Seismic Analysis for a Reactor Building with High Frequency Ground Motion

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1 ABSTRACT

Current seismic hazard assessments express hazard in terms of a Uniform Hazard Spectrum (UHS). High frequency content is typically present in the UHS for Nuclear Power Plants (NPP) in Central and Eastern North America. It was found that this high frequency content in the UHS has significant effects on the seismic response of a structure when using conventional analysis methodologies. In several analytical cases, the high frequency content contributes to an increase in the floor response spectra, especially for those elevations close to the ground. In reality, however, it is well known that high frequency content of ground motion has much lesser damage effect to Structures, Systems, and Components (SSCs) of a NPP than low frequency content (except functional performance of some vibration sensitive components, such as relays). The challenge is how to reflect this reality in seismic analysis of a NPP.

The main purpose of this paper is to investigate effects on seismic response of a reactor building by applying multiple sets of artificial acceleration time histories (instead of the conventional one set of broadband envelop time histories) as seismic ground motion input.

In this paper, a literature review of existing techniques to mitigate the effects from the high frequency contents of the ground motion is conducted. An imaginary free field UHS with significant high frequency content is presented and is used for the research purpose of this paper. Multiple sets of time histories are derived from the UHS corresponding to different frequency contents. These time histories are used as input for seismic analysis of a simplified stick model for a typical reactor building. A fixed base analysis for the stick model is performed by using STARDYNE, which is a well-established finite element software for seismic analysis. The seismic wave incoherency effects on building response are considered using ACS SASSI, a computer software for Soil-Structure Interaction (SSI) analysis. Hard rock condition is considered in the analysis. Floor response spectra at both basemat of the reactor building and top of the internal structure are generated and presented. The results from ACS SASSI and STARDYNE are compared.

It was found that seismic wave incoherency has significant effects on the seismic response of the reactor building in the high frequency range. The use of multiple sets of time histories also have some effects on the seismic response. Although as shown in this paper the effects of multiple sets of time histories are not as significant as those of wave incoherency for buildings based on hard rock and with large and rigid foundations, the use of multiple sets of time histories may provide another way to mitigate the seismic response resulting form a UHS regardless the types of foundations and supporting media. Further studies related to the use of multiple sets of time histories are required as discussed in this paper.

2 INTRODUCTION

For assessment of existing nuclear power plants, the seismic ground motion may be defined in terms of UHS. According to IAEA DS422, “A uniform hazard response spectrum is developed by selecting the values of the response spectral ordinates that correspond to the exceedance frequencies of interest from the seismic hazard curves.” The UHS represents the effects of the earthquake ground motion magnitude and distance parameters, which are determined to be significant contributors to seismic hazard for the site at a specified uniform probability level.

There are many topics associated with the development of UHS. This paper studies the high frequency effects of the UHS. In the seismic analysis of a NPP, high frequency ground motions are those caused by
seismic events that produce exceedances of standard USNRC Regulatory Guide 1.60 spectra at high frequencies. Probabilistic Seismic Hazard Analyses (PSHAs) for sites of operating NPPs located in the Central and Eastern North America (CENA) suggest that site-specific UHS spectral shapes for CENA sites were distintively different from the Regulatory Guide 1.60 standard spectral shape, which was used in the design of most of the operating NPPs in North America. The UHS for CENA sites (particularly rock sites) tended to reach maximum acceleration values above 20 Hz, while the western US have maximum acceleration values in the 2-9 Hz range.

SSCs with low fundamental frequencies are generally unaffected by high-frequency content of the input seismic motion. Structures with high fundamental frequencies have very low displacements and correspondingly low stresses. In general, it is relative displacement that causes structural damage, and high-frequency motions are characterized by low, non-damaging relative displacements. It has been shown that high-frequency motions (above approximately 10 Hz) are not damaging to most nuclear power plant SSCs (see EPRI 1015108).

In the past, the nuclear power industry developed a number of improvements to determine site-specific response spectra to address the high frequency ground motion issues. These improvements include 1) the use of a Cumulative Absolute Velocity (CAV) filter to remove the effect of low magnitude earthquakes, that have negligible potential for causing damage to nuclear plants, from the PSHA, 2) the use of revised CENA ground motion models in the PSHA, 3) the use of a performance goal approach to determine the site-specific performance-based response spectra, and 4) a methodology to account for ground motion incoherency effects in seismic design analyses. The first three improvements are related to the development of site-specific ground motion input, while the fourth provides a tool to mitigate seismic response after the site-specific ground motion is defined.

