Evaluation of Acceleration Time-Histories for Design of Nuclear Facilities at Kalpakkam (India)

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SUMMARY:
Probabilistic seismic hazard analysis (PSHA) has been conducted for a nuclear power plant (NPP) site at Kalpakkam located in the southern part of Peninsular India. The logic tree approach has been used to obtain the uniform hazard spectra (UHS) for return periods of 475 and 10000 years in terms of spectral accelerations. Hazard deaggregation has been carried out for return periods of 475 and 10000 years. It is inferred that the power plant site is mainly affected by the earthquake sources located at short distances and by low to moderate magnitude earthquakes. The natural accelerograms each recorded on rock (or stiff site) have been selected and are spectrally matched with the UHS of 475 and 10000 years return period by wavelet adjustment procedure using RSPMatch2005 program. Thus spectrum compatible acceleration time-histories are obtained for the dynamic analysis of various NPP facilities at Kalpakkam.

Keywords: PSHA, logic tree, uniform hazard spectra, wavelet adjustment, acceleration time-histories

1. INTRODUCTION

The degree of loss resulting from earthquakes is within human control in comparison to the control on earthquake occurrence. The code regulations prescribe additional dynamic time-history analyses (linear / nonlinear) for the design of critical facilities, highly irregular buildings and base-isolated structures. The nonlinear dynamic analysis of any structure or facility requires earthquake scenario in the form of acceleration time-histories. There are different options for obtaining suites of accelerograms for use in engineering design and assessment. In seismically active regions, recorded accelerograms are available but in intraplate regions such as Peninsular India, acceleration time-histories are limited. Hence using recorded accelerograms with peak ground acceleration (PGA) similar to the expected PGA, obtained using seismic hazard analysis (SHA) is common. Seismic hazard analysis (SHA) involves the quantitative estimation of ground-shaking hazards at a particular site (Kramer, 1996). Safe design of a structure or facility is possible with the knowledge of the seismic hazard at a particular site or the region. In the present study, probabilistic seismic hazard analysis (PSHA) is carried out to estimate the design ground motion parameters for the nuclear power plant (NPP) facilities being established at Kalpakkam region, Tamil Nadu, South India. The probability of ground motion occurrence or its exceedance has been predicted with the knowledge of the seismicity and seismotectonic details of the region. According to the seismic zonation map drawn by the Bureau of Indian Standards (IS 1893: 2002), Kalpakkam is placed in Zone III. The increased zonal value for the Kalpakkam region is attributed to the increased seismicity of the PI (e.g., earthquakes such as Latur 1993 M_w 6.1, Jabalpur 1997 M_w 5.7 and Bhuj 2001 M_w 7.7)

The probabilistic approach to hazard analysis is not limited to the consideration of worst-case scenarios but extended to looking at all feasible scenarios and its related consequences. The probability of occurrence of such scenarios is becoming an additional key aspect to be quantified in order to rationally and quantitatively handle the uncertainty. The hazard is computed by considering the uncertainties in characterizing the earthquake sources and prediction of ground motion using logic tree approach. The recorded accelerograms are not available for Kalpakkam region in particular and for

Peninsular India in general except for Bhuj earthquake. Hence the recorded accelerograms have been obtained from the earthquake databases around the world and spectrally matched with the uniform hazard spectra (UHS) obtained from the PSHA. The most widely used approaches being the use of scaled recorded accelerograms. In the present study, wavelet adjustment in time domain has been used to obtain the spectrum compatible acceleration time-histories for NPP facilities.

2. PSHA FOR KALPAKKAM REGION

Probabilistic seismic hazard analysis (PSHA) determines the frequency with which a ground motion parameter (e.g., PGA, PGV, a level of Modified Mercalli Intensity) exceeds a certain value (e.g., 0.3 g) during some fixed time in the future (McGuire, 2004). Probabilistic method includes characterisation of earthquake recurrence and gives an aggregate risk from potential earthquakes of different magnitude occurring at many different source-to-site distances. The conventional Cornell-McGuire approach (Cornell, 1968, McGuire, 1995) is adopted for carrying out the PSHA. The seismicity and seismotectonic details of the region which are within a distance of 300 km around Kalpakkam are utilized in the PSHA for the development of ground motions for the NPP site. In this study, the seismic hazard is assessed by cataloguing the historical and available instrumental events. The catalogue is homogenised and updated such that it consists of only the main and independent events. The characteristics of seismic sources such as its geometry and activity are assessed before the hazard analysis. The PSHA results are presented in the form of uniform hazard spectra (UHS) and peak ground acceleration for different return periods.

