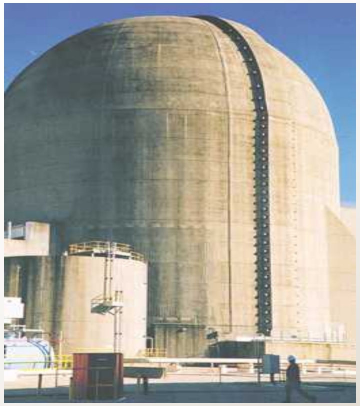
Modeling Vertical Free-Field Motion for SSI Analysis Consistent with Vertical Design Motion Development



DOE/PEER/UNR Workshop

International Workshop on Large-Scale Shake Table Testing for the Assessment of

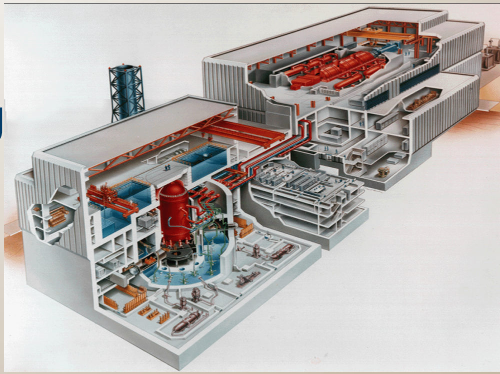
Soil-Foundation-Structure System Response for Seismic Safety of DOE Nuclear Facilities

May 18, 2021

Farhang Ostadan

Manager of Earthquake Engineering Center

Bechtel Corporation



EPRI Report

https://www.epri.com/#/pages/product/3002011804/

Current Practice

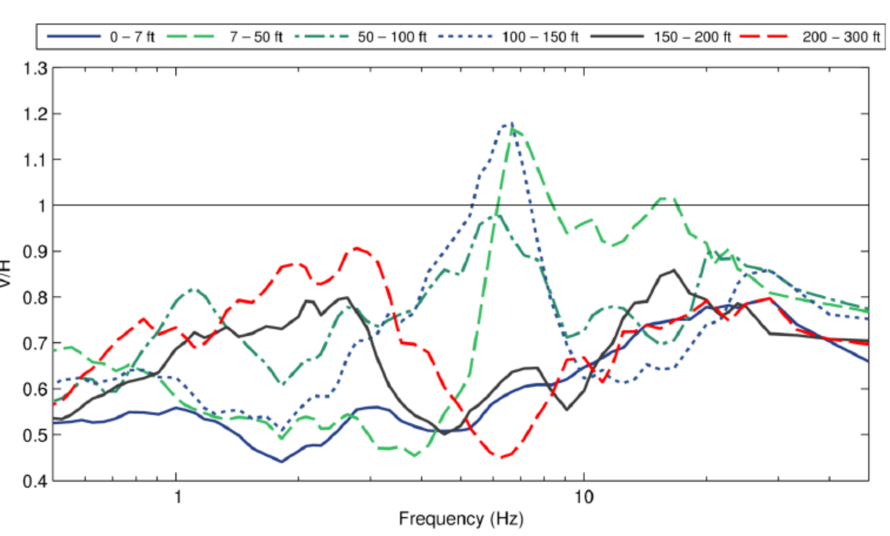
- Development of seismic design motion for NPP application begins with PSHA and follows with a robust site amplification analysis (NUREG/CR 6728) to develop the horizontal design response spectra (GMRS, FIRS)
- For vesical design response spectra development, vertical P-wave analysis is no longer performed. P-wave amplifications are found to be spurious and not consistent with observation
- Instead, applicable V/H spectral ratios are used in practice to develop vertical design spectra. There are few publications outlining the formulation of the V/H ratios
- For horizontal SSI analysis, the horizontal design spectra or associated time histories are used for analysis
- For vertical SSI analysis, vertical P wave is modeled in the free-field
  - ✓ This approach is inconsistent with development of the vertical design spectra
  - ✓ SSI results are overly conservative (ISRS for equipment design)
  - ✓ Results in buoyancy stability issues for plant structures with embedment (shallow and deep embedment)

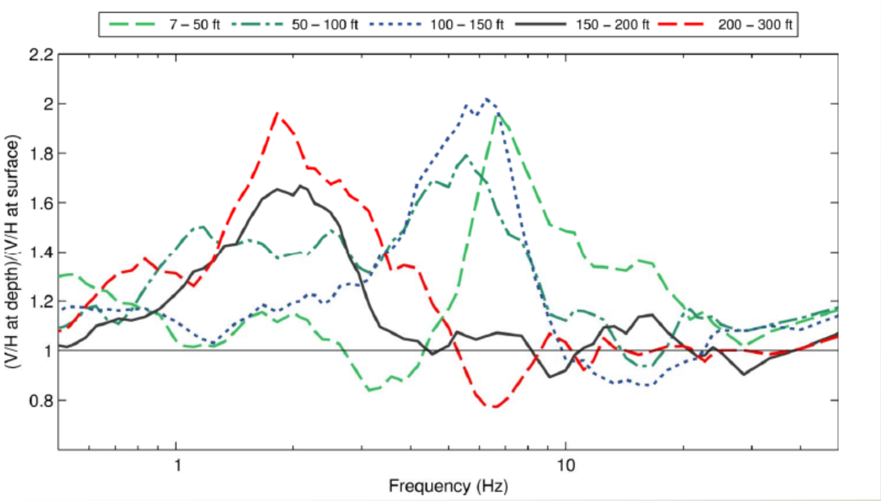
BECHTEL

New Approach

- For SSI analysis of embedded structures using the substructuring methods (SASSI), the free-field motion within the embedment depth of the structures needs to be computed. In other SSI formulation, free-field motion for the full height of the soil column is needed
- In the new approach, the free-field motion at each depth in the model is computed using the horizontal motion at the same depth and applying applicable V/H ratio to get the vertical motion
- This approach is formulated in frequency domain using RVT (random vibration theory) in an iterative process to get he vertical spectra at all depth of interest for SSI analysis
- In this approach, free-field SSI vertical motion is consistent with the approach used for development of the vertical design spectra
- The vertical SSI results are more realistic and are reduced from the results using P-wave analysis

