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COMPARISON OF SEISMIC QUALIFICATION CHALLENGES FOR NUCLEAR POWER PLANTS IN NORTH AMERICA AND PENINSULAR INDIA

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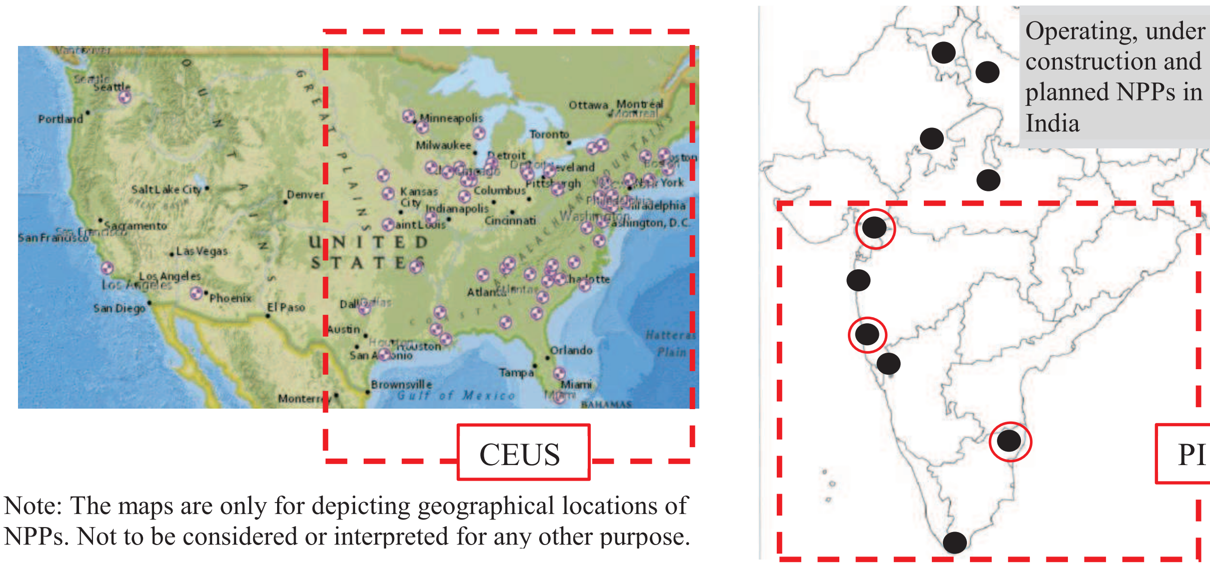
ABSTRACT

The seismic design basis for the Nuclear Power Plants (NPPs) in the United States is prescribed in United States Nuclear Regulatory Commission (USNRC) Regulatory Guide 1.60. The generic seismic design basis response spectrum for the NPPs in Canada is given in the Canadian nuclear standard CSA N289.3. Both these spectra are based on the strong motion earthquake records from the west coast of the North American continent. The Uniform Hazard Response Spectrum (UHRS), required for the Seismic Probabilistic Risk Assessment (SPRA) of a typical relatively older east coast plant (built more than three decades ago) is based on the east coast records and is quite different from its design basis. The differences between the east and the west coast spectra and the methodology of obtaining the structural response for the former on the basis of the latter have been reported in the literature. On the other side of the world, India is emerging as a major player in nuclear power generation. Although the Indian sub-continent and North America are situated on diametrically opposite sides of the globe, there are some striking similarities between the challenges related to the seismic qualification of NPPs situated in the Eastern North America (ENA) and Peninsular India (PI). The lessons learned in ENA can be effectively utilized in order to establish the seismic design and evaluation criteria of NPPs in PI. This paper compares the similarities and differences between the challenges on seismic qualification of structures, systems and components in NPPs situated on two diametrically opposite geographic locations.

