Methods to Account for Shallow Site Effects in Hybrid Broadband Ground-Motion Simulations

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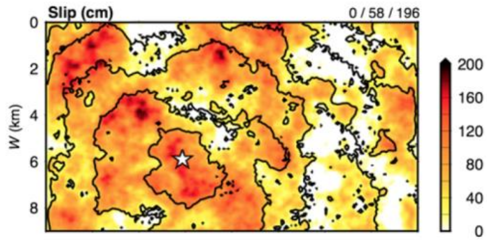
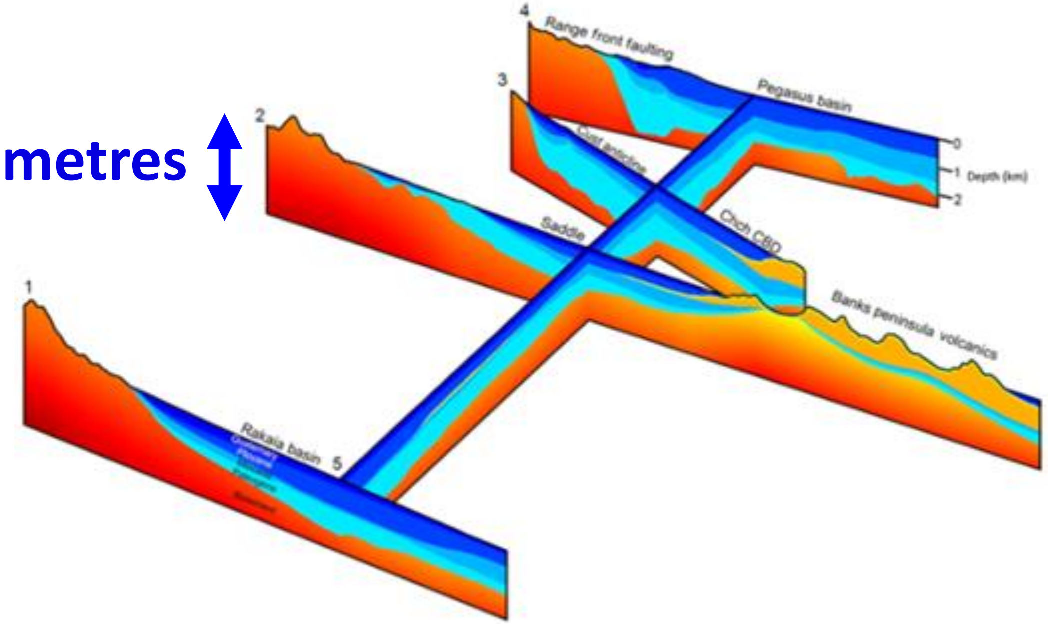
QuakeCoRE – DT1 Call | 27 July 2023

Research Focus



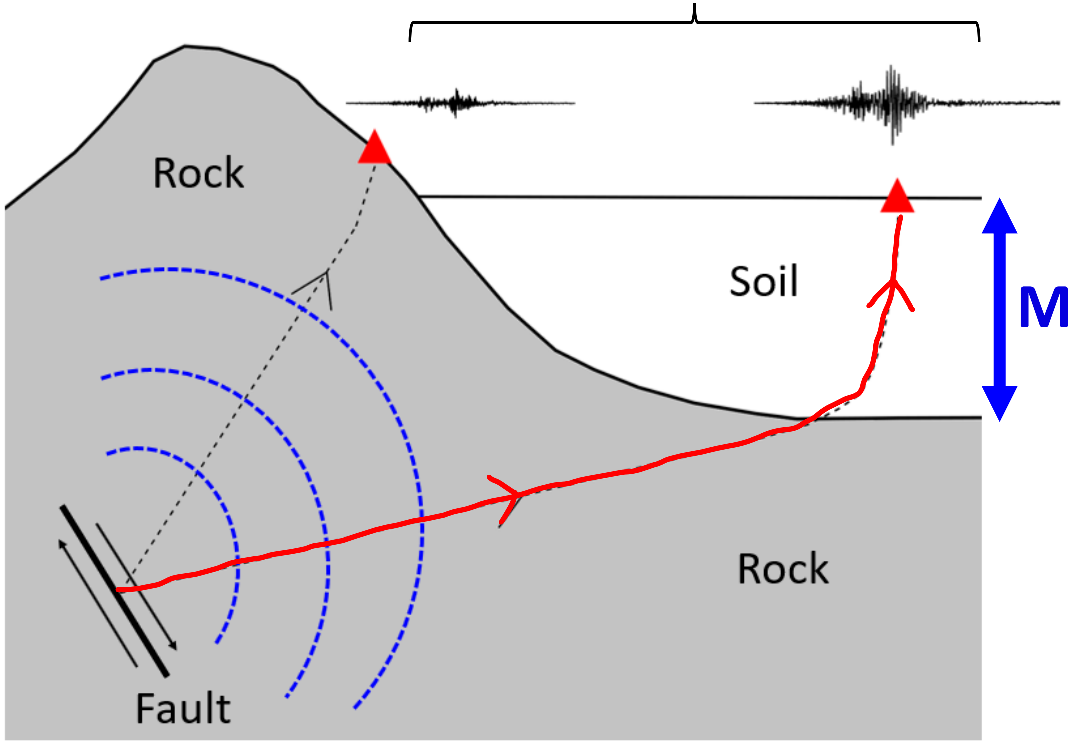
1. Source

Kilometres



2. Path

3. Local Site Effects



Metres

Challenge: Multiscale phenomena!

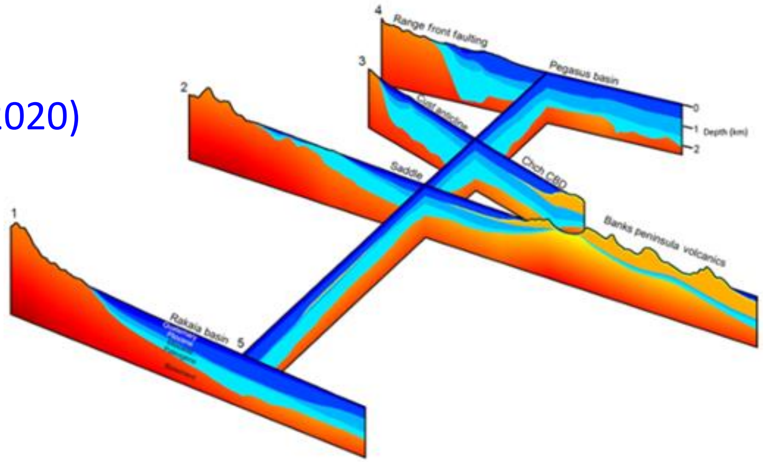
Hybrid Broadband Ground-Motion Simulations

Graves & Pitarka (2010, 2015, 2016) Method

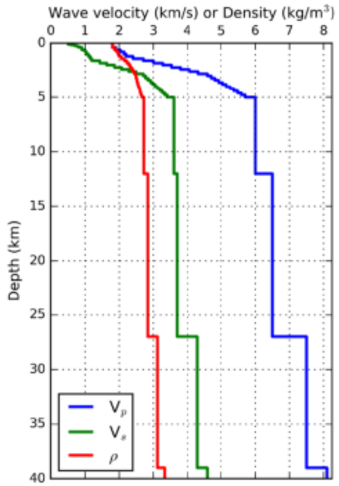
Low-Frequency (LF) ⟵ 1 Hz (this study) ⟶ **High-Frequency (HF)**

3D Wave Propagation

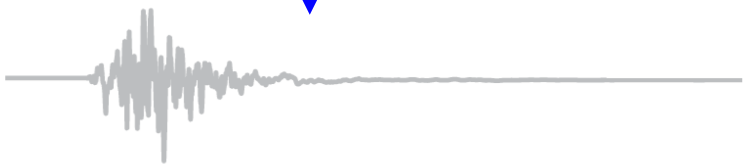
3D NZVM
(Thompson et al., 2020)



Simplified Physics ~ 1D



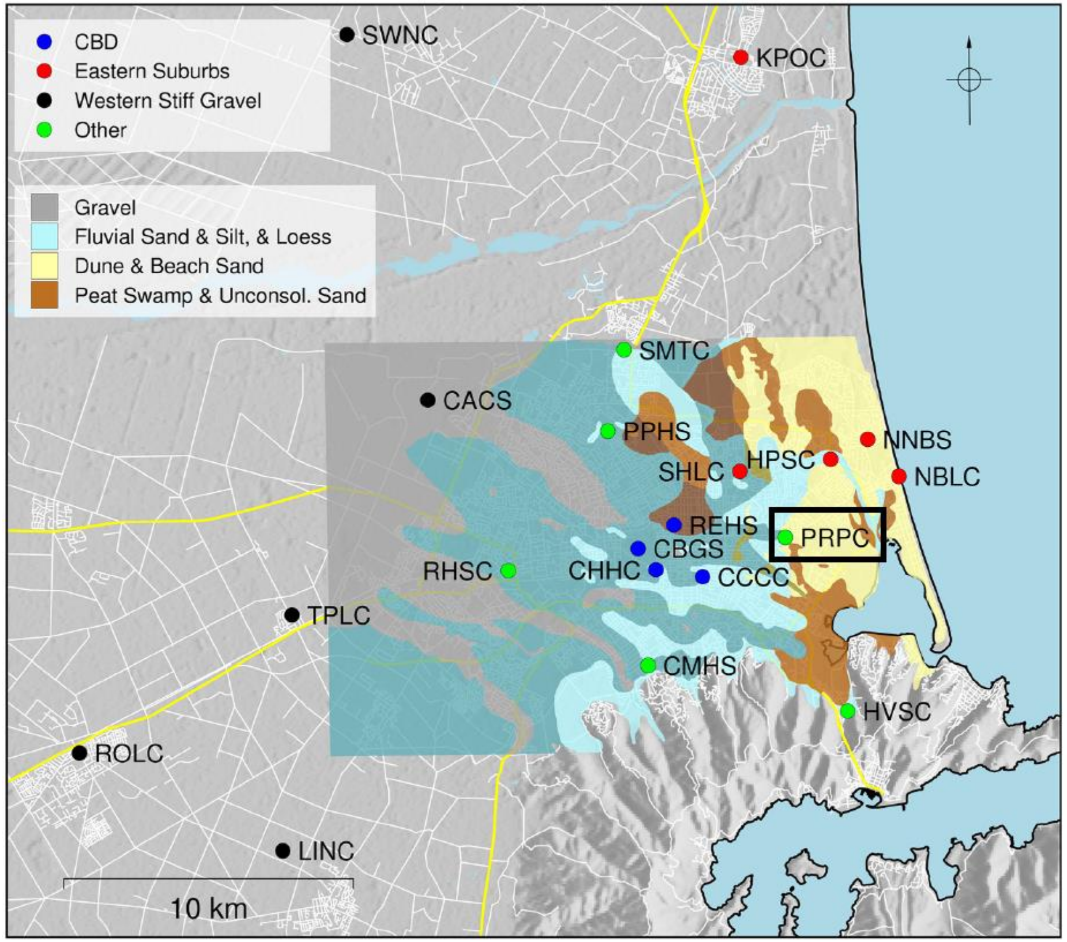
Regional 1D Model



Broadband (BB)

