Resilience of Nuclear Power Plants to Withstand Large Earthquakes: An Overview

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Abstract

This paper provides an overview of the experience gained from seismic assessments, component testing, insights from probabilistic seismic hazard analysis (PSHA), seismic PRAs and performance of structures, systems and components (SSCs) in actual earthquakes many of which have been very large and exceeded the plant design basis. The recent Fukushima earthquake has focused attention of the nuclear industry to assess and make provisions to cope with the beyond design basis events that lead to station blackout, flooding and loss of heat sinks. Based on the review of available information, the paper discusses assessments and strategies being followed by various countries. Recommendations are made to focus attention to the most vulnerable SSCs in a nuclear power plant.

1. Introduction

The recent seismic events such as the Japanese March 2011 earthquake and tsunami [1] and the North Anna earthquake [4] in the eastern United States, where the design basis earthquake was exceeded, have heightened the public concern regarding the safety of the nuclear power plants worldwide. This has led the nuclear regulators and the industry to re-assess the safety of the existing and the new plants. The Japanese March 2011 seismic induced tsunami event inundated the safety systems and posed grave challenge to achieve cold shutdown in the Fukushima Daiichi units 1-4[3]. It is not fully confirmed but strongly believed that the plant safety systems survived the magnitude 9.0 earthquake. A nearby plant at Onagawa, that is much closer to the epicentre, saw even higher seismic motion and survived mostly undamaged [2]. The North Anna earthquake, the largest seen to date in the eastern United state exceeded the plant design basis. Extensive review and inspections showed that the plant did not suffer any damage. The performance of nuclear SSCs and even SSCs of similar industrial plants in more than 100 actual earthquakes has demonstrated potential margins to withstand large earthquake demands.

Valuable experience has been gained over the last three decades concerning the effects of earthquakes on nuclear power plant SSCs [5]. Major lessons, learned from the experience gained through nuclear power plants being subjected to actual earthquakes, are:

- There is significant unquantified conservatism in the seismic analysis and design methods and procedures implemented by the nuclear industry,
- Piping and distribution systems with proper anchors and protected from interactions with nearby un-anchored or unqualified components perform very well and have not failed due to seismic inertia loading, and

- Efforts currently underway to quantify and understand such conservatisms will allow these systems to be evaluated in the future by simplifying the design process and by evaluating the design margins for the Beyond Design Basis Earthquake (BDBE).

2. Seismic Hazard

One of the most important steps in seismic design and evaluation of SSCs of nuclear power plants is the evaluation of the seismic hazard at the site (Figure1). The design engineers are obliged to be aware of how seismic hazard is quantified and to understand how it is developed by the geologists, seismologists and geotechnical engineers. Seismic hazards at the site of nuclear power plants include: (a) ground shaking, (b) excessive ground deformations or failure (due to fault rupture, liquefaction, and landslides), and (c) inundation of coastal areas caused by tsunamis and seiches.

The PSHA for a site accounts for all possible earthquakes at the site along with their individual probabilities of occurrence. PSHA for a site produces either a uniform hazard response spectra (UHRS) for different probabilities of exceedance or a hazard curve for each ground motion parameter showing variation of its annual probability of exceedance. Recently, regular building codes as well as nuclear codes have adopted the use of PSHA outcomes.

Site response analysis to determine the ground motion response spectra (GMRS) is performed to account for the effects of local subsurface (soil). One of following three approaches is generally followed in the site response analysis: (a) using attenuation equations applicable to local site conditions, (b) applying code-specified foundation amplification factors to modify reference rock response spectra obtained using rock attenuation equations, or (c) performing dynamic site response analysis using one-dimensional, two-dimensional, or three-dimensional modelling of local subsurface site. For nuclear power plants, and nuclear facilities, dynamic site response analysis is required according to regulatory requirements (IAEA's SSG-9, US NRC's Reg. Guide 1.208, CNSC's RD-310 and RD-337). The dynamic analysis accounts for non-linear soil properties of different soil-strata at the site including shear-strain-dependent shear wave velocity and damping that controls wave propagation during ground shaking.

Geologic hazards due to different forms of ground failures could be of concern in siting of nuclear power plants and nuclear facilities. Examples of ground failure include surface fault rupture, liquefaction, landslides, and dynamic settlement. Most effective strategy in dealing with potential geologic hazards is to investigate their presence at considered sites and placing the nuclear facility or nuclear power plant where the hazard could be accommodated.

