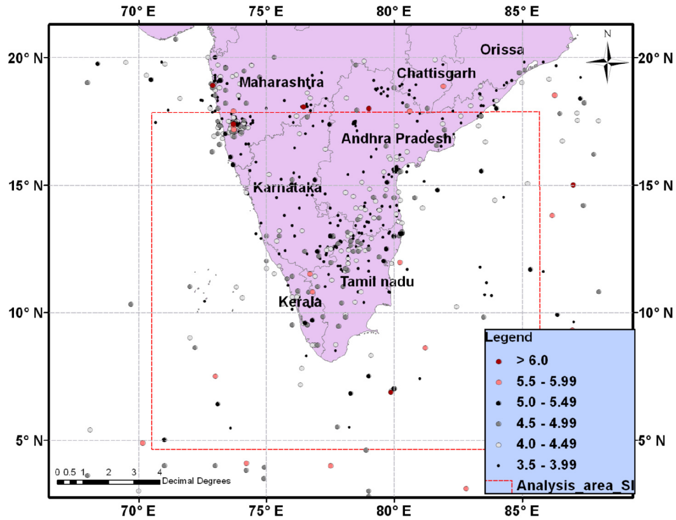

Figure 7: Epicentre distribution and analysis area for south India.

Magnitude (M_w)	Bandwidth (H) in km
3.75	27.0575
4.25	43.4948
4.75	68.4529
5.25	117.5171
5.75	287.4365
6.25	501.6688

Table 1: Bandwidth for magnitude bins.

Figure 8 shows the bandwidth parameters obtained from the curve. The reference year was determined by assigning various probability of detection for each magnitude bin separately for onshore and offshore earthquakes.

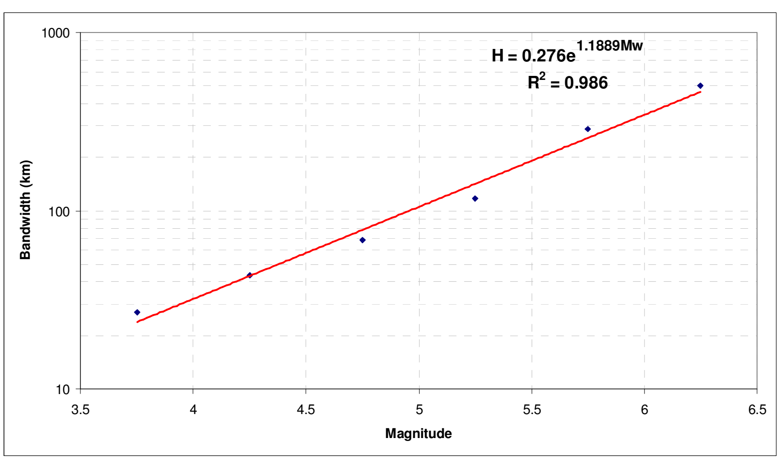

Figure 8: Magnitude-bandwidth relation to estimate the parameter c and d.

As an example the probability of detection for magnitude bin 4.0 to 4.49 for both onshore and offshore earthquakes is given in Table 2. The reference year so obtained is summarized in Table 3.

Time period (D_i)	Onshore		Offshore	
	Probability (p_i)	Effective return period (p_iD_i)	Probability (p_i)	Effective return period (p_iD_i)
1000 - 1500	0.05	25	0.005	2.5
1500 - 1800	0.15	45.00	0.05	15.00
1800 - 1850	0.25	12.50	0.15	7.50
1850 - 1900	0.35	17.50	0.25	12.50
1900 - 1950	0.50	25.00	0.30	15.00
1950 - 1960	0.60	6.00	0.50	5.00
1960 - 1970	0.75	7.50	0.65	6.50
1970 - 1980	0.85	8.50	0.75	7.50
1980 - 1985	0.88	4.40	0.80	4.00
1985 - 1990	0.92	4.60	0.85	4.25
1990 - 1995	0.95	4.75	0.90	4.50
1995 - 2000	0.98	4.90	0.95	4.75
2000 - 2005	0.98	4.90	0.98	4.90
2005 - 2008	0.98	2.94	0.98	2.94

Table 2: Probability assignment for various time periods.

Magnitude bin (M_w)	Reference year	
	Onshore	Offshore
> 6.0	1639	1764
5.5 - 5.99	1687	1836
5.0 - 5.49	1736	1860
4.5 - 4.99	1785	1884
4.0 - 4.49	1835	1914
3.5 - 3.99	1882	1951

Table 3: Reference year for each magnitude bin.

