Seismic Evaluation of Equipment for Seismic Demand Based on Uniform Hazard Spectra (UHS) – Implications and Impact

Ying An[1] and Ravi Jategaonkar[1]
[1] Candu Energy Inc., Mississauga, Ontario, Canada
(Ying.An@candu.com)
(Ravi.Jategaonkar@candu.com)

Abstract

Per the recent changes in the CSA standard N289.1, a re-assessment of the seismic capacity of an existing nuclear power plant may be required whenever new seismological and geological data indicate that the site seismic hazard has changed since the original design. The seismic uniform hazard spectra (UHS) are considered in addition to the original Design Ground Response Spectra (DGRS) expressed in terms of standard spectrum. UHS usually show higher accelerations and rich energy content at the medium to high frequencies. The concept of the UHS is illustrated. Comparisons of UHS and DGRS are presented to show the fundamental differences between UHS and DGRS. This paper shows the engineering challenge due to UHS. A practical approach is proposed to address this challenge in this paper.

1. Introduction

As per the recent changes in the CSA standard N289.1 [1], seismic evaluation of Structures, Systems and Components (SSCs) shall be performed using standard-shape Design Ground Response Spectra (DGRS), and site-specific ground response spectra, which are defined in the form of a site specific seismic hazard curve. Per CSA N289.1 [1], a re-assessment of the seismic capacity of an existing nuclear power plant may be required whenever any modification is made to the existing plant based on the new seismological and geological data indicate that the estimated site seismic hazard has changed since the original design of the plant.

The existing seismic design of Nuclear Power Plants (NPPs) is generally based on a Design Base Earthquake (DBE) whose input seismic response spectra have been scaled from the standard shape of DGRS specified in the regulatory document [2] using site-specific ground-motion value such as Peak Ground Acceleration (PGA). For NPPs in USA, their seismic designs were based on the standard design spectra given in the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.60 [3]. The shape of the standard DGRS was originally developed from studies by Newmark and his colleagues in the 1970s [3], [4]. However, the recent studies on the seismic ground motion have indicated the conventional representation of ground motion using the spectrum given in [1] [2] [3] [4] may not be adequate in certain frequency range. These studies, such as [5] [6] [7] [8], have shown that, for rock sites in Eastern North America (ENA) and Central Eastern United States (CEUS), the frequency content of these standard design spectra may be inadequate for frequencies above 10 Hz and conservative for frequencies below 10 Hz. In addition, it is well recognized that the standard DGRS does not present the same probability of an exceedance over the full frequency range of interest. Therefore, to address this deficiency, the present trend in engineering practice is to develop a site specific spectrum that represents a uniform probability of exceedance over the entire frequency range of interest [9] and hence the term uniform hazard spectrum. The UHS represents uniform probability of exceedance at each point for a seismic hazard at the site over the entire frequency range. The UHS are obtained by performing a site specific study by considering sources of near-field earthquake and far-field earthquake. With the UHS as an alternative seismic demand for NPPs, the seismic evaluation of equipment emerges as a new engineering challenge as UHS are different from the conventional DGRS in nature.

This paper firstly describes the concept of UHS and then illustrates the differences between UHS and standard DGRS. It discusses further the implications of the seismic demands upon the seismic evaluation of equipment due to the UHS. The impacts due to the seismic demand from UHS are also assessed on the practices for seismic evaluation of equipment for NPPs. A practical approach is proposed to address the challenge of seismic evaluation of equipment for the seismic demand from the UHS.

2. Uniform Hazard Spectrum (UHS)

The UHS is a characterization of the ground motion amplitude which is expected at a specified probability, as a function of vibration frequency. That is, the UHS represents the effects of the earthquake ground motion magnitude and distance parameters determined to be significant contributors to seismic hazard for a site at the specified probability level. Thus in a uniform hazard spectrum, at every point on the spectrum the ground acceleration has an equal probability of exceedance at the corresponding frequency indicated in the spectrum. This concept is illustrated in Figure 1.

The UHS are obtained by performing a site specific study by considering sources of near-field earthquake and far-field earthquake. In other words, the UHS is essentially a composite of various types of earthquake that contribute to hazard. A significant part of the amplitude in high frequencies can be traced to the contributions from smaller magnitude earthquakes closer to the site; while the large distant earthquakes are the major contributors to the amplitude in low frequencies as shown in Figure 2. The shape of UHS in the region of low frequencies is usually indicative of the contribution of distant sources to the hazard. As the frequency increases i.e., the UHS become more peaked, reflecting increasing contribution of nearby smaller earthquakes to the seismic hazard.

