Complex Site Response: Does One-Dimensional Site Response Work?

ESG4 UCSB

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Collaborators and Acknowledgements

- At Tufts
  - Eric M. Thompson, Assistant Research Professor
  - Luis Dorfmann, Associate Professor
  - James Kaklamanos, Ph.D. Student
- Collection of V_s Data in Japan
  - Yasuo Tanaka, Kobe University
  - Robert Kayen, United States Geologic Survey

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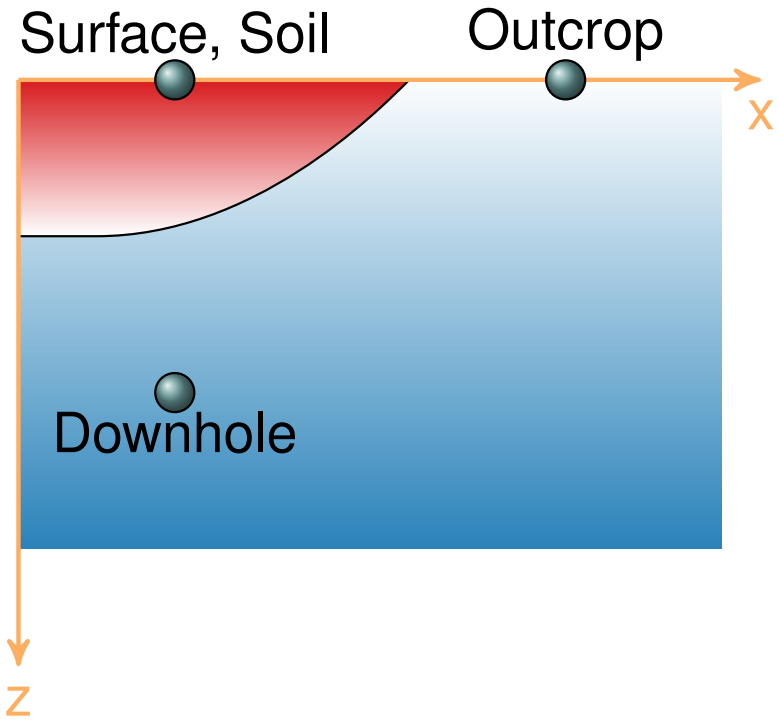
Site Response

- Results from wave propagation in the near surface
- Often isolated from soil/outcrop or soil/downhole ground motion pairs (Steidl et al., 1996; Baise et al., 2003; Thompson et al., 2009)
- Blind predictions are challenging (Boore, 2004; Kwok et al., 2008)

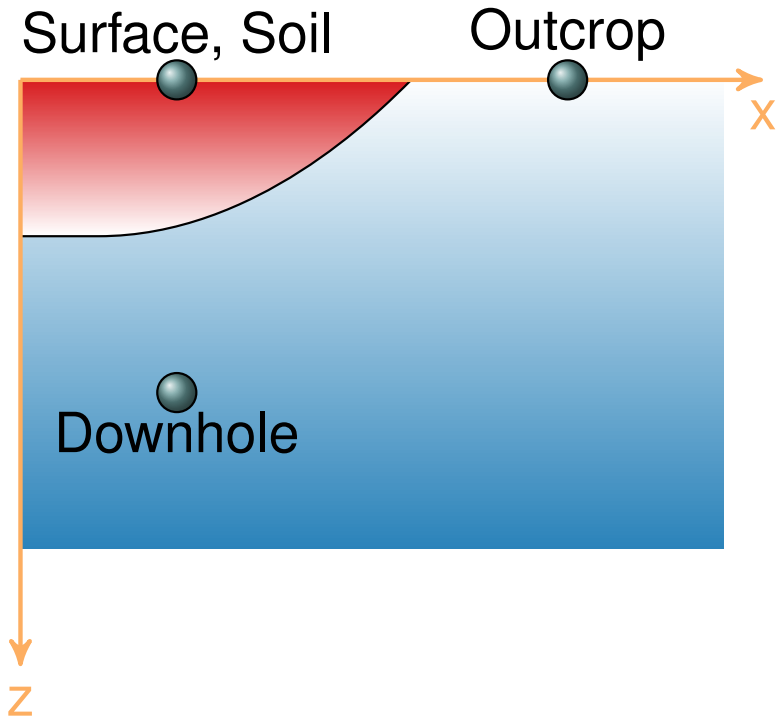


Why is site response so hard to predict?

Complexity in Site Response

Site Response requires specifying

- Soil media
- Soil behavior
- Propagation of waves
- Input rock motion (downhole or outcrop)



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Soil Media

- Homogeneous vs. Heterogenous
- One-dimensional (1D) vs. Two-dimensional (2D) vs. Three-dimensional (3D)

Complexity in Site Response

Site Response requires specifying

- Soil media
- **Soil behavior**
- Propagation of waves
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Soil Behavior

- Linear Elastic
- Equivalent-linear
- Nonlinear

Complexity in Site Response

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- **Propagation of waves**
- Input rock motion (downhole or outcrop)

Propagation of waves

- Vertical incidence
- Planar waves
- SH waves
- Path effects

Complexity in Site Response

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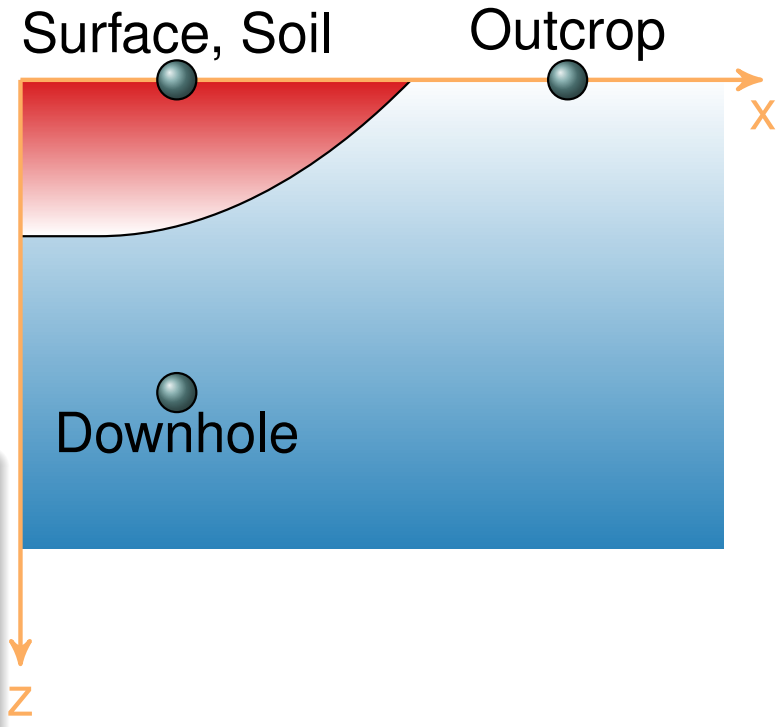

Most common assumptions (SH1D):

- 1D horizontal and homogeneous layers
- Equivalent linear soil behavior
- Vertical incidence of planar SH waves

Project Goals

Does SH1D work for site response prediction or not?
If not, how complex is site response?

Goal 1: Develop a classification system to characterize sites in terms of complexity.

Goal 2: Use the classification system to choose sites specifically for addressing site response topics.

- *Use sites that fit SH1D to study nonlinear soil behavior*
- *Use sites that don't fit SH1D to study soil heterogeneity or alternative wave propogation effects.*

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Focus on weak motions at vertical arrays

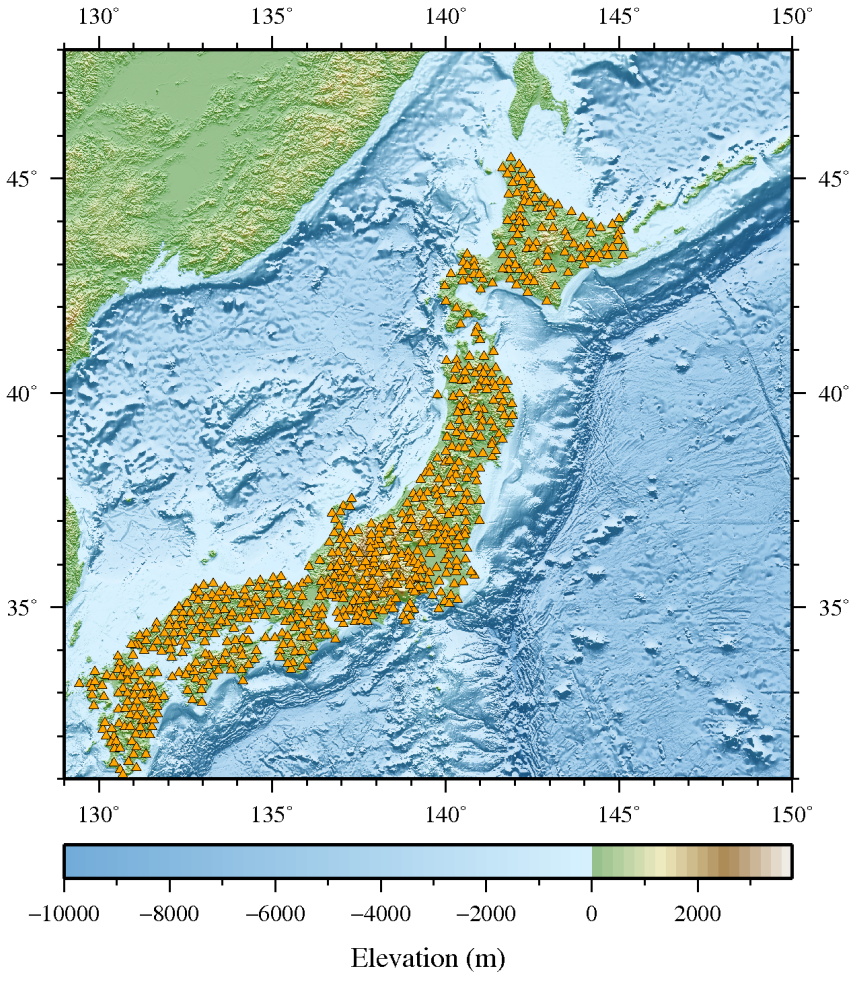
- Removes nonlinear effect in order to focus on soil media and wave propagation
- Averages site response over multiple events to reduce SNR and estimate variability
- Vertical array reduces ambiguity of the *input motion* and reduces source/path effects

Examples

- Port Island - linear vs nonlinear behavior (Baise et al., 2001)
- Treasure Island - surface waves (Baise et al., 2003)
- KiK-Net - soil heterogeneity (Thompson et al., 2009)

Japan's KiK-Net Array

- Since 1996
- Over 300 surface downhole vertical arrays (downhole station generally at 100 m depth)
- V_s profiles for each site
- Web accessible data
- Seismically active region (lots of strong and weak motion records)