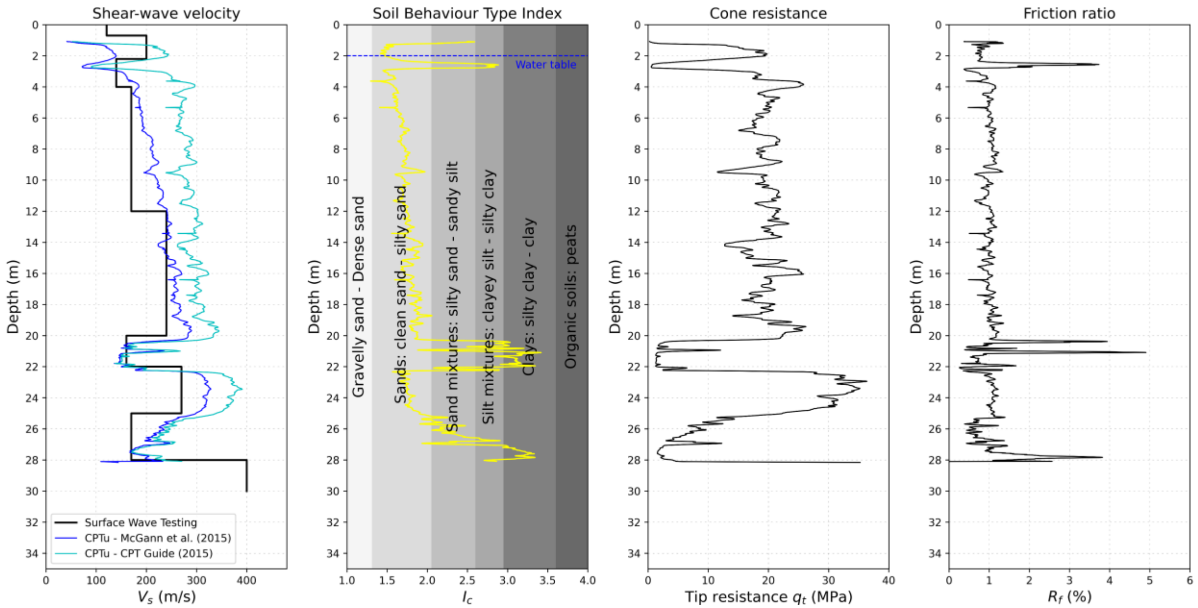
Case Study

Strong-motion station PRPC



Site-Characterization Data

$$V_{s30} = 196\, m/s$$

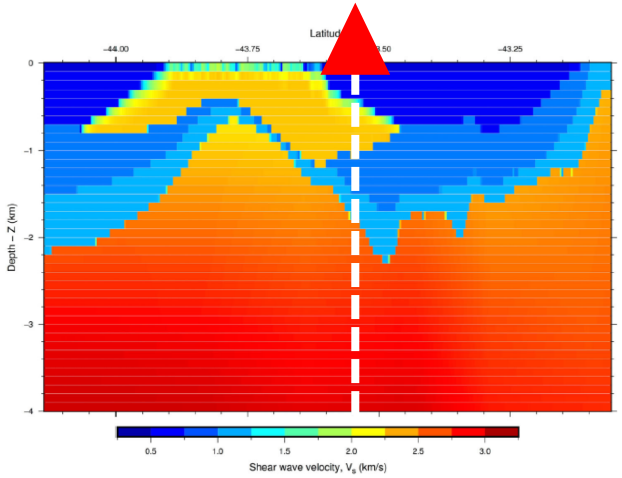


Two earthquakes considered

Event	Date	Magnitude, Mw	Observed PGA (g)
Event 1	09 May 2011	4.9	0.05
Event 2	22 February 2011	6.2	0.62

Simulated Vs Profiles

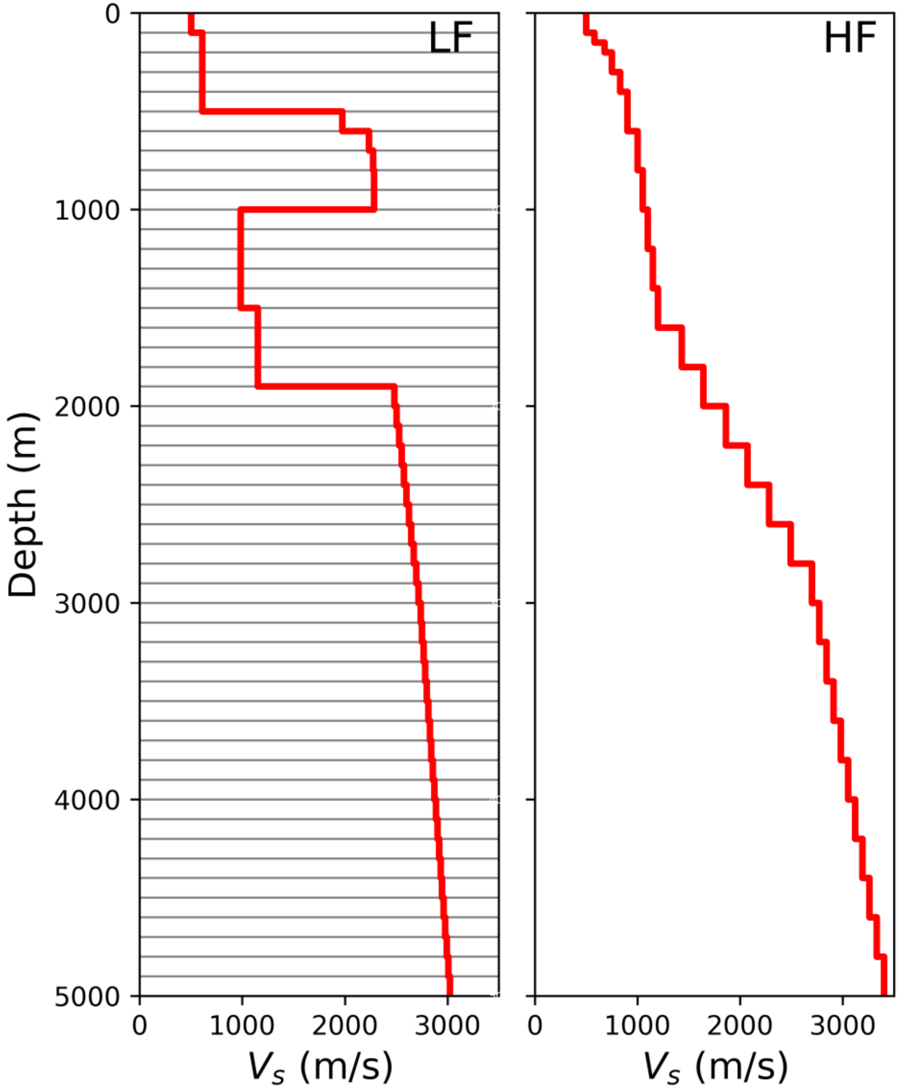
Site PRPC



3D NZVM

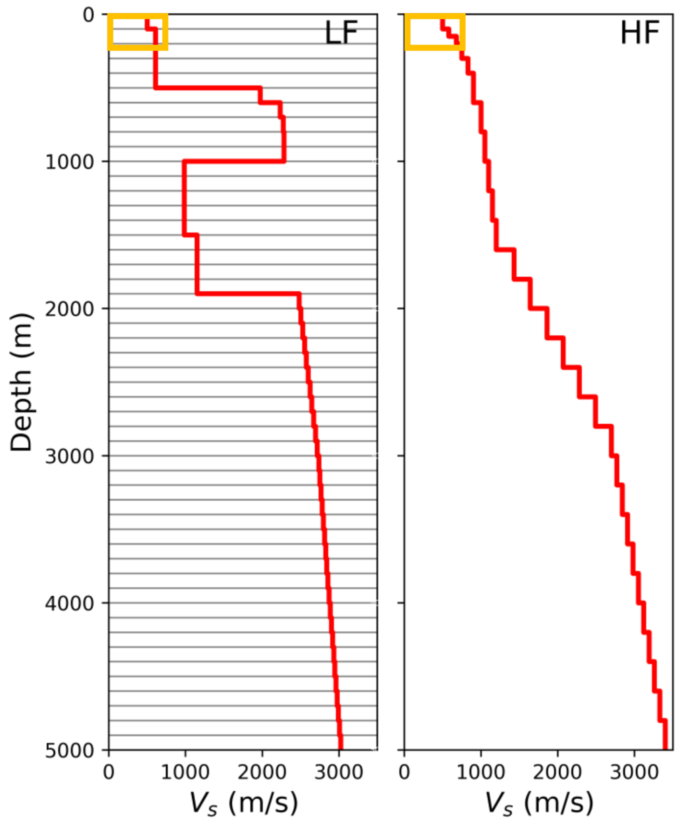
Low-Frequency (LF)

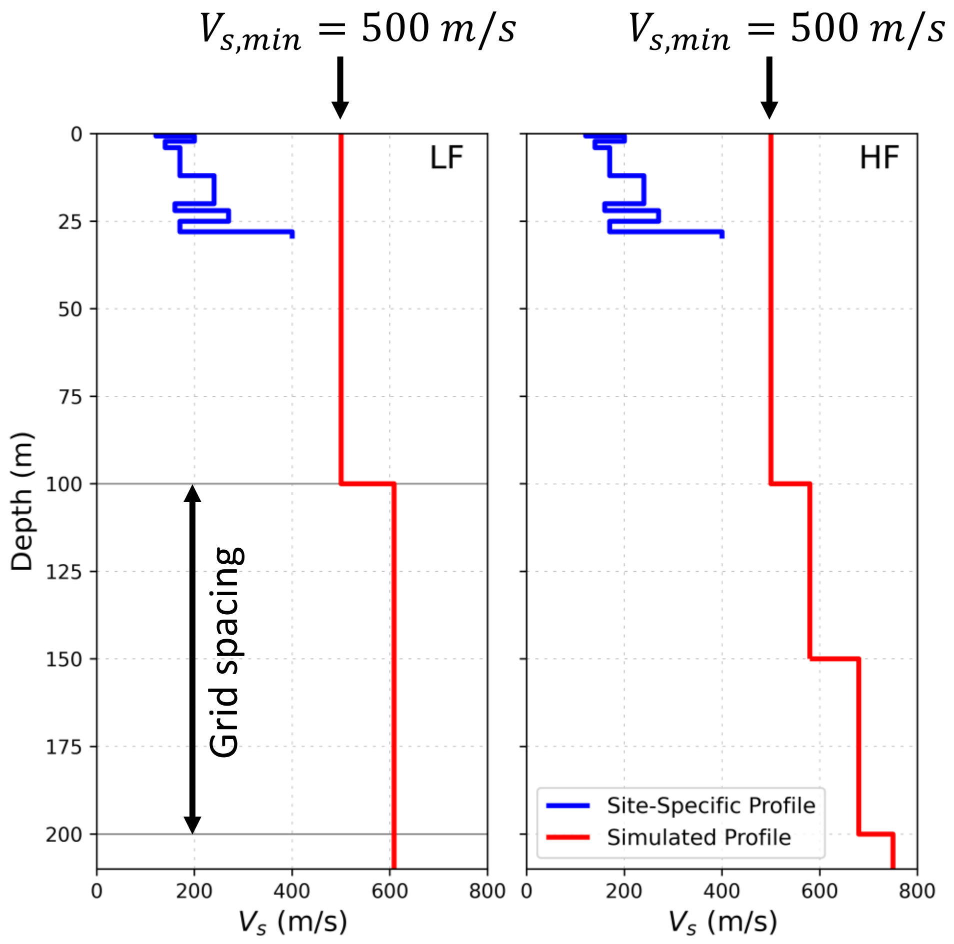
High- Frequency (HF)



