QuakeCoRE FP1 monthly meeting on 28th November 2019

QuakeCoRE
NZ Centre for Earthquake Resilience
Te Hiranga Rū

Evaluation of a new iterative linear procedure for ground response analysis using frequency-dependent soil parameters at KiK-net stations

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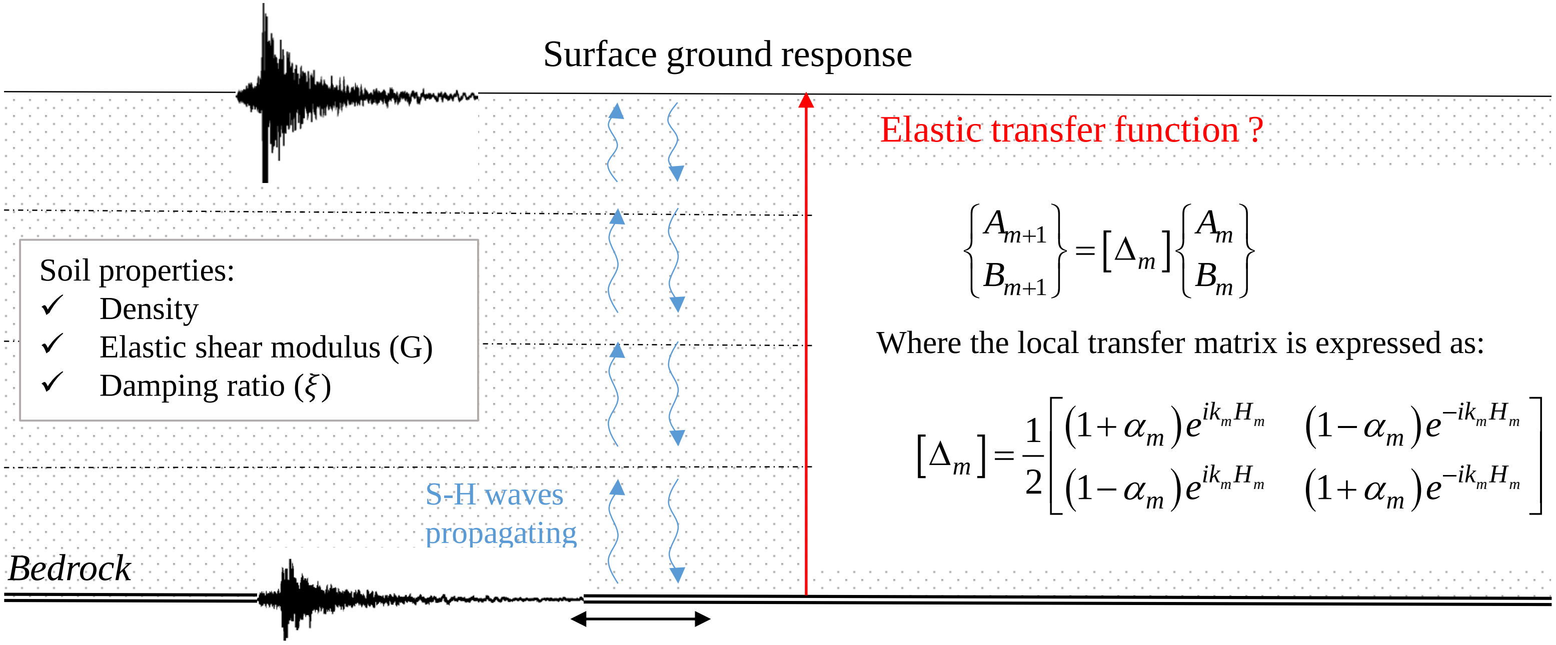
THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Frequency domain methods for 1-D total stress analysis

☐ Linear solution

1) Using a visco-elastic shear stress (τ) – shear strain (γ) model: $\tau = G(1 + 2i\xi)\gamma$

2) Along with elastic transfer functions (e.g., Haskell-Thompson matrix) in the frequency domain.



Surface ground response

Elastic transfer function ?

$$\begin{Bmatrix} A_{m+1} \\ B_{m+1} \end{Bmatrix} = [\Delta_m] \begin{Bmatrix} A_m \\ B_m \end{Bmatrix}$$

Where the local transfer matrix is expressed as:

$$[\Delta_m] = \frac{1}{2}\begin{bmatrix} (1+\alpha_m)e^{ik_m H_m} & (1-\alpha_m)e^{-ik_m H_m} \\ (1-\alpha_m)e^{ik_m H_m} & (1+\alpha_m)e^{-ik_m H_m} \end{bmatrix}$$

Soil properties:
- ✓ Density
- ✓ Elastic shear modulus (G)
- ✓ Damping ratio (ξ)

S-H waves propagating

Bedrock

Base motion

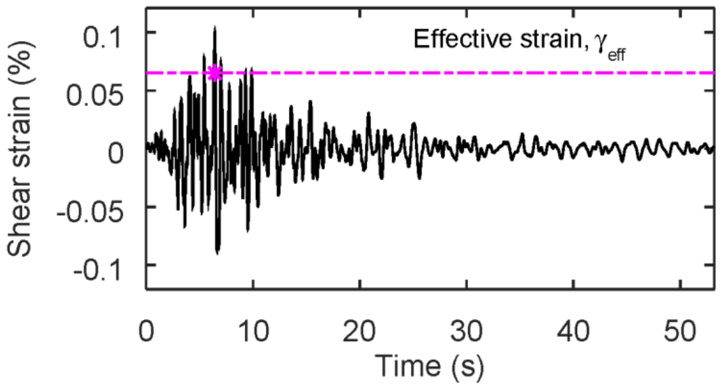
Frequency domain methods for 1-D total stress analysis