2.1. Seismicity of Kalpakkam Region

The seismicity and seismotectonic details of the region which falls within a distance of 300 km radius around Kalpakkam have been collected and reviewed. The geographical coordinates of Kalpakkam are 12.55°N and 80.18°E. The earthquake catalogue with earthquakes of $M_w \geq 3.5$ have been compiled for the period from 1807 to 2008 A.D. by collecting earthquake data from the various earthquake data centres. Two major earthquakes that have occurred in the study region are the one west of Pondicherry (*MMI* VII, 1867) and the Pondicherry earthquake (M_w 5.5, 2001). Detailed geophysical studies e.g., Murthy et al. (2002) and Subrahmanyam et al. (2006), brought to light that the region is tectonically active and controlled by two major Pre-Cambrian lineaments, namely the Moyar-Bhavani Attur (MBA) lineament in the northern part and Palghat-Cauvery lineament in the southern part of the Cauvery basin. The Pondicherry earthquake (M_w 5.5, 2001) epicentre was on the offshore extension of MBA lineament.

A complete earthquake catalogue with a uniform magnitude scale is a pre-requisite for a reliable parameterization of the magnitude distribution at each source. The relationship proposed by Johnston (1996), based on worldwide data of stable continental earthquakes, has been used to convert other measures of magnitude to the moment magnitude (M_w). A total of 23 earthquakes from Peninsular India were identified with both intensity and magnitude estimates and a relationship as given in Eqn. 2.1 was established by performing the linear regression on this data. The relationship between magnitude (M_w) and Modified Mercalli intensity scale (I_0) for PI is given as:

$$M_w = 2.381 + 0.4452\ (I_o) \qquad (2.1)$$

The dynamic window declustering process is used for producing the catalogue with only main shocks (Gardner and Knopoff, 1974). The total number of earthquakes is 174 and after the dynamic window declustering process, the total number of main shocks is 142 (80 % of the main shocks).

2.2. Catalogue Completeness

For the time period under consideration, it is crucial to ensure that all earthquakes have been recorded for each magnitude range of interest. Completeness analyses have been carried out using two methods:

Stepp's method (Stepp, 1972) and Visual Cumulative (CUVI) method (Mulargia and Tinti, 1985). The completeness periods based on Stepp's method and CUVI method for the different magnitude classes are given in Table 2.1. For magnitude range 4 to 4.49, Stepp's method gave a completeness period of 50 years starting from 1959 for a catalogued period of 1807 to 2008. For magnitude ≥ 5, the whole catalogue period is taken as the completeness period.

Table 2.1. Results of completeness analysis using Stepp's and CUVI methods

Magnitude range	**Stepp's method**		**CUVI method**	
	Completeness year	**Completeness period (years)**	**Completeness year**	**Completeness period (years)**
$3.5 \leq Mw \leq 3.99$	1969	40	1968	41
$4 \leq Mw \leq 4.49$	1959	50	1968	41
$4.5 \leq Mw \leq 4.99$	1959	50	1966	43
$Mw \geq 5$	1807	202	1807	202

2.3. Seismogenic Source Zone Scenarios

The PI shows diffuse intraplate seismicity; hence only area source zones are used in the hazard analysis. The region having an area of radius 300 km around the Kalpakkam NPP site is divided into area source zones such that the earthquake occurrence is uniformly distributed within the source. Two seismic source zone *scenarios* have been proposed in the present study. In the first scenario (Scenario 1), the region is divided into three seismic source zones i.e., SZ1, SZ2 and SZ3 (Fig. 2.1.) and the seismicity parameters are evaluated for each of the zones. All the available seismotectonics information and seismicity data of the study region are made use of in the source zonation. Due consideration was also given to the historical seismicity data while forming different source zones. To some extent, neotectonic information about the existing fault system of the study area is also made use of in the demarcation of the zonal boundaries. For the second scenario (Scenario 2), the three zones are combined as a single source zone and the whole catalogue is used to obtain the seismicity parameters.