INTRODUCTION

NPPs in North America can be broadly classified into two categories in accordance with their geographical location. Figure 1 shows most of the NPPs in the US on the eastern side of the Rockies referred to as the Central and Eastern US (CEUS) plants and few of them on the west side known as the Western US (WUS) plants. Canadian NPPs, all being on the east coast are simply categorized as the east coast or ENA plants. The seismic design basis of the most of the NPPs in US (McGuire et al., 2001) and some of the ones in Canada (Dar and Hanna, 2012) is based on the NBK spectrum, named after its creators Newmark, Blume and Kapur (1973) and prescribed by the USNRC (1973, 2014) Regulatory Guide 1.60. The Design Basis Earthquake (DBE) of some of the Canadian NPPs was derived from the generic response spectrum given in the Canadian Standards Association (CSA) nuclear standard CSA N289.3 (1981, 2010) based on NUREG/CR-0098 (Newmark and Hall, 1978). Both of these (NBK and CSA spectra) are derived from the west coast earthquake records. After the 1988 Saguenay earthquake in Canada (Boore and Atkinson, 1992), it was noticed that the frequency content of the east coast earthquake records was significantly different from the west coast records. An alternative design spectrum for the east coast to the generic design basis given in CSA (1981, 2010) has been proposed by Atkinson & Elgohary (2007), defined as the ENA spectrum The SPRA of a typical east coast NPP with the DBE based on the NBK or the CSA spectrum becomes challenging because the seismic input to the SPRA is typically a UHRS similar to the ENA spectrum. Some of the older plants with very limited seismic qualification in Canada were considered as NPPs without any DBE and were assessed later for the applicable Review Level Earthquake (RLE) in accordance with the Seismic Margin Assessment (SMA) methodology outlined in the Electric Power Research Institute (EPRI) report NP-6041 (EPRI, 1991). The difference in the response spectra of the DBE and the RLE is one among several seismic qualification challenges to the NPPs in Canada (Dar et al., 2014).



Note: The maps are only for depicting geographical locations of NPPs. Not to be considered or interpreted for any other purpose.

Figure 1: Schematics of NPPs in US and India, with majority in the CEUS and PI respectively. Red circles in PI show the sites considered in this paper; clockwise from right Kalpakkam, Jaitapur and Kakrapar. (Source for US map: U.S. Energy Information Administration (http://www.eia.gov))

On the other side of the globe, India's nuclear power generation capacity is planned to increase from 4340 MW (in 2010) to 20GW by 2020 aiming for 63 GW by 2032 (Vishnoi & Narayan, 2010). Starting from the Tarapore NPP in 1969, slowly advancing through the commissioning of several NPPs over the subsequent decades and finally arriving at the newly constructed Kudankulam plant in 2011 coupled with various other proposed projects, India's nuclear power generation program appears to be ambitious. In India, the NBK spectrum (Newmark et al., 1973) was revisited by Ghosh et al. (1986) for rock sites, and, by Ghosh and Sharma (1987), and Ghosh (1988) for soil sites based on the WUS earthquake records. These authors reported deviations in spectral accelerations from the NBK spectrum for rock and soil sites. These studies were later revisited, and amalgamated with modifications in the smooth spectral shapes in the Bhabha Atomic Research Centre (BARC) report BARC/1998/E/016 by Ghosh et al. (1998). For want of sufficient number of earthquake records on site, the Atomic Energy Regulatory Board (AERB) safety guide SG/D-23 (2009) recommends the use of smooth spectra given in the AERB guide SG-S11 (1990) which are based on the WUS records. Thus the design bases recommended by BARC, AERB, USNRC and CSA, are all based on the same source of earthquakes records; the WUS. Indian standard IS-1893 (2002) recommends seismic design spectra for various locations in India. As shown in Figure 1, most of the Indian NPPs are located in PI. According to Raghu Kanth and Iyengar (2007), the spectral shape recommended by IS-1893 (2002) is conservative over low frequencies but unconservative over high frequencies with respect to the PI spectrum. This is similar to the difference between the ENA (Atkinson and Elgohary, 2007) and the CSA spectra. Several other similarities and differences with regard to the seismic qualification challenges of NPPs in the ENA and PI are discussed in this paper.

COMPARISON OF DESIGN CRITERIA OF EXISTING PLANTS IN US, CANADA AND INDIA

Although the design of an existing NPP may be based on a site specific response spectrum or any other spectrum, the design basis spectra given by the regulator or available in the literature are considered here for the purpose of comparison. In Canada the DBE is considered equivalent to the Safe Shut down

Earthquake (SSE) in the US. From here onwards, the term DBE is used to represent the seismic hazard relevant to safe shut-down systems. The Site Design Earthquake (scaled to 1/2 of the DBE) in Canada and the Operating Basis Earthquake (OBE in US and India) are not discussed for brevity. Four horizontal response spectra are compared with one another; 1. NBK (USNRC), 2. CSA, 3. BARC (1998), and 4. AERB (1990). The vertical spectra are discussed later. Figure 2 (a) and (b) show the NBK and the CSA spectra respectively at 5% damping consisting of straight line segments on the tripartite log scale. The NBK spectrum's control frequencies are 0.1Hz, 0.25Hz, 2.5Hz, 9Hz and 33Hz. The CSA spectrum's control frequencies are 0.02Hz, 0.08Hz, 7Hz and 33Hz with two damping dependent frequencies between 0.08Hz and 7Hz.