☐ Equivalent-Linear (EL) solution

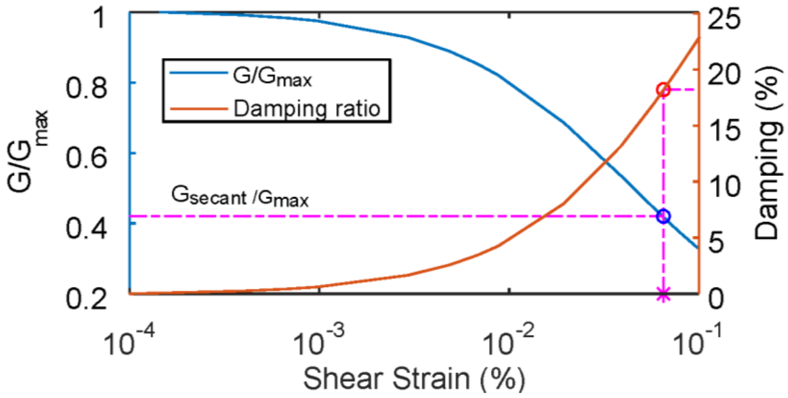
1) Using a visco-elastic shear stress (τ) – shear strain (γ) model: $\tau = G(1 + 2i\xi)\gamma$

2) Along with elastic transfer functions (e.g., Haskell-Thompson matrix) in the frequency domain.

3) Both soil paramaters G and ξ are adjusted depending on the maximum shear strain amplitudes developed.



(a) Example of effective shear strain derived from a time-history soil response.



(b) Matching soil properties with shear modulus reduction and soil damping ratio curves.

The procedure is repeated until convergence of the solution (Equivalent-Linear method).

Frequency domain methods for 1-D total stress analysis

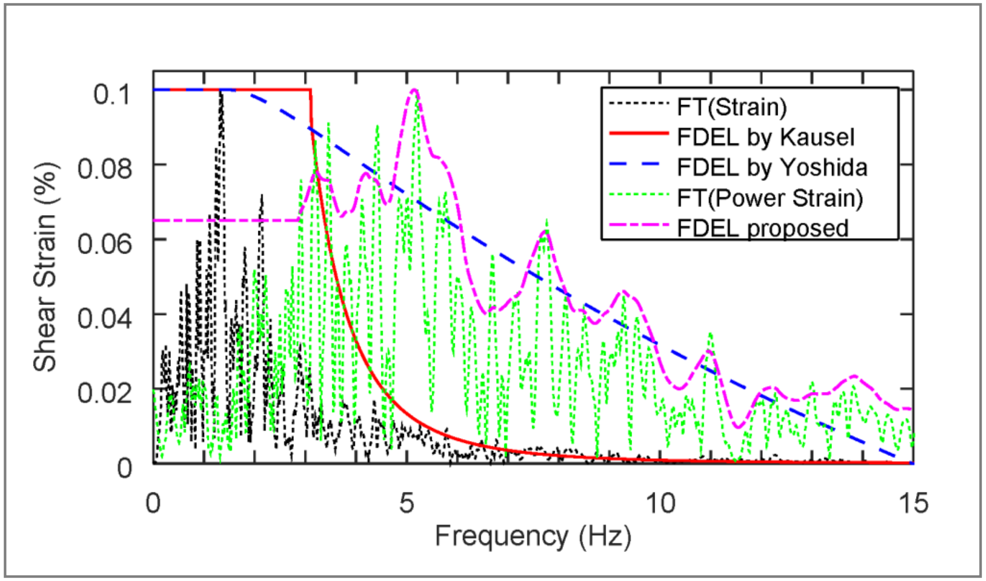
❑ FDEL methods available in the literature

1) **Sugito et al. (1994)** first proposed a frequency-dependent shear strain that derives directly from the FT of strain time-history.

2) **Kausel and Assimaki (2002)** modified this formulation using shape fitting parameters to smooth the frequency-dependent strain spectrum and ease convergence.

3) Alternatively, **Yoshida et al. (2002)** proposed another method for frequency-dependent shear strain that relies on logarithmic shape function.

4) More recently, **Meite et al. [1]** utilize the **power strain intensity measure** to derive frequency-dependent strain amplitudes.



