Seismic Hazard at the Historical Site of *Kancheepuram* in Southern India

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ABSTRACT :

A Probabilistic Seismic Hazard Assessment (PSHA) at Kancheepuram was carried out under the aegis of an Indo-Italian Significant Bilateral Project on seismic vulnerability of historic centers in Southern India between the University of Pavia, Italy, and the Indian Institute of Technology Madras, India. The scope of the hazard study was the definition of the seismic input in terms of horizontal/vertical UHS for structural analysis of the heritage structures in Kancheepuram. The standard Cornell-McGuire method and the Zone-Free approach by Woo (1996) have been used for hazard computation after the compilation of a composite earthquake catalogue for Kancheepuram. To make the catalogue statistically consistent with the Poisson's model of earthquake occurrence, the declustering process was carried out by using a dynamic spatial-temporal windowing technique. Completeness analysis of the catalogue was performed by both the Visual Cumulative, Mulargia (1987) and Stepp (1973) methods. Ground Motion Prediction Equations (GMPEs) developed for Peninsular India and three other shallow crustal earthquake models have been used to estimate ground motion attenuation. Epistemic uncertainty in the seismic hazard was addressed by using a logic tree framework assuming completeness analysis, maximum cut-off magnitude, seismogenic zoning and attenuation relations as separate branches of the logic tree. The computed seismic hazard at Kancheepuram is slightly higher than that specified by the current seismic code, IS-1893 (2002). Deaggregation of the seismic hazard for peak ground acceleration predicts low seismicity at Kancheepuram controlled by weak to moderate earthquakes with sources located at short distances from the site.

KEYWORDS: Seismic hazard analysis, historical centers, South India, Kancheepuram

1. INTRODUCTION

Peninsular India, long-considered to be an aseismic, Stable Continental Region (SCR) of the Indian plate, has witnessed quite a few devastating earthquakes (e.g. Koyna, 1967 M_W 6.3; Killari, 1993 M_W 6.4; Jabalpur, 1997 M_W 6.0; Bhuj, 2001 M_W 7.7) in the recent past. Apart from these recent major earthquakes, which have occurred in rather unexpected locations, widespread occurrence mild earthquakes (with $M_W \approx 3.5$) indicates an ongoing seismic activity in the Indian peninsula.

The seismic zoning map in the main Indian seismic code (IS: 1893) was originally conceived in 1962 and revised recently for the fourth time in its fifth revision (IS:1893, 2002) after a series of major earthquakes in the SCR. However, the intensity-based seismic zoning adopted in the code is not probabilistic in its definition of earthquake occurrence, thereby imposing hurdles in choosing design ground motion values within a performance-based design framework. Recourse to customized Probabilistic Seismic Hazard Analysis (PSHA) has to be made in many cases. A significant bilateral Indo-Italian research project currently underway between the University of Pavia, Italy and the Indian Institute of Technology Madras, funded by the Italian Ministry of Foreign Affairs and the Indian Department of Science and Technology, is carrying out the seismic risk assessment of the historical urban nucleus and a monumental structure at Kancheepuram in the Tamil Nadu State of South India.

From past PSHA studies (e.g. Jaiswal and Sinha, 2007), an observable result is that frequent small magnitude earthquakes and infrequent large magnitude earthquakes govern the seismic hazard in Peninsular India (PI). However, there are some particular zones (i.e. Koyna and Kutch) where the seismicity is more active than the rest. The region under study was, in 2002, reclassified as being in Zone III of earthquake hazard from Zone II, with the implication that the maximum expected macroseismic intensity (MSK 64) is VII. The seismicity of the region, from historical data and current observations, is certainly low. However, the seismic resistance of neither the traditional building practices in this region, nor the conventional structural restoration procedures employed by the Archaeological Survey of India (ASI) in monuments under their authority, have really been established. The PSHA study which aims at defining the seismic input for the structural analyses of the heritage and monumental structures, gains significance in this context. The largest recorded earthquake in our study area in northern Tamil Nadu is the 5.5 M_W Pondicherry earthquake in 2001. This study is one of the first attempts at microzonation of the seismic hazard at Kancheepuram.