Site and Data Criteria

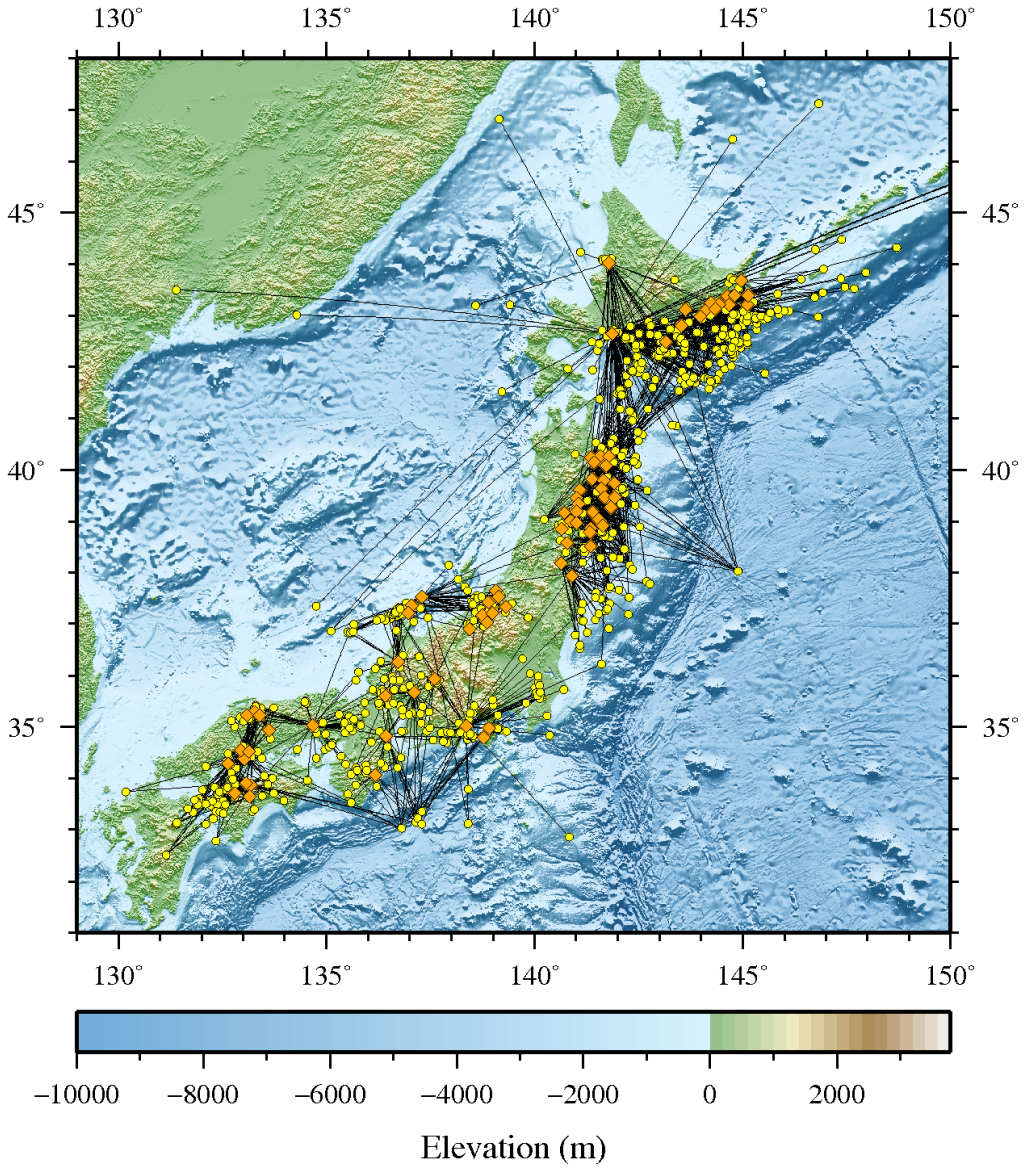
We chose sites that met the following criteria:

- Velocity profile available
- Signal to noise ratio < 5 from 0.5 to 20 Hz
- At least 10 weak motions $(PGA_d < 0.1g)$
- At least 1 strong motion $(PGA_s > 0.3g)$

74 stations meet this criteria (using data collected before 2011)

Data for this study

- 74 sites
- 1000 Earthquakes
- 1800 Earthquake records
- Site conditions range from shallow to deep soil sites



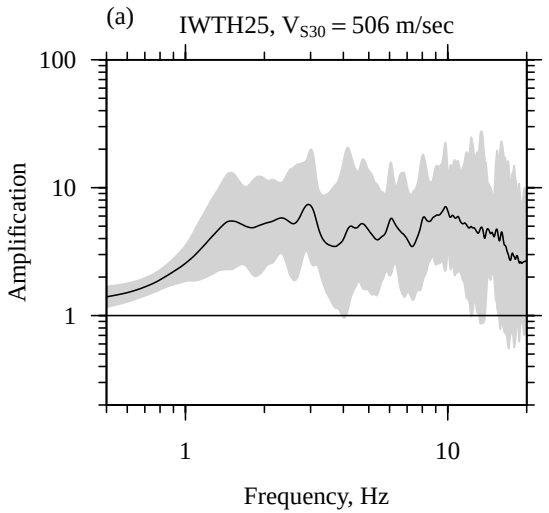
Comparing observed versus predicted site response

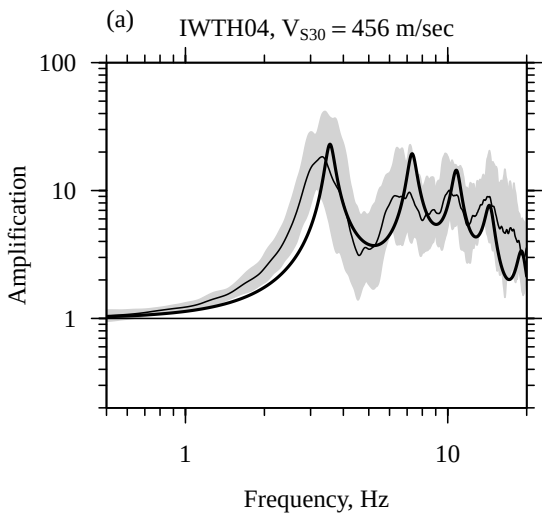
Empirical transfer function (ETF)

- Spectra of the entire record
- Use complex time series (Steidl et al., 1996)
- Present median and 95% confidence intervals

Theoretical transfer function (TTF)

- SH1D (linear) - Thomson-Haskell (Thomson, 1950; Haskell, 1953)
- SHAKE (equivalent linear)
- DEEPSOIL (nonlinear)





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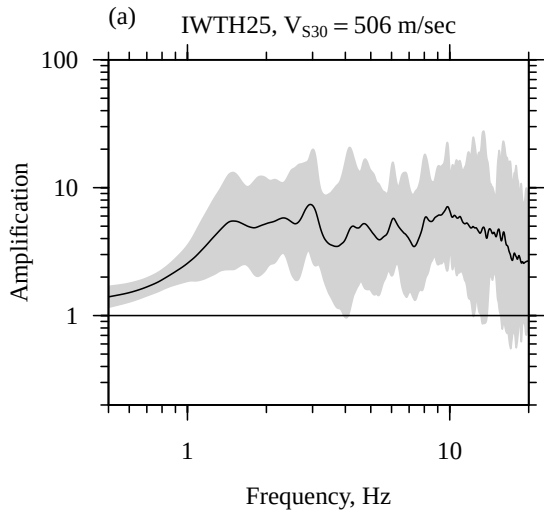
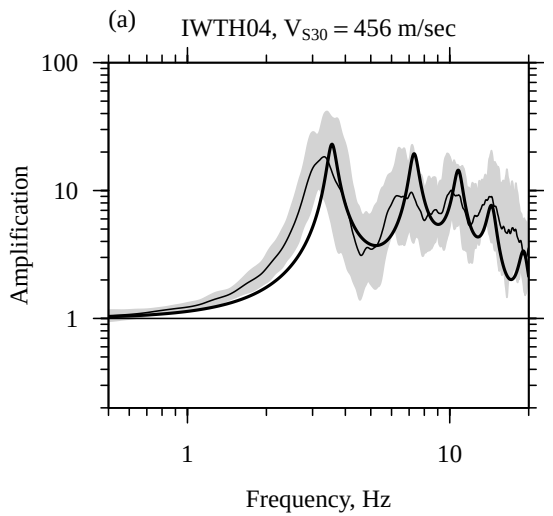
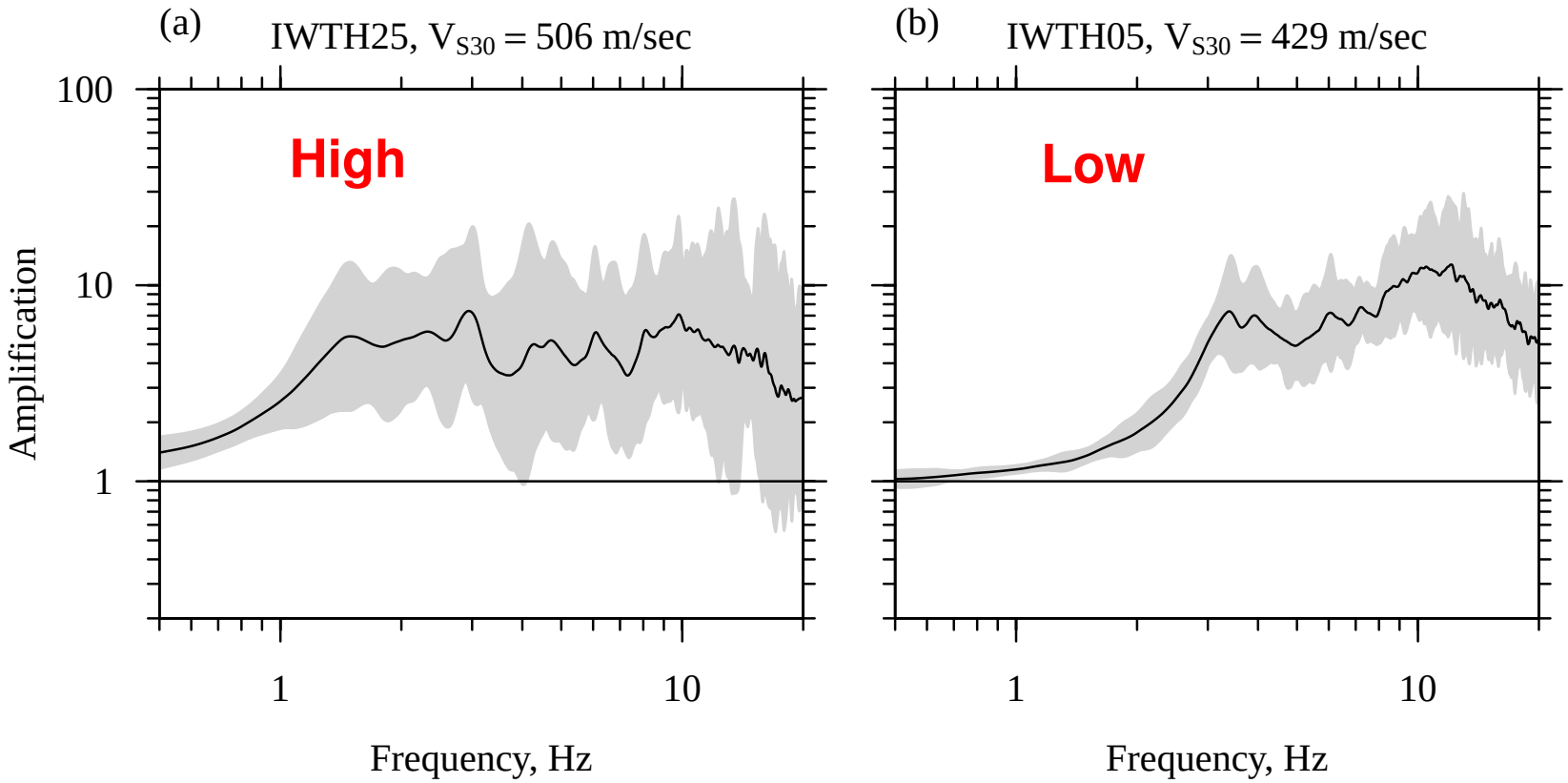