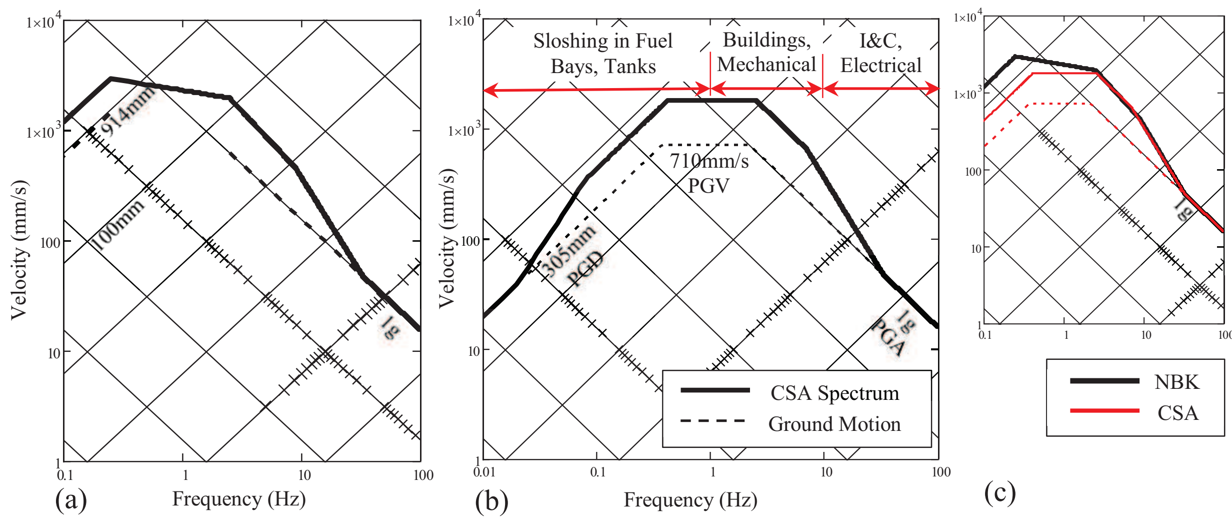


Figure 2: 5% damped spectra normalized to 1g (a) NBK (USNRC), (b) CSA and (c) Comparison

On the tripartite log chart, the ground motion is depicted in terms of three parameters; Peak Ground Displacement (PGD), Peak Ground Velocity (PGV) and Peak Ground Acceleration (PGA). The NBK spectrum only mentions the PGA (=1g) on the right and ground displacement (=914 mm) at this PGA on the left, which is not the PGD. The CSA spectrum on the other hand does provide the three parameters of ground motion and their amplification in three distinct zones dominated by; displacement, velocity and acceleration. The NBK's lowest frequency limit is 0.1 Hz, whereas the CSA reaches down to 0.01 Hz. The response spectrum drawn on a tripartite log scale with the ground motion parameters; PGD, PGV and PGA, provides a panoramic view of risk distribution in a NPP to an experienced seismic risk analyst. Figure 2 (b) shows broad categorization of safety systems in accordance with the frequency range in a response spectrum. Below 1 Hz, liquid storage structures are prone to sloshing and above 10 Hz, Instrumentation and Control (I&C) and some electrical components are likely to respond to the seismic demand. The buildings with mechanical components generally respond between 1 and 10 Hz, to the frequency range of interest given in the EPRI report 1025287 (2012). In Figure 2 (c), the two spectra are very close to each other for frequencies above 7Hz. Below 7Hz, the gap between the spectral displacements of the two spectra grows larger in comparison with the gap in the spectral accelerations. However, looking at the frequency content of both these spectra, they are considered similar for the purpose of this paper and only the NBK spectrum is discussed here onwards.

Figure 3 (a) shows 5% damped BARC (1998) and AERB (1990) smooth spectra for rock and soil sites. Figure 3 (b) shows the same spectra plotted with the NBK spectrum. As evident from Figure 3 (b), the BARC rock spectrum is in agreement with the NBK spectrum over high frequencies beyond 9 Hz. The peaks of BARC soil and rock spectra are close to the two peaks of NBK spectra at its control frequencies, 2.5 Hz and 9 Hz respectively. This implies that the NBK spectrum, beyond 2.5Hz, is an envelope spectrum for rock and soil sites. The ascending branches of the BARC rock and soil spectra for frequencies below 2.5Hz are above the NBK spectrum. The amplification factors in this zone (below 2.5 Hz) are generally governed by displacement rather than acceleration. In Figure 3 (c), the AERB spectra do not exhibit the asymptotic behaviour in the displacement zone (at frequencies less than 2.5 Hz) which is unusual (Malhotra, 2006), especially for a standard spectra in a design guide. The same is expected for the BARC spectra. One of the possible reasons of this phenomenon observed by Malhotra (2015) is that the "ground motion prediction equation is unable to capture the physics of a single degree of freedom system responding to ground motion". Using these spectra for design and/or evaluation purposes, especially for sloshing analysis of fuel bays, requires caution due to the high displacements at low frequencies, applicable to the sloshing mode of a liquid storage structure (Malhotra et al., 2000). USNRC has reintroduced the NBK spectrum (exactly as in the previous version) in Revision 2 of its Regulatory Guide 1.60 (2014) without any comments on unusual displacement at low frequencies. Other publications from USNRC such as NUREG/CR-0098 (Newmark and Hall, 1978) and publications from the Earthquake Engineering Research Institute (Newmark and Hall, 1982) have not commented on any excessive displacements at low frequencies as witnessed in the BARC and AERB spectra, despite the fact that all these studies are based on more or less the same set of records. It can also be concluded that all the spectra in Figure 2 and Figure 3 are devoid of high frequency content since all of them have peaks below 10Hz.