Tsunamis and seiche are body waves of water developed due to shaking of ground underlying bodies of water. Tsunamis are fast moving waves of open wide bodies of water while seiches are resonant wave oscillation in enclosed bodies of water. Destruction to shoreline structures is attributed to great forces developed due to collision of swelled of water waves with land and due to current of inflow and outflow of water. In addition, flooding of coastal areas is caused by tsunamis and seiches. For the methodology of assessment of tsunami hazard see for example U.S.NRC NUREG/CR-6966 [12].

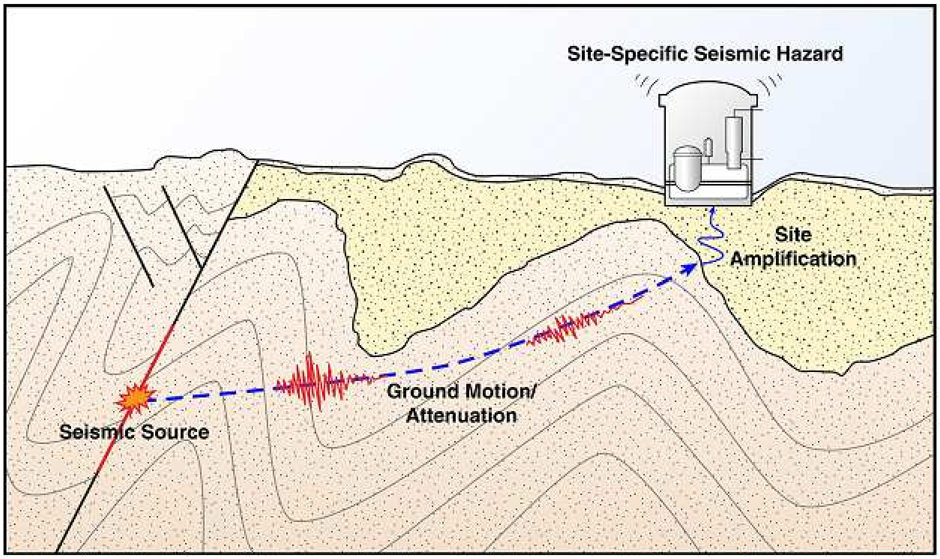

Figure 1 Earthquake Hazard and GMRS

3. Post Fukushima Actions and Response by Nuclear Industry Worldwide

The March 2011 Fukushima earthquake and tsunami disaster in Japan gave a big jolt to the world and especially the nuclear industry and immediately launched the industry to critically examine the safety of their plants, adequacy of the design basis and ability of the plants to cope with the unexpected beyond design basis events. Based on the review of literature the following summarizes the activities and actions taken by some of the key nuclear industry organizations worldwide.

3.1 IAEA

The IAEA led international effort to devise the process of learning and acting upon lessons following the accident at TEPCO's Fukushima Daiichi Nuclear Power Station in order to strengthen nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide, [5]. As a result, the IAEA prepared a draft Action Plan covering all these safety aspects, [9]. The purpose of the IAEA Action Plan is to define a programme of work to strengthen the global nuclear safety framework. The implementation of the Action Plan through the full cooperation and participation of Member States along with the involvement of many other stakeholders would be the key to its success in strengthening nuclear safety.

Strengthening nuclear safety in light of the accident at TEPCO's Fukushima Daiichi Nuclear Power Station is addressed through mainly the following 12 actions.

3.1.1 <u>Safety assessments in the light of the accident</u>

Member States would be required to undertake assessment of the safety vulnerabilities of nuclear power plants against site-specific hazards in the light of lessons learned to date from the accident. Member states are to implement the necessary corrective actions in a timely manner stemming from the safety assessments. At the same time, the IAEA is to develop a methodology and make it available for Member States that may wish to use it in carrying out their national assessments.

3.1.2 IAEA peer reviews

The IAEA is required to strengthen its peer reviews by incorporating lessons learned and by ensuring that these reviews appropriately address regulatory effectiveness, operational safety, design safety, and emergency preparedness and response. Member States are required to provide experts for peer review missions.

3.1.3 Emergency preparedness and response

Member States are required to strengthen emergency preparedness and response by conducting a prompt national review and thereafter regular reviews of their emergency preparedness and response arrangements and capabilities, with the IAEA providing support and assistance through Emergency Preparedness Review (EPREV) missions.

3.1.4 National regulatory bodies

Member States are required to strengthen the effectiveness of national regulatory bodies by conducting a prompt national review and thereafter regular reviews of their regulatory bodies, including an assessment of their effective independence, adequacy of human and financial resources and the need for appropriate technical and scientific support, to fulfil their responsibilities.

3.1.5 Operating organizations

Member States are required to strengthen the effectiveness of operating organizations with respect to nuclear safety by ensuring improvement, as necessary, of management systems, safety culture, human resources management, and scientific and technical capacity in operating organizations. The IAEA is required to provide assistance to Member States upon request.

