Lessons Learned from KiK-net Data for Site Response Modelling Input Parameters, Assumptions, and Decisions

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JIM KAKLAMANOS

Associate Professor of Civil Engineering,
Merrimack College, North Andover,
Massachusetts, USA

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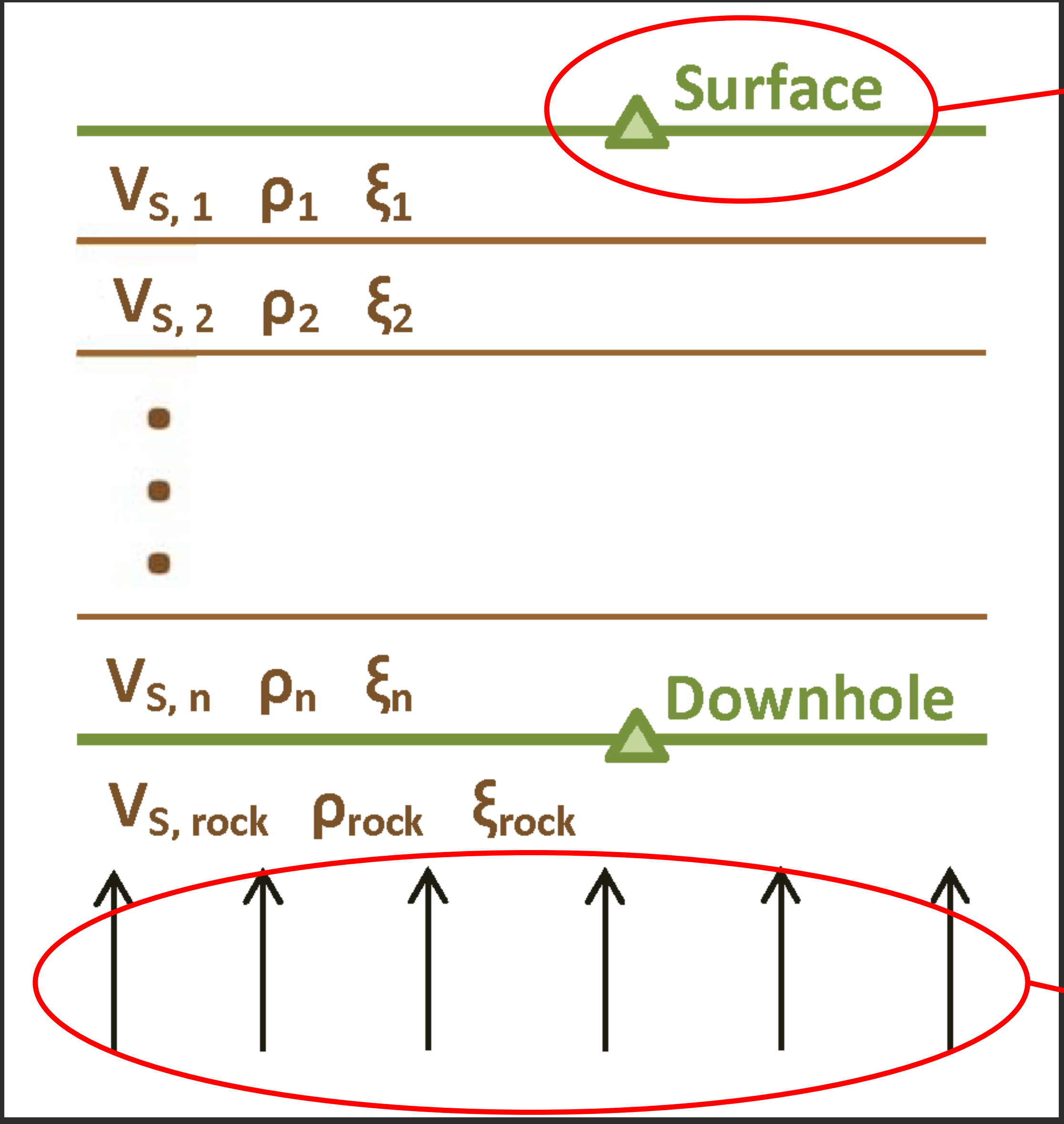
Background: site response analyses



Output:

Output ground motion (surface)

Soil Model:

- Linear
- Equivalent-linear
- Nonlinear

Input:

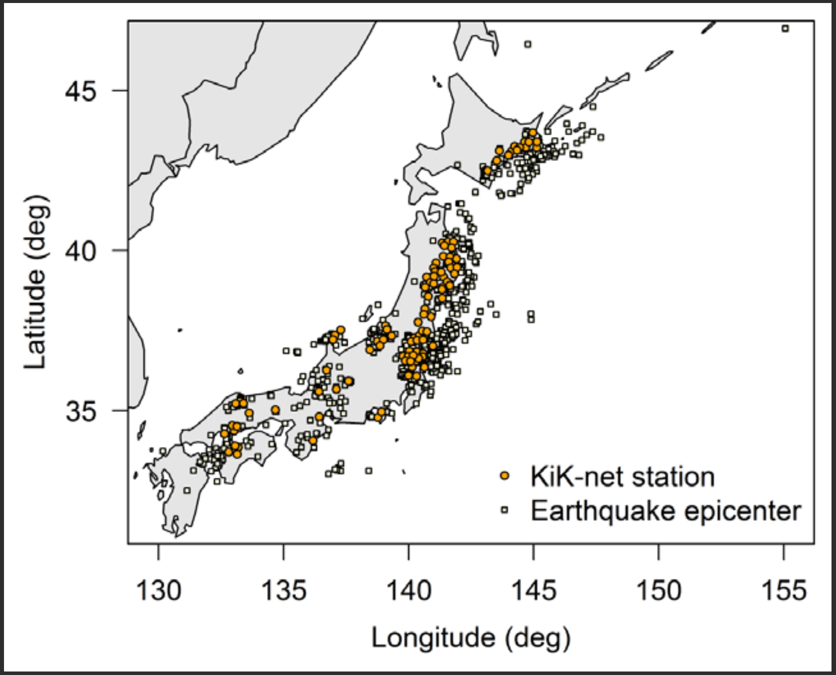
1D Soil profile

- S-wave velocity, V_S
- Density, ρ
- Damping ratio, ξ
- Additional parameters

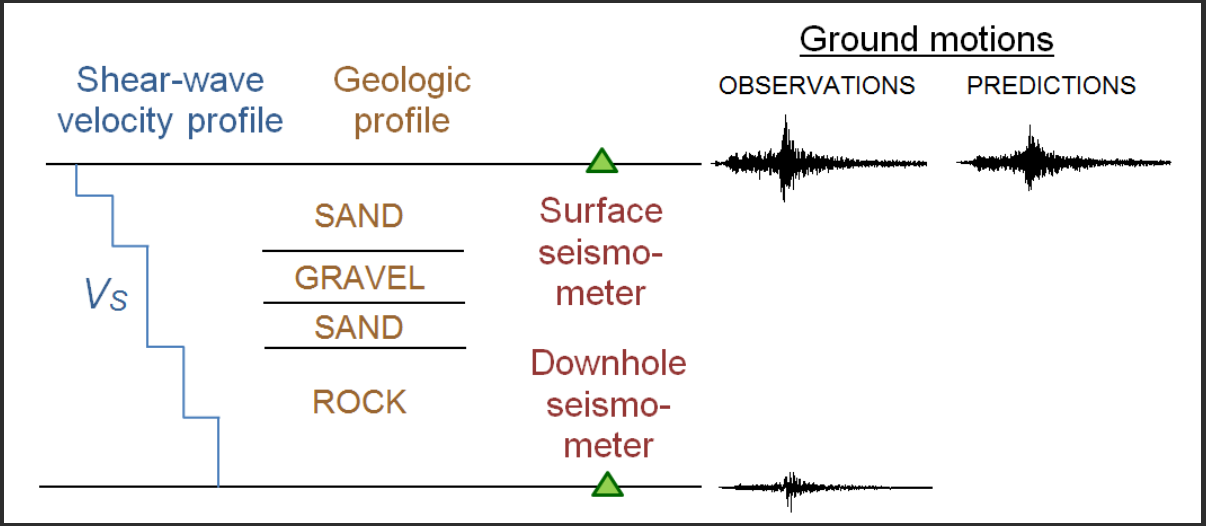
Input ground motion (downhole or outcrop)

Kaklamanos and Bradley (2018)

- **Study location:** Kiban-Kyoshin network (KiK-net) of vertical seismometer arrays in Japan
- **Site response studies:** Linear (L), equivalent-linear (EQL), and nonlinear (NL) analyses of 5626 ground-motion records at 114 KiK-net stations
- **Research goals:** Analyze the uncertainty resulting from common site response modeling assumptions using a large dataset of observations, and offer recommendations for site response modeling improvements

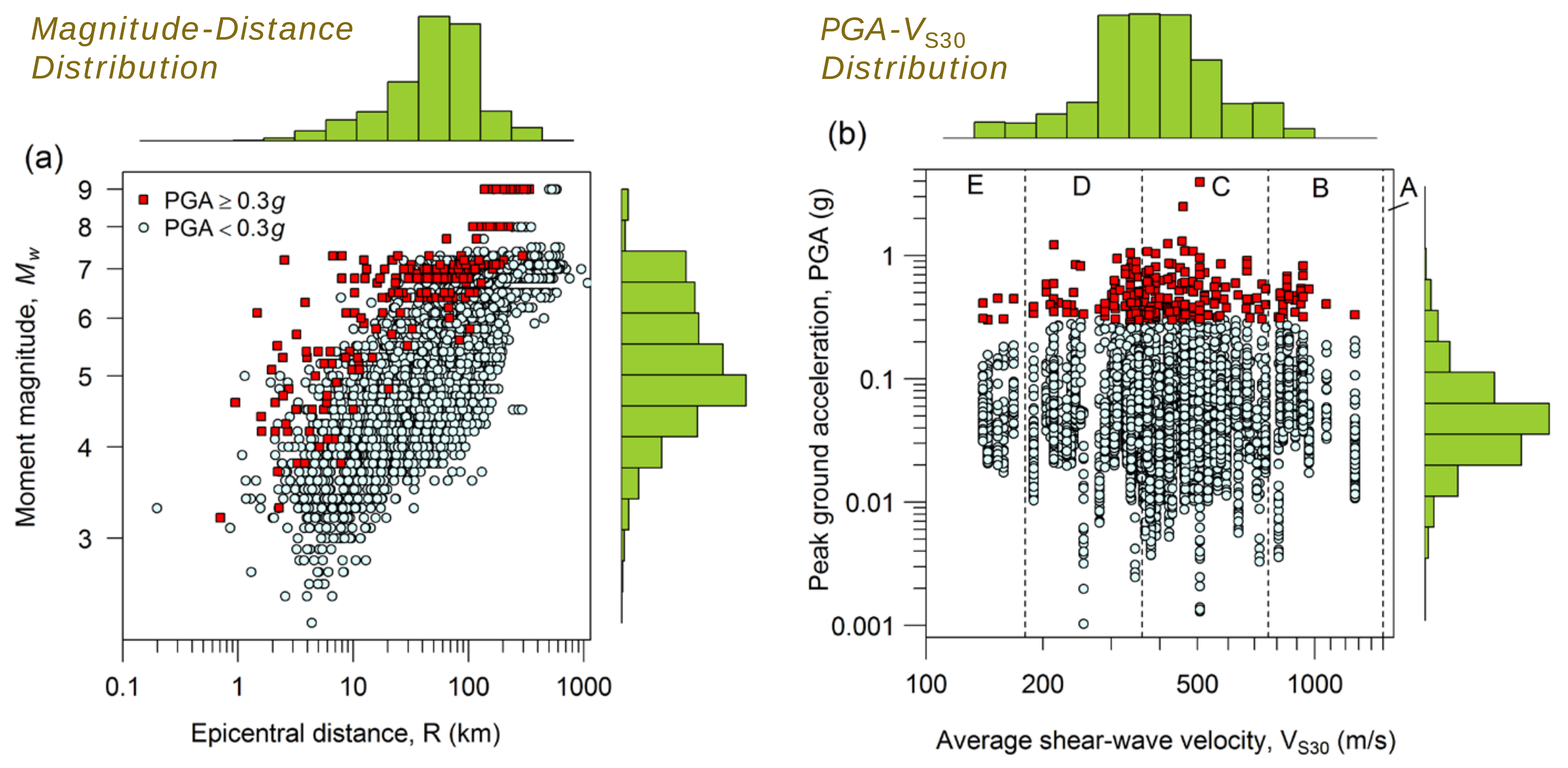


Kaklamanos, J., and B. A. Bradley (2018). Challenges in predicting site response using 1D analyses: Conclusions from 114 KiK-net vertical seismometer arrays, *Bull. Seismol. Soc. Am.* (in press).



Kaklamanos and Bradley (2018)

