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Seismotectonic Investigations for Siting of Nuclear Power Plants, Assessment of Design Basis Ground Motion and Tsunami Hazard

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Abstract

The paper describes seismotectonic investigations for assessment of earthquake and tsunami hazard for designing of different types of structures of Nuclear Power Plants. The assessment is based on study of geology, remote sensing, seismicity within 300km, identifying causative faults, paleoseismolgy to ascertain activeness of faults and assigning maximum potential to them. Spectral acceleration is estimated based on deterministic approach considering various types of source, path and receiver effects. Regarding the tsunami hazard assessment, modeling of possible tsunamis from Andaman-Sumatra and Makran source zones is carried out giving arrival times of tsunami, wave height and inundation distance. Tsunami effect on nuclear power plant sites of India is assessed.

Keywords: Earthquake and tsunami hazard, Nuclear Power Plants in India, seismotectonic investigations

1. Introduction

For exponentially increasing need of energy in India there is no viable source other than the nuclear power. Nuclear energy is clean, green and in general safe. Out of 439 nuclear power plants operated worldwide, there are about 30 cases of malfunction or human error (Rastogi, 2011). Most of these were timely controlled. Only a few could not be controlled (e.g. Three Mile Island, USA) resulting into serious accidents out of which only Chernobyl in 1986 turned catastrophic. So far worldwide, there is one example of damage due to tsunami (Fukushima in March 2011). The Nuclear Power Plants at Fukushima Daiichi could be shutdown automatically during the time when the shaking was going on. Although about 28000 persons have died or are missing due to tsunami, not a single person has died due to radiation. The Kashiwazaki Kariwa Nuclear Power Plant at Chuetsu in Niigata prefecture in Western Japan was designed for Mmax 6.5 (design acceleration 0.45g). It experienced the 2007 M_w 6.8 earthquake with a focal depth 10 km and epicenter 16km from the nuclear power plant which triggered peak ground acceleration of 0.68g. Nevertheless, the plants could be shutdown automatically

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during the earthquake. There were damages to the grid transformer and some damage to the ducting buried pipelines and overflowing of spent fuel water due to sloshing and mud from outside coming into the building through the cable penetrations. The plants have been repaired and have come back to operation after regulatory clearance. The two nuclear power plants at North Virginia in USA witnessed magnitude M_w 6.8 earthquake at 18 km epicentral distance on 23rd August 2011. The earthquake resulted into the ground motion exceeding safe shutdown earthquake level of ground motion. Nothing happened to the plant and by December 2011, the plants came back in operation after a very detailed analytical seismic qualification by utility and a review by US National Regulatory Commission.

Nuclear power plants designed in India since 1975 have been designed for earthquake loading (Rastogi, 2011). In India, Nuclear Power Plants (NPPs) at seven sites (2 to 6 plants at each site) viz., Tarapur, Rawatbhata (Rajasthan), Kalapakkam, Narora, Kakrapar, Kaiga and Kudankulam (Fig. 1) have been assigned Design Basis Ground Motion (DBGM) using state of the art techniques. DBGM is also estimated for the possible future plants at Gorakhpur, Haryana; Mithivirdi, Gujarat; Jaitapur, Maharashtra; Kovvada, Srikakulam, Andhra Pradesh and Tirunelveli, Tamilnadu (Rastogi, 2011). The older generation plants at Tarapur and Madras are being re-evaluated for seismic loading as per International Atomic Energy Agency (IAEA) Safety Standard. Though the Kalapakkam plant did not suffer any damage due to 2004 tsunami, it was successfully shut down for checking. However in the aftermath of Fukushima accident, re-assessment of earthquake and tsunami hazard has been done for NPPs of India.

Earthquake hazard assessment near nuclear power plants involves study of geology, remote sensing and seismicity in an area of 300km radius, identification of causative faults, paleoseismology to ascertain activeness of faults and assignment of maximum earthquake potential to the causative faults. Spectral acceleration is estimated based on stochastic finite fault source model deterministic method for Jaitapur NPP considering various types of source, path and receiver effects. Regarding the tsunami hazard assessment, modeling of possible tsunamis from Andaman-Sumatra source region and Makran source region is carried out. Based on the assessment, arrival times of tsunami, wave height and inundation distances are estimated and its effect on nuclear power plant sites of India is assessed.

2. Earthquake Ground Motion Generation for Designing of Nuclear Power Plants in India

Nuclear Power Plants (NPP) in India are designed for two levels of earthquakes, viz., Operating Basis Earthquake (OBE) (S1) and Safe Shutdown Earthquake (SSE) (S2). For these two levels of earthquakes, it is required to arrive at the Site Specific Design Basis Ground Motion (DBGM).

The DBGM at all frequencies including PGA is arrived at using synthetic time histories generated by deterministic methods for active faults in the vicinity of the plant for their strike, dip, depth of focus and the source, path & local site amplification parameters. The envelope of these is the site specific DBGM.