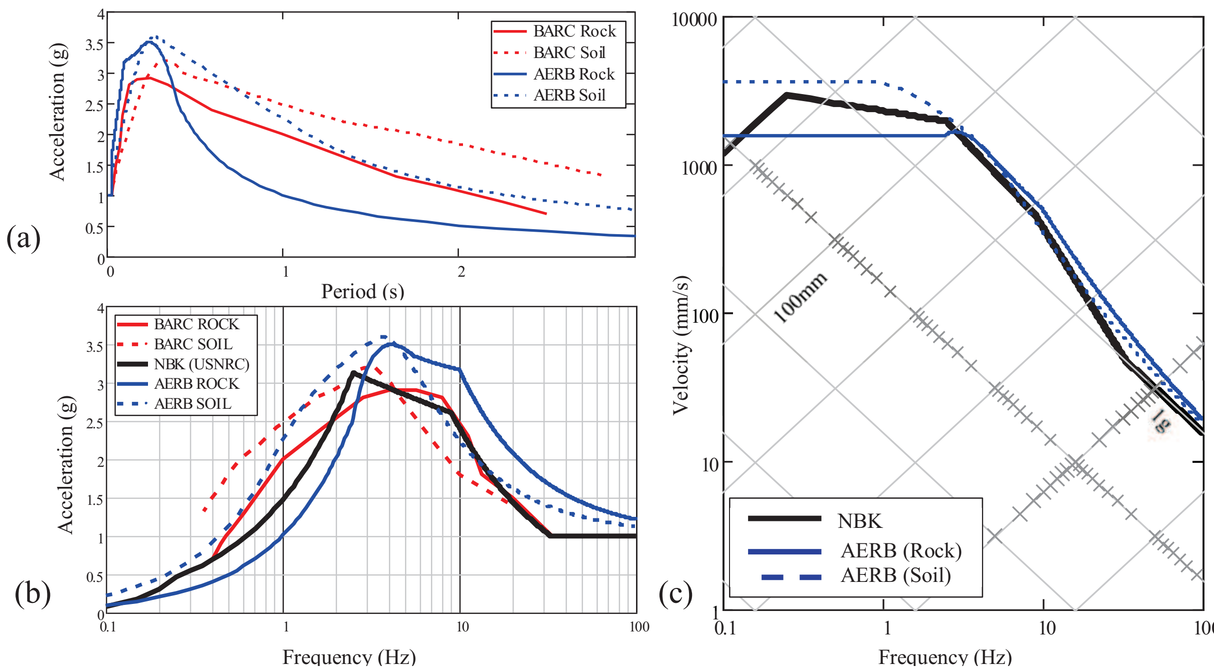


Figure 3: Comparison of 5% damped spectra, anchored to 1g, of (a) BARC (1998) and AERB (1990), (b) BARC (1998), AERB (1990) and NBK (USNRC, 1973, 2014) and (c) AERB with NBK on tripartite log scale. (The BARC curves shown in this paper are approximations, derived from the BARC (1998) report and replotted.)

CHALLENGES IN SMA / SPRA OF EXISTING NPPs AND FUKUSHIMA REQUIREMENTS

The main difference between the SMA and SPRA from the seismic hazard view point is that the SMA begins with a seismic demand (RLE) and meets it generally through some modifications to an existing plant, whereas the SPRA quantifies the existing seismic capacity, in terms of fragilities with no modifications to the plant. The DBE of an existing NPP whether in ENA or PI is likely to be without the high frequency content. The evaluation hazard of such NPPs, in form of a UHRS, required in a SMA or SPRA, is almost certain to be similar to the ENA spectrum (Atkinson and Elgohary, 2007), or, to the PI spectrum (Raghu Kanth and Iyengar, 2007). Such similarities and differences in the process of seismic qualification of NPPs in these two regions along with various challenges with regard to design, SMA, SPRA and Fukushima requirements are discussed below.

