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Estimation of design basis earthquake using region-specific M_{max}, for the NPP site at Kalpakkam, Tamil Nadu, India

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HIGHLIGHTS

- ► Maximum magnitude was estimated by establishing regional rupture character.
- ► Ground-Motion Prediction Equations are ranked using MMI values and used to get PGA.
- ► Safe Shutdown and Design Basis Earthquake are estimated based on region specific parameters.
- ► Site-specific spectrum is established considering the average and normalized response spectrum.

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ABSTRACT

The objective of the paper is to estimate Safe Shutdown Earthquake (SSE) and Operating/Design Basis Earthquake (OBE/DBE) for the Nuclear Power Plant (NPP) site located at Kalpakkam, Tamil Nadu, India. The NPP is located at 12.558°N, 80.175°E and a 500 km circular area around NPP site is considered as 'seismic study area' based on past regional earthquake damage distribution. The geology, seismicity and seismotectonics of the study area are studied and the seismotectonic map is prepared showing the seismic sources and the past earthquakes. Earthquake data gathered from many literatures are homogenized and declustered to form a complete earthquake catalogue for the seismic study area. The conventional maximum magnitude of each source is estimated considering the maximum observed magnitude ($M_{\max}^{obs}$) and/or the addition of 0.3 to 0.5 to $M_{\max}^{obs}$. In this study maximum earthquake magnitude has been estimated by establishing a region's rupture character based on source length and associated $M_{\max}^{obs}$. A final source-specific M_{max} is selected from the three M_{max} values by following the logical criteria. To estimate hazard at the NPP site, ten Ground-Motion Prediction Equations (GMPEs) valid for the study area are considered. These GMPEs are ranked based on Log-Likelihood (LLH) values. Top five GMPEs are considered to estimate the peak ground acceleration (PGA) for the site. Maximum PGA is obtained from three faults and named as vulnerable sources to decide the magnitudes of OBE and SSE. The average and normalized site specific response spectrum is prepared considering three vulnerable sources and further used to establish site-specific design spectrum at NPP site.

1. Introduction

Earthquakes have been proven as more disastrous hazard for Nuclear Power Plant (NPP) facility than any other natural hazards. NPP needs to be designed for the worst scenario of a maximum possible earthquake in the region considering region specific seismic hazard analysis. Seismic hazard analysis is concerned with getting an estimate of the strong-motion parameters at a site for the purpose of earthquake resistant design or seismic safety assessment. The parameters used to represent ground motion at a particular site are peak ground acceleration and response spectra. The main objective of seismic hazard analysis of NPP site is to estimate the design earthquake ground motion which is also known as the seismic input motion or the control motion. The design earthquake ground motion is based on the seismicity and geologic conditions at the site and expressed in such a manner that it can be applied for the dynamic analysis of structures, systems and components (NUREG-0800, 2007). The ground motion should be defined for free field conditions, at the level of ground surface or key embedment depths and in line with user requirements (IAEA SSG-9, 2010). Two levels of design earthquake ground motions are needed to arrived at: (1) Operating/Design basis earthquake (OBE/DBE) and (2) Safe Shutdown earthquake (SSE). The OBE and SSE are defined

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in the U.S. Nuclear Regulatory Commission, Standard Review Plan (NUREG-0800, 2007), which are further refined by International Atomic Energy Agency (IAEA) and Atomic Energy Regulatory Board (AERB) as given below:

1.1. Operating/design basis earthquake (OBE/DBE)

The OBE is defined as the ground motion for which those features of the nuclear power plant necessary for continued operation without undue risk to the health and safety of the public will remain functional (Regulatory Guide 1.208, 2007). The OBE is termed as seismic level 1 (SL-1) internationally (NS-G-3.3, 2002) and S1 in Indian AERB guide (S11, 1990). SL-1/S1 ground motion can be reasonably expected to be experienced at the NPP site once during the operating life of the plant. The SL-1 ground-motion is less severe than SSE and is the more likely earthquake for the region. The factors that need to be considered as per IAEA while making decisions on the level of ground motion chosen to represent SL-1/S1 are:

- Seismotectonic evaluation: the relative exposure of the site to multiple sources of seismicity; the frequency of earthquakes from each such source with respect to the lifetime of the plant.
- Design considerations: the safety implications of the required loading combinations and stress limits; the plant type.
- The post-earthquake situation: the implications of the agreed required action following SL-1; the regional need for the plant to continue to operate safely after an earthquake which may have damaged other electricity generating plants.
- Plant inspection considerations: the cost and safety implications of designing and/or constructing the plant to a higher level of SL-1, compared with the possibility of more frequent inspections for a lower level of SL-1.

1.2. Safe shutdown earthquake (SSE)

The SSE is defined as the ground motion in which certain structures, systems and components must be designed to remain functional (Regulatory Guide 1.208, 2007). The SSE is termed as seismic level 2 (SL-2) internationally (NS-G-3.3, 2002) and S2 in Indian AERB guide (S11, 1990). The SL-2/S2 level earthquake is associated with the most stringent safety requirements and corresponds directly to ultimate safety requirements. IAEA recommends that the SL-2/S2 level of ground motion should be determined based on the seismotectonic evaluation, detailed knowledge of the geology and engineering parameters of the strata beneath the site area.

The main objective of this study is to carry out seismic hazard analysis of nuclear power plant to estimate the design earthquake ground motion based on regional seismicity and geologic conditions.

2. Seismic study area

The geological, seismological, geophysical and deep geotechnical investigations of the site should be collected and analyzed to select a seismic study area for a seismic hazard analysis. A seismotectonic map of NPP site can be generated by compiling the above data around NPP facility. Kalpakkam NPP is located in South India, a part of Peninsular India at 12.558°N and 80.175°E, where more than 12 earthquakes of magnitude six and above have been reported. Peninsular India is also called as stable continental region (SCR) technically and is located on thin lithosphere and fast moving plate, part of Gondwanaland (Kumar et al., 2007). South Indian seismicity is neither understood properly nor given importance since it is of micro-dimensions (Reddy, 2003). The recent earthquakes of Jabalpur (1997), Killari (1993) and Bhuj (2001) were occurred in the SCR of PI. Gupta (2006a) highlighted that Stable Continental Regions are more vulnerable to earthquakes than once thought. This conclusion given by Gupta (2006a) based on Chapman conference on SCR earthquakes discussion and presentation.

The seismic study area is usually generated by considering the region of 320 km (200 miles) radius around NPP location as per Regulatory Guide 1.208 (2007) and/or typical 300 km radius around the site as per IAEA and AERB, which is being adopted by several researchers. Earthquake occurred beyond 200 miles (320 km) do not affect the NPP site in Western countries, hence 320 km was suggested for the seismic study area in Regulatory Guide of U.S. Nuclear Regulatory Commission (Regulatory Guide 1.208, 2007). This has been followed in the rest of the world where a poor literature on past earthquake damage with distance from the epicenter is available. Even though this guideline is widely used, nuclear regulatory suggest the extension of seismic study area in the following circumstances:

- ***Regulatory Guide 1.208 (2007)***. The areas of investigation may need to be expanded beyond those specified above in regions that include capable *tectonic sources, relatively high seismicity, or complex geology, or in regions that have experienced a large, geologically recent earthquake identified in historical records* or by paleoseismic data.
- ***IAEA SSG-9 (2010)***. The size of the relevant region may vary, depending on the geological and tectonic setting, and its shape may be asymmetric in order to include distant significant seismic sources of earthquakes. Its radial extent is typically 300 km. In intraplate regions, and in the particular case of investigations into the potential for tsunamis (IAEA NS-G-3.5, 2003), the investigations may need to consider seismic sources at greater distances from the site. If it can be demonstrated easily that there are major tectonic structures closer to the site than the radius indicated, then studies should concentrate on this part of the region.

In any case IAEA recommends that the size of the region to which a method for establishing the hazards associated with major external phenomena need to be applied shall be large enough to include all the features and areas that could be of significance in the determination of the natural and human induced phenomena under consideration and for the characteristics of the event (IAEA NS-R-3, 2003). Recently Roshan and Basu (2010) considered an area of 400 km x 400 km around the NPP site for probabilistic seismic hazard analysis. Very limited numbers of recorded ground motion data are available to decide seismic study area in India. Close observation of past earthquake damage distribution maps shows that high seismicity region with deep soil deposits have experienced MMI (Modified Mercalli Intensity) of VII for great earthquakes located about 1000 km distance. Low to moderate seismicity region with shallow soil deposits have experienced intensity of V for moderate earthquakes located at about 500 km distance. This can help to infer that moderate earthquakes in PI can cause damage beyond a radial distance of 300 km from the site. In order to earmark seismic study area for NPP site, available damage distribution map i.e. Isoseismal map has been considered in this study. More information about Indian Isoseismal maps can be found in Szeliga et al. (2010) and Martin and Szeliga (2010). Structural damage (intensity of European Macro seismic (EMS) V and above) was observed beyond 300 km in many of earthquakes in India. Among these earthquakes, Coimbatore earthquake is the geologically largest earthquake in south India and tectonically closest to the proposed NPP site. Coimbatore had experienced an earthquake of magnitude 6.0 on Richter scale at 10.80° N, 76.80° E on 8th of February 1900. Study of damage distribution was reported beyond 400 km and intensity map for the Coimbatore earthquake is given in Fig. 1. Seismic study area for this study has been selected as 500 km radius around the

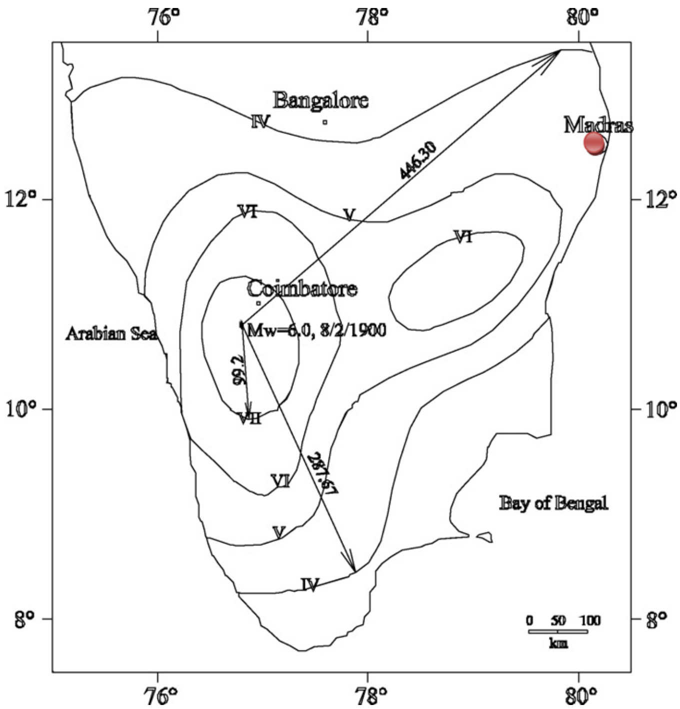

Fig. 1. Damage distribution of the past largest earthquake reported in Peninsular India – Coimbatore earthquake of Mw 6.0, 8th Feb 1900.

proposed NPP site considering the damage distribution and the tectonic province. The location of the proposed site with the marking of seismotectonic study areas is shown in Fig. 2.

3. Geology of seismic study area

The geological formation of the seismic study area (SSA) is considered as one of the oldest land masses of on the earth's crust. Most of the SSA is classified as Gneissic complex/Gneissic Granulites with major inoculation of greenstone and allied supracrustal belt. The geology deposits close to the NPP site and eastern part of the study area is a coastline having the alluvial fill in the pericratonic rift. Fig. 2 shows the geology and geotectonic provinces around the seismic study area with the location of the same. The major tectonic constituents in the southern India include the massive Deccan Volcanic Province (DVP), the South Indian Granulite Terrain (SIGT), the Dharwar Craton (DC), the Cuddapah Basin (CB), the Godavari Graben (GG) and the Mahanadi Graben (MG), the Eastern and the Western Ghats on the eastern and western coast of India, respectively. South Indian/seismic study area land mass geology has been studied by several researchers on macro scale.

The major cities under SSA include Vijayawada, Bangalore, Chennai, Mysore, Coimbatore, Thrissur, Kozhikode and tectonically active Trincomalee in Srilanka. The circular area of 500 km radius from the NPP has different geodynamic and tectonic settings. The bedrocks on which the study area is located, comprises of charnockite and garnetiferous granite gneisses (Boominathan, 2011) of Archean age intruded by Post-Archean dolerite dykes covered by recent coastal sands. The thickness of the sand layers in the study area varies between 6.0–9.5 m and the top of fresh rock varies from 10–15 m (Katti et al., 1994; Ghosh and Banerjee, 1989). In the west, the study area comprises of Karnataka Craton of Archean–Proterozoic Peninsular granitic gneiss. On the northern side, there is the Palar basin constituting the permo – carboniferous Gondwana sediments bounded by faults. To the north is late Precambrian Cuddapah basin and to the south is Cauvery basin comprising late Jurassic–Cretaceous–Paleocene sediments (Shanti Kumar, 1999). The water table in the area is at a depth of 1.25–8.5 m below the ground level with the ground water movement towards the sea (Katti et al., 1994). The area between Chennai Chengalpattu is covered by reddish soil, with isolated hillocks of Charnockite and Khondalite.

Major faults in the area are at the crystalline basement and the boundaries of sedimentary basin (Shanti Kumar et al., 1999). A system of NE-SW as well as NW-SE lineaments and faults exist in the area of south Indian Granulite Terrain. In the northern part, it is defined by a Cuddapah basin where a high level of seismicity is associated with the associated faults. Towards the east, the area being a coastal, the coast of Chennai and Ramanathapuram show typical convexities (Ramasamy, 2006). The intrusion of swarms of dolerite dykes is concentrated in Sholingar–Gudiyattam–Krishnagiri belt. Valdiya (1998) highlighted that the seismic activity is generally confined to linear belts related to trans-current and terrain-bounding faults and shear zones, implying that the Precambrian faults are being reactivated in the present time based on purely

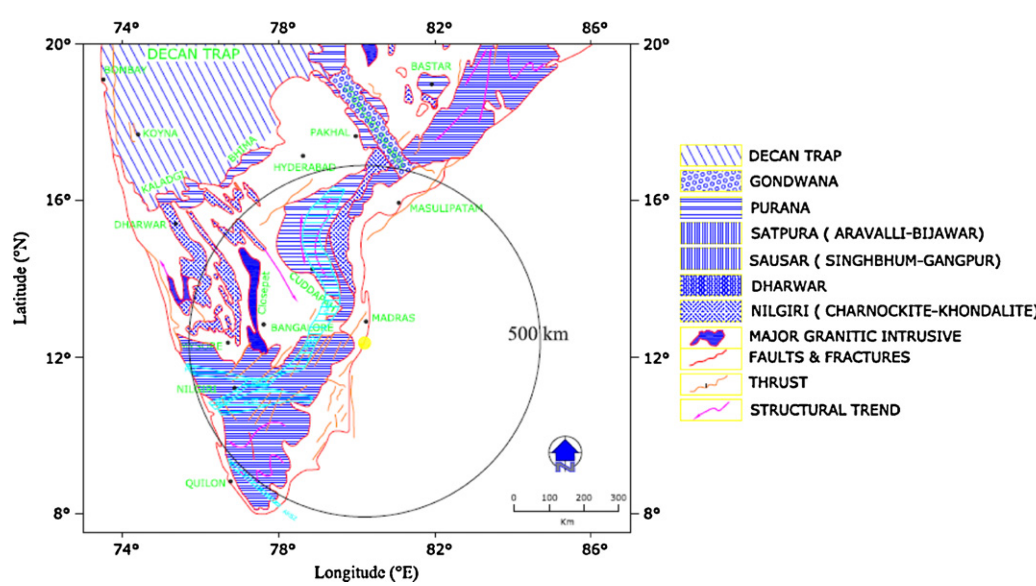

Fig. 2. NPP site with newly considered seismic study area and geology.

geological studies. Crystalline rocks of the late Proterozoic age occupy over 80% of the area of Tamilnadu, while the rest is covered by Phanerozoic sedimentary rocks along the coastal belt and river valley (GSI, 2000). At Kalpakkam, sand sheet deposited over mud by the tsunami begins at 25 m from the shore extending up to 420 m inland (Srinivasalu et al., 2007). All along the coast towards east, a zone of 500 m to 3.0 km is covered by mud with stagnant water, where the water table is at shallow depth (Boominathan, 2011 and Shanti Kumar et al., 1999). About 20 km SSW of Kalpakkam near Cheyyur and Kaliveli tank two faults have been found, possibly representing the boundary between crystalline basement and the Cauvery basin. South and Southeast of this fault is the Cauvery basin.