This paper summarizes the methodology adopted in the current research following the standard Cornell-McGuire approach for PSHA, commencing from the compilation of a comprehensive catalogue of earthquakes, proceeding to processing of catalogue data, selection of seismogenic zones and Ground Motion Prediction Equations (GMPEs). A zone-free approach based on kernel estimation methods [Woo, 1996] has also been explored as an alternative to the classical Cornel-McGuire approach, thereby, overcoming the subjective issue of seismogenic zoning intrinsic to the latter. Epistemic uncertainty in hazard definition has been tackled within a logic-tree framework that considers two different hazard models for the PSHA, different procedures for catalogue processing (declustering, completeness analysis), seismogenic zoning scenarios and different GMPE. The output of the PSHA consists of horizontal and vertical probabilistic seismic hazard curves and horizontal and vertical uniform hazard spectra at the site for reference return periods of 95, 475, 975 and 2475 years on stiff soil and level ground surface. Deaggregation analysis of the PSHA results for the PGA has been performed to identify the controlling earthquake (M-d-ε) for the site.

2. PROCESSING OF EARTHQUAKE CATALOGUE

In order to follow the standard approach of PSHA, a new comprehensive earthquake catalogue for Kancheepuram city is compiled from different sources by including all historical and instrumental events within a circular area of 250 km radius with Kancheepuram as its centre (12.83°N, 79.70°E). Catalogues of earthquakes of magnitude ≥ 3.0 in PI, are available from Chandra (1977), Rao and Rao (1984), Guha and Basu (1993), Iyengar (1999), and Jaiswal and Sinha (2007). Internationally recognized earthquake catalogues on the internet, such as the National Earthquake Information Centre (NEIC), the International Seismological Centre (ISC), and the Indian Meteorological Department (IMD) have also served as sources for historical and instrumental data. The composite catalogue for Kancheepuram spans a period of 500 years from 1507-2007 AD.

The historical part of the catalogue covers the period 1507–1967 and the instrumental part starts from 1968 to December 2007. In order to convert macroseismic intensity measures of few historical earthquakes into magnitude measures, a magnitude-intensity (M-I) relationship for peninsular India has been developed (Eqn. 2.1) from 23 Peninsular Indian earthquakes which contain independent measures of both Modified Mercalli (MM) intensity and moment magnitude (M_W).

$$M_W = 2.381 + 0.445 I_0 \tag{2.1}$$

In order to homogenize the earthquake catalogue with a single magnitude measure (i.e. moment magnitude, M_W), conversion relationships proposed by Johnston (1996) have been adopted in this study. A declustering algorithm is then applied to remove the dependent earthquake events from the catalogue. Due to the Poissonian assumption of earthquake occurrence intrinsic of the Cornel-McGuire approach for PSHA, implying that earthquake events are random and memory-less, foreshocks and aftershocks have to be removed from the earthquake catalogue. The declustering algorithm developed by Gardner and Knopoff (1974), who claimed that foreshock and aftershock events are dependent on the size of main earthquake event, has been chosen. The time and distance window parameters would be different based on the main event's magnitude. This approach is also called as the dynamic time-spatial windowing method. The earthquake events ($M_W \geq 3.0$) before dynamic window declustering process were 277 and after the declustering process 224 (80 % main events) (see Figure 2). Only those events with magnitude $M_W \geq 3.5$, therefore of significance in structural engineering, numbering 142 (i.e. 51% of the original catalogue) have been considered in the current study. From Figure 1, it can be observed that earthquake catalogue is largely composed of a significant number of mild, distant events and a small number of moderate, close events from Kancheepuram.