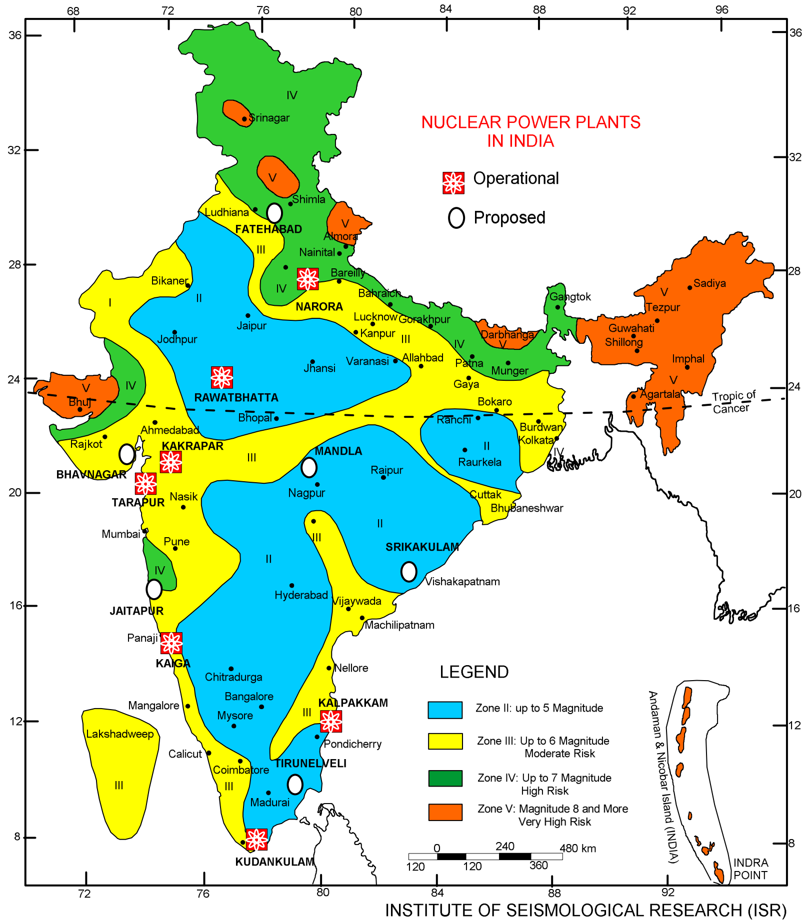

Figure 1. Seismic Zoning map of India (Bureau of Indian Standards, 2000) and Nuclear power plants (existing and proposed)

The OBE (S1) level ground motion corresponds to the maximum level of ground motion which has been experienced by the site in the past or which can reasonably be expected at the site. All the structures must safely withstand OBE (S1) with no damage. All systems and components necessary for the uninterrupted functioning of the NPP are designed to remain operable during the ground motions associated with the OBE (S1) [In general in India, OBE (S1) is taken as 50% of SSE (S2)]. Such analysis has to be available. Repercussion of not having it is that in case an earthquake occurs, the plant remains in shutdown condition till these calculations are done and clearance is obtained from regulator. This will lead to huge penalty on the utility in terms of economic loss to the plant. The ground motion for Virginia earthquake of 23rd August 2011 at North Anna NPP exceeded the SSE level ground motion (Fig.s 2 and 3) and detail analysis and checking had to be done.

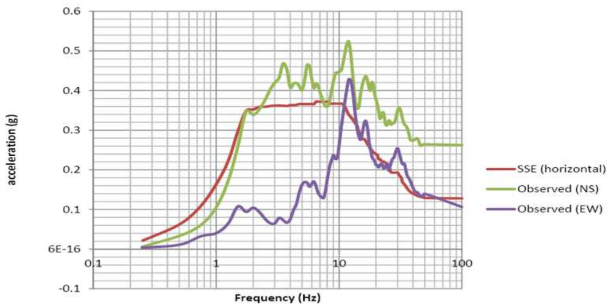

Figure 2. Comparison of horizontal ground motion with the SSE level for Virginia plant

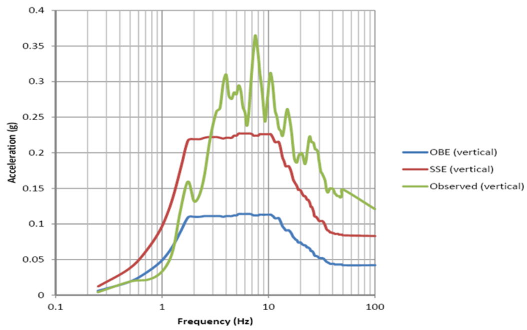

Figure 3. Comparison of vertical ground motion with the OBE and SSE levels for Virginia plant

The SSE is that earthquake which is based upon an evaluation of maximum earthquake potential considering the regional and local geology and seismotectonic environ. SSE is the maximum level of ground motion for which the safety and safety related structures, systems and equipment of NPP, which are required for immediate and long term shutdown of the plant, decay heat removal, containment of activity and those which are required to prevent the accident or to mitigate the consequences of accidents which otherwise could result in potential off-site exposures higher than the limits specified by the regulatory body are required to be qualified.

If recorded time history of a local strong earthquake is available that is changed as the input ground motion at the Engineering Bed Layer. If not, it is estimated by Deterministic or Probabilistic methods. In the Deterministic Seismic Hazard Analysis (DSHA), the ground motion is estimated from a given set of seismological parameters, such as earthquake magnitude and the distance from the earthquake rupture zone to the site of interest. The techniques of deterministic methods are based on different assumptions and require different input parameters: the 'Empirical Green's Function technique' requires foreshock/aftershock of a large earthquake, 'Semi empirical technique' requires attenuation relationship of the area, 'the stochastic finite fault modeling technique' requires stress drop, geometric attenuation, inelastic attenuation and kappa. In the second method, referred to as Probabilistic Seismic Hazard Analysis (PSHA), ground motion is estimated statistically using all possible earthquake sources and magnitudes together with their expected probabilities of occurrence. Due to less data available for peninsular India PSHA is not preferred.