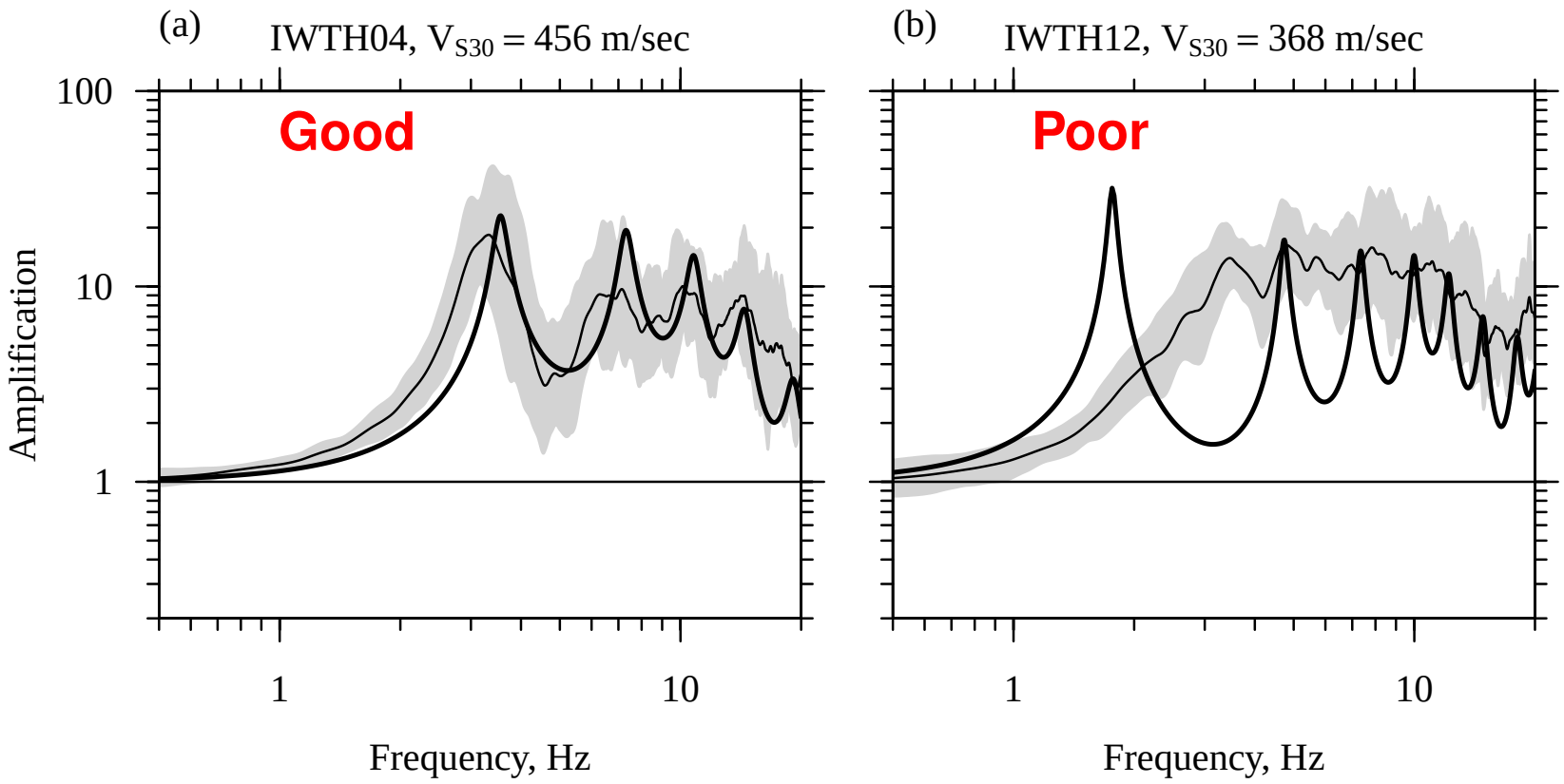


Intra-event variability



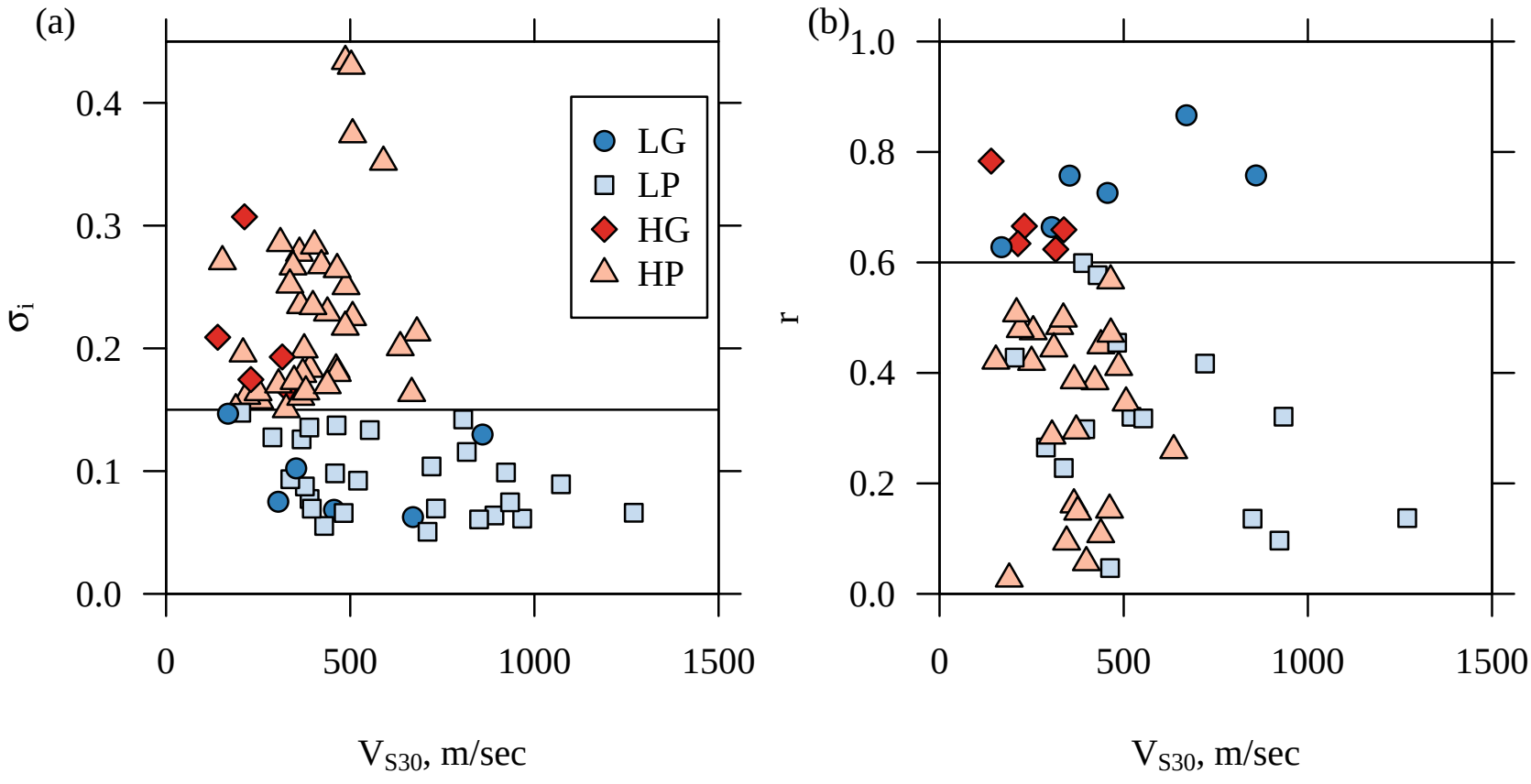
Use a cut-off of $\sigma = 0.15$ between High and Low intra-event variability.

Fit to SH1D

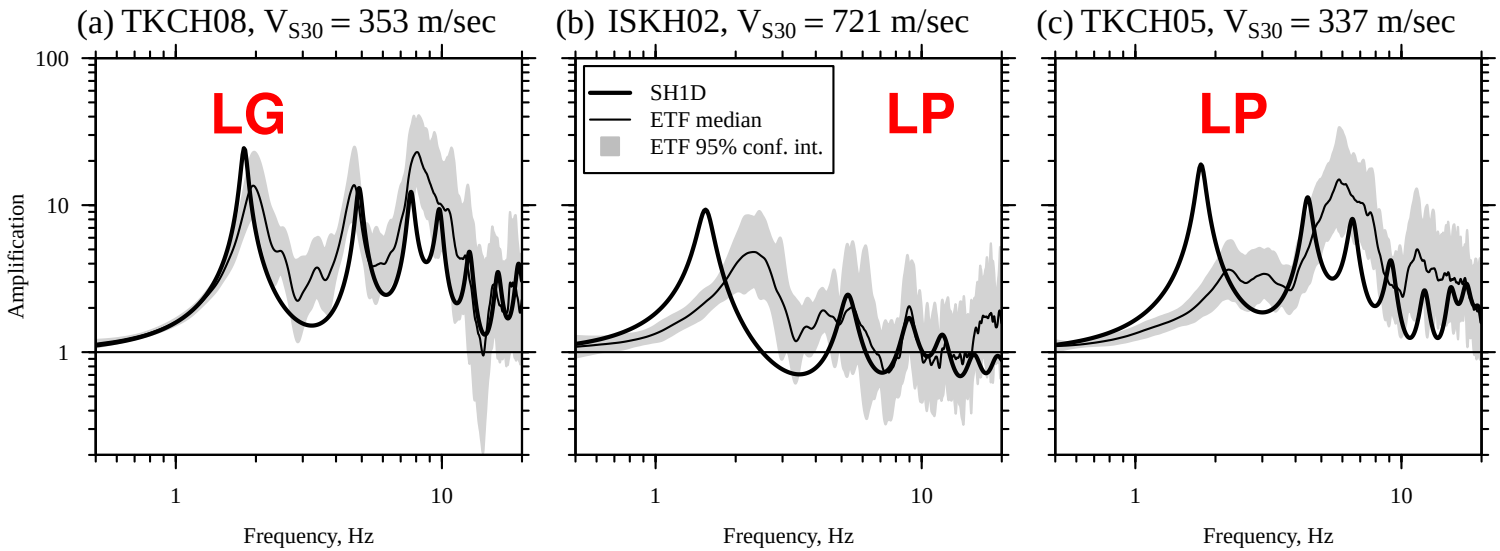


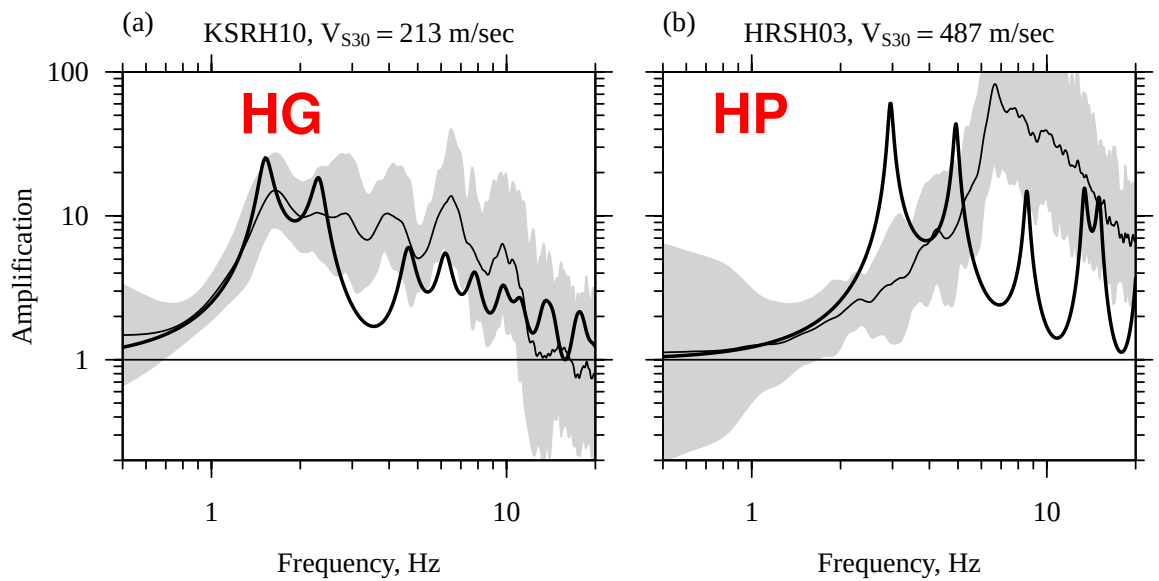
Use a cut-off of $r = 0.6$ between Good and Poor fit to SH1D.