Regional 1D Model

Considerations for the Modelling of Shallow Site Effects





1. Two different approaches

2. Linear viscoelastic model

3. $V_{s,min}$ is too high and the spatial resolution too coarse

4. Local site effects are captured to some extent

Approaches to Model Site Effects

- 3D/2D/1D Time-Domain Site-Response Analysis (SRA)
- 1D Frequency-Domain Site-Response Analysis
- Square-Root-Impedance (SRI) Method
- Site-Response Component of Ground-Motion Models (GMMs)

Question

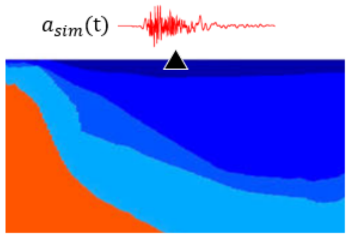
How to use these approaches to adjust the simulated ground motion to account for shallow site effects (~ max. 100 m depth)? This adjustment has to…

1. Deal with two different simulation approaches (LF and HF)
2. Incorporate soil nonlinearity
3. Model actual site conditions (lower V_S and finer spatial resolution than in simulation)
4. Not double-count local site effects already captured in the simulation

Types of adjustment

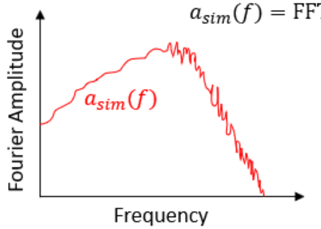
Frequency-Domain Adjustment

Step 1. Obtain the acceleration time series, $a_{sim}(t)$, produced by the regional-scale simulation

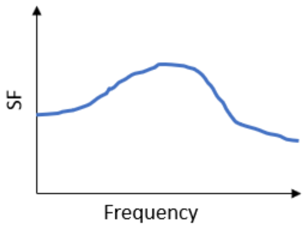


Step 2. Using the fast Fourier transform (FFT) compute the discrete Fourier transform of $a_{sim}(t)$ to get the Fourier amplitude, $a_{sim}(f)$

$$a_{sim}(f) = \mathrm{FFT}(a_{sim}(t))$$

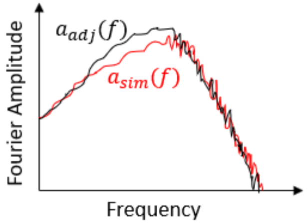


Step 3. Obtain the site correction factor, SF



Step 4. Apply the SF to the Fourier amplitude obtained in Step 2 to get an adjusted Fourier amplitude, $a_{adj}(t)$

$$a_{adj}(f) = SF(f) \cdot a_{sim}(f)$$

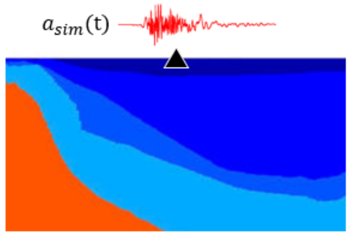


Step 5. Apply the inverse fast Fourier transform (IFFT) to the adjusted Fourier amplitude obtained in Step 4 to produce the adjusted acceleration time series, $a_{adj}(t)$

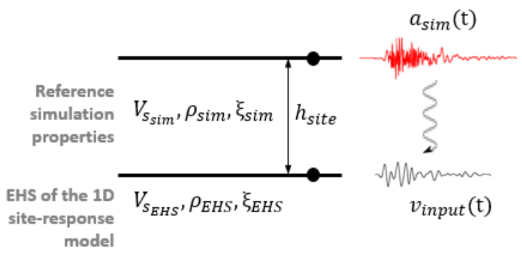
$$a_{adj}(t) = \mathrm{IFFT}\left(a_{adj}(f)\right)$$

Time-Domain Adjustment

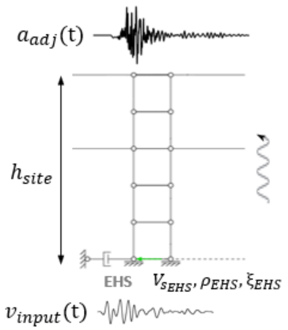
Step 1. Obtain the acceleration time series, $a_{sim}(t)$, produced by the regional-scale simulation



Step 2. Deconvolve $a_{sim}(t)$ down to a reference condition compatible with the elastic half-space (EHS) that will be consider in Step 3



Step 3. Using the deconvolved motion, $v_{input}(t)$, obtained in Step 2 as the input motion, perform 1D time-domain nonlinear site-response analysis to obtain the adjusted ground motion, $a_{adj}(t)$



Methods

	Method	Concept	Site-Characterization Data Required
Frequency-Domain Adjustment (SF)	1	Based on the site-response component of a GMM	V_{s30}
	2	Similar to Method 1 but includes a host-to-target Vs-profile adjustment to the reference condition	V_{s30}
	3	Combines the SRI method with the nonlinear component of Method 1	V_s profile ρ profile k_0
	4	Combines the theoretical 1D transfer function with the nonlinear component of Method 1	V_s profile ρ profile D_{min} profile
Time-Domain Adjustment	5	Based on 1D time-domain nonlinear site-response analysis	V_s profile ρ profile D_{min} Nonlinear parameters

Less data → More data

Method 1 – Frequency-Domain Adjustment

f_{site} is the site-response component of a GMM

$V_{s30,actual} = 196\ m/s$

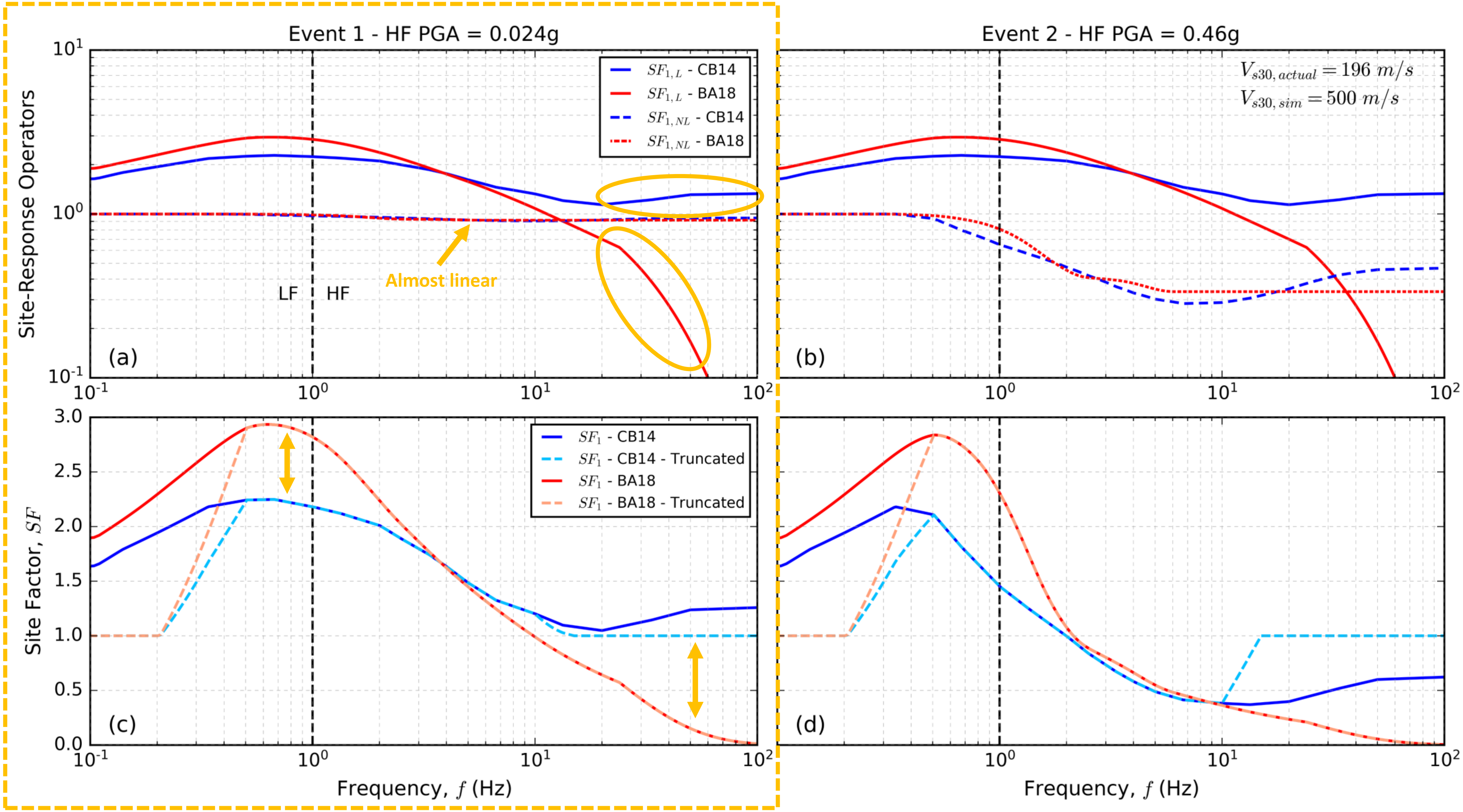
IM_{rock}

$$SF_1 = \frac{\exp[f_{site,actual}]}{\exp[f_{site,sim}]} = \frac{\exp[f_{L,actual} + f_{NL,actual}]}{\exp[f_{L,sim}]}$$