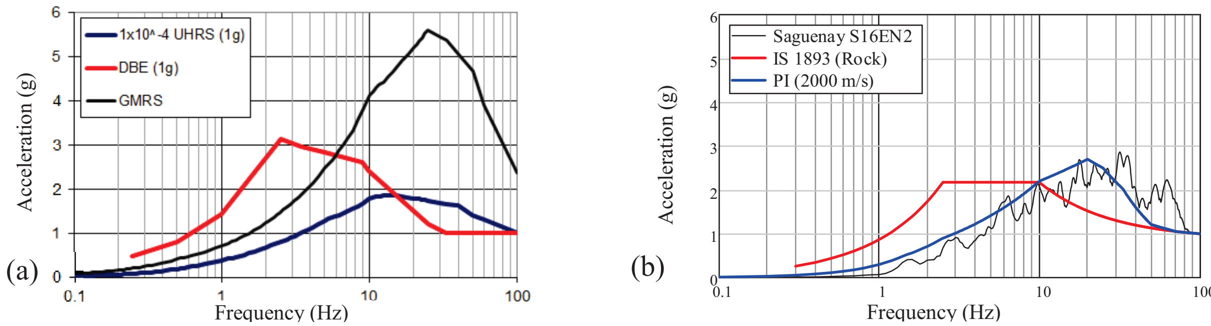


Figure 4: 5% damped response spectra normalized to 1g (a) DBE and UHRS at Bruce site (Canada), with the corresponding GMRS (Dar et al., 2014) (b) UHRS and IS-1893 in PI (Raghu Kanth and Iyengar, 2007) with Saguenay (1988) S16EN2 record (http://www.earthquakescanada.nrcan.gc.ca.)

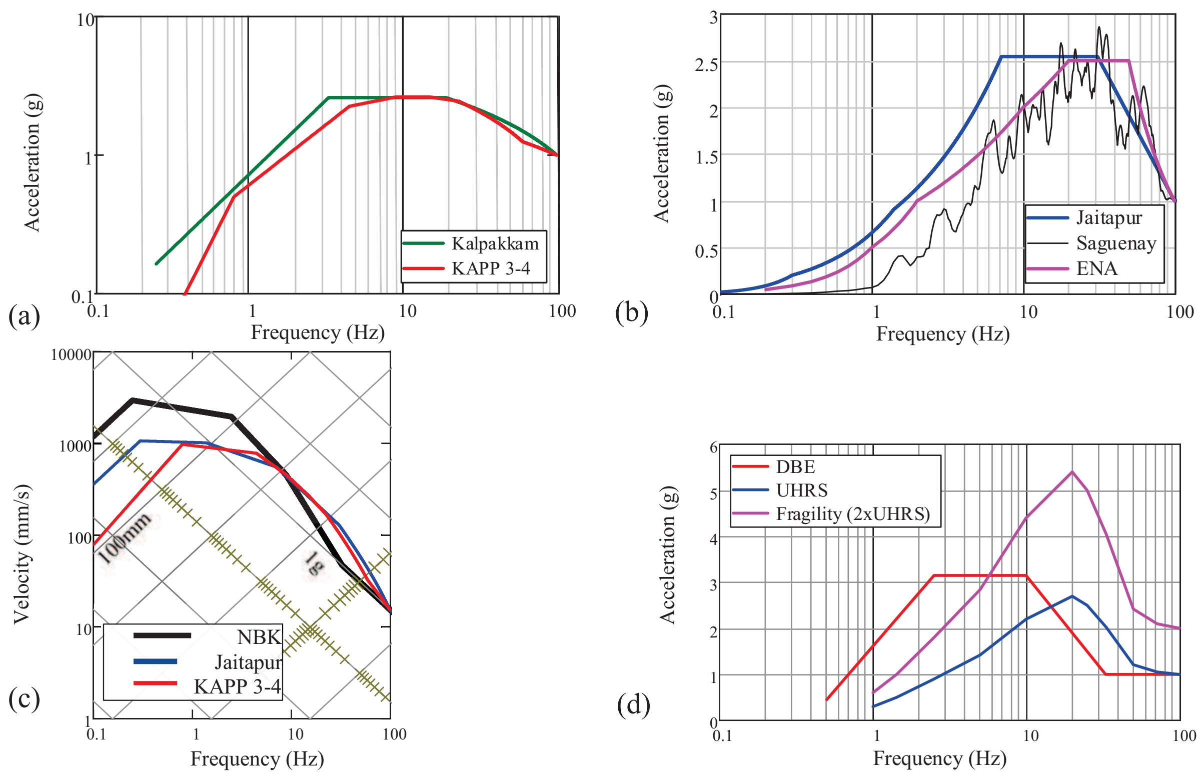


Figure 5: 5% damped horizontal response spectra normalized to 1g (a) Kalpakkam (Anbazhagan et al., 2013) and KAPP 3-4, (Chhatre, 2014), (b) Jaitapur (Rastogi and Chhatre, 2014), Saguenay(1988), Canada S16EN2 record and ENA (c) Comparison (tripartite scale), (d) Example UHRS and corresponding fragility