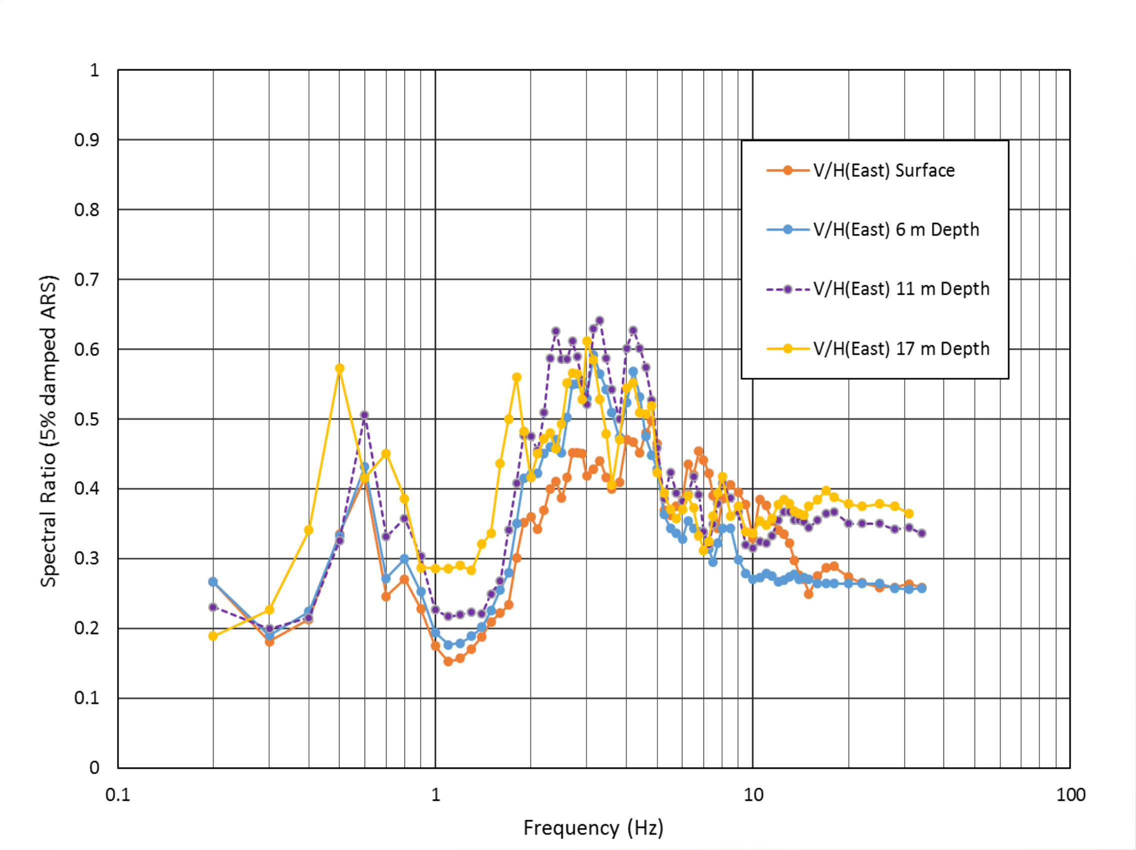
Depth-dependent Vertical-to-Horizontal (V/H) Ratios of Free-Field Ground Motion Response Spectra for Deeply Embedded nuclear Structures (BNL-107612-2015-R, 2/2015)





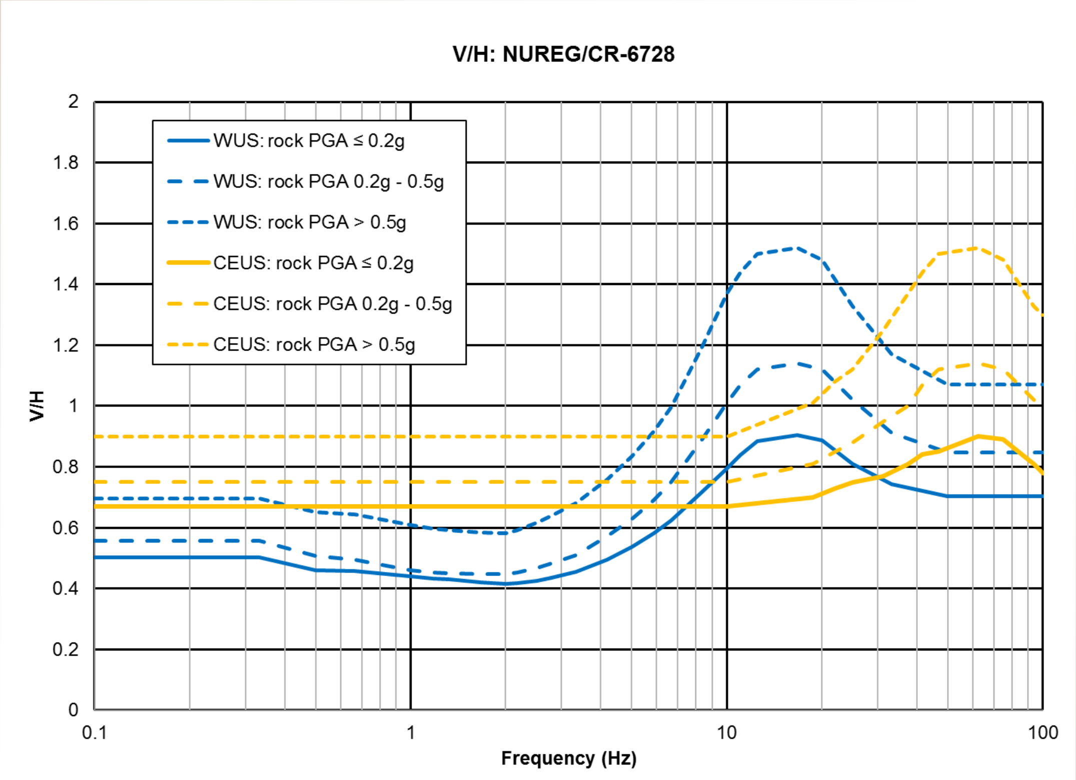
(Data from 45 vertical arrays: California, Japan, Alaska, Taiwan)

Lotung SSI Experiment (1980s)



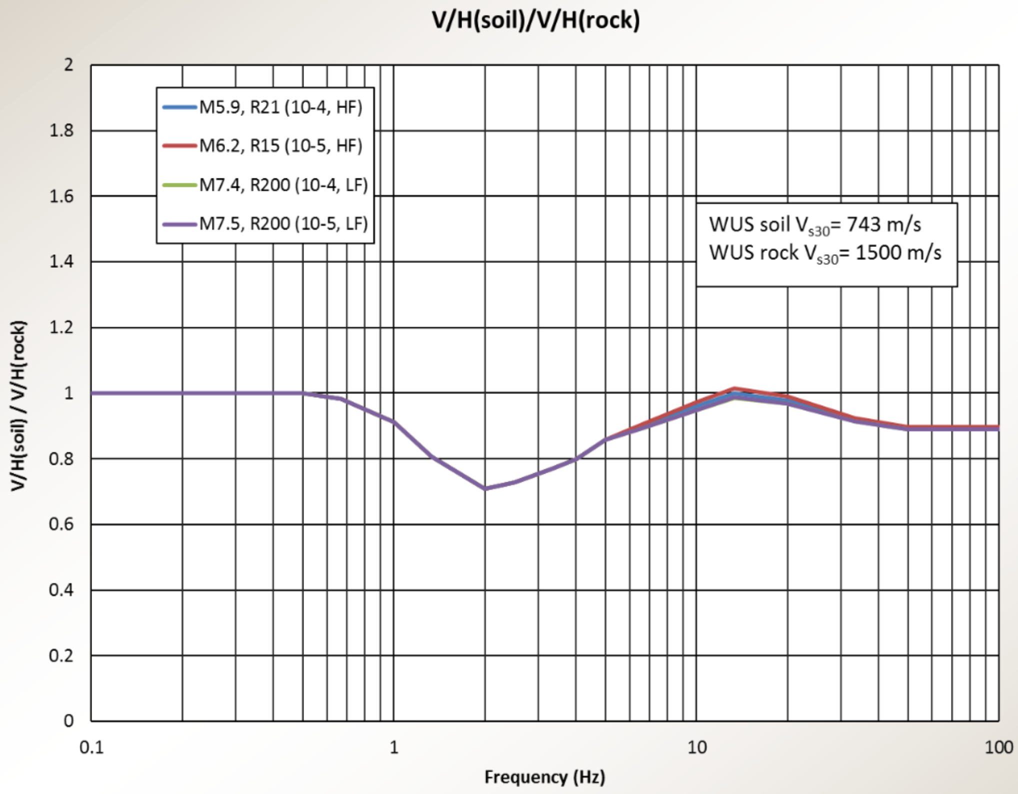
V/H Spectral Ratio from Lotung LSST No. 7 Free-Field records