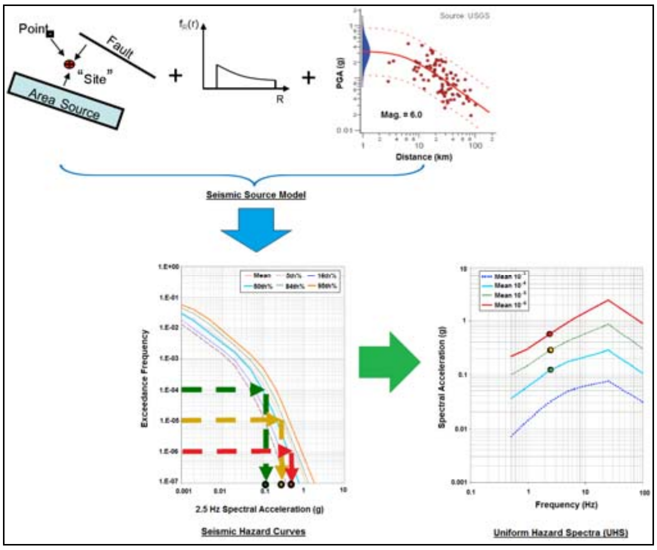

Figure 1 Illustration of UHS Concept

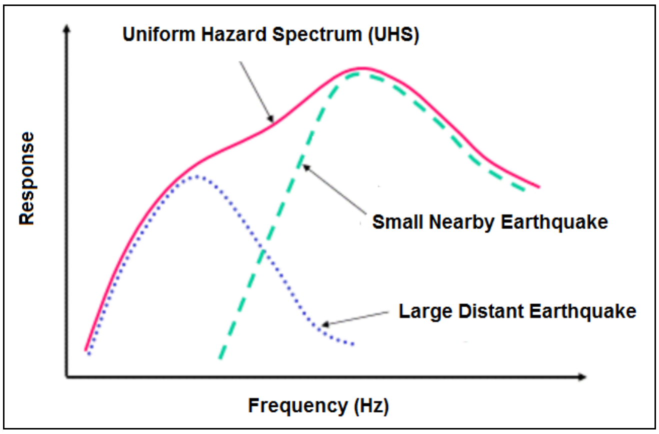

Figure 2 Illustration of UHS Composition from Different Earthquakes

3. Comparison of Typical UHS and Standard DGRS

The standard DGRS specified in CSA N289.3 and US NRC RG 1.60, which most of the nuclear facilities in North America were designed for, were developed in 1970s using data from earthquakes on softer sites in California. As indicated in Section 2, that the eastern earthquakes have different characteristics compared to those in Western U.S. (WUS) as shown in Figure 3. The comparisons are presented to demonstrate the differences between the UHS and standard DGRS.

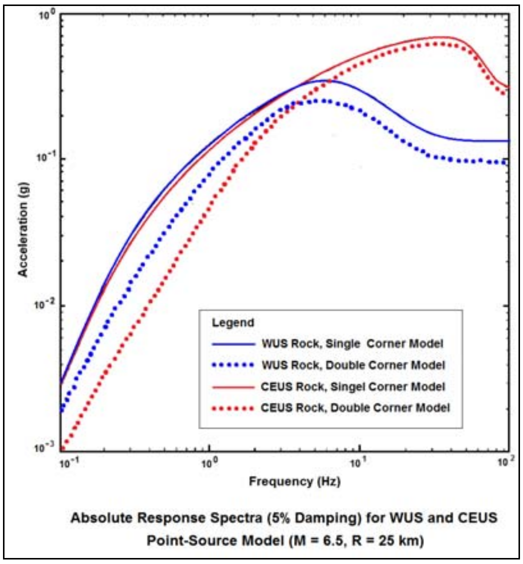

Figure 3 Comparison of WUS UHS and CEUS UHS (Source: NUREG/CR 6728 [7])

3.1 ENA vs. Standard DGRS (Rock Sites)

The important studies on ENA UHS can be found in the publications by Atkinson and her colleagues [5] [6]. Based on Atkinson's study [6], a typical ENA UHS and a standard DGRS as specified in the CSA N289.3 and US NRC RG 1.60 for rock sites are compared to various site-specific spectra in Figure 4. Note that all spectra are normalized in terms of spectral acceleration over PGA.