4.2 Attenuation relationship

The ground motion parameter gets attenuated from source to site. The resulting ground motion at the site is determined using the attenuation relationship. These attenuation relationships are empirical equations which estimate the ground motion parameter as a function of independent parameters characterizing the earthquake and the site.

The attenuation relationship suggested by the Working Committee of Experts for microzonation of the Indian landmass formed by the National Disaster Management Authority (Iyengar et al.)[35] was used. The functional form of the attenuation relationship is

$$\ln\left(\frac{S_a}{g}\right) = C_1 + C_2 M + C_3 M^2 + C_4 r + C_5 \ln\left(r + C_6 e^{C_7 M}\right) + C_8 \log(r) f_0 \tag{13}$$

where S_a is the spectral acceleration, r is the hypocentral distance in kilometers, M is the earthquake moment magnitude and $f_0 = \max(\ln(r/100),0)$. The attenuation relationship accounts for geometrical spreading, anelastic attenuation and magnitude saturation. The attenuation coefficients for different regions can be used to construct the mean and response spectrum on A-type rock in any part of India. It was developed from a simulated database of 80,000 samples by a two step stratified regression following Joyner and Boore[36] approach. However, in the present study, the coefficients calculated for south India were used.

5 RESULTS AND DISCUSSION

The hazard was estimated by forming a grid of 0.5° × 0.5° over the study region (4.667°N to 17.889°N and 70.409°E to 85.687°E). At every grid point, an influence area of 300 km radius was considered and all earthquakes lying within this area were considered for analysis. The density was estimated at every 10 km. The minimum cut-off magnitude considered for hazard analysis was $M_w = 4.0$. Magnitude uncertainty of ±0.49 was considered for every magnitude. The PGA obtained for 475 years return period from the fixed kernel technique considering bandwidth parameters calculated for the whole south Indian region is shown in Fig. 10a. Similarly the PGA obtained for 475 years return period from the adaptive kernel technique is shown in Fig 10b.

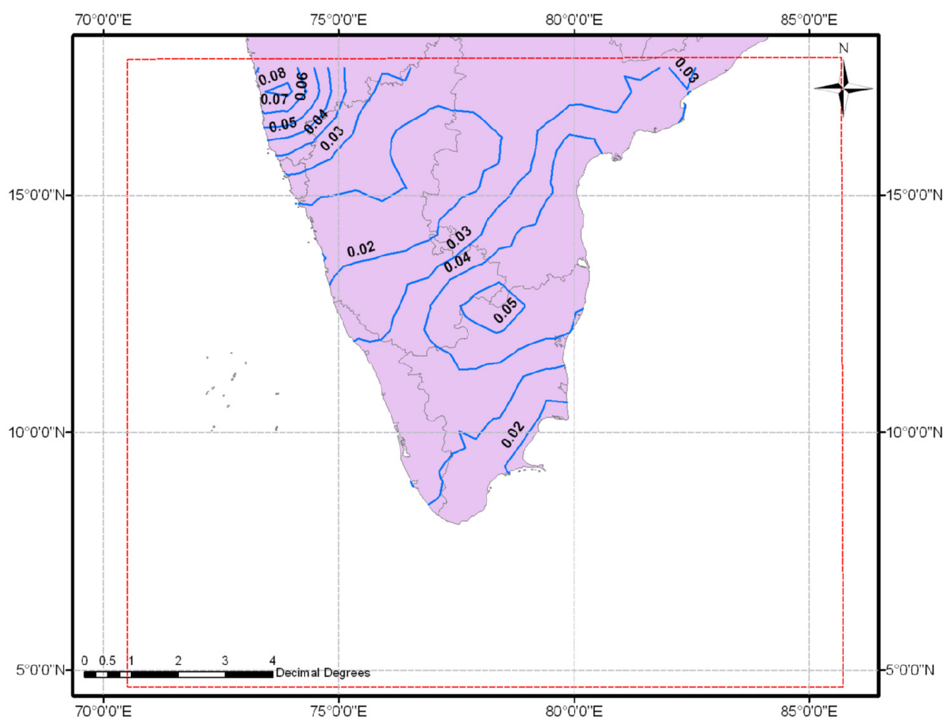

Figure 10a: PGA for 475 years return period by fixed kernel technique

It can be seen that the PGA values marginally differ among the two kernel techniques. Also the hazard value obtained for 475 years return period is quite low when compared to previous studies carried out for a few regions of the study area. Table 4 presents the PGA values for Chennai, Bengaluru, Koyna and Ongole for 475 years return period.