Commonly Used V/H Ratios



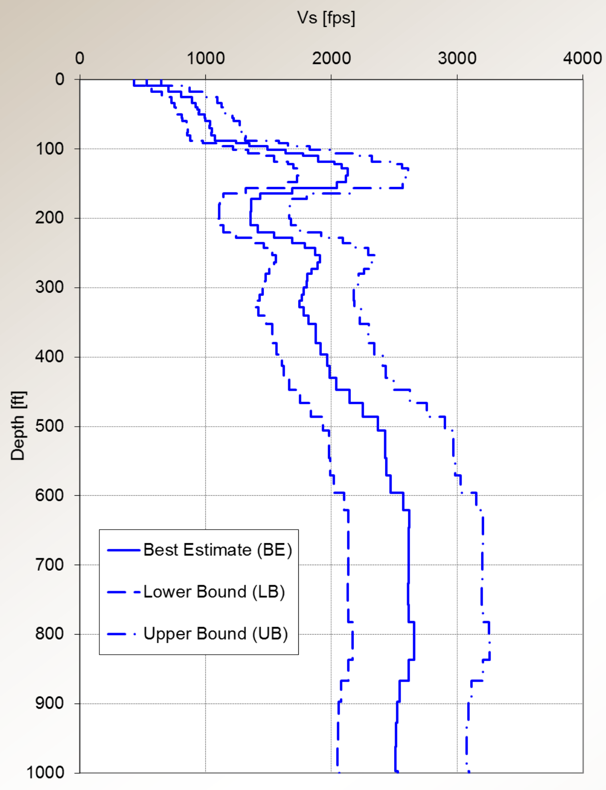
V/H ratios for WUS rock and CEUS Hard Rock Sites, NUREG/CR-6728 at 5% spectral damping

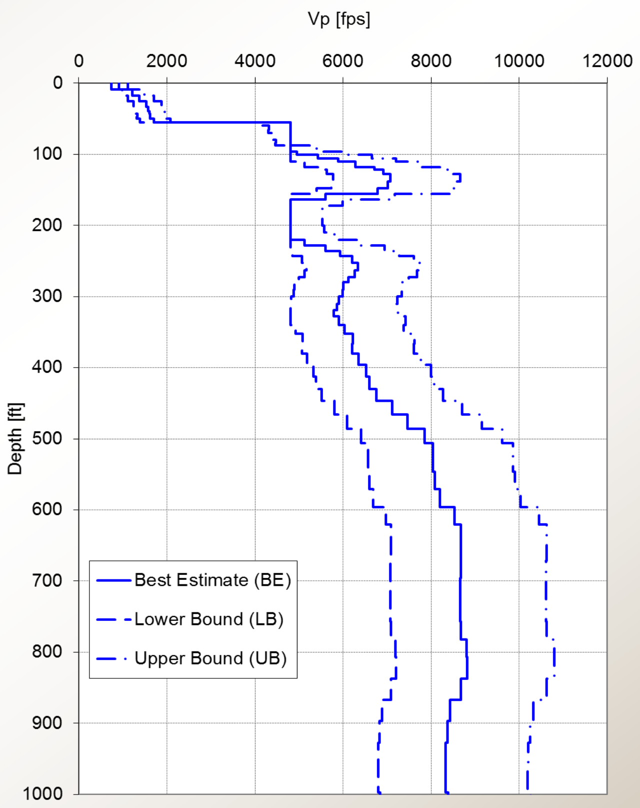
Commonly Used V/H Ratios



Gülerce and Abrahamson V/H(WUS,soil) / V/H(WUS,rock) for a suite of controlling magnitudes and distances for VS30 of 743 m/sec and 1,500 m/sec at 5% spectral damping

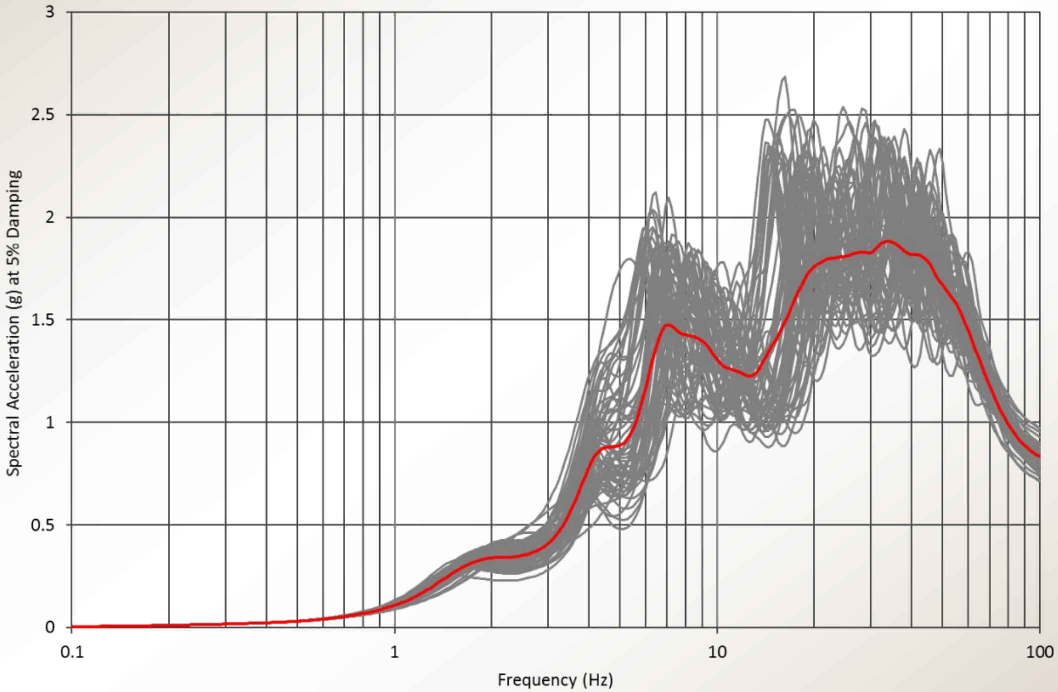
Anomalies Associated with P-wave Site Amplification