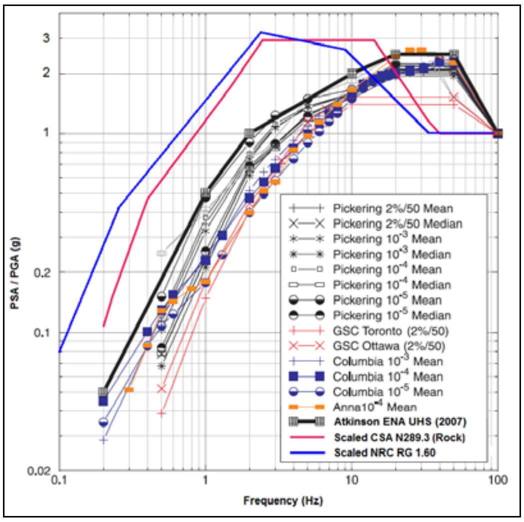

Figure 4 Comparison of Typical ENA UHS and Standard DGRS and Various Site-specific Spectra (5% Damping, Source: Atkinson [6]).

It is obvious from Figure 4 that the frequency content of the standard design spectra are much less than that of ENA UHS for frequencies above 20 Hz while opposite situation observed below 10 Hz for rock sites in Eastern North America (ENA). The contrary distributions of frequency contents typically highlight the major difference between the traditional standard DGRS and ENA UHS. It's also observed that the UHS for ENA rock sites is greatly enriched in high frequency energy starting from about 10 Hz and depleted rapidly in low frequency energy below 3 Hz, relative to standard DGRS used for nuclear power plant design in ENA.

Another significance of ENA UHS is to bring the concern on the seismic capacities of high-frequency sensitive SSCs since the standard DGRS normally has much lower seismic demand in high frequencies (e.g., above 20 Hz) compared with ENA UHS.

3.2 CEUS UHS vs. Standard DGRS (Rock Sites)

A typical comparison of CEUS UHS vs. standard DGRS (Newmark-Hall and RG 1.60 spectra) is presented in Figure 5 which is from NUREG 6728 [7]. The similar observation of the contrary distributions of frequency contents of CEUS UHS and standard GRS are found from this comparison. The shapes of ENA and CEUS are similar and generally show peak spectral responses at about 20 to 30 Hz frequency. However, ENA generally has broader flat peak between 20 Hz to 50 Hz and the amplitudes of CEUS UHS below 20 Hz deplete faster than those of ENA.

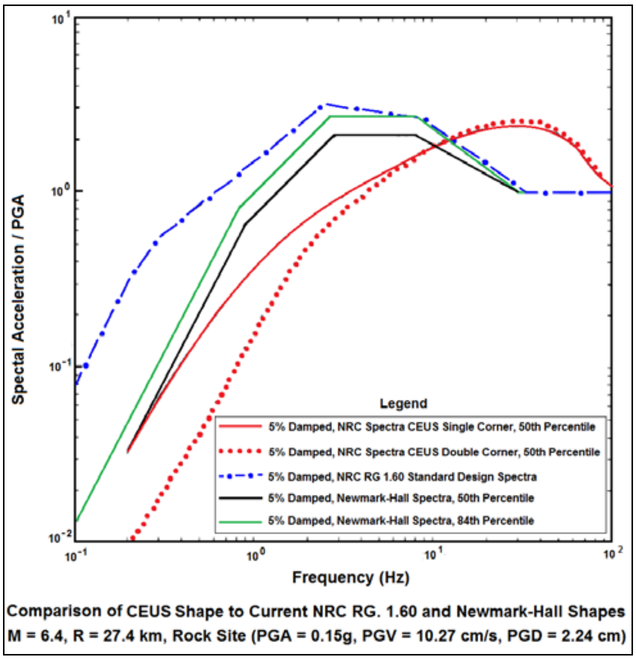

Figure 5 Comparison of Typical CEUS UHS and Standard DGRS (Source: NUREG/CR 6728 [7])

4. Implications for Seismic Evaluation of Equipment Due to UHS

From the comparisons of typical UHS and standard DGRS, the implications for seismic evaluation of equipment are explored in this section.

Since the UHS is derived considering sources of significant earthquake ground motions from different sources, the inclusion of small nearby earthquakes in the UHS tend to produce overly conservative results i.e., high peak ground acceleration at the high frequencies. These small close distance earthquakes generally have low energy and low damage potential. Therefore, engineering design or seismic evaluation using UHS directly have to deal with excessively conservative seismic demand, especially in the high frequency range.