The current paper investigates the effects of using multiple sets of time histories in addition to considering seismic wave incoherency. An imaginary free field UHS with significant high frequency content is presented in Section 3 and is used for the research purpose of this paper. Multiple sets of time histories are derived from the UHS corresponding to different frequency contents. These time histories are used as the input for seismic analysis of a simplified stick model for a typical reactor building. A fixed base analysis for the stick model is performed in Section 4 by using STARDYNE. The seismic wave incoherency effects on building response are considered in Section 5 using ACS SASSI. Hard rock condition is considered in the seismic wave incoherency analysis. Floor response spectra at both the base slab of the reactor building and top of the internal structure are generated and presented. The results from ACS SASSI and STARDYNE are compared. Findings and discussions are summarized in Section 6.

3 HIGH FREQUENCY GROUND MOTION AND TIME HISTORIES

A sample UHS1 with significant high frequency contents is presented in Figure 1. The UHS is defined in the frequency range from 0.5 to 20 Hz. No special values are calculated above 20 Hz. The shape of the curve between 20 Hz and 100 Hz is arbitrarily chosen. As seen in Figure 1, the research UHS has a peak spectral acceleration of 1.08g at a frequency range of 20 to 40 Hz. The peak ground acceleration (PGA) is plotted for reference at frequency of 100 Hz, a standard choice for a UHS. The PGA is 0.43g.

Since UHS envelops a number of significant earthquake ground motions, response spectrum analysis or time history analysis using single set of artificial acceleration time histories derived from the UHS can overestimate the damage potential for nuclear power plant SSCs. Engineering design using the UHS directly as the conventional ground response spectra can be unduly conservative, as the broadband envelope of the significant earthquake ground motions exaggerates the seismic energy input to the structure by individual earthquakes. In addition, small non-damaging earthquakes produce high ground accelerations at high frequencies; these events have low energy and low damage potential.

For the research purpose of this paper, three sets of time histories for the UHS in Figure 1 are presented in Figures 2 to 4. These time histories are developed using spectral-matching approach. One

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1 It is noteworthy that the UHS and time histories presented hereafter in this paper are provided by a seismologist for research purpose of the current paper only. They are not intended to be used in any real design. Also, the development of the UHS and time histories are not the scope of this paper. This paper emphasizes the results of using multiple sets of time histories provided as is.
broadband set, Figure 2, is generated to match the entire UHS frequency range from $0.5 - 20$ Hz. A low-frequency set, Figure 3, matches just the low-frequency part of the spectrum, from $0.5 - 2$ Hz, while a high-frequency set matches only the high-frequency part of the spectrum, from $2 - 20$ Hz. The spectrum matching for these time histories are illustrated in Figures 2 to 4. It is apparent in these figures that the spectra of the modified records match the target over the selected frequency range very closely and can fall short outside this range.

Figure 1. A Research UHS

Figure 2. Broadband Time History Matched for $0.5 - 20$ Hz
Figure 3. Low Frequency Time History Matched for 0.5 – 2 Hz

Figure 4. High Frequency Time History Matched for 2 – 20 Hz

4  FIXED BASE ANALYSIS BY STARDYNE

For the research purpose of this paper, a simplified stick model for a reactor building is developed and is presented in Figure 5. The reactor building consists of an internal structure enclosed by a cylindrical containment wall, both supported on a common base slab with a diameter of approximately 60 meters. The internal structure houses the concrete vault, reactor, steam generators, pressurizers and various other equipment and systems. For the seismic analysis in this paper, the reactor building and internal structure are represented by means of a three-dimensional model as shown in Figure 5. The containment wall and the internal structure (together with the vault) are modelled by two separate sticks representing the stiffness and mass of the structure.
A seismic analysis for the stick model was performed using the three sets of time histories presented in Figures 2 to 4 as seismic ground motion input. The horizontal floor response spectra from STARDYNE are presented in Figure 6 for the basemat and top of the internal structure. In STARDYNE analysis, the stick model is restrained at the base for all directions, i.e., the reactor building is modeled as fixed base. It is seen as expected that the spectrum at the basemat corresponding to the broadband time history is similar to the UHS presented in Figure 1 since this is a fixed base analysis. It is also seen that, for the top of internal structure, the broadband time history spectrum envelops most of the spectra from the low and high frequency time histories. The most interesting finding is that at top of the internal structure, the peak spectral acceleration is reduced from around 6g of broadband time history to 4.8g of the multi-sets (i.e., low and high) time histories. This comparison shows that by using multi-sets time histories it is possible to reduce the seismic response from single-set broadband time history.