Determination of ground motion parameters requires expertise in the field of geology, seismology and engineering as these parameters control the spectral shape, spectral amplitude and the frequency contents. To account for uncertainties in the earthquake parameters, a range of variation in the parameters is considered. In some of the methods attenuation relation is required. For Peninsular India so far Iyengar and Raghukanth (2004) have developed an attenuation relation. However, this is based on extrapolated accelerogram of the clipped Bhuj earthquake record at Bhuj station. Hence, it can't be relied. Hence, for stable continental region of India the best available technique is the stochastic finite fault modeling technique using EXSIM Program.

Using worldwide data of Active Tectonic Regions, Next Generation Attenuation (NGA) relations have been developed. We have not used these relations in the present study as these are for active regions and not for stable regions. However, these are recommended for the Indian region as well (personal discussion with Dr. Chin-Hsun Yeh of National Center for Research in Earthquake Engineering, Taipei, Taiwan). Hence, a short description of these relations is given. A sample calculation for M_w6 earthquake gave slightly higher acceleration values as compared to those obtained from EXSIM program.

3. Definition of Active/Capable Fault within a Radius of 300km as per the Indian Atomic Energy Regulatory Board (AERB) Guidelines

Active fault: The active fault is confirmed on the basis of geological data. A fault or a tectonic structure is considered active if,

1. It has shown movement at or near the surface, within the past 35,000 years or movement of a recurring nature within the past 500,000 years.
2. It has generated micro and macro-seismicity.

Field Checks for Active Fault: The fault being active or otherwise is confirmed by looking at the terraces of the rivers and nallas which are crossing the lineament for any movement in the Quaternary deposits (terraces) of 2.0 million years of age. Field evidences such as juxtaposition of dissimilar materials & missing or repeated strata, truncation of strata or structures, slickensides, gouge of fault breccias, offset drainages, tilting or changes in elevation of terraces, topographic scarps/triangular facets or ridges, anomalous stream gradients, subsurface information from dug well core with continuity of dykes/veins across lineaments etc. should also be carefully looked at for establishing the fault to be active or otherwise.

Capable fault: A fault which may not be an active fault i.e. a dead fault, but if it has a structural relationship with an active fault identified by criteria (1) and (2) above, such that movement of the active fault can reasonably be expected to be accompanied by movement of the dead fault then such a dead fault is called a capable fault.

4. Rejection Criterion for a Plant Site

If such an active or a capable fault exists at a plant site within a 5 km radius, the plant is to be rejected, as it can generate an earthquake very close to the plant and may have a surface rupture or surface deformation such as faulting or folding just below the plant for which plant cannot be designed.

5. Geological Investigations within 300km radius around the Nuclear Facility

To define the controlling earthquake for generating Safe Shut down Ground Motion for NPPs, a detailed study of regional geology and seismotectonic features in the region of 300 km radius from site is required to be conducted to delineate the faults/lineaments based on the satellite imageries, referring the published seismotectonic literature (GSI, 2000; Rastogi, 2011), gravity anomaly map and also seismicity map based on Micro Earthquake (MEQ) and Earthquake data (historical as well as recorded) in the region followed by field check. The field check should be carried out at three levels; study of Local site, Intermediate range, and Regional scale. The local site investigation covers an area of radial distance 5 km and the study is carried out at a geological map scale of 1:5,000/1:10,000.The intermediate range investigation covers a radial distance of 50 km from the site and the study is carried out using a map prepared to a scale of 1:25,000/1:50,000. The regional investigation covers a radial distance of 300 km from the site and the study is carried out using a map at scale of 1:250,000/1:1,000,000.

Based on the seismotectonic knowledge, field check, and as per the definitions given in the AERB guidelines, the faults are given status of active/capable fault and a maximum earthquake potential (in terms of magnitude) and depth of focus are assigned. If the faults are found to be active geologically in the field check, the 3D satellite images are checked for tell-tale signs of recent movements like pressure ridges and abrupt change of streams. Such locations are favorable sites for trenching and paleoseismological studies which yield recurrence interval of large earthquakes.

6. Assigning Maximum Earthquake Potential, Epicentral Distance and Depth of Focus

After delineating the active/capable faults within a region of 300 km, for deriving the seismic parameters, it is required to give the maximum earthquake potential in terms of magnitude to each of active/capable faults and the corresponding depth of focus. Usually the maximum magnitude is assigned as the magnitude experienced in the area plus 0.5. In Kachchh maximum magnitude is assigned 8. In Peninsular India except in Kachchh the maximum magnitude that can happen is 6.8 (Johnston, 1994). Generally in zone IV and along Narmada the maximum magnitude could be 6.5 to 6.8, in zone III (barring Narmada) it could be 6 and in zone II it could be 5 to 5.5. Focal depth is usually taken as 10-15 km. In some tectonic zones large earthquakes are known to have occurred at deeper depths, e.g., 22-25 km in Kachchh and 35 km in Narmada and focal depths may be assumed as such.

Methodology of design of NPP for two levels of earthquakes i.e., OBE (S1) and SSE (S2)

The present methodology being adopted for the design of Nuclear Power Plant considers two levels of Earthquake, i.e., OBE (S1) and SSE (S2). OBE (S1) takes into account an earthquake that has already occurred in the site vicinity for its magnitude, epicenteral distance and depth of focus, while SSE (S2) design basis considers a level of an earthquake higher than the magnitude of the occurred earthquake.

Checking of NPPs for Beyond Design Basis Earthquake after the damage to Fukushima Daiichi due to tsunami

After the Fukushima incident NPP's in India are being looked at afresh for their safety to an earthquake of Beyond Design Basis Event level.