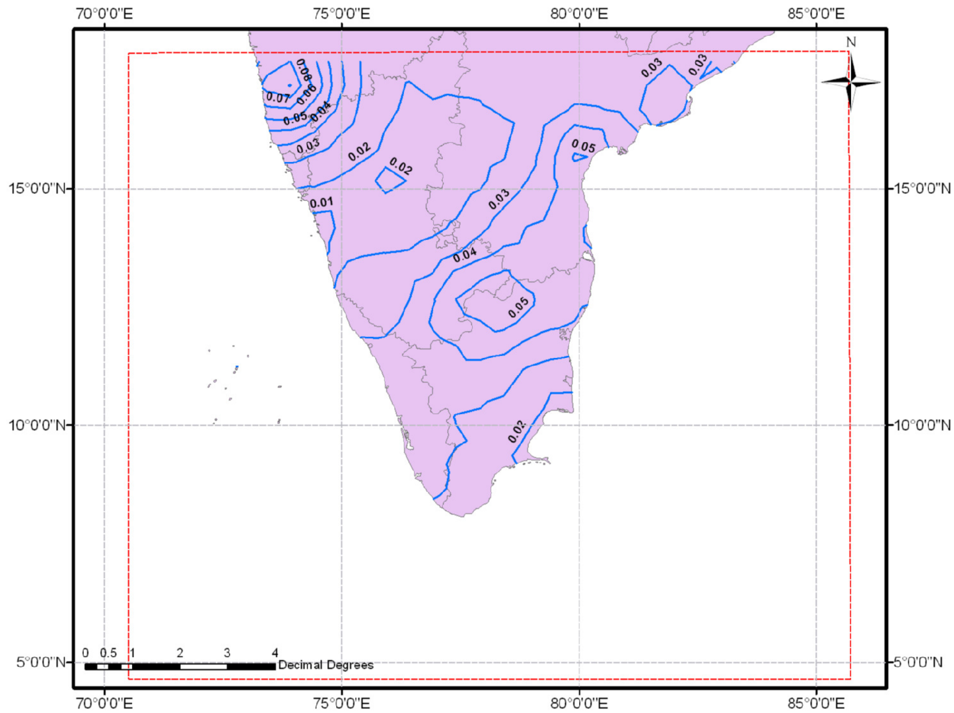

Figure 10b: PGA for 475 years return period by Adaptive kernel technique

Site	Studies	PGA (g)
Chennai	Iyengar et al.[35]	0.06
	Ramanna and Dodagoudar [13,14]	0.08
	Fixed kernel (present study)	0.04
	Adaptive kernel (present study)	0.04
	Jaiswal and Sinha[39]	0.03
	IS 1893:2002[37]	0.08
Bengaluru	Iyengar et al.[35]	0.03
	Vipin et al.[38]	0.10
	Fixed kernel (present study)	0.05
	Adaptive kernel (present study)	0.05
Koyna	Iyengar et al.[35]	0.12
	Jaiswal and Sinha[39]	0.2
	Fixed kernel (present study)	0.07
	Adaptive kernel (present study)	0.08
Ongole	Iyengar et al.[35]	0.06
	Fixed kernel (present study)	0.04
	Adaptive kernel (present study)	0.05

Table 4: PGA for various regions in south India from previous studies

The UHS were determined for the selected regions by calculating the bandwidth parameters considering the earthquake epicentres lying within the influence area of 300 km radius from the site. The bandwidth parameters so obtained for four different sites are summarized in Table 5.

Site	c	d
Site 1	0.4616	0.9678
Site 2	0.9441	0.8459
Site 3	0.3013	0.9227
Site 4	3.5285	0.4675

Table 5: Bandwidth parameters for various sites

The UHS for these sites are shown in Fig. 11a to 11d. It can be observed that there exist large differences in spectral values due to change in the way the bandwidth parameters were determined. For Site 1 a percentage difference in peak spectral value of 8% (percentage calculated with respect to fixed technique) is seen between the kernel techniques irrespective of whether the parameter was determined at local level or regional level. However a difference of 10% (percentage calculated with respect to local parameters) was observed in the peak spectral value for fixed technique when the bandwidth parameters were varied. For adaptive technique

