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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