3.1.6 IAEA Safety Standards

The IAEA is required to review and strengthen its Safety Standards and improve their implementation.

3.1.7 International legal framework

To improve the effectiveness of the international legal framework, Member States are required to work towards establishing a global nuclear liability regime that addresses the concerns of all States that might be affected by a nuclear accident with a view to providing appropriate compensation for nuclear damage.

3.1.8 Member States planning to embark on a nuclear power programme

To facilitate the development of the infrastructure necessary for Member States embarking on a nuclear power programme, Member States are required to create an appropriate nuclear infrastructure based on IAEA Safety Standards and other relevant guidance.

3.1.9 Capacity building

Member States with nuclear power programmes and those planning to embark on such a programme are required to strengthen and maintain capacity building by developing, maintaining and implementing their capacity building programs, including education, training and exercises at the national, regional and international levels; to continuously ensure sufficient and competent human resources necessary to assume their responsibility for safe, responsible and sustainable use of nuclear technologies.

3.1.10 Protection of people and the environment from ionizing radiation

Member States, IAEA, and other stakeholders are required to ensure the on-going protection of people and the environment from ionizing radiation following a nuclear emergency by facilitating the use of available information, expertise and techniques for monitoring, decontamination and remediation both on and off nuclear sites.

3.1.11 Communication and information dissemination

Member States are required to enhance transparency and effectiveness of communication and improve dissemination of information. Member States are to strengthen the emergency notification system, and reporting and information sharing arrangements and capabilities. In addition, Member States are to enhance the transparency and effectiveness of communication among operators, regulators and various international organizations, and strengthen IAEA's coordinating role in this regard, underlining that the freest possible flow and wide dissemination of safety related technical and technological information enhances nuclear safety.

3.1.12 Research and development

Relevant stakeholders are required to effectively utilize research and development in nuclear safety, technology and engineering, including that related to existing and new design-specific aspects.

3.2 Canada

In response to Fukushima Daiichi accident, the Canadian Nuclear Safety Commission (CNSC) established the CNSC Fukushima Task Force to review licensees' responses to the CNSC request to re-examine the safety cases of their nuclear power plants. The Task Force completed its review and documented its findings and recommendations in the CNSC Fukushima Task Force Report (Task Force Report), [10]. The Canadian nuclear industry is following up and implementing the CNSC's 3-year action plan requirements based on lessons learnt for March 2011 Fukushima earthquake. The

Canadian Post-Fukushima Action Plan, [11], has site-specific actions and is consistent with international reviews and benchmarks, best practices and evolving standards.

The Task Force recommendations have been categorized in the draft Action Plan as follows:

- Technical and operational recommendations, which pertain to design and operational enhancements to strengthen reactor defence in depth and technical cooperation at the international level to be implemented through existing regulatory oversight operations.
- Regulatory recommendations, which require Commission approval to amend the regulatory framework and Commission approval and direction to enhance emergency preparedness. Implementation will be through revised priorities by CNSC staff.

The CNSC's draft Action Plan identifies 33 actions that address 13 Task Force Report recommendations. These actions and tasks are grouped in three parts.

For Part 1 Strengthening reactor defence in depth, the CNSC Task Force recommended strengthening each layer of defence built into the Canadian NPP design and licensing philosophy. In particular, certain design enhancements for severe accident management – such as containment performance to prevent unfiltered releases of radioactive products, control capabilities for hydrogen and other combustible gases, and adequacy and survivability of equipment and instrumentation – will be evaluated and implemented wherever practicable; some of which have already been implemented.

For Part 2 Enhancing emergency response, the Task Force identified further improvements to be achieved through streamlining emergency preparedness between onsite and offsite authorities. These improvements are described in the actions outlined below. Commission consideration will be sought for all measures required to strengthen interaction with provincial and federal emergency planning authorities and where legislation may be needed. The CNSC has no regulatory mandate to interact in these areas; nevertheless, the CNSC is committed to facilitating discussions and liaising with appropriate regulatory authorities to address the concerns expressed by the Task Force.

For Part 3 Improving regulatory framework and processes, the Task Force identified further improvements to existing regulations and supporting regulatory documents and to the licensing basis to strengthen the oversight of existing programs and of programs currently being considered for potential new nuclear power plants.