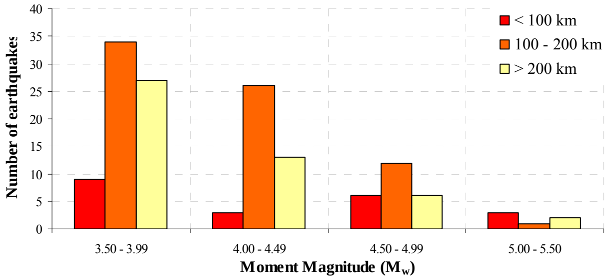

Figure 1 Some statistics of the composite earthquake catalogue compiled for Kancheepuram (1507-2007 AD).

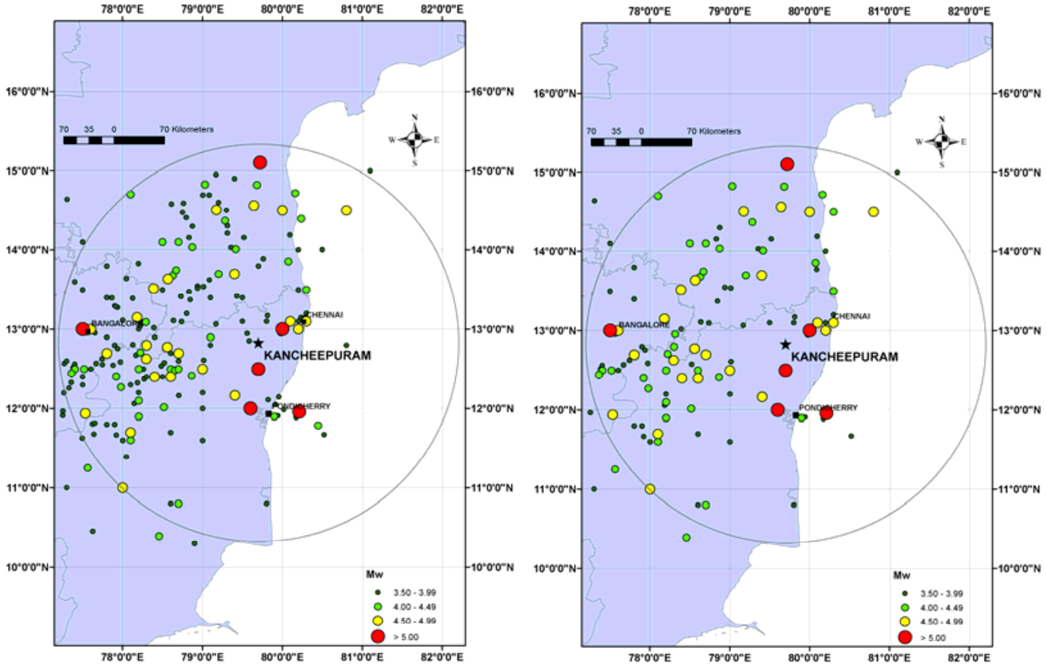

Figure 2 Maps showing the seismicity of the region from 1507 AD (a) before declustering (b) after declustering.

3. SEISMOGENIC ZONING

Peninsular India is a Precambrian SCR, which has practically remained firm against lateral thrusts and mountain building activities. In past studies of PSHA in PI, there have been several attempts to delineate and define the seismic source zones in PI. However, neither are these exhaustive and free from subjectivity, nor do they give specific information to identify source zone in our study area. In order to overcome this setback, two seismogenic source zone scenarios have been identified and selected in this study.

In the first zoning model, the entire circular area (250 km radius with Kancheepuram as centre) has been considered as one zone based on the dispersion of observed seismicity. This part of the Tamil Nadu State has mostly been considered as one seismic source zone in the literature (Chandra, 1977). Several other seismic hazard studies, e.g. Parvez *et al*. (2003), Gupta (2006), have considered a single seismic source zone in this area, a choice attributable to the low observed seismicity.

Data collected on the regional seismotectonic and geological setting along with the observed seismicity, has also led to the definition of the second seismogenic scenario comprising of three source zones (Zones 1, 2 and 3 in Figure 3). Recent seismotectonic studies reveal that a regional system of NE-SW and NW-SE trending active faults, lineaments, and fracture swarms do exist in these zones.