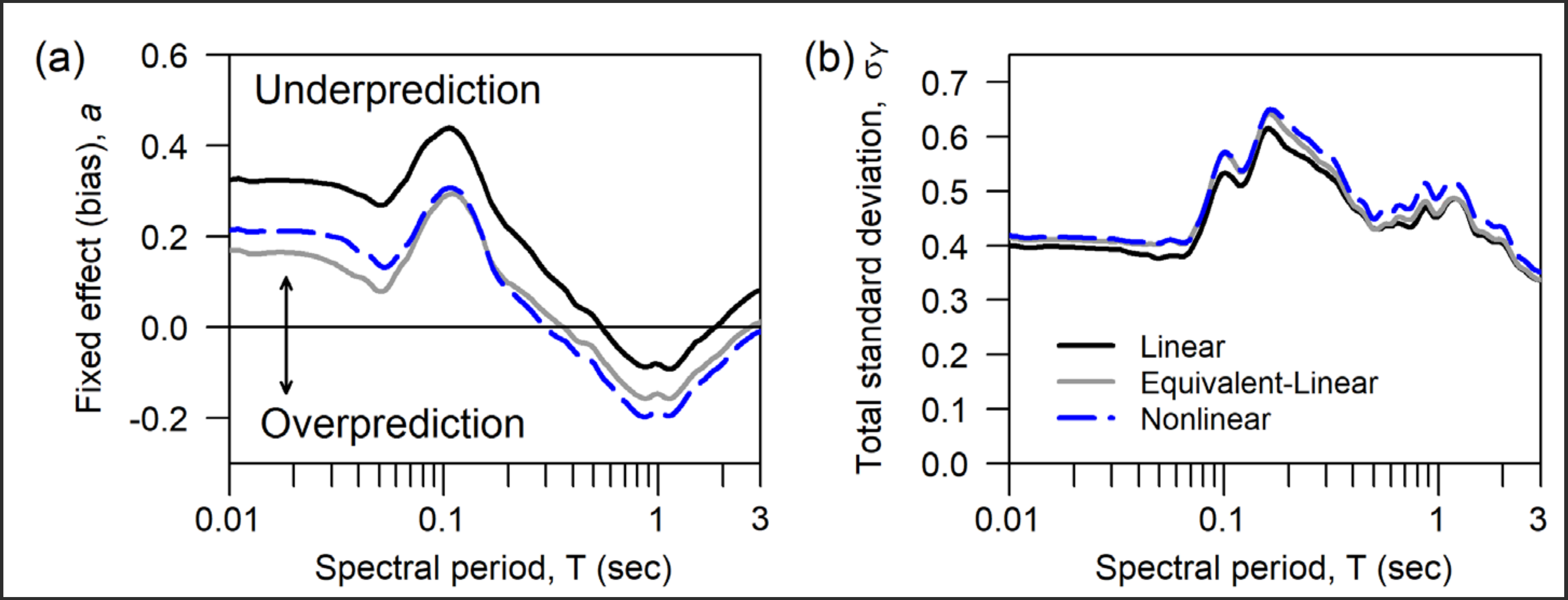
Distributions of sites and ground motions:



Downhole sensor depths: 100 to 900 m; mean = 160 m

Bias and variability: all records

Model bias (mean residual) | Total standard deviation



Key conclusion:

All models are biased towards underprediction of ground motions at high frequencies (short spectral periods), where nonlinear effects are strongest.

Husid Intensity

Husid Intensity (HI): the temporal accumulation of Arias Intensity (AI) normalized by its maximum value (at t = t_{max})

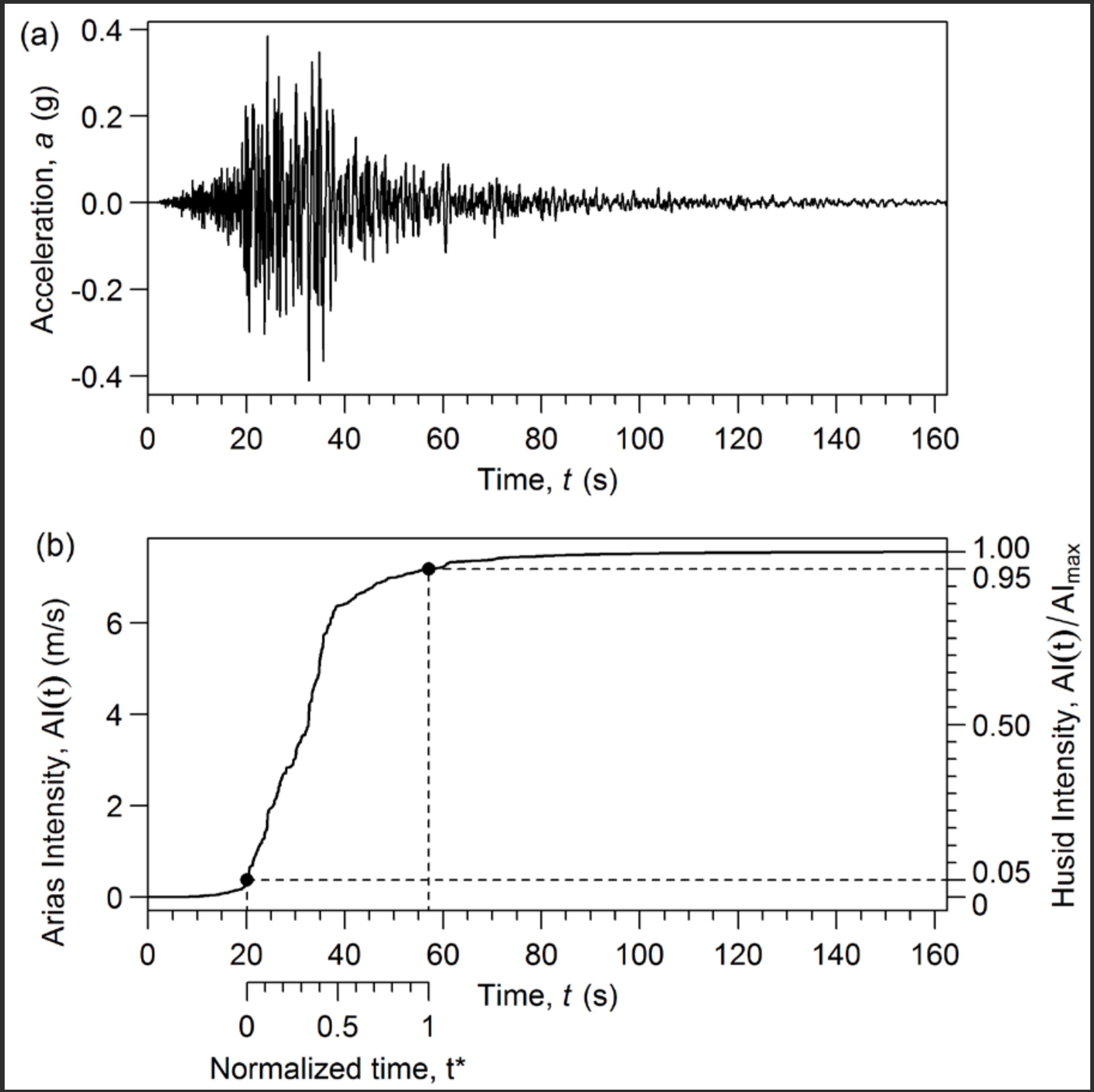
$$\boxed{\mathrm{HI}(t) = \frac{\mathrm{AI}(t)}{\mathrm{AI}_{\max}} = \frac{\int_0^t a^2(t)\,\mathrm{d}t}{\int_0^{t_{max}} a^2(t)\,\mathrm{d}t}}$$