7. Historical and Recorded Earthquake Data

For determining the design basis earthquake, all available seismotectonic and geological database for an area within a distance of 300 km of the site is compiled in order to assess the maximum earthquake potential associated with different geological formations. The seismotectonic database comprises of locations and magnitudes (or epicentral intensities) of earthquakes having magnitudes 3 and above. The earthquake database includes all the historic as well as instrumentally recorded earthquakes which have occurred within an area of radius 300 km from site.

In India, All the historical & the recorded earthquakes in a radius of 300 km from each site are collected from the national and local agencies. Similarly, the Micro Earthquake (MEQ) data are taken from the agency which is operating the seismic stations in the zone of plant site.

8. Intensity-Magnitude Correlation Based on Indian Earthquake Data

Regarding the conversion of intensity of historical earthquake to magnitude, India did not have a correlation of its own for intensity and magnitude. The relation generally used is

$$M = 2/3I_0 + 1$$

The magnitude-intensity correlations for Indian region on soft rock & hard rock have now been developed using the data on intensity and magnitudes for the Indian earthquakes collected from "Seismotectonic Atlas of India and its Environs, GSI, 2000 " different other sources (Rastogi, 2011). The best fit correlation of magnitude & intensity for the Indian data are as follows:

$$M_w = 0.65\ I_e + 0.91 \qquad \text{(for soft soil)}$$

$$M_w = 0.43\ I_e + 2.43 \qquad \text{(for hard rock)}$$

9. Next Generation Attenuation Relationships (Deterministic Method)

Five sets of ground-motion models were developed for shallow crustal earthquakes in the western United States and similar active tectonic regions. These relationships used latest large earthquake recordings. The models were developed for wider ranges of magnitudes, distances, site conditions and response spectral periods of vibration. The models are briefly described as follows.

Abrahamson and Silva (2008)

This relationship is applicable to magnitudes 5–8.5, distances 0–200 km, and spectral periods of 0–10s. In place of generic site categories (soil and rock), the site is parameterized by average shear-wave velocity in the top 30 m (VS30) and the depth to engineering rock. In addition to magnitude and style of faulting, the source term is also dependent on the depth to top of rupture; for the same magnitude and rupture distance, buried ruptures lead to larger short-period ground motions than surface ruptures. The hanging-wall effect is included with an improved model that varies smoothly as a function of the source properties (M, dip, depth), and the site location.

Boore and Atkinson (2008)

This ground-motion prediction equation (GMPE) is applicable for average horizontal-component ground motions as a function of earthquake magnitude, distance from source to site, local average shear-wave velocity, and fault type. Equations are for peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-absolute-acceleration spectra (PSA) at periods between 0.01s and 10s. For periods less than 1s, the analysis used 1,574 records from 58 mainshocks in the distance range from 0 km to 400 km (the number of available data decreased as period increased). The primary predictor variables are moment magnitude (M), closest horizontal distance to the surface projection of the fault plane (*RJB*), and the average shear-wave velocity from the surface to 30 m (*Vs*30). The equations are applicable for M=5–8, *RJB*<200 km, and *VS*30=180–1300 m/s.

Campbell and Bozorgnia (2008)

This GMPE presents a new empirical ground motion model for PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01–10s valid for magnitudes ranging from 4.0 up to 7.5–8.5 (depending on fault mechanism) and distances ranging from 0–200 km. The model explicitly includes the effects of magnitude saturation, magnitude-dependent attenuation, style of faulting, rupture depth, hanging-wall geometry, linear and nonlinear site response, 3-D basin response, and inter-event and intra-event variability.

Chiu and Youngs (2008)

This GMPE presents a model for estimating horizontal ground motion amplitudes caused by shallow crustal earthquakes occurring in active tectonic environments. The model provides predictive relationships for the orientation independent average horizontal component of ground motions. Relationships are provided for peak acceleration, peak velocity, and 5% damped pseudo-spectral acceleration for spectral periods of 0.01 to 10 seconds. The model incorporates improved magnitude and distance scaling forms as well as hanging-wall effects. Site effects are represented by smooth functions of average shear wave velocity of the upper 30 m ($Vs30$) and sediment depth. The new model produces slightly lower ground motions in the distance range of 10 to 50 km and larger ground motions at larger distances.

Idriss (2008)

This GMPE presents a model for estimating the horizontal pseudo absolute spectral accelerations (PSA) generated by shallow crustal earthquakes. But site-specific dynamic response calculations are recommended for estimating spectral ordinates for sites with Vs30 ranging between 450 and 900 m/s.

10. Stochastic Simulation using Finite-Fault Model based on Dynamic Corner Frequency Approach

In the stochastic approach, the seismic signal is represented with a random Gaussian noise superimposed on a known (deterministic) Fourier amplitude spectrum of the ground motion. The shear-wave amplitude spectrum in the frequency domain is the product of filter functions representing the source, propagation, and site effects. Stochastic finite-fault models have been developed to simulate records of large earthquake (Beresnev and Atkinson 1997; 1998). In the finite-fault approach, the rectangular fault plane is divided into small sub-faults, and each sub-fault is considered to be a point source. The rupture starts at the hypocenter and propagates kinematically until each sub-fault is triggered. The regional dependence of duration and amplitude on distance are employed in the simulations to model the propagation effects. Finally the ground motion at a receiver from the entire fault is obtained by summing up the contribution from each sub-fault with a proper time delay considering the corner frequency as a function of time. Finite fault model based on dynamic corner frequency is formulated in a computer program EXSIM (Motazedian and Atkinson, 2005). This program is used to simulate the ground motions. The term EXSIM comes from EXtended fault SIMulation.