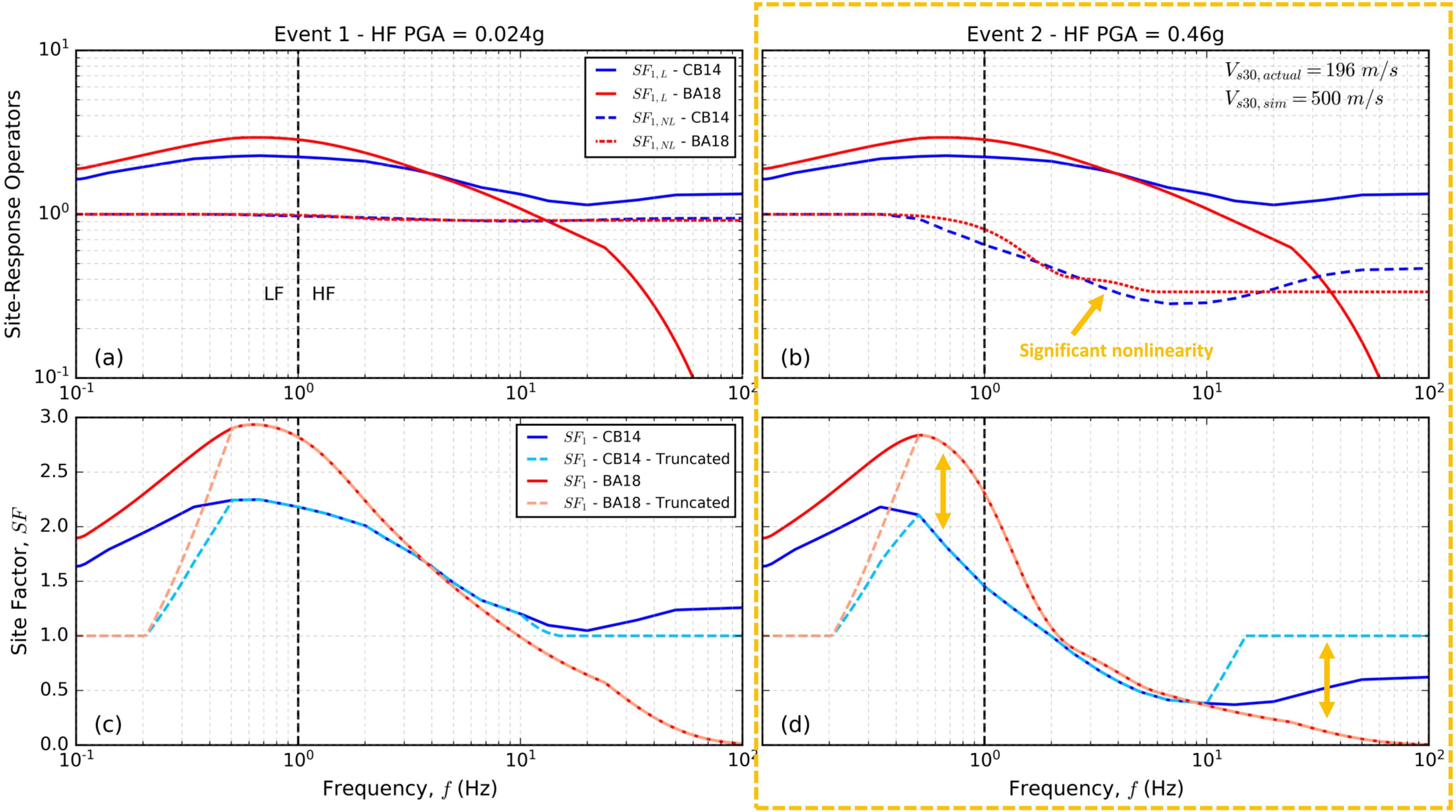
$V_{s30,sim} = 500\ m/s$

$$SF_1 = SF_{1,L} \cdot SF_{1,NL}$$

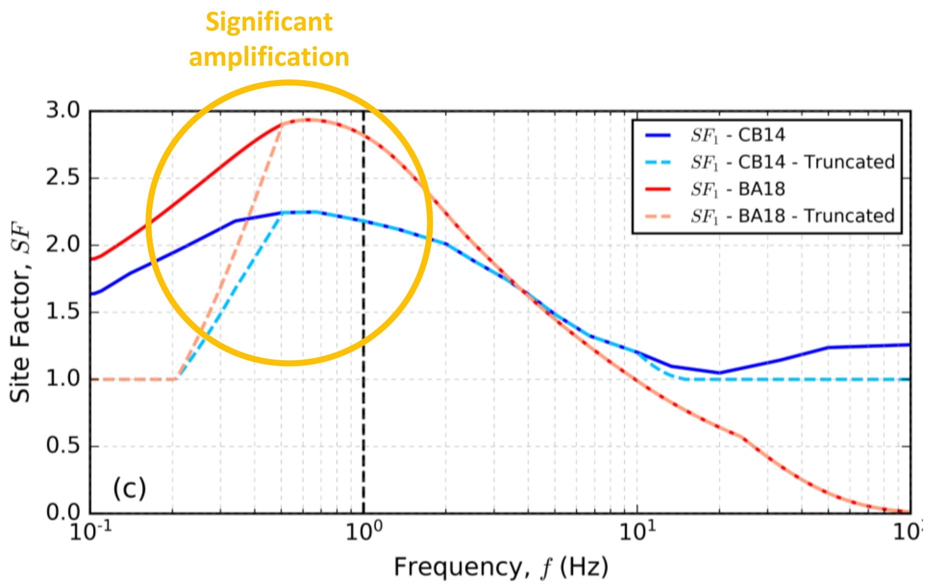
Method 1 – Frequency-Domain Adjustment



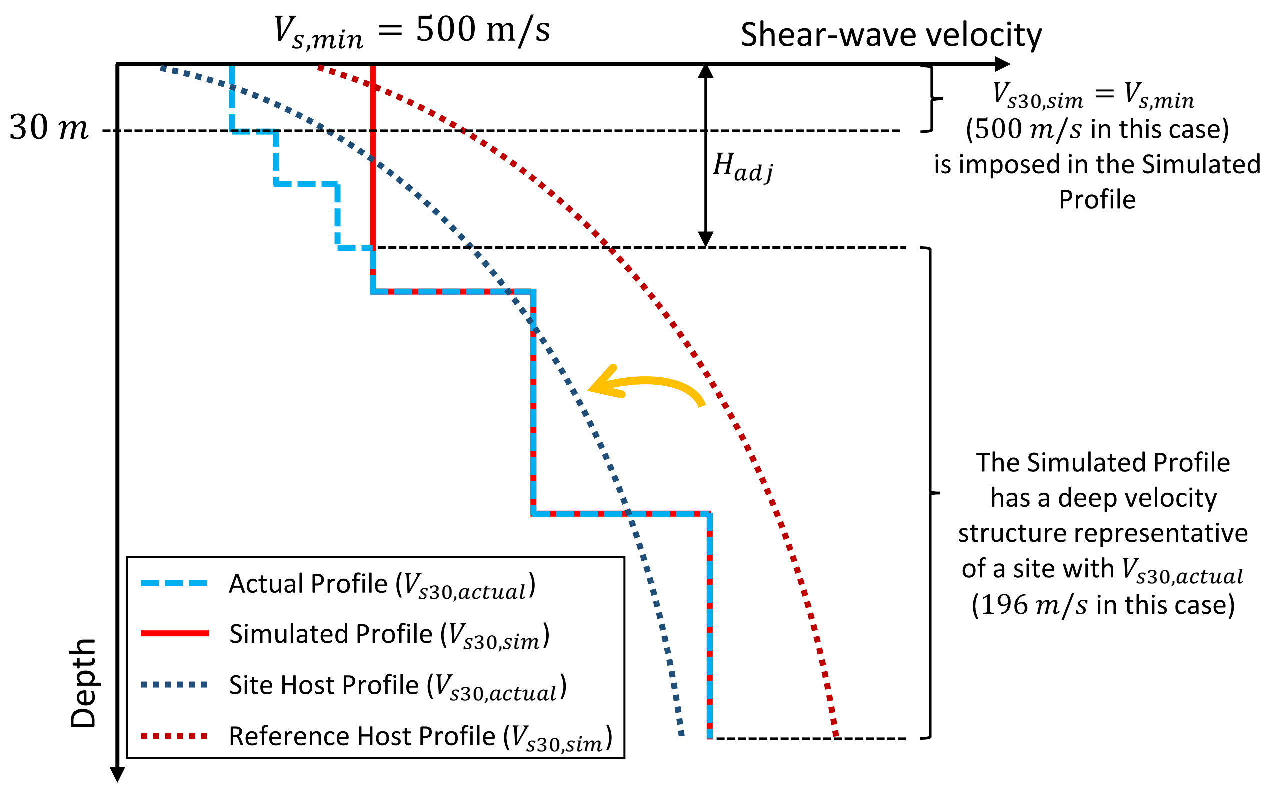
Method 1 – Frequency-Domain Adjustment



Method 1 – Frequency-Domain Adjustment



Validation studies have shown <u>systematic overamplification at low frequencies</u> (e.g., de la Torre et al., 2020; Lee et al., 2020)



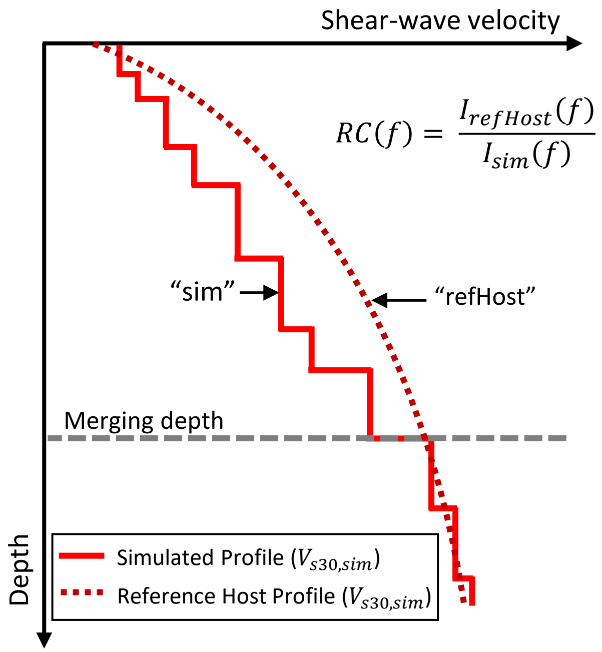
$$SF_1 = \frac{\exp[f_{site,actual}]}{\exp[f_{site,sim}]}$$

Host-to-target correction issue

Method 2 – Frequency-Domain Adjustment

$$SF_2 = RC \cdot SF_1$$

$$RC = \frac{I_{refHost}}{I_{sim}} = \frac{\sqrt{\frac{\rho_R V_{s,R}}{\bar{\rho}_{refHost} V_{s,refHost}}}}{\sqrt{\frac{\rho_R V_{s,R}}{\bar{\rho}_{sim} V_{s,sim}}}}$$