Indian Ocean geology is the third largest of the world's oceans, and is comprised of diverse and complex features. The evolution of the Indian Ocean, the present morphology and tectonics of the bordering continental margins are the consequences of the breakup of Eastern Gondwana land and subsequent seafloor spreading between the constituent continents viz., Madagascar, Seychelles, India, Antarctica, and Australia, since the Early Cretaceous (Murthy et al., 2011). The recent occurrence of earthquakes in coastal regions of the East as well as West Coasts of India has invoked interest among the earth scientists to study the coastal seismicity in relation to morphological and tectonic lineaments associated with coastal and near-shore regions of the continental shelf (Murthy et al., 2010). Much work needs to be done in understanding the tectonics of the Bay of Bengal and the Arabian Sea to address coastal and marine geohazards of the region (Murthy et al., 2011). Here, it can be noted that macro scale geological studies are carried out for land part and limited studies are found for ocean part. In total, limited geological studies are available in micro scale for the seismic study area.

4. Seismotectonics of seismic study area land part

The seismic study area is located in the Precambrian stable continental region (SCR), which is believed to be practically remaining firm against the lateral thrusts and mountain building activities. However, during its evolution, this land mass was subjected to intense tectonic activity, giving rise to a complex system of folds, faults and weak zones in the ancient basement composed of Archean and Proterozoic rocks (Krishnan, 1953 and 1966; Arogyaswamy, 1961; Gupta, 2006b). Main evolutionary units and the associated tectonic features in the peninsular shield of India are presented by Gupta (2006b) after modifying from Eremenko et al. (1969). Gupta (2006b) highlighted that the Eastern Ghats of the peninsula were uplifted during the post-Cuddapah and pre-Gondwana times. The western margin of the Eastern Ghats is a major boundary fault, which has shown the presence of recent rejuvenation giving rise to low magnitudes shocks. The developments of local zones of weakness along with crustal adjustments are likely to take place due to great structural disturbances during the geological past. Different levels of sporadic seismic activity in various parts of the peninsula are the manifestation of such adjustments. The necessary driving forces are perhaps provided by the slow straining of the peninsular shield of India as a result of the collision of the Indian and Eurasian plates and also due to local block tectonics (Khattri, 1994; Gupta, 2006b).

Geology and seismic source map details available for the seismic study area are quite old and not up to date. In this study new seismic source map has been generated by importing seismic sources which have been used for the seismic hazard analysis of the study area by other researchers. Seismotectonic details of geology, rock type, faults orientation with length, lineaments, shear zones and seismic events catalogue are complied. The well defined and documented seismic sources have been published in the Seismotectonic Atlas-2000 by Geological Survey of India (SEISAT, 2000). Geological survey of India has compiled all the available geological, geophysical and seismological data for the entire India and has published seismotectonic maps hard copy in 2000 and updated published softcopy in 2010. Seismotectonic Atlas (SEISAT, 2000) contains 43 maps in 42 sheets of 3°x4° sizes with a scale of 1:10, 00,000, which also describes the tectonic framework and seismicity. SEISAT was prepared with the intention that it can be used for the seismic hazard analyses of Indian cities. In this analysis, seismotectonic map of the study area is generated by merging SEISAT maps and considering the seismic sources which fall within the study area. SEISAT (2000) has given many seismic sources for this study, however, only the seismic sources which have experienced earthquakes in the past are considered. Seismicity and activity of the tectonic plates always change based on neotectonic activity in the region. Thus, it is necessary that any seismic hazard should include the recent seismicity. An extensive literature survey has been carried out to collect seismic sources from the recent publications as detailed below.

Ganesha Raj and Nijagunappa (2004) have mapped major lineaments of length more than 100 km in Karnataka State using satellite remote sensing data and correlated with the earthquake occurrences. They have highlighted that there are 43 major lineaments and 33 earthquakes with magnitude above 3 (since 1828) in the State. About 23 of these earthquakes were associated with 8 major lineaments, which they have named as active lineaments. The Mandya-Channapatna-Bangalore lineament, the Lakshman Thirtha-KRS-Bangalore lineament, and the Chelur-Kolar-Battipalle lineament are some of the seismically active lineaments identified by Ganesha Raj and Nijagunappa (2004) (Anbazhagan, 2007 and Anbazhagan et al., 2009). Ganesha Raj and Nijagunappa (2004) also stated that earthquakes are confined to the southern part of the state indicating that south Karnataka is seismically more active, which are about 200 km from the proposed NPP site.

Ramasamy (2006) studied active tectonics of South India by remote sensing and identified a number of faults and lineaments in the southern part of India. Identified faults and lineaments were correlated with geological features and were also used for the seismic hazard mapping of Tamil Nadu by Menon et al. (2010). Ramasamy (2006) painted a fair picture of the active tectonic scenario of South India using remote sensing and analyzing ground based datasets/observations. He had amalgamated these details with visibly displayed tectonic, fluvial, coastal and hydrological systems. Seismogenic sources mapped by remote sensing were also compared with past earthquakes and Bouger gravity anomaly. Findings of anomalies and the tectonic features by Ramasamy (2006) indicates that the southern part of the Indian Peninsula is tectonically active due to the northerly to north–northeasterly directed compressive force related to post collision tectonics. This active tectonic model visualized for South India gives a further clue that the whole Indian plate is whirling like a worm with alternate E–W arching and deepening, along with block and transform faulting from Cape Comorin in the south to the Himalayas in the north (Ramasamy, 2006).

The geotectonic of the seismic study area covers several lineaments/faults mapped by Ramasamy (2006). These include five major N-S/NNE-SSW trending faults (Tevaram-Stanley reservoir, Krishnagiri-Cape comorin, Gudiyattam-Cape comorin, Tanjore–Avadaiyarkoil and Kumbakonam–Muttupet lineaments) and the NE-SW lineaments which have formed in portions of Tamilnadu, Kerala and Karnataka. The faults extend from Pondicherry in the NE to Kambam valley in the SW (Mio-Pliocene sandstone). Further, SW lineaments which are parallel to NE forms a well defined tectonic valley in Kambam and within these lineaments Suruliar River has developed a wider flood plain. Among many of the lineaments towards NW-SE directions, six major ones are Pambar river, Ponnaiyar river, Vellar river, Cauvery river towards the SE, Bangalore in the NW- up to the east coast of Tamil Nadu and Nagamalai–Pudukottai (Precambrian quartzites).

Gupta (2006b) carried out a comprehensive analysis of seismotectonic characteristics of India and neighborhood and had delineated the probable seismic sources. About 21 possible seismic sources were identified in the peninsular India including the Kutch area along with the epicenters of past earthquakes with magnitude 3.0 or above. These sources were based on the tectonic features and the associated seismic activity in peninsular India. Gupta (2006b) had delineated 5 sub sources which together form source no 73, in the south Indian granulite terrain. A system of NE-SW and NW-SE trending faults and lineaments exist in this zone. The sub sources 'a' to 'e' in this zone were described based on the clustering of epicenters around some faults and lineaments. Source zones 'c' to 'e' are located in the present seismic study area. Part of the NE–SW trending source no 72 in Gupta (2006b) corresponds to a linear disposition of epicenters with the location of the M 5.8 Bellary earthquake of 1843 have also been accommodated in the seismic study area. The seismic source 74 was delineated by Gupta (2006b) considering Cuddapah basin. High level of seismicity associated due to localized faults and lineaments within the boundary of source zone 74 is defined as 'a' in the northern part. Part of seismic source 75 corresponds to WNW–ESE trending fault and 81 correspond to a very broad basis of epicenters in the Bay of Bengal.

5. Seismotectonics of coastal seismic study area

The NPP site is located on the seashore of the Bay of Bengal and more than 50% of the seismic study area comes under the sea bed, where much work remains in understanding the tectonics of Bay of Bengal and Arabian Sea to address the coastal and marine geohazards. Indian Ocean is the third largest ocean of the world and is comprised of diverse and complex tectonic features (Murthy et al., 2011). Studies available for the Eastern Continental Margin of India (ECMI) are briefly presented here. Tectonic lineaments over the shelf regions of ECMI were demarcated by analyzing geophysical data acquired through magnetic and gravity methods by Murty et al. (2002). The study areas considered was Visakhapatnam and Vizianagaram, off Andhra coast, Palar and Cauvery basins of the Tamil Nadu shelf. The free-air gravity anomaly map was given which is characterized by a significant north-south trending linear gravity low with major discontinuities and indicating major fault zones. The Mw 5.5 Pondicherry earthquake in 2001 has been interpreted as an offshore extension of the fault-plane Moyar–Bhavani–Attur (MBA) lineament. The authors highlighted the recent reactivation of the Precambrian shear zones in the offshore regions of Tamil Nadu, particularly the MBA lineament and need for detailed studies to locate the coastal and offshore lineaments, coupled with information on recent seismicity, which can throw light on the neo-tectonic activity within the South Indian shield (Murty et al., 2002).

Murthy et al. (2010) discussed seismicity of the equatorial region of the Central Indian Ocean basin, associated with Late Miocene lithospheric deformation in Indian sub-continent considering Geophysical studies carried out by the Regional Centre of National Institute of Oceanography, Visakhapatnam for the last 8 years (Murty et al., 2002; Subrahmanyam et al., 2007; Sarma et al., 2009). Land–ocean tectonics (LOTs) over the ECMI is shown by Murty et al. (2010) with blocks of Visakhapatnam (B-I), Ongole (B-II) and Pondicherry (B-III). The seismic study area covers two blocks (B-II and B- III). Murthy et al. (2010) highlighted that the structural lineament map of this area indicates the presence of all the three types of regional fault pattern, namely NW–SE, NE–SW and W–E. It can also be noted here that Sarma et al. (2009) delineated the offshore extension of the Gundlakamma Fault from marine magnetic data in B-II and this block had been subjected to structural deformation for the last 3000 Ma in the Plate tectonic history (Reddy and Chandrakala, 2004). Pondicherry block (B-III) forms a part of the Cauvery Basins, which is one of the three Gondwana Grabens of the east coast of India, the other two being the Krishna–Godavari and Mahanadi basins on the northern part. Ongole block (B-II) forms a part of the Eastern Ghat Granulite Belt. Detailed geophysical studies by Subrahmanyam et al. (1995a,b) and Murty et al. (2002) had indicated that the Cauvery Offshore basin is a fault-controlled basin. Gravity and magnetic study by Murthy et al. (2010) indicated offshore extension of two major Precambrian lineaments, namely the Moyar–Bhavani Attur (MBA) Lineament in the northern part and the Palghat–Cauvey Lineament (PCL) in the southern part of the Cauvery basin. Murthy et al. (2010) concluded that the observed moderate seismicity is mainly due to the reactivation of pre-existing structural lineaments, which are also associated with major and minor river channels, like the Kandivalasa (Vizianagaram,), Gundlakamma (Ongole) and Cauvery (Pondicherry). The fault reactivation and the associated seismicity hence are more predominant on the east coast (Murthy et al., 2010). Murthy et al. (2010) said that "Though the Eastern Continental Margin of India (ECMI) is considered as a passive margin, coastal seismicity due to the reactivation of the pre-existing tectonic lineaments extending offshore represents a potential natural hazard. In this context, the ECMI appears to be much more vulnerable compared to its counterpart on the west".

Balakrishnan et al. (2009) had generated a new tectonic map of India as the existing tectonic maps of India produced by the GSI and ONGC were largely based on the geological map of India combined with the topographic maps and the lineations evident in satellite pictures of the earth's surface. This new map considered a third dimension by introduction of 3D geophysical data by ensuring substantial advance in the study of the crystal structures in depth. Different geological formation joints and Rifts presented by him are located in the seismic study area. These joints and rifts are pre existing zones of weakness, where stress concentrations are more and capable of generating intraplate earthquakes (Gangopadhyay and Talwani, 2003) in the future.

The study area also experienced Tsunami during the disastrous 2004 Tsunami Earthquake. Kalpakkam Township and the housing colony of Department of Atomic Energy (DAE) were very badly affected and only Tsunami inundation was reported in the pits on the NPP coastal area and in the sea water intake pump house. Kalpakkam nuclear power station was shut down soon after sea water rushed into a pump station and no radiation leak or damage to the reactor was reported (Sc99ews, 2004). Almost 1000 houses were damaged, and a seawall 2 m high and 4 km long was collapsed, however the plant area remained unaffected by the tsunami. Kalpakkam School's compound wall was damaged, and electric poles were uprooted near the school grounds. The tsunami waves deposited a large quantity of sea sand near a pedestrian bridge. Water pipelines along the bridge were thrown off the bridge (Sheth et al., 2006).

A fresh seismic source map was generated for the study area considering regional geological and seismological investigations around 500 km radius using literature review, study of maps, remote sensing data and above-discussed seismic sources. Seismic sources are numbered independently for discussions and analysis. Table 1 lists the seismic sources within the seismic study area along with the coordinates and length of each seismic source. Fig. 3 shows the seismic sources around the NPP site within a circular area of 500 km. It can be seen in Fig. 3 that seismic sources are densely located close to the NPP site land side

Table 1
Details of delineated seismic sources in the seismic study area.