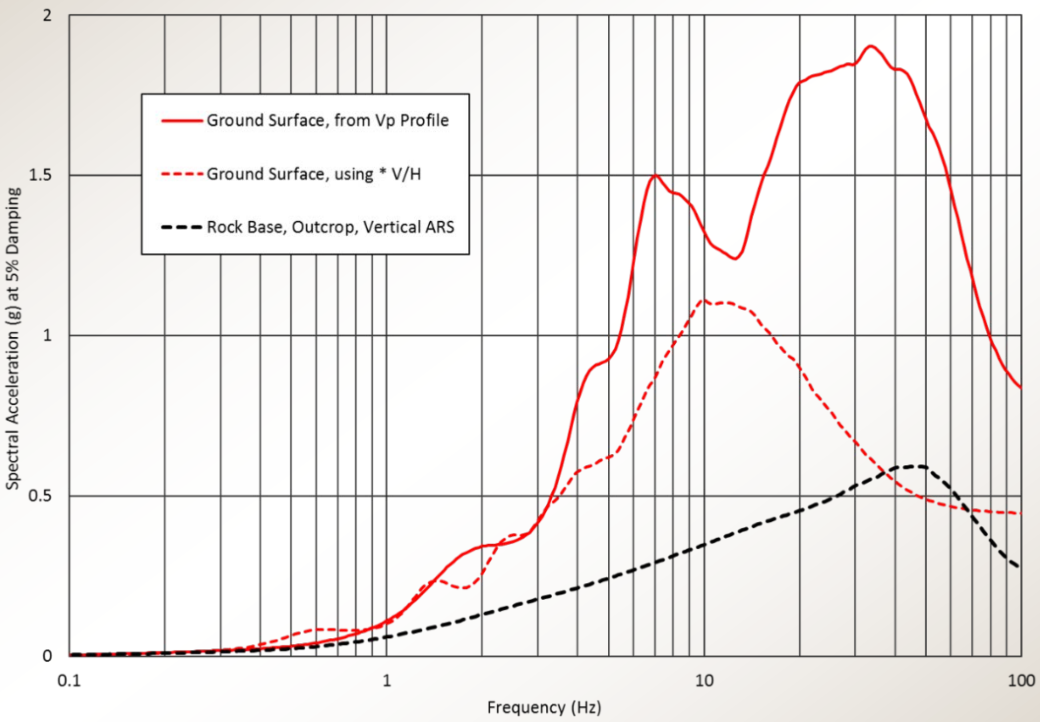
Shear and P-wave Velocity Profiles at a Soil Plant Site in US

Anomalies Associated with P-wave Site Amplification



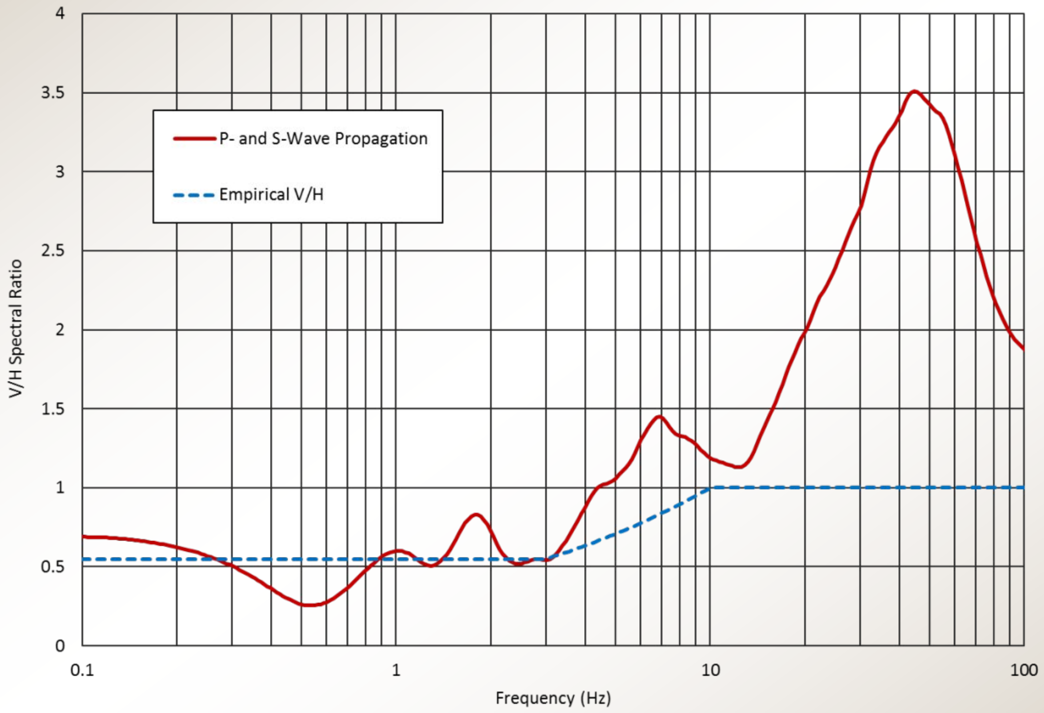
Randomized P-wave Profile

Anomalies Associated with P-wave Site Amplification



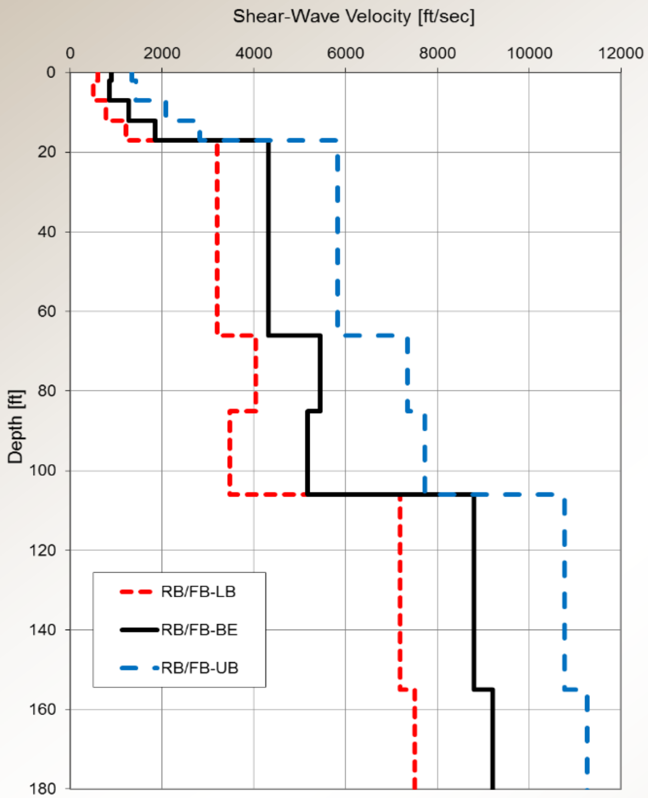
Responses at the Surface

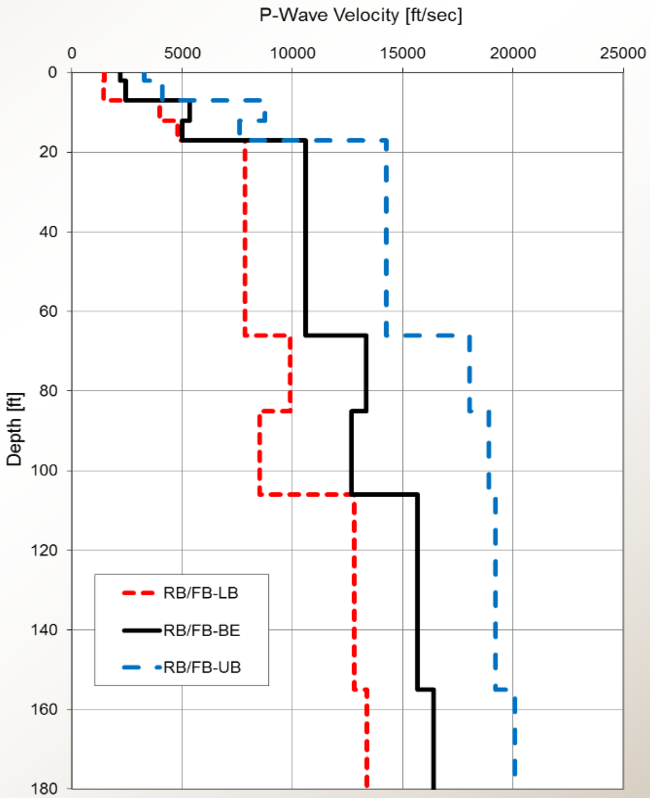
Anomalies Associated with P-wave Site Amplification