Taxonomy

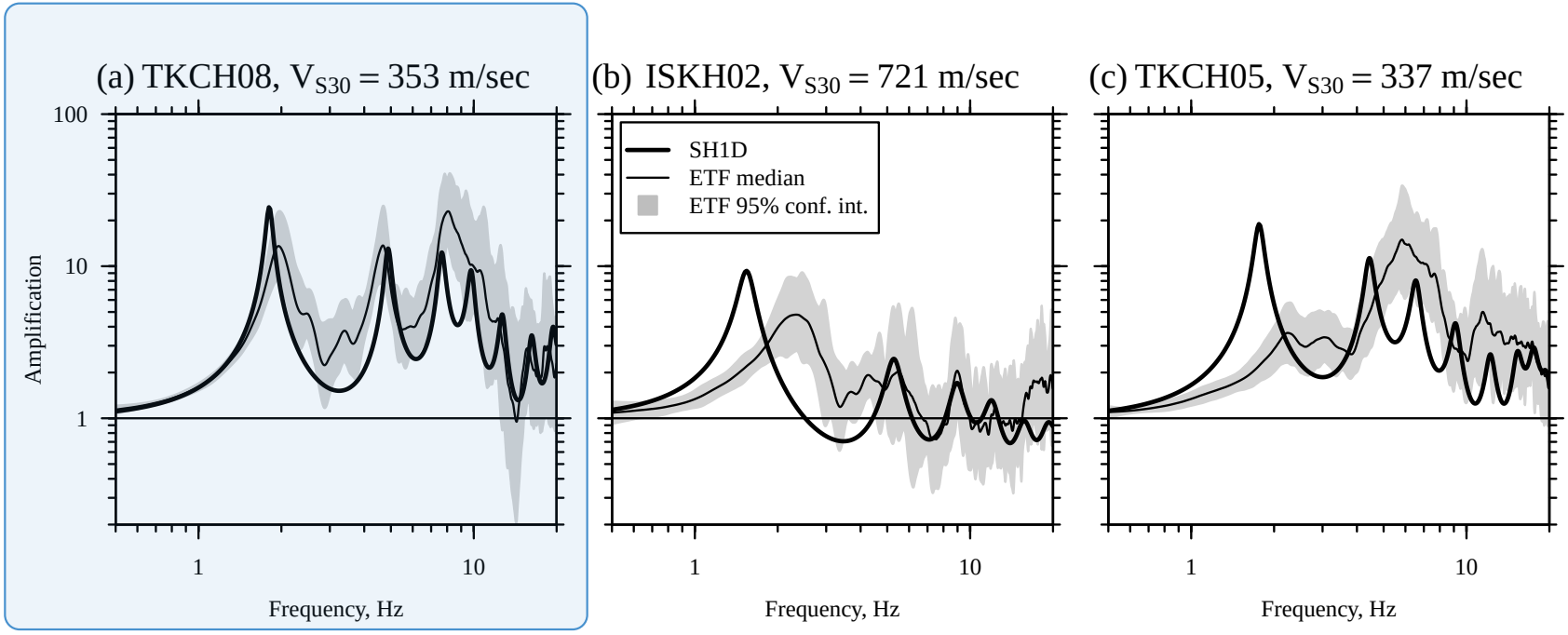

(a)
0.4
0.3
0.2
0.1
0.0
σ_i
LG
LP
HG
HP
0
500
1000
1500
V_{S30}, m/sec
(b)
1.0
0.8
0.6
0.4
0.2
0.0
r
0
500
1000
1500
V_{S30}, m/sec

Taxonomy - LG, LP, HG, HP





LG and LP sites



Six LG Sites

Station	V_{S30} (m/s)	Earthquake				
		Date	Magnitude	Depth (km)	PGA^D (g)	PGA^S (g)
IWTH04	456	2003/05/26	7	71	0.154	1.305
IWTH08	305	2008/07/24	6.8	108	0.059	0.392
IWTH27	670	2003/05/26	7	71	0.170	0.905
MYGH11	859	2005/08/16	7.2	42	0.105	0.471
NMRH04	168	2003/09/26	8	42	0.156	0.446
TKCH08	353	2003/09/26	8	42	0.130	0.509