S. no.	Source ID	Starting point		Ending point		Mw Reported	No. of events of above 3.5	Length of the source (km)
		Long	Lat	Long	Lat			
1	B1	80.3771	16.0963	80.1082	15.7344	4.2	2	50.1819
2	B2	77.2192	9.8040	76.5660	10.2080	4.1	3	85.4081
3	C1	80.8795	11.9929	80.0319	11.7486	5.6	4	98.0842
4	F1	80.5413	13.6123	80.3045	12.2575	5.1	9	454.5166
		80.3045	12.2575	79.9801	11.8981			
		79.9801	11.8981	79.4306	11.6295			
		79.4306	11.6295	78.2170	10.6421			
5	F14	79.8106	12.4108	79.0401	11.9959	4.8	2	97.3503
6	F17	79.8233	11.8488	76.5169	16.0276	5.5	14	596.7893
7	F23	78.6799	12.4402	79.0669	12.9034	4.5	7	67.1278
8	F35	78.4123	13.0000	78.4270	11.6790	4.6	8	147.0096
9	F4	80.0618	12.4116	79.6239	12.7395	4.6	5	172.7732
		79.6239	12.7395	79.2042	12.8524			
		79.2042	12.8524	78.9364	12.8120			
		78.9364	12.8120	78.7077	12.6376			
10	F42	79.5945	11.9197	76.3428	10.5886	6.0	7	391.0915
11	L48	79.7484	11.5695	77.4169	9.2862	4.6	4	362.8594
12	F52	77.0881	12.7484	77.6594	11.5193	4.8	10	151.0348
13	F57	76.6658	13.5763	77.5847	12.2409	5.1	6	180.4679
14	F6	80.2542	12.9097	78.1273	12.2844	5.1	12	246.9285
15	F7	79.9145	12.1767	79.3465	13.0000	5.1	10	288.8820
16	F75	75.9813	10.8295	79.2740	13.5672	5.6	16	478.3010
17	F81	79.5821	16.7806	80.1074	15.3693	5.5	5	167.9697
18	F82	79.4943	16.0000	80.0621	14.2226	5.1	5	207.5325
19	L2	80.2500	13.0418	74.7737	12.6394	5.1	17	610.5774
20	L3	78.1374	12.9062	77.5488	8.0479	4.1	13	544.1723
21	L30	75.8145	11.1438	76.7119	12.6928	4.7	2	199.4153
22	L32	79.4549	13.8022	80.1575	14.7022	4.1	4	127.0725
23	L9	79.7913	11.8179	77.2705	9.3747	4.6	6	390.3577
24	M3	76.6873	10.1096	77.1014	9.2424	4.7	2	106.8574
25	M4	77.0042	9.9589	76.3085	9.6663	4	1	83.9959
26	S1	79.1631	13.0009	78.7705	15.3598	4.9	10	493.2343
		78.7705	15.3598	80.0307	16.8172			
27	S2	80.1014	15.9863	80.6475	16.9999	5.5	5	131.4535
28	S3	78.5822	11.6237	77.5750	11.4424	4.6	4	114.1295
29	M10	79.0320	14.7799	80.0691	15.1803	5	1	123.7033
30	F18	78.8901	11.9486	79.8948	11.9245	4.2	4	111.7500
31	F19	79.2645	11.9678	78.4161	12.5843	4.6	9	116.8649
32	F24	79.2184	13.0690	80.2764	13.4207	4	5	124.4817
33	F9	80.0974	13.0000	80.2918	13.4015	4.8	7	49.6370
34	C2	81.0953	12.3258	80.0383	12.0752	4	2	121.4794
35	F21	79.5178	12.9889	78.5661	12.6191	4	6	113.6291
36	F25	79.5095	14.0223	78.9666	12.8653	4.6	9	142.3394
37	F26	78.0000	13.1138	79.7647	13.3378	4.9	6	198.0032
38	S5	78.4042	13.5476	78.2854	12.9993	4.8	5	62.3798
39	F53	76.6962	13.0500	79.0632	9.6571	4.3	9	461.7108
40	F43	79.7774	10.6740	76.8225	11.1187	4.7	6	332.6924
41	L4	77.4757	9.8024	77.9045	12.8775	4.3	10	345.2351
42	M9	76.9978	10.3008	77.7521	8.1898	4.5	2	250.3644
43	F55	78.5549	11.6943	77.1122	12.4951	4.5	21	383.0077
44	F22	78.9946	12.6882	78.6543	11.9707	4.1	5	88.3214
45	F61	77.0957	13.0000	77.9866	12.0568	4.2	7	144.4410
46	M11	78.5607	14.9342	77.6295	14.5243	4	2	113.4290
47	F36	78.6243	11.7914	78.6162	12.6444	4.5	10	95.4823
48	LL	79.1013	13.1674	79.6105	13.2220	4.3	2	56.9424
49	F27	78.6896	13.3247	80.0200	13.8228	4	7	158.0178
50	F32	74.5490	13.8401	78.3005	13.3485	4	6	149.2557

when compared to sea side and away from the NPP site land side.

6. Seismicity around NPP site

Seismicity of an area is the basic issue to be examined in seismic hazard analysis for evaluating seismic risk. Detailed knowledge of active faults, lineaments and the associated seismicity is required to quantify seismic hazard and risk. The Indian plate consisting of the Indian subcontinent and the adjoining oceanic areas is sandwiched between the seismically active Himalayan belt in the north and the intense intraplate crustal deformation zone (Neprochnov et al., 1998; Krishna et al., 1998) in the equatorial region of the central part of Indian Ocean. As a result, it is currently under intense regional compressive stress field. This is evident from the fact that during the last 50 years, the Peninsular India has witnessed eight earthquakes of moderate size, the majority of them spatially coincide with paleo rifts and clustered around the pre-existing structural features (Rajendran, 2000). High-magnitude intraplate earthquakes of Killari (Mw 6.2, 1993), Jabalpur (Mw 5.8, 1997), and Bhuj (Mw 7.7, 2001) have claimed several human lives, and moderate earthquakes in Kerala (M 5.0, 2000), Karnataka (M 4.3, 2001), and Tamil Nadu (M 5.6, 2001) in the southern peninsular India have created enough concern to understand the temporal and spatial

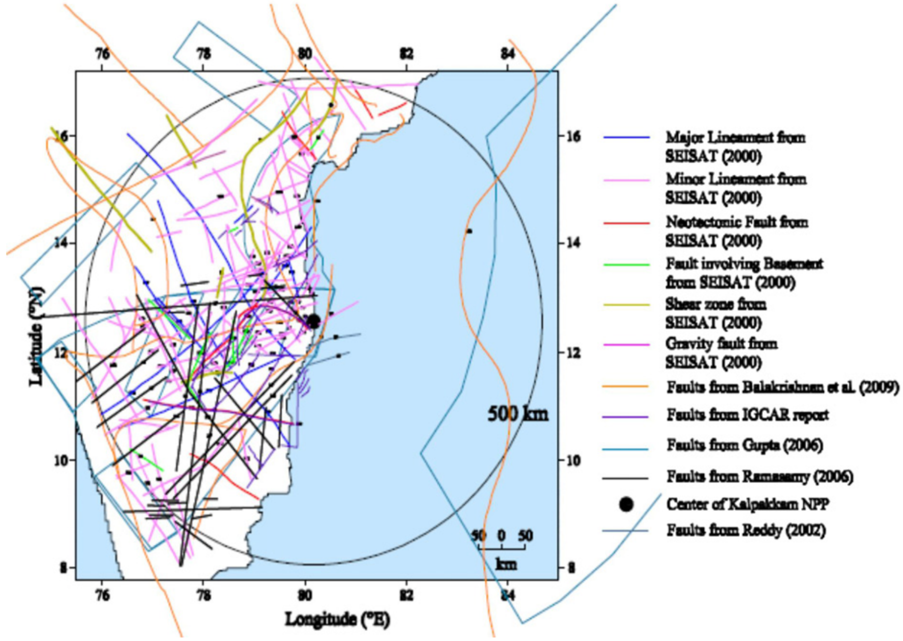

Fig. 3. Seismic source map of the seismic study area around NPP site.

behavior of seismically active faults, and the frequency of recurrence. Several researchers have compiled earthquake data of India, particularly Jaiswal and Sinha (2007a); Anbazhagan (2007); Menon et al. (2010); NDMA (2010); Martin and Szeliga (2010); Szeliga et al. (2010); Kolathayar and Sitharam (2012); Nath and Thingbaijam (2012). In this study earthquake data are compiled in two portions i.e. historical data and instrumental data. The historic data has been compiled from Oldham (1883); Basu (1964); Kelkar (1968); Tandon and Srivastava (1974); Rastogi (1974); Chandra (1977, 1978); Kaila and Sarkar (1978); Rao and Rao (1984); Srivastava and Ramachandran (1985); Biswas and Dasgupta (1986); Guha and Basu (1993) and Bilham (2004). The instrumental data has been compiled from national and international agencies. The national agencies include the Bhabha Atomic Research Centre (BARC), Indian Meteorological Department (IMD), Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam and National Geophysical Research Institute (NGRI), Hyderabad; International agencies include the International Seismological Centre (ISC) data file (for the time period between 1964 and 2011), Incorporated Research Institution for Seismology (IRIS), Harvard seismology, Amateur Seismic Centre (ASC) and the U.S. Geological Survey (USGS)/National Earthquake Information Center (NEIC) catalog (for the time period 1976–2011).

The earthquake data complied were in different scales of measures such as earthquake intensity scale (I), body wave magnitude (m_b), surface wave magnitude (M_S), local magnitude (M_L) and moment magnitude (M_W). A complete earthquake catalogue with a uniform magnitude scale of past earthquakes is a prerequisite for a reliable parameterization of the magnitude distribution used in the seismic hazard analysis as discussed below:

6.1. Homogenization

In this study, earthquake catalogue is homogenized by following the moment magnitude (M_W) scale. In the recent studies by Menon et al. (2010), NDMA (2010), Kolathayar and Sitharam (2012), Nath and Thingbaijam (2012), the authors had homogenized the earthquake data corresponding to seismic study area using Scordilis (2006). Regional relations between M_W and other scales of earthquake measurement developed by Kolathayar and Sitharam (2012) are similar to Scordilis (2006). So, the events which have either M_s, m_b or M_L magnitude scale are converted to M_W using these equations. In previous studies, various intensity scales were used to evaluate earthquakes in India (Martin and Szeliga, 2010). Most of the researchers had considered the reported intensity as Modified Mercalli Intensity (MMI) scale and used Gutenberg and Richter (1956) empirical relation to convert MMI to M_W as given in equation 1.

$$Mw = \frac{2}{3}MMI + 1 \tag{1}$$

Menon et al. (2010) highlighted that the Gutenberg and Richter (1956) relation is based exclusively on Californian data and cannot be used for Indian earthquakes without corroborating its applicability. Lai et al. (2009) proposed a new correlation between MMI and M_W based on 23 PI earthquakes between 1969 and 2001 with independent measures of MMI (I_0) and moment magnitude (M_W) identified from different sources as given in equation 2.

$$Mw = 0.445MMI + 2.381 \tag{2}$$

This relation is also used by Menon et al. (2010) and Anbazhagan et al. (2012a,b). This relation is the relation given in equation 2 has been used in the present study to convert Intensity values to the moment magnitude in the seismic study area, the comparison of which with the conventional equation is shown in Fig. 4. It is observed that the Gutenberg and Richter (1956) equation underestimate M_W values up to the MMI of VI and over estimate beyond MMI of VI.

6.2. Declustering

Since the earthquake data are compiled from many sources, repetition of the same data and also foreshocks and aftershocks for instrumental data occurs which need to be removed by declustering. Declustering is the separation of the dependent events (i.e., foreshocks, aftershocks, and clusters) from the background seismicity (Reasenberg, 1985). The declustering by the static window method is based on the removal of foreshocks and aftershocks which fall within a constant time and distance window. In the current study, a uniform time window of 30 days (from the time

Table 2
List of earthquakes data of Mw more than 4.5 and epicenter distance from proposed NPP site. Events with less than 100 km are marked in bold italic.

Sl No	Longitude (°E)	Latitude (°N)	Year	Month	Date	Mw	Depth (km)	Epicenter Distance (km)
1	77.919	12.405	1968	8	2	4.5	NA	251.43
2	78.65	12.49	1968	8	13	4.5	NA	169.74
3	80.02	16.64	1996	8	4	4.5	NA	454.22
4	77.43	12.82	1984	3	20	4.5	21	306.62
5	77.1	9.8	2011	11	18	4.5	33	459.31
6	78.6	12.47	1984	11	27	4.5	NA	175.41
7	79.64	14.56	2003	7	17	4.6	10	230.42
8	80.1	15.6	1800	10	18	4.6	NA	338.36
9	*79.6*	*12*	*1819*	*6*	*20*	*4.6*	*NA*	*89.09*
10	80	14.5	1820	12	31	4.6	NA	216.82
11	78.4	12.4	1858	12	30	4.6	NA	198.15
12	78.1	11.6	1859	12	17	4.6	NA	254.13
13	78.6	12.5	1859	12	17	4.6	NA	175.25
14	78.2	11.9	1860	1	17	4.6	NA	231.48
15	79.4	13.7	1860	2	2	4.6	NA	153.46
16	78.2	11.9	1861	3	4	4.6	NA	231.48
17	78.7	10.8	1864	1	5	4.6	NA	255.17
18	78.7	12.7	1865	8	2	4.6	NA	164.77
19	78.1	9.9	1856	3	17	4.6	NA	374.95
20	78.6	12.5	1859	2	5	4.6	NA	175.25
21	78.1	11.7	1959	12	17	4.6	NA	249.68
22	80.1	15.6	1971	7	29	4.6	NA	338.36
23	76	11.4	1858	8	13	4.7	NA	481.76
24	76.8	9.69	2001	1	7	4.7	16	492.48
25	78	11	1952	5	9	4.7	NA	297.50
26	77.53	11.94	2004	7	6	4.8	133	302.03
27	78.3	12.8	1971	11	26	4.8	NA	210.22
28	78.234	12.777	1977	1	16	4.8	NA	217.20
29	78.29	12.62	1977	8	13	4.8	NA	209.72
30	78.388	13.514	1977	10	23	4.8	NA	225.35
31	82.11	16.2	2003	5	7	4.8	4.5	458.58
32	*80.2*	*13*	*1966*	*4*	*10*	*4.8*	*NA*	*49.23*
33	*79.41*	*12.17*	*1988*	*5*	*19*	*4.8*	*NA*	*95.38*
34	79.17	14.5	1977	1	6	4.9	NA	243.14
35	76.79	9.69	2000	12	12	4.9	14	493.33
36	79.64	16.43	1995	5	24	4.9	55.2	434.64
37	78.567	13.637	1977	8	16	4.9	NA	215.33
38	78.18	13.15	1991	4	19	4.9	NA	231.39
39	78.3	12.8	1974	5	23	4.9	NA	210.22
40	79.72	15.1	1970	1	16	5.0	NA	287.15
41	79	12.5	1859	1	3	5.1	NA	130.81
42	80	14.5	1869	9	1	5.1	NA	216.82
43	77	13	1916	1	7	5.1	NA	356.45
44	*80.3*	*13.1*	*1807*	*12*	*10*	*5.1*	*NA*	*61.85*
45	*80.3*	*13.1*	*1816*	*9*	*16*	*5.1*	*NA*	*61.85*
46	*79.7*	*12.5*	*1822*	*1*	*29*	*5.1*	*NA*	*53.21*
47	*80*	*13*	*1823*	*3*	*2*	*5.1*	*NA*	*52.86*
48	*80.1*	*11.70*	*1959*	*10*	*13*	*5.1*	*NA*	*95.77*
49	*79.6*	*12*	*1867*	*7*	*3*	*5.5*	*NA*	*89.09*
50	80	16	1959	10	12	5.5	NA	383.23
51	78.34	16.54	1998	4	9	5.5	NA	487.53
52	80.1	15.6	1967	3	27	5.5	15	338.36
53	76.7	11.5	1882	2	28	5.6	NA	403.91
54	*80.31*	*11.79*	*2001*	*9*	*25*	*5.6*	*23*	*86.71*
55	76.7	10.7	1900	2	8	6.0	70	438.17

of occurrence of the main shock) and a uniform spatial window of 30 km (distance from the main shock) have been adopted. The values adopted for the temporal and spatial window should be appropriate for the intraplate seismicity of Peninsular India, which should not produce large rupture areas over a long period of time as that at the plate boundary (Lai et al., 2009).