3.3 Japan

Following the March 2011 Fukushima earthquake and tsunami disaster, the Japanese nuclear industry has undergone very challenging times and been subjected to extensive scrutiny, critical investigations and reviews. The outcome of all the investigations, reviews and assessment is to implement plans with the following objectives [8]: building resilience against external hazards, loss of AC/DC power, loss of heat sink, threats to containment integrity to avoid large scale land contamination by all means. As well, implement detailed emergency planning, rebuild regulatory requirement and strengthen Regulatory body, create utility' self-policing organization JANSI, emulating INPO in the US, enhance education of nuclear engineering and achieve integration of safety, security and safeguard. All of the above with the aim to restore public trust in the nuclear industry.

3.4 United States

In light of the accident at the Fukushima Dai-ichi facility on March 11, 2011, the United States Nuclear Regulatory Commission (NRC) has taken many actions [6] that include:

- performance of inspection activities at all U.S. nuclear power plants to evaluate licensee implementation of procedures and equipment which could mitigate beyond design basis events;
- establishment of a Task Force which identified lessons learned which could be implemented to further enhance the safety of U.S. nuclear power plants; and
- commencement of a program to identify and take specific near-term and long-term regulatory actions related to these lessons learned.

The NRC actions are broken into 3 tiers: Tier 1: near-term to be Completed by 2016, Tier 2: require critical skill sets or further technical assessment and Tier 3: require further long-term study/scoping. In response to the USNRC, the US industry has adopted the following approach: develop the Screening, Prioritization, and Implementation details (SPID), interact with NRC to gain endorsement, develop positions that enable SPRA's to meet NRC schedule, re-examine EPRI 04-06 and update if necessary, use for hazard and GMRS calculation, gather current data on site properties, develop uniform calculation of site amplification factors, develop uniform calculation of hazard and GMRS.

3.5 France

In April 2011, the French Government required [7] a Complementary Safety Assessment (CSA) of all the nuclear installations with respect to extreme situations: earthquake, flooding, loss of heat sink, station black-out and all of them combined. Similar "stress tests" were performed in all European and some neighbouring countries under the coordination of the European Commission.

The technical specifications were defined by the national safety authorities group (ENSREG). The test consists of two parts. First the installation is examined with respect to its licensing base. Then the safety margins are evaluated with respect to the postulated extreme situations. To meet the short deadline, EDF developed a "rapid SMA" method for the beyond design assessment. The margins were generically evaluated with respect to a review level of 1.5 x Safe Shutdown Earthquake.

A Nuclear Rapid Response Force (FARN) having the capacity of deploying in 24-48 hours personnel and equipment required for severe accident prevention and management for a multi-unit site is also proposed. EDF concluded that the seismic capacity of the containment and of the structures and equipment which, in the event of failure, would compromise the safety functions is at least 1.5 times the SSE.

The list of existing and new systems to be included in a "kernel" is close to being finalized and assessment of the existing components as well as design and implementation of new components will be carried out for the 58 units during the coming years.

4. Performance of Fukushima & Onagawa NPPS at March 2011 Earthquake & Tsunami

The earthquake and its effects [5] were strongest at the 3-unit Onagawa Nuclear Power Station (NPS), the 6-unit Fukushima Daiichi NPS, the 4-unit Fukushima Daini NPS, and the single operating unit of the Tokai NPS (see Figure 2). The three Onagawa units were the closest to the epicentre of the earthquake, and more significantly, closest to the largest tectonic subduction zone displacements caused by the earthquake. They experienced the strongest earthquake motions and some of the highest tsunami waves of any of the plants affected by the March 2011 earthquake. The strength and the duration of the shaking are several times those used for the design of most nuclear power plants around the world. An IAEA mission to Onagawa NPS was organized and conducted on July 30th through August 11th of 2012 (IAEA, 2013). The mission summarized their finding by stating that the Onagawa plant was "remarkably undamaged."

