Ground Motion Input in Seismic Evaluation Studies

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Impacts on Risk Assessment of Uniform Hazard Spectra

S. C. Wu, R. T. Sewell

Risk Engineering, Inc.

Prepared for
U.S. Nuclear Regulatory Commission

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Ground Motion Input in Seismic Evaluation Studies

Impacts on Risk Assessment of Uniform Hazard Spectra

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ABSTRACT

This report documents research on the subject of conservatism and variability in seismic risk estimates. Particularly, it examines the effects of the uniform hazard spectrum (UHS) for deriving probabilistic estimates of risk and in-structure demand levels, as compared to the more-exact use of realistic time history inputs (of given probability) that depend explicitly on magnitude and distance. The approach differs significantly from the conventional procedure in its exhaustive treatment of the ground-motion threat, and in its more detailed assessment of component responses to that threat.

It is found that the approximate uniform hazard in-structure spectrum (UH-ISS) obtained based on UHS appear to be very close to the more-exact results directed computed from scenario earthquakes. The conclusion does not depend on site configurations and structural characteristics. In addition, UH-ISS has composite shapes and may not correspond to the characteristics possessed a single earthquake. The shape is largely affected by the structural property in most cases and can be derived approximately from the corresponding UHS. Motions with smooth spectra, however, will not have the same damage potential as those of more realistic motions with jagged spectral shapes. As a result, UHS-based analysis may underestimate the real demands in non-linear structural analyses.

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Section 1

INTRODUCTION

This report documents elements of Phase 2 research on the subject of conservatism and variability in seismic risk estimates. The Phase 1 project was originally undertaken to identify potential sources of error arising from approximations in the development and use of ground-motion input in seismic evaluation studies, and to determine the magnitude of such potential errors. Phase 1 resulted in a report that documented the effects of ground-motion characterization bases on magnitude-dependent assessments of seismic hazard, fragility, and risk results (1).

Phase 2 consists of studies to examine specific additional aspects of the characterization and use of ground-motion input in seismic evaluation studies. The first part of Phase 2 addresses the impacts of using artificial versus real (empirical) time-history inputs to assess structure and equipment demands. The second part examines the effects of using the uniform hazard spectrum (UHS) as input for deriving probabilistic estimates of risk and in-structure demand levels, as compared to the more-exact use of realistic time history inputs (of given probability) that depend explicitly on magnitude and distance. All analyses for this study pertain to linear structure and equipment responses subject to ground motions in the Eastern US area. The approach throughout Phase 2 differs significantly from that in Phase 1, particularly in its more exhaustive treatment of the ground-motion threat, and in its more detailed assessment of component responses to that threat.

1.1 BACKGROUND

The significant topics addressed in Phase 1 were: (1) the relative conservatisms inherent in using Western U.S. type spectral shapes to characterize the seismic threat at Eastern U.S. sites; (2) the impact of magnitude disaggregation on assessments of seismic fragility, hazard, and risk; (3) the implications of nonlinear dynamic response modeling on magnitude-dependent results; (4) the effect of alternate motion parameterizations (PGA, spectral acceleration average over a frequency range of interest, inelastic spectral acceleration at a given frequency) on fragility and risk results; and (5) the impact of strong-motion duration on fragility estimates.

To address these topics, Phase 1 implemented methods for development and use of motion characterization considerably more detailed than those used in normal seismic evaluation practice. Hazard assessment and fragility assessment were conducted on a magnitude-dependent basis. A large number of highly realistic magnitude-dependent motions were simulated. Magnitude-dependent fragility families were obtained using nonlinear time-history analysis for the simulated motions and an extensive set of structural model parameters. The methods employed in fragility assessment were quite similar to those implemented in the state-of-the-art fragility study of the Diablo Canyon turbine building (2). Magnitude-dependent hazard and fragility results were combined to obtain magnitude-dependent risk estimates, revealing the contributions to core-damage frequency from each magnitude range considered. Results of this type of seismic risk assessment were compared with results from methods of seismic risk assessment normally implemented in practice. The sensitivity of seismic fragility curves and computed seismic risk estimates, to a variety of parameters (PGA, average spectral acceleration, and inelastic spectral acceleration) for characterizing ground motion input, was examined.

Despite the detail of Phase 1 investigation, a number of important issues regarding ground-motion input to seismic evaluation studies still remained to be addressed or clarified. These issues include

- Does the UHS define the most appropriate basis of ground-motion input in a seismic probabilistic risk assessment (PRA) or seismic margin assessment (SMA)?
- Can realistic, expected input to equipment mounted in structures be obtained in a practical way? Through use of a single motion time history, either artificial or real? Through use of a small suite of time histories?
- How can the multitude of possible spectral shapes be represented by practical descriptions of input ground motion, particularly to capture the expected impacts on system responses which are sensitive to simultaneous impacts on both low-frequency and high-frequency components? [In a real earthquake motion, input demands at low frequency and high frequency will vary from average demands in a random, yet (weakly) correlated way, with resulting random effects on system response. Because system response (failure or success) is not a simple linear function of motion demands at individual component frequencies, the expected impacts on system response may not be very well represented by component demands derived from a single motion with a smooth response spectrum.]

- Is there an appropriate (i.e., consistent with the seismic hazard) and practical (i.e., manageably small) set of scenario earthquake motions that may be used to produce realistic input for seismic evaluations? How can such earthquakes be developed or identified? How can it be insured that these earthquakes are physically consistent?

Each of these questions implies that the UHS shape may not be representative of specific real motions that might be expected in real earthquakes. Consequently, evaluation demands determined using the UHS shape as the basis for input may likewise not be representative of real earthquake demands. For a system that responds primarily to a narrow range of frequencies, the variations in spectral shape found in real earthquake motions would intuitively be less important than for multiple-frequency systems. Yet, in the typical case, nuclear power plants (NPPs) systems will respond importantly to multiple frequencies, and hence, maintaining realistic variations in input spectral shape may likely be important.

The critical issue to be resolved in Phase 2 investigation, therefore, is whether one must rely on realistic scenario earthquakes to adequately represent evaluation demands for structures and equipment mounted in structures, or whether a suitable procedure may be found for one to adequately assess evaluation demands using the UHS (or using motions derived simply therefrom).

To resolve this issue, it was decided that a much more complete description of the seismic threat would be needed to ascertain the adequacy of the UHS. Such a description of the seismic threat would be most accurately conveyed by a large suite of ground motions (with realistic variabilities in spectral shape) obtained from a comprehensive set of scenario earthquakes developed for all magnitude-distance pairs. To complete the description of the seismic threat, associated values of annual probability for each motion would be required. The motions and their respective probabilities could then be used in any way; i.e., to evaluate probabilities of in-structure demands, probabilities of component and system response states (including component and system failures), etc. These results could be readily compared with corresponding results derived from use of the UHS shape alone.