The complete homogenized earthquake catalogue consisting of 919 events is obtained. Fig. 5 shows the pictorial representation of epicentral locations of all the earthquake events considered in this study. The catalog contains 578 events of M_w less than 3.0 and 341 events of M_w above 3.0. The lower-bound earthquake magnitude cutoff level for the design of NPP facilities based on cumulative absolute velocity (CAV) model is close to M_w of 4.5 (EERI and DOE, 2005). Table 2 lists the events with M_w more than 4.5 and rows marked in bold italic are the events occurred very close to NPP site i.e., within 100 km radial distance from the NPP site. The Pondicherry earthquake of Mw 5.6 occurred in 2001 about 40 km off the coast of Pondicherry and 86.71 km from NPP site. The largest earthquake in the seismic study area is Coimbatore earthquake of M_w 6.0 reported on the 8th February 1900. List of number of events of various magnitude ranges above M_w 3 is given in Table 3. It can be noted here that the number of earthquakes of M_w 4.5 and above is about 55.

7. Regional seismotectonic parameters

Possible seismic sources presented in Fig. 3 and available seismic data in Fig. 5 are coupled together to develop a new seismotectonic map for the seismic study area. Seismotectonic map showing faults, lineaments, shear zone and past earthquake events is shown in

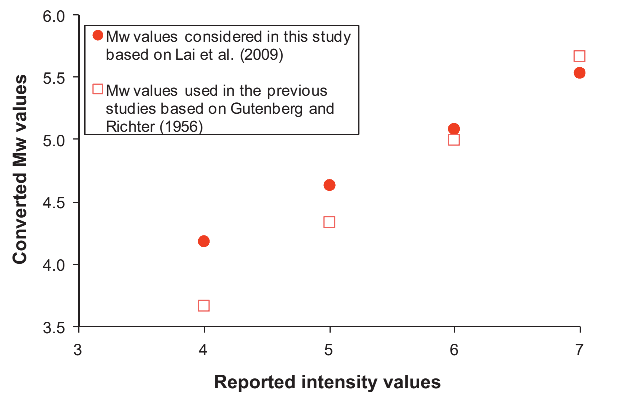

Fig. 4. Comparison of converted intensity and moment magnitude values in this study and previous study.

Fig. 6. This map is used to find out maximum observed earthquake magnitude close to each source. The seismic source which has experienced earthquake is considered as a potential source for the future earthquake. The shortest surface distance (epicenter distance) from the potential seismic source to NPP site has been estimated.

7.1. Analysis and interpretation of the seismic data

Earthquake catalogue forms the backbone of seismic hazard assessment, providing the detailed insight into the seismicity of a region required to develop seismogenic zoning scenarios in conjunction with seismotectonic and geological information (Lai et al., 2009). The complete earthquake data considered in the study are further analyzed to find out representative seismicity characters of the region. Fig. 7 shows the plot of all the available earthquake data in the time history. Fig. 8 shows the histogram of the earthquake data in the study area. It can be noted clearly from Fig.s 7 and 8 that for a specific period of the interval there is no earthquake data found. Based on seismic instrumentation of south India, one can say that instrumental data for the seismic study area might have been recorded after Gauribidanur seismic array (GBA) set up in the year 1965. So earthquake data reported before 1965 are considered as non-instrumental/historic data and those reported after 1965 are instrumental data. Fig. 9a and 9b shows the time history of historic/non-instrumental data and instrumental data respectively. It can be noticed from these Fig.s that non-instrumental data has no earthquake with $M_W < 3.0$ (see Fig. 9a). Also, the number of events recorded is more in the instrumental data.

Table 3
Summary of earthquakes events of Mw above 3.0 in seismic study area.

Earthquake magnitude (M_W) range	Number of events
3 to <3.5	130
3.5 to <4.0	108
4 to <4.5	48
4.5 to <5.0	39
5 to <5.5	9
>5.5	7

7.2. Focal depth of the earthquake

Establishing the focal depth of future earthquake is a tough and important job for any seismic hazard analysis. Knowledge about the depth distribution of the diffuse seismicity (e.g. derived from the seismological database) should be incorporated in the seismic hazard evaluation (IAEA SSG-9, 2010). Most of the seismic hazard analyses which have been carried out in the seismic study area have considered the lowest depth or depth corresponding to minor earthquakes. A summary of depths considered in previous works is given in Table 4 for the seismic study area. In this study, a complete catalogue has been studied to select the appropriate depth of the seismic study area. Average focal depths for the mild earthquakes in the south Indian shield are reported to be within an upper-crustal layers and for moderate earthquakes are close to Moho depth in the region i.e. 34 km to 70 km. Summary of focal depth for the seismic study area based on the catalogue is given in Table 5.

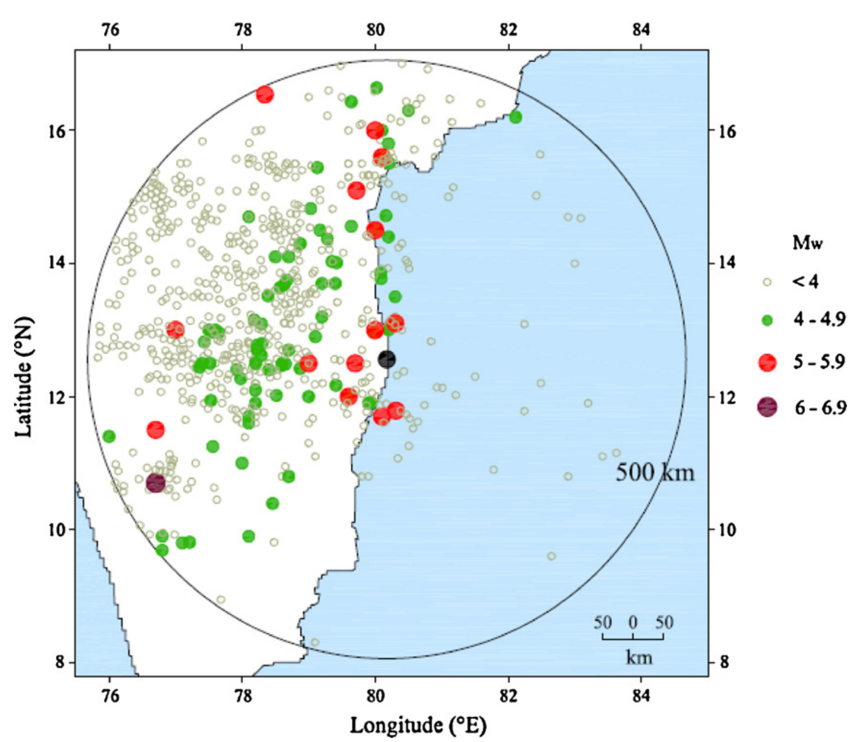

Fig. 5. Locations of the earthquakes around NPP site.

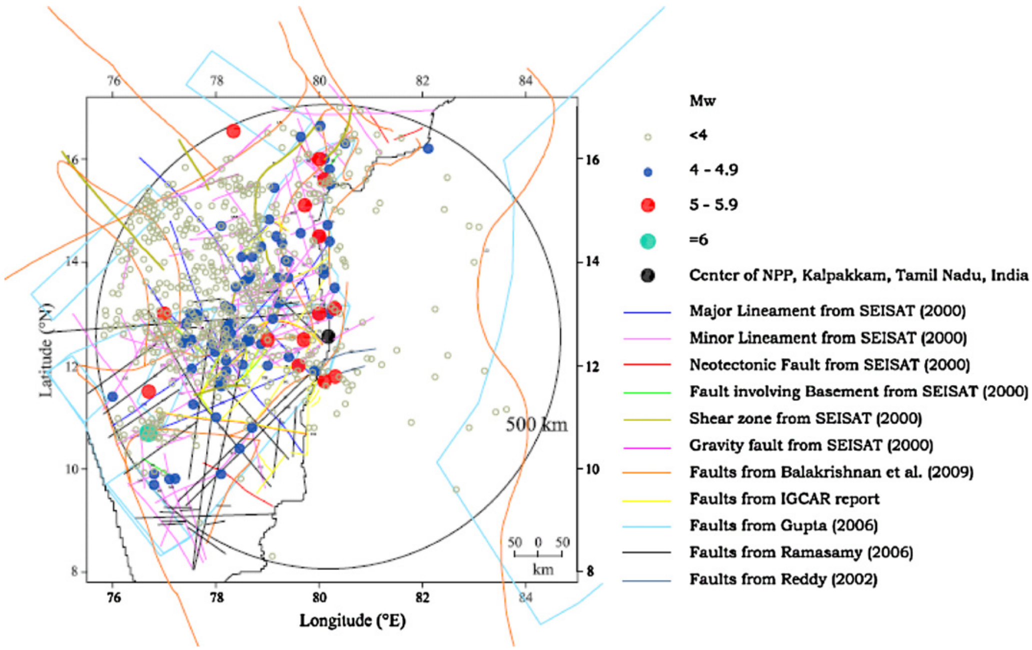

Fig. 6. New seismotectonic map for NPP site.

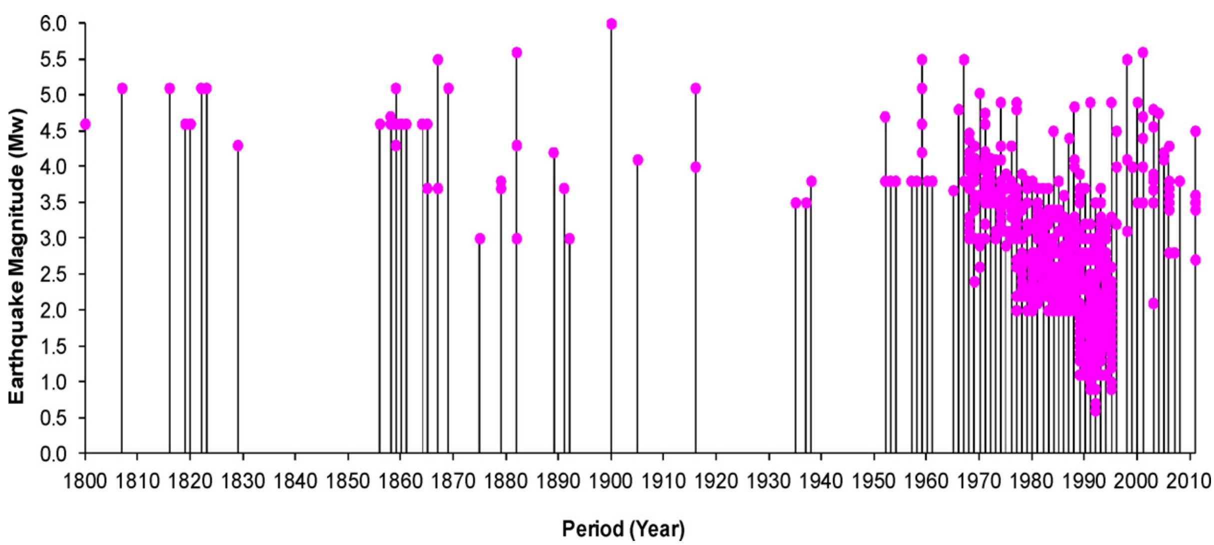

Fig. 7. The time history of available data for the seismic study area.

Further, focal depth of past earthquakes is analyzed with magnitude and distance from the NPP site. Fig. 10a and 10b show the plots of depth versus magnitude and epicenter distance from the NPP site respectively, considering the earthquakes of M_W 4 and above. Depth of earthquakes of magnitude less than 4 is not considered because it has limited application for engineering design and also there is uncertainty in depth evaluation in distant seismic instrumentation in southern India. From Fig. 10 it can be noted that very few earthquakes have focal depth less than 10 km for Mw less than 5. Earthquakes of M_W more than 5 have occurred with a minimum focal depth of 15 km and average focal depth of 36 km. Based on this, depth of future earthquake is taken as 15 km for M_W of 5 and above.

Table 4
Focal depths considered for the seismic study area by different researchers.

S. no.	Authors	Focal depth considered for seismic hazard analysis (km)
1	Jaiswal and Sinha (2007a,b, 2008)	10
2	Anbazhagan et al. (2009)	15
4	Menon et al. (2010)	0–12
5	NDMA (2010)	5–25
6	Roshan and Basu (2010)	10–30
7	Boominathan (2011)	10
8	Sitharam and Vipin (2011)	15
9	Nath and Thingbajam (2012)	15–25
10	Ramanna and Dodagoudar (2012)	17

Table 5
Summary of focal depth considered in the seismic study area.

Magnitude (M_w)	Depth reported (km)		Average depth (km)
	Minimum	Maximum	
<3.5	10	15	12.5
3.5 to 3.99	5	39	16.44
4.0 to 4.49	4	70	29.6
4.5 to 4.99	10	133	35.8
>5.5	15	70	36

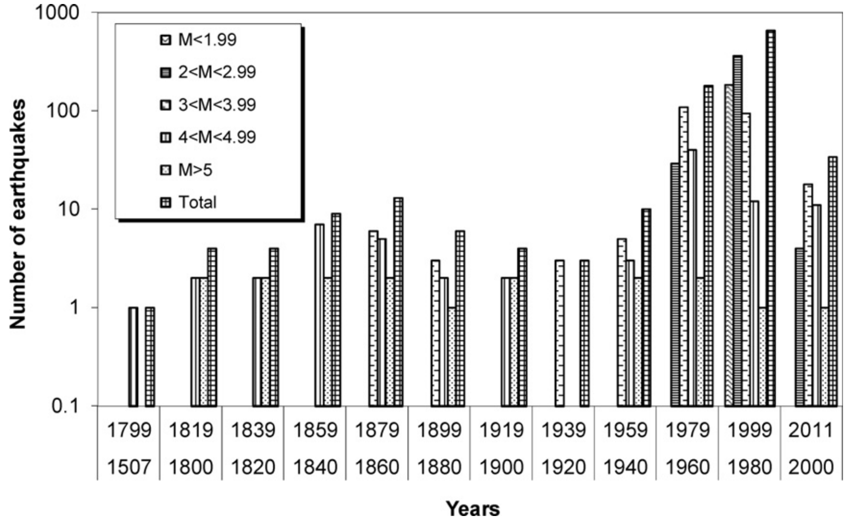

Fig. 8. Histogram of earthquake data in the study area.

8. Maximum possible earthquake magnitude (M_{max})

Knowledge of maximum possible earthquake magnitude (M_{max}) is essential in many seismic engineering applications/designs. It reflects the potential of seismic strain which is expected to be released in the region. M_{max} is the magnitude of the largest earthquake thought to be possible within a specified area or seismic source zone. By definition, no earthquakes are to be expected

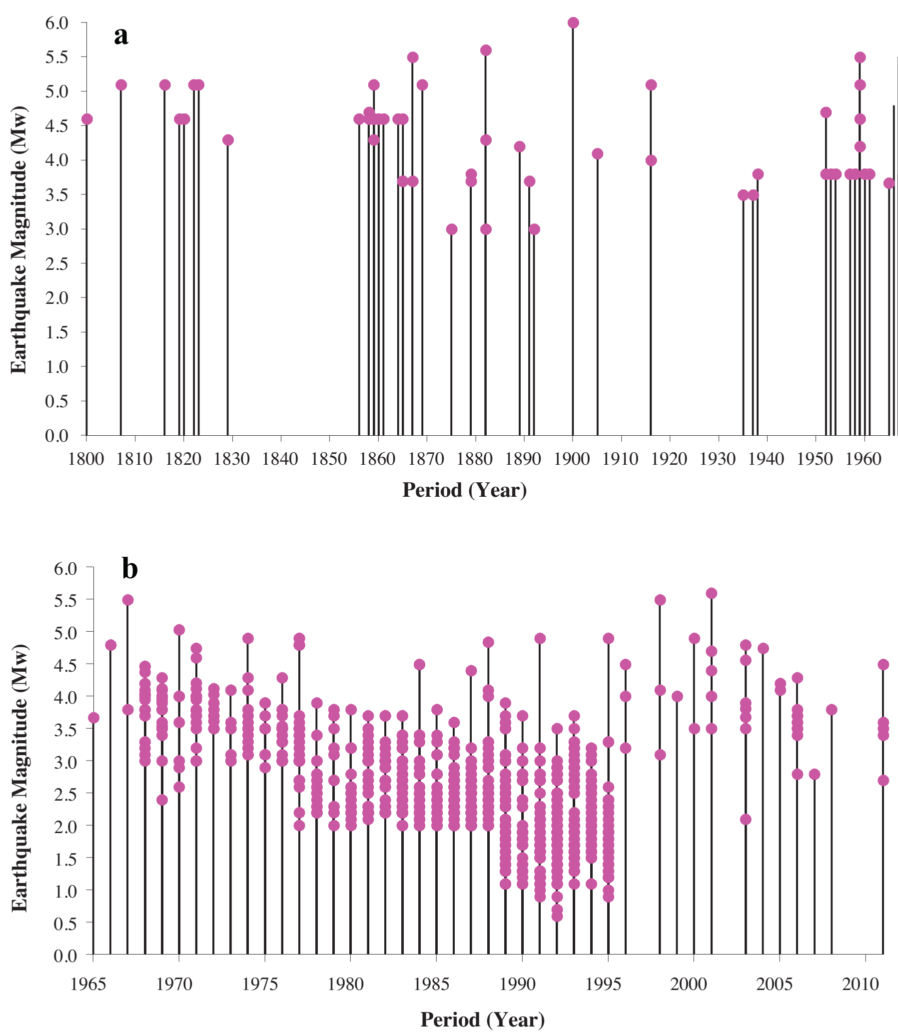

Fig. 9. (a) The time history of historic/non- instrumental earthquake data. (b) The time history of instrumental earthquake data.