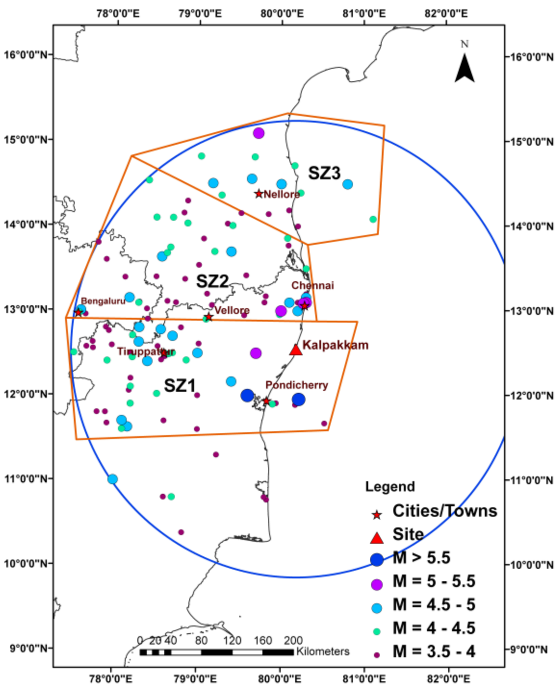

Figure 2.1. Source zone scenario 1 composed of three seismic zones (SZ1, SZ2, SZ3)

2.4. Earthquake Recurrence Relationship

The annual occurrence rate of earthquakes with magnitude greater than or equal to *m* in a particular source zone is given by (Gutenberg and Richter, 1944)

$$\log_{10}(\lambda_m) = a - bm \tag{2.3}$$

where λ_m is the mean annual rate of occurrence of magnitude *m*. The Gutenberg-Richter parameters '*a*' and '*b*' obtained for the Kalpakkam region based on Scenario 2 are 4.87 and 1.18 respectively. The annual rate is estimated based on the completeness period evaluated using both the Stepp's and CUVI methods. The annual rate of occurrence of earthquakes of magnitude *m* bounded by the minimum magnitude of engineering significance (m_0) and the maximum potential magnitude (m_{max}) is given by

$$\lambda\ (m).=.\ \lambda_{m0}\ [exp(-\beta\ (m - m_0) - exp(-\beta\ (m_{max} - m_0)]\ /\ [1 - exp(-\beta\ (m_{max} - m_0)] \tag{2.4}$$

where λ_{m0} is the mean annual rate of occurrence of m_0 and $\beta = b.\ ln(10)$. The minimum magnitude of 3.5 is adopted in the hazard analysis. The seismicity parameters obtained from the present study are compared with previous studies such as by Menon et al. (2010) for Tamil Nadu. The Gutenberg-Richter parameters '*a*' and '*b*' obtained by them are 5.06 and 1.13 respectively. The uncertainty in the determination of maximum magnitude is reduced by considering two potential maximum magnitudes: $m_{\mathrm{max1}} = (M_{\mathrm{obs}} + 0.3)$ and $m_{\mathrm{max2}} = (M_{obs} + 0.5)$, where M_{obs} is the maximum observed magnitude in the source zone. The M_{obs} in SZ 1 of the first scenario is 5.5. Hence the two maximum magnitudes are: 5.8 and 6. Likewise, the M_{obs} in SZ2 and SZ3 is 5.0 and hence $m_{\mathrm{max1}} = 5.3$ and $m_{\mathrm{max2}} = 5.5$. In the case of second scenario, $M_{\mathrm{obs}} = 5.5$. Hence the m_{max1} and m_{max2} are 5.8 and 6 respectively.

2.5. Ground Motion Prediction Equations

In order to account for uncertainty in the prediction of attenuation of ground motion, three different attenuation relationships are used in the study. Attenuation models developed for shallow crustal earthquakes have been used because the earthquakes in Peninsular India have occurred only within a depth of 35 km. The three attenuation relationships are: (i) Ambraseys et al. (2005), (ii) Boore and Atkinson (2008) and (iii) Iyengar et al. (2010). The applicability of the three attenuation relationships to Peninsular India is validated with the recorded PGA values, namely the Koyna earthquake (M_w = 6.5), the Jabalpur earthquake (M_w = 5.7) and the Kutch aftershock (M_w = 5.7).