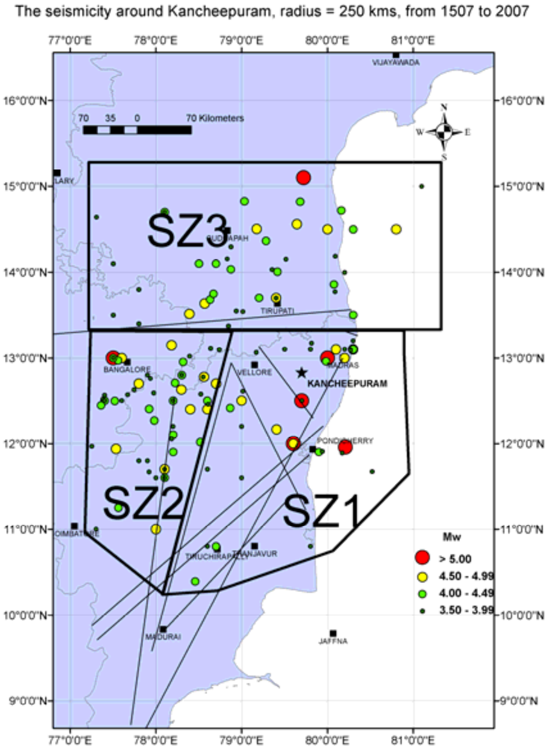

Figure 3 Second seismic source zone scenario composed of three different seismic zones.

3.1. Completeness analysis of the catalogue

The historical earthquake record is usually more complete for large earthquakes than for small earthquakes. Small earthquakes can go undetected for a variety of physical and demographic reasons. Fitting a straight line such as that implied by the Gutenberg-Richter (G-R) law through recurrence data in which the mean rate of exceedance of small earthquakes is underestimated will tend to flatten the line. As a result, the actual mean rate of small earthquakes will be underestimated and the mean rate of large earthquakes will be overestimated. Two different completeness analysis procedures, viz. Mulargia *et al.* (1985), Visual Cumulative (CUVI), and Stepp (1973), have been chosen and completeness periods have been calculated for different magnitude classes and for different seismic source zones. These completeness periods are then used to compute the G-R magnitude-frequency recurrence relationship (Eq.3.1), and parameters "a" and "b" reported in Table 3.1. (10^a = mean yearly number of earthquakes of magnitude greater than or equal to zero, b is the relative likelihood of large to small earthquakes, and λ_M is the mean annual rate of exceedance i.e. the number of earthquake events equal to or greater than magnitude *M* per year).

$$\log(\lambda_M) = a - bM \qquad (3.1)$$

Table 3.1 Parameters "a" and "b" of the Gutenberg-Richter recurrence relationship obtained in this study.

First Scenario	**Method**	**b**	**a**	**M_{max}**
Single Zone	Stepp	1.26	5.33	5.50
	CUVI	1.22	4.80	5.50
Second Scenario	**Method**	**b**	**a**	**M_{max}**
Zone 1	Stepp	0.85	2.86	5.50
	CUVI	1.02	3.52	5.50
Zone 2	Stepp	0.93	3.62	5.00
	CUVI	0.63	2.24	5.00
Zone 3	Stepp	0.83	3.16	5.00
	CUVI	0.59	1.96	5.00

4. SELECTION OF GROUND MOTION PREDICTION EQUATIONS (GMPEs)

Due to lack of strong motion data in peninsular India, no GMPE developed from natural ground motion records is currently available. PI is similar to many other SCR of the world where data is scarce and not representative of the existing hazard. In recognition of this problem, GMPEs have been chosen based on the following criteria:

- Compatibility of model with seismotectonic and geological setting of study area (e.g. shallow crustal, intraplate earthquakes, etc.)
- Preferably developed from a database of natural ground motion records
- The structural period range of the GMPE is appropriate for engineering applications

Four different shallow crustal attenuation models, i.e. Abrahamson and Silva (1997) “AS97”, Ambraseys *et al.* (2005) “ADSS05”, Campbell and Bozorgnia (2008) “CB08”, and Raghu Kanth and Iyengar (2007) “RKI07”, were ultimately chosen after comparisons with some strong motion data from PI. Ground motion parameters have been estimated on reference rock outcropping (average $V_{s,30}$ 750-1500m/s).