The approach in Phase 2, therefore, relies on an entirely new format for conducting probabilistic risk assessment; one that does not make use of seismic hazard and fragility curves, but rather, is based on fundamental (scenario) events (motions) and their probabilities for all possible cases. Knowing the scenario motion time histories and their probabilities, whatever responses of interest (in-structure demands, component failures, system failures, etc.)

can be computed directly, and corresponding risk measures can be directly obtained. The approach is more detailed and precise than conventional methods used for seismic risk assessment, because it introduces no simplifying approximations in characterizing the motion threat, which in turn affects the nature and accuracy of component and system response assessments. Thus, it serves as an accurate analysis for comparison of results with conventional methods that do introduce such approximations in motion characterization and seismic risk methodology.

Because this approach to seismic risk assessment is new, a principal task in Phase 2 work has been to fully develop the methodology, which will involve a rigorous approach for developing scenario motion time histories. This development, however, has been only a means to an end; that of being able to assess the most representative, simplified motion input to seismic evaluation studies. To accomplish this objective systematically and provide meaningful answers to the questions noted above, two distinct elements of project study in Phase 2 were identified.

- Part 1. Impacts of the Use of Artificial Motion Inputs

Before impacts on system responses, inelastic responses, risk measures, and the like are considered for (M,R)-dependent motions, a more basic concern to be addressed has to do with the appropriateness of using artificial time history inputs in seismic evaluation studies. Overall, the fundamental aspect of Part 1 study is to determine whether or not artificial motions, generated to match a UHS shape using common procedures and recommendations for motion simulation, produce realistic evaluation demands for nuclear power plant structures and equipment; i.e., demands generally representative of those computed for strong empirical earthquake motions. The intent in Part 1 is not to address what specific (M,R) pairs might dominate evaluation-demand risks or failure risks, and hence, to ascertain whether or not artificial motions adequately represent effects of those specific risk-dominant magnitudes and distances. Rather, the intent is to test simply if a single artificial motion input would generally tend to either possess or produce fundamental characteristics that are deficient with respect to corresponding characteristics expected from a real strong ground motion. All analyses undertaken for Part 1 study pertain to linear structure and equipment responses.

- Part 2. Realistic Evaluation of In-Structure Demand Risks

The purpose of this study is to develop realistic and accurate descriptions of risk-consistent floor motions (in-structure response spectra) to be used as input to equipment, and to test whether or not the UHS can be used as a basis for developing realistic risk-consistent input to equipment mounted in structures. All analyses for this study pertain to linear structure and equipment responses subject to typical ground motions in the EUS area.

The first aspect of this study is to obtain uniform-hazard in-structure spectra directly by using scenario motion time history inputs (and their probabilities) and evaluating in-structure demands for each scenario time history. Knowing the in-structure demands and their annual rates of occurrence, the probability of exceeding any given level of in-structure demand can be determined; alternatively, the in-structure demand level corresponding to a given annual probability of exceedance can be evaluated. A plot of in-structure demands, as a function of equipment vibration frequency, for a fixed annual probability level, results in a uniform-hazard in-structure spectrum (UH-ISS). An approximation to the UH-ISS can be obtained simply by generating an artificial motion that closely matches the UHS, and calculating the in-structure spectrum (ISS) corresponding to this input. For instance, a 10^{-4} UH-ISS can be approximated as a corresponding ISS computed in response to an artificial motion that is closely compatible with the 10^{-4} UHS.

The second aspect of this study is to examine how shapes of scenario ISS [derived from motions for given magnitude-distance (M,R) pairs] compare with shapes of UH-ISS and shapes of ISS derived from artificial motions generated from the UHS shape.

Evaluation of NPPs under severe conditions, having the potential to induce accidents or adverse impacts within a plant, has been the objective in developing both the Individual Plant Examination (IPE) and the Individual Plant Examination of External Events (IPEEE) programs, undertaken in response to the NRC's severe-accident policy (3,4,5,6). The IPEEE program includes the evaluation of NPP severe-accident resistance to earthquake events. This study, therefore, relates directly to seismic evaluations performed for IPEEEs, and technical reviews of such evaluations.

The first part has been completed, results in a report (7). that documents the adequacy of using artificial ground motions as inputs for SMA and PRA. The major conclusions from Part 1 are:

1. Single artificial motions simulated to match Eastern U.S. target spectra have no apparent tendency to possess gaps in the energy content found in their power spectral densities. In simulating multiple artificial motions to match, on average, a given response spectrum, while maintaining realistic variations in spectral amplitude and shape, situations can be introduced that tend to produce gaps in PSDs of (isolated cases of) individual motions. Such cases arise, however, only when the target spectrum is matched very closely with a small number of motions. In addition, the spurious PSD gaps that sometimes result are found over high frequencies, and primarily for simulation of Western U.S. type motions. Furthermore, such gaps were not observed to result in deficient overall (average) response demands.

Consequently, from the observations in this study, it may be concluded that artificial motions possess PSDs generally representative of those found in real earthquake motions, for the frequency range of interest.

2. Evaluation demands computed for single artificial motions are generally similar to corresponding demands computed for empirical motions. In a limited number of comparisons with results produced for artificial motions matching Eastern U.S. target spectra, the response over higher-mode frequencies was notable under-estimated in comparison to demands produced for empirical motions. This discrepancy, however, is largely attributed to variations in the empirical motion spectra, for a given motion anchor basis, relative to the shape of the target spectrum, and to inconsistencies between the spectral shapes of individual motions and of the uniform hazard spectrum. Average evaluation demands computed for multiple artificial motions result in similar comparisons with empirical-based demands, as observed for corresponding cases of single artificial-motion input.
3. Average linear evaluation demands produced for the multiple artificial motions are similar to those produced for corresponding cases of single artificial-motion input. It is expected, however, that non-linear evaluation demands, and demands on nuclear-power-plant systems, would have greater sensitivity to this difference in characterization of motion input.
4. Fundamental differences have been observed in structural responses and ISS demands for Eastern U.S. motion inputs relative to Western U.S. motion inputs. The Eastern U.S. motions generally excite a greater degree of higher-mode response. This leads to an entirely different distribution of seismic forces than observed for Western U.S. motions and than typically assumed in seismic evaluation and design practice. The greater contribution from higher-modes leads to floor motions that are significantly greater, for a given base shear, than those observed for Western U.S. motions.

1.2 STUDY ORGANIZATION

A detailed outline of this study is provided in Section 2. The study approach and parameters are fully described in that section, including the methods used to generate artificial ground motions, the ground motion attenuation models used, the properties of the structural models, and other variables employed in developing the approximate and the more-exact uniform hazard in-structure spectrum (UH-ISS) based on magnitude and distance disaggregation.

Section 3 presents the results of the more-exact in-structure response spectrum analyses conducted directly using scenario earthquake ground motions as inputs. Section 4 presents the approximate in-structure response spectrum analyses conducted using generated motions derived from the UHS. Impacts of using the approximate methods are discussed.