2.6. Uniform Hazard Spectra

The annual rate of exceedance of a given threshold value y^* of the selected ground motion parameter *Y* is given by

$$E(Y \geq y^*) = \sum_{i=1}^{3} \lambda_i \iint_{RM} P[Y(m,r) \geq y^* \,|m,r]\ f_R(r)\ f_M(m)\, dm\, dr \tag{2.5}$$

where λ_i is the average annual rate of occurrence of earthquakes of magnitude greater than or equal to m_0 for the i^{th} source which is estimated using Eqn. (2.4). The probability density functions (PDFs) f_R(r) and f_M (m) describe the probabilities of earthquake occurrence at *r* distance from the site and occurrence of earthquake of different magnitude classes within source *i* respectively. The term $P[Y\ (m, r) \geq y^*]$ represents the probability of exceedance of a threshold value of ground motion parameter y^*, for a given magnitude *m* and source to site distance *r*. The annual rate of exceedance of different levels of selected ground motion parameter is assumed to follow Poisson distribution and for a time of interest *t*, say 50 years, the probability of exceeding the given level y^* is given by

$$P(Y \geq y^*, t) = 1 - e^{-E(Y \geq y^*)t} \tag{2.6}$$

The reciprocal of the annual rate of exceedance of a particular level of ground motion is the return period (RP), of that level of ground motion. A computer program, CRISIS 2007 Version 1.1 (Ordaz et al., 2007) is used to compute the seismic hazard for the Kalpakkam NPP site. The four controlling parameters of the logic tree considered in this study are (a) seismogenic zoning scenarios (SSZ1 and SSZ2), (b) estimation methods of catalogue completeness periods [Stepp's (ST) and CUVI (CU) methods], (c) maximum magnitude [m_{max1} (M1) and m_{max2} (M2)] and (d) attenuation relationships [Ambraseys et al., 2005 (AMB); Boore and Atkinson, 2008 (BA) and Iyengar et al., 2010 (IY)]. The UHS corresponding to 475 and 10000 years return periods for the Kalpakkam are depicted in Fig. 2.2. The response spectrum for design basis earthquake (DBE, 475 years return period) as given in IS code (IS 1893-Part 1, 2002) for rock sites is compared with the PSHA results.

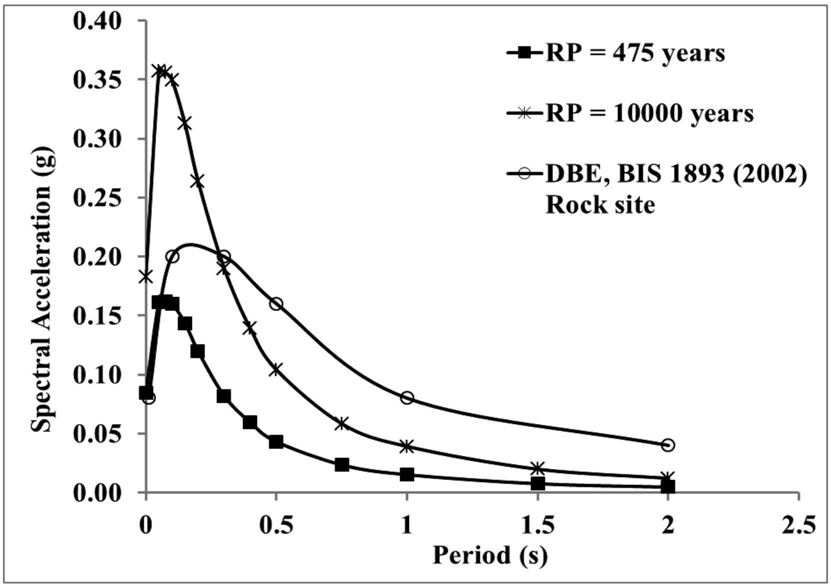

Figure 2.2. UHS for different return periods compared with the DBE and MCE of IS (1893: 2002)

3. SPECTRUM COMPATIBLE ACCELERATION TIME-HISTORIES

The recorded accelerograms are selected based on the future earthquake scenarios computed from the hazard deaggregation. The dominating events obtained using hazard deaggregation, are the most likely ones to cause the selected target seismic-hazard level. Therefore, the dominating events are used as scenario events for assessing new and existing engineered structures and infrastructure facilities. The weights similar to that assigned in the PSHA have been used to obtain the final weighted average magnitude and distance (M and R) pair. The records are spectrally matched with the target spectra using RSPMatch2005 based on the wavelet adjustment procedure.