Another issue is that there is big gap between the UHS and standard DGRS below 10 Hz as shown in Figure 4 and Figure 5. Generally, except for some electrical and Instrumentation & control systems devices, various Systems, Structures, Components used in any nuclear power plants in North America have characteristic of low frequency item and therefore, the seismic qualification of these items based on the standard DGRS shape specified in CSA N289.3 or NRC RG 1.60, characterized by higher amplifications in the dominant structural response frequency range (2 to 10 Hz) was satisfactory. If, however, as per the new requirement per UHS, the seismic demand for SSCs in nuclear power plants will be substantially low. An important question is whether it really provide adequate safety factor against the earthquake with a low exceedance probability (e.g., 10^{-4}).

As a result, for seismic evaluation of equipment, the real challenge is how to address the demands in both low and high frequency ranges from the standard DGRS and newly UHS.

5. Experiences and Practices in U.S. to Address Challenges Due to UHS

Since 1990s, the Individual Plant Examination of External Events (IPEEE) were requested for each nuclear power plant licensee by US NRC to identify and report all plant-specific vulnerabilities to severe accidents caused by external events including the expected site-specific earthquake [10]. Site-specific UHS were developed from Probabilistic Seismic Hazard Analysis (PHSA) in order to determine the seismic ground motions with exceedance probability of interest for IPEEE.

One of the concern that the industry has consider was the effect of high frequency components present in the ground motion as indicated by a typical UHS curve. EPRI investigated the effects of high frequency on nuclear power plant SSCs and documented the findings in EPRI-TR-102470 [11]. Based on this investigation and other experiences, US NRC developed Interim Staff Guidance (ISG) for the review of new reactor licensing applications that contain use of high frequency ground motion input in the seismic design and evaluations of structures, systems and components [12].

EPRI technical report [11] provided results of the investigation for damaging effects of high frequency ground motions. In this report, it is concluded that high frequency seismic motions (i.e., greater than 10 Hz) is found to be significantly less damaging than low-frequency ground motions since structures and equipment at nuclear power plants have additional capacity above yield to absorb the small displacements associated with high frequency earthquake input. No element within the load transfer path would undergo an intra-element distortion in excess of the spectral displacement content of the input motion at the effective frequency of the equipment when it undergoes this level of distortion. For most practical cases, even if all of the distortion is concentrated into a single element, this element will not fail if its distortion capability exceeds the spectral displacement of the input motion at the effective frequency of the equipment. Since the weak-link elements of most items of rugged industrial equipment can accommodate distortions of at least 0.1 inch, spectral accelerations of less than 1g at frequencies of 10 Hz or greater are unlikely to result in equipment failure. Therefore, it is reasonable to conclude that the damaging frequency range for majority of equipment is less than 10 Hz.

Industry and the NRC worked closely to establish the acceptable method to define the site-specific seismic ground motions in past decade. The principal outcomes of these efforts has been the publication of Regulatory Guide (RG) 1.208 [13], entitled as "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion" and issued in 2007. This RG establishes an acceptable regulatory approach to implement the derivation of site-specific ground motions. The development of regulations for earthquake ground motions by U.S. NRC is shown in Figure 6. Basically, the performance-based approach in RG 1.208 uses the methodology documented in ASCE 43-05 [14] to adjust/modify the site-specific UHS by a design factor generated from information from the seismic hazard curves so that the ground motions can be defined for practical engineering.

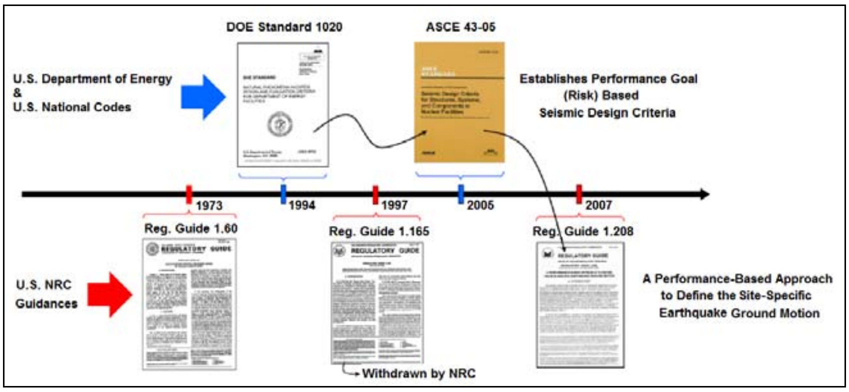

Figure 6 Development of Regulations for Earthquake Ground Motions by U.S. NRC

6. Proposed Approach to Address the Challenges Due to UHS in Canada

6.1 Challenges for Seismic Evaluation of Equipment for UHS

6.1.1 Design Concerns

Regarding the seismic evaluation of equipment by analysis, there may be following design concerns for applying UHS.