Similarities in Seismic Design and Evaluation Criteria of ENA and PI

Figure 4 (a) shows the difference between the UHRS (1x10^{-4} probability) and the deterministic DBE spectra at Bruce site in Canada (Dar et al., 2014) which intersect at around 12 Hz. Figure 4 (b) compares the PI (Raghu Kanth and Iyengar, 2007) and IS-1983 spectra which intersect at around 10 Hz. The maximum shear wave velocity considered by Raghu Kant and Iyengar (2007) is 2000 m/s which is within the range of shear wave velocities considered at Bruce Site (Kinectrics, 2014). The DBE at Bruce site and IS-1893 spectrum both lack high frequency content whereas the UHRS at Bruce and in PI are rich over high frequencies. Figure 4 (b) also shows the similarities between the PI and the Saguenay (1988) response spectra.

Design response Spectra in PI Compared with ENA and NBK Spectra

The Design Basis Ground Motion (DBGM) with high frequency content (Chhatre, 2014) has been used for the design of the 700MWe Pressurized Heavy Water Reactors. Twin units of such design are under construction at Kakrapar in PI. The site specific DGBM has been derived from few earthquake records available on stable continental region (generic term for ENA or PI) and a good number of synthetic time histories generated for the site specific parameters. Normalized response spectra of three NPPs in PI are shown in Figure 5; Kalpakkam, Jaitapur and Kakrapar Atomic Power Project Units 3 and 4 (KAPP 3-4). Figure 5 (a), demonstrates the similarity between the site specific smoothed spectrum for Kalpakkam (Anbazhagan et al., 2013) with the mean plus sigma spectrum at Kakrapar (KAPP 3-4) (Chhatre, 2014). Figure 5 (b) shows similarities among the mean plus sigma Jaitapur (Rastogi and Chhatre, 2014), Saguenay (1988) Site 16EN2 and the ENA (Atkinson and Elgohary, 2007) spectra. Figure 5 (c) shows comparison of NBK with KAPP 3-4 and Jaitapur spectra. The Jaitapur and KAPPA 3-4 demonstrate the asymptotic behaviour at low frequencies in Figure 5 (c). All these figures demonstrate that the design spectra in PI recommended by various authors are similar to the ENA spectrum but different from the NBK spectrum.

Fragility Lower Than the Design Basis?

Fragilities are expressed as multiples of the UHRS but never compared with the DBE. Figure 5 (d) shows an example where the fragility (=2x UHRS) curve falls short of the DBE at frequencies less than 6Hz. This is not desirable for a building with the fundamental frequency of, say, 3Hz, because of the capacity being much shorter than the DBE. In a probabilistic analysis, the DBE is not applicable but in a deterministic sense, the capacity curve being lower than the DBE may be questionable due to perceived operability risk.

Fukushima Requirements

The 2011 Tohoku, Japan earthquake and tsunami encouraged Beyond Design Basis (BDB) assessments of NPPs across the world (Dar et al., 2014). According to EPRI report 1025287 (2012), if the SSE of a NPP is above the Ground Motion Response Spectrum (GMRS, derived as a combination of UHRS with $1x10^{-4}$ and $1x10^{-5}$ probabilities) within the 1-10 Hz frequency range, then the BDB assessment of any SSCs is not required except for some components susceptible to high frequency excitation such as relays. Due to the similarities between the ENA and PI spectra, NPPs in PI are likely to be affected by this requirement.