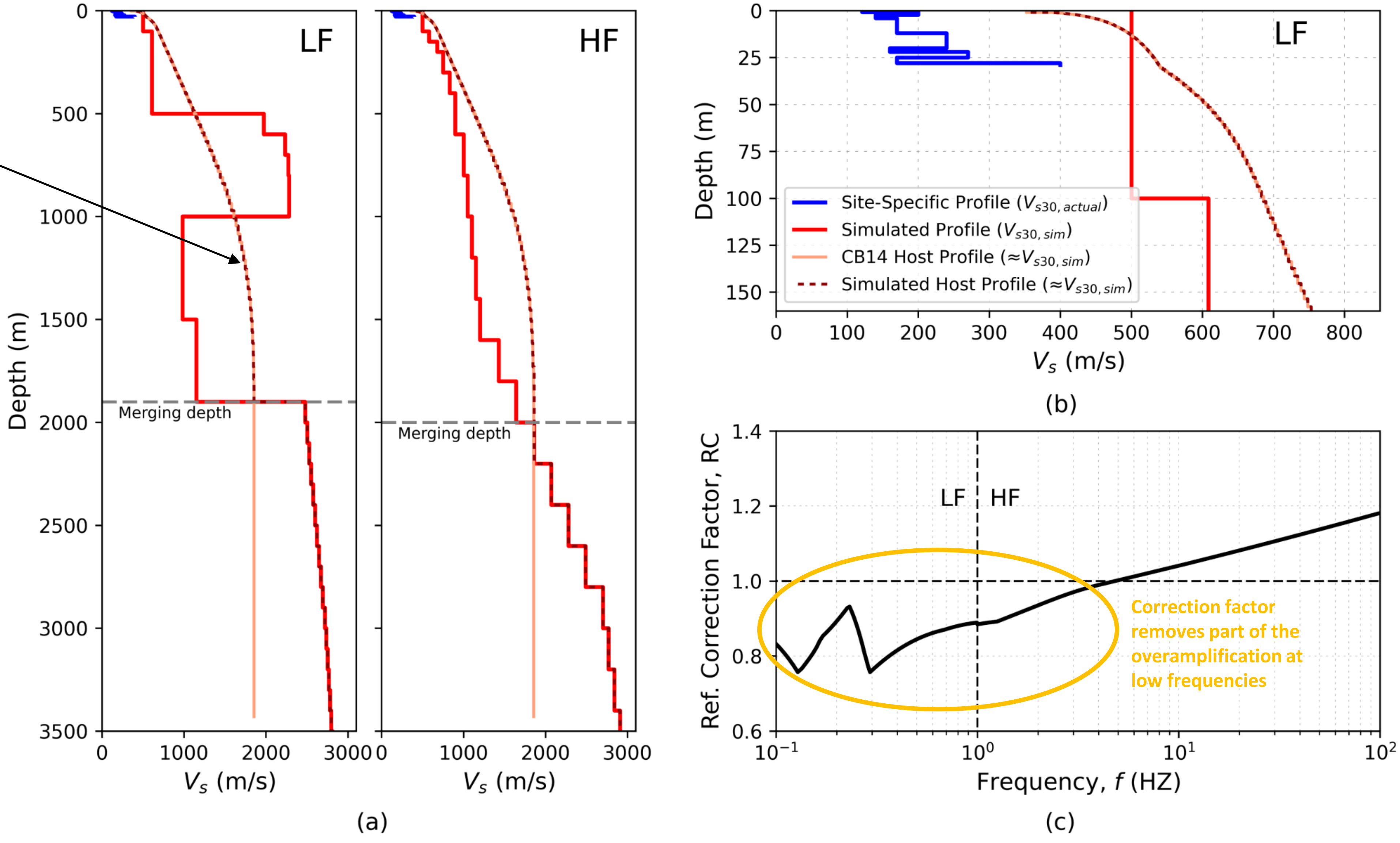


Application	Concept
Definition of $SF_1(f)$	Reference Host Profile ($V_{s30,sim}$) → $SF_1(f)$ → Site Host Profile ($V_{s30,actual}$)
Method 1 Inconsistent with definition of $SF_1(f)$	Simulated Profile ($V_{s30,sim}$) → $SF_1(f)$ → Actual Profile ($V_{s30,actual}$)
Method 2 Partially consistent with definition of $SF_1(f)$	Step 1: Simulated Profile ($V_{s30,sim}$) → $RC(f)$ → Reference Host Profile ($V_{s30,sim}$) Step 2: Reference Host Profile ($V_{s30,sim}$) → $SF_1(f)$ → Actual Profile ($V_{s30,actual}$)

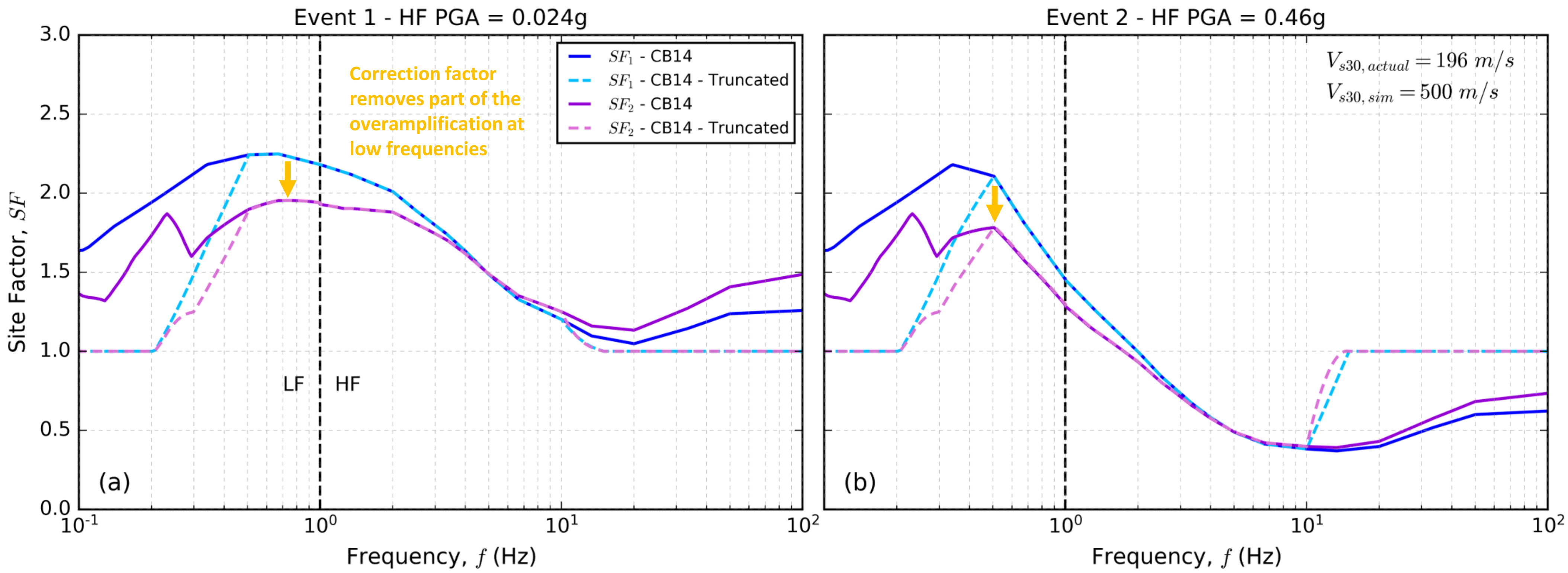
The site correction factor is applied to a reference condition consistent with the GMM

Method 2 – Frequency-Domain Adjustment

Host profile of the CB14 model provided by Linda Al Atik (Al Atik & Abrahamson, 2021)



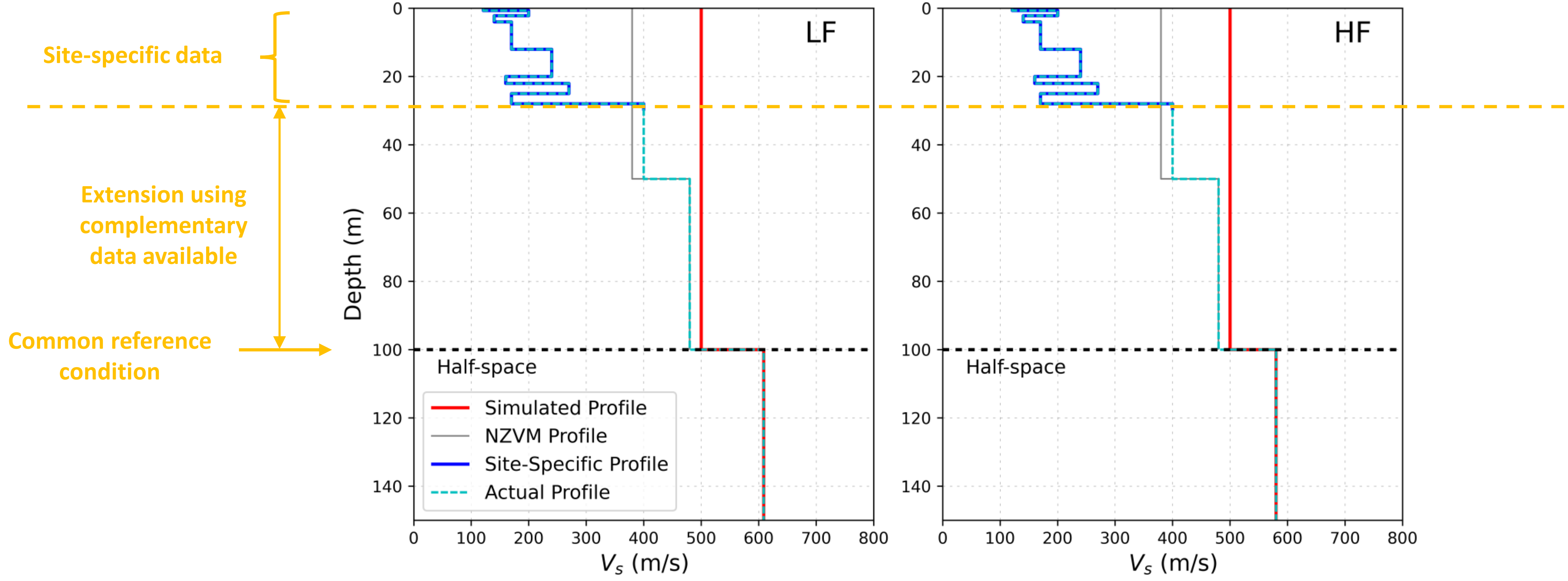
Method 2 – Frequency-Domain Adjustment



The amplification is still significant at low frequencies. Possible reasons:

- Quality of the reference host profile (Al Atik & Abrahamson method only works well for very stiff sites)
- Differences between the actual profile and the corresponding host profile (e.g., stronger basin effects present in the database used to develop the GMM for $V_{s30,actual}$)