11. Validation of the EXSIM (Extended Fault Simulation) Program

Validation of the EXSIM program used for the generation of synthetic ground motion has been carried out by matching the synthetically generated spectra with the spectra of recorded earthquakes of Bhachau, Saguenay (ENA site in Canada) and Koyna earthquake for frequencies up to 100 Hz. For all the three earthquakes the parameters defining source, path and local site effect are kept same in the dynamic corner frequency based model (using EXSIM program). Mean plus One Sigma and Mean minus One Sigma of the response spectra of the time histories are computed and compared with spectra of the recorded time history. It is found that four randomly generated synthetic time histories (taking the expected ranges of kappa, Q and stress drop for the three earthquakes) are sufficient to represent the spectra of recorded time history to fall between Mean +/-sigma spectra of the simulated time histories. For the purpose of calibration, synthetic ground motions have been generated for Saguenay (Canada ENA site), hard rock site and Bhachau (India) hard rock site (Chopra et al., 2010) and Koyna (India) hard rock site in Stable Continental Region. The comparison of spectra of recorded and synthetically generated time histories is shown in Fig.s 4, 5 and 6, respectively. The spectra of observed data are generally within the +/- sigma range of synthetic spectrum. For the Saguenay and Bhachau earthquakes the synthetic spectra in the frequency range 1-5Hz are slightly over estimated.

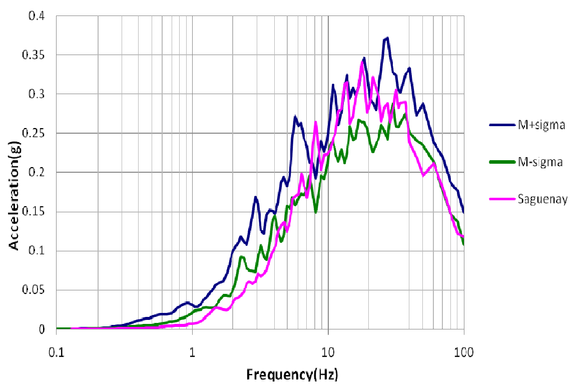

Figure 4. **Comparison of spectra of recorded data with synthetically generated spectra for Saguenay M_w=6, ED=41Km , DOF=29 km (25/11/1988)**

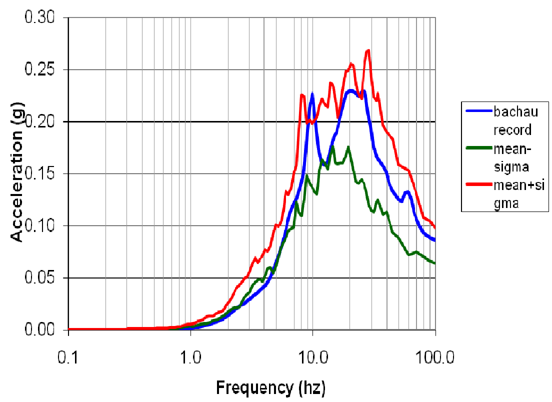

Figure 5. **Comparison of spectra of recorded data with synthetically generated spectra for Bhachau (Bhuj M_w=4.6, ED=25 km, DOF=10 km (13/5/2007)**

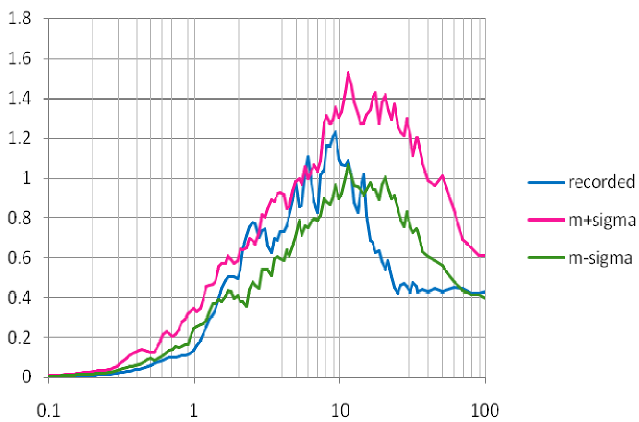

Figure 6. **Comparison of spectra of recorded data with synthetically generated spectra for Koyna of M=6.5 (1967)**

The recorded response spectra of Koyna is lower than the synthetically generated spectra beyond 9 Hz, as the seismic instruments used during 1970 and before were of 20 sps, which can record frequency content only up to 10 Hz.

12. SSGM and DBGM Generation for Jaitapur NPP(JNPP)

The Site Specific Ground Motion (SSGM) is defined by a spectral acceleration at all frequencies including PGA for the site.

Derivation of SSGM and DBGM Spectra

The field check of 5 km, 50 km and 300 km radius area of JNPP has been conducted by GSI, The deep seismic sounding studies in the sea have been carried by KDMIPE, Deharadun until about 15 km from the coast. Shallow seismic sounding studies have been conducted by NIOT in front of the Madhban Plateau in the offshore area close to the site. The resistivity study has been done by GSI. MEQ network of 6 stations in the vicinity of the plant is operating since 2004. The MEQ network of Koyna is operating since 1970.