3.1. Hazard Deaggregation

The deaggregation of hazard determines the contribution made to the overall hazard, by each magnitude (M) and source to site distance (R) bins. They are accumulated in separate bins and represented as a joint probability distribution for a given return period at all periods. The marginal distributions of distance $f_R(r)$ and magnitude $f_M(m)$ are obtained as follows: for a given distance $R = r_1$, the annual exceedance rates of all magnitude bins (m_1, m_2,…, m_n, where n is the number of magnitude bins) are summed to obtain the marginal value for distance r_1. Similarly the marginal values for all distances from r_1 to r_k (where k is the number of distance bins) are obtained and hence the marginal distribution $f_R(r)$. Likewise the marginal distribution for magnitude $f_M(m)$ is obtained. The marginal values are then divided by the total exceedance rate to obtain the percentage contribution by different distance and magnitude bins. The marginal values of magnitude and distance are multiplied by the respective magnitude and distance bin values and summed up to obtain the mean values. Fig. 3.1. and 3.2. display the deaggregation of hazard for two return periods of 475 and 10000 years (spectral period = 0 s) respectively. The logic tree branch SSZ2STM2IY (Scenario 2, Stepp's method, m_{max2}, Iyengar et al., 2010) is used to depict the hazard deaggregation. The deaggregation analyses performed for the PGA (horizontal component) have predicted low values of ground shaking at Kalpakkam which are the characteristics of the site whose seismicity is controlled by low to moderate earthquakes with sources located at short distances from the site.

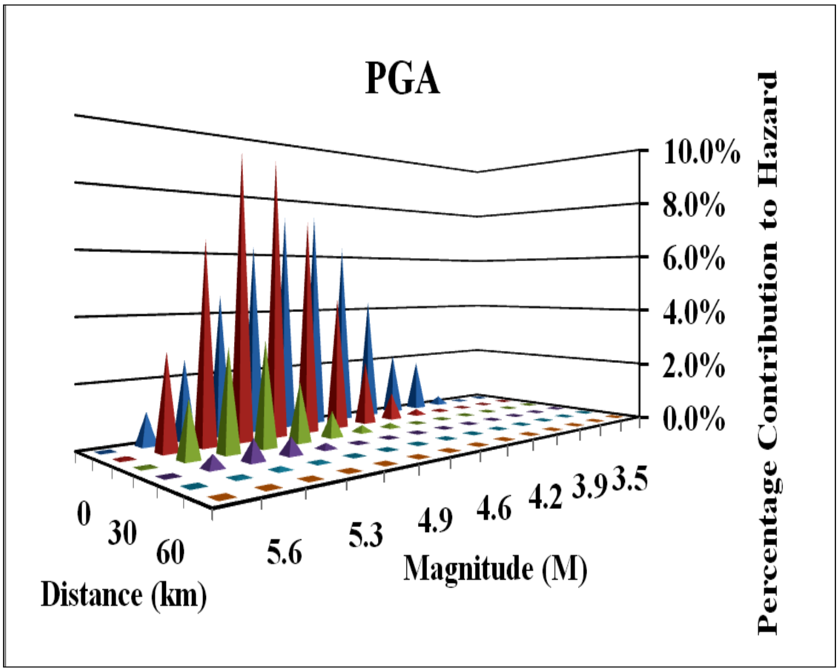

Figure 3.1. Deaggregation of hazard for PGA - contributed by logic tree branch: SSZ2STM2IY (RP = 475 years)

