New Approach for Seismic Vertical SSI analysis of Structures with Embedded Foundations

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DOE/NRC DOE/NRC Natural Phenomena Hazards Workshop
October 23-24, 2018, Rockville, Maryland

EPRI Report 3002011804
March 2018
A literature survey was conducted to review the recent findings for vertical motion.

It was noted that some researchers attribute the vertical motion to shear wave propagating in an angle which produces both horizontal and vertical motion upon reflection and refraction.

It was also noted that researchers have avoided performing PSHA analysis for vertical motion because most often it results in controlling events quite different from controlling events attributed to the horizontal motion at the same return period.


Data from the 696 KiK-Net stations was analyzed.

The borehole depths from 696 KiK-Net stations vary from 99 m to 3,510 m.
Literature Survey and Review (696 KiK-Net stations)

Histogram plot of the number of the records used for different depth ranges.

Number of Records

Depth of Borehole (m)

100 100-150 150-200 200-300 300-1000 > 1000

Histogram plot of the number of the records used for different depth ranges
Histogram plot of the number of the records used for different VS30 ranges
Mean (V/H)d / (V/H)s for the five binned VS30 categories
Mean $(V/H)d/(V/H)s$ for the four binned depth values of the sensor location.
Literature Survey and Review (696 KiK-Net stations)

\[(V/H)_{d}/(V/H)_{s} \text{ vs Average Surface Horizontal PGA}\]

\[
\begin{align*}
\text{Frequency (Hz)} & \quad 0.1 & \quad 1 & \quad 10 & \quad 100 \\
(V/H)_{d}/(V/H)_{s} & \quad 1 & \quad 2 & \quad 3 \\
\end{align*}
\]

\(V/H)_{d}/(V/H)_{s}\) for three binned mean surface horizontal PGAs
V/H)d/(V/H)s for three binned mean surface horizontal PGAs
Literature Survey and Review (BNL-107612-2015-IR)
Current Models for Spectral V/H Ratios for Ground Surface Motion

- RG 1.60 provides site-independent H and V spectra and the ratio of V/H
- NUREG/CR 6728 is widely used. This document provides V/H ratios for Western and Eastern US based on the maximum acceleration (PGA) for rock sites
- In appendix J, NUREG/CR 6728 provides a procedure for V/H ratio for soil sites for WUS sites. The ratio still needs to be modified for CEUS soil sites
Literature Survey and Review
Issues with Vertically Propagating P-Wave

- In order to demonstrate the anomalies associated with vertically propagating P-wave, a deep soil site in Central Eastern US (CEUS) was selected for analysis.
- The PSHA has been performed for the site and the seismic hazard data for the hard rock at a depth of approximately 1,000 ft are available.
- The site best estimate shear wave velocity profile has been simulated into 60 profiles in order to include the variability of the velocity data in the site amplification analysis.
- For site response P-wave analysis, the P-wave velocity profiles corresponding to the 60 simulated shear wave velocity profiles are obtained using the Poisson’s ratio.
- Using the hard rock PSHA data and the applicable V/H ratio for the hard rock at the subject site, the vertical response spectrum for the Uniform Hazard Spectrum at 1.0E10-4 MAFE corresponding to the de-aggregated high frequency ARS was obtained.
- The site amplification using P-wave was also performed. The acceleration response spectra at the surface (total of 60 spectra) and the median spectra were obtained.
Issues with Vertically Propagating P-Wave

Vp Profiles for CEUS Deep Soil Site
Issues with Vertically Propagating P-Wave

Vertical response spectra at the ground surface
Issues with Vertically Propagating P-Wave

Vertical response spectra at the ground surface from two methods
Issues with Vertically Propagating P-Wave

V/H spectral ratio at the ground surface from two methods
Recent Method for develop of V/H Spectral Ratio for WUS Sites

- The paper by Gulerce and Abrahamson (2011) provides the methodology for development of spectral V/H ratios for WUS sites.

- The key input parameters needed for Gulerce/Abrahamson model are the magnitude and distance of the controlling events, which are readily available from PSHA data for horizontal motion and the Vs30 reflecting the average shear wave velocity in the upper 30 m of the site profile.

- The V/H ratio can be adjusted for different Vs30 values.
Most Recent Approach to Developing Vertical Design Motion Used by the Industry Today

V/H ratio from magnitude 7 vertical strike-slip earthquakes 5 km away from the fault (Rrup ¼ 5 km) and 30 km away from the fault (Rrup ¼ 30 km) for (a, left figure) 20 Hz, and (b, right figure) 1 Hz, Gulerce and Abrahamson (2011) at 5% spectral damping
Task 2. Model of Vertical Ground Motions for SSI Analysis

SASSI Model Layout for SSI Analysis

Structure
Interaction Nodes
Excavated Soil
Layered Soil Profile
Halfspace
Input Motion
SASSI Methodology

- SASSI uses the Flexible Volume method to combine the substructures of building structure, excavated soil volume, and the free-field impedance.

- SASSI works in frequency domain, i.e., at each frequency, the response of the system is computed, and the results of all frequencies are combined to produce the final SSI responses through inverse FFT (For time-history approach), or through inverse PSD (for RVT approach). All terms in the SASSI Equations of Motion are frequency dependent.

