Enclosure 3
Topical Report (Redacted)

11111-000-30R-K01G-00002

babcock & wilcox mPower

Implementation of Random Vibration Theory for Seismic Soil-Structure interaction (Redacted Version)

June 2013

Bechtel Topical Report

This material is based upon work supported by the Department of Energy under Award Number DE-NE0000583.

ACKNOWLEDGEMENTS

The authors (Farhang Ostadan and Nan Deng) wish to thank their colleagues at Bechtel for their valuable assistance in completing this report. The authors are especially appreciative of the efforts of Dr. Robert Kennedy (RPK Structural Mechanics Consulting) for his review. Dr. Kennedy's suggestions have been incorporated in this report.

EXECUTIVE SUMMARY

This report demonstrates the suitability of Random Vibration Theory (RVT) for application to soil-structure interaction (SSI) analysis, in lieu of traditional time history (TH) analysis. While RVT has been utilized in recent years to develop site-specific ground motion, the use of RVT [

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Recent SSI studies have shown that time history-based seismic responses are sensitive to the selection of seed time histories. In response, the industry plans to utilize multiple sets of time histories in an SSI analysis. The examples presented in this report show [

Since RVT only requires a response spectrum as input (rather than multiple time histories), [

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SSI models inherently include a wide range of damping values to represent soil and structural damping properties. Ground motion models used in a probabilistic seismic hazard analysis (PSHA) to develop design spectra are typically based on 5% spectral damping. However, development of target spectra at different damping values is not a well-established process and requires approximation in estimating target spectra at lower and higher damping levels. In addition, [

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Given the need to obtain a stable mean response that is not sensitive to selection of time histories and the wide scatter of the time history ISRS results at damping levels other than 5%, [

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ACRONYMS

ARS	Acceleration Response Spectra
ASCE	American Society of Civil Engineers
CEUS	Central and Eastern United States
CSDRS	Certified Seismic Design Response Spectra
ISRS	In-Structure Response Spectra
NRC	Nuclear Regulatory Commission
PSD	Power Spectral Density
PSHA	Probabilistic Seismic Hazard Analysis
RG	Regulatory Guide
RVT	Random Vibration Theory
SASSI	System for Analysis of Soil Structure Interaction (computer code)
SRP	Standard Review Plan (Nuclear Regulatory Commission NUREG-0800)
SSI	Soil-Structure Interaction
TH	Time History
WUS	Western United States
ZPA	Zero-Period Acceleration

1.0 PURPOSE/ABSTRACT

This report provides the background, methodology, and implementation of Random Vibration Theory (RVT) used for seismic soil-structure interaction (SSI) analysis. The use of RVT for SSI analysis represents [

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2.0 INTRODUCTION

RVT has been used extensively in recent years for seismic site response analysis and development of design ground motion for nuclear power plants. Since RVT methodology remains essentially the same when applied to SSI, technical publications and regulatory review of RVT for site response analysis has been used in review of the background for SSI application. Following the background discussion in Section 3, Section 4 presents the approach and theoretical formulation of RVT methodology. Section 4 also discusses the implementation of RVT in the computer program SASSI2010 (2012). Section 5 provides a summary of the examples modeled and [

] Section 6 provides a summary and conclusion. References are cited in Section 7. Note the mPower project has [

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3.0 BACKGROUND ON RANDOM VIBRATION THEORY (RVT)

3.1 Current Time History Approach and the Regulatory Basis

The current approach for SSI analysis of nuclear safety-related structures is to use acceleration time history as input. For design purposes, the acceleration design response spectra are developed (typically at 5% critical damping) following NRC Regulatory Guide (RG) 1.208 and the soil column analysis methods described in NUREG/CR-6728. Once the design spectra are available, time histories are generated by matching/enveloping the design spectra and subsequently used in the seismic analysis. There are a number of guidelines available for generation of time histories. These guidelines are outlined in NRC Standard Review Plan (SRP) 3.7.1, ASCE 4-98 and NUREG/CR-6728. In SRP 3.7.1 (2007), several options are provided to generate time histories. The most widely adopted option is to match the seed time histories to target design spectra at only one damping and maintain the requirements for matching and statistical independence (Option 1, Approach 2 from SRP 3.7.1).