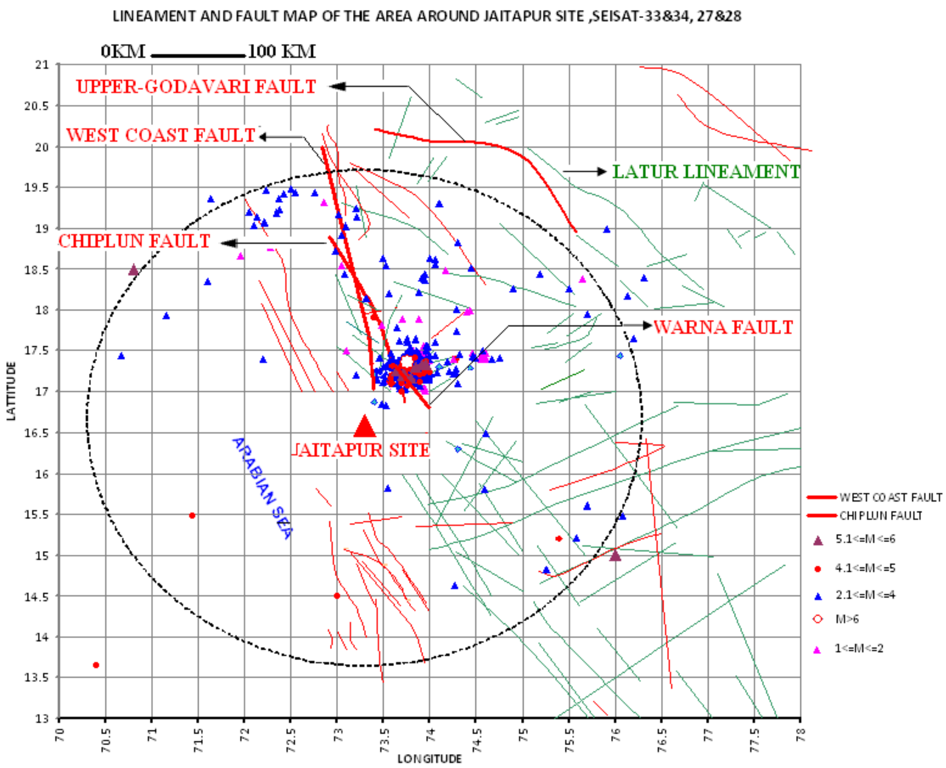

Figure 7. Seismicity map of Jaitapur site

Based on these studies, the controlling fault for Jaitapur site is Chiplun fault at 64 km epicentral distance with potential of magnitude 7 at depth of focus of 15 km and Koyna-Warna fault at 89 km epicentral distance with potential of magnitude 7 with depth of focus 15 km (Fig. 7). Based on this, the synthetic ground motions for JNPP were generated using the regional and site specific ground motion parameters, viz., stress drop, geometric attenuation, quality factor, crustal amplification factor (CAF), high frequency filter parameter kappa and local site amplification. As there are large uncertainties in defining the ground motion parameters, a parametric variation of these parameters is done to account for the uncertainty in the ground motion. The 108 time histories (27x4) have been generated, with 4 random time histories for each combination of parametric variation of stress drop (140, 170 and 200 bar), Kappa (0.01, 0.013, 0.016) and Q ($84f^{0.65}$, $118f^{0.65}$, $152f^{0.65}$). As the synthetic ground motion time series generated by EXSIM program are not base line corrected inside the EXSIM program, it requires base line correction outside the EXSIM program. Base line corrections have been applied to all the 108 time histories and a mean + one sigma spectrum is arrived at. After the base line correction of time histories, the SSGM spectrum follows constant acceleration value, i.e., peak ground acceleration (PGA) at high frequency and a constant displacement, i.e., peak ground displacement (PGD) in low frequency which is the expected behaviour of the response in both high frequency and low frequency regions. The envelope of the ground motion from the active faults is considered as SSGM and is shown in Fig. 8. The DBGM is derived by smoothening of the SSGM by joining peaks as shown in Fig. 8.

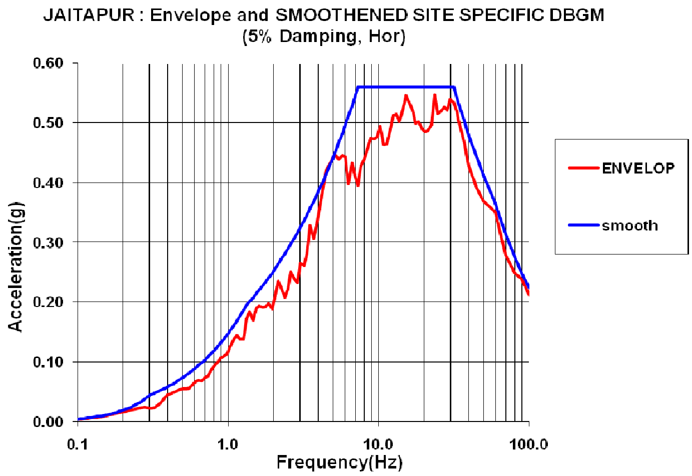

Figure 8. SSGM and DBGM of 5% damping SSE for Jaitapur site

13. Possible run-up and Travel Times in India for Tsunami in the East and West Coast

East coast of India is affected by tsunami generated along Andaman-Sumatra subduction zone while the west coast is affected from Makran subduction zone (Rastogi and Jaiswal, 2006). Modeling of tsunami amplitude, travel time and run-up has been made for the Indian coasts from both the sources using shallow water non-linear model Tunami - N2 code (Jaiswal et al., 2009; 2011, Singh et al., 2012). The bathymetry data is taken from ETOPO-1. For tsunami run-up and inundation map, high resolution of 3 arcs second SRTM data has been used. Vertical displacement of the sea bottom is calculated with the Mansinha and Smylie (1971) method. For each run, we produced travel time map, directivity and possible maximum wave height at the targeted coastline. The results show a highly variable impact for tsunamis generated by the two source zones. The model results also show that the distribution of maximum amplitude in the Indian Ocean basin is primarily controlled by the classical effects of the directivity.