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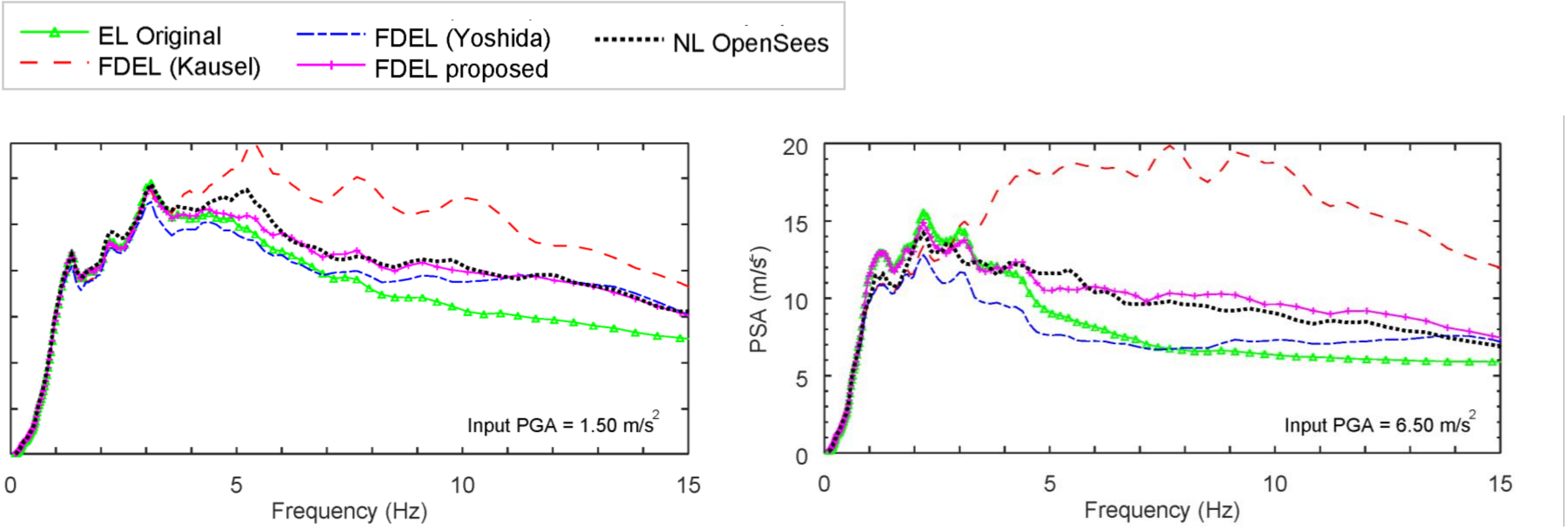
[1] Meite, R., Wotherspoon, L., McGann, C.R., Green, R.A., Hayden, C., in process. An iterative linear procedure using frequency-dependent soil parameters for site response analyses. Soil Dynamics and Earthquake Engineering.

A new method for EL analysis with frequency-dependent soil parameters (FDEL)

- **Comparison against the existing FDEL methods**



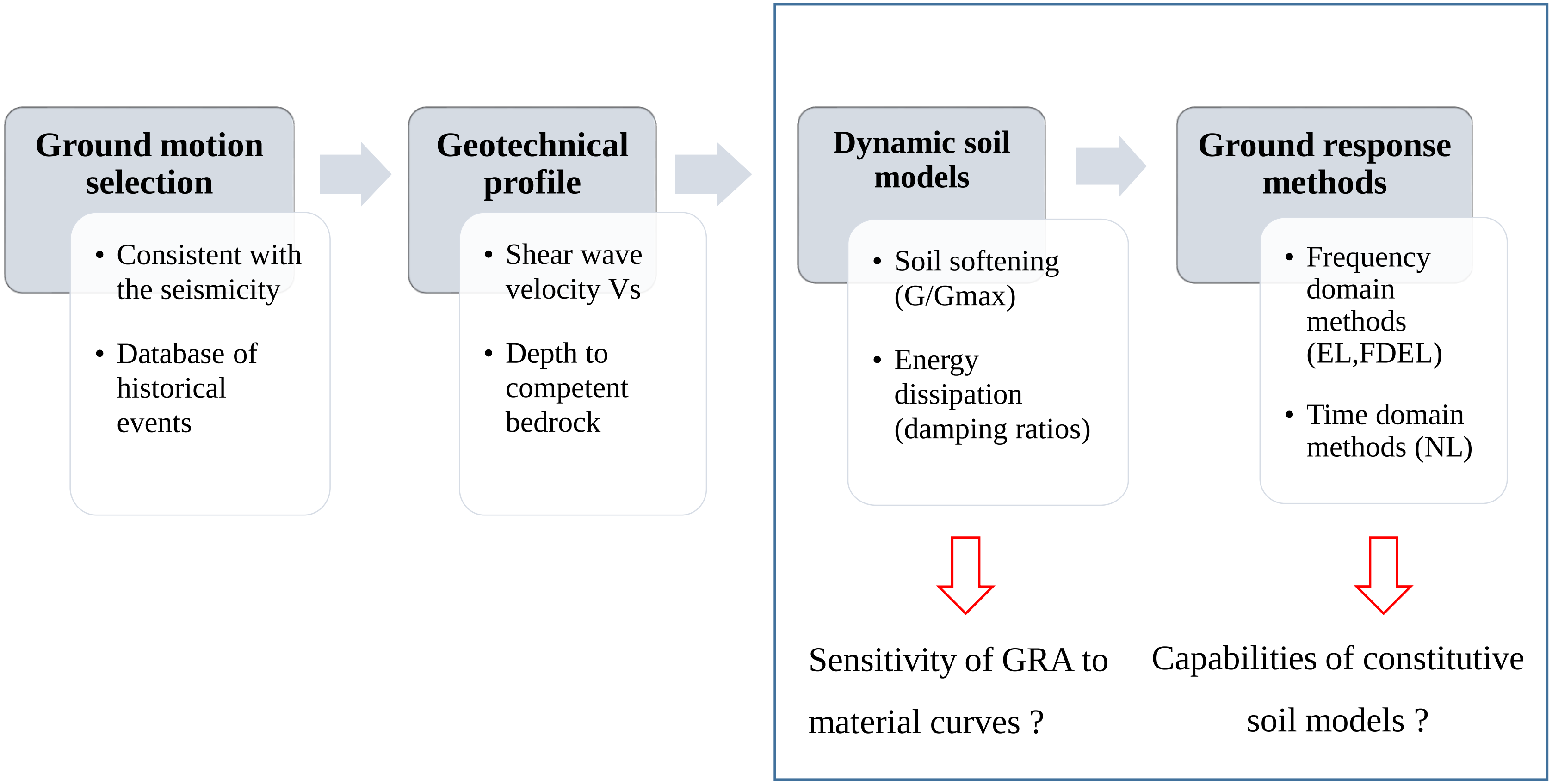
(a) (b)