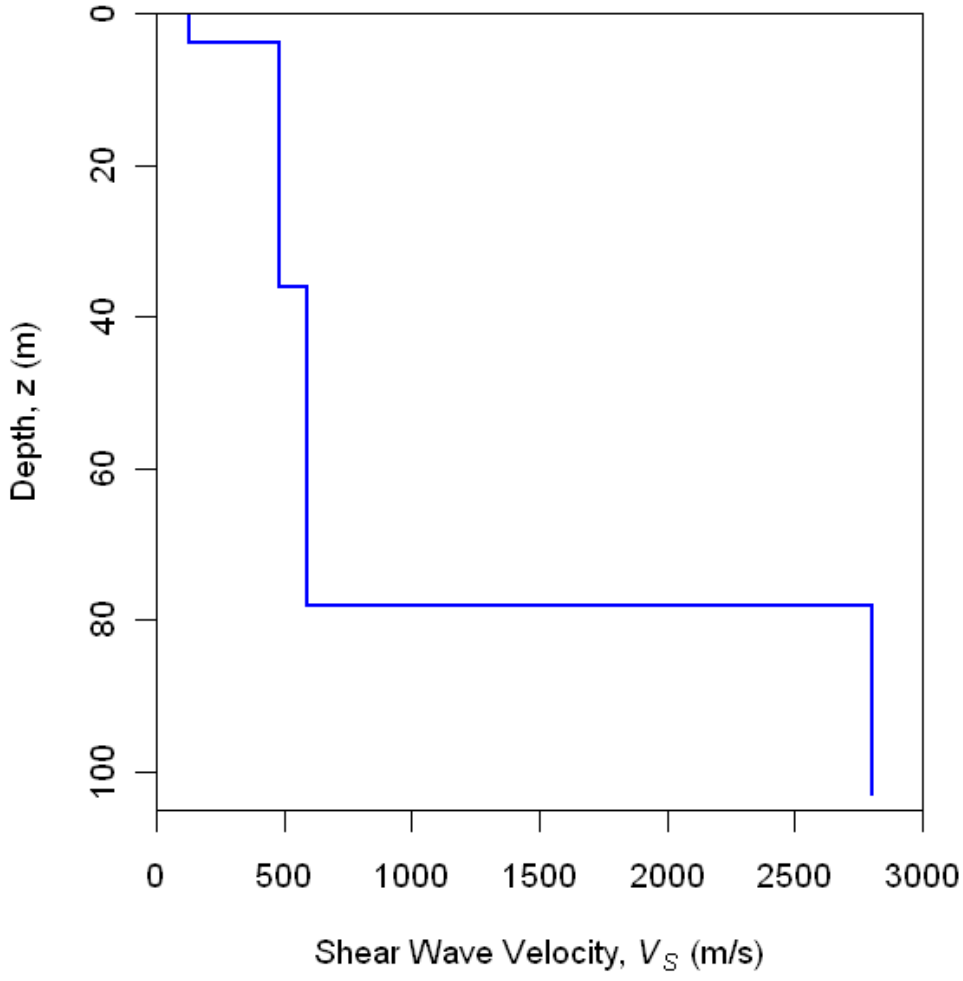
LG - Isolate nonlinear soil behavior

TKCH08

Soil over rock site -

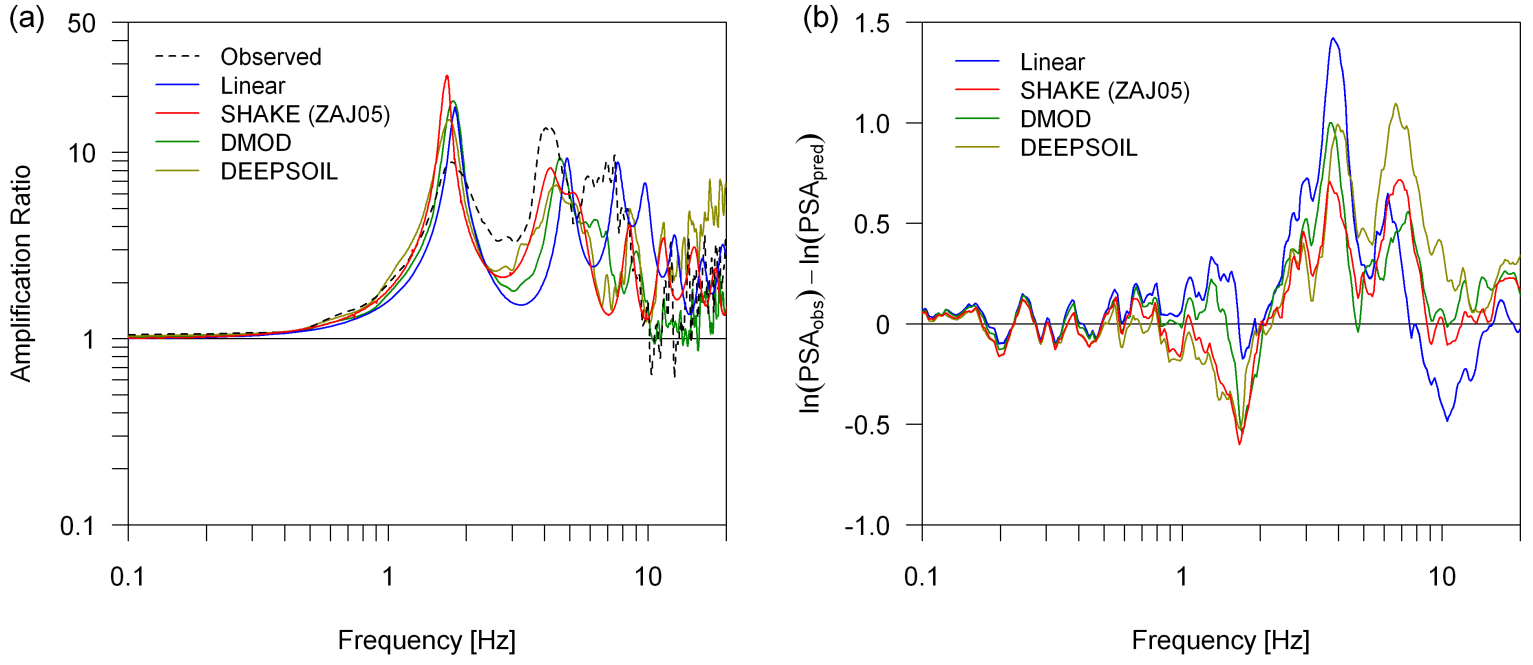
$V_s(30) = 353$m/s

$PGA = 0.509g$



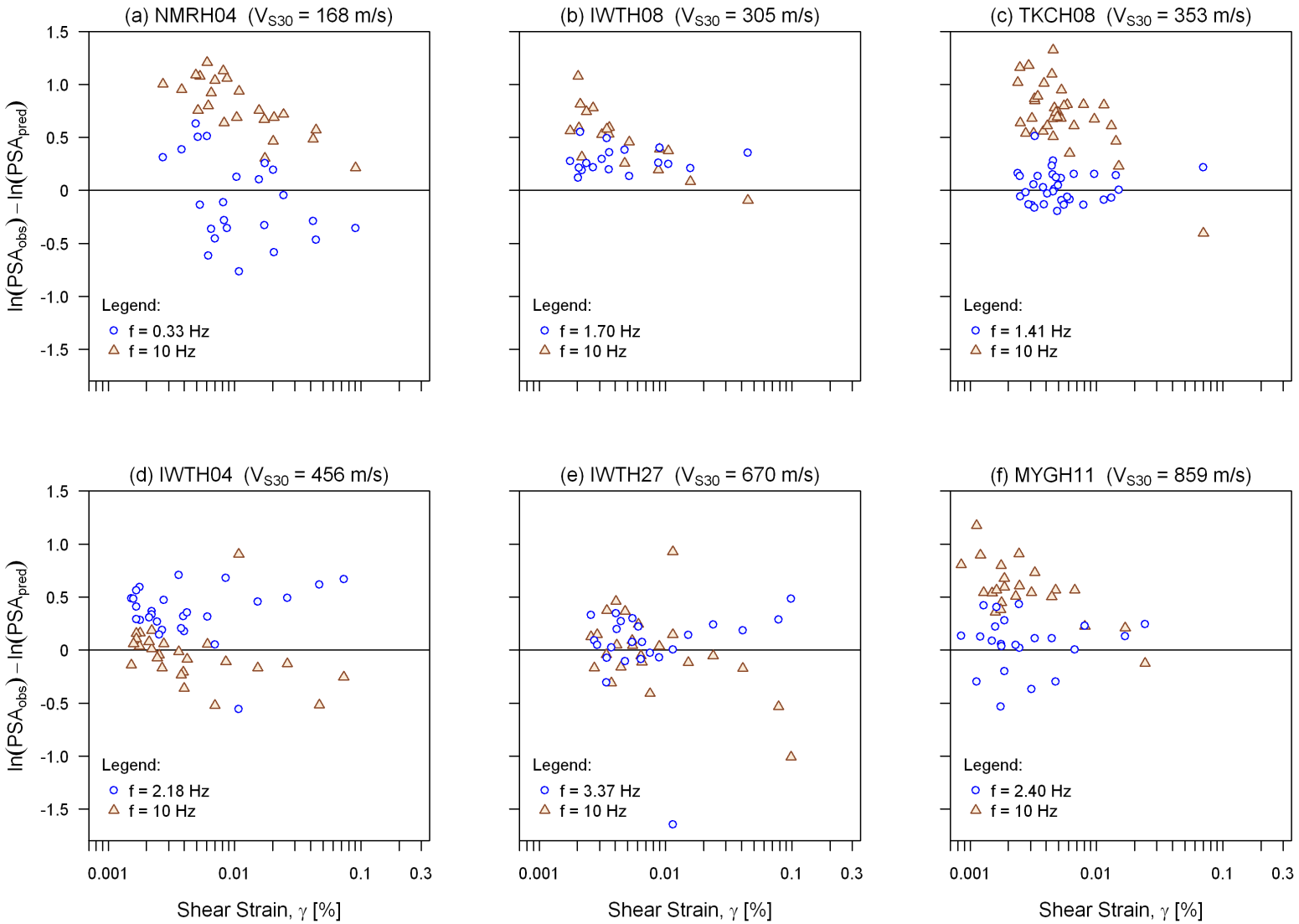
LG - TKCH08

We can evaluate different SH1D formulations.

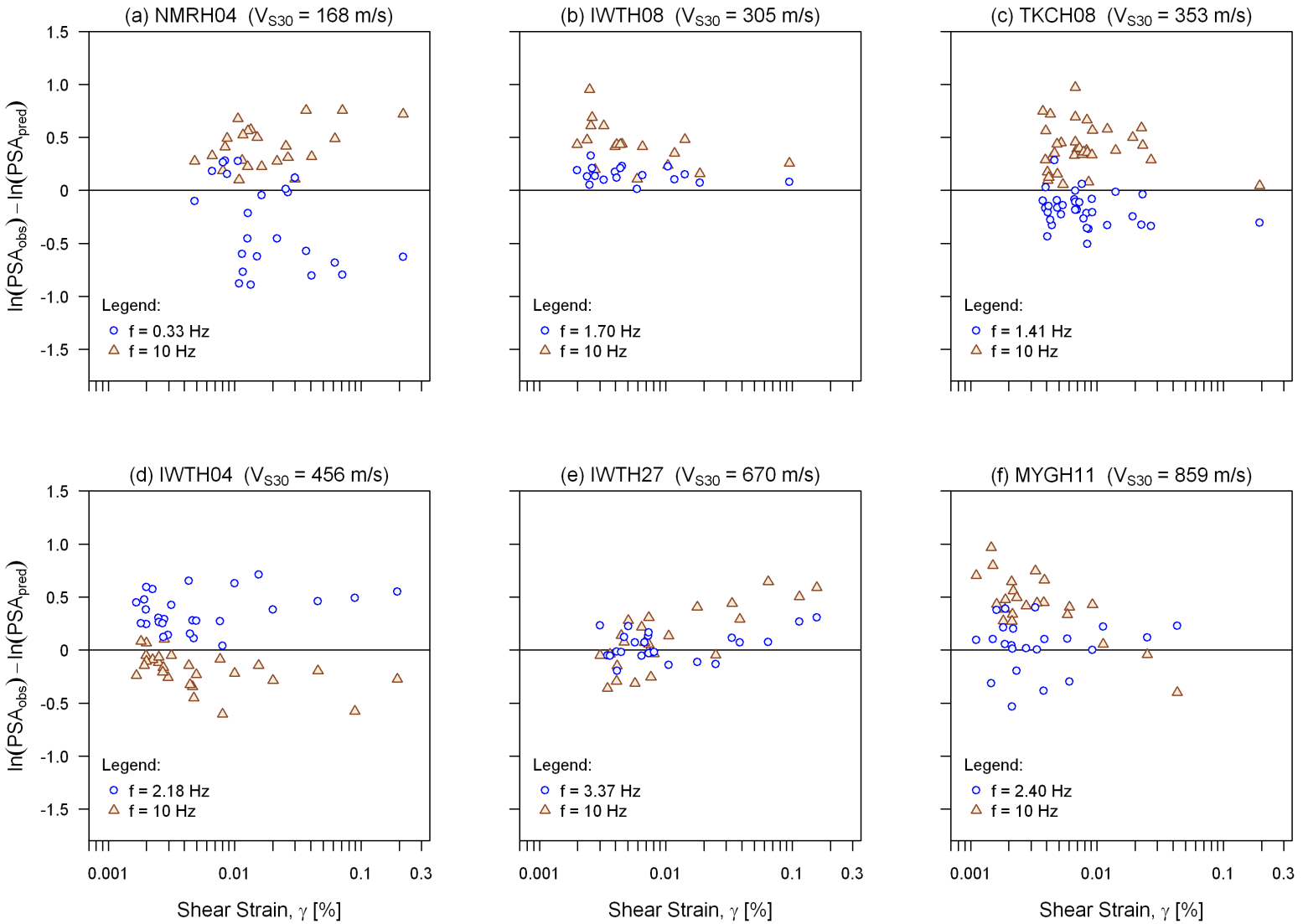


The nonlinear and equivalent linear programs improve the goodness of fit over the linear model.

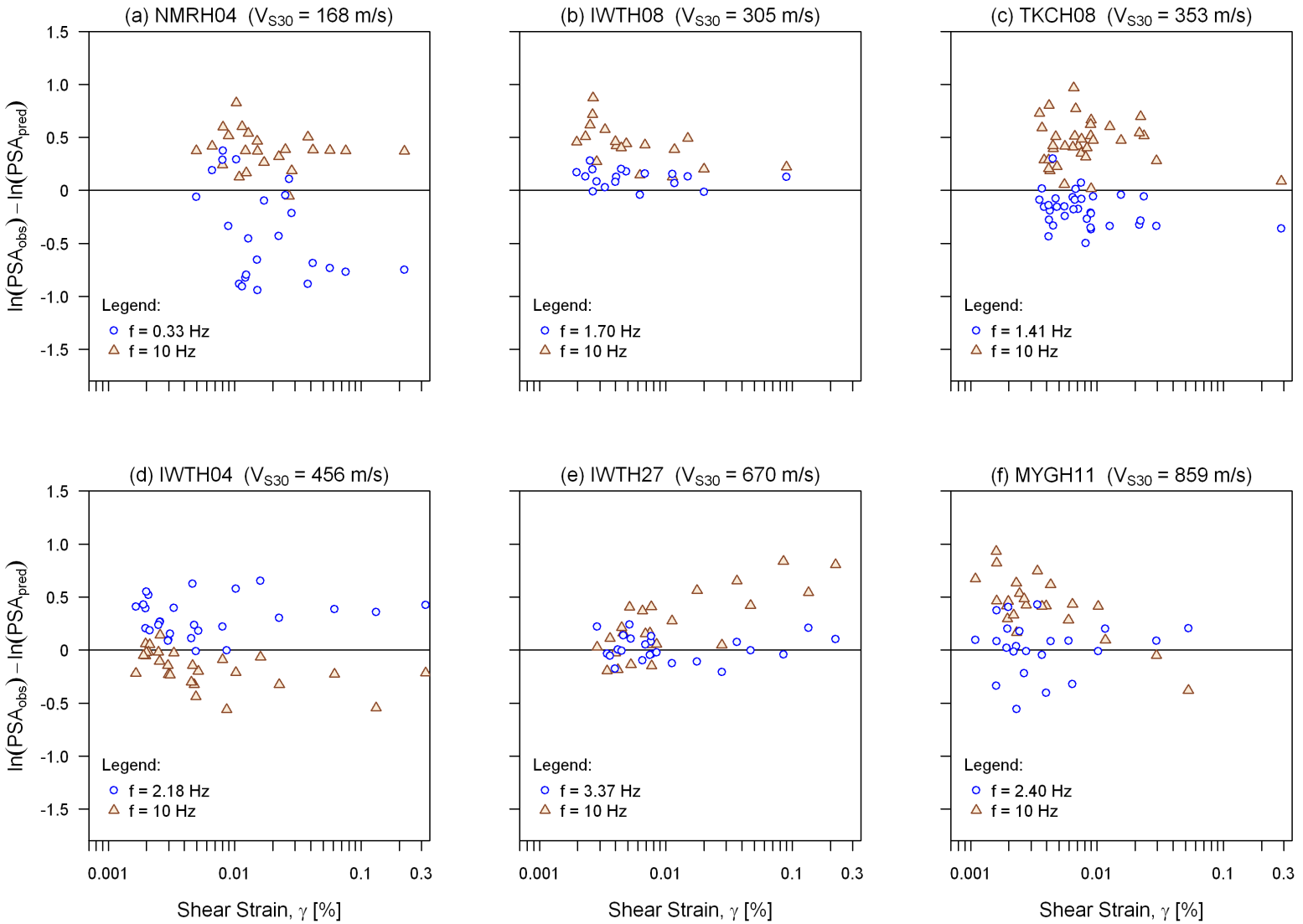
LG sites - Linear



LG sites - Equivalent Linear

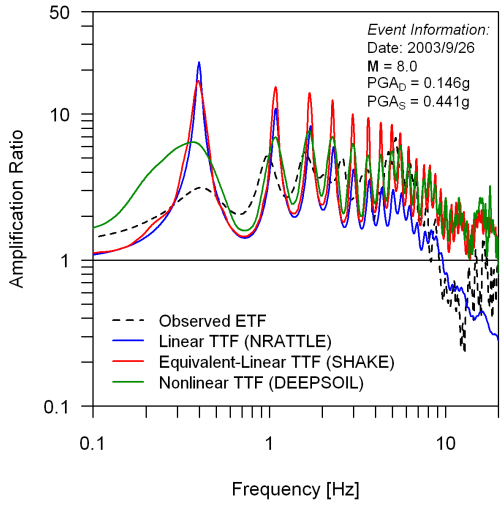


LG sites - Nonlinear

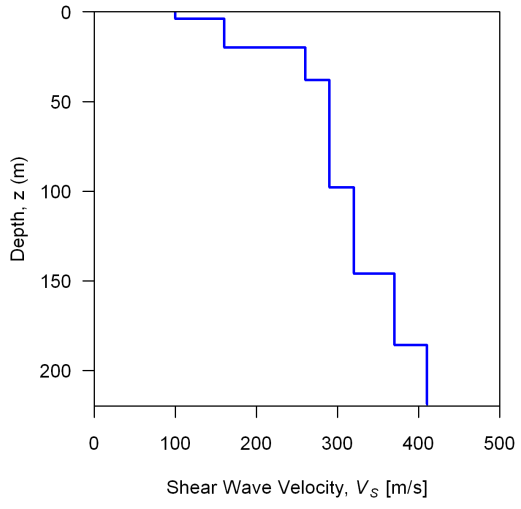


NMRH04 (V_{S30} = 168 m/s)

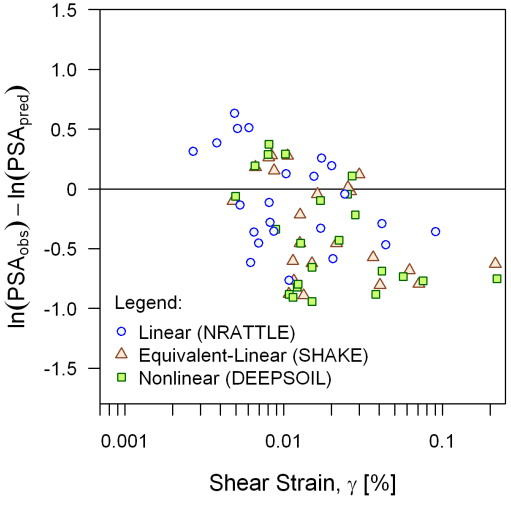
(a) Amplification Ratios for Nonlinear Event