Section 5 show how shapes of the scenario ISS (derived from motions of a given magnitude and distance) compared with shapes of US-ISS and shapes of ISS derived from artificial motions generated from the UHS shape.

Finally, Section 6 summarizes the comparisons and provides conclusions pertaining to the impacts, on seismic evaluation studies, of using UHS to generate artificial motions to develop in-structure demand spectra.

Section 2

DESCRIPTION OF STUDY APPROACH AND PARAMETERS

This chapter provides an outline of the basic study approach, and identifies the set of parameter variations used in producing the numerous results. The intended use of the parameter study results, for making comparisons and drawing relevant conclusions, is also explained.

2.1 OUTLINE OF STUDY

The approach of this study is outlined as follows:

- Selection of the ground motion model appropriate for study in the EUS.
- Selection of structural models to be used to derive UH-ISS.
- Generation of realistic scenario earthquakes (with variabilities in spectral shapes) based on magnitude and distance disaggregation.
- Evaluation of UH-ISS based on scenario earthquakes.
- Evaluation of UHS corresponding to the UH-ISS.
- Derive approximate UH-ISS based on UHS.
- Comparisons of various UH-ISS results.
- Comparisons of the shapes of scenarios ISS and UH-ISS.

We intend to introduce a new format of seismic hazard and risk analysis using scenario earthquakes directly and use this new approach as the basis to study if UHS can be used to derive the approximate UH-ISS. Some elements of this outline are further illustrated below.

2.2 MODELS AND PARAMETERS

2.2.1 Ground Motion Model

The ground motion model chosen in this study is taken from (8) which has the following form:

$$\ln Y = C_1 + C_2(M - 6) + C_3(M - 6)^2 - C_4 \ln R_M - (C_5 - C_4) \max(\ln(R_M/100), 0) - C_6 R_M + \epsilon_U + \epsilon_R \quad (2-1)$$

$$R_M = \sqrt{(R^2 + C_7^2)} \quad (2-2)$$

where Y is the spectral acceleration or peak ground acceleration, C_1 through C_7 are constants determined from modeling results, M is the magnitude and R is the closest horizontal distance to the rupture surface, ϵ_U and ϵ_R are random variables representing prediction variabilities resulting from uncertainty (U) and randomness (R). This latest model derived from random vibration theory is judged to be representative for earthquakes in the EUS. Coefficients are given in Table 2-1.

2.2.2 Structural Model

Three structural models are used to examine the effects of using the simplified and the more-exact approaches to derive the UH-ISS. These models are identified and described as follows:

- A five degree-of-freedom (DOF) model of a hypothetical NPP five-story building having 3-Hz fundamental vibration frequency. The model has uniform mass and stiffness.
- A five degree-of-freedom model of a real, four-story NPP control building having 7-Hz fundamental vibration frequency. This model was used as the basis for fragility analyses and failure probability calculations in Phase 1 study (1).
- A two degree-of-freedom model of a hypothetical two-story NPP building having 10-Hz fundamental vibration frequency. The model has uniform mass and stiffness.

Structural damping in all cases is assumed to be 5% (of critical) in the first two modes. [The value of 5% is typical of values recommended for seismic margin evaluations (9)]. Damping ratios for higher modes are computed based on Rayleigh damping. Tables 2-2 to 2-4 present basic dynamic characteristics of the three structural models.

2.2.3 Generation of Artificial Ground Motions

Regulatory guidelines on the development of artificial time-history inputs for design purposes are contained in NUREG-0800, the Standard Review Plan (10). These guidelines are based on recommended power spectral density (PSD) requirements which have been developed to be compatible with design-type response spectra. Such PSD requirements have been documented, for instance, in NUREG/CR-3509 (11), Reference (12), and NUREG/CR-5347 (13). Artificial motions generated using these recommended guidelines have greatest validity to motions characteristic of the Western U.S., as design procedures for nuclear power plants have predominantly relied on the empirical database of strong motions recorded in the Western U.S., primarily California. Such design procedures include the criteria found in the AEC Regulatory Guide 1.60 (14) and in NUREG/CR-0098 (15).

Here we use the same approaches discussed in details in the first part of this study (8). Two types of artificial motions will be generated. The first type of motions have jagged spectral shapes, representing variabilities as seen in real earthquakes. The other type of motions have smooth spectral shape, matching a target spectrum closely. Both types of motions are found to not have any deficiency compared to the records generated by the real earthquakes.

2.2.4 Evaluation of UHS

A uniform hazard spectrum (UHS), as its name implies, is a spectrum of a certain kind of ground motion measurement associated with a fixed exceedance probability, uniformly across all frequencies. Basically it contains the information of the ground motion amplitudes predicted for a given (annual) exceedance probability at a given site for all single-degree-of-freedom (SDOF) structures. To construct a UHS, one only needs a ground motion model (usually in terms of ground motion attenuation equations for various frequencies) and an earthquake recurrence model that describes how often, how large and where earthquakes occur. Assume that the ground motion model can be expressed as

$$A_f = g_f(m, r) + \epsilon_f \quad (2 - 3)$$

where A_f is the spectral amplitude of interest, $g_f(m, r)$ is the ground motion attenuation function of magnitude, m , and distance, r , and ϵ_f is a random variable, representing the randomness in the model; all variables are for a specific frequency f . $\ln(\epsilon)$ is usually assumed normally distributed with a mean of 0 and a standard deviation of σ_f . Also assume that a joint density function of magnitude and distance, $f_{MR}(m, r)$ and a mean recurrence rate λ represent the recurrence patterns of the earthquakes of interest¹. The annual probability

¹Here we implicitly assume that the mean annual recurrence rate, λ , is sufficient to describe the temporal behaviors of earthquakes. This simplified assumption, known as the Poisson model, is commonly adopted in seismic hazard analysis.

that the ground motion amplitude, A_f , will exceed a certain level, a , can be written as

$$P[A_f \geq a] = \lambda \int_R \int_M P[A_f \geq a|m, r] dm dr \quad (2-4)$$

Basically the total hazard in Equation 2-4 is calculated by disaggregating the contribution to various combinations of magnitude-distance pairs. Using the ground motion attenuation function in Equation 2-3, $P[A_f \geq a|m, r]$ can be expressed as

$$P[A_f \geq a|m, r] = 1 - \Phi \left(\frac{\ln(a) - \ln(g(m, r))}{\sigma_f} \right) \quad (2-5)$$

where Φ is the cumulative distribution function of a standard normal random variable.

By systematically varying a for different frequencies and performing interpolation if necessary, one can obtain, for example, spectral amplitudes that corresponding to 10^{-4} annual exceedance probability for all frequencies; this is a Uniform Hazard Spectrum.