Comparison of geometric mean pseudo-spectral accelerations calculated at surface between the EL method, both existing FDEL methods proposed by Kausel and Assimaki, and Yoshida et al., the proposed FDEL method [1] and the NL model, using control motions with PGA scaled respectively at (a) 1.50 m/s² (~0.15g) and (b) 6.50 m/s² (~0.66g).

[1] Meite, R., Wotherspoon, L., McGann, C.R., Green, R.A., Hayden, C., in process. An iterative linear procedure using frequency-dependent soil parameters for site response analyses. Soil Dynamics and Earthquake Engineering.

Sensitivity of 1-D ground motion predictions to analysis codes and material models using KiK-net vertical arrays

❑ **Uncertainties in the computational process**



Ground motion selection

- Consistent with the seismicity
- Database of historical events

Geotechnical profile

- Shear wave velocity Vs
- Depth to competent bedrock

Dynamic soil models

- Soil softening (G/Gmax)
- Energy dissipation (damping ratios)

Ground response methods

- Frequency domain methods (EL,FDEL)
- Time domain methods (NL)

Sensitivity of GRA to material curves ?

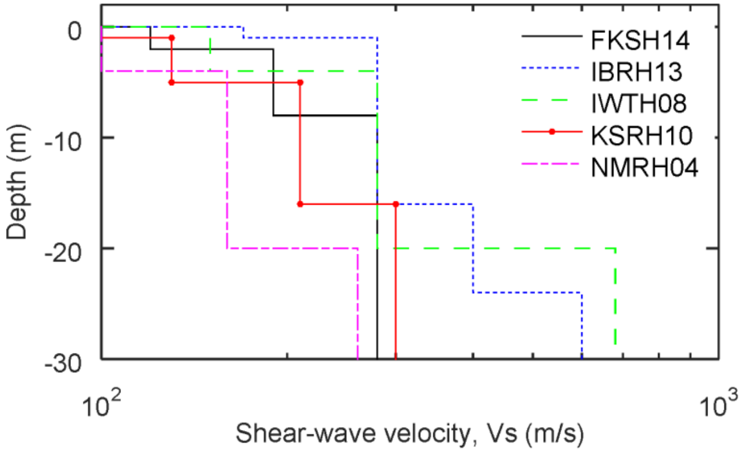
Capabilities of constitutive soil models ?

1-D soil response models at KiK-net[2] sites

- ☐ **Investigations conducted at 5 KiK-net stations**

Station name	FKSH14	IBRH13	IWTH08	KSRH10	NMRH04
Nature of soil deposits at the upper 30 meters	Sands and Gravels	Weathered rock	Weathered rock	Clays	Sands and Gravels
$V_{s,30}$ (m/s)	237	335	305	213	168
Fundamental site period, T_0 (s)	1.17	0.50	0.58	1.16	2.99
Site class according to NZS1170.5 standard	D	C	C	D	E
Depth to water table potentially identified (m)	52	16	10	16	8
Depth to bedrock so that Vs ≥ 1000 m/s	52	34	50	36	> 186
Depth the borehole seismometer	147	100	100	255	216

Graduate increase in shear-wave velocity profiles at the upper 30 m: ⇨



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[2] Kiban–Kyoshin network (KiK-net) database available at http://www.kyoshin.bosai.go.jp.

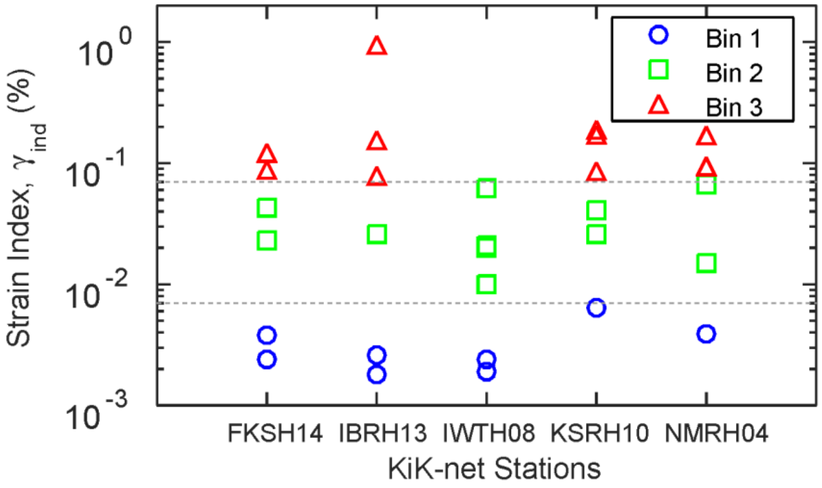
1-D soil response models at KiK-net[2] sites