Normalized time,

$t^* \in [0, 1]$: the portion of the record between 5% and 95% Husid Intensity

$$t^* = 0 \;\leftrightarrow\; \mathrm{HI(t)} = 0.05$$

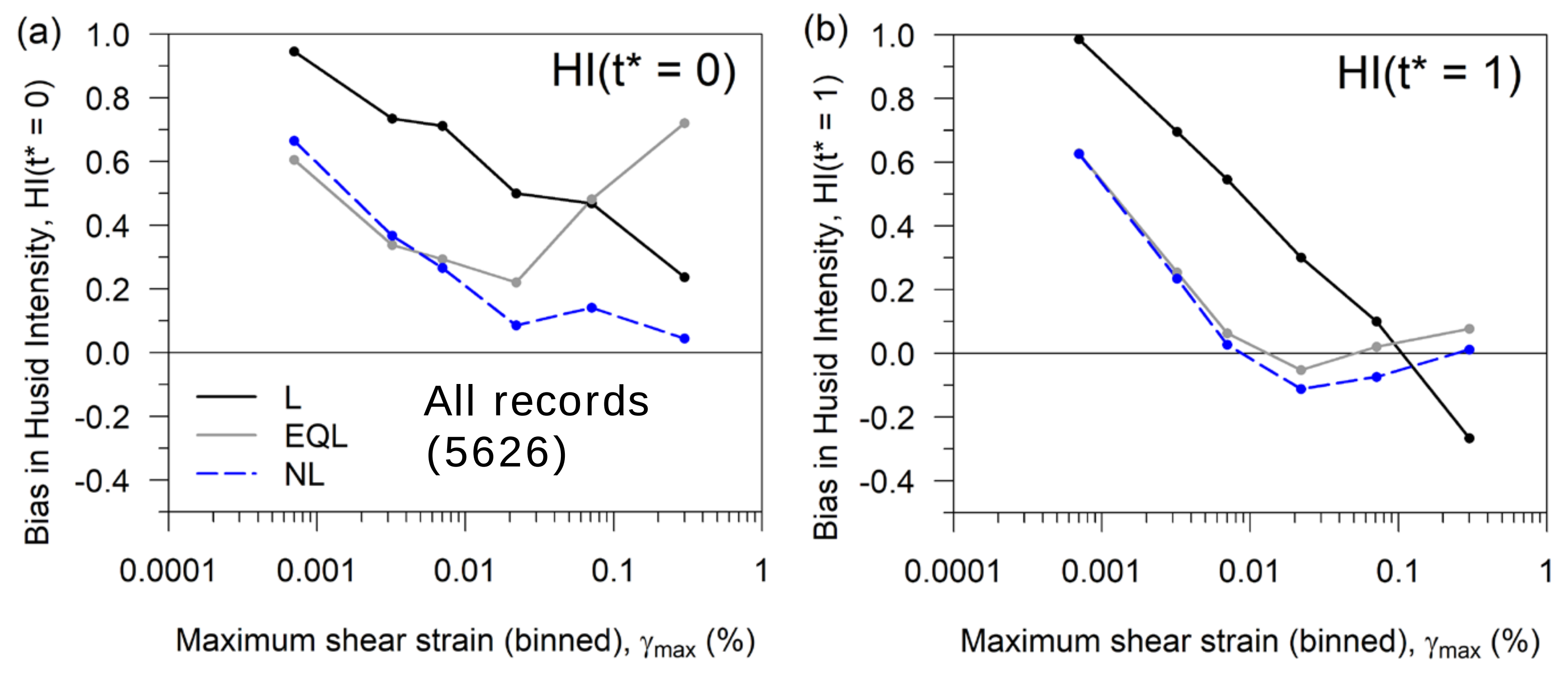
$$t^* = 1 \;\leftrightarrow\; \mathrm{HI(t)} = 0.95$$



Model bias in terms of Husid Intensity

Early in record (5% HI)

Late in record (95% HI)



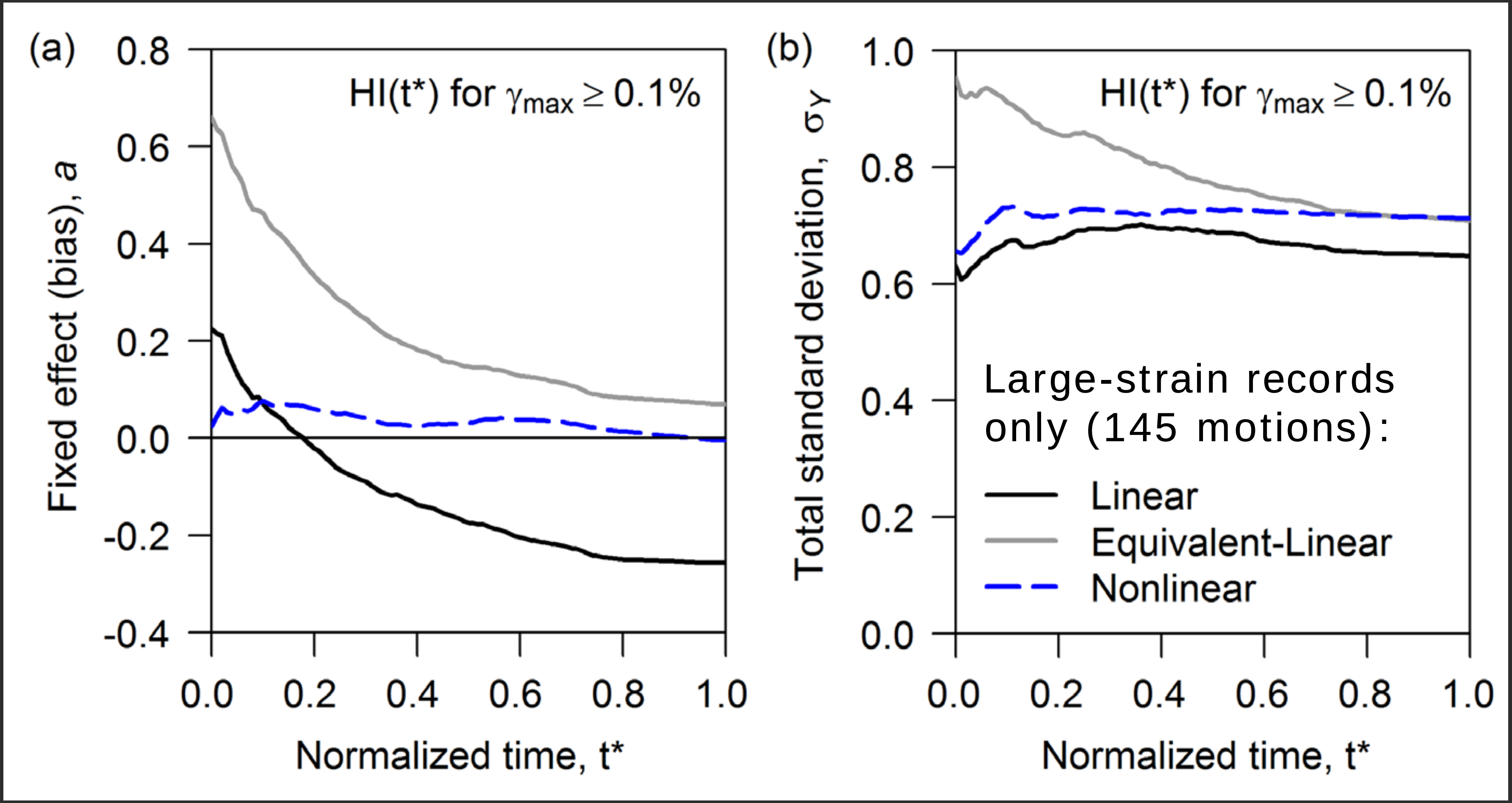
Key conclusions:

- Across all models, the strongest bias is observed for *small-strain records.*
- For $\gamma_{max} \geq 0.05\%$, the EQL model is shown to have excessive bias early in the ground motion record, but this bias is obscured when the entire record is considered.