Method 3 – Frequency-Domain Adjustment



Linear component based on the SRI Method

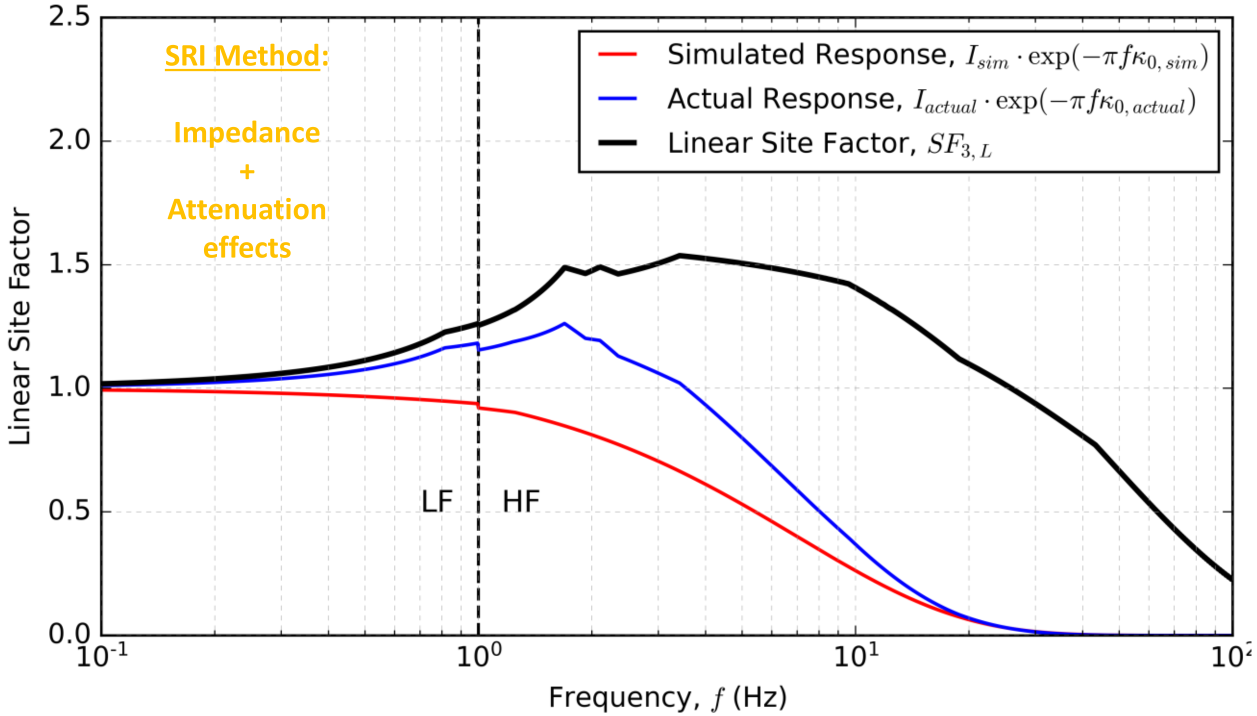
$$SF_{3,L} = \frac{TF_{SRI,actual}}{TF_{SRI,sim}} = \frac{\sqrt{\dfrac{\rho_R V_{s,R}}{\bar{\rho}_{actual} V_{s,actual}}}}{\sqrt{\dfrac{\rho_R V_{s,R}}{\bar{\rho}_{sim} V_{s,sim}}}} \cdot \exp[-\pi f(\kappa_{0,actual} - \kappa_{0,sim})]$$

Constant value: 0.045 s

Can be estimated using Vs30-based correlations

Method 3 – Frequency-Domain Adjustment

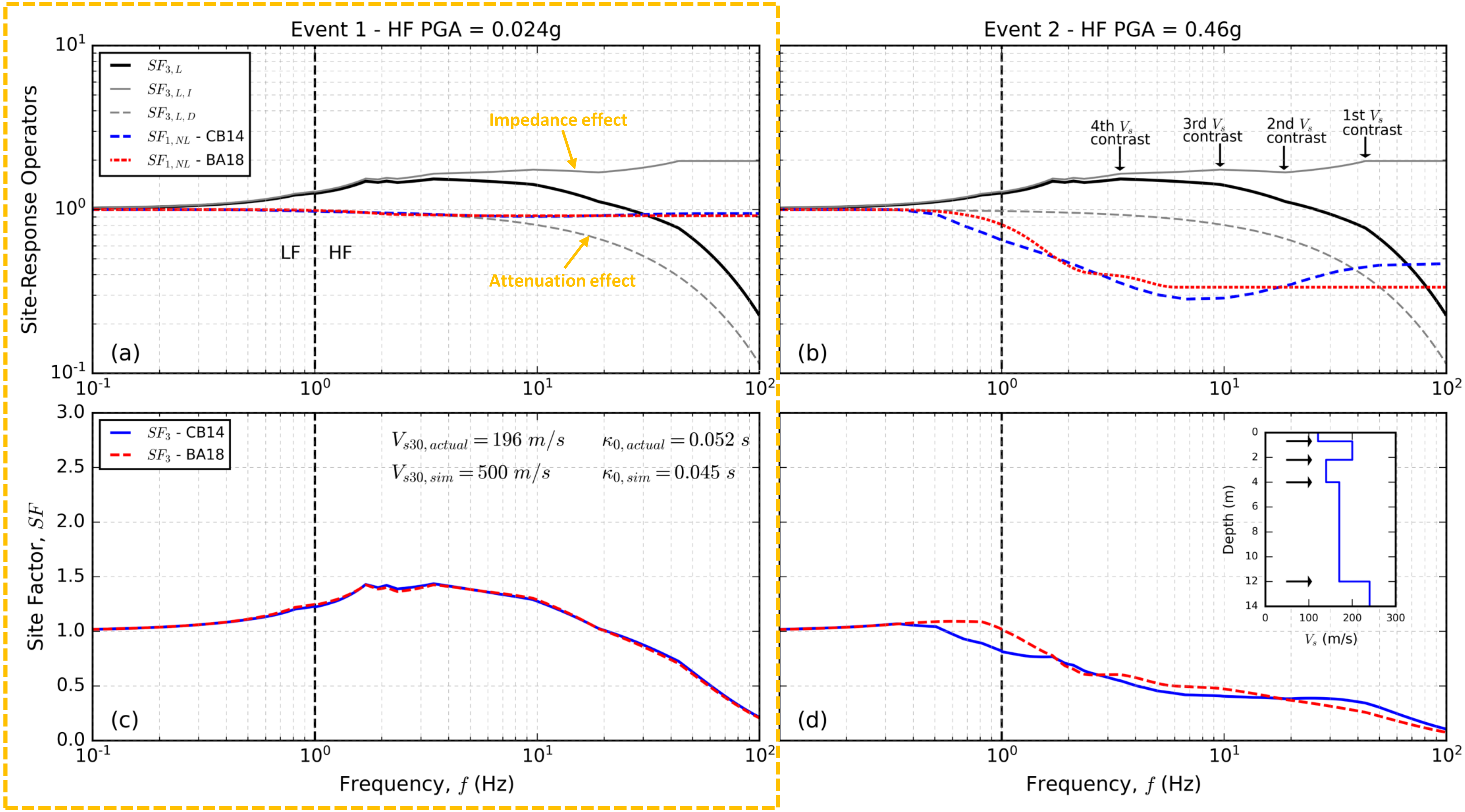
$$SF_{3,L} = \frac{I_{actual} \cdot \exp(-\pi f \kappa_{0,actual})}{I_{sim} \cdot \exp(-\pi f \kappa_{0,sim})}$$