For the Makran Fault of strike 250°, the directivity is found to be directed towards India. If the source is considered along the western part of Makran, the travel time increases. The estimated possible arrival time and tsunami amplitude (m) at various places due to Makran source (M8.0 & M9.0) is given in Table 1. The Tsunami run up for Makran source for (M8.0) is shown in Fig. 9.

Andaman-Sumatra, 1300km long fault, is divided into five segments each segment is assumed to have different fault parameters. The northern three segments are found to be contributing to the tsunami amplitude affecting east coast of India. The combined effect of all the segments is also estimated. The observed and estimated possible arrival time and amplitude at various places due to Andaman-Sumatra (M9.3) is given in Table 2. The Tsunami run up for Andaman-Sumatra (M9.3) is shown in Fig. 10. This estimate gives 5-6 m run up at Nagapattinam, Tamilnadu. Thus, these results will be useful in planning the protection measures against inundation due to tsunami and in the implementation of a warning system.

The scenario of tsunami effect on NPP appears to be satisfactory. The Kalapakkam plant came within the range of inundation for 2004 tsunami. As the ancillary facilities and cables etc were already designed to be kept at sufficient height, there was no damage. The existing coastal plants at Tarapur, Kaiga, Kudankulam and the proposed ones at Mithivirdi, Jaitapur, Tirunelvelli and Srikakulam are at elevations above the tsunami run-up.

14. Conclusion

A detailed procedure has been evolved which involves field check study, collection of eartqhauke data, delineation of active/capable fault, consideration of subsurface fault, assigning maximum potential to each of the faults and use of synthetic ground motion. With this procedure, it is possible to generate the ground motion for any nuclear power plant site in India for its design.

Assessment of Tsunami Hazard has also been carried out for both East and West Coast of India for Tsunami runup and their travel time. This will be very helpful in planning the protection measures against inundation due to tsunami and in the implementation of a warning system.

Table 1. The estimated possible arrival time and tsunami amplitude (m) at various places due to Makran source (M8.0 & M9.0)

Place	Arrival Time (in hrs)	Max. Amplitude (m) (M8.0)	Max. Amplitude (m) (M9.0)
Lakhpat (23.49⁰N, 68.49⁰E)	2.45	1.2	1.5
Koteshwar 23.70⁰N, 68.52⁰E)	2.55	1.5	1.8
Jakhau (23.14⁰N, 68.45⁰E)	3.02	2.5	2.8
Mandvi (22.51⁰N, 68.32⁰E)	3.10	1.0	1.3
Mundra (22.85⁰N, 69.73⁰E)	3.20	1.2	1.5
Kandla (23.00⁰N, 70.10⁰E)	3.30	1.8	2.0
Okha (22.47⁰, 69.08⁰E)	2.35	2.5	2.6
Salya (22.32⁰N, 69.59⁰E)	3.05	2.1	2.5
Sikka (22.48⁰N, 69.82⁰E)	3.15	1.6	1.9
Bedi (22.32⁰N, 70.02⁰E)	4.02	1.5	1.7
Navlakhi (22.97⁰N, 70.02⁰E)	4.45	1.5	1.8
Dwarka (22.14⁰N, 69.01⁰E)	2.10	1.0	1.2
Veraval (20.9⁰N, 70.36⁰E)	2.52	1.3	1.5
Navabandar (21.43⁰N,69.80⁰E)	3.02	1.2	1.4
Gulf of Kambhat (22.19⁰N, 72.38⁰E)	5.30	1.5	1.5
Suvali (21.08⁰N, 72.63⁰E)	5.30	1.0	1.2
Mumbai (18.91⁰N, 72.90⁰E)	4.45	2.0	2.2
Goa (15.50⁰N, 73.83⁰E)	3.08	1.0	1.3
Karwar (12.20⁰N, 77.33⁰E)	3.12	1.0	1.5
Mangalore (12.91⁰N, 74.88⁰E)	3.36	1.0	1.2