Model uncertainty vs. normalized time for large-strain ground motions

Model bias (mean residual)

Total standard deviation

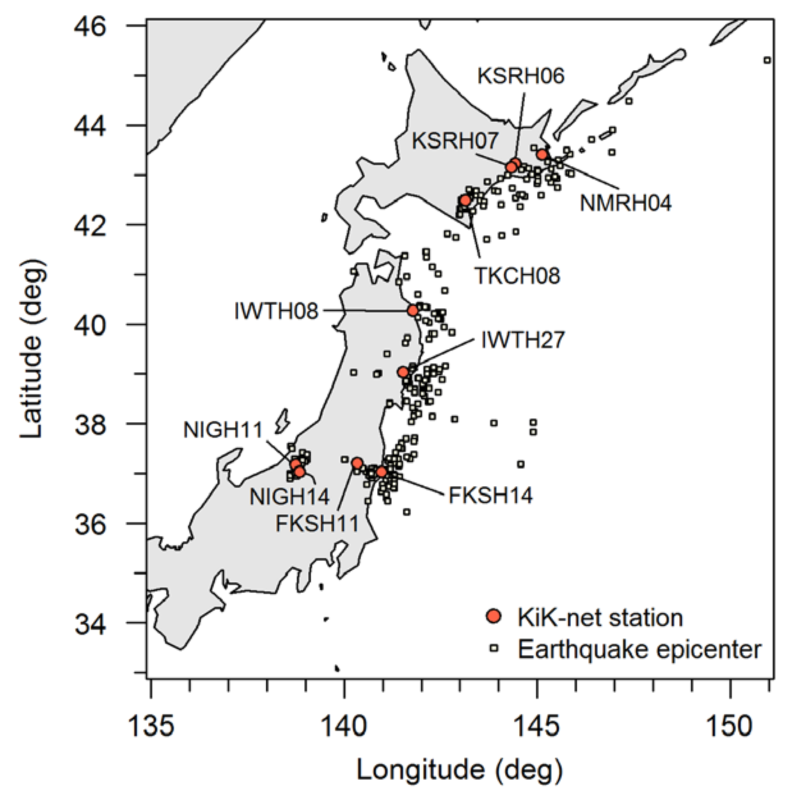


Large-strain records only (145 motions):

Physical adjustments to model inputs

- Potential explanations for the persistent underprediction of high-frequency ground motions by all site response models:
  1. Poorly characterized soil properties and constitutive model parameters
  2. Breakdowns in the one-dimensional (1D) site response assumptions
- To explain this bias, we test four physical hypotheses regarding soil profiles and constitutive model parameters at ten sites that are well-modeled by 1D site response (classified as LG by Thompson et al., 2012)

Kaklamanos, J., B. A. Bradley, A. N. Moolacattu, and B. M. Picard (in preparation). Physical hypotheses for improving 1D site response estimation assessed at 10 KiK-net vertical array sites: soil profiles and constitutive model parameters.

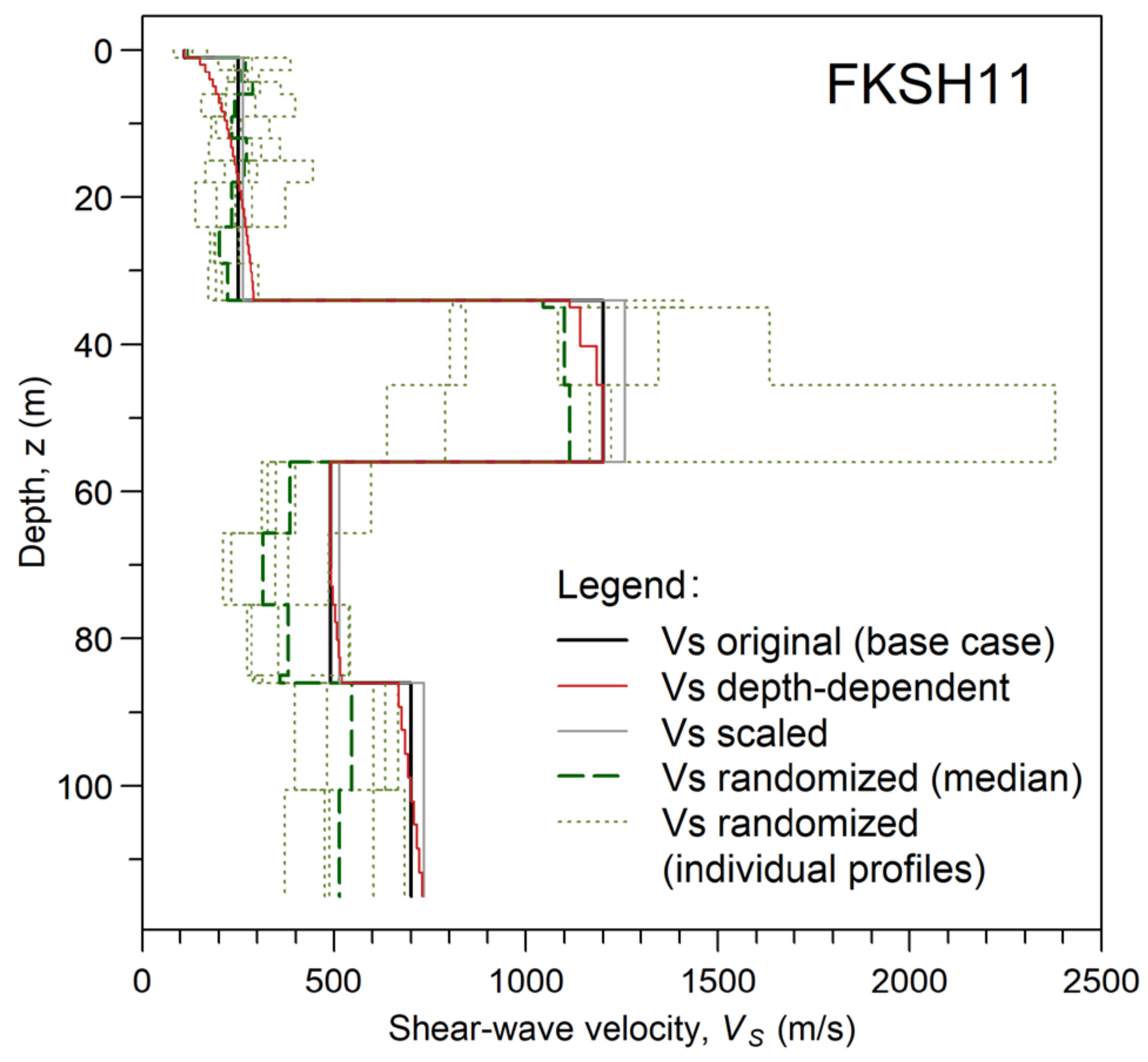


398 ground motions at 10 sites

Physical adjustments to model inputs

Physical adjustments:

1. Apply a depth-dependent V_S gradient within layers
2. Decrease the small-strain damping ratio (by half)
3. Increase the small-strain shear modulus (by 10%)
4. Randomize the V_S profile (Toro, 1995)



Application of a depth-dependent V_S gradient

Hypothesis: The V_S profiles provided on the KiK-net website may be too coarse, and the impedance contrasts between successive layers may be larger than those in reality.