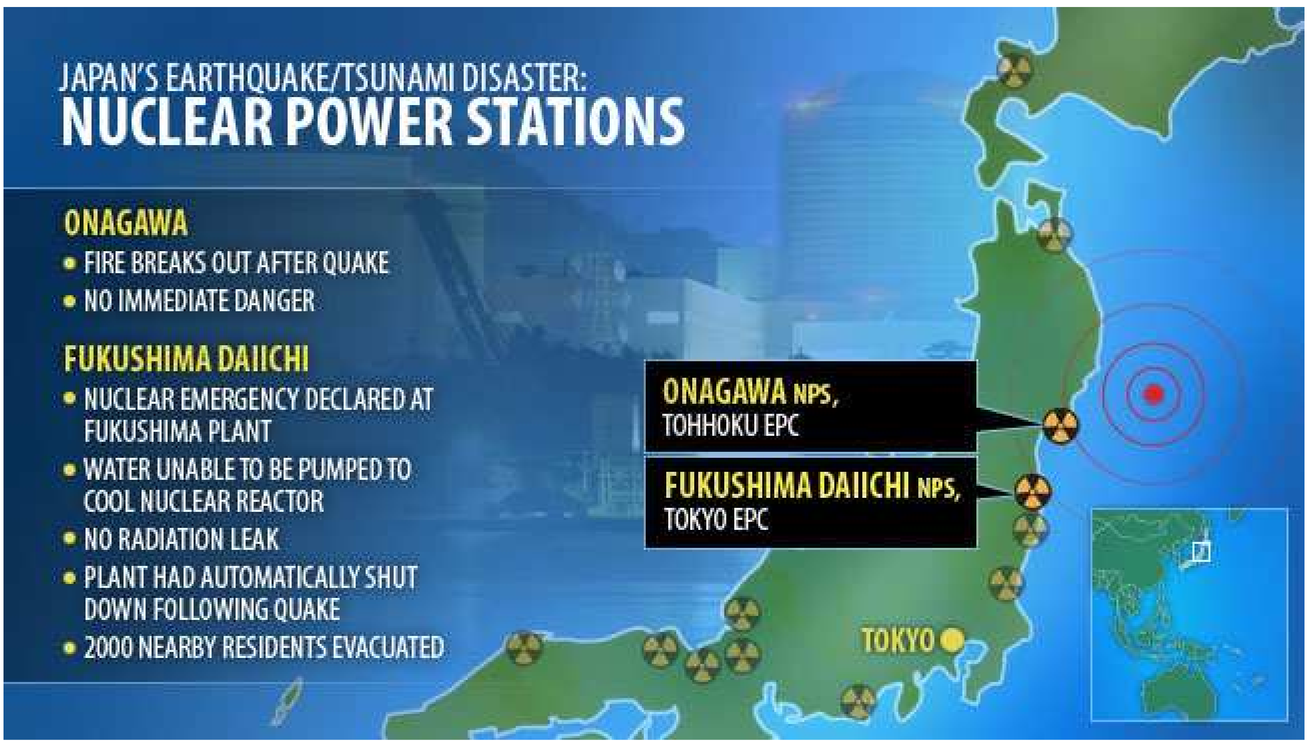

Figure 2 NPS sites affected by the March 2011 earthquake

All three Onagawa units were equipped with numerous accelerometers and recorded a large number of floor response records – strong motion records within the structures themselves that show the actual earthquake motions experienced at the location of the instrument (and nearby equipment, piping, etc.). Based on these measurements, it is concluded that the plant components were tested by accelerations that approached or exceeded their designs. The tsunami actually caused more damage than the earthquake, but its effects were contained. The site level was 14.8m above sea level before the earthquake. During the earthquake, the site and surrounding region dropped about one meter, which left the site at about 13.8m above sea level. The recorded height of the primary tsunami wave was about 13m – leaving about a meter of margin. That is close, but was enough for this earthquake. The most serious damage from the tsunami within the plant was due to a partial inundation of the Unit 3 Reactor Building through the intake structure, which the IAEA (2013) report discusses in detail. The primary lesson is that even in the presence of adequate tsunami walls, seismically induced flooding is possible and needs to be considered. The lack of damage to the Ongawa SSCs was primarily due to the good engineering design of the plant, including most non-safety related features.

The most important structural and earthquake engineering lesson for nuclear plants likely comes from the performance of the non-safety related structures and non-structural features at Onagawa. These were designed to much lower seismic design criteria than their safety related counterparts, yet they also performed well, with no unexpected damage. There was some damage in to structures to make it clear that even minor design omissions were the cause of damage in this large earthquake.

5. Summary

The recent Fukushima earthquake has focused attention of the nuclear industry to assess and make provisions to cope with the beyond design basis events that lead to station blackout, flooding and loss of heat sinks. Based on the review of available information, the paper summarized assessments and strategies being followed by various countries. The lessons learnt from these events are compelling the industry to require:

- strengthening of defence-in-depth: improve capabilities to withstand prolonged loss of power and heat sinks, improve response to containment challenge and performance, implementation of severe accident management program including definition and evaluation of seismic design margin of safety systems,
- enhancing emergency preparedness and response: emergency mitigating equipment and resources, integrated emergency plans at various government levels, performing full-scale exercises, and
- improving communication to improve transparency in building trust with the public.

On the positive side, the experience related to performance of the well designed nuclear and industrial facilities from March 2011 earthquake and earlier more than 100 real earthquakes confirm that the plant structures systems and components have significant margins and resilience to withstand larger than design earthquake demand.

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