2.2.5 Evaluation of UH-ISS

A uniform hazard in-structure spectrum (UH-ISS) can be obtained much the same way as the uniform hazard spectrum. Here the interest is not the response of a structure itself, but rather, the response of an equipment that is mounted on the structure. The parameter of interest could be the spectral velocity of the equipment (subject to the vibrations of the structure during earthquakes). As a result, the ground motion attenuation function (of the structure) cannot be used explicitly in deterring the UH-ISS. A logical way to evaluate the exceedance probability of the in-structure response, A_{Sf} , is again to disaggregate the contribution to various M-R pairs, as

$$P[A_{Sf} \geq a] = \lambda \int_R \int_M P[A_{Sf} \geq a|m, r] dm dr \quad (2-6)$$

Here the response variable, A_{Sf} , is a function of the structure itself, S , and the frequency of the equipment, f . We can further disaggregate $P[A_{Sf} \geq a|m, r]$ to

$$P[A_{Sf} \geq a|m, r] = \int_{\tilde{y}} P[A_{Sf} \geq a|\tilde{y}(m, r), m, r] d\tilde{y} \quad (2-7)$$

where $\tilde{y}(m, r)$ stands for a particular ground motion time history for a given m and r . Given $\tilde{y}(m, r)$ and the structure S , calculating $P[A_{Sf} \geq a|\tilde{y}(m, r), m, r]$ becomes a standard structure analysis problem.

Substitute Equation 2-7 to Equation 2-6, we get the following form to derive the uniform hazard in-structure spectrum:

$$P[A_{Sf} \geq a] = \lambda \int_R \int_M \left(\int_{\tilde{y}} P[A_{Sf} \geq a|\tilde{y}, m, r] d\tilde{y} \right) dm dr \quad (2-8)$$

Equation 2-8 implies that to calculate $P[A_{Sf} \geq a]$, we can first calculate the conditional probability $P[A_{Sf} \geq a|\tilde{y}, m, r]$ for a given ground motion time history, magnitude and distance, and then multiply the conditional probability by the likelihood of seeing such a time history, magnitude and distance. Numerically, we need to consider all possible $\tilde{y}(m, r)$ that collectively, represent the characteristics of a given (m, r) and all possible combinations of (m, r) that may induce the seismic hazard. Note that, mathematically, we can rewrite Equation 2-8 by changing the order of integration to

$$\begin{aligned} P[A_{Sf} \geq a] &= \lambda \int_{\tilde{y}} \left(\int_R \int_M P[A_{Sf} \geq a|m, r, \tilde{y}] dm dr \right) d\tilde{y} \\ &= \lambda \int_{\tilde{y}} P[A_{Sf} \geq a|\tilde{y}] d\tilde{y} \end{aligned} \quad (2-9)$$

With the integration over $\tilde{y}$ at the outer loop, Equations 2-10 implies that one may be able to generate motions from some kinds of "composite spectrum" for the structure to determine the equipment response. A UHS for the structure appears to be a logical choice for this composite spectrum. This approach, if done properly, has the benefit of employing fewer motions to derive the UH-ISS. However, it is not clear how to generate motions from "composite spectrum" correctly without disaggregating again on magnitudes and distances.

Once all motion inputs, structural model variations, and parameters defining in-structure spectra have been developed, response analyses need to be conducted to determine evaluation demands for structures and equipment. In all cases introduced in this report, structures are considered to behave linearly and vibration responses are evaluated using multiple-degree-of-freedom stick models subjected to base input. Hence, linear dynamic analyses of lumped mass models are conducted to obtain time histories of floor-motion responses for the structural models subjected to the artificial and empirical motion inputs. From time histories of floor absolute accelerations, equipment evaluation demands are computed as in-structure (floor) response spectra.

2.2.6 Evaluation of Approximate UH-ISS

There are two possible ways to derive the UH-ISS from UHS. The first one is to generate a single motion that closely matches the target UHS. This motion then is used as the input to evaluate the approximate UH-ISS. The second approach, similar to the more-exact approach,

is to generate a small number of motions, that on the average matches the target UHS, but individually has realistic variability in the spectral shapes. The approximate UH-ISS is obtained by averaging the individual UH-ISS derived from these motions. Both approaches will be employed and the results will be compared against the more-exact UH-ISS in the study. The damping used in all ISS analyses is 5%. Again, 5% is a representative value of equipment damping recommended for use in SMA evaluation procedures (9).

2.2.7 Comparisons of various UH-ISS results

Here we shall compare the various UH-ISS derived from the more-exact approach and the approximate approaches for the three structures. We seek to determine if the UHS-based UH-ISS are adequate, and, under what conditions, are these approximate results adequate.

2.2.8 Comparisons of the shapes of scenarios ISS and UH-ISS

Here we show the shapes of the more-exact UH-ISS and the approximate UH-ISS and study how these UH-ISS compare with the ISS for various magnitudes and distances.

Table 2-1

Coefficients of the ground motion attenuation function using L_g magnitude. (Spectral acceleration and PGA are in the unit of g.)

Freq.	C_1	C_2	C_3	C_4	C_5	C_6	C_7
1.0	-0.12	2.05	-0.34	0.90	0.59	0.0019	6.8
2.5	0.90	1.70	-0.26	0.94	0.65	0.0029	7.2
5.0	1.60	1.24	0	0.98	0.74	0.0039	7.5
10.0	2.36	1.23	0	1.12	1.05	0.0043	8.5
25.0	3.54	1.19	0	1.46	1.84	0.0010	10.5
PGA	2.07	1.20	0	1.28	1.23	0.0018	9.3

Table 2-2
Dynamic Characteristics of 3-Hz, Five-Story (5 DOF) Building Model

Property	Mass, Element, or Mode Number				
	1	2	3	4	5
Mass (k-s ² /in)	20.00	20.00	20.00	20.00	20.00
Stiffness (k/in)	90000	90000	90000	90000	90000
Frequency (Hz)	3.04	8.87	14.0	18.0	20.5
Damping (%)	5.00	5.00	6.68	8.17	9.15
Displacement of:	Normalized Mode Shapes				
Mass #1	+1.70	-.456	-.597	+.549	+.326
Mass #2	+.326	-.597	-.170	-.456	-.549
Mass #3	+.456	-.326	+.549	-.170	+.597
Mass #4	+.549	+.170	+.326	+.597	-.456
Mass #5	+.597	+.549	-.456	-.326	+.170

Table 2-3
Dynamic Characteristics of 7-Hz, Four-Story (5 DOF) Building Model

Property	Mass, Element, or Mode Number				
	1	2	3	4	5
Mass (k-s ² /in)	12.90	12.63	4.05	12.58	8.81
Stiffness (k/in)	209300	220800	283900	253900	195100
Frequency (Hz)	7.01	19.3	31.2	36.2	63.1
Damping (%)	5.00	5.00	6.76	7.60	12.4
Displacement of:	Normalized Mode Shapes				
Mass #1	+.062	-.156	-.161	-.152	+.012
Mass #2	+.114	-.171	+.047	+.164	-.088
Mass #3	+.144	-.707	+.128	+.032	+.451
Mass #4	+.174	+.576	+.140	-.143	-.077
Mass #5	+.191	+.170	-.192	+.106	+.126