Figure 6. STARDNYE Fixed Base – Basemat (Left) and Top of Internal Structure (Right)

5 SSI ANALYSIS BY ACS SASSI

Seismic wave incoherency occurs because of horizontal spatial variation of both horizontal and vertical components of earthquake ground motion. The lack of extensive recorded data has previously prevented its incorporation into dynamic analysis of nuclear power plant structures. EPRI NP-6041-SLR1, ASCE 4-98,
ASCE/SEI 43-05 and US DOE-STD-1020 recommended response spectrum reduction factors to account for incoherency effects. These reduction factors are a function of foundation plan dimension and frequency.

Recent studies have concluded that these spectral reductions are still overly conservative and have evaluated sensitivity to nuclear power plant foundation and structure characteristics. The spectral reduction factors are highly dependent on the shape of the free-field ground response spectrum and must account for induced rotation effects on structure response.

EPRI 1013504 developed coherency functions expressing relationships between ground motion at separate locations as a function of separation distance and frequency. These coherency functions are incorporated into soil-structure interaction analysis programs. Incoherency transfer functions (ITFs) are developed to define the relationship between free-field ground motion at discrete points on the foundations. In general, each component of horizontal ground motion induces a horizontal translation and a torsional component. Vertical ground motion induces a vertical translation of the foundation as well as rocking components about the horizontal axes. Translational ITFs are principally a function of foundation area, whereas rotational ITFs are a function of foundation area and foundation shape.

Scaling functions based on ITFs can also be applied to the amplitude of the Fourier transform of the free-field ground motion to produce a modified ground motion that can be used in standard seismic response analysis methods. This simplified approach may be used at rock sites with free-field ground motions with significant high-frequency content.

Seismic analyses incorporating soil-structure interaction and ground motion incoherency (see EPRI 1013504) demonstrate a significant reduction in high-frequency seismic response as measured by floor (structure) response spectra. The calculation of ITFs depends on foundation area and is independent of site soil conditions. However, resulting spectral reductions strongly depend on site-specific free-field spectrum shape and associated site soil conditions. Because seismic wave incoherency is primarily a high-frequency phenomenon, observed reductions in foundation response spectra are much smaller for soil sites, as soil-specific ground motion is generally deficient in the high-frequency range.

In this paper, the seismic wave incoherency effects are considered using ACS SASSI software. The stick model presented in Figure 1 is used to represent the superstructure of a reactor building. According to Section 3.7.2 of USNRC SRP, “For structures founded on materials having a shear wave velocity of 8,000 feet per second or higher, under the entire surface of the foundation, a fixed base assumption is acceptable”. For the research purpose of this paper and the comparison with STARDYNE fixed base results, the shear wave velocity in the current ACS SASSI analysis is assumed to be 8000 ft/sec. uniformly for the supporting media.

Similar to the STARDYNE fixed base analysis, the three sets of time histories presented in Figures 2 to 4 are used in the ACS SASSI analysis. The floor response spectra considering seismic wave incoherency are presented in Figure 7 for both the basemat and the top of the internal structure.

For the basemat, it is observed that the peak acceleration is less than 0.8g and the ZPA is less than 0.3g. This is already a reduction of more than 20% by considering seismic wave incoherency effects, comparing to the UHS presented in Figure 1. The overall reductions are significantly larger than those allowed in Table 3.3-2 of ASCE 4-98, which may be applied in the absence of a SSI analysis. This observation reinforces the industry opinion that the reduction factors given in ASCE4-98 are conservative.