Considering the fact that source-to-site distance definitions vary with GMPEs, in order to ensure consistency while quantitatively comparing different GMPEs in executing hazard computations with the same computer program, the definition of distance has been homogenized using conversion relationships developed by Scherbaum *et al.* (2004). These relationships are based on simulated data and modeled as gamma distributed random variables. The hypocentral distance (r_{hyp}) was chosen as the simplest definition for area seismic sources.

Table 4.1 An example of magnitude-dependent distance conversion calculated by using the method by Scherbaum *et al.* (2004) considering the mean hypocentral depth equal to 17 km.

	M_W = 5		**M_W = 5.5**		**M_W = 6**	
R_{JB} (km)	**R_{Hyp} (km)**	**R_{Rup} (km)**	**R_{Hyp} (km)**	**R_{Rup} (km)**	**R_{Hyp} (km)**	**R_{Rup} (km)**
1	22.9	6.0	23.6	5.7	24.8	5.4
4	23.0	8.7	23.8	8.4	25.1	8.1
7	23.7	11.4	24.5	11.1	25.8	10.9
10	24.8	14.1	25.6	13.9	27.0	13.6
13	26.2	16.8	27.1	16.6	28.5	16.4

5. PROBABILISTIC SEISMIC HAZARD ASSESSMENT (PSHA)

After a number of sequential processes, namely compiling the earthquake catalogue, defining seismic source zones, and choosing the appropriate attenuation equations, the PSHA had been carried out using the computer program EZ-FRISK® 7.25 (Risk Engineering Inc.) for the classical Cornell-McGuire approach and KERFACT (Woo, 1996) for the zone-free method. The self-organized seismic activity rate from earthquake catalogue have replaced, in the zone free approach, the standard Gutenberg-Richter relationships. Lastly, the epistemic uncertainties in PSHA have been accounted for within a logic-tree framework. The controlling parameters of the logic-tree considered in this study are the algorithm used to implement the PSHA, seismogenic zoning scenarios, completeness period estimation methods, GMPEs, and the maximum cut-off magnitude in the hazard computations. The logic tree is composed for 35 branches for the horizontal ground motion component (see Figure 4), whereas 17 branches for the vertical component. As only Ambraseys *et al.* (2005) and Abrahamson and Silva (1997) allow calculation of spectral acceleration for the vertical component, the number of logic tree branches are reduced for the vertical ground motion.