- **30 ground motions considered (60 records), grouped in 3 bins of seismic intensities**

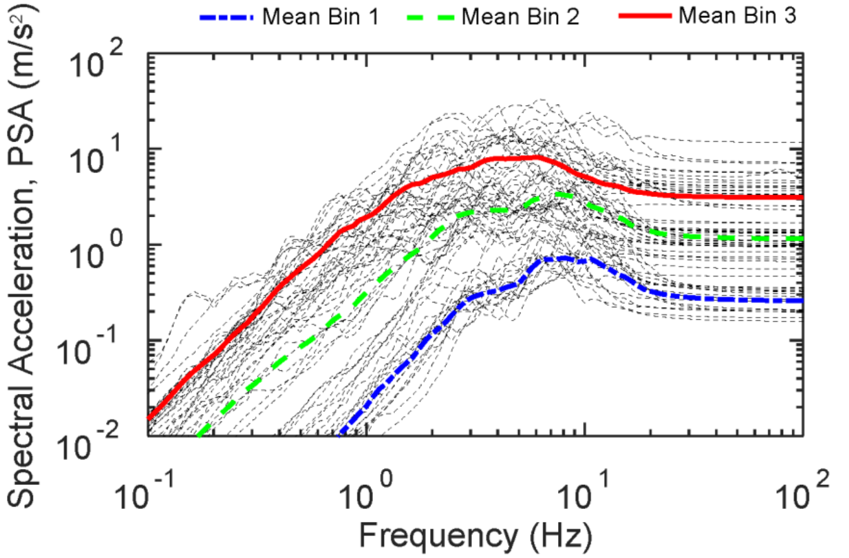
The strain index was employed as ground motion criteria to span a range of soil deformations:

$$\gamma_{ind} = \frac{PGV}{V_{s,30}}$$

Where PGV referred to as the Peak Ground Velocity recorded at surface and $V_{s,30}$ denotes the averaged shear-wave velocity at the upper 30 m.



(a) Distribution of ground motion records with respect to the strain index at the five KiK-net stations.



(b) PSA recorded at the ground surface and geometric mean spectra for three bins of ground motion intensities.

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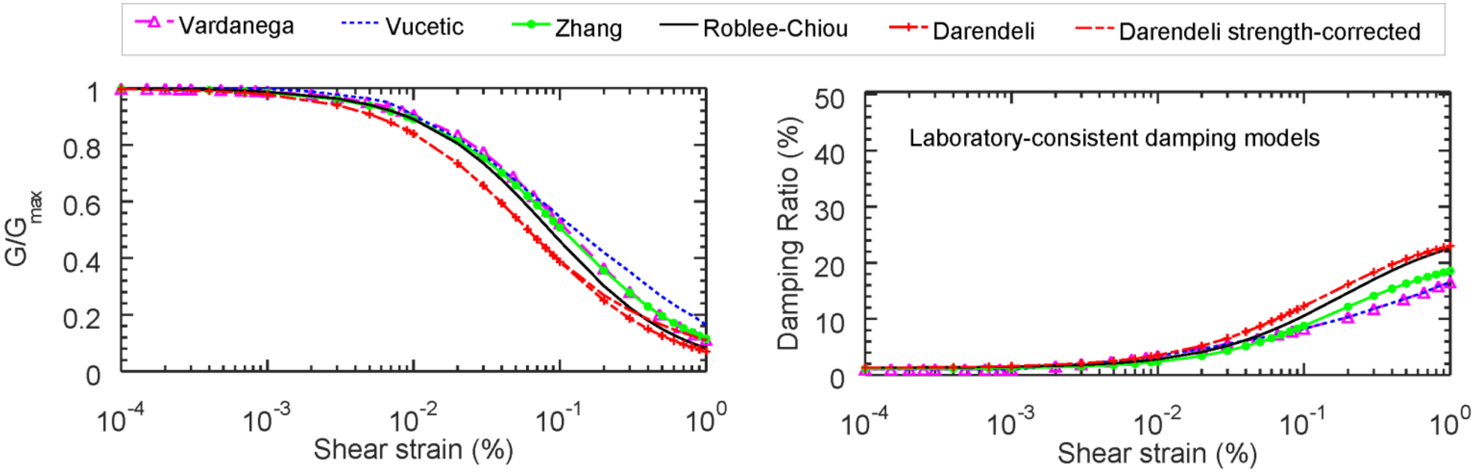
[2] Kiban–Kyoshin network (KiK-net) database available at http://www.kyoshin.bosai.go.jp.