Capacity Spectrum and 'Critical' Earthquake

In the post Fukushima environment, the expectation of engineers (trained to perceive numbers) and of the public at large, is to define a BDB event as a multiple of the DBE of a NPP. The SMA qualifies a NPP for a RLE and hence the BDB capacity can be expressed as a ratio of the PGAs of the RLE and the DBE. However, the SPRA does not provide the overall plant level capacity or the High Confidence Low Probability of Failure spectrum (called HCLPF here) because its purpose is to arrive at the Severe Core Damage Frequency (SCDF) of a NPP and not at its HCLPF which would be the representative of a limiting or *critical* earthquake. In case of a newly designed NPP, the seismic risk can be evaluated at the design stage leading to the *critical* earthquake corresponding to an acceptable SCDF. According to CNSC regulatory document REGDOC 2.5.2 (CNSC, 2014), for new NPPs, the minimum acceptable HCLPF is 1.67 times the DBE. For an existing plant the HCLPF margin over the DBE is recommended as 1.5 in CSA N289.1 (2008). While for a new plant this may sound reasonable, applying this criteria to an existing plant in the ENA becomes challenging because of the UHRS and the DBE spectrum shapes being different despite having the same PGA as shown in Figure 5 (d), where the fragility spectrum is below the DBE. The numbers such as 1.67 or 1.5 do not relate to SCDF and appear to have been derived from the ratio of ultimate and service stress limits given in the design codes. According to Ghobarah et al. (1992), the “philosophy of design is completely different from the concept of margin or withstand capacity” and “the design process is neither capable of nor expected to determine how much overcapacity exists”.

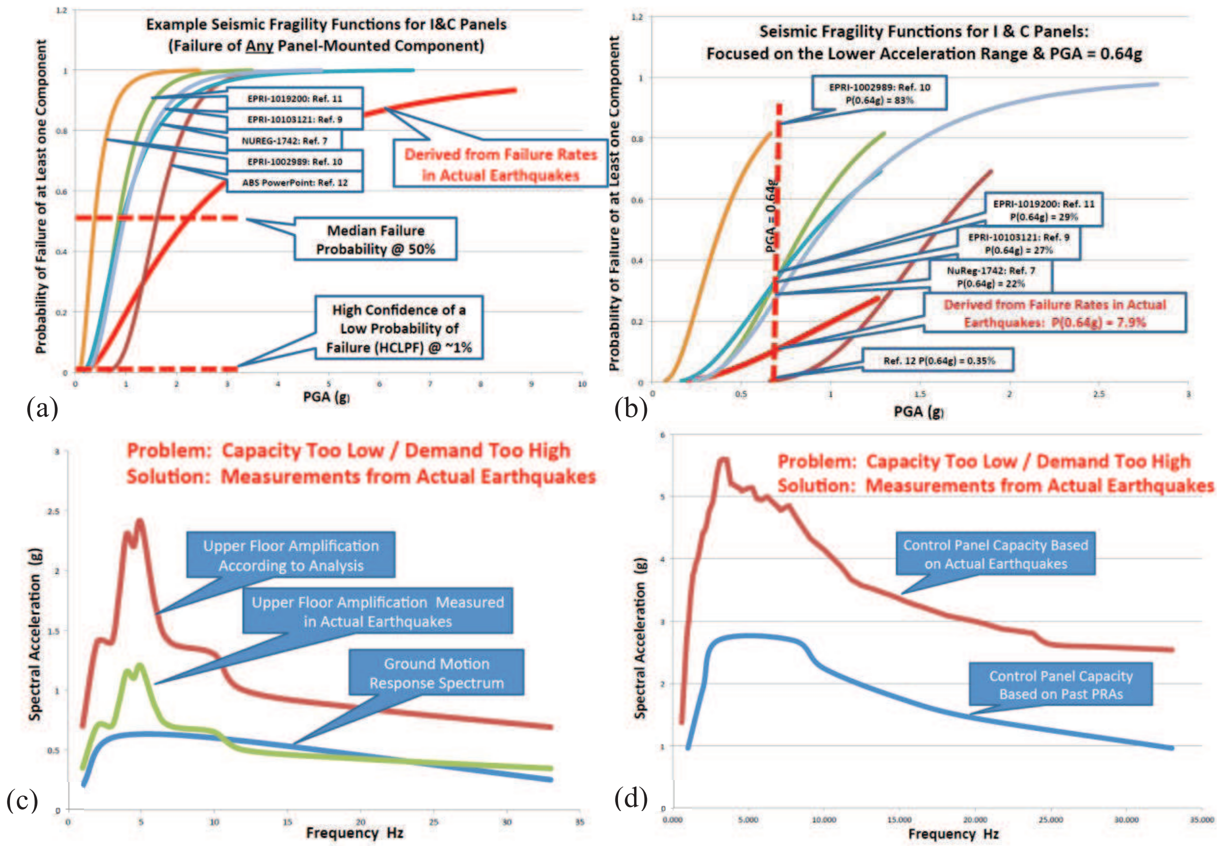


Figure 6: (a) Comparison of fragility curves, (b) Fragility functions of I&C panels, (c) Theoretical vs experienced amplification and (d) Probabilistic vs experienced capacities. (Reproduced from the presentation by Yanev et al. (2013) at COG external hazard workshop, Mississauga).