Action: Within each layer, the constant value of V_S is replaced with a depth-dependent exponential gradient centered on the median V_S for the layer.

$$\boxed{V_s(z) = \overline{V_s}\left[\frac{\sigma_v'(z)}{\overline{\sigma_v'}}\right]^n}$$

where:

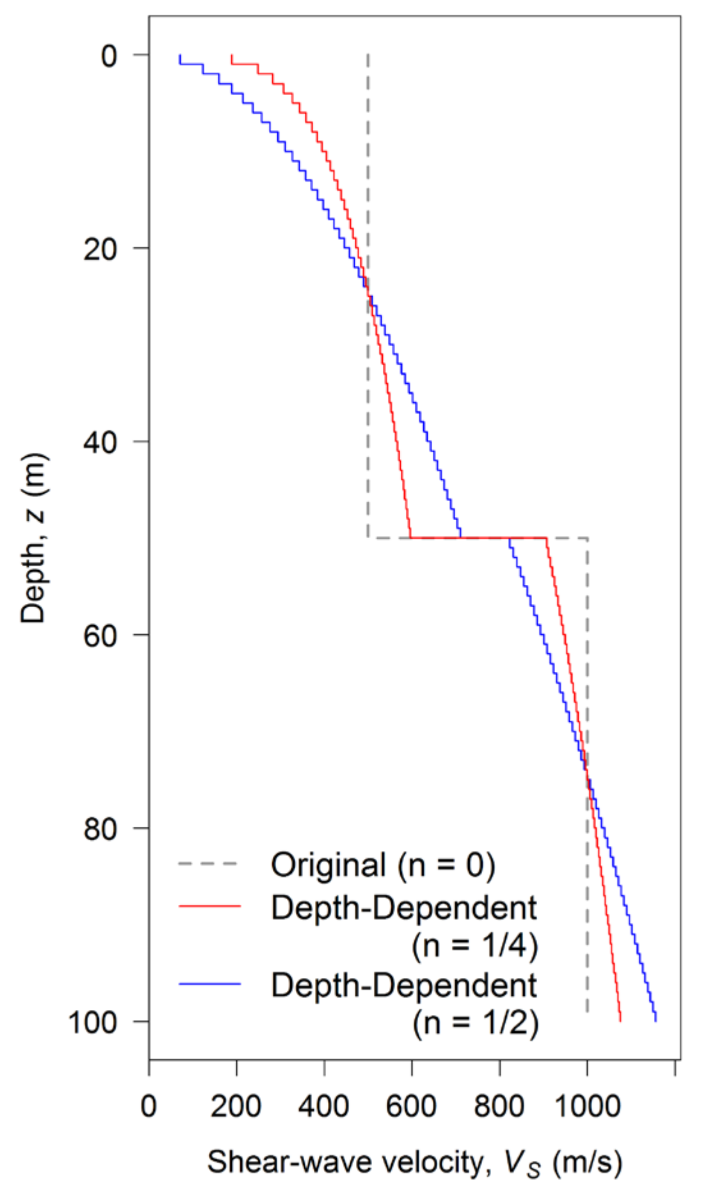
$V_s(z)$ = shear-wave velocity at depth *z*

$\overline{V_s}$ = average shear-wave velocity throughout layer (constant)

$\sigma_v'(z)$ = vertical effective stress at depth *z*

$\overline{\sigma_v'}$ = vertical effective stress at layer midpoint

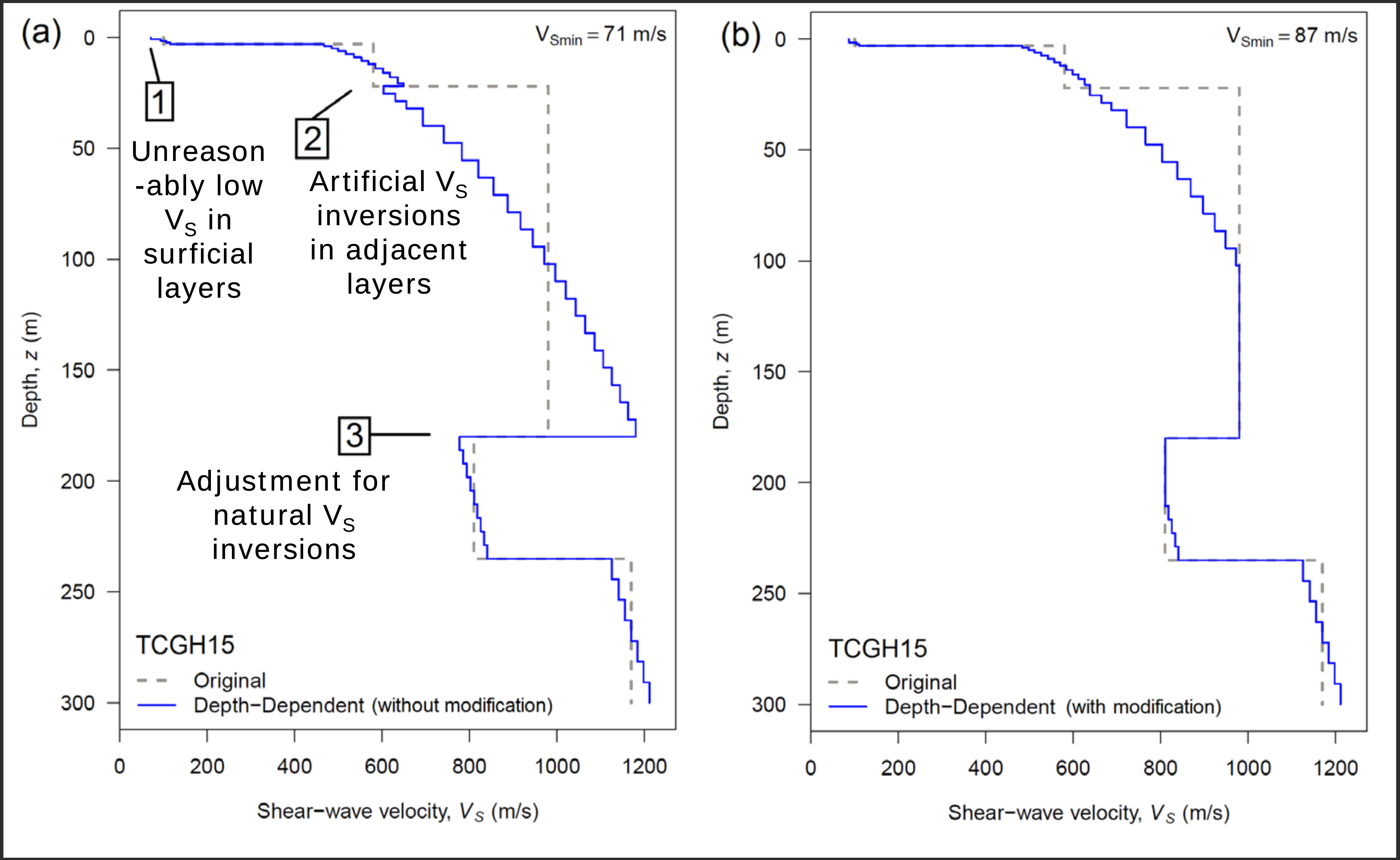
n = stress exponent (1/4 for clays, silts, and sands; 1/3 for gravels and rocks)