1-D soil response models at KiK-net sites

- **A range of material curves tested (x 5 sets)**

Soil models	Soil types	Strain applicability
Darendeli (2001),	Sands, clays and silts	Low to moderate strains, < 0.5 %
Roblee and Chiou (2004)	Sands, clays and silts using GeoIndex	Low to large strains, < 4 %
Zhang (2005)	Mineral soils grouped by geological age	Low to moderate strains, < 0.3 %
Matasovic and Vucetic, MKZ (1993a)	Sands	Adjustable, generally ≤ 1%
Menq (2003)	Sandy and gravelly soils	Low to moderate strains, ≤ 1%
Vucetic (1993)	Plastic soils (silts and clays)	Low to moderate strains, ≤ 1%
Vardanega and Bolton (2013)	Plastic soils (silts and clays)	Low to moderate strains, ≤ 1%

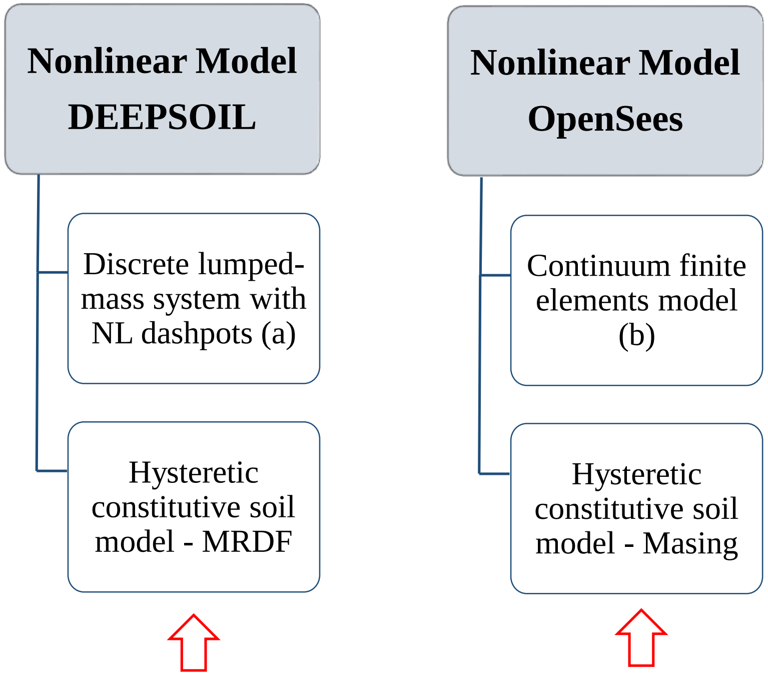
Material curves for clay:



1-D soil response models at KiK-net sites

- ❑ **4 ground response methods (codes) tested**

Including 2 time domain methods:



Nonlinear Model DEEPSOIL

Discrete lumped-mass system with NL dashpots (a)

Hysteretic constitutive soil model - MRDF

Nonlinear Model OpenSees

Continuum finite elements model (b)

Hysteretic constitutive soil model - Masing

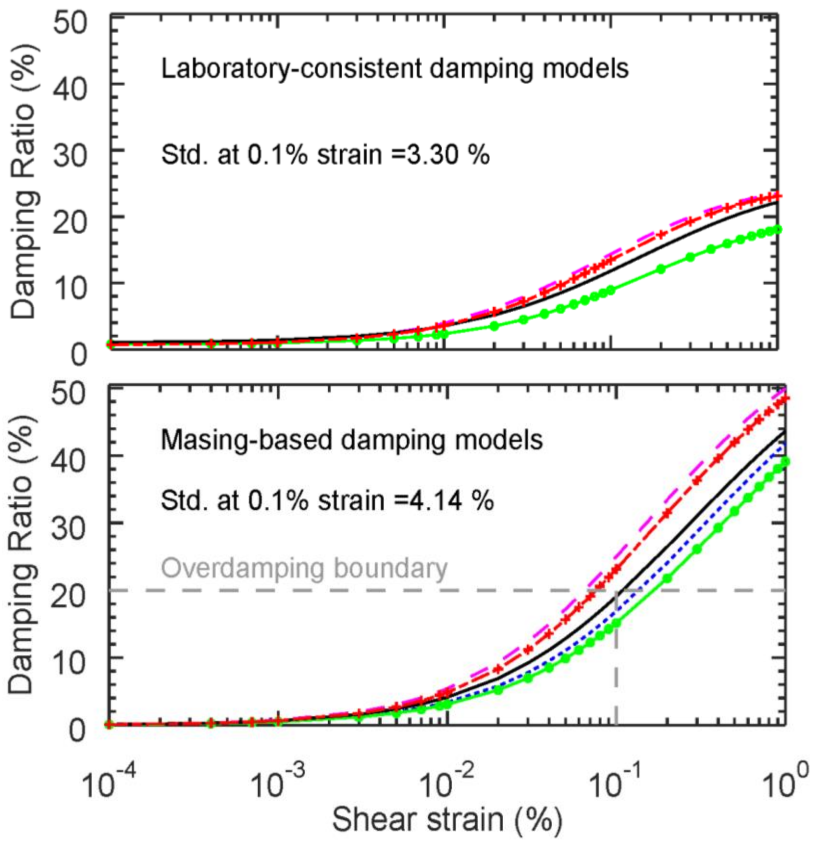
Inputs

G/Gmax curves

Damping ratio curves

G/Gmax curves

Laboratory consistent vs. Masing-based damping curves:



Menq model — MKZ model — Zhang model — Roblee-Chiou model — Darendeli model

1-D soil response models at KiK-net sites

- ☐ **4 ground response methods (codes) tested**

Including 2 frequency domain methods:

Equivalent-linear (EL)