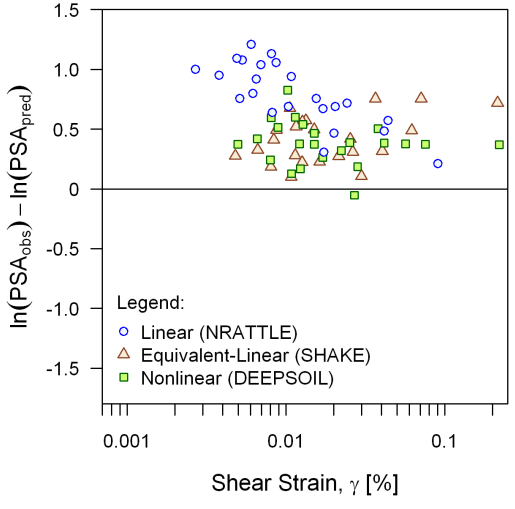
(b) V_S Profile



(c) Logarithmic Residuals of PSA at f = f_0 = 0.33 Hz



(d) Logarithmic Residuals of PSA at f = 10 Hz



MYGH11 (V_{S30} = 859 m/s)

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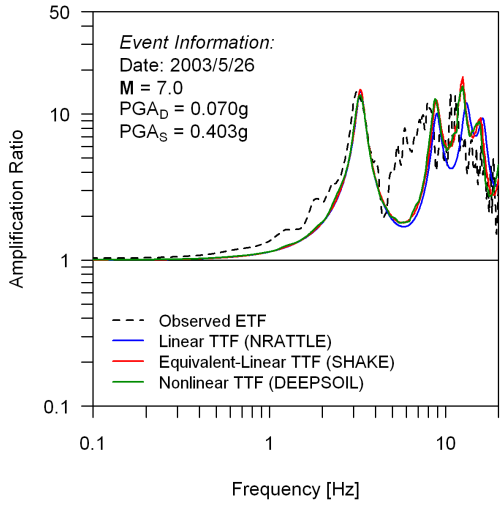
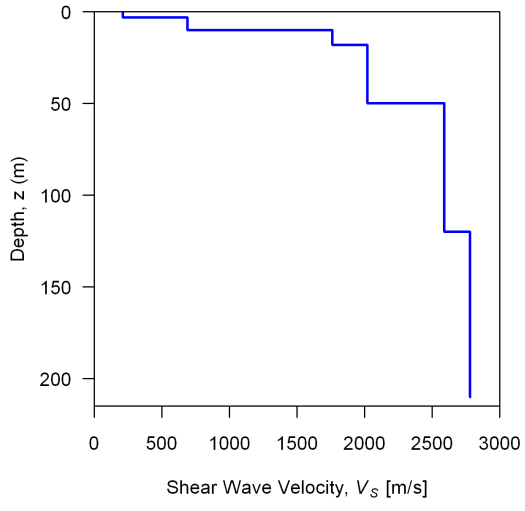
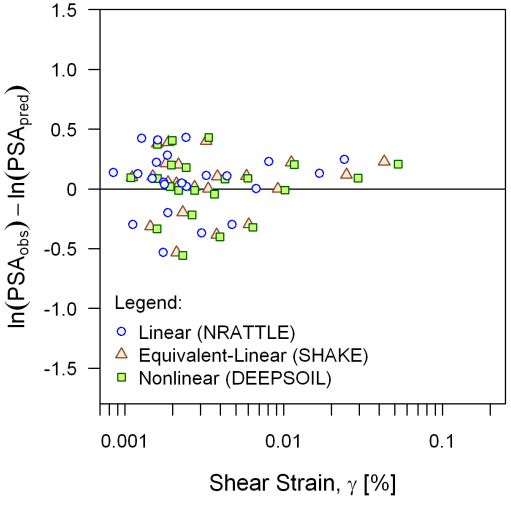


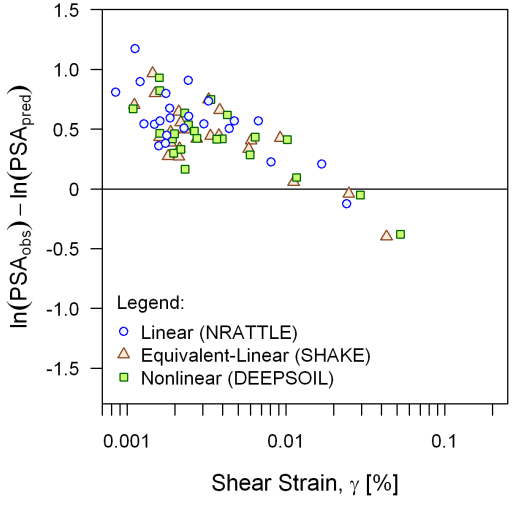
(b) V_S Profile



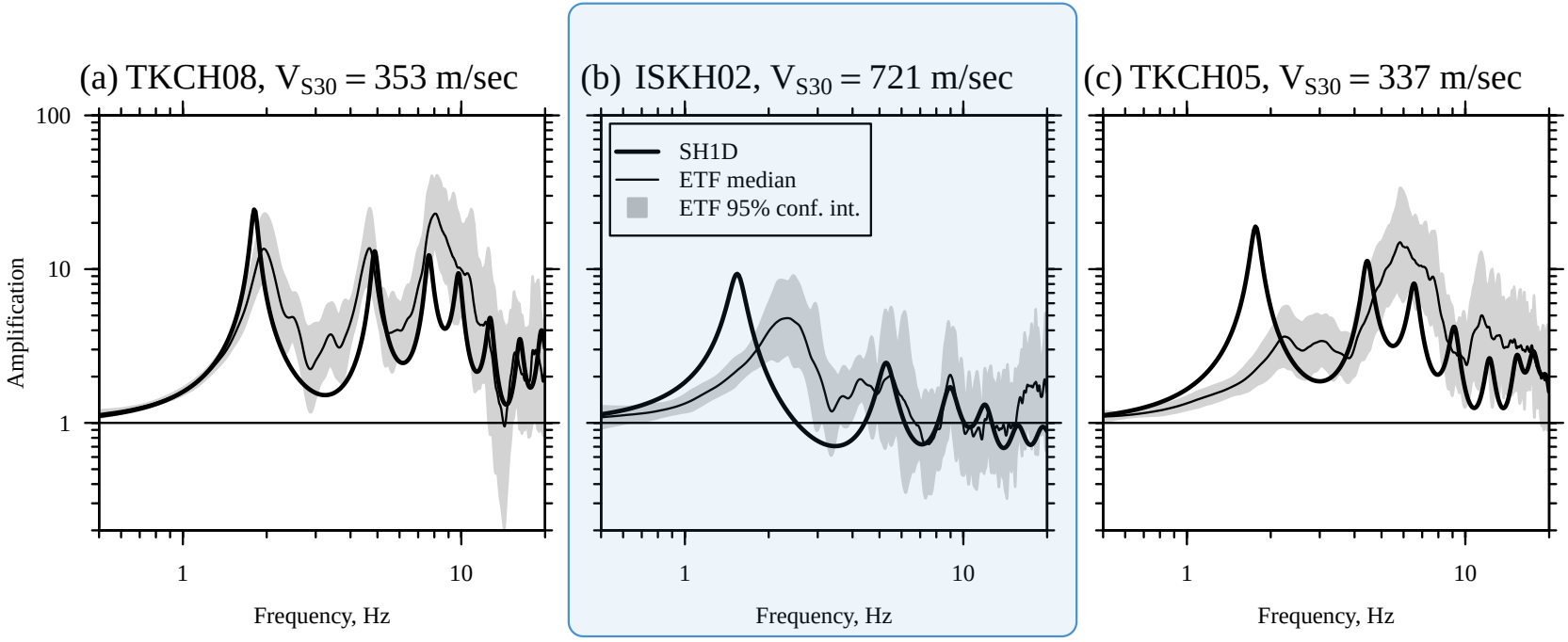
(c) Logarithmic Residuals of PSA at f = f_0 = 2.4 Hz