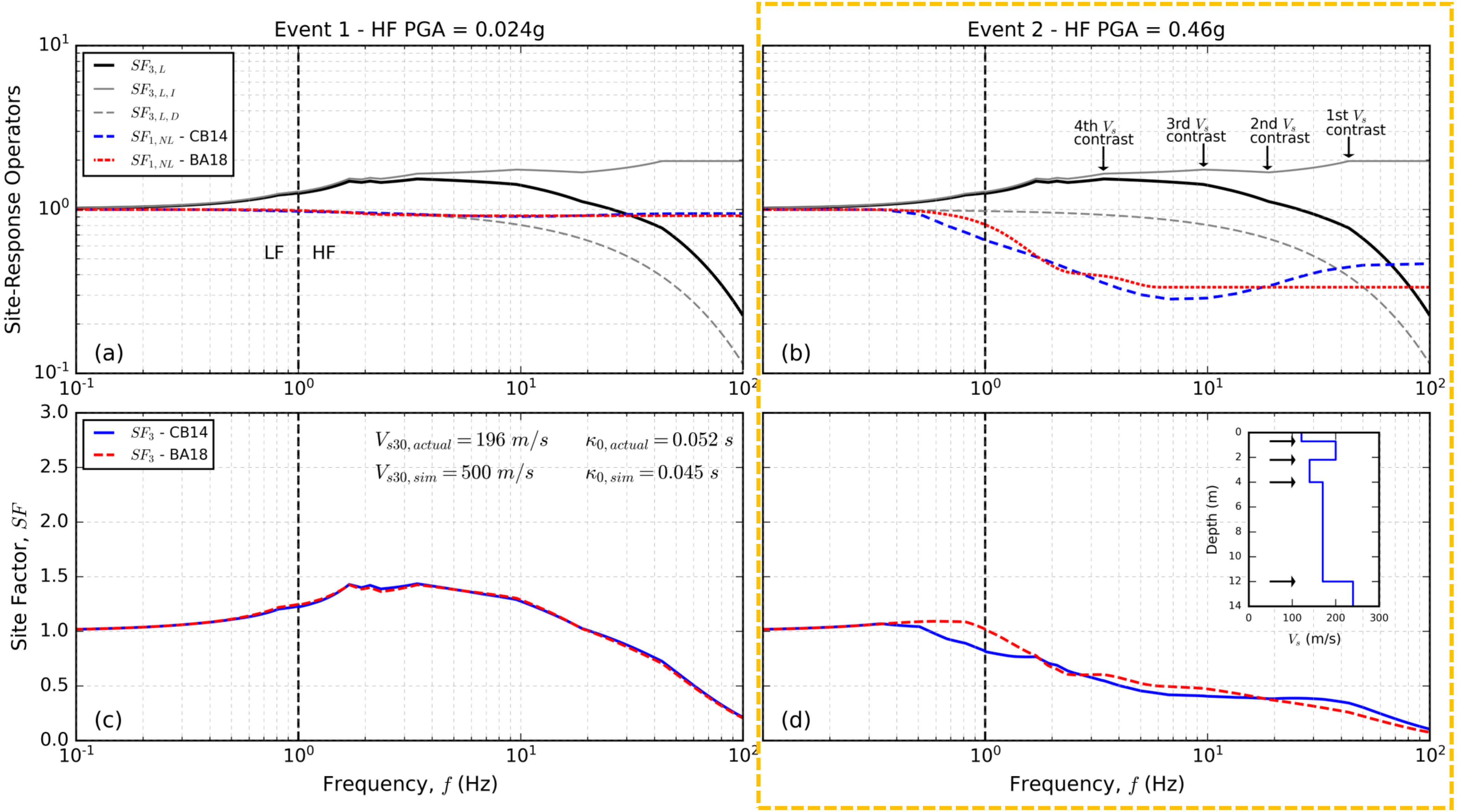
Nonlinear component from Method 1

$$SF_3 = SF_{3,L} \cdot SF_{1,NL}$$

Method 3 – Frequency-Domain Adjustment

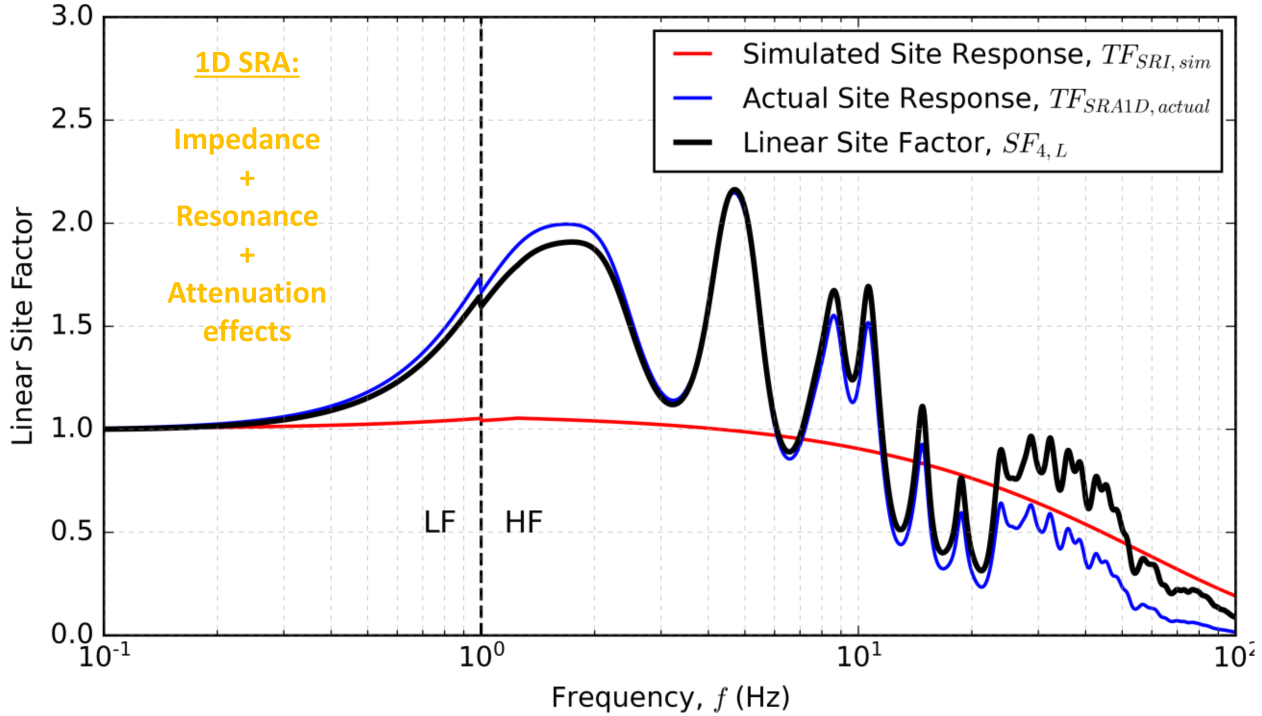


Method 3 – Frequency-Domain Adjustment



Method 4 – Frequency-Domain Adjustment

$$SF_{4,L} = \frac{TF_{SRA1D,actual}}{TF_{SRI,sim}}$$

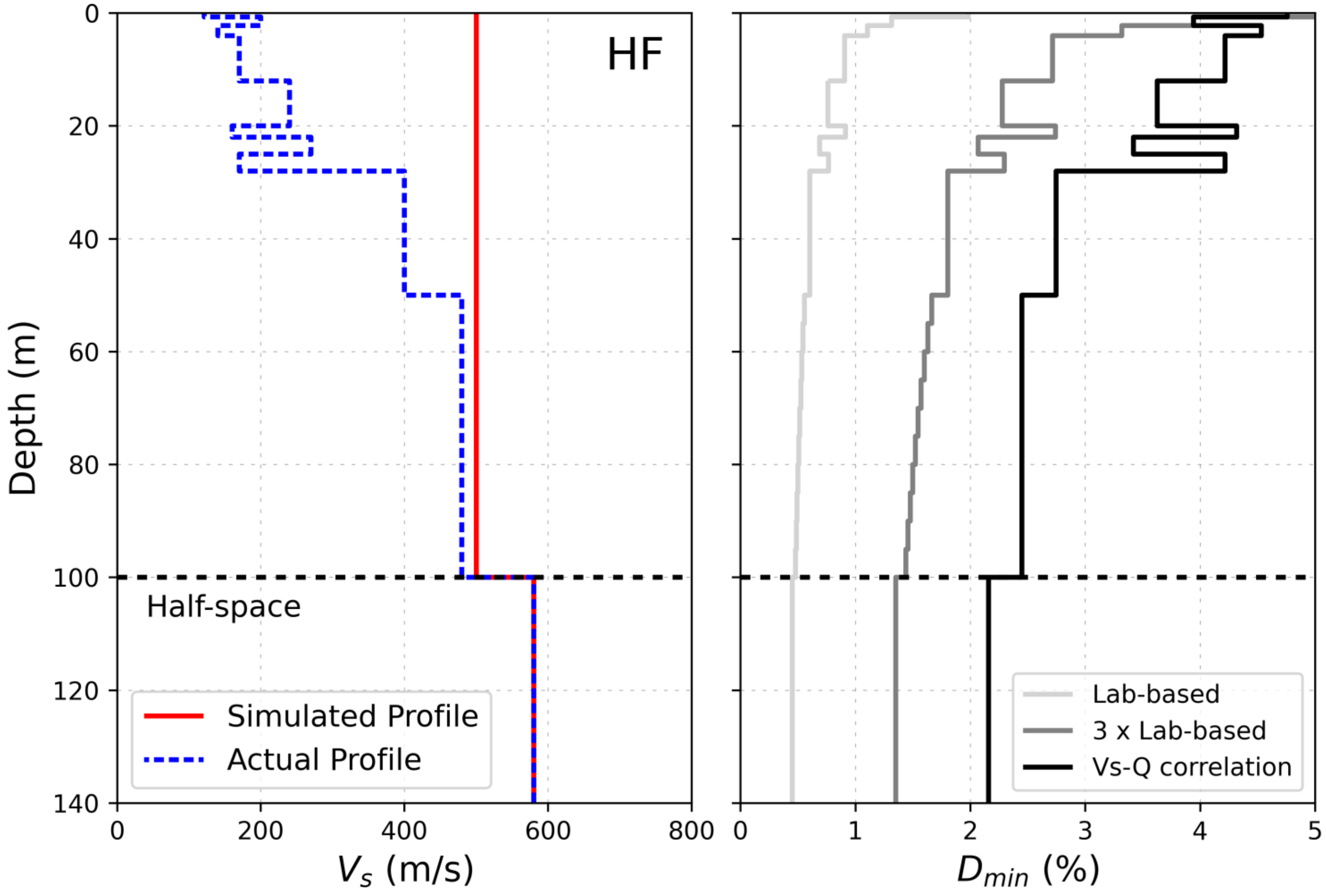


Nonlinear component
from Method 1

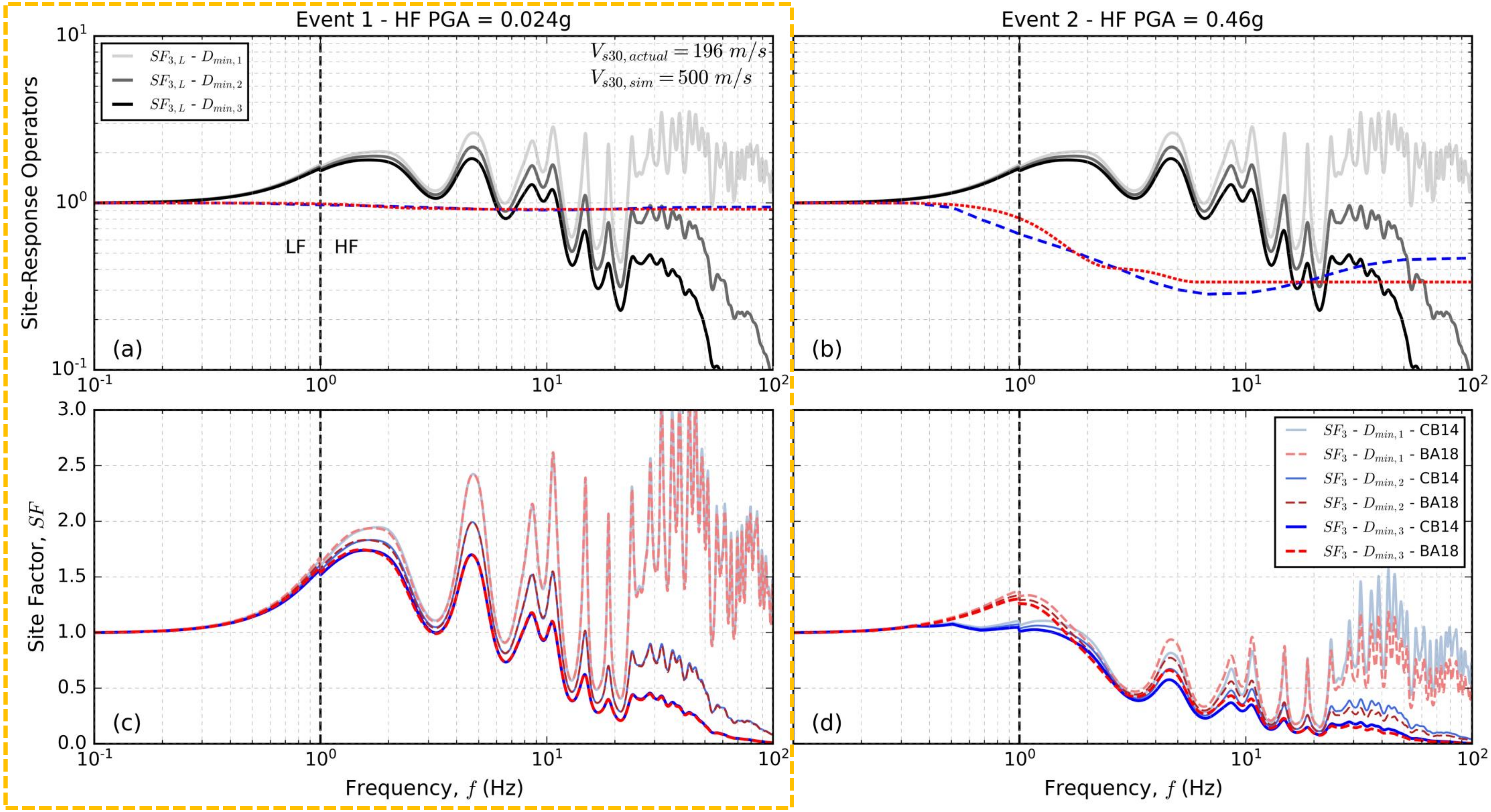
$$SF_4 = SF_{4,L} \cdot SF_{1,NL}$$

Method 4 – Frequency-Domain Adjustment

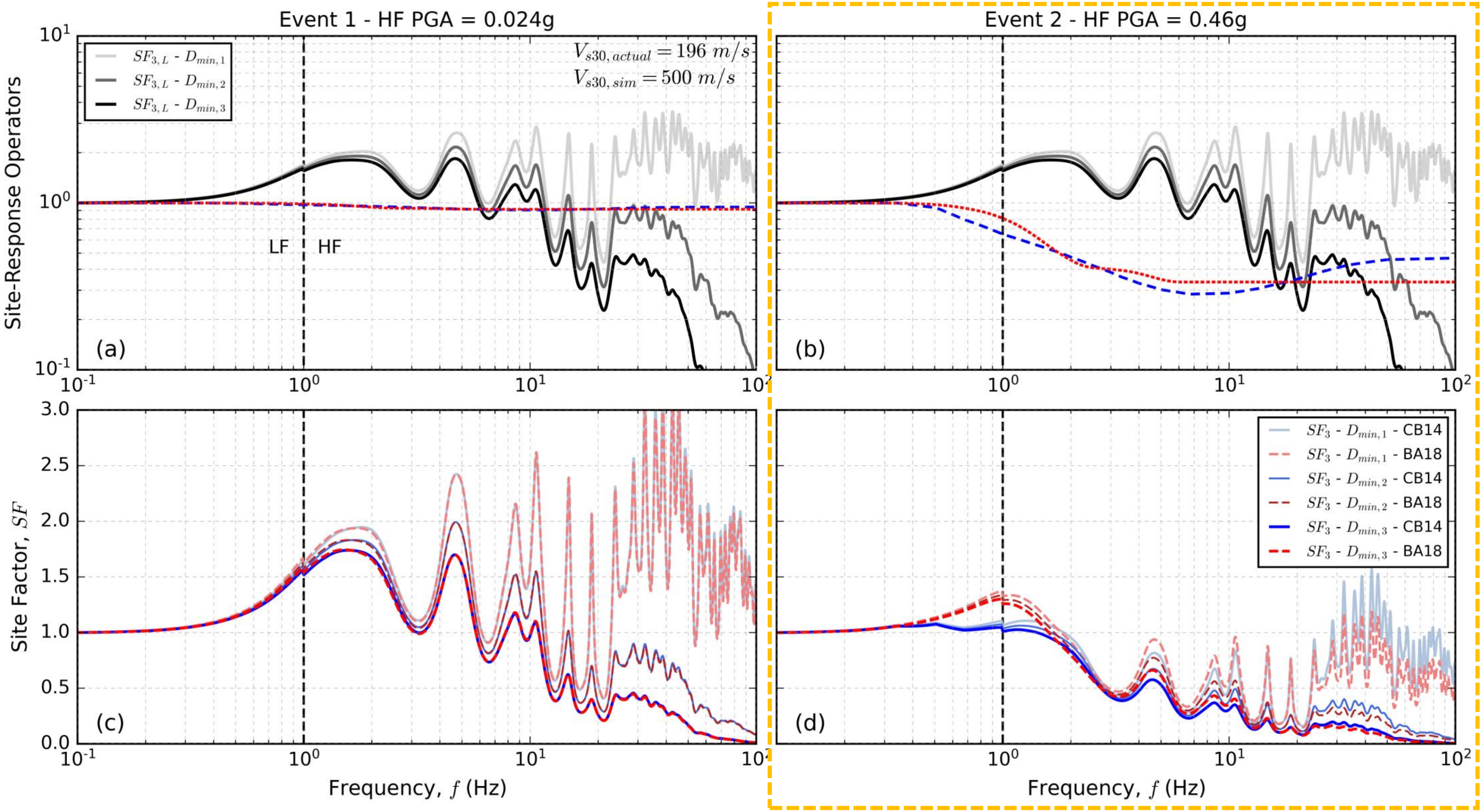
Lab-based Dmin (material damping) does not capture the actual damping in the field (material damping + wave scattering)



Method 4 – Frequency-Domain Adjustment

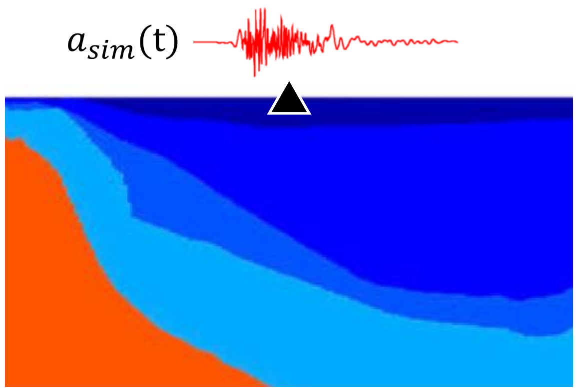


Method 4 – Frequency-Domain Adjustment

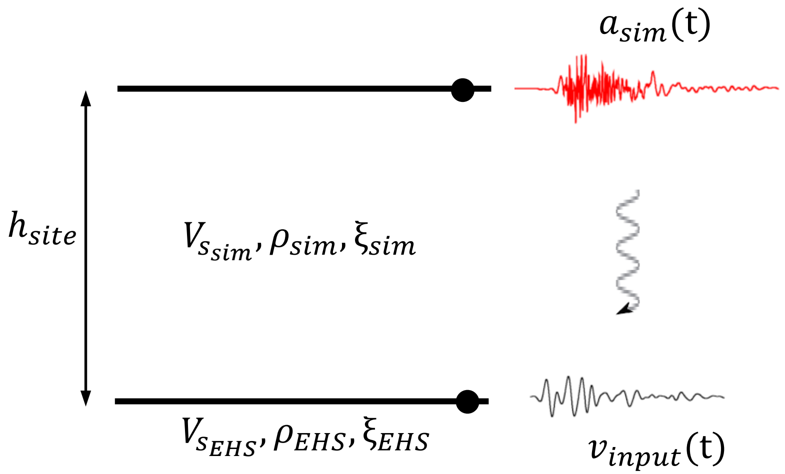


Method 5 – Time-Domain Adjustment

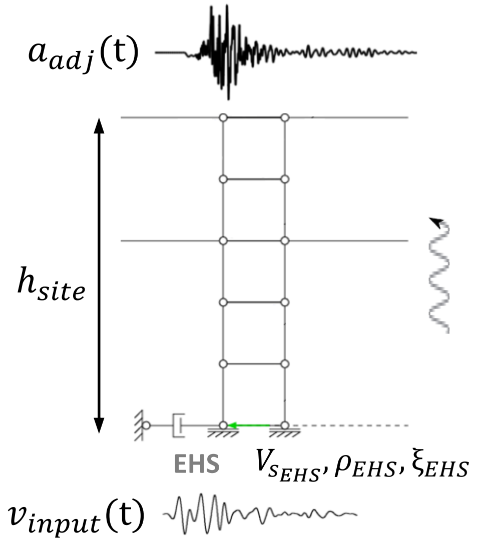
1. Obtain simulated ground motion



2. Perform deconvolution



3. Perform 1D Site-Response Analysis