Comparison of V/H Ratio

Anomalies Associated with P-wave Site Amplification

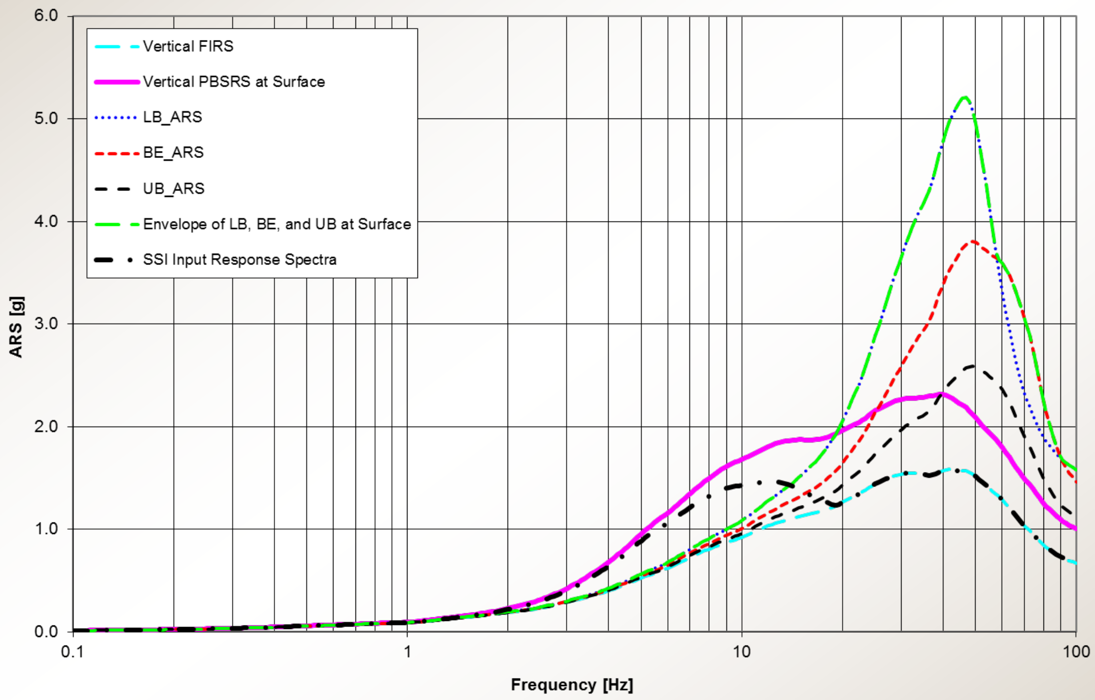




Shear and P-wave Velocity Profiles at a Rock Plant Site in US

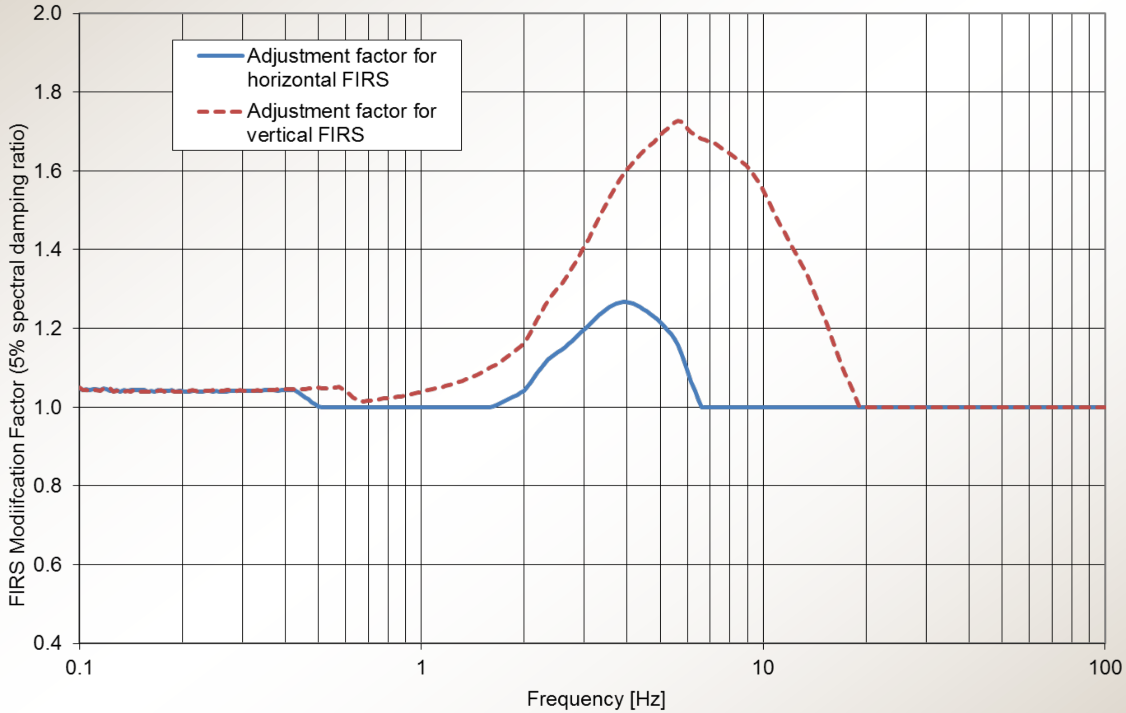
BECHTEL

Anomalies Associated with P-wave Site Amplification



Vertical Responses at the Surface

Anomalies Associated with P-wave Site Amplification



Adjustment Factors to be Applied to FIRS to Obtain SSI Input Response Spectra

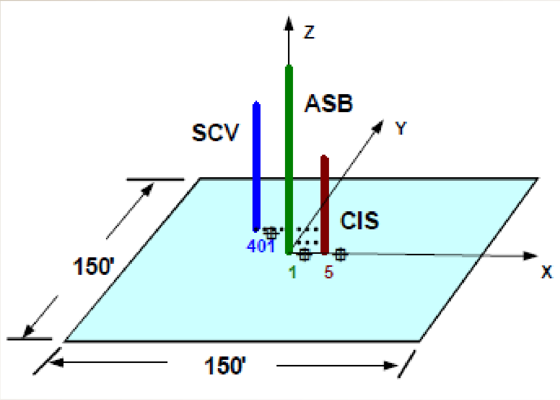
Anomalies Associated with P-wave Site Amplification