Other options require matching the seed time histories to the target design spectra at multiple damping ratios, and checking the power spectra of the time histories. This latter approach is seldom used since the methods for generation of site-specific target design spectra at multiple damping ratios and associated power spectra are not fully developed and accepted by any specific standard. In addition, there is little regulatory guidance for such methods.

Generation of time histories to match the target design spectra requires seed time histories that must be appropriate for the design spectra and site geotechnical and seismological settings. The choices for appropriate seed time histories are very limited for regions such as the Central and Eastern United States (CEUS) where few recorded strong motion data are available. The seed time histories are often selected by modifying available strong motion records, often from Western United States (WUS) or other applicable globally recorded data. The lack of choices for appropriate seed time histories is compounded by the observation that linear structural seismic analysis results can be sensitive to the choice of seed time histories. Over the years, many studies have shown that when multiple seed time histories are matched to the same design spectra and used for structural analysis, the results can vary significantly (Ostadan et al., 1996; Mertz et al., 2011). [

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3.2 Previous Formulations and Application of RVT

While the use of RVT has been explored and evaluated for the last 20-30 years, the use of RVT for characterization of site ground motion was only included in RG 1.208 in 2007. The computer program PLUSH (Romo et al., 1977) uses the RVT formulation developed by Vanmarcke (1975) and others. PLUSH requires input motion to be specified in terms of design acceleration response spectra. Using the RVT formulation, PLUSH calculates the peak factors and seismic responses at any confidence level specified by the user, including the mean maximum responses. The formulation for the peak factor is one of the original formulations and is not able to accurately represent design spectra with very high frequency content typical of CEUS sites.

In recent applications for seismic site response analysis, RVT has been applied to soil column analysis. A description of the formulation and its application can be found in papers by Silva et al. (1997), Rathje et al. (2008, 2010), Deng and Ostadan (2008, 2011). RVT is ideal for implementation in frequency domain analysis because it can capture the maximum values that allow iteration on soil properties in a typical soil column analysis using the equivalent linear method. [

] The validity of RVT methodologies for site response analysis has been demonstrated by verification examples in the literature (e.g., the examples provided in the above cited papers). RG 1.208 identifies RVT methods as an acceptable alternative to time history analysis.

Site motion characterization using RVT has been utilized for Combined License Applications currently under review by the NRC. Site motion characterization using RVT was reviewed by the NRC as part of the draft SER for the South Texas Project and the NRC concluded that use of RVT was acceptable.

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4.0 RVT FOR SSI ANALYSIS

4.1 Approach

4.1.1 Basic Computational Steps

This section describes the details of the formulation of RVT used in SASSI2010 (most recent version of Bechtel's proprietary program). In this formulation, the following main computational steps are followed:

[

] Theoretical formulations of the steps described above are discussed next.

4.1.2 Theoretical Formulation

The formulation adopted for RVT and peak factors herein was first developed by Der Kiureghian (1983). In this formulation the relation between the displacement response and acceleration input for single degree of freedom system has been defined by:

$$S_d(\omega) = \left|H^2(\omega)\right| S_a(\omega) \tag{1}$$

where $S_d(\omega)$ is the relative displacement PSD, $S_a(\omega)$ is the acceleration PSD, and $H(\omega)$ is the transfer function between displacement response and absolute acceleration input of a single degree-of-freedom oscillator with frequency ω_o and damping ξ expressed in Equation 2.

$$\left|H^2(\omega)\right| = \frac{1}{(\omega_o^2 - \omega^2)^2 + 4\xi^2\omega_o^2\omega^2} \tag{2}$$

The mean of the maximum relative displacement response of the oscillator (definition of a mean relative displacement response spectrum) is given by:

$$D = p\sqrt{\lambda_0} \tag{3}$$

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Where p is a peak factor defined in Equation (4), and λ_0 is the zero moment of the response defined in Equation (6). This approach follows Davenport (1964) and Der Kiureghian (1980).

$$p = \sqrt{2 \ln \nu(0)\tau} + \frac{0.5772}{\sqrt{2 \ln \nu(0)\tau}} \tag{4}$$

where $\nu(0)$ is the mean zero crossing rate of the response between 0 and τ and is equal to:

$$\nu(0) = \frac{1}{\pi}\sqrt{\frac{\lambda_2}{\lambda_0}} \tag{5}$$

and where τ is the strong motion duration of the earthquake.