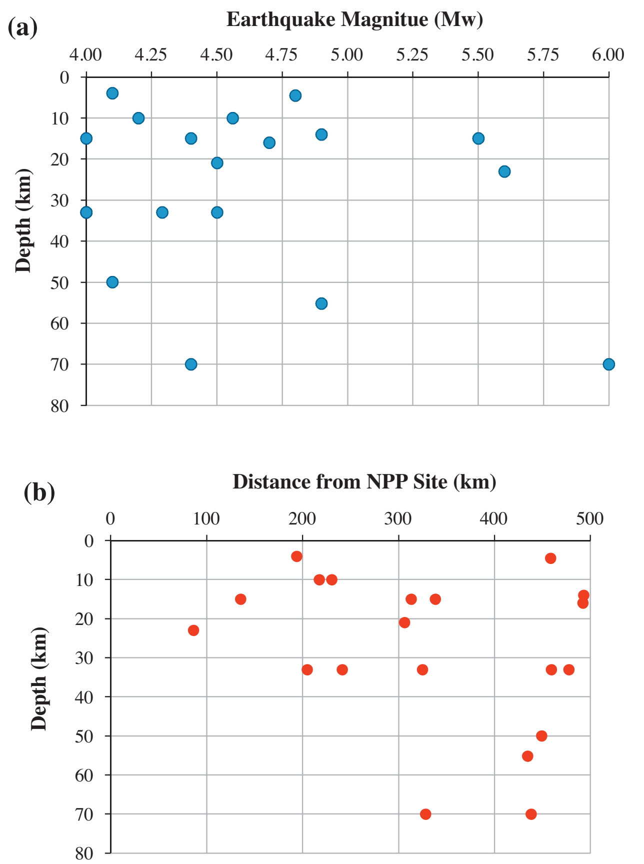

Fig. 10. a and 10b: Distribution of focal depth of regional earthquakes of Mw more than 4.

with magnitude exceeding M_{max} (Joshi and Sharma, 2008). Little literature is available on developing appropriate techniques for the estimation of region-specific maximum earthquake magnitude. The available data of earthquakes are often too less to reflect the full potential of faults or thrusts in the region (Joshi and Sharma, 2008). At present there is no generally accepted method for estimating the value of M_{max} (Kijko, 2004). Mueller (2010) highlighted the criteria and methods that are widely used to estimate the M_{max} for data-poor regions followed by the Electric Power Research Institute/Seismicity Owners Group (EPRI/SOG, 1988) to conduct a comprehensive, then state-of-the-art seismic-hazard analysis for the CEUS, eliciting hazard models and assessments from six expert earth-science teams. Methods to estimate the M_{max} for data-poor regions as given by Mueller (2010) are:

1. Magnitude of the largest observed earthquake with or without an added increment.
2. Statistical analysis of the catalog to estimate the sizes and recurrence times of extreme events.
3. Judgment based on physical dimensions, crustal setting, crustal expression of potential seismogenic sources.
4. Extrapolating the frequency-magnitude curve to long recurrence times (for example, the 1000-year earthquake).
5. Expanding the local dataset by importing seismicity data from global tectonic/geologic analog regions (substituting space for time)
6. Saturation of the m_b magnitude scale [EPRI/SOG specified M_{max} in terms of m_b]

Most of the scientists working in this area argued that a "significantly higher degree of confidence in the maximum earthquake is possible when placed in the context of the global dataset" (Mueller, 2010).

In India, most widely used method to estimate M_{max} is deterministic method and recently researchers have started using probabilistic methods suggested by Kijko and Sellevol (1989). Very widely used method to estimate M_{max} is adopting the largest observed earthquake magnitude, with or without an added increment. In this method, M_{max} is calculated for the seismic study area and the same M_{max} value is adapted to all the sources or M_{max} is calculated for each seismic source/zone. Summary of M_{max} estimation by different researchers for the seismic study area is given in Table 6.

Wheeler (2009) suggested several methods to estimate M_{max} in parts of the Central and Eastern United States and adjacent Canada (CEUSAC) and pointed out that short historical-seismicity records decrease the defensibility of several methods. According to Wheeler (2009), the largest observed earthquake in a specified area provides an unarguable lower bound on M_{max} in the area. Beyond that, all methods are undermined by the enigmatic nature of geologic controls on the propagation of large ruptures. As there is lack of data in the seismic study area, most of the methods mentioned by Wheeler (2009) cannot be applied in present work.

AERB recommends alternate procedures to select maximum magnitude to estimate S2 ground motion for the design of Nuclear power Plant (AERB/SG/S-11, 1990). Summary of the alternate approach given in AERB/SG/S-11 section 2.3.3.1 is presented below:

1. Use of maximum historic earthquake magnitude- Relied if large slip rates were reported from several centuries catalogues.
2. The maximum earthquake magnitude should not be less than that of adding an equivalent of at least one unit of MMI scale–for the region with reliable catalogue exists.
3. The Paleoseismicity method- Areas where fault scarps are preserved and adequate stratigraphic studies are available
4. The fault rupture method – maximum fault rupture length applicable to the region

Approach 1 and 3 are not applicable to the seismic study area because of insufficient data. Approach 2 is a deterministic procedure based on regional maximum observed earthquake magnitude. Approach 4 is based on the rupture character of seismic source and is region specific and this procedure is also recommended in IAEA SSG-9 (2010). In this study, M_{max} of the seismic sources in the seismic study area is estimated considering the following region-specific approaches:

A. Deterministic Approaches
   1) Taking maximum observed magnitude in the region as M_{max}
   2) M_{max} = Maximum observed + an increment of 0 to 3.2 (Wheeler, 2009).
B. Fault rupture method

Approach A-1: Maximum observed magnitude in the study area i.e., 6.0 (Sl. No. 1 in Table 6) is considered as M_{max} of the seismic study area. This method is simple and provides an unarguable lower bound for M_{max} (Wheeler, 2009).

Approach A-2: This approach is adopted by considering an increment of one unit of MMI to the maximum observed magnitude of each source for the worst scenario. One unit of MMI scale corresponds to M_W of 0.67 as per equation 1 and 0.45 as per equation 2. These values are close to an increment of 0.5 and results in the energy release of about ten times the energy released for the observed magnitude. These values have also been used in previous studies in PI (see Sl. No. 4, 6 and 7 of Table 6). Considering the uncertainty in the seismicity data of the study area, worst scenario earthquake of NPP site can be estimated by

Table 6
Maximum magnitude considered by the different researchers for the seismic study area.

Sl No.	Author	Maximum Magnitude	Remarks
1	Earthquake Design Basis for Kalpakkam Site	6.0	Maximum observed earthquake in the South India
2	Jaiswal and Sinha (2007a and 2007b; Jaiswal and Sinha, 2008) Southern Craton (SC) Eastern Passive Margin (EPM)	6.7 ± 0.57* 6.7 ± 0.71+ 6.53 6.4 ± 0.56* 6.4 ± 0.71+ 7.5#	*Cramer's Approximation +Bayesian Approximation #Geological consideration (From Seeber et al., 1999)]
3	Anbazhagan et al. (2009)	+0.5	Maximum observed earthquake ($M_{max}^{oberved}$) in each source plus 0.5
4	Menon et al. (2010)	*Maximum observed and +0.3*	$M_{max}^{oberved}$ *and* $M_{max}^{oberved}$ *+ 0.3*
5	NDMA (2010) Southern Craton Eastern Passive Margin Bay of Bengal	 6.8 6.1 6.7	 Maximum likelihood in Kijko's approach
6	*Roshan and Basu (2010)*	$M_{max}^{oberved}$*+ 0.67*	*Magnitude value is upgraded in line with AERB/SG/S-11(AERB, 1990)*
7	*Boominathan (2011)*	*6.2*	$M_{max}^{oberved}$*+0.5*
8	Sitharam and Vipin (2011)	+ 0.5	$M_{max}^{oberved}$ in each source plus 0.5

incrementing the maximum observed magnitude by one magnitude (M_W) unit. So, the probable future earthquake (observed magnitude + 1) energy release will be 31.6 times the maximum energy released on each seismic source for the observed magnitude. Fig. 11 shows the energy variation for maximum observed magnitude and incremented magnitudes with the increments of 0.45, 0.5, 0.67 and 1. This method is also simple and can be applied anywhere; however application of the increment method to estimate M_{max} is inconsistent (Wheeler, 2009).

Approach B: In this study regional rupture character has been established by considering the maximum earthquake reported and the possible seismic source. Procedure to establish regional specific rupture character has been presented by Anbazhagan et al. (2012a and b). The same procedure is followed here to establish rupture character of the seismic study area considering the data given in Table 1. Subsurface rupture length (RLD) of each seismic source has been estimated by using well accepted correlation between RLD and magnitude (M_W) by Wells and Coppersmith (1994) for the maximum observed magnitude of each source. Percentage Fault Rupture (PFR) is the ratio of subsurface rupture length (RLD) to Total Fault Length (TFL) expressed in percentage and is calculated for all the seismic sources listed in Table 1 (Anbazhagan et al., 2012a,b). Anbazhagan et al. (2012a,b) plotted PFR against TFL and found that PFR follows a unique trend for the specific region and magnitude range. A detailed discussion about maximum magnitude estimation and relation between PFR and TFL for the seismic study area can be found in Anbazhagan et al. (2012b). Possible worst scenario PFR is established by considering minimum, maximum and average PFR in three lengths bins as given in Table 7. For each length bin, PFR for worst scenario earthquake has been taken as five times the average PFR which is also more than the maximum reported PFR. PFR for the worst scenario (see Table 7) is taken as the regional rupture character of the seismic study area. RLD is calculated based on the length of each source and the regional rupture character, which gives the M_{max} of each source used in the relation given by Wells and Coppersmith (1994). M_{max} for each source estimated from the above three approaches is listed in Table 8. To get the OBE magnitude, source-specific M_{max} i.e., a single value of M_{max} for each source is to be considered. So, final M_{max} for each seismic source to calculate hazard values is selected based on the following criteria:

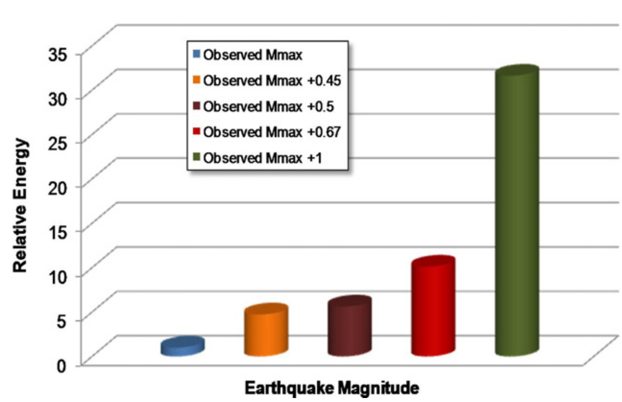

Fig. 11. Relative energy for the maximum observed magnitude and increment of 0.45, 0.5, 0.67 and 1.

- If M_{max} from approach B is greater than M_{max} from approach A-1, maximum of all the three is considered as final M_{max}.
- If M_{max} from approach B is less than M_{max} from approach A-1, then average of three M_{max} is considered.
- If the M_{max} from approach A-2 is more than approach B and RLD of the particular source less than 15% of the total length, then M_{max} from approach A-2 is considered as maximum magnitude.
- If the M_{max} from approach A-2 is more than approach B and ruptures the particular source more than 15% then M_{max} has been estimated considering maximum RLD as 15% of total length of the source.

The last column of Table 8 gives the final M_{max} considered for the analysis taking into account the above points.

Table 7
Regional rupture character for various distance bins.

length bins (km)	PFR (% TFL)			PFR (% TFL) for Worst scenario (WS)	Ratio of PFR for WS to maximum PFR
	Minimum	Maximum	Average		
<200	0.53	7.45	2	10	1.3
200 –500	0.27	3.22	1	5	1.6
>500	0.18	1.04	0.62	3	2.9

9. Ground motion prediction equations (GMPEs)

The effects of the earthquake can be minimized by understanding the seismic hazard along with the strong motion produced by the earthquakes in various parts of the country. Since the ground-motion or vibration produced by earthquakes causes structural damage, engineers demand for design ground-motion. Hence, the knowledge of strong ground-motion is important to assure the safety of the structure like power plants, dams, bridges etc. and also to decide upon the design ground-motion at a particular region. Strong ground-motion at a particular region can be properly assessed by using the appropriate GMPE valid for that region. An important step in any seismic hazard analysis is the selection of appropriate GMPEs, which are important for predicting the level of

Table 8
Estimation of maximum magnitude for seismic sources.