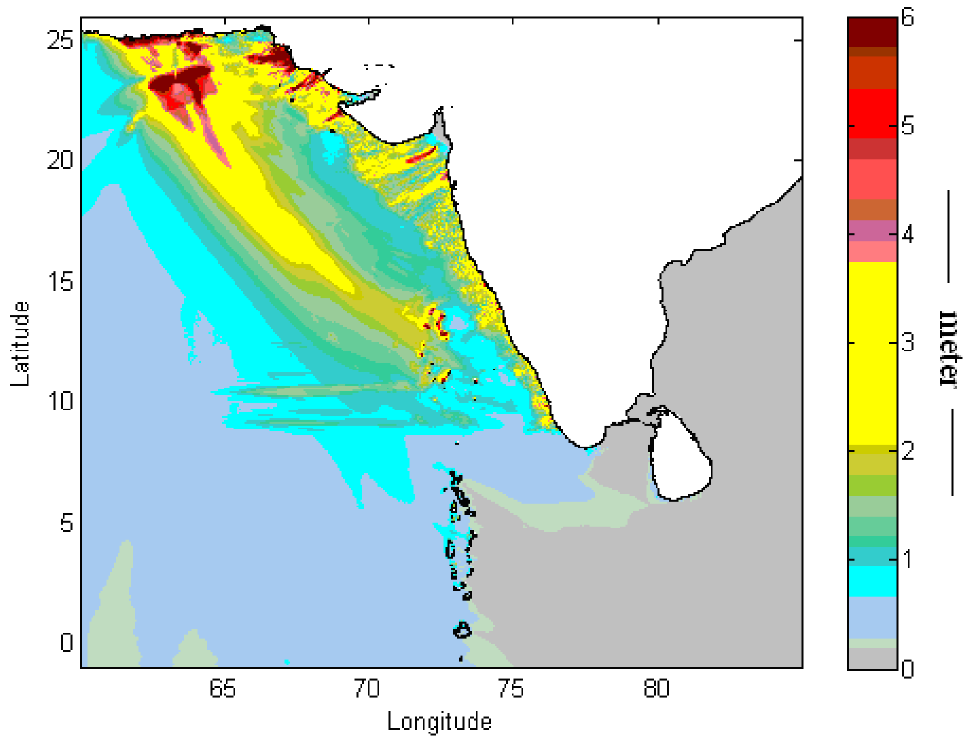

Figure 9.

Directivity of Tsunami from M8.0 earthquake in Makran coast

Table 2. The observed and estimated possible arrival time and amplitude at various places due to Andaman-Sumatra (M9.3)

Station location	Travel time Observed	Computed Travel time	Observed maximum wave height (m)	Computed maximum wave height (m)
Machilipatnam (16.15^{0}N, 81.20^{0}E)	3 hr 08 min	2 hr 56 min	2.8	2.1
Visakhapatnam (17.65^{0}N, 83.28^{0}E)	2 hr 36 min	2 hr 18 min	2.9	1.6
Chennai (13.10^{0}N, 80.32^{0}E)	2 hr 34 min	2 hr 10min	3.2	2.3
Neendakara (08.93^{0}N, 76.54^{0}E)	4 hr 09 min	3 hr 55 min	2.2	1.1
Port Blair (11.68^{0}N, 92.77^{0}E)	0 hr 15 min	0 hr 08 min	3.5	2.2
Paradip (20.26^0 N, 86.70^0 E)	2 hr 28min	2 hr 20 min	3.2	2.1
Cochin (Kochi) (09.97^{0}N, 76.27^{0}E)	4 hr 42 min	4 hr 05 min	1.5	1.1
Tuticorin (08.75^{0}N, 78.20^{0}E)	3 hr 25 min	3 hr 02 min	1.8	1.3

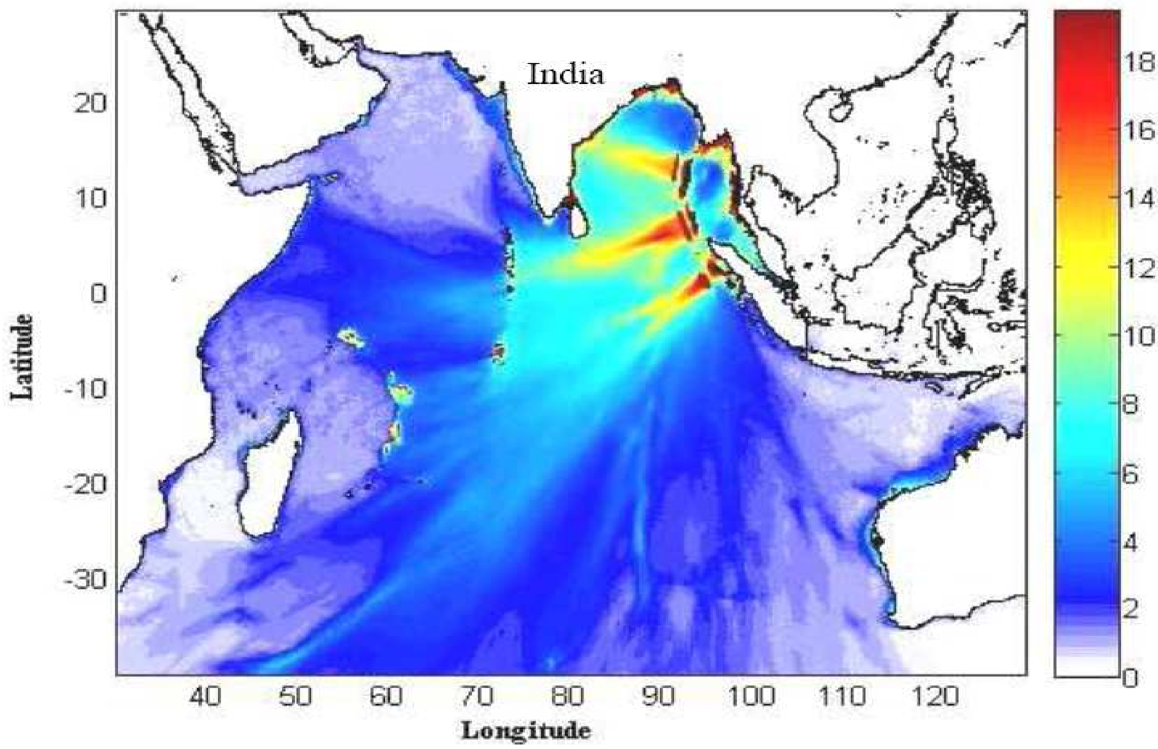

Figure 10. Directivity of Tsunami from M9.3 earthquake in Andaman-Sumatra source.

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