- The soil strata is modeled as a perfectly layered visco-elastic profile overlaying a uniform half-space.

- The free-field motion is defined at the layer interfaces and is first determined through site response analysis.
While for horizontal motions the assumptions fit reasonably well with the field observations, this is not the case for vertical motion. As discussed before, the assumption of P-wave propagation produced a vertical motion both inconsistent with recorded motion and overly conservative, resulting in challenges for design of SSCs and for seismic stability evaluation.

It is observed that the P-wave incidence assumption is introduced only for the convenience of numerical solutions of site response analysis. We should introduce new assumptions consistent with current field observation and the practice for development of vertical design motion. Since the current seismological and engineering practice is to use the site-and-magnitude-specific V/H ratios to produce vertical rock outcrop motions, it is natural that we should use the same V/H approach to produce the vertical input motions for SSI analysis.

The V/H approach has been implemented in the updated version of SASSI that maintains the site applicable V/H ratio in the free-field solution.
Standard Plant LMSM Vertical SSI Analysis

- SSI analyses of the LMSM (published version of the nuclear island model) are performed. The model has 40 ft embedment. The vertical ARS responses due to P-wave and V/H approach generated vertical motions were compared at the key nodal points.

- The analyses results presented is for a CEUS deep soil profile with RG 1.60 input motions and a CEUS rock site with site-specific motion.
Program on Technology Innovation:
Effect of Seismic Wave Incoherence and Building Response
EPRI Report TR-1013504
November 2006

The model is embedded to 40 ft. in the subsurface profile with a rigid wall built around the perimeter.
Soil Profile

Deep Soil Profile - Wave Velocity

Wave Velocity (ft./sec)

Depth from Grade (ft.)

Vs

Vp

Deep Soil Profile - Damping

Fraction of Critical Damping

Depth from Grade (ft.)
Task 3.1A: Input Motion

Input Motion - RG 1.60 H and V ARS at Grade. Scaled to 0.3g

- RG 1.60, H
- RG 1.60, V
- V/H

Spectral Acceleration (g)

Frequency (Hz)
Vertical Input Motions

By P-Wave

By V/H Approach
V/H Ratios for Input Motions

By P-Wave

By V/H Approach
Vertical ARS on SCV Stick

**Vertical ARS at Node 34**

- **Vert. - P-Wave Input**
- **Vert. - V/H Input**

**Vertical ARS at Node 45**

- **Vert. - P-Wave Input**
- **Vert. - V/H Input**

**Vertical ARS at Node 145**

- **Vert. - P-Wave Input**
- **Vert. - V/H Input**
Vertical ARS on ASB Stick

Vertical ARS at Node No. 118
- Vert. - P-Wave Input
- Vert. - V/H Input

Vertical ARS at Node 212
- Vert. - P-Wave Input
- Vert. - V/H Input

Vertical ARS at Node No. 1
- Vert. - P-Wave Input
- Vert. - V/H Input
Vertical ARS on CIS Stick

Vertical ARS at Node No. 229

Vertical ARS at Node No. 26
CEUS Rock Profile

EPRI - BE Rock Site Profile
Wave Velocity [ft/sec]

EPRI - BE Rock Site Profile
Damping Ratio [%]

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Vertical Input Motions

By P-Wave

By V/H Approach
V/H Ratios for Input Motions

By P-Wave

By V/H Approach
Vertical ARS on SCV Stick

Vertical ARS at Node No. 45

Vertical ARS at Node No. 34

Vertical ARS at Node No. 145
Vertical ARS on ASB Stick

**Vertical ARS at Node No. 118**

**Vertical ARS at Node No. 212**

**Vertical ARS at Node No. 1**
Vertical ARS on CIS Stick

Vertical ARS at Node No. 229

Vertical ARS at Node No. 26
Regulatory Constrains

- Regulatory Guide 1.208 (March 2007), recommends a performance-based approach to define the site-specific earthquake ground motion, provides specific recommendations for development of horizontal and vertical motion from the PSHA to site amplification and development of the performance-based response spectra.
- In Section 5.2, vertical spectrum, it states: Vertical response spectra are developed by combining the appropriate horizontal response spectra and the most up-to-date V/H response spectral ratios appropriate for either CEUS or WUS sites.
- For CEUS soil sites, NUREG/CR 6728 describes a procedure to determine a WUS-to-CEUS transfer function that may be used to modify the WUS V/H soil ratios.
SRP 3.7.1 Rev 4 (Dec 2014) in the section for defining FIRS states: “the FIRS for the vertical direction is obtained with the vertical to horizontal (V/H) ratios appropriate for the site”. Similar guidance has been provided for definition of vertical PBSRS. Similar guidance is provided in Interim Staff Guidance ISG-17 as it relates to the vertical spectrum.

As noted above the methodology of using V/H ratio to develop vertical motion is fully consistent with the regulatory guidance and maintains the latest development that is appropriate for the site for spectral V/H ratio.

In this regard no regulatory constraint is expected for adoption of the V/H methodology for SSI analysis.
The proposed method for vertical SSI analysis maintains the consistency between the method used in developing the vertical design motion and its application to SSI analysis for embedded structures. It avoids the anomalies associated with vertically propagating P-waves and results in a more realistic responses for structural and equipment design.