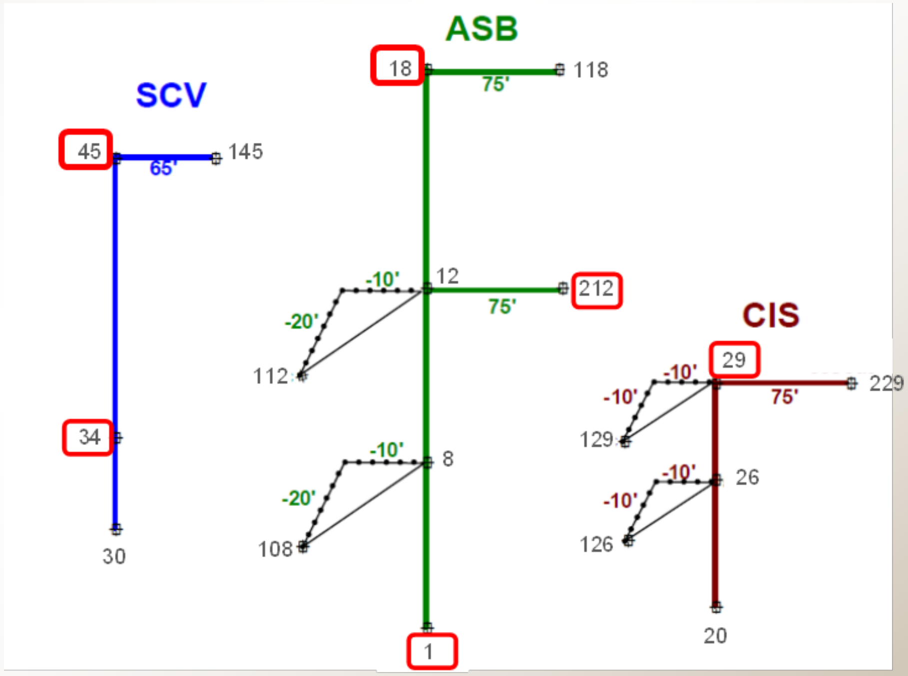
- There are anomalies and over prediction of vertical ground motion when P-wave propagation is used
- Several studies concluded that the vertical motion at low and mid frequency is the results of refraction and reflection of shear waves and not from P-wave body waves
- The P-wave analysis results conflict empirical V/H ratio relationship developed based on recorded motion
- The V/H ratio operators operate on H spectra to get the V spectra

UNR Shear Box

- In development of the horizontal spectra, the UNR shear box offer unique opportunities to evaluate:
  - ✓ Effect of one-dimensional versus two-dimensional shaking on soil nonlinearity and site response
  - ✓ Assessment and verification of equivalent linear soil models versus nonlinear models and their limits
  - ✓ Validation data for site response nonlinear analysis
  - ✓ Site properties at high level of soil strain particularly soil damping (out of reach of laboratory testing, RCTS)
  - ✓ Resonance of thin soft soil layers on rock or stiff soil layers
  - ✓ Begin to provide SSI data for extreme shaking for validation of nonlinear SSI solutions