The moments of the response are defined as follows:

$$\lambda_n = \int_0^\infty \omega^n S_d(\omega) d\omega \tag{6}$$

where n = 0, 1, 2 for the zero (λ_0), first (λ_1), and second (λ_2) moments of the response.

Following Vanmarcke (1975) and Igusa and Der Kiureghian (1983), $\nu(0)$ is adjusted with the parameter δ, where

$$\delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0 \lambda_2}} \tag{7}$$

The steps to calculate the [

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4.2 Implementation in SASSI

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Figure 4-1 [ ]

5.0 VERIFICATION

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Figure 5.3-18(a) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-18(b) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-18(c) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-19(a) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-19(b) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-19(c) [ ]

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Figure 5.3-20(a) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-20(b) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-20(c) [ ]

 [CCI per Affidavit 4(a)-(d)]

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Figure 5.3-21(a) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-21(b) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-21(c) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-22(a) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-22(b) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-22(c) [ ]

 [CCI per Affidavit 4(a)-(d)]

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Figure 5.3-23(a) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-23(b) [ ]

 [CCI per Affidavit 4(a)-(d)]

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Figure 5.3-23(c) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-24(a) [ ]

 [CCI per Affidavit 4(a)-(d)]

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Figure 5.3-24(b) [ ]

[CCI per Affidavit 4(a)-(d)]

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Figure 5.3-24(c) [ ]

 [CCI per Affidavit 4(a)-(d)]

6.0 SUMMARY AND CONCLUSION

Random Vibration Theory has been utilized in recent years for site response analysis to develop site-specific design motion. An earlier formulation of RVT has been applied to a probabilistic method for two-dimensional SSI analysis (Romo, et al, 1977). [

] Use of RVT for development of design input motion is a common industry practice today and its use has been accepted by the United States NRC.

Current guidance is to develop acceleration time histories that match a design response spectrum. These time histories are then used as the input motions for SSI analysis. Several options are available to generate and modify time histories. The most commonly used method modifies time histories to match/envelop the design target spectra at one spectral damping level, typically at 5% damping. This damping level is used for most ground motion attenuation models in probabilistic seismic hazard analysis.

Recent SSI studies have shown that seismic responses of interest can be sensitive to the selection of seed time histories. This observation has been replicated herein using the verification examples presented in this report. [

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Uncertainties in obtaining appropriate mean responses from a single time history have resulted in recommendations to use multiple sets of time histories, matched to the design response spectrum, for linear SSI analysis. The SSI analysis results from these multiple sets of time histories can then be averaged for design. However, detailed criteria or an application guide on selection of seed time histories has not been provided. [

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Since the SSI models include a wide range of damping values to represent the soil and structural damping properties, including the high damping associated with the foundation radiation damping, the SSI responses are naturally sensitive to the input motion and its spectral values at a wide range of damping levels. Currently matching time histories to a set of target spectra with a wide range of damping is very challenging and involves approximation in its process with unknown accuracy of the resulting solution. Development of the target spectra at other damping values is not a well-established process and requires approximation in estimating the target spectra at low and high damping levels, mainly due to the fact that the ground motion models used in the probabilistic hazard analysis to develop design spectra are based on 5% spectral damping only. In addition, modifying time histories to match multiple spectra often results in excessively conservative time histories in order to envelop all target spectra. Given these difficulties, [

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In this report, [

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 [CCI per Affidavit 4(a)-(d)]

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