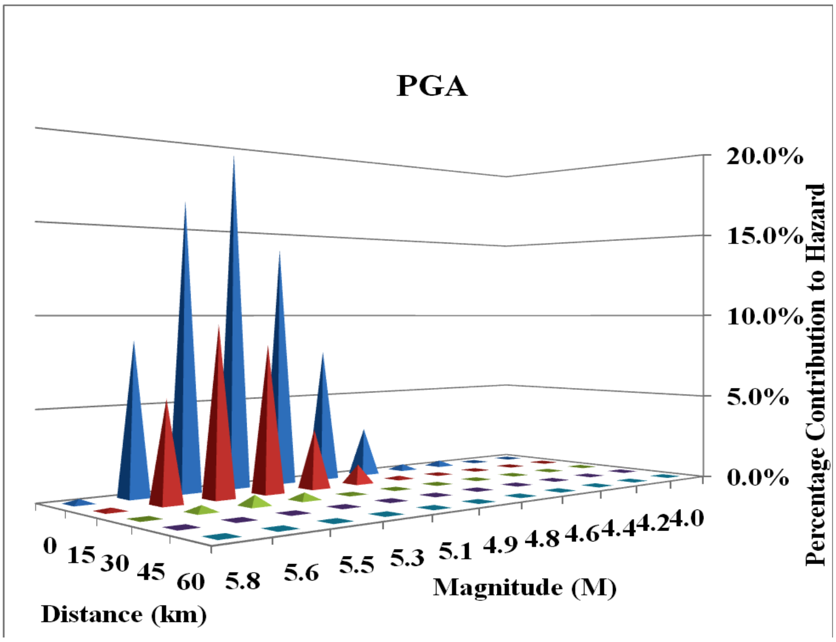

Figure 3.2. Deaggregation of hazard for PGA - contributed by logic tree branch: SSZ2STM2IY (RP = 10000 years)

3.2. Criteria for Selecting the Recorded Accelerograms

A particular accelerogram is chosen such that the magnitude and epicentral distance are closer to the magnitude-distance (M-R) pair obtained by the hazard deaggregation. This M-R pair contributes more to the hazard at a site. The UHS are estimated at the bedrock level since the NPP structures are constructed on the bedrock, at Kalpakkam. Hence, the accelerogram is also chosen such that the accelerographs are stationed at sites whose shear wave velocities are equal to or greater than 1000 m/s. The geological characteristics of the recording station and the placement of accelerometer are the first criterion in the selection of real records. Elimination of difference between the target spectrum and the spectrum of the recorded accelerogram will reduce the number of dynamic analyses required to estimate the inelastic response of the structure. Wavelet adjustment preserves the long period non-stationary phasing of the original time-history. The accelerogram whose spectral shape closely matches the UHS are selected using the root mean square (RMS) difference between the normalized record and target spectral acceleration (Hancock et al., 2006):

$$Sa_{rms} = \sqrt{\frac{\left(\frac{Sa_0(T_i)}{PGA_0} - \frac{Sa_s(T_i)}{PGA_s}\right)^2}{N}} \tag{3.1}$$

where N is the number of periods at which the spectral shape is specified, $Sa_0(T_i)$ is the spectral acceleration at T_i, PGA_0 is the peak ground acceleration of the recorded accelerogram, $Sa_s(T_i)$ is the spectral acceleration from the target spectrum at T_i and PGA_s is the zero-period anchor point of the target spectrum. For the present study, two records have been selected that closely match the magnitude and distance criteria obtained from the hazard deaggregation. These two records are taken from the PEER (Pacific Earthquake Engineering Research centre) database and are given in Table 3.1. The records from the site having shear wave velocity greater than 1000 m/s are used.

Table 3.1. Seismological characteristics of the two natural accelerograms selected by imposing spectrum-compatibility with the UHS corresponding to 475 years return period

Component	**Record ID**	**Earthquake**	**Year**	M_w	***R* (km)**	**Fault type**	**Station**	**Shear wave velocity (m/s)**	**PGA (g)**
Geometric Mean	NGA1715	Northridge	1994	5.28	13.2	Reverse	LA-Wonderland Ave	1222.5	0.045
Geometric Mean	NGA1709	Northridge	1994	5.28	18.4	Reverse	LA-Griffith Park Observatory	1015.9	0.047

3.3. Wavelet Adjustment Method

The program, RSPMatch2005 has been used to match spectrally the recorded accelerogram by adding wavelets in the time domain. The wavelets are added to acceleration time-histories with appropriate amplitude and phasing so that the peak of each response matches the target amplitude of the UHS. The response spectrum matching involves non-uniform manipulation of a recorded acceleration time-history to obtain a ground motion with a specified target response spectrum. This procedure is popular in engineering design practice because the variance of the resulting structural response from the dynamic analyses using various earthquake records is reduced, enabling an estimate of the mean response to be found with fewer analyses than with other techniques (Hancock et al., 2006).The three input files required are:

1. The seed accelerogram (accelerogram to be adjusted)
2. The input parameter file
3. The target spectrum file

The input parameter file consists of data like the number of passes over which the accelerogram is to be adjusted, frequency band, number of iteration (5-20), convergence or adjustment scale factor (1.0), tolerance (0.05), wavelet model, number of cycles for wavelet model (10), number of sub-iteration interpolation, off-diagonal reduction factor (0.7), etc. The wavelet model used is the sinusoidal corrected displacement compatible wavelet with automatic reduction to prevent overhang. The amplitude of the wavelet adjustment function at time *t* is determined from the sum of the amplitudes of the wavelets at that time, $a_j(t)$, multiplied by their individual scale factors b_j, as

$$Adjustment(t) = \sum_{j=1}^{j=N_w} b_j \cdot a_j(t) \tag{3.2}$$

where N_w is the total number of wavelets. The b vector consisting of wavelet scale factors b_j, is found using the amplitude of the required adjustment and the inverse of the cross-correlation matrix C:

$$b = C^{-1} \cdot \delta R \tag{3.3}$$

where C is a square matrix with elements that describe the amplitude of each response, at the time the response needs to be adjusted, under the action of each wavelet; δR is a vector of required adjustment, the difference between the peak response of the unadjusted time-history and the response of the target spectra for each period to be matched.

3.4. Results of Wavelet Adjustment

The seed accelerogram is the selected accelerogram (NGA1715). In the present study, the program is set up to adjust the accelerogram in three passes over progressively wider frequency bands; the first pass matches the starting time-history from 1 to 100 Hz, the second pass matches the time-history created by the first pass over the frequency range of 0.2 to 100 Hz and the third pass matches the modified time-history over the frequency range of 0.1 to 100 Hz. Fig. 3.3. depicts the target spectrum and the spectrum to be matched. Fig. 3.4. depicts the matched spectrum after wavelet adjustment. Hence the wavelet adjustment method results in modified acceleration time-histories whose response spectra are compatible to the target spectra (UHS) and Fig. 3.5. shows the original and modified acceleration time-histories for the return period of 475 years. The above procedure has been repeated for the other record, NGA1709, to obtain the acceleration time-histories.