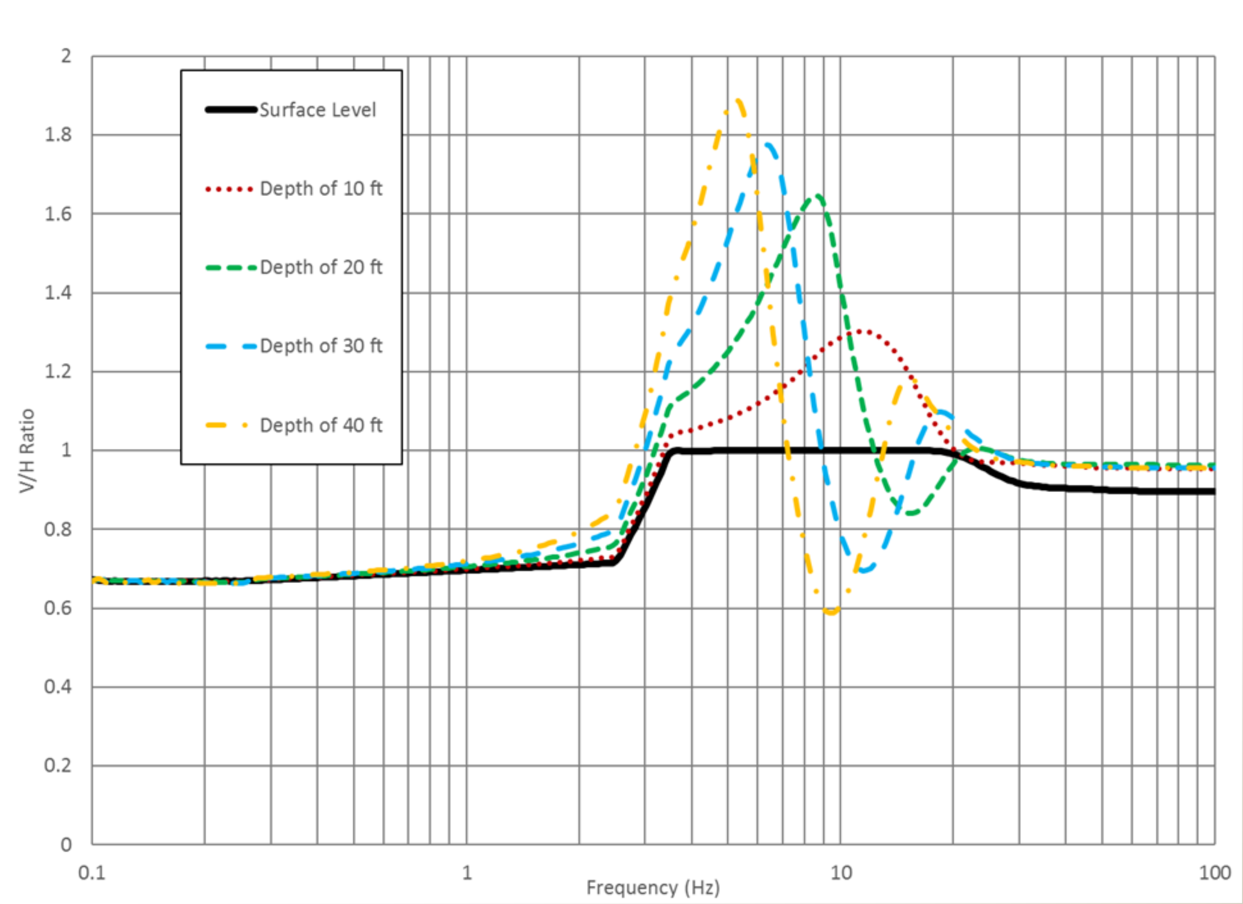
SSI Case Study





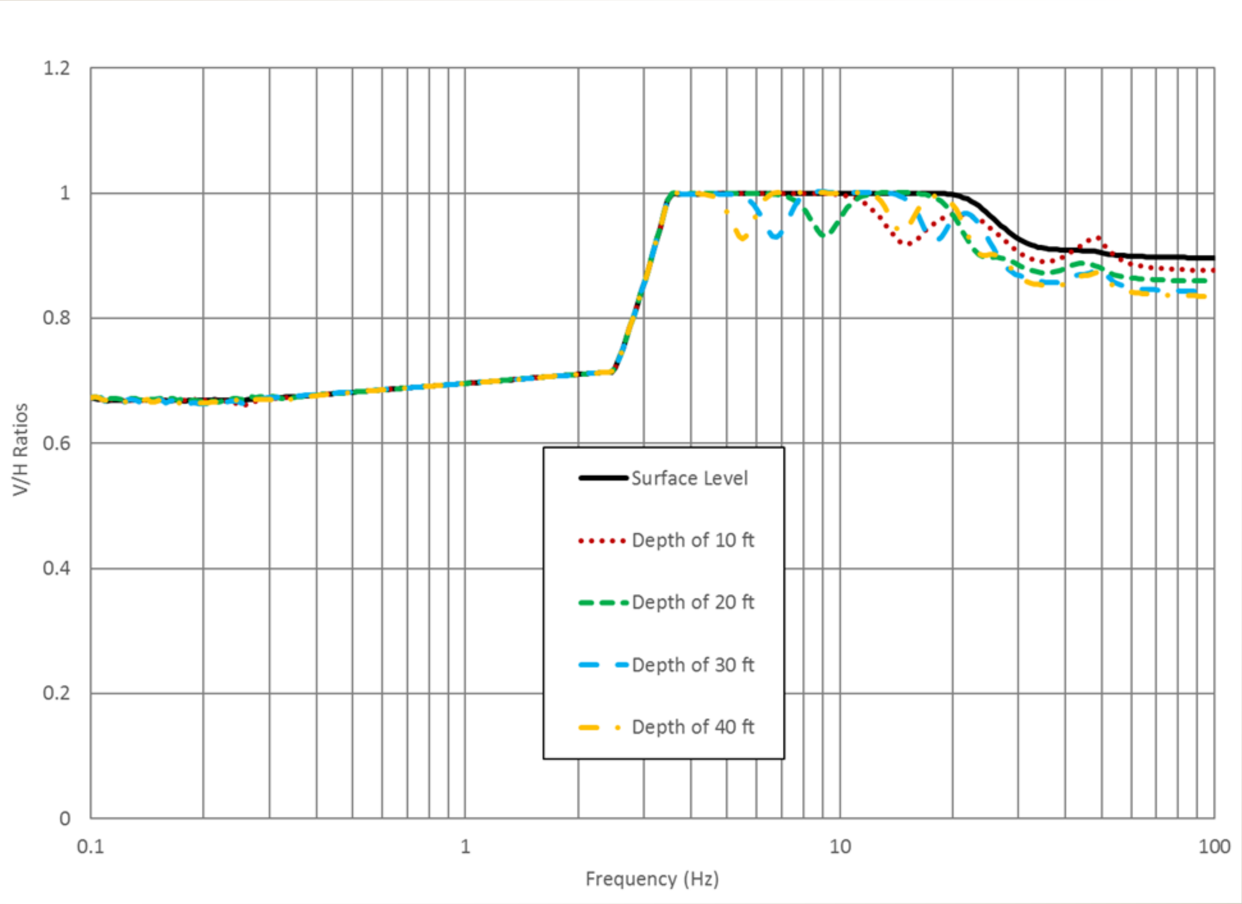
Adopted AP1000 Lumped Mass Stick Model (LMSM)

SSI Case Study



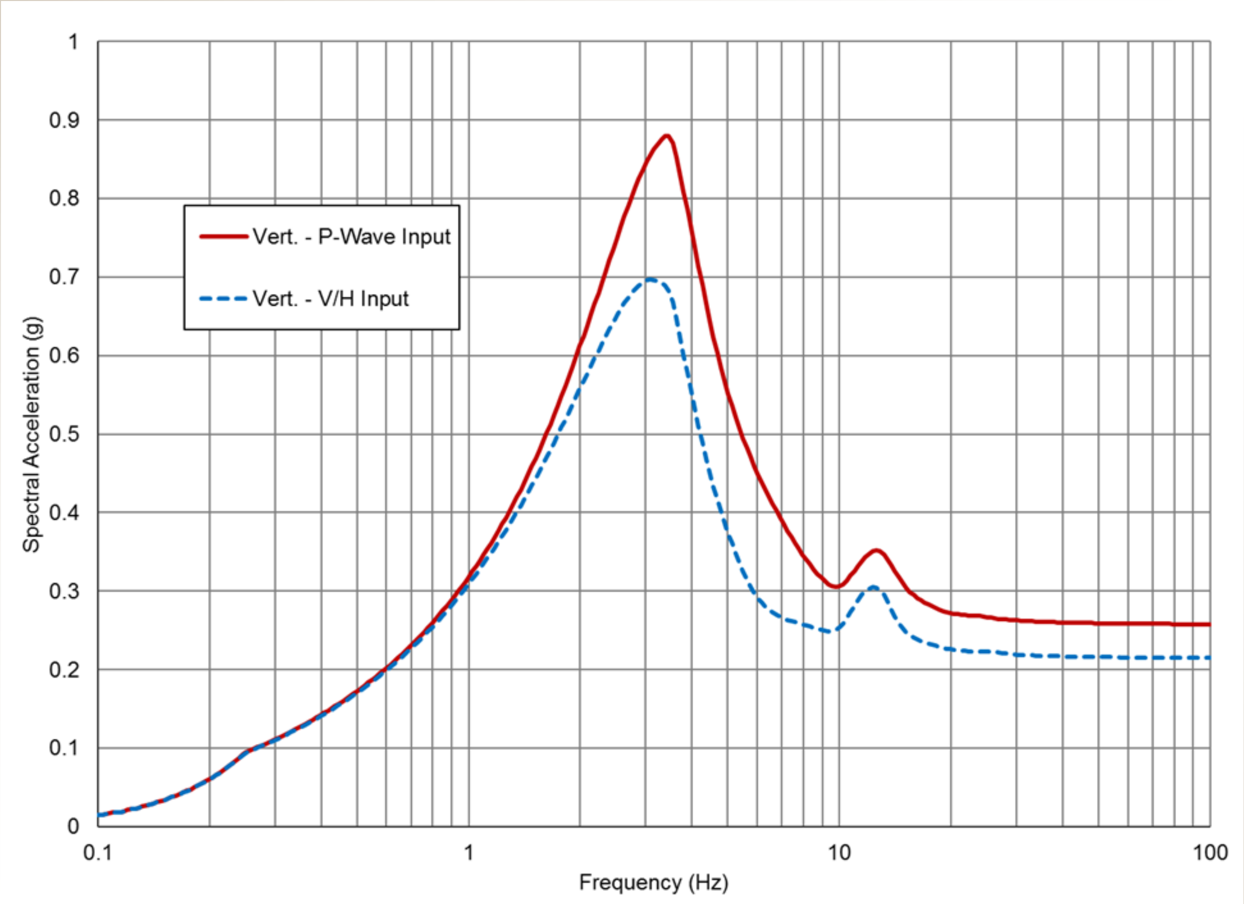
V/H ratios in the Soil Profile due to P-wave Propagation Input, RG 1.60 Input Motion