Application of a depth-dependent V_S gradient

Without modification

With modification



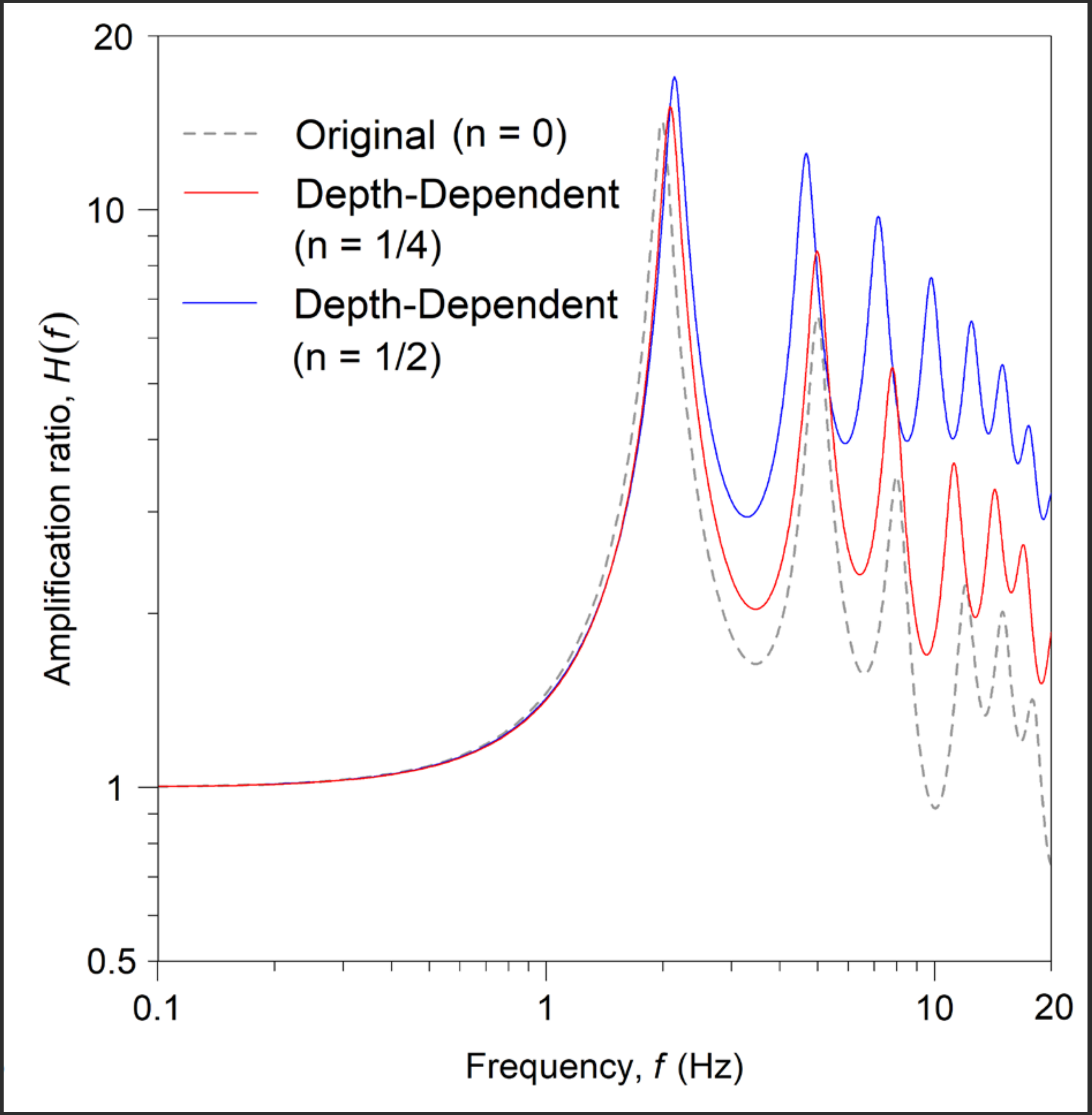
1 Unreasonably low V_S in surficial layers

2 Artificial V_S inversions in adjacent layers

3 Adjustment for natural V_S inversions

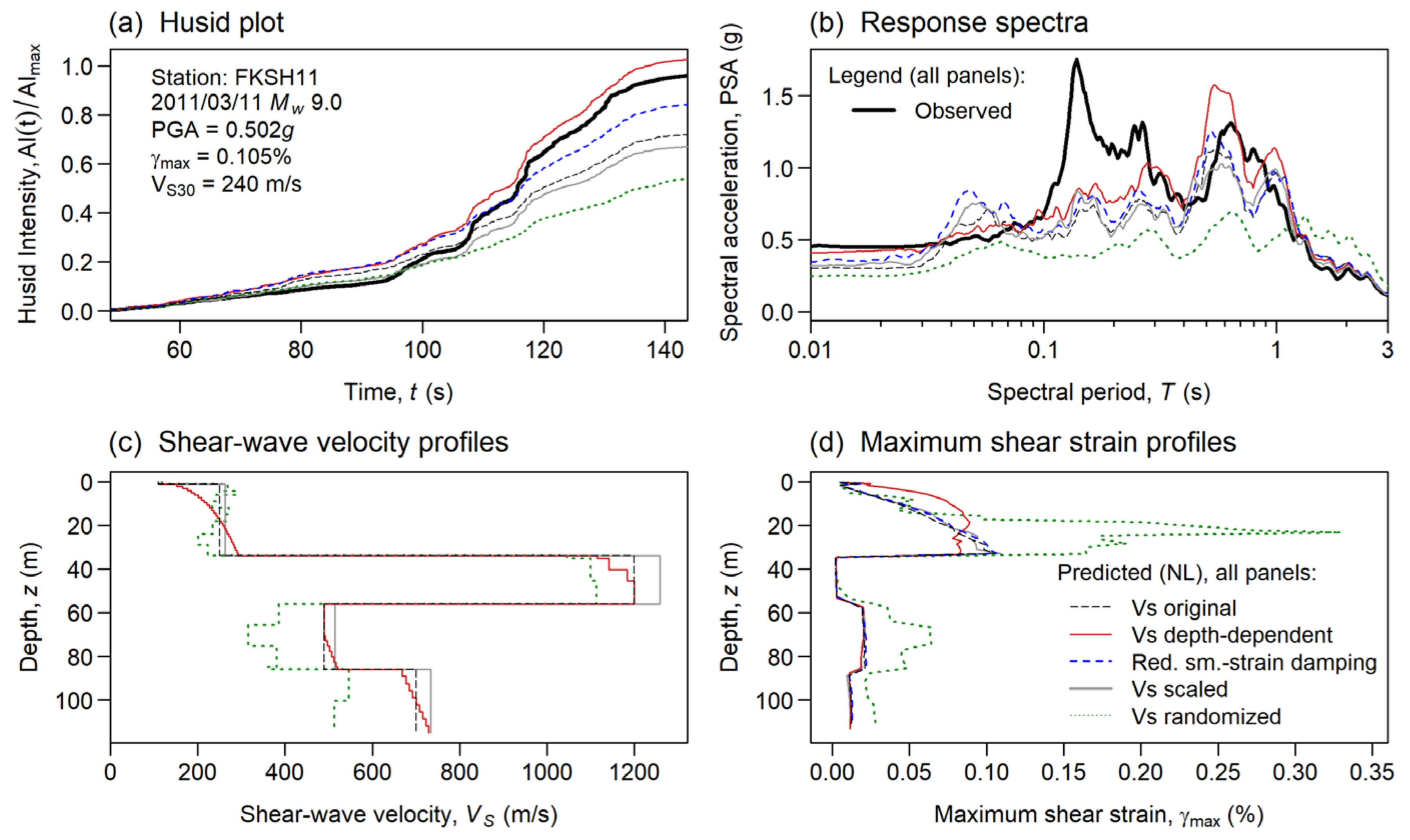
Application of a depth-dependent V_S gradient