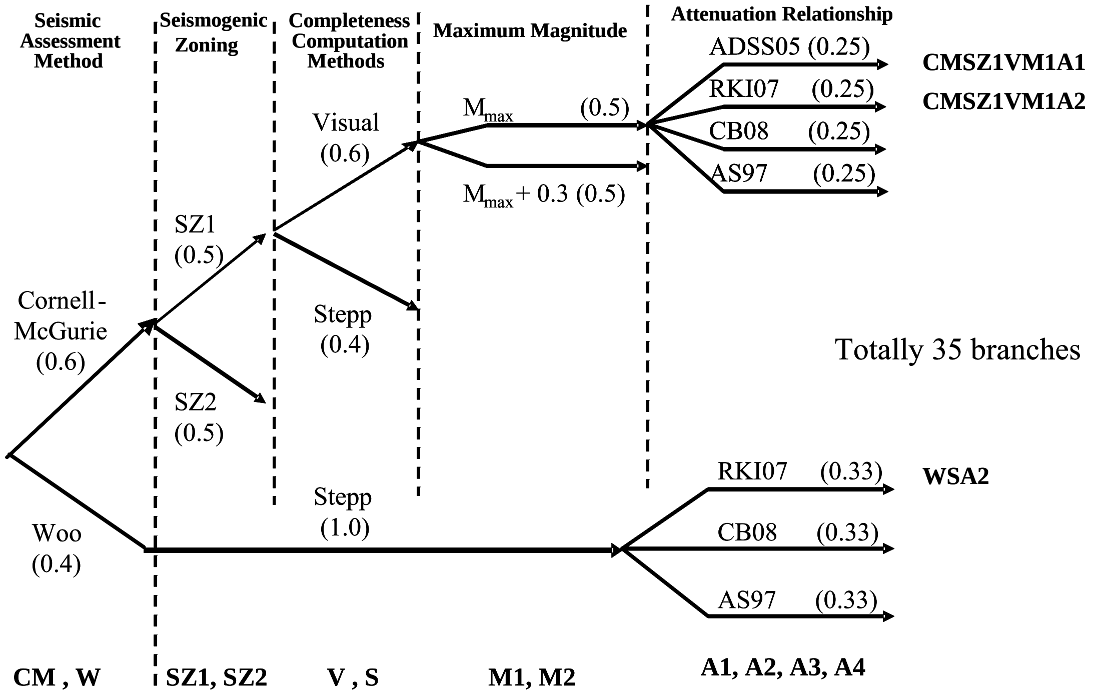

Figure 4 Parameters and weighting factors adopted for the horizontal ground motion component in the logic tree

The uniform hazard spectra (UHS) for different reference return periods (T = 72, 475, 975, and 2,475 years) for rock/stiff site conditions have been computed from different GMPEs. The spectral acceleration is calculated for an equal return period (or equivalently annual probability of exceedance) from 0 to 4 seconds. The outcome of the current PSHA study, in terms of mean UHS for the horizontal and vertical components for different return periods on rock are plotted along with the Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) (BIS: 1893, 2002) in Fig. 5a) and b).

The DBE spectrum, comparable to 475-year return period, and MCE spectrum, comparable to 2,475-year return period, clearly underestimate the spectrum ordinates at low structural period for both directions. Finally, the deaggregation of PSHA results for PGA from one of the logic tree branches (CMSZ1SM1A2) illustrated in Figure 6, demonstrates that there is clearly a hazard contribution from small earthquakes at short distances from Kancheepuram. The deaggregation result from the same logic tree branch for the 2,475-year return period (Figure 6b) shows the contribution of relatively moderate magnitude event and at short distances from Kancheepuram (still within source zone 1). There is no hazard contribution to the PGA from long-distance earthquakes for both 475 and 2,475 year return periods.

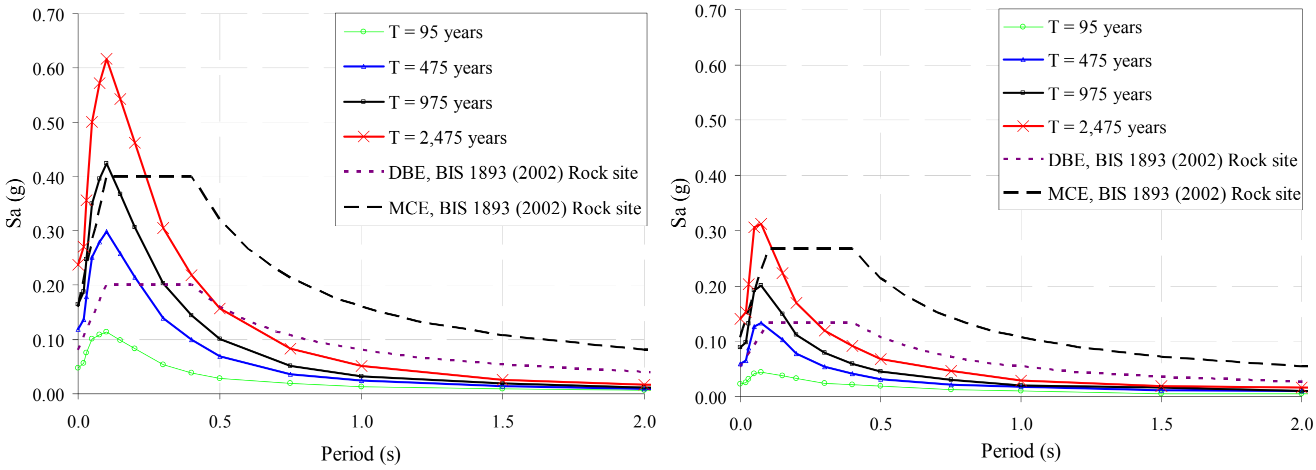

Figure 5 (a) Horizontal and (b) vertical component mean UHS for different return period and BIS 1893 spectra