Table 2-4
Dynamic Characteristics of 10-Hz, Two-
Story (2 DOF) Building Model

Property	Mass, Element, or Mode Number	
	1	2
Mass ($\text{k-s}^2/\text{in}$)	10.00	10.00
Stiffness (k/in)	103380	103380
Frequency (Hz)	10.0	26.2
Damping (%)	5.00	5.00
Displacement of:	Normalized Mode Shapes	
Mass #1	+.526	+.851
Mass #2	+.851	-.526

Section 3

UNIFORM HAZARD IN-STRUCTURE SPECTRA BY SCENARIO EARTHQUAKES

This section presents the procedures and the results of evaluating uniform hazard in-structure spectra (UH-ISS) using scenario earthquakes directly, as discussed in Section 2. This approach requires generation of realistic ground motion time histories with realistic variabilities in spectral shape. These motions, collectively, should represent the characteristics of the seismic threat at a specific site. Detailed procedures and results are presented and discussed as follows.

3.1 GENERATE SCENARIO EARTHQUAKES

For practical engineering applications in the Eastern US (EUS), we select (L_g) magnitude 5.0 and 7.8 as the minimum and the maximum magnitudes of the earthquakes of interest. We use the ground motion attenuation function, as presented in Section 2, as a representative model used in the EUS. The distance of interest is from 10 to 500 km. We discretize magnitude in the 5.0 – 7.8 range into 15 equally-spaced values with an interval of 0.2 (i.e., 5.0, 5.2, 5.4, ..., 7.8). Similarly, we discretize distance into the following 32 values: 10, 20, 30, ..., 200, 225, 250, ..., 500; these values are equally-spaced with an interval of 10 between 10 and 200 and with an interval of 25 between 200 and 500. As a result, we have 480 (i.e., 15×32) magnitude-distance pairs, each having potential to induce seismic hazard with different characteristics.

To illustrate how magnitudes and distances affect the spectral ordinates and their shapes, the median predicted spectral velocity for these magnitude-distance pairs are plotted in Figures 3-1 to 3-15. Note how spectral shapes vary with different magnitudes and distances. Small magnitude earthquakes tend to have relatively more high frequency contents (e.g., comparing Figure 3-1 and 3-15). Ground motion amplitudes attenuate relatively faster at high frequencies (e.g., comparing plots within Figure 3-1). Also note that spectral amplitudes decrease roughly below 0.5 Hz, depending on the magnitude (not shown in the figures). These spectra will be used as the target spectra to generate realistic ground motions. In addition, their shapes will also be used for comparison with the shapes of uniform hazard spectra (UHS).

To capture the characteristics of earthquakes with different magnitudes at different distances, we generate 50 motions for each magnitude-distance pair based on its median spectral velocity. The simulation procedures are discussed in the first part of this study (1). The frequency range of interest is from 1 to 25 Hz, including the fundamental frequencies of the three structures (3, 7 and 10 Hz respectively) in this study. Individually, each motion has "jagged" spectral shape as those induced by real earthquakes, yet collectively their average spectrum matches the target spectrum very closely. The total number of motions generated in this study is 24000 (i.e., $15 \times 32 \times 50$), making it impractical to show each motion individually. To illustrate, we show only a very small fraction of these motions. Figure 3-16 depicts the response spectra of the 50 simulated motions and how the average spectrum matches the target response spectrum for the magnitude 6.4, distance 20 km case. The average of the spectra of the simulated motions is constrained to match within 3% of the target spectrum at selected frequencies (1, 2.5, 5, 10 and 25 Hz) where ground motion attenuation equations are available. The standard deviation of the (log) spectral amplitudes is also matched with the same precision at the given frequencies.

Figure 3-17 to 3-20 show time histories of 20 of the 50 motions generated for this case. These motions have different characteristics as displayed in their time histories and in their response spectra (Figure 3-16). These motions, together with other motions generated for different magnitudes and distances, form the basis for conducting further analysis using scenario earthquakes directly.

3.2 DETERMINE UH-ISS

We illustrate the procedures of using these simulated motions directly to determine UH-ISS by the following example.

Suppose that we want to determine the 10^{-4} UH-ISS for the third floor of the 3 Hz structure in the EUS. Since there is no explicit method to calculate the spectral amplitude corresponding to a specified exceedance probability, we need to solve this problem iteratively. A starting value of in-structure PSV is used to determine the exceedance probability using the methods described in Section 2. If this probability is found to be higher (or lower) than 10^{-4} , we increase (or decrease) the PSV amplitude level and re-do the analysis until we find a specific PSV amplitude level that gives the exceedance probability of 10^{-4} . (Alternatively, a wide range of in-structure PSV values can be used to determine the corresponding exceedance probabilities; these (in-structure PSV, exceedance probability) pairs could serve as the data base for interpolation for other combinations of PSV-probability pairs of interest.) This

procedure then is repeated for all the frequencies that are required to define the in-structure spectrum.

Figures 3-21 depicts the (conditional) probability of exceeding 10 (cm/s) of in-structure PSV for six different frequencies at the third floor of the 3 Hz structure given the occurrences of earthquakes with various magnitudes and distances. As shown in the figure, for a given frequency, the exceedance probability decreases with distance while increases with magnitude. Also note that the 3 Hz case has relatively higher (conditional) exceedance probability for a given magnitude and distance because the in-structure response is mostly amplified by the structure around its fundamental frequency.

To obtain the (marginal) probability of exceeding 10 (cm/s) of the in-structure PSV, the conditional probability (given magnitude and distance) needs to be weighted by the likelihood of having such events and then integrated over all possible events (magnitudes and distances). These likelihoods (in this case, the recurrence probabilities), which serve as the weights for the conditional probabilities, are fully described in the earthquake recurrence model for a specific site. For illustration, we choose the site of the Millstone nuclear power plant as a representative site in EUS. Four area sources are identified as the possible contributors to the seismic hazards (16). Their individual recurrence rates and the total recurrence rate are depicted in Figure 3-22 and 3-23. Note that the recurrence rates are mostly dominated by the first two sources as shown in Figure 3-22. Also note that since these sources are area sources, there is no single magnitude-distance pair that dominates the hazard. This may not apply to the WUS where active fault segments are usually identified and the fault segments tend to generate characteristic earthquakes. To determine the (marginal) probability of exceeding 10 (cm/s) of the in-structure PSV as a function of magnitudes and distances, the (conditional) probability of exceedance for each magnitude-distance pair in the plots of Figures 3-21 is multiplied by the corresponding occurrence rate (Figure 3-23). The final results are shown in Figure 3-24. These three-dimensional plots represent the exceeding probability contributed by various magnitude-distance pairs; the total probability of exceedance is represented by the volume of the curves in each plot. In this particular case, the starting value of the in-structure PSV (10 cm/s) does not yield the desired probability 10^{-4} ; another trial value of the in-structure PSV is required to re-do the analysis. The whole processes need to be repeated for all three structures at all the floors for all the frequencies of interest.