SSI Case Study



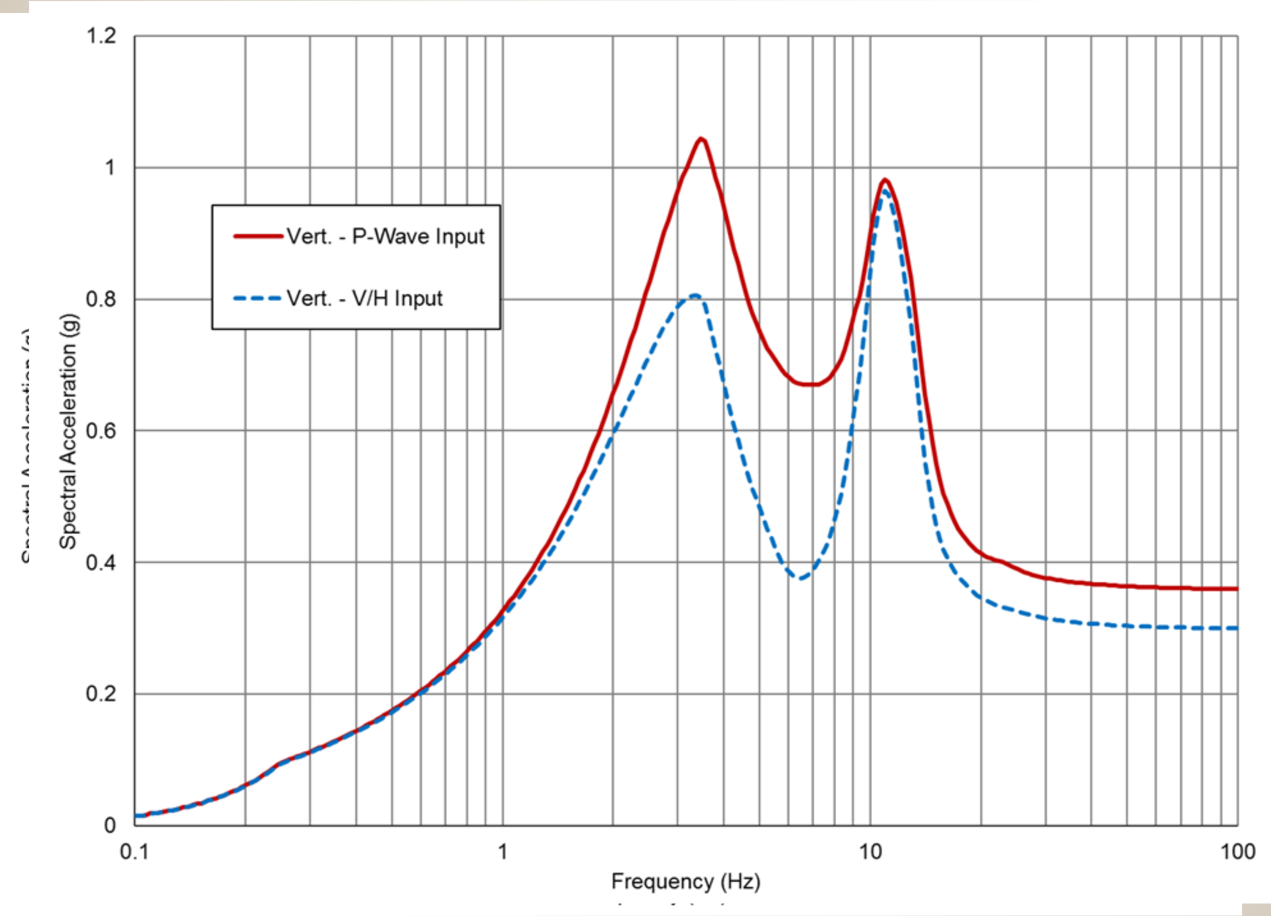
V/H ratios in the Soil Profile due to Consistent V/H Input, RG 1.60 Input Motion

SSI Case Study



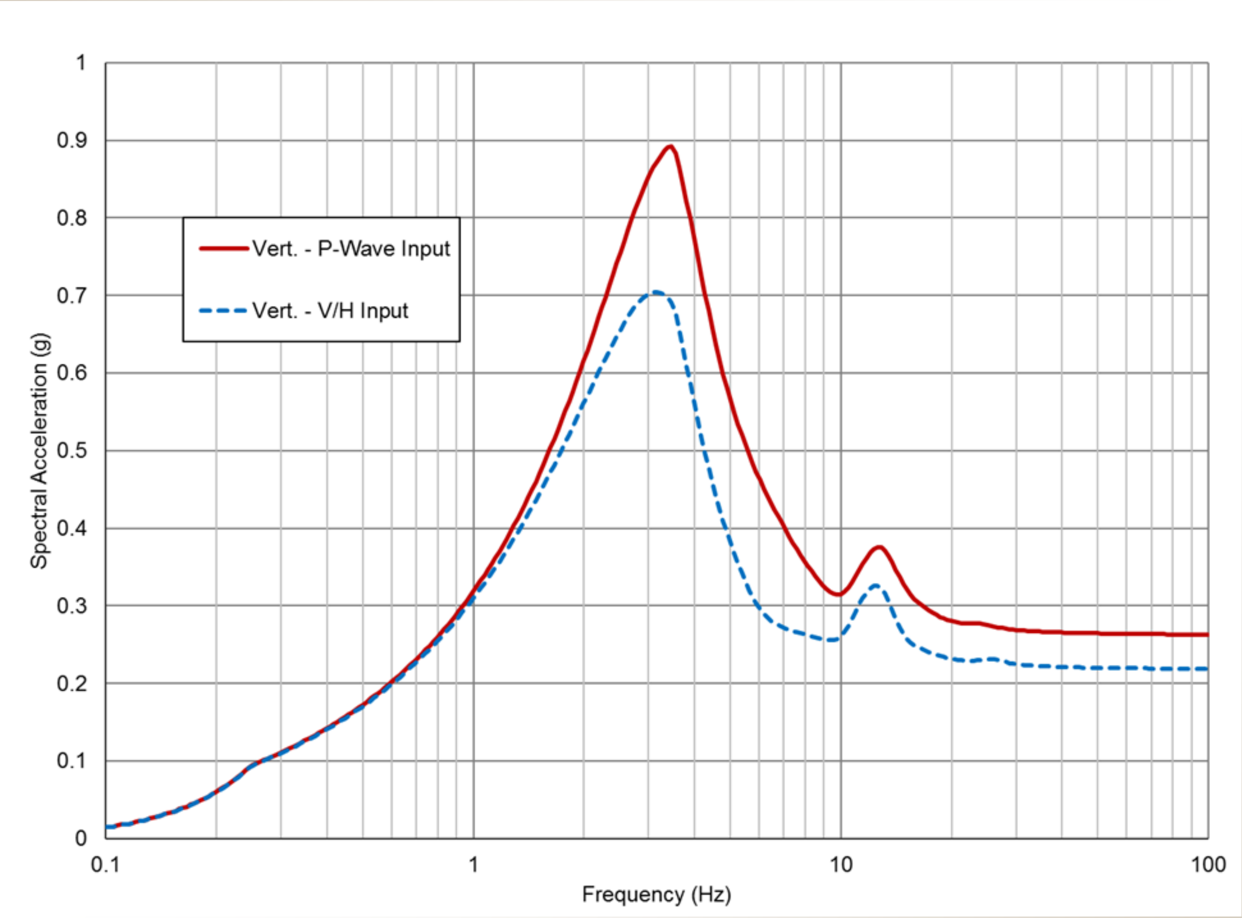
Comparison of Vertical ARS at Node 1 on Foundation

SSI Case Study



Comparison of Vertical ARS at Node 18, top of ASB

SSI Case Study



Comparison of Vertical ARS at Node 29, Top of CIS

SSI Case Study

Total Vertical Seismic Load (kips)			
	ASB	CIS	SCV
P-Wave Input	2.608×10^4	2.600×10^4	2.403×10^3
Consistent V/H Input	2.137×10^4	2.130×10^4	1.925×10^3
Mean Basemat Pressure (ksf)			
	ASB	CIS	SCV
P-Wave Input	1.159	1.156	0.107
Consistent V/H Input	0.950	0.947	0.086

Comparison AP1000 on Deep Soil Profile: Total Vertical Seismic Load and Mean Basemat Seismic Pressure

BECHTEL

Closure

Consistent V/H Ratio Approach for vertical SSI analysis has been approved by ASCE 4 committee for implementation in ASCE 4-22 in progress at this time

Thank You

Comments/Questions