- Elastic transfer functions
- Effective level of shear strain

Modified equivalent-linear (FDEL)

- Elastic transfer functions
- Frequency-dependent shear strain

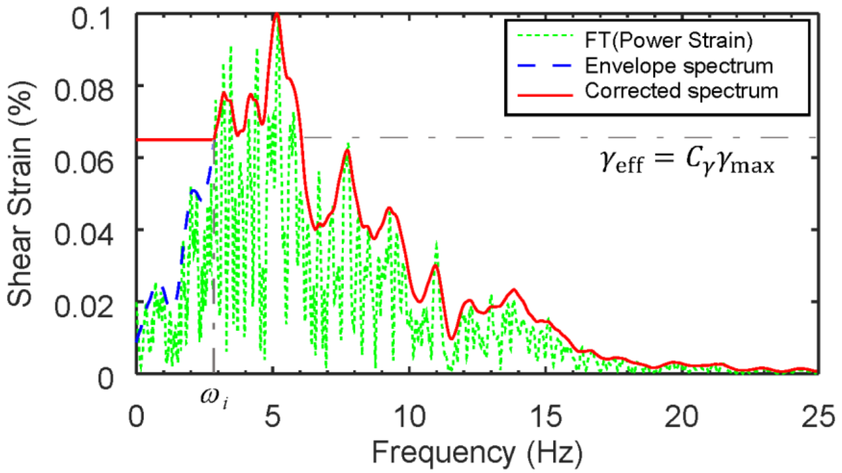
Inputs

G/Gmax curves

Damping ratio curves

G/Gmax curves

Damping ratio curves



Frequency-dependent shear strain amplitudes (FDEL) versus effective shear strain amplitude (EL).

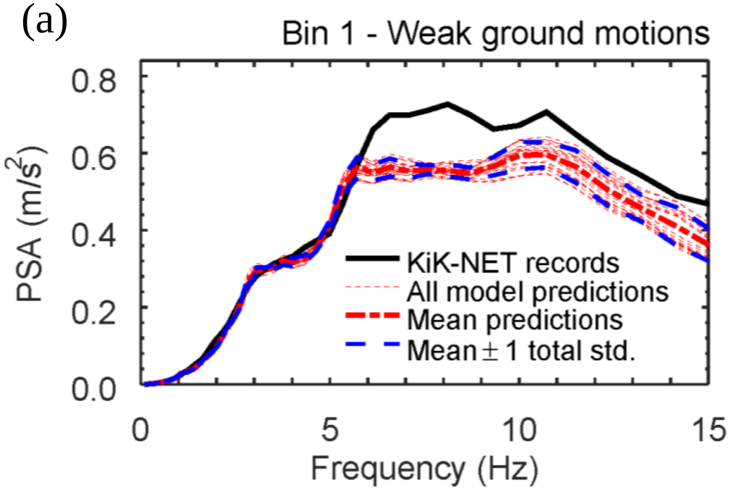
1-D soil response models at KiK-net sites

☐ Scattering in model predictions

A comparison between geometric mean PSA from 20 soil models, including 4 GRA methods x 5 material curves:

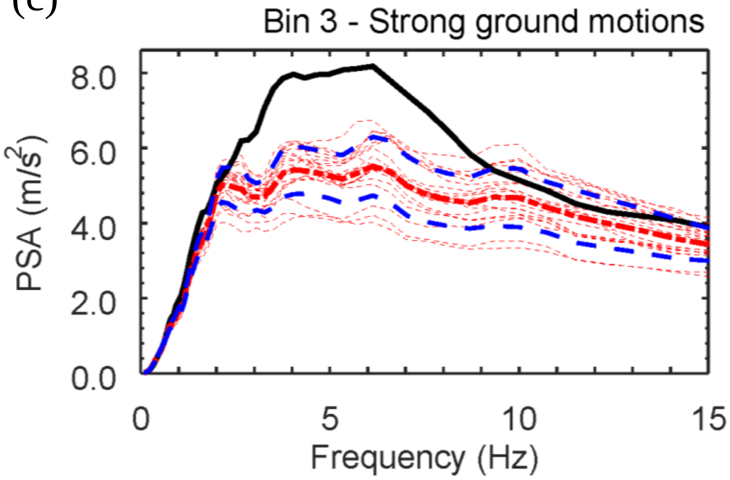
$$\overline{PSA}_{mat_i,GRA_j} = \left(\prod_{k=1}^{N_{records}} PSA_{i,j,k}\right)^{\frac{1}{N_{records}}}$$

(a)



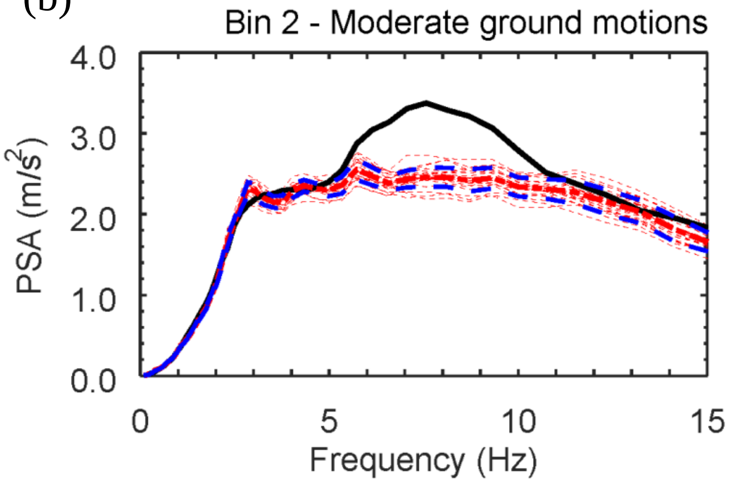
Bin 1 - Weak ground motions

(c)