Source ID	Observed magnitude (M_w)	Approach B			M_{max} as per approach A-1	M_{max} as per approach A-2	M_{max} considered for hazard analysis
		TFL (km)	RLD (% of TFL) as per rupture character (km)	M_{max}			
B1	4.2	50.182	5.0182	5.3	6.0	5.2	5.3
B2	4.1	85.408	8.5408	5.7	6.0	5.1	5.7
C1	5.6	98.084	9.8084	5.8	6.0	6.6	6.1
F1	5.1	454.517	13.6355	6.4	6.0	6.1	6.4
F14	4.8	97.35	9.7350	5.8	6.0	5.8	5.8
F17	5.5	596.789	17.9037	6.3	6.0	6.5	6.5
F23	4.5	67.128	6.7128	5.5	6.0	5.5	5.5
F35	4.6	147.01	14.7010	6.1	6.0	5.6	6.1
F4	4.6	172.773	17.2773	6.2	6.0	5.6	6.2
F42	6	391.092	11.7328	6.3	6.0	7.0	7
L48	4.6	362.859	10.8858	6.3	6.0	5.6	6.3
F52	4.8	151.035	15.1035	6.1	6.0	5.8	6.1
F57	5.1	180.468	18.0468	6.3	6.0	6.1	6.3
F6	5.1	246.929	7.4079	6	6.0	6.1	6.1
F7	5.1	288.882	8.6665	6.1	6.0	6.1	6.1
F75	5.6	478.301	14.3490	6.5	6.0	6.6	6.6
F81	5.5	167.97	16.7970	6.2	6.0	6.5	6.5
F82	5.1	207.532	6.2260	5.9	6.0	6.1	6.1
L2	5.1	610.577	18.3173	6.3	6.0	6.1	6.3
L3	4.1	544.172	16.3252	6.2	6.0	5.1	6.2
L30	4.7	199.415	19.9415	6.3	6.0	5.7	6.3
L32	4.1	127.073	12.7073	6	6.0	5.1	6
L9	4.6	390.358	11.7107	6.3	6.0	5.6	6.3
M3	4.7	106.857	10.6857	5.9	6.0	5.7	5.9
M4	4	83.996	8.3996	5.7	6.0	5.0	5.7
S1	4.9	493.234	14.7970	6.5	6.0	5.9	6.5
S2	5.5	131.454	13.1454	6	6.0	6.5	6.3
S3	4.6	114.13	11.4130	5.9	6.0	5.6	5.9
M10	5	123.703	12.3703	6	6.0	6.0	6
F18	4.2	111.75	11.1750	5.9	6.0	5.2	5.9
F19	4.6	116.865	11.6865	5.9	6.0	5.6	5.9
F24	4	124.482	12.4482	6	6.0	5.0	6
F9	4.8	49.637	4.9637	5.3	6.0	5.8	5.7
C2	4	121.479	12.1479	6	6.0	5.0	6
F21	4	113.629	11.3629	5.9	6.0	5.0	5.9
F25	4.6	142.339	14.2339	6.1	6.0	5.6	6.1
F26	4.9	198.003	19.8003	6.3	6.0	5.9	6.3
S5	4.8	62.38	6.2380	5.5	6.0	5.8	5.8
F53	4.3	461.711	13.8513	6.4	6.0	5.3	6.4
F43	4.7	332.692	9.9808	6.2	6.0	5.7	6.2
L4	4.3	345.235	10.3571	6.2	6.0	5.3	6.2
M9	4.5	250.364	7.5109	6	6.0	5.5	6
F55	4.5	383.008	11.4902	6.3	6.0	5.5	6.3
F22	4.1	88.321	8.8321	5.7	6.0	5.1	5.7
F61	4.2	144.441	14.4441	6.1	6.0	5.2	6.1
M11	4	113.429	11.3429	5.9	6.0	5.0	5.9
F36	4.5	95.482	9.5482	5.8	6.0	5.5	5.8
LL	4.3	56.942	5.6942	5.4	6.0	5.3	5.4
F27	4	158.018	15.8018	6.2	6.0	5.0	6.2
F32	4	149.256	14.9256	6.1	6.0	5.0	6.1

ground shaking. GMPEs are the equations which relate the ground-motion parameters like Peak Ground Acceleration (PGA), Spectral Acceleration (SA) etc., with earthquake magnitude (M_W in most of the cases) and the distance (epicentral or hypocentral). GMPEs are used to estimate the seismic hazard values at rock level in a particular region for different period which play very important role in evaluating liquefaction hazard, design of structures, determining earthquake induced forces that can lead to the instability of earth structures etc. The basic component of Seismic Hazard Analysis (SHA) is a region-specific attenuation model for the estimation of ground-motion parameters at a given site for different earthquake scenario. Appropriate GMPE to calculate ground-motion in terms of PGA or spectral acceleration (SA) is a pre-requisite for any type of seismic hazard analysis for a particular region.

Detailed requirements for Ground motion prediction models: Attenuation relationships for NPP are given in IAEA SSG-9 (2010). The important requirements are given below:

- The attenuation relationships should be compatible with the reference site condition.
- Attenuation relationships should be selected to meet the following general criteria:
  - GMPE should be current and well established at the time of the study.
  - GMPE should be consistent with the types of earthquake and the attenuation characteristics of the region of interest; they should match as closely as possible with the tectonic environment of the region of interest.
  - GMPEs should make use of local ground motion data where available.
  - Caution should be exercised in comparing selected attenuation relationships with recorded ground motions from small, locally recorded earthquakes.
- Seismic intensity data may also be used to estimate attenuation relationships in those regions of the world where instruments for recording strong motion have not been in operation for a long enough period of time to provide suitable amounts of instrumental data. These data should be used at least in a qualitative manner to verify that the attenuation relationships used to calculate the seismic hazard are representative of the regional attenuation characteristics.

Even though PI (where the study area is located) was experienced more than 12 earthquakes of M_W above 6, very limited region specific GMPEs are available for SHA.

9.1. Suitability of ground-motion prediction equations

Most of the stable continental regions in the world have poor strong-motion data and are not representative of the existing seismic hazard in the region (Menon et al., 2010). For the area having poor seismic record, the alternative is to develop synthetic ground-motion models. Regional synthetic ground-motion model should include seismotectonic and geological settings (e.g., shallow crustal intraplate earthquakes) in the region. Several GMPEs have been developed worldwide considering synthetic ground motion data. However there are only few GMPEs developed for India because of the limited availability of recorded earthquake data and regional seismotectonics models. Several GMPEs developed elsewhere can be used in India if seismotectonics of both the regions match well. Use of GMPEs which have been developed for other regions is in practice in many of the Indian seismic hazard analyses.

There was no region specific ground motion predictive equation before 2004 for Peninsular India, in particular, South India. Now there are many attenuation equations to determine the PGA values for a given earthquake of known magnitude and hypocentral distance. Two regionally developed GMPEs and eight GMPEs developed for other intraplate regions are available. The GMPEs developed in Eastern North America (ENA) are applicable to the intraplate regions of our country because of the similarity in regional tectonics (Bodin et al., 2004). RaghuKanth and Iyengar (2007) have observed that their model for India has predictions similar to the available models for other intraplate regions. Schweig et al. (2003) discussed the similar features shared by ENA and PI in terms of observed seismogenic activities and known seismotetonics. Based on the results of ground-motion attenuation analysis for 2001 Bhuj earthquake, Cramer and Kumar (2003) suggested that the ground motion attenuation in ENA and PI is comparable. Table 9 gives the list of applicable GMPEs for the seismic study area with the abbreviations used in the paper for discussion. Table 10 gives the functional form and validity of ten GMPEs with coefficients for PGA (or spectral acceleration at zero period) and remarks. Fig. 12 shows a comparison of all applicable GMPEs for earthquake moment magnitude of 6 and up to a hypocentral distance of 500 km.

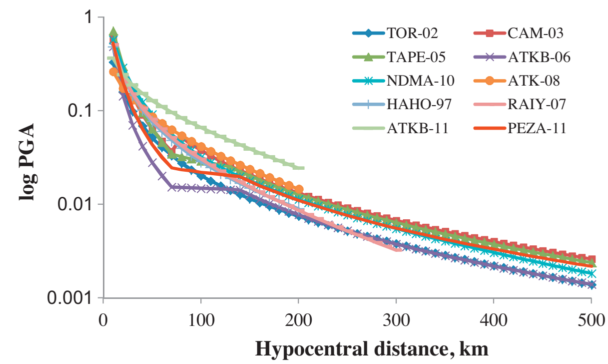

Fig. 12. Comparison of available GMPEs for the region considering earthquake magnitude of 6.0 (modified after Anbazhagan et al., 2012).

9.2. Selection of best suitable GMPEs for the seismic study area

Proper selection of GMPEs among available GMPEs is significant in predicting the level of ground shaking and it is the key element in any seismic hazard analysis (Bommer et al., 2010). The GMPEs for a region must be capable of capturing the essence of ground motions i.e. earthquake source, path and site attributes at the same time. GMPE developments over the past four decades have shown rather consistency in the associated variability and epistemic uncertainty notwithstanding the increasing complexities (Strasser et al., 2009; Douglas and Mohais, 2009; Douglas, 2010; Nath and Thingbaijam, 2011). This necessitates the selection and ranking of GMPEs (Bommer et al., 2005; Cotton et al., 2006; Sabetta et al., 2005; Scherbaum et al., 2004, 2005; Hintersberger et al., 2007; Nath and Thingbaijam, 2011) and consequent usage of multiple GMPEs in a logic tree framework for the hazard analysis. Generally, the practice is to take two-three GMPEs and estimate the PGA for the required earthquake magnitude and compare the calculated values with the observed ones. But taking 2–3 GMPEs arbitrarily and comparing with the observed values may not give the appropriate results, because of lack of systematic and comprehensive procedure. Hence, in this study an attempt has been made to select the best GMPEs to calculate the hazard values at NPP site.

Best suitable GMPEs can be selected considering the criteria suggested by Bommer et al. (2010) and by carrying out the efficacy tests proposed by Scherbaum et al. (2009) and Delevaud et al. (2009). Efficacy test refers to quantitative suitability assessment of a GMPE for a particular region. This will provide a

Table 9
Available GMPEs with their Abbreviations considered for seismic study area.

Sl. No.	Ground-Motion Prediction Equation (GMPE)	Abbreviation of the Equation
1	Hwang and Huo (1997)	HAHO-97
2	Toro (2002), extension of Toro et al. (1997)	TOR-02
3	Kenneth W. Campbell (2003)	CAM-03
4	Tavakoli and Pezeshk (2005)	TAPE-05
5	Atkinson and Boore (2006)	ATKB-06
6	Raghukanth and Iyangar(2007)	RAIY-07
7	Atkinson (2008), modification of Boore and Atkinson (2008)	ATK-08
8	The National Disaster Management Authority, Govt. Of India, New Delhi (2010)	NDMA-10
9	Atkinson and Boore (2011), modification of Boore and Atkinson (2008)	ATKB-11
10	Pezeshk et al. (2011)	PEZA-11

ranking order for a suite of GMPEs towards the appropriate selection based on observed earthquakes in the region. In the present study, the information-theoretic approach proposed by Scherbaum et al. (2009) has been used. The efficacy test makes use of average sample log-likelihood (LLH) for the ranking purpose. The method has been tested successfully by Delavaud et al. (2009) and applied to India by Nath and Thingbaijam (2011). Nath and Thingbaijam (2011) have given suites of GMPEs for Himalayas, Northeast India and Peninsular India. Authors have not included recent GMPEs such as NDMA-10, ATKB-11, PEZA-11 and considered entire PI as one region i.e. Intra-plate region. Hence for this study, efficacy test has been carried out by considering Macroseismic intensity map of 1900 Coimbatore earthquake and PGA – European Macroseismic Scale (EMS, Grünthal, 1998) relation at rock sites as is given by Nath and Thingbaijam (2011) for Indian crustal earthquakes. Further in this study, the PGA variations with distance using all the ten GMPEs are discussed. Based on the trend of variation, the hypocentral distance range 0–500 km has been divided into four segments namely 0–100 km, 100–200 km, 200–300 km and 300–500 km. In order to accurately assess the ground motion at various distances, the GMPEs valid for the seismic study area are ranked for the four distance segments. The method of selection of GMPEs based on the distance segments and the ranking is new when compared to the conventional procedures which give a cumulative ranking. This procedure has been confirmed by Delevaud (December 2011- personal communication). Ranking of GMPEs for the distance segments is attempted in order to capture the regional wave propagation character precisely.

The efficacy test makes use of average sample log-likelihood (LLH) for the ranking purpose. In order to quantify the suitability of GMPEs for Coimbatore, ranking estimator i.e., log likelihood values (LLH) values are calculated for all the GMPEs, which gives a ranking order for the set of GMPEs considered. Firstly, PGA has been estimated for the earthquake of Mw 6.0 using all GMPEs and then it is converted to EMS using the relation between PGA and EMS by Nath and Thingbaijam (2011). Fig. 13 shows the intensity derived from the GMPEs as a function of distance from the maximum reported earthquake in the region. LLH for each GMPE is calculated for four distance segments using the equation given by Delavaud et al. (2009). The LLH values, the ranking of GMPEs corresponding to LLH values and the number of times the GMPE has repeated in the first half of the ranking are given in Table 11. The best performances are attributed to the equations that are present in the first half of the ranking order i.e., first to fifth equations (Delavaud et al., 2009). The ranking order is obtained based on the available isoseismal map in the seismic study area and is used for the seismic hazard analysis. It can be noted here that GMPEs given by TOR-02, ATKB-06, PEZA-11, RAIY-07 and NDMA-10 come in the first half of the ranking more than two times for different segments. Seismic hazard values in terms of the PGA and SA are calculated for the seismic study area considering seismic sources, associated maximum possible earthquake magnitude and the five highly ranked GMPEs.

10. Deterministic seismic hazard analysis

Deterministic Seismic Hazard Analysis (DSHA) is an earliest approach and originated from nuclear power industry applications. DSHA is widely used for some significant structures. DSHA is being carried out for a particular earthquake, either assumed or realistic. The DSHA approach uses the known seismic sources sufficiently near the site and available historical seismic and geological data to generate discrete, single-valued events or models of ground motion at the site. Typically one or more earthquakes are specified by magnitude and location with respect to the site. Usually the earthquakes are assumed to occur in the portion of the site closest to the site. The site ground motions are estimated deterministically, given the magnitude, source-to-site distance, and site condition. Maximum magnitude for each source given in Table 8 and sources parameters given in Table 1 have been used for DSHA. The shortest distance from each source to NPP site has been determined using seismotectonic map presented in Fig. 6 and minimum hypocentral distance from each source to NPP site has been estimated considering focal depth of 15 km. PGA is estimated considering applicable ten GMPEs and maximum value is taken as the final PGA. Table 12 gives the PGA value from each source for ten GMPEs. Maximum PGA of 0.30 g was obtained from the GMPEs of TAPE-05 and NDMA-10 for seismic source F4. From Table 12, it can be observed that almost all GMPEs give PGA more than 0.1 g for the seismic sources F4, F1 and F6. These are the vulnerable sources for the NPP site in seismic study area. Refined seismotectonic map of Kalpakkam for a circular radius of 100 km is shown in Fig. 14. These sources are longer than 150 km,

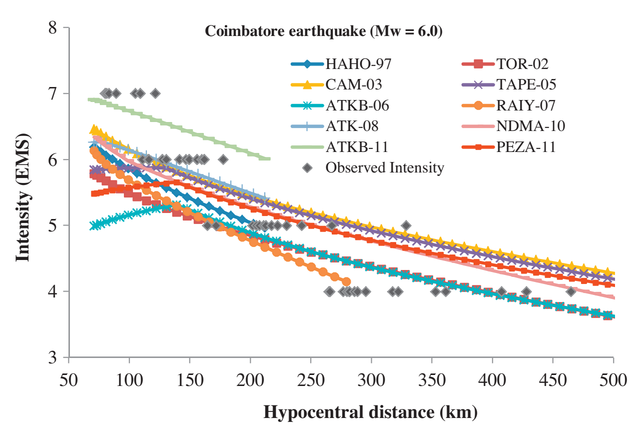

Fig. 13. Plot of intensity as a function of hypocentral distance for the maximum reported earthquake of Mw 6.0 in Coimbatore for ranking GMPEs.

Table 10
Summary of the available GMPEs for seismic study area and used for ranking.