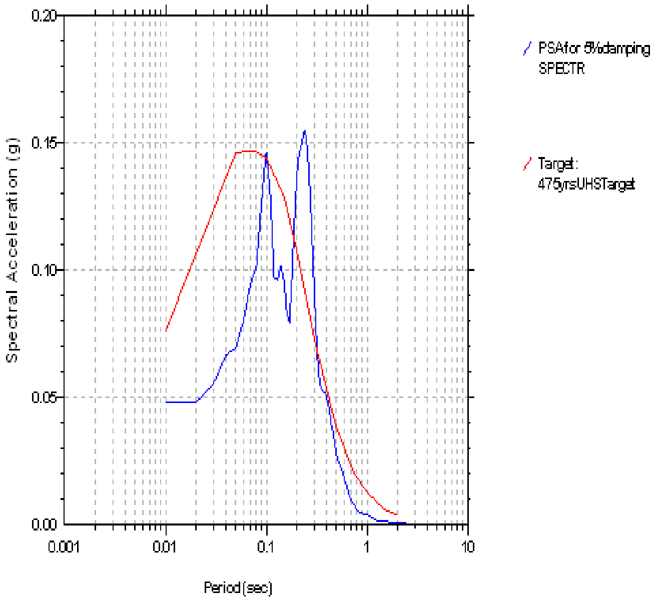

Figure 3.3. Response spectrum matching - before wavelet adjustment

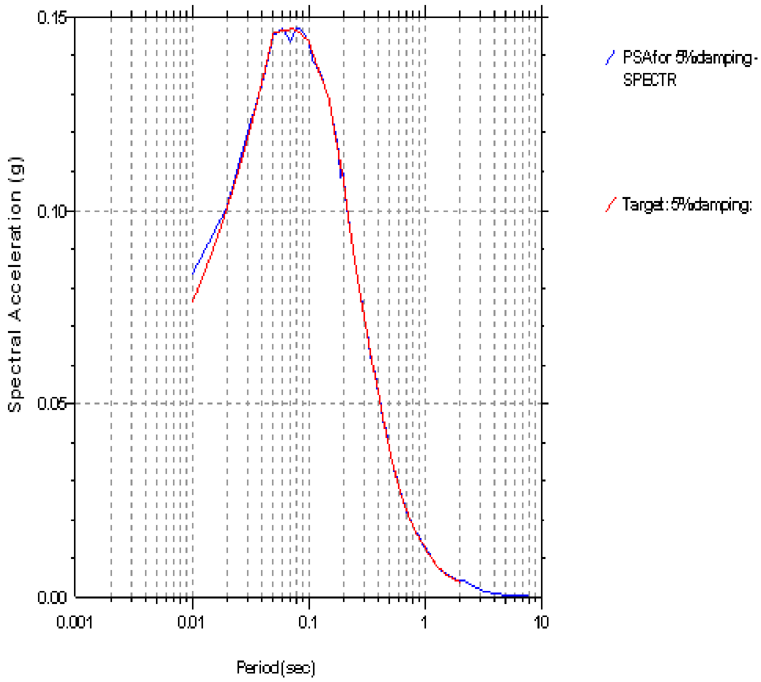

Figure 3.4. Response spectrum matching - after wavelet adjustment

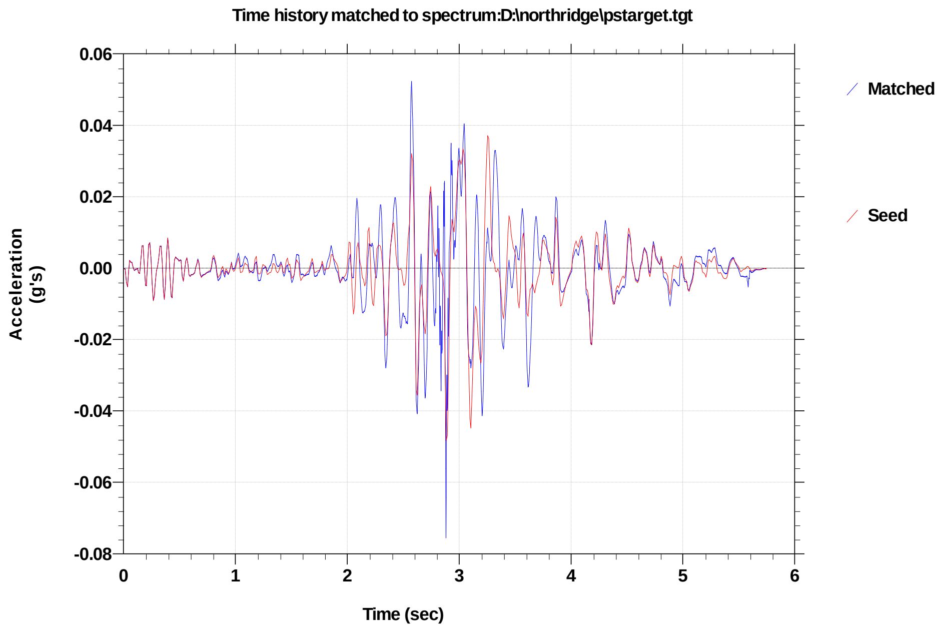

Figure 3.5. Original and modified acceleration time-histories

5. CONCLUSIONS

The hazard due to likely occurrence of earthquake in the Kalpakkam region is estimated using probabilistic approach. The peak ground acceleration (PGA) at Kalpakkam corresponding to 10% probability of exceedance in a life span of 50 years (return period = 475 years) is 0.084g and for a return period of 10000 years, the PGA is 0.183g. The deaggregation analyses performed for the PGA (horizontal component) have predicted low values of ground shaking for the Kalpakkam NPP site which are the characteristics of the site whose seismicity is controlled by low to moderate earthquakes with sources located at short distances from the site. The magnitude and distance pairs obtained from the deaggregation analysis are used as a basis to search from the strong-motion databases to obtain the time-histories of actual earthquakes that have similar magnitudes and distances. The site-specific acceleration time-histories whose response spectra are compatible with the UHS are developed. These acceleration time-histories will be of immense use for the nonlinear dynamic analysis of the safety and non-safety related structures of the NPP facility.

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