To further demonstrate the effects of seismic wave incoherency, the horizontal floor response spectra for the basemat corresponding to the broadband time histories are compared in Figure 8 for STARDYNE fixed-base, ACS SASSI (coherent), and ACS SASSI (incoherent). It is evidenced that the results from STARDYNE fixed-base and ACS SASSI (coherent) are similar, which indicates that the simplified fixed-base assumption is reasonable and the traditional SSI analysis has little effects when the shear wave velocity is high. However, as can be seen in Figure 8, the seismic wave incoherency has major effects on the seismic response of the reactor building for frequencies higher than 10 Hz. The peak acceleration at the basemat has been reduced from more than 1.25g of STARDYNE fixed base to less than 0.75g of ACS SASSI (incoherent), and the ZPA from 0.43g to less than 0.3g. It can be observed in Figure 8 that the seismic wave incoherency has little effects on the seismic response in the low frequency range. The current findings confirm that seismic wave incoherency effects can significantly reduce high frequency response for structures founded on hard rock and with large foundation.
The interesting findings in this study are the comparison of the results of multi-sets time histories versus single-set broadband time histories. As seen in Figure 7, similar to the observations in the STARDYNE fixed-base analysis in the previous section, the response spectra from broadband time history mostly envelop those from multi-sets time histories. By using multi-sets time histories, the peak acceleration at top of the internal structure has been reduced from about 4.8g of broadband to 3.7g.

Figure 7. ACS SASSI (incoherency) – Basemat (Left) and Top of Internal Structure (Right)

Figure 8. STARDYNE and ACS SASSI comparison - Basemat

6 CONCLUSION

In this paper, a seismic analysis of a typical reactor building is presented using a UHS with high frequency content. Floor response spectra are generated at both base slab and top of the internal structure. The results are obtained using STARDYNE for fixed-base analysis and ACS SASSI for seismic wave incoherency.

It is shown in this paper that the application of multiple sets of time histories instead of the conventional single set of broadband time histories can reduce the seismic response of the reactor building for rock condition. It is seen as expected that seismic wave incoherency has major effects on high frequency seismic response of the reactor building founded on hard rock. Although not shown in this paper, the application of multiple sets of time histories may also reduce the seismic response for other soil conditions. On the other hand, seismic wave incoherency has lesser effect when the building is founded on soft soil condition.
Seismic wave incoherency effects are most significant for buildings with large and rigid foundations. It is evidenced in the fixed-base STARDYNE analysis that the use of the multi-sets time histories can affect the seismic response regardless of foundation types. In case of buildings with significant mass and rigidity eccentricities, the seismic wave incoherency may increase the torsional seismic response significantly, while it is expected that the use of multiple sets of time histories can still be beneficial to buildings with eccentricities.

In summary, the application of multiple sets of time histories instead of the conventional single set of broadband time histories provides an alternative to mitigate seismic response. However, this concept of using multiple sets of time histories has to be rationalized and investigated further before it is accepted by the nuclear industry. First of all, this concept is more suitable for UHS but may not be appropriate for the standard spectral shape given in RG1.60, since the UHS represents both far field and near field earthquakes while the standard GRS mainly represents the effect of far field earthquakes. Secondly, further studies by seismologists and engineers are required for generating multiple sets of time histories for a single UHS. For example, how to factor in the building frequencies; how many sets of time histories and at what frequency ranges are appropriate; how many seconds each of the time histories should have; what are the PGAs for each set; what are the target power spectrum density for each set; what are the suitable acceptance criteria etc. Thirdly, but not last, appropriate and refined analysis models are required for high frequency analysis. The stick model used in this research paper provides a simplified and fast way to gain some insights. But for real design works related to high frequency analysis, stick models may not be suitable to capture the high frequency modes, and other refined models are required.

It is obvious that when multiple sets of time histories are applied, the analysis efforts will be increased significantly by comparison to a single set. However, these additional efforts may be justified if hardware design changes can be avoided.

REFERENCES

ASCE 4-98 (2000), Seismic Analysis of Safety-Related Nuclear Structures
ASCE/SEI 43-05, Seismic design Criteria for Structures, Systems and Components in Nuclear Facilities
EPRI NP-6041-SLR1 (1991), A methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1)
EPRI 1013504 (2006), Program on Technology Innovation: Effects of Seismic Wave Incoherence on Foundation and Building Response
EPRI 1015108 (2007), Program on Technology Innovation: The Effects of High-Frequency Ground Motion on Structures, Components, and Equipment in Nuclear Power Plants
IAEA DS422 (2009), Evaluation of Seismic Hazards for Nuclear Installations
USNRC Standard Review Plan (SRP), Section 3.7, Revision 3 – March 2007