Estimation of parameters based on CPT

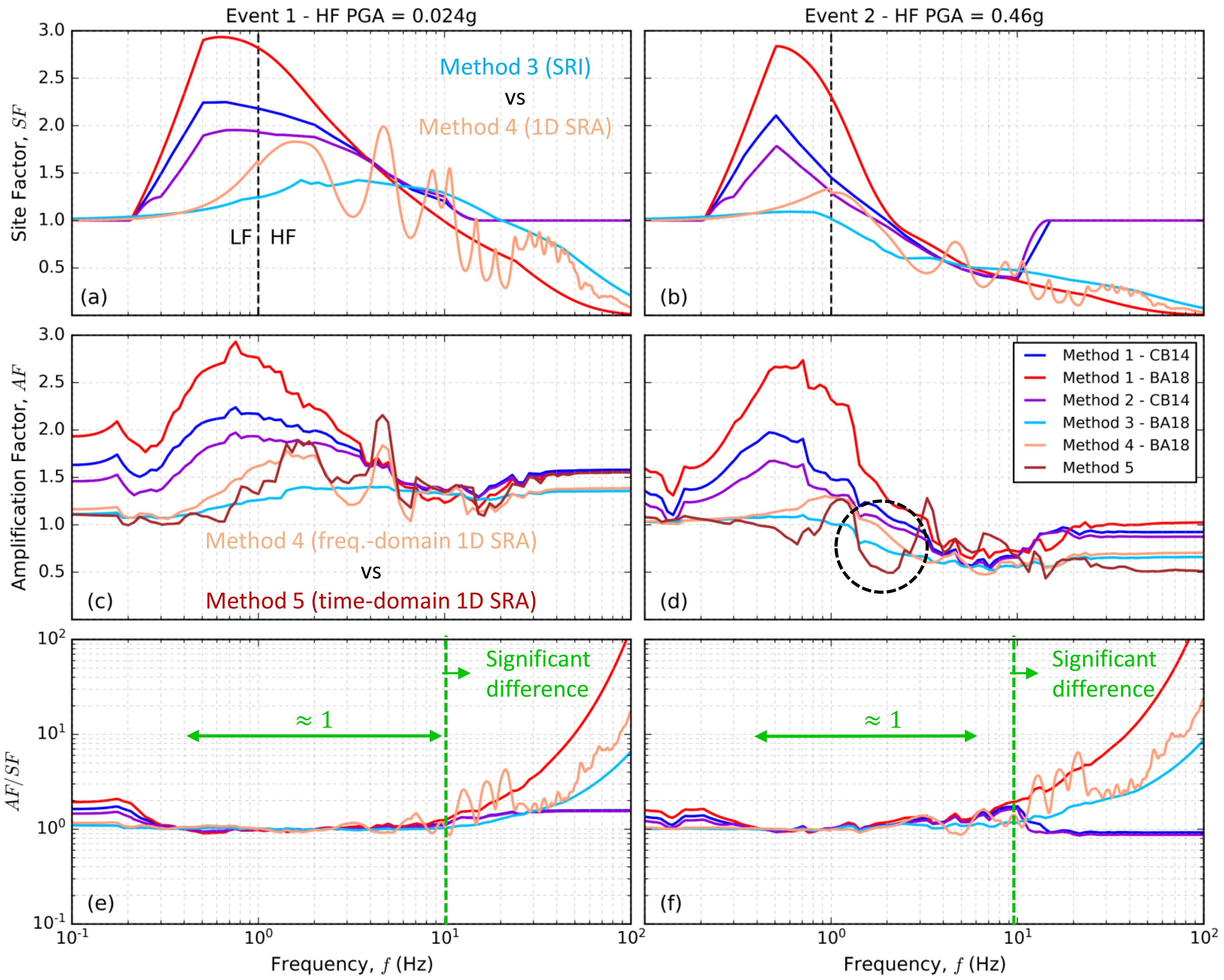
Software	OpenSees (FEM)
Constitutive models	Non-Cohesive soils: PDMY02 Model Cohesive soils: PIMY Model

Comparison

$$SF = \frac{FAS_{actual}}{FAS_{sim}}$$

$$AF = \frac{SA_{actual}}{SA_{sim}}$$

$$\frac{AF}{SF}$$



Closing Remarks

- Five different methods to adjust hybrid broadband ground-motion simulations were presented and compared
- They represent a wide range of options (e.g., when different amounts of site-characterization data are available)
- Methods 1 and 2 only require Vs30. Method 2 represents an improvement over Method 1
- Methods 3 and 4 can be applied when a Vs profile is available. They consider an ergodic (i.e., general) treatment of nonlinear site effects
- Method 5 requires additional data (e.g., CPT, advanced lab testing), but involves a site-specific treatment of nonlinear site effects
- SF directly maps to AF over a wide range of vibration periods

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