It is usually informative to disaggregate hazard on magnitudes and distances as shown in Figure 3-24. Take the 3 Hz case, for example, the total hazard comes mostly from earthquakes with magnitude around 6.4 and distance around 30 km. This disaggregation will provide valuable information if a small number of scenario earthquakes are to be developed and used in subsequent analysis as an approximation to the much more expensive, full-blown approach used in this study.

3.3 RESULTS FOR UH-ISS

Here we show in Figure 3-25 the 10^{-4} UH-ISS for the first, the third and the fifth floors of the 3 and the 7 Hz structures and both floors for the 10 Hz structure. These more-exact UH-ISS will serve as the basis for comparison with UH-ISS derived from approximate approaches. As expected, higher floors tend to demand higher spectral amplitudes for a given structure and a given exceedance probability. UH-ISS is also likely to have peak(s), representing amplification of structures near their natural frequencies.

It is noted that most of the analysis expense comes from the structure analysis portion in evaluating UH-ISS. This is even more severe when the ground motion time history is long (for earthquakes with large magnitude and long distance) or when non-linear structural analysis is required (not in this study). Once the (conditional) exceedance probability is obtained for each magnitude-distance pair, it is fairly easy to change the site configuration (i.e., the recurrence probability of earthquakes with certain magnitudes and distances, such as in Figure 3-23) to obtain the UH-ISS for a new site, provided that the ground motion model remains valid. Also note that the total recurrence rate of earthquakes usually serves only as a scaling parameter; it will not affect the shape of the UH-ISS. The relative contribution to UH-ISS from earthquakes with different magnitudes and distances and how the shape of the UH-ISS varies with the change of contributions are of more interest.

For comparison purposes, we introduce a hypothetical site with the recurrences probabilities of earthquakes as shown in Figure 3-26. This site configuration represents a California site where line sources, as opposed to area sources, usually dominate the hazard. In this hypothetical case, hazard is expected to be dominated by earthquakes within a smaller range of magnitudes and distances. It is expected that the approximate approaches based on UHS shall give results closer to the more-exact approach since the UHS is likely to possess characteristics of earthquakes with a certain magnitude at a certain distance. In other words, ground motions generated based on the UHS (detailed to be discussed in the next section) will likely be the scenario earthquakes that control the UH-ISS. Results of this case are shown in Figure 3-27.

Figure 3-1. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 5.0 at various distances (r , km).

Figure 3-2. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 5.2 at various distances (r , km).

Figure 3-3. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 5.4 at various distances (r , km).

Figure 3-4. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 5.6 at various distances (r , km).

Figure 3-5. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 5.8 at various distances (r , km).

Figure 3-6. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 6.0 at various distances (r , km).

Figure 3-7. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 6.2 at various distances (r , km).

Figure 3-8. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 6.4 at various distances (r , km).

Figure 3-9. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 6.6 at various distances (r , km).

Figure 3-10. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 6.8 at various distances (r , km).

Figure 3-11. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 7.0 at various distances (r , km).

Figure 3-12. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 7.2 at various distances (r , km).

Figure 3-13. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 7.4 at various distances (r , km).

Figure 3-14. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 7.6 at various distances (r , km).

Figure 3-15. Predicted median PSV (cm/s) for earthquakes with magnitude (m) 7.8 at various distances (r , km).

Figure 3-16. (Left) Target PSV and the average PSV of 50 simulated motions +/- one standard deviation (sigma) for the magnitude (m) 6.4, distance (r) 20 km case; (Right) PSV of the 50 simulated motions.

Figure 3-17. Five selected ground motion time histories simulated for the magnitude 6.4, distance 20 km case. Note that scales are different for each motion.

Figure 3-18. Five selected ground motion time histories simulated for the magnitude 6.4, distance 20 km case. Note that scales are different for each motion.

Figure 3-19. Five selected ground motion time histories simulated for the magnitude 6.4, distance 20 km case. Note that scales are different for each motion.

Figure 3-20. Five selected ground motion time histories simulated for the magnitude 6.4, distance 20 km case. Note that scales are different for each motion.

Figure 3-21. (Conditional) probability of exceeding 10 (cm/s) of in-structure PSV for six different frequencies at the third floor of the 3 Hz structure given the occurrences of earthquakes with various magnitudes and distances.

Figure 3-22. Recurrence rates of earthquakes of four area sources near the Millstone Nuclear Power Plant as a function of magnitudes and distances.

Figure 3-23. Total Recurrence rate of earthquakes as a function of magnitudes and distances near the Millstone Nuclear Power Plant site.

Figure 3-24. Probability (as a function of magnitudes and distances) of exceeding 10 cm/s of the in-structure PSV at the third floor of the 3 Hz structure at Millstone for frequencies: 1, 3, 5, 8, 10 and 25 Hz. The volume of the plots represents the total probability of exceedance contributed by earthquakes with all possible magnitudes and distances.

Figure 3-25. UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively. The results are obtained by using the scenario earthquakes directly.

Figure 3-26. Recurrence rates of earthquakes as a function of magnitudes and distances for a hypothetical site.

Figure 3-27. UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the hypothetical site.

Section 4

UNIFORM HAZARD IN-STRUCTURE SPECTRUM DERIVED FROM UHS

This section presents results of evaluating uniform hazard in-structure spectra (UH-ISS) using approximate approaches, as discussed in Section 2. To evaluate the UH-ISS associated with a certain exceedance probability, a UHS corresponding to the same probability is obtained first. Based on the UHS, a ground motion time history is then generated to smoothly match the spectrum. This motion in turn is used as the input for evaluating the approximate UH-ISS. Alternatively, a small number of motions with realistic variabilities in spectral shape could also be generated to fit the target spectrum. These more realistic motions then can be used as input in subsequent analysis to evaluate the UH-ISS. Both simplified approaches, which are derived from generating motions based on the UHS, require generation of very few motion time histories for structural analysis. As a result, most of the analysis effort needed in the more-exact approach is reduced. We shall compare UH-ISS derived from the two simplified approaches to the more-exact results obtained in Section 3. Specific procedures and results are outlined and discussed as follows.

4.1 DETERMINE UHS

We use the same recurrence models and ground motion models used in the previous section to construct the UHS. Magnitude range of interest is from (L_g) 5.0 to 7.8, discretized to 15 equally-spaced values with an interval of 0.2. Distance range is from 10 to 500 km, discretized to 32 values with an interval of 10 km between 10 and 200 km, and an interval of 25 km between 200 and 500 km. The total number of magnitude-distance pairs is 480. The total number of motions used in the analysis is 24000 (50 motions per magnitude-distance pair).