(d) Logarithmic Residuals of PSA at f = 10 Hz

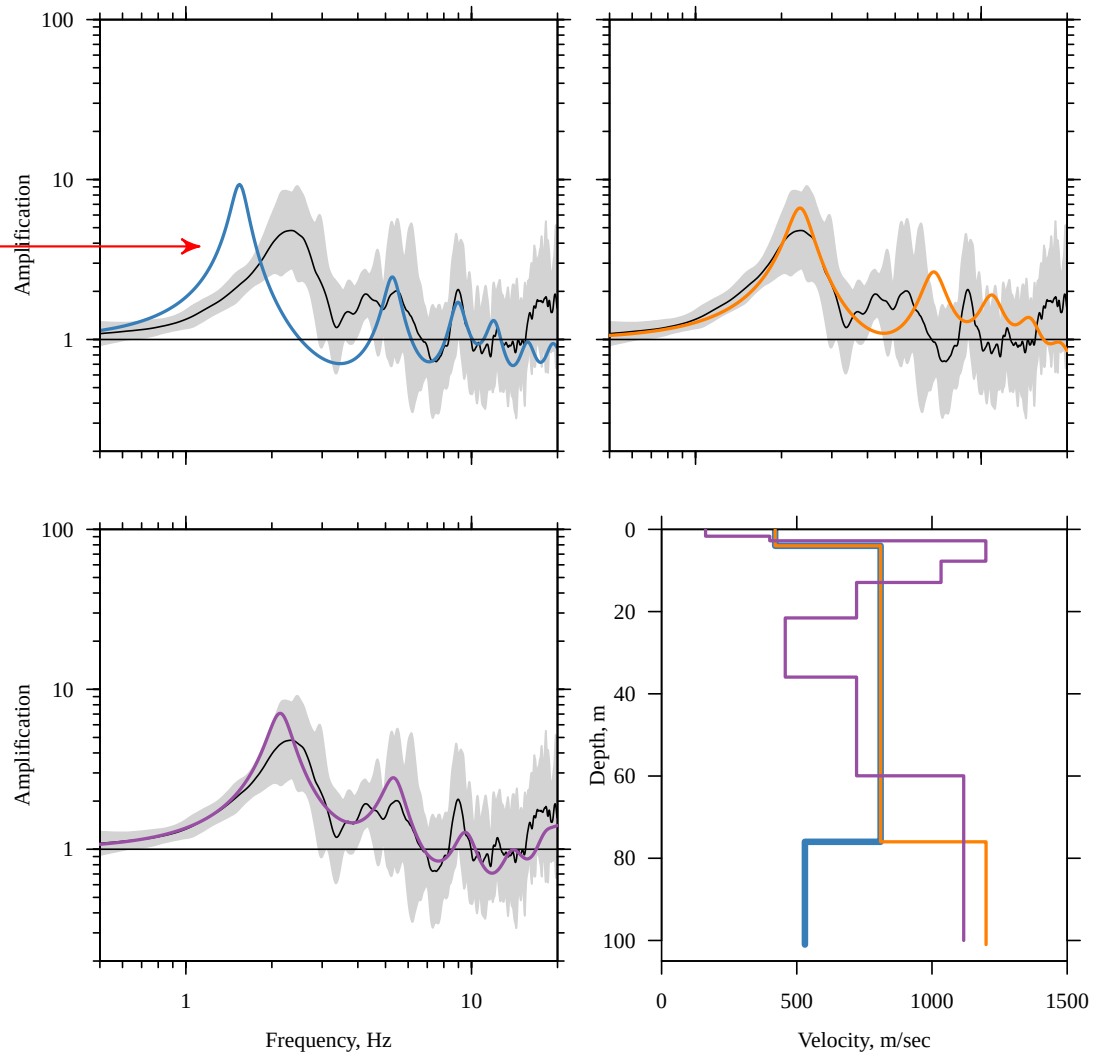


LP - Low Noise, Poor Fit to SH1D



Uncertainty in 1D Profile

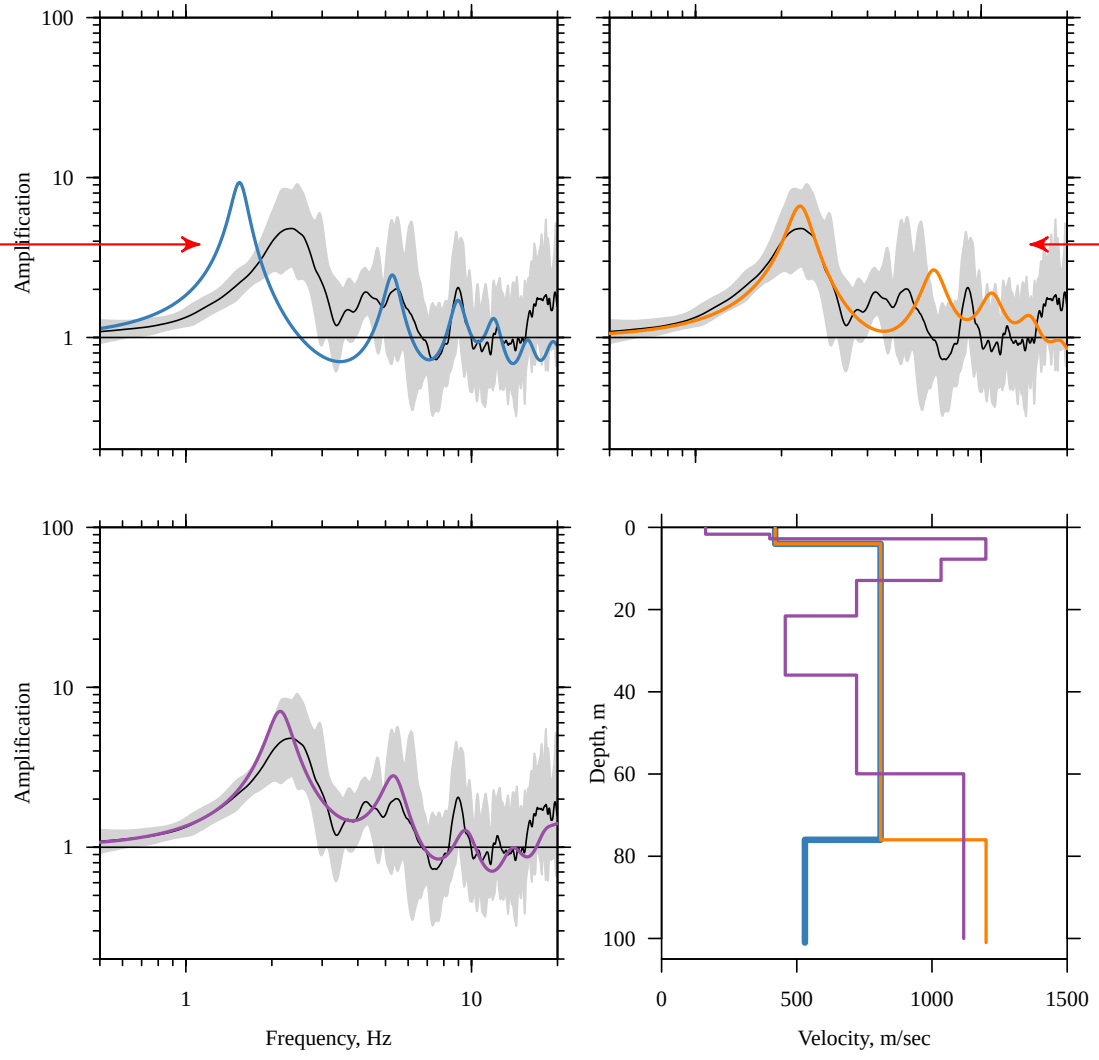
Original model



Uncertainty in 1D Profile

Original model

Increase damping and base layer velocity

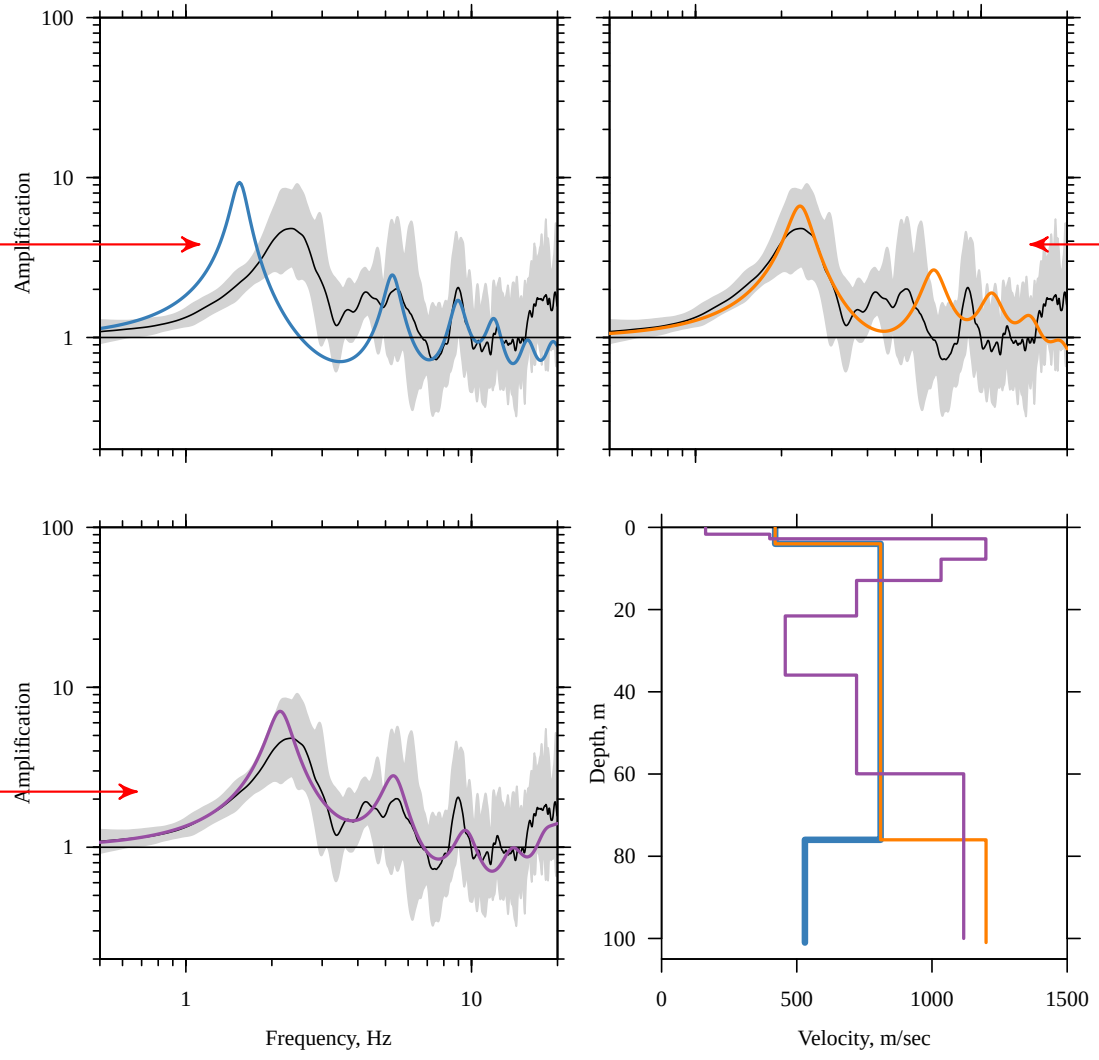


Uncertainty in 1D Profile

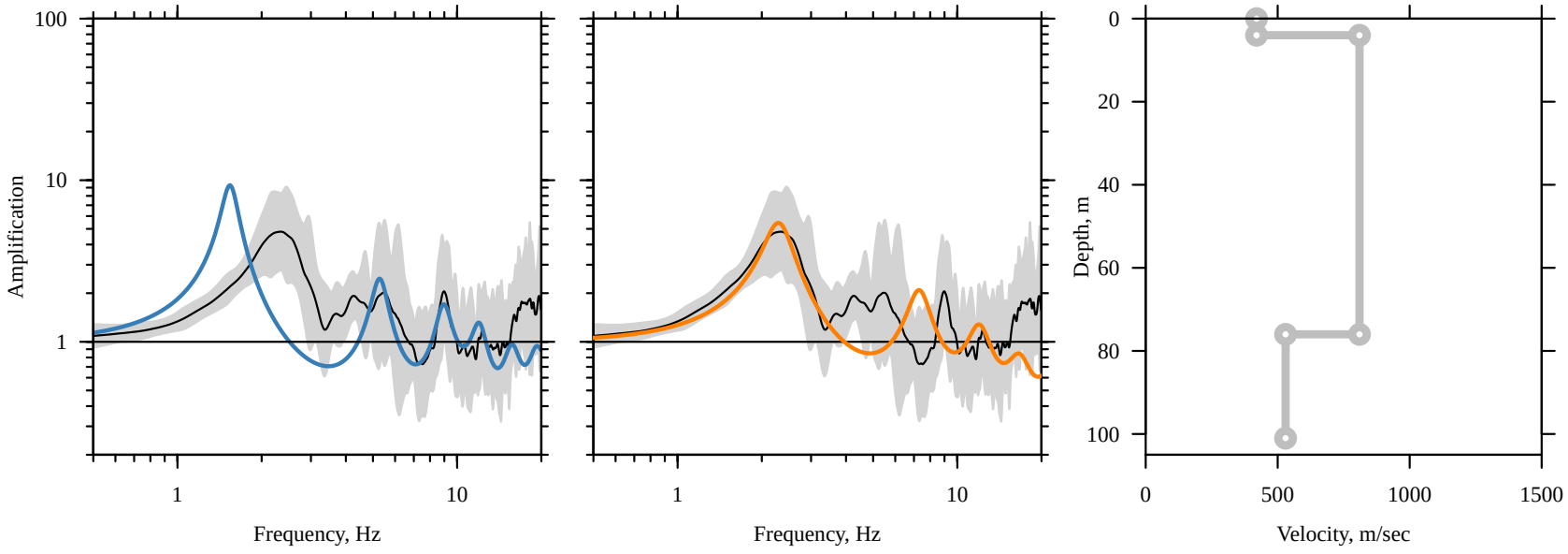
Original model

Increase damping and base layer velocity

Increase layering and optimize

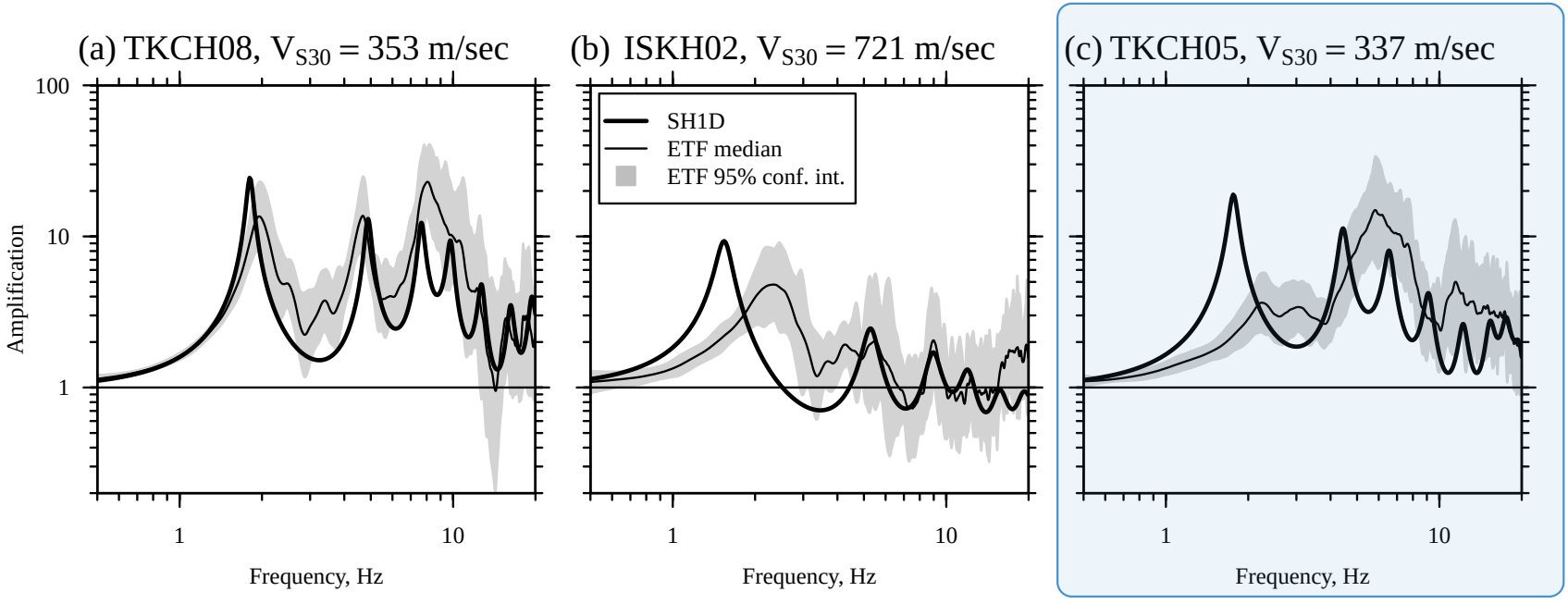


Non-vertical Incidence



Shift peak by changing incidence angle to 31°

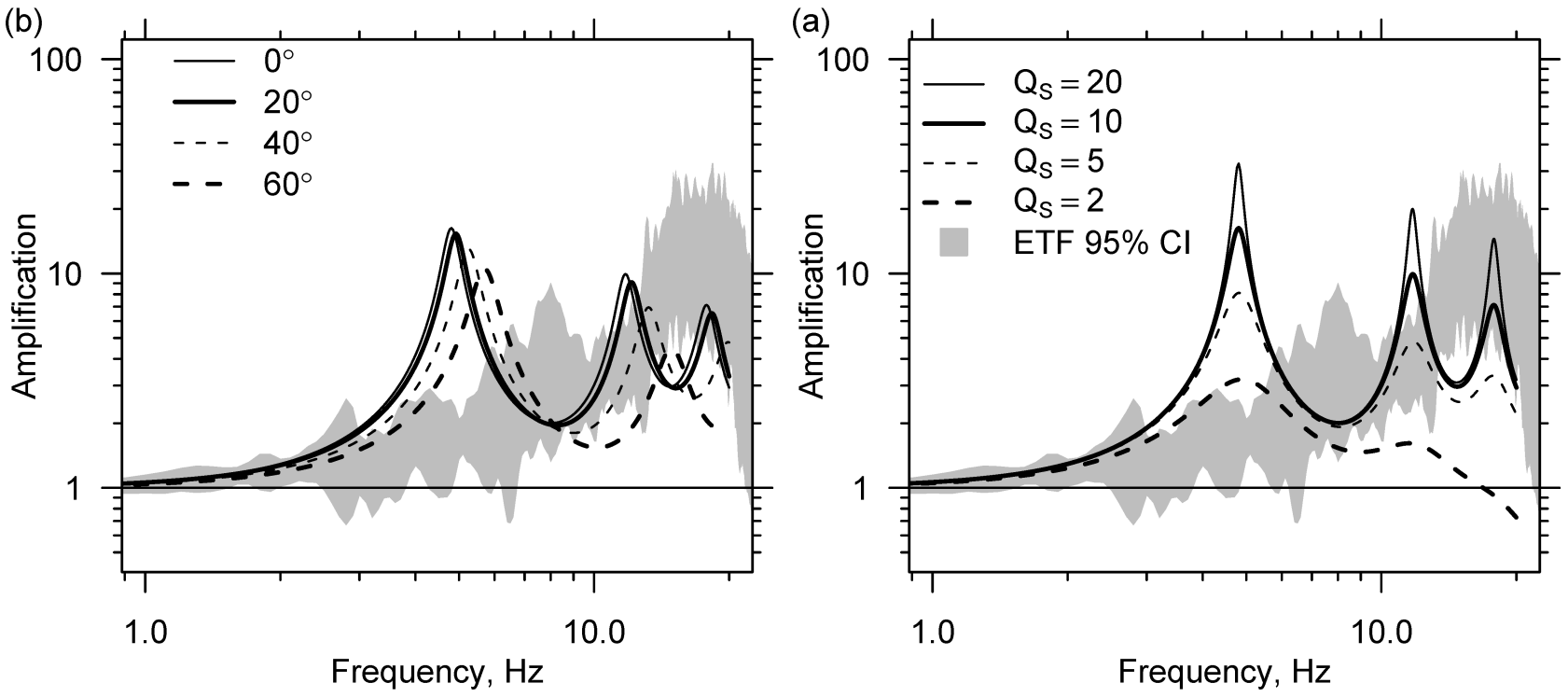
Three-dimensional heterogeneity



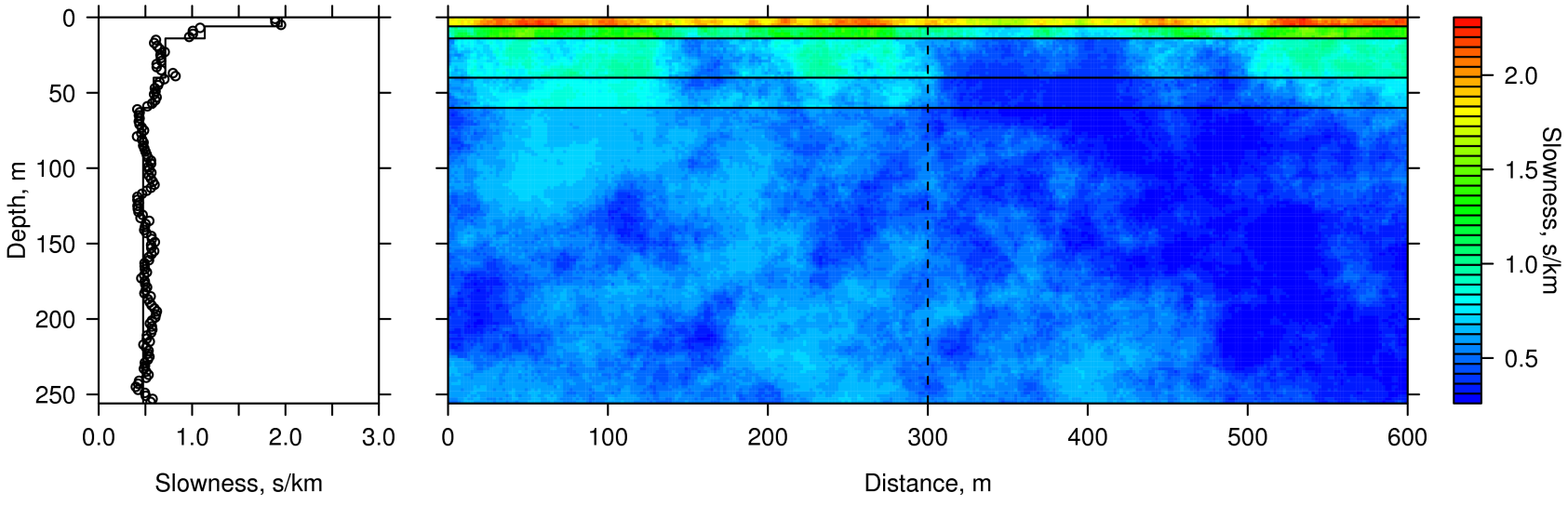
In Thompson et al. (2009)

We demonstrated that scattering of waves in a heterogeneous material can remove peak in ETF.

Try non-vertical incidence and attenuation



Including spatial variability



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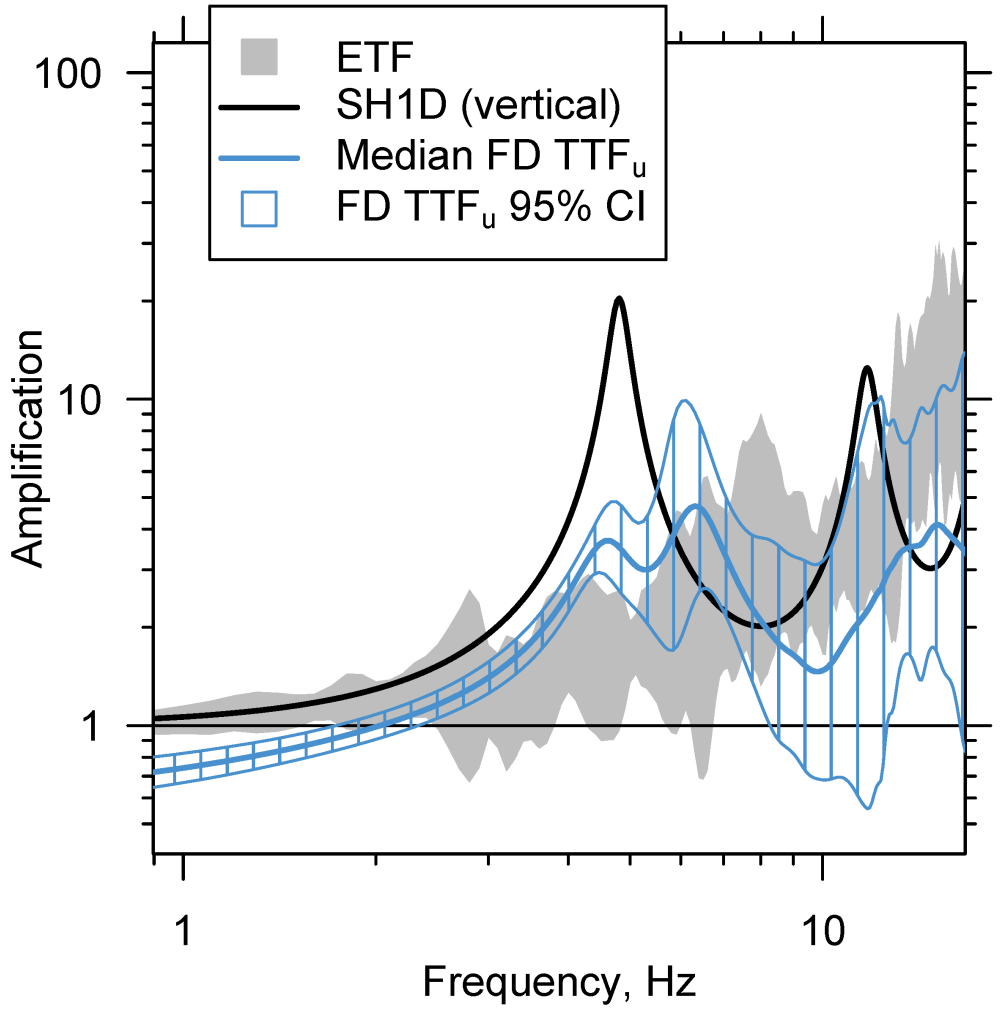

Discussion

Using weak motions at vertical arrays, we have. . .

- developed a classification systems that characterizes site response complexity in terms of:
  - intraevent variability
  - goodness of fit to SH1D
- used the classification system to:
  - isolate nonlinear soil behavior and test existing site response programs
  - identify sites with a misfit to SH1D
  - identify sites with high intraevent variability

Discussion, cont.

When we isolate nonlinear behavior, we find. . .

- nonlinear soil behavior consistently affects the high frequency spectral accelerations
- V_s30 is not always the best indicator of nonlinear behavior
- SHAKE and DEEPSOIL capture much of the nonlinear soil response

Discussion, cont.

When sites do not exhibit SH1D behavior for weak motions, the cause may be from. . .

- nonvertical incidence of the wave field
- uncertainty in the 1D V_s profile
- spatial heterogeneity leading to scattering of waves

Future Work

More work to be done on. . .

- Isolating the nonlinear soil behavior and improving nonlinear models (LG)
- Studying *interesting sites* (LP)
- Investigating source and path effects that cause high intraevent variability (HG)

Questions?

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