CHALLENGES ON EXPERIENCE DATA AND AMPLIFICATION

Seismic qualification based on experience data is acceptable in the US (EPRI, 1991) and Canada (CSA N289.1, 2008). Experience data for the four earthquakes in India, Koyna (1967, 1994), Bhuj (2001) and Muzaffarabad (2005), presented by Chhatre (2011) contains valuable information on many systems and components, applicable to the nuclear industry. An earthquake is a realistic test of Structures, Systems and Components (SSCs) in a NPP. Experience data produces concrete evidence of survival of those systems and components that may not pass an analysis. Figure 6 (a) shows that the fragility curve derived through experience data is much less conservative than the curves using various methods in practice (Yanev et al., 2013). Figure 6 (b) shows the seismic fragility of an I&C panel to be 7.9% at 0.64g PGA whereas the highest fragility obtained by the other methods is at 83%. Figure 6 (c) shows the difference between the amplification by analysis and experience, whereas Figure 6 (d) shows the difference between the capacities for the same. Academic interest in recording and studying the amplification of ground motion in existing structures during real earthquakes is practically invisible.

OTHER CHALLENGES

Damping

In various regulatory documents and nuclear standards 5% damped response spectra is generally recommended for buildings in NPPs. Considering the design of a typical containment concrete structure, or a turbine hall with a multitude of mechanical and electrical components, the 5% damping meant for residential buildings does not appear to be reasonable. The building codes do not differentiate damping of industrial buildings from residential. Research is required in this direction.

Vertical Response Spectrum and Amplification

Vertical response spectrum is generally considered as 2/3rd of the horizontal (CSA N289.3, 2010; AERB, 1990) that is not applicable to the ENA (USNRC Reg. Guide 1.208, 2007). Owing to the resonance of shear walls and columns to the high frequency vertical excitation, test response spectra of I&C components installed at such locations are likely to be affected. In a recent SPRA study (Kinectrics, 2014), I&C and some electrical components are reported to have the lowest fragilities construing that the seismic risk is concentrated in such components. However, the experience data (Chhatre, 2011: Yanev et al., 2013) can be effectively utilized as an evidence of survival of similar components in actual earthquakes. The buildings in general, being more rigid in vertical direction than the horizontal, are likely to resonate to high frequency excitation. The amplification of vertical excitation is required to be studied in greater detail in the ENA and PI.

CONCLUSIONS

It is concluded that the challenges faced in the seismic qualification process of NPPs in the ENA are similar to those in the PI. The shapes and frequency contents of DBE spectra recommended by the AERB, BARC, CSA and USNRC as well as their differences with the high frequency ENA and PI spectra are similar. The high displacement demand of the AERB and BARC spectra over low frequencies may be challenging for sloshing analyses of fuel bays for NPPs in PI with DBEs similar to these spectra. Further investigation of BARC and AERB spectral amplification factors for frequencies below 2.5Hz is warranted. Inclusion of a plant level HCLPF capacity spectrum corresponding to a *critical* earthquake in the regulatory guides is required. Such spectrum should relate to an acceptable SCDF rather than the DBE multiplied by arbitrary numbers such as 1.67 or 1.5. Comparison of fragility spectra of SSCs in a NPP with the applicable DBE is required in order to evaluate their operability risk. Lessons learned in the SPRA, SMA and Fukushima analysis of the NPPs in the ENA are likely to be applicable to the NPPs in PI and vice versa. The use of experience data and its exchange between the NPPs in the ENA and PI should to be encouraged. Design guides should capture the fact that the vertical response spectrum being 2/3rd of the horizontal is not applicable to the ENA or PI. Significant difference has been noted between the experienced and the theoretical amplification of ground motion during actual earthquakes in existing structures. Academic activity with regard to the amplification experience data of existing structures is required to be promoted.

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NOMENCLATURE

AERB Atomic Energy Regulatory Board (India)

BARC Bhabha Atomic Research Centre

CSA	Canadian Standards Association	CEUS	Central Eastern Unites States
DBE	Design Basis Earthquake	ENA	Eastern North America
GMRS	Ground Motion Response Spectrum	I&C	Instrumentation and Control
HCLPF	High Confidence Low Probability of Failure	NBK	Newmark, Blume and Kapur
NPP	Nuclear Power Plant	OBE	Operating Basis Earthquake
PGA	Peak Ground Acceleration	PGD	Peak Ground Displacement
PGV	Peak Ground Velocity	PI	Peninsular India
SCDF	Severe Core Damage Frequency	SDE	Site Design Earthquake
SMA	Seismic Margin Assessment	SSE	Safe Shut-down Earthquake
SPRA	Seismic Probabilistic Risk Assessment	SSCs	Structures, Systems and Components
UHRS	Uniform Hazard Response Spectrum	WUS	Western United States
USNRC	United States Nuclear Regulatory Commission		

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