Effects on amplification spectra: increased amplification at high frequencies



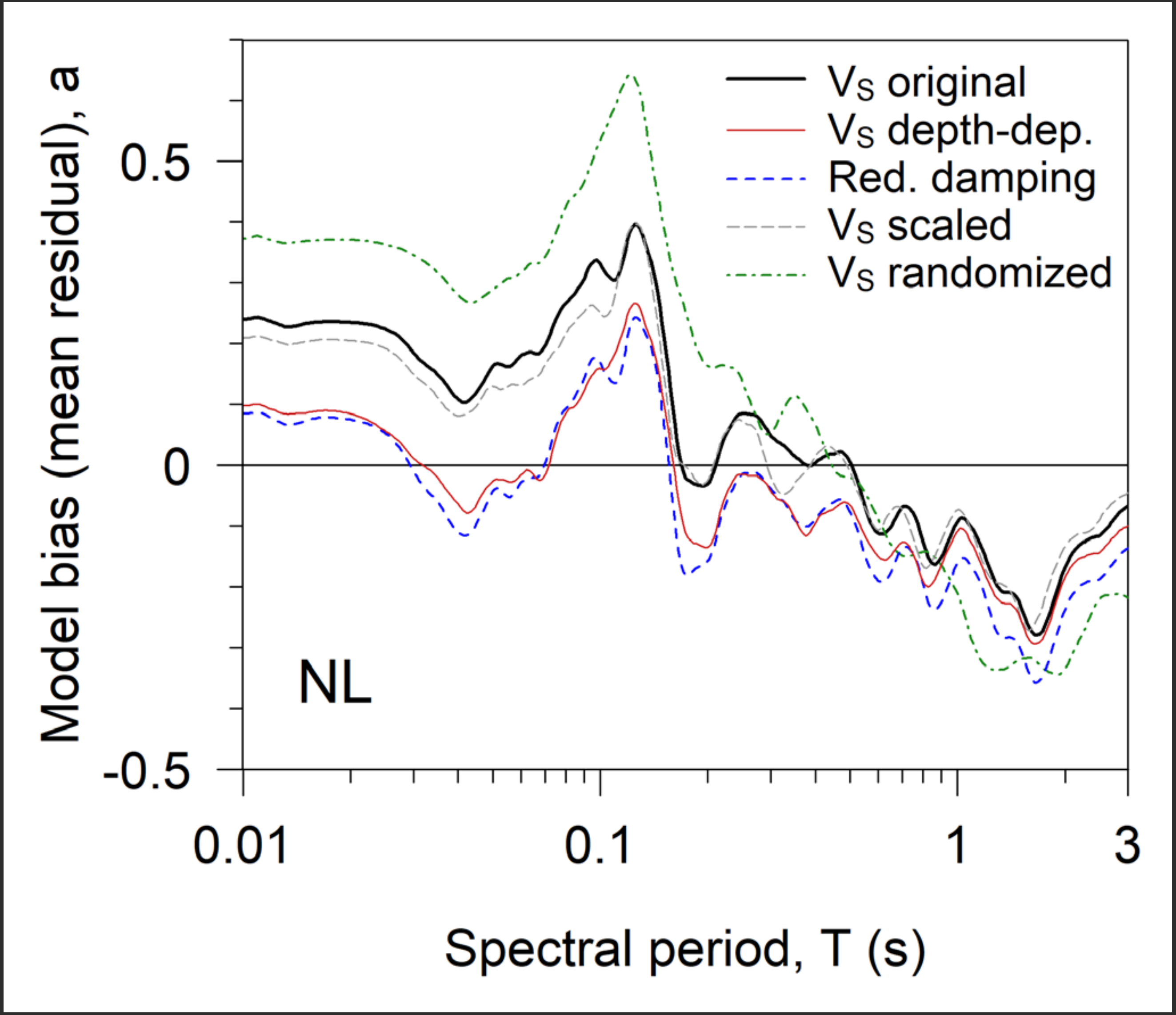
Results for an example ground motion

Example site response observations and NL predictions for the 2011/03/11 M_w 9.0 Tohoku-Oki earthquake at FKSH11



Model bias for each physical adjustment

NL model bias (mean residual) as a function of spectral period for the alternative physical hypotheses (all 10 sites and 398 ground motions)



Conclusions

- Persistent site response model biases at high frequencies suggest that: (1) many of these sites may experience a breakdown in the 1D site-response assumptions; and/or (2) the subsurface data provided for KiK-net sites (i.e. velocity profiles and broad soil type) may be over-simplified.
- When using Husid Intensity to assess the temporal evolution of model uncertainty, the EQL model is shown to have excessive bias early in the ground motion record, but this bias is obscured when the entire record is considered. At maximum shear strains of approximately 0.05% and greater, the NL model is preferred.
- By applying a depth-dependent V_S gradient within layers (an adjustment to the original coarse V_S profiles), excessive impedance contrasts and strain localizations are reduced, resulting in decreased model bias at high frequencies
- Other factors besides the selection of the constitutive model type, such as the characterization of the shear-wave velocity profile and material properties, often have a more profound influence on model bias (especially at high frequencies).

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Contact: KaklamanosJ@merrimack.edu