We continue to use 10^{-4} as the target probability for the UHS. Similar to the procedures used in the previous section, iterations are needed to determine the UHS. A starting value of PSV is used to determine the exceedance probability using the procedures discussed in Section 2. If this probability is found to be higher (or lower) than 10^{-4} , we then increase (or decrease) the PSV level and re-do the analysis until we find the specific PSV level that yields the 10^{-4} exceedance probability. This procedure then is repeated for all the frequencies that define the UHS. Note that given the ground motion model and the recurrence rates of earthquakes, UHS can be determined analytically without using scenario earthquake time histories (see

Figure 4-1. 10^{-4} Uniform Hazard Spectrum for the Millstone site.

Equations 2-1 to 2-3). We shall use the scenario earthquake time histories directly, however, since they are available and they provide better insight into the evaluation process.

For simplicity, intermediate results similar to Figures 3-21 and 3-24 are not shown. The 10^{-4} UHS for the Millstone site using the same recurrence and the ground motion models is presented in Figure 4-1. It is noted that the shape of a UHS is usually a combination of many possible shapes generated by earthquakes with different characteristics; there may not exist earthquakes with a certain magnitude and distance that have this particular shape. In this particular case, however, the shape of the UHS is very similar to the spectral shape generated by earthquakes with magnitude 6.2 and distance 20 km (see Figure 3-7).

4.2 DETERMINE UH-ISS

Based on the 10^{-4} UHS, one artificial ground motion is generated to match the UHS. For comparison purposes, we actually generate four such motions, each closely matching the target UHS. Figure 4-2 shows the target UHS and the response spectra of the artificial motions. Figure 4-3 shows the acceleration time history of the four motions. Note that although these motions all match the target UHS well, their duration and frequency content are generated to have different characteristics for comparison purposes. These motions are then used to generate the in-structure spectra for the three structures, as an approximation to the 10^{-4} UH-ISS.

4.3 RESULTS FOR APPROXIMATE UH-ISS

Figures 4-4 to 4-7 show the approximate UH-ISS based on the four artificial motions. We also plot the more-exact UH-ISS with each of the four motions for most of the floors of the structures, as shown in Figures 4-8 to 4-10. In all the plots, the approximate approaches yield results very close to one another and to the more-exact results.

We also use the other approximate approach where a small number (ten in this case) of motions are generated. Each motion has jagged spectral shape while the average of the spectra matches the target UHS. Figure 4-11 shows the response spectra of these motions and the fit of the average spectrum. Figures 4-12 and 4-13 show the acceleration time history of these motions. The approximate 10^{-4} UH-ISS is obtained by the average of the ten UH-ISS (using the ten motions as inputs), as shown in Figure 4-14. Figures 4-15 and 4-17 show comparisons of the approximate and the more-exact UH-ISS obtained in Section 3. Again, for all practical purposes, the UH-ISS derived from UHS is very close to the more-exact UH-ISS.

For further exploration of the adequacy of the approximate approaches, we also evaluate the UH-ISS using the two approximate methods for the hypothetical site discussed in the previous section. The corresponding UHS is generated first, as shown in Figure 4-18. Four ground motions that smoothly match the target UHS are generated, as shown in Figures 4-19 and 4-20. UH-ISS generated by the four motions and the comparisons of these UH-ISS are shown in Figures 4-21 to 4-27. The approximate results are found to be very close the more-exact result. The results of using UHS and motions with jagged spectral shapes to derive UH-ISS are shown in Figures 4-28 to 4-34. Again, the average of the UH-ISS derived from the UHS matches well the more-exact UH-ISS.

4.4 DISCUSSION

The results presented above indicate that UHS can be used as the basis to generate one or very few motions to derive UH-ISS, and, possibly, to be used for other analyses that require explicit motion time history as inputs. In other words, hazard analysis based on magnitude (and distance) disaggregation may not be necessary if the structural system is linear (as assumed in this study). However, this conclusion may not be generalized to situations where non-linear behaviors of structures are important. In these cases, the damage potential of motions depends on the response measures over a range of frequencies. Motions with jagged spectral shape (as generated in this study for different magnitudes and distances) inherently will have different impact on the structures than motions with smooth spectral shapes (as generated to fit a UHS) (see, for example, (17)). Further study is required to clarify the impact of using UHS-based motions on the hazard and risk assessment.

Figure 4-2. Target Uniform Hazard Spectrum and the response spectra of four artificial motions generated to fit the target spectrum. Each of the four motions fits the target within 3%.

Figure 4-3. Simulated ground motion time histories that fit the target UHS.

Figure 4-4. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the Millstone site based on artificial motion 1.

Figure 4-5. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the Millstone site based on artificial motion 2.

Figure 4-6. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the Millstone site based on artificial motion 3.

Figure 4-7. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the Millstone site based on artificial motion 4.

Figure 4-8. Comparisons of UH-ISS generated by the four artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 3 Hz structure.

Figure 4-9. Comparisons of UH-ISS generated by the four artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 7 Hz structure.

Figure 4-10. Comparisons of UH-ISS generated by the four artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 10 Hz structure.

Figure 4-11. (left) Target Uniform Hazard Spectrum and the average response spectrum of ten artificial motions generated to fit the target spectrum; (right) response spectra of the ten artificial motions.

Figure 4-12. Simulated ground motion time histories that fit the 10^{-4} UHS.

Figure 4-13. Simulated ground motion time histories that fit the 10^{-4} UHS.

Figure 4-14. Approximate UH-ISS for various floors of the three structures for the Millstone site based on the average UH-ISS produced by ten artificial motions.

Figure 4-15. Comparisons of UH-ISS generated by the average of UH-ISS by ten artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 3 Hz structure.

Figure 4-16. Comparisons of UH-ISS generated by the average of UH-ISS by ten artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 7 Hz structure.

Figure 4-17. Comparisons of UH-ISS generated by the average of UH-ISS by ten artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 10 Hz structure.

Figure 4-18. 0.05 Uniform Hazard Spectrum for the hypothetical site.

Figure 4-19. Target Uniform Hazard Spectrum and the response spectra of four artificial motions generated to fit the target spectrum. Each of the four motions fits the target within 3%.

Figure 4-20. Simulated ground motion time histories that fit the target UHS.

Figure 4-21. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the hypothetical site based on artificial motion 1.

Figure 4-22. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the hypothetical site based on artificial motion 2.

Figure 4-23. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the hypothetical site based on artificial motion 3.

Figure 4-24. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the hypothetical site based on artificial motion 4.

Figure 4-25. Comparisons of UH-ISS generated by the four artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 3 Hz structure.

Figure 4-26. Comparisons of UH-ISS generated by the four artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 7 Hz structure.