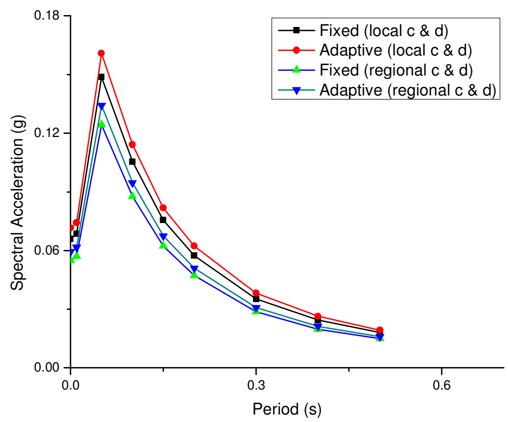

Figure 11a: Impact on UHS for Site 1

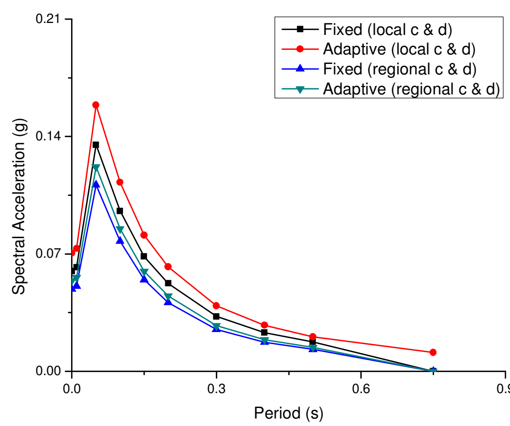

Figure 11b: Impact on UHS for Site 2

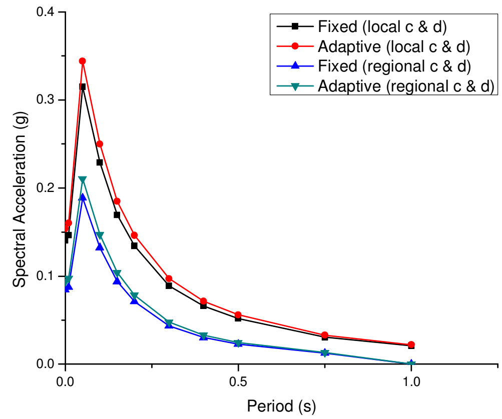

Figure 11c: Impact on UHS for Site 3

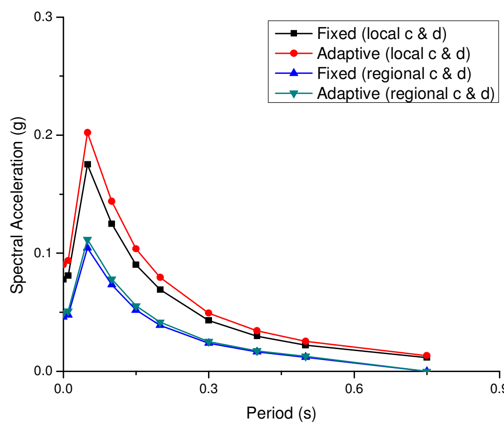

Figure 11d: Impact on UHS for Site 4

a difference of 16.5% (percentage calculated with respect to local parameters) was observed in the peak spectral value when the parameters were varied. The % difference in the peak spectral values for all the four sites are summarized in Table 6.

Site	% Difference between fixed and adaptive kernel techniques		% Difference between local and regional parameters	
	Using local parameters	Using regional parameters	for fixed technique	for adaptive technique
Site 1	8	8	10	16.5
Site 2	17.5	10	18	23
Site 3	9	11.5	40	38
Site 4	15.4	7	40	45

Table 6: Impact on peak spectral acceleration

6 CONCLUSIONS

Seismic hazard analysis has been carried out for whole of south India using the fixed kernel and adaptive kernel technique. It was found that the hazard results varied among the kernel and adaptive kernel technique in regions of very high seismic activity and in regions of very low seismic activity. In regions of very high seismic activity, the adaptive kernel technique resulted in slightly higher results (Ongole and Koyna) and in regions of low seismicity, it yielded lower values (Northern Karnataka region) when compared to fixed kernel technique. Further the impact on the hazard value by varying the bandwidth parameter was analyzed. An important observation was made that there was significant difference in the hazard values when the bandwidth parameter was calculated for smaller region (regional seismicity) and larger region (south India catalogue). The difference was more noticeable for Site 3 and Site 4. Hence it is very important to carry out further study on the influence of the bandwidth parameter on the seismic hazard analysis. With regards to the technique, the adaptive kernel technique is more appropriate kernel technique since it takes into consideration the spatial clustering of the earthquake epicentres.

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