Sl. No	Abbreviation of the GMPE	Functional form of the GMPE (peak ground acceleration in g)	Constants		Validity		Remarks
					Magnitude Range (M_W)	Distance Range (km)	
1	HAHO-97	$\ln(Y_{BR}) =$ $C_1 + C_2M + C_3 \ln[\sqrt{R^2+H^2} + R_0(M)] + C_4\sqrt{R^2+H^2} + \in$ $R_0(M) = 0.06\exp(0.7M)$ M-moment magnitude, R- Epicentral distance (km) and H- Focal Depth (km)	C_1	-2.904	5.0–7.5	5–200 (Depth 6–15)	GMPE is appropriate for seismic hazard assessment at far-field rock (3.5 km/s).
			C_2	0.926			
			C_3	-1.271			
			C_4	-0.00302			
			$\sigma_{\ln(YBR)}$	0.309			
2	TOR-02	$\ln Y = C_1 + C_2(M-6) + C_3(M-6)^2 - C_4 \ln R_M -$ $(C_5 - C_4)\max\left[\ln\left(\frac{R_M}{100}\right), 0\right] - C_6R_M + \varepsilon_e + \varepsilon_a$ Extended-source effects Approach (1) $R_M = \sqrt{R^2 + C_7^2[\exp(-1.25 + 0.227M)]^2}$ M is moment magnitude, R is the closest horizontal distance to the rupture (km) Approach (2) $R_M = R_f + 0.06\exp(m_{blg})$ For attenuation equations in terms of m_{blg} or $R_M = R_f + 0.089\exp(0.6M)$ for attenuation equations in terms of moment magnitude. In the above two equations, R_f is the shortest (slant) distance to the fault rupture.	C_1	2.20	5.0–8.0	1–500	Extended-source effect has been introduced in order to account for large magnitudes and short distances. Applicable to hard rock (defined as having average shear-wave velocities of 6000 ft/s at the surface)
			C_2	0.81			
			C_3	0.00			
			C_4	1.27			
			C_5	1.16			
			C_6	0.0021			
			C_7	9.3			
3	CAM-03	$\ln Y = c_1 + f_1(M_w) + f_2(M_W, r_{rup}) + f_3(r_{rup})$ $f_1(M_w) = c_2M_w + c_3(8.5 - M_w)^2$ $f_2(M_w, r_{rup}) = c_4 \ln R + (c_5 + c_6M_w) r_{rup}$ $R = \sqrt{r_{rup}^2 + [c_7 \exp(c_8M_w)]^2}$ $f_3(r_{rup}) = \begin{cases} 0 & for \quad r_{rup} \le r_1 \\ c_9(\ln r_{rup} - \ln r_1) & for \quad r_1 < r_{rup} \le r_2 \\ c_9(\ln r_{rup} - \ln r_1) + c_{10}(\ln r_{rup} - \ln r_2) & for \quad r_{rup} > r_2 \end{cases}$ r_{rup} is closest distance to fault rupture $r_1 = 70km$ and $r_2 = 130km$	c_1	0.0305	5.0–8.2	r_{rup} = 1–1000	PGA was assumed to represent the value of PSA at 0.01-sec period. Hard rock with a shear-wave velocity of 2800 m/sec Appropriate for estimating hazard on hard rock for $M_w \geq 5.0$ and $r_{rup} \leq 70$ km. It has been extended for larger distances using stochastic ground-motion estimates.
			c_2	0.633			
			c_3	-0.0427			
			c_4	-1.591			
			c_5	-0.00428			
			c_6	0.000483			
			c_7	0.683			
			c_8	0.416			
			c_9	1.140			

Table 10 (*Continued*)

Sl. No	Abbreviation of the GMPE	Functional form of the GMPE (peak ground acceleration in g)	Constants		Validity		Remarks
					Magnitude Range (M_W)	Distance Range (km)	
			c_{10}	-0.873			
		Aleatory standard deviation of ground motion are given by $\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12} M_W \; for \; M_W < M_1 \\ c_{13} \quad for \; M_W \geq M_1 \end{cases}$ Where $M_1 = 7.16$					
			c_{11}	1.030			
			c_{12}	-0.0860			
			c_{13}	0.414			
4	TAPE-05	$\ln(Y) = f_1(M_w) + f_2(r_{rup}) + f_3(M_w, r_{rup})$ $f_1(M_w) = C_1 + C_2(M_w) + C_3(8.5 - M_w)^{2.5}$ $f_2(r_{rup}) =$ $\begin{cases} C_9 \ln(r_{rup} + 4.5) \quad r_{rup} \leq 70km \\ C_{10} \ln\left(\frac{r_{rup}}{70}\right) + C_9 \ln(r_{rup} + 4.5) \quad 70 < r_{rup} \leq 130km \\ C_{11} \ln\left(\frac{r_{rup}}{130}\right) + C_{10} \ln\left(\frac{r_{rup}}{70}\right) + C_9 \ln(r_{rup} + 4.5) r_{rup} \geq 130km \end{cases}$ $f_3(M_w, r_{rup}) = (C_4 + C_{13} M_w) \ln R + (C_8 + C_{12} M_w) R$ $R = \sqrt{r_{rup}^2 + (C_5 \exp[C_6 M_w + C_7 (8.5 - M_w)^{2.5}])^2}$ r_{rup} is defined as the closest distance to the fault rupture (km) The aleatory standard deviation of ln *Y* is defined as a function of earthquake magnitude and is modeled as follows: $\sigma_{\ln Y} = \begin{cases} c_{14} + c_{15} M_W \quad M_W < 7.2 \\ c_{16} \quad M_W \geq 7.2 \end{cases}$	C_1	1.14	5.0–8.2	Upto 1000	GMPE and finite source relationships predict equal ground-motion amplitude at low frequencies and near-source distances, but for large ($M_w \geq 6.4$) earthquakes at distances>100 km the results estimate larges amplitudes. Boore (2000) suggested $\rho_s = 2.8\ g/cm^3$ and $\beta_s = 3.6$ km/sec for ENA were used in this study as input to the stochastic simulation models
			C_2	0.623			
			C_3	-0.0483			
			C_4	-1.81			
			C_5	-0.652			
			C_6	0.446			
			C_7	-0.0000293			
			C_8	-0.00405			
			C_9	0.00946			
			C_{10}	1.41			
			C_{11}	-0.961			
			C_{12}	0.000432			
			C_{13}	0.000133			
			C_{14}	1.21			
			C_{15}	-0.111			
			C_{16}	0.409			

Table 10 (*Continued*)

Sl. No	Abbreviation of the GMPE	Functional form of the GMPE (peak ground acceleration in g)	Constants		Validity		Remarks
					Magnitude Range (M_W)	Distance Range (km)	
5	ATKB-06	$LogPSA = c_1 + c_2 M + c_3 M^2 + (c_4 + c_5 M) f_1 + (c_6 + c_7 M) f_2 + (c_8 + c_9 M) f_0 + c_{10} R_{cd} + S$ M is moment magnitude **M** and R_{cd} is closest distance to the fault $f_0 = \max\left(\log\left(\frac{R_0}{R_{cd}}\right), 0\right)$ $f_1 = \min(\log R_{cd}, \log R_1)$ $f_2 = Max\left(\log\left(\frac{R_{cd}}{R_2}\right), 0\right)$ $R_0 = 10$, $R_1 = 70$, $R_2 = 140$and S = 0 for hard-rock sites	c_1	0.907	4.0–8.0	Upto 1000	Hard-rock sites (with shear-wave velocity ≥2 km/sec) in the northeastern United States and southeastern Canada The equation may over predict the near-source ground motion, if there are significant saturation effects that are not accounted for in the simulation model.
			c_2	0.983			
			c_3	-0.0660			
			c_4	-2.70			
			c_5	0.159			
			c_6	-2.80			
			c_7	0.212			
			c_8	-0.301			
			c_9	-0.0653			
			c_{10}	-0.000448			
6	RAIY-07	$\ln(y_{br}) = c_1 + c_2(M-6) + c_3(M-6)^2 - \ln(r) - c_4 r + \ln(\varepsilon_{br})$ $y_{br} = \frac{S_a}{g}$ *M* is Moment magnitude and *r* is hypocentral distance	c_1	1.6858	5.0–8.0	30–300	The results are valid at bedrock level with $V_S = 3.6$ km/s. For other site conditions equation is to be modified using site factors
			c_2	0.9241			
			c_3	-0.0760			
			c_4	0.0057			
7	ATK-08	$Y_{ENA} = FY_{BA08}$ $\log F = c_0 + c_1 R_{jb} + c_2 R_{jb}^2$ M is moment magnitude and R_{JB} is closest horizontal distance to the surface projection of the fault plane (Y_{BA08}) $\ln Y = F_M(M) + F_D(R_{JB}, M) + F_s(V_{S30}, R_{JB}, M) + \varepsilon\sigma_T$ $F_D(R_{JB}, M) = [c_1 + c_2(M - M_{ref})]\ln\left(R/R_{ref}\right) + c_3\left(R - R_{ref}\right)$ For $\mathbf{M} \le \mathbf{M}_h$, $F_M(M) = e_1 U + e_2 SS + e_3 NS + e_4 RS + e_5(M - M_h) + e_6(M - M_h)^2$ For $\mathbf{M} > \mathbf{M}_h$, $F_M(M) = e_1 U + e_2 SS + e_3 NS + e_4 RS + e_7(M - M_h)$ $U = 1$, $SS = 0$, $NS = 0$, $RS = 0$ for unspecified fault – type $M_{ref} = 4.5$, $R_{ref} = 1km$ $F_s = F_{LIN} + F_{NL}$ $R = \sqrt{R_{JB}^2 + h^2}$ $F_{LIN} = F_{NL} = F_s = 0$	c_0	0.287	5.0–8.0	R_{JB}<200	Uncertainty in median ENA GMPEs is a factor of 1.5–2 for M ≥5 at distances from 10 to 70 km. Uncertainty is greater than a factor of 2 for large events (M ≥7) at distances within 10 km of the source.
			c_1	0.0012			
			c_2	0.0000023			
			c_1	-0.66050			
			c_2	0.11970			
			c_3	-0.01151			
			h	2.54			
			e_1	-0.53804			

Table 10 (*Continued*)

Sl. No	Abbreviation of the GMPE	Functional form of the GMPE (peak ground acceleration in g)	Constants		Validity		Remarks
					Magnitude Range (M_W)	Distance Range (km)	
			e_2	-0.50350			
			e_3	-0.75472			
			e_4	-0.50970			
			e_5	0.28805			
			e_6	-0.10164			
			e_7	0.0000			
			M_h	6.75			
8	NDMA-10	$\ln\left(\frac{S_a}{g}\right) =$ $C_1 + C_2M + C_3M^2 + C_4r + C_5\ln(r + C_6e^{C_7M}) + C_8\log(r)f_0 + \ln(\in)$ $f_0 = \max\left(\ln\left(r/100\right), 0\right)$ Sa is the spectral acceleration, M is the moment magnitude, r is the hypocentral distance in kilometers	C_1	-5.2182	4.0–8.5	1–500	These results can be used to construct the mean and (mean + sigma) response spectrum on A-type rock in any part of India.
			C_2	1.6543			
			C_3	-0.0309			
			C_4	-0.0029			
			C_5	-1.4428			
			C_6	0.0188			
			C_7	0.9968			
			C_8	0.1237			
9	ATKB-11	$Y'_{ENA} = YF_{BA08}F_{ENA}$ $\log F_{ENA} = c(T) + d(T)R_{jb}\log F_{BA08} =$ $\max(0, 3.888 - 0.674M) - \max(0, 2.933 - 0.510M)\log(R_{jb} + 10)$	$c(T)$	0.419			The GMPEs are in good agreement with the ground-motion data for moderate-magnitude events.
			$d(T)$	0.00211			
			Y	Y_{BA08}			
10	PEZA-11	$\log\left(\bar{Y}\right) =$ $c_1 + c_2M_w + c_3M_w^2 + (c_4 + c_5M_w)\min\left\{\log(R), \log(70)\right\} +$ $(c_6 + c_7M_w)\max[\min\{\log\left(\frac{R}{70}\right), \log(\frac{140}{70})\}, o] + (c_8 +$ $c_9M_w)\max\left\{\log\left(\frac{R}{140}\right), 0\right\} + c_{10}R$ Where $R = \sqrt{R_{rup}^2 + c_{11}^2}$ $\bar{Y}$ is the median value of PGA or PSA (g), M_w is the moment magnitude and R_{rup} is the closest distance to fault rupture (km) The mean aleatory standard deviation of $\log\left(\bar{Y}\right)$ is modeled as follows: $\sigma_{\log\bar{Y}} = \begin{cases} c_{12}M_w + c_{13} & M \le 7 \\ -6.95\times10^{-3}M_w + c_{14} & M > 7 \end{cases}$	c_1	1.5828	5.0 – 8.0	R_{rup} up to 1000 km	GMPE underpredicts the observations at close distances (upto 60 km). There is a good agreement between the ground-motion predictions of this equation and the ENA database at large distances ($R_{rup} \ge 200$ km).
			c_2	0.2298			
			c_3	-0.03847			
			c_4	-3.8325			
			c_5	0.3535			
			c_6	0.3321			
			c_7	-0.09165			
			c_8	-2.5517			
			c_9	0.1831			
			c_{10}	-0.0004224			
			c_{11}	6.6521			
			c_{12}	-0.02105			
			c_{13}	0.3778			
			c_{14}	0.2791			

Table 11
Ranking of GMPEs.

Sl. No.	GMPEs	0 – 100 km		100 – 200 km		200 – 300 km		300 – 500 km		Number of times repeated in top five ranks
		LLH	Rank	LLH	Rank	LLH	Rank	LLH	Rank	
1	HAHO-97	2.5722	6	2.4038	4	NA	NA	NA	NA	1
2	TOR-02	2.4791	3	2.3342	1	2.1882	2	1.9837	2	4
3	CAM-03	2.6411	9	2.5002	8	2.3667	7	2.1972	6	0
4	TAPE-05	2.5516	4	2.4908	7	2.3523	6	2.1733	5	1
5	ATKB-06	2.3541	1	2.3494	2	2.1897	3	1.9811	1	4
6	RAIY-07	2.5668	5	2.4038	3	2.1760	1	NA	NA	3
7	ATK-08	2.6266	8	2.5135	9	NA	NA	NA	NA	0
8	NDMA-10	2.6051	7	2.4576	6	2.3116	5	2.1010	3	2
9	ATKB-11	2.7620	10	2.6580	10	NA	NA	NA	NA	0
10	PEZA-11	2.4727	2	2.4480	5	2.3100	4	2.1342	4	4

Note: NA- Not Applicable

Table 12
Peak ground acceleration from deterministic seismic hazard analysis.