- For SSCs with low frequencies (below 10 Hz), seismic loads from the UHS are lower than from the DGRS; as shown in Section 6, the seismic demand based on UHS may be underestimated

- There is no recommended analysis methodology for using UHS (e.g., modal superposition, directional combinations, equivalent static coefficient, time history in terms of duration, directional correlation, V/H ratio)

- Modeling difficulties for piping and structures to include high frequencies (above > 32 Hz) at which UHS usually shows high seismic demand

- Excessive computational efforts in the time history method thanks to the high frequency effect of UHS

- Assessment of structural integrity under high frequency components of motion

- Consideration of Seismic stress cycles containing high frequency components of motion (a characteristic of UHS)

6.1.2 Testing Concerns

If the seismic qualification/evaluation of equipment is done by testing, the following concerns should be addressed when UHS is used as seismic input.

- For UHS, the Vertical/Horizontal ratio is no longer 2/3. This poses a problem for the biaxial inclined shaker table test

- Difficulty in generating time history for a tri-axial shaker table that can deliver the required high acceleration at a high frequency per UHS demand

- The UHS-based RRS is likely higher than the DGRS-based RRS, making failure due to over-testing caused by higher g-values and more cycles more likely.

- Suppliers may be unable to meet the UHS-based RRS

- The current common practices in IEEE Standards (e.g., IEEE Std. 344) are not still based on the standard DGRS. It is therefore difficult to reconcile the UHS demand with the requirements of the Standard?

6.2 Proposed Approach for Existing NPPs

The current CSA N289 standards [1], [2] require that any modification to the existing structure be assessed using both, the standard shape DGRS and also UHS. The following steps may be followed to address the challenges due to UHS.

- The site specific UHS with the exceedance probability of 10^{-4} should be established by PHSA and adjusted/modified by the techniques recommended in Annex B of CSA N289.1;

- Once the UHS-based ground motions determined, the plant-wide probabilistic based Seismic Margin Assessment (SMA) may be performed to assess the seismic margins of selected SSCs as recommended by the U.S. NRC in the Policy Issue SECY-93-087 [15]

- Any deficiency found in SMA may be addressed by design modification or improvement in order to meet the UHS seismic demand

6.3 Seismic Evaluation of Equipment

- A screening analysis shall be conducted to identify the representative equipment which should be assessed to site-specific UHS demand; the screening criteria include selection based on importance to plant safety; location in areas that experience large high frequency seismic response; highly stressed structures, systems and components; and sensitivity to high frequency motion.

- Typically, the selected structures, systems and components would include safety related items such as the reactor vessel and internals, steam generator supports, reactor coolant system, representative piping systems, containment structures, and high frequency sensitive electrical and electro-mechanical components such as circuit breakers, motor control centre starters, relays and switches.

- For those selected equipment for assessment against the UHS demand, the evaluations assess the ability of the equipment to maintain its safety function over the full frequency range of the UHS seismic input motion. Evaluations are generally analytical; however, specific shake table testing will be performed where components are known to be sensitive to high frequency motion or must perform safety-related functions during a seismic event.

7. Conclusion

The site-specific uniform hazard spectra are considered as another ground motion in addition to the standard DGRS for NPPs. Thus is a new requirement and in the absence of established practice in the industry, to deal with the seismic demand based on UHS for equipment is the common challenge in the nuclear industry. In this paper, the concept of the UHS is schematically illustrated. The comparisons of typical UHS and standard DGRS are presented to show the fundamental differences between the two. Typically, a site-specific UHS exhibit higher ground acceleration in the high frequency zone and low ground accelerations in low frequency zone, compared to the ground accelerations as per standard shaped spectrum. This paper discusses the engineering challenge of how to address high accelerations at medium and high frequencies, at the same time meeting the seismic requirements in the low frequency zone as per the standard shaped spectrum and presents a possible approach to deal with the challenge.

8. References

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