Figure 4-27. Comparisons of UH-ISS generated by the four artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 10 Hz structure.

Figure 4-28. (left) Target Uniform Hazard Spectrum and the average response spectrum of ten artificial motions generated to fit the target spectrum; (right) response spectra of the ten artificial motions.

Figure 4-29. Simulated ground motion time histories that fit the 0.05 UHS.

Figure 4-30. Simulated ground motion time histories that fit the 0.05 UHS.

Figure 4-31. Approximate UH-ISS for various floors of the three structures with fundamental frequencies equal to 3, 7 and 10 hz respectively for the hypothetical site based on average.

Figure 4-32. Comparisons of UH-ISS generated by the average of UH-ISS by ten artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 3 Hz structure.

Figure 4-33. Comparisons of UH-ISS generated by the average of UH-ISS by ten artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 7 Hz structure.

Figure 4-34. Comparisons of UH-ISS generated by the average of UH-ISS by ten artificial ground motions and by scenario earthquakes directly (denoted as UH-ISS in the legend) for the 7 Hz structure.

Section 5

SHAPES OF SCENARIO ISS AND UH-ISS

In this section we show how shapes of scenario in-structure spectra (ISS) compare with shapes of UH-ISS derived from different approaches. The variations of the UH-ISS derived from different approaches are fairly small, as discussed in the previous two sections; the UH-ISS evaluated directly by scenario earthquakes are displayed in Figures 3-25 and 3-27.

5.1 RESULTS

Figures 5-1 to 5-8 show the average ISS of the motions with various magnitudes and distances for the first floor of the 3 Hz structure; Figures 5-9 to 5-16 and Figures 5-17 to 5-24 show that for the 7 and 10 Hz structures respectively.

Similar to UHS, UH-ISS is a composite spectrum contributed by earthquakes with different characteristics. The relative contribution is reflected in the likelihood of such events as well as in the potential of exceeding a certain response level given such events. There usually may not exist earthquakes with a specific magnitude and distance that resemble the composite spectrum (UHS or UH-ISS). It is observed that the shape of the 10^{-4} UH-ISS for the Millstone site is quite similar to the shape of ISS with magnitude 6.2 and distance 30 km in this specific case. This indicates that this combination of magnitudes and distances may have the (relatively) most contributions to the UH-ISS. It is also noted that ISS generally has the same shape of the original spectrum, only amplified at frequencies around the natural frequencies of the structures.

Figure 5-1. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-2. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-3. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-4. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-5. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-6. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-7. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-8. In-structure PSV (cm/s) for the first floor of the 3 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-9. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-10. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-11. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-12. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-13. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-14. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-15. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-16. In-structure PSV (cm/s) for the first floor of the 7 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-17. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-18. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-19. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-20. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-21. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-22. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-23. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Figure 5-24. In-structure PSV (cm/s) for the first floor of the 10 Hz structure for earthquakes with magnitude, m , and distance, r .

Section 6

SUMMARY AND CONCLUSION

This report documented the second part of the Phase 2 research concerning the adequacy of using UHS as the basis for deriving inputs for evaluating UH-ISS.

For comparison purposes, a new format of seismic hazard analysis is developed. It does not make use of seismic hazard and fragility curves, but rather, is based on fundamental scenario motions and their probabilities for all possible cases. Knowing the scenario motion time histories and their probabilities, any responses of interest (in-structure demands, component failures, system failures, etc.) can be computed directly, and corresponding risk measures can be directly obtained. The approach is more detailed and precise than conventional methods used for seismic risk assessment, because it introduces no simplifying approximations in characterizing the motion threat, which in turn affects the nature and accuracy of component and system response assessments. Thus, it serves as an accurate analysis for comparison of results with conventional methods that do introduce such approximations in motion characterization and seismic risk methodology.

The specific objective of this study is (1) to develop the methodology of using the scenario motions for seismic hazard and risk assessment, (2) to verify if UHS can be used as the basis to derive UH-ISS for seismic hazard and risk analysis and (3) how the shapes of UH-ISS compared with the shapes of scenario ISS. The basic approach in this study has been to compare demands, using the scenario earthquakes and the approximate approach using UHS based motions. All results have been obtained assuming linear structural response.

The results of comparisons considered in this study lead to development of the following conclusions:

1. The new format of seismic hazard and risk analysis, i.e, using scenario motions directly as inputs for hazard and risk evaluation, provides the basis for comparisons with results derived from more traditional methods. In addition, the new method also provides more insight into the relative contribution to hazard and risk from earthquakes with different magnitudes and distances through disaggregation. These results may

help identify a smaller set of scenario earthquakes, if needed, to be used for further analysis. It is noted, however, that this practice is fairly expensive because of the large resources needed to compute structural responses for each of the motions, especially in a non-linear environment.

2. The approximate UH-ISS obtained based on UHS appear to be very close to the more-exact results directed computed from scenario earthquakes. Two approximate methods, one using a single motion that smoothly matches the target UHS as input to derive UH-ISS, the other using a small number of motions that have realistic variabilities in the spectral shape, produce very similar results. The conclusion does not change with regard to the site configurations and the structural characteristics in the limited cases studied in this report. This finding indicates that UHS may be used as the basis to derive other hazard and risk evaluation that requires explicit ground motions as inputs, at least in the case where structures behave linearly.
3. Similar to the UHS, UH-ISS has composite shapes and may not correspond to the characteristics possessed by any single earthquake. The shape is largely affected (mainly amplified) by the structural property in most cases. The shape of a UH-ISS can be derived approximately from the corresponding UHS.
4. Further study is needed to clarify how adequate UHS-based analysis will be when non-linear structural behavior occurs in assessing component and system risks. It is expected that motions with smooth spectra may not have the same damage potential as those of more realistic motions with jagged spectral shapes. As a result, UHS-based analysis may underestimate the real demands.

Section 7

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11. ABSTRACT (200 words or less)

This report documents research on the subject of conservatism and variability in seismic risk estimates. Particularly, it examines the effects of the uniform hazard spectrum (UHS) for deriving probabilistic estimates of risk and in-structure demand levels, as compared to the more-exact use of realistic time history inputs (of given probability) that depend explicitly on magnitude and distance. The approach differs significantly from the conventional procedure in its exhaustive treatment of the ground-motion threat, and in its more detailed assessment of component responses to that threat. It is found that the approximate uniform hazard in-structure spectrum (UH-ISS) obtained based on UHS appear to be very close to the more-exact results directly computed from scenario earthquakes. The conclusion does not depend on site configurations and structural characteristics. In addition, UH-ISS has composite shapes and may not correspond to the characteristics possessed in a single earthquake. The shape is largely affected by the structural property in most cases and can be derived approximately from the corresponding UHS. Motions with smooth spectra, however, will not have the same damage potential as those of more realistic motions with jagged spectral shapes. As a result, UHS-based analysis may underestimate the real demands in non-linear structural analyses.

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