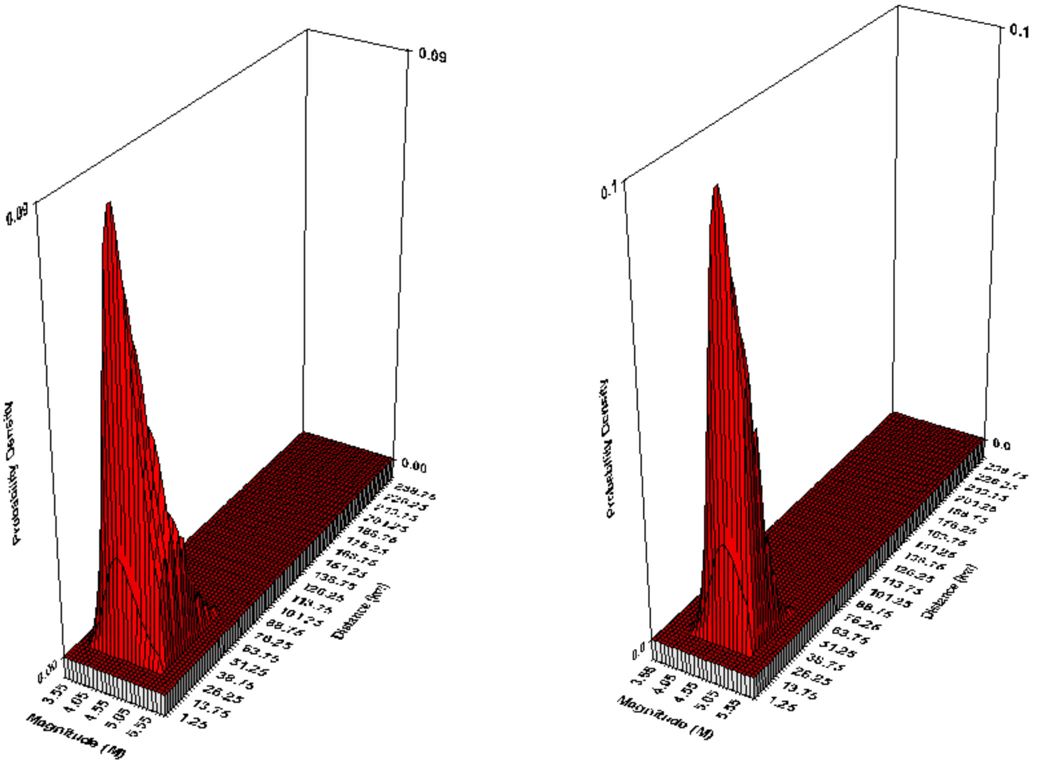

Figure 6. The deaggregation results for PGA value at 0.08g and 0.12g for (a) T = 475 and (b) 2,475 years, using GMPE Raghu Kanth and Iyengar (2007).

6. CONCLUSIONS

The scope of work presented in this paper was to define the seismic input for structural assessment of heritage structures at Kancheepuram in Southern India, based on a detailed PSHA study. The PSHA and deaggregation analysis performed for the PGA (horizontal component) have predicted low values of ground shaking for Kancheepuram which are characteristic of a site whose seismicity is controlled by weak to moderate earthquakes with sources located at short distances from the site. The horizontal PGA expected in Kancheepuram (from the mean hazard curve of the logic-tree), on stiff ground, with a 10% probability of exceedance in 50 years (which corresponds to a return period of 475 years) is 0.118g, whereas, that with a 2% probability of exceedance in 50 years (or a return period of 2475 years) is 0.238g.

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