Sl. No.	Source ID	Shortest surface distance (km)	M_{max}	PGA (g)									
				HAHO-97	TOR-02	CAM-03	TAPE-05	ATKB-06	RAIY-07	ATK-08	NDMA-10	ATKB-11	PEZA-11
1	B1	353.27	5.3	NA	0.0016	0.0024	0.0018	0.0010	NA	NA	0.0016	NA	0.0019
2	B2	449.22	5.7	NA	0.0014	0.0023	0.0020	0.0011	NA	NA	0.0016	NA	0.0019
3	C1	82.07	6.1	0.0410	0.0281	0.0537	0.0356	0.0168	0.0441	0.0568	0.0480	0.0888	0.0256
4	F1	26.25	6.4	0.2005	0.1299	0.1929	0.2287	0.0997	0.2148	0.1778	0.2584	0.2586	0.1331
5	F14	43.70	5.8	0.0716	0.0493	0.0610	0.0592	0.0261	0.0744	0.0767	0.0816	0.1142	0.0424
6	F17	75.22	6.5	0.0656	0.0429	0.0848	0.0560	0.0255	0.0708	0.0892	0.0847	0.1384	0.0377
7	F23	129.06	5.5	0.0121	0.0095	0.0162	0.0136	0.0079	0.0122	0.0171	0.0119	0.0225	0.0125
8	F35	195.91	6.1	0.0102	0.0083	0.0149	0.0148	0.0090	0.0098	0.0168	0.0131	0.0280	0.0125
9	F4	17.00	6.2	0.2386	0.1576	0.2510	0.2994	0.1378	0.2509	0.1838	0.2999	0.2650	0.1842
10	F42	95.92	7.0	0.0719	0.0455	0.0919	0.0800	0.0390	0.0746	0.0981	0.0995	0.1556	0.0519
11	L48	119.71	6.3	0.0280	0.0198	0.0376	0.0366	0.0200	0.0295	0.0437	0.0349	0.0708	0.0271
12	F52	302.63	6.1	NA	0.0040	0.0073	0.0071	0.0042	NA	NA	0.0061	NA	0.0061
13	F57	290.17	6.3	NA	0.0051	0.0095	0.0096	0.0058	0.0046	NA	0.0085	NA	0.0080
14	F6	35.43	6.1	0.1171	0.0779	0.1052	0.1139	0.0497	0.1235	0.1170	0.1446	0.1721	0.0740
15	F7	49.13	6.1	0.0805	0.0540	0.0664	0.0682	0.0297	0.0859	0.0920	0.0980	0.1380	0.0455
16	F75	149.46	6.6	0.0256	0.0184	0.0353	0.0385	0.0236	0.0259	0.0425	0.0359	0.0702	0.0295
17	F81	312.69	6.5	NA	0.0052	0.0102	0.0106	0.0064	NA	NA	0.0093	NA	0.0085
18	F82	185.52	6.1	0.0112	0.0090	0.0163	0.0161	0.0099	0.0110	0.0184	0.0143	0.0308	0.0137
19	L2	53.04	6.3	0.0870	0.0573	0.0701	0.0738	0.0321	0.0937	0.1030	0.1099	0.1552	0.0478
20	L3	229.55	6.2	NA	0.0070	0.0128	0.0128	0.0077	0.0076	NA	0.0114	NA	0.0106
21	L30	385.37	6.3	NA	0.0030	0.0058	0.0058	0.0035	NA	NA	0.0048	NA	0.0049
22	L32	159.85	6.0	0.0133	0.0104	0.0187	0.0181	0.0113	0.0135	0.0212	0.0160	0.0352	0.0158
23	L9	92.69	6.3	0.0411	0.0278	0.0539	0.0416	0.0206	0.0441	0.0598	0.0500	0.0946	0.0295
24	M3	484.37	5.9	NA	0.0014	0.0025	0.0022	0.0013	NA	NA	0.0017	NA	0.0021
25	M4	455.88	5.7	NA	0.0013	0.0023	0.0019	0.0011	NA	NA	0.0016	NA	0.0018
26	S1	275.04	6.5	NA	0.0066	0.0126	0.0132	0.0079	0.0063	NA	0.0119	NA	0.0106
27	S2	381.30	6.3	NA	0.0031	0.0059	0.0059	0.0035	NA	NA	0.0049	NA	0.0050
28	S3	206.32	5.9	NA	0.0065	0.0114	0.0107	0.0065	0.0073	NA	0.0094	NA	0.0095
29	M10	291.82	6.0	NA	0.0040	0.0071	0.0067	0.0040	0.0035	NA	0.0058	NA	0.0058
30	F18	77.02	5.9	0.0376	0.0262	0.0491	0.0293	0.0135	0.0401	0.0501	0.0418	0.0779	0.0215
31	F19	120.65	5.9	0.0193	0.0143	0.0260	0.0233	0.0129	0.0202	0.0290	0.0215	0.0471	0.0188
32	F24	83.18	6.0	0.0368	0.0255	0.0482	0.0316	0.0151	0.0394	0.0508	0.0419	0.0796	0.0232
33	F9	49.90	5.3	0.0559	0.0390	0.0459	0.0422	0.0186	0.0579	0.0625	0.0612	0.0937	0.0312
34	C2	45.24	6.0	0.0816	0.0551	0.0688	0.0700	0.0306	0.0863	0.0898	0.0975	0.1339	0.0475
35	F21	87.39	5.9	0.0314	0.0221	0.0412	0.0275	0.0134	0.0335	0.0436	0.0345	0.0685	0.0208
36	F25	138.65	6.1	0.0185	0.0138	0.0254	0.0253	0.0159	0.0192	0.0293	0.0224	0.0481	0.0215
37	F26	97.97	6.3	0.0379	0.0258	0.0499	0.0405	0.0205	0.0406	0.0561	0.0459	0.0892	0.0290
38	S5	215.76	5.8	NA	0.0056	0.0096	0.0088	0.0053	0.0060	NA	0.0077	NA	0.0079
39	F53	301.44	6.4	NA	0.0052	0.0099	0.0101	0.0061	NA	NA	0.0089	NA	0.0082
40	F43	214.10	6.2	NA	0.0078	0.0143	0.0143	0.0087	0.0089	NA	0.0128	NA	0.0119
41	L4	254.95	6.2	NA	0.0059	0.0108	0.0107	0.0064	0.0059	NA	0.0095	NA	0.0090
42	M9	433.36	6.0	NA	0.0019	0.0034	0.0032	0.0019	NA	NA	0.0026	NA	0.0029
43	F55	204.14	6.3	NA	0.0091	0.0169	0.0173	0.0105	0.0108	NA	0.0156	NA	0.0141
44	F22	132.05	5.7	0.0139	0.0108	0.0189	0.0170	0.0101	0.0143	0.0207	0.0147	0.0330	0.0151
45	F61	249.64	6.1	NA	0.0056	0.0101	0.0099	0.0059	0.0057	NA	0.0087	NA	0.0084
46	M11	319.43	5.9	NA	0.0031	0.0055	0.0050	0.0029	NA	NA	0.0043	NA	0.0045
47	F36	173.60	5.8	0.0096	0.0079	0.0136	0.0125	0.0077	0.0095	0.0150	0.0110	0.0249	0.0114
48	LL	96.91	5.4	0.0172	0.0129	0.0225	0.0141	0.0072	0.0176	0.0227	0.0158	0.0276	0.0122
49	F27	137.10	6.2	0.0206	0.0152	0.0282	0.0288	0.0177	0.0214	0.0329	0.0256	0.0539	0.0236
50	F32	158.64	6.1	0.0148	0.0114	0.0207	0.0206	0.0128	0.0150	0.0238	0.0183	0.0396	0.0175

Note: NA – Not Applicable and PGA about 0.1 and above are shaded in yellow color.

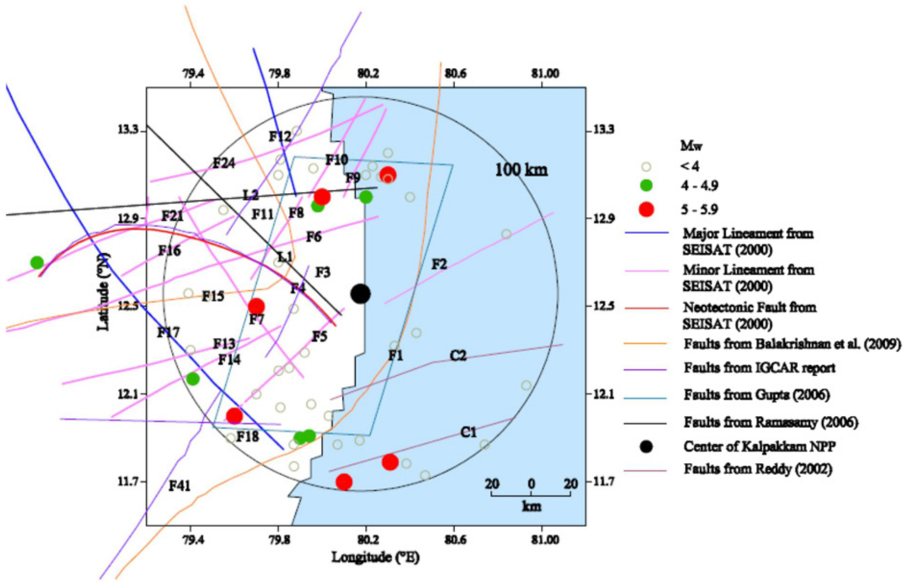

Fig. 14. Seismotectonic map of Kalpakkam NPP site for 100 km radius.

experienced earthquake magnitude of Mw above 4.5 and capable of getting ruptured for more than 10 km as per regional rupture character.

11. Site specific spectrum

Site specific spectrum (SSS) is useful to generate design spectrum of structures. In this study, SSS is derived from the five best top ranked GMPEs for the study area. Table 11 shows ranking GMPEs based on efficacy test elaborated in the previous section. Top high ranked GMPEs for seismic sources F4, F1 and F6 (within 100 km) are ATKB-06, PEZA-11, TOR-02, TAPE-05 and RAIY-07. Spectral acceleration as function (Spectral coefficients) period of these GMPEs can be found in respective research paper for 5% damping. SSS is developed for vulnerable seismic source of F4, F1 and F6 considering respective M_{max} and the shortest distance from the NPP site. It can be noted here that F4 is Neotectonic Fault from SEISAT (2000) and also called as Palar Fault in Kalpakkam seismotectonic studies. Fault F1 is identified by Balakrishnan et al. (2009) based on detailed geological studies carried out by Oil and Natural Gas Corporation Ltd. F6 is an active lineament marked in SEISAT (2000) in the Seismotectonic map of India. Fig. 15a, 15b and 15c show the SSS at rock site condition for three vulnerable sources F1, F4 and F6 respectively, considering five highly ranked GMPEs. These response spectra are used to develop smoothed response spectra for design purpose as per IBC (2009) procedures. Maximum and minimum smoothed spectrums are estimated for each source considering five response spectrums as given in Fig. 15. Averaged smoothed spectrum from maximum and minimum smoothed spectra has been developed. Smoothed spectrum compensates peak, valleys and shape variation in response spectrum from each GMPE. These smoothed spectral is normalized with respect to spectral acceleration at zero period (PGA) and given for spectral acceleration versus frequency. Fig. 16 shows the smoothed average spectrum for three vulnerable sources considering five GMPEs. This can be considered as site specific normalized design spectrum for 5% damping at the rock level for the proposed NPP site. It can be noted from Fig. 16 that the peak spectral acceleration noticed for the frequency range of 3.75 to 16.67 Hz and period of 0.05 to 0.285 seconds. These values are comparable with Roshan and Basu (2010) studies and normalized spectrum given by Chopra and Choudhury (2011) considering the recorded data of magnitude of 3.5 to 5.7 in the Bhuj region, India.

12. Results and discussion

In this study, an attempt has been made to estimate Safe Shutdown Earthquake (S2/SL2) and Operating Basis Earthquake (S1/SL1) considering region specific parameters such as seismic study area based on past earthquake damage distribution, maximum magnitude considering region's rupture character, regional focal depth and best suitable ground motion prediction equations. The new seismotectonic map has been prepared for study area, which can be useful for the future seismic studies. Seismic hazard values estimated for the NPP site at the bedrock condition where shear wave velocity is 2000 m/s and above. The result of DSHA typically gives peak ground acceleration in horizontal directions. In the absence of GMPEs for vertical component, it may be reasonable to assume a prescribed ratio between vertical and horizontal ground motion. Empirical evidence has shown that the vertical to horizontal ratio varies typically from half to over one, and is larger for large magnitudes that occur at close distances. In this study vertical ground motion is assumed to be 2/3 times of horizontal ground motion in the absence of vertical GMPEs. Based on this study Safe Shutdown Earthquake (S2/SL2) is associated with the most stringent safety requirements and corresponds directly to ultimate safety requirements. Controlling magnitude of 6.2 (M_W) with a distance of 17 km arrived as SSE for the proposed NPP site. Maximum expected peak horizontal acceleration at bedrock level is 0.30 g and peak vertical acceleration at bedrock level is 0.20 g. Operating Basis Earthquake (S1/SL1) should be half of SSE values, peak horizontal acceleration at bedrock level is taken as 0.15 g and peak vertical acceleration at bedrock level is 0.1 g. This value is different from values arrived from a conventional study which does not account the region specific parameters. These values can be used for the worst scenario design of NPP facility and select ground motions to arrive time history analysis and response parameters at the ground.

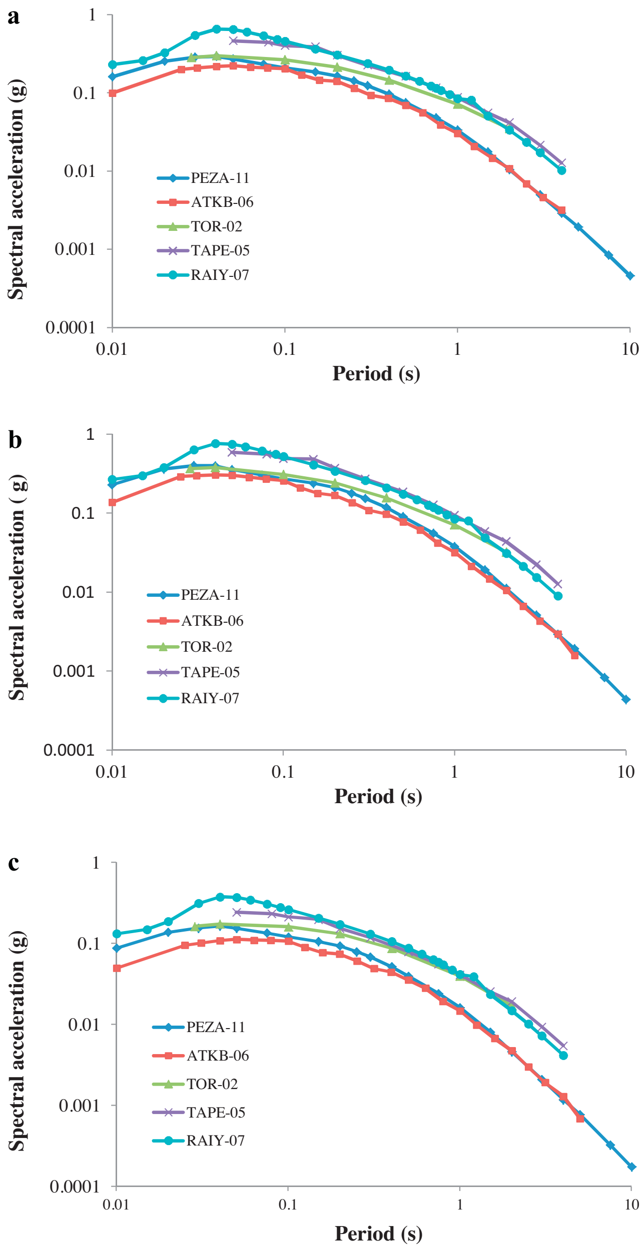

Fig. 15. Response spectrum from source F1 (a), F4 (b) and F6 considering five GMPEs.

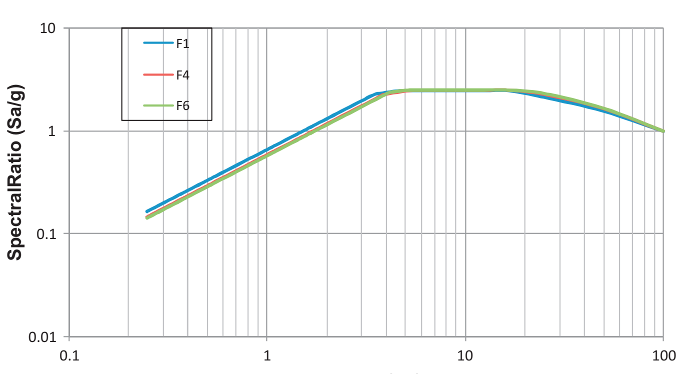

Fig. 16. Normalized smoothed spectrum from three vulnerable sources.

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