Bin 3 - Strong ground motions

(b)



Bin 2 - Moderate ground motions

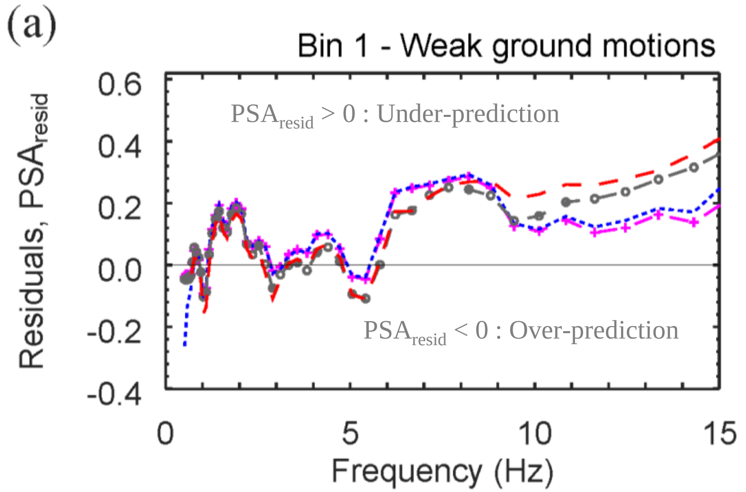
1-D soil response models at KiK-net sites

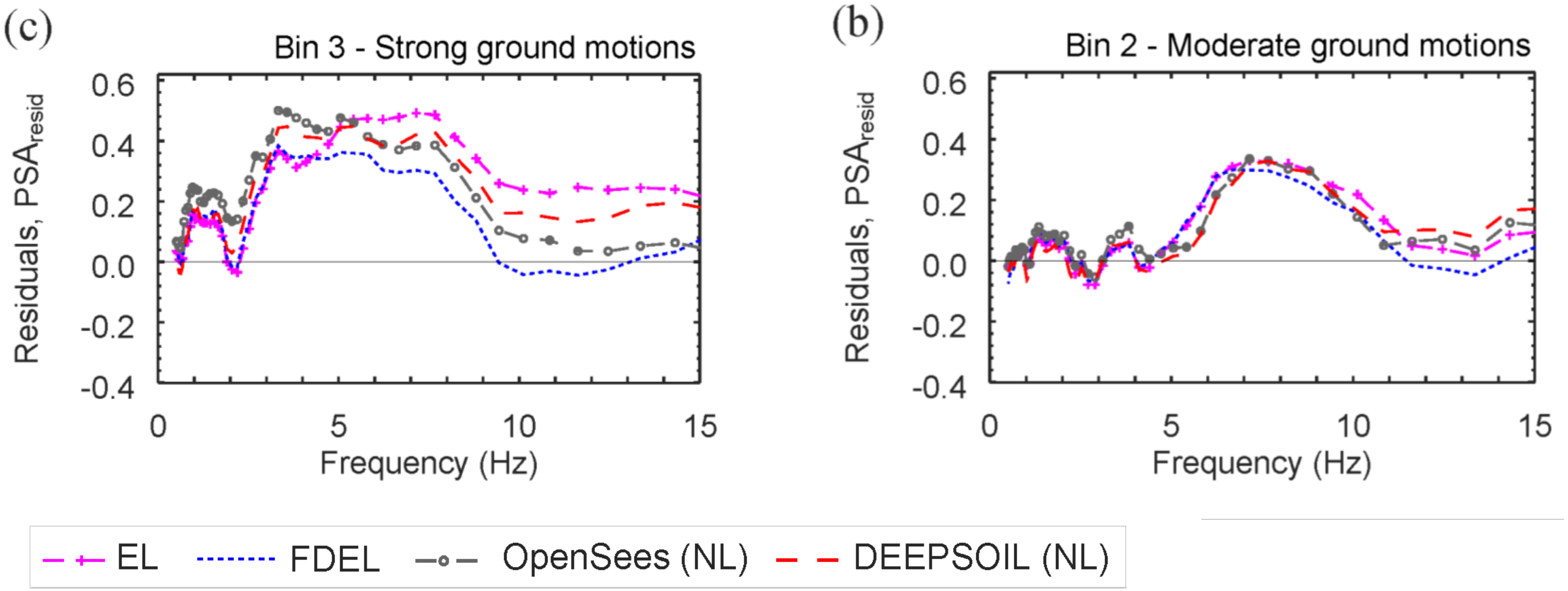
- ☐ **Performance of GRA methods (codes)**

A comparison of mean PSA residuals obtained across all GRA methods (x4) tested:

$$\overline{PSA}_{GRA_j} = \left(\prod_{i=1}^{N_{mat}} \prod_{k=1}^{N_{records}} PSA_{i,j,k} \right)^{\frac{1}{N_{mat} N_{records}}}$$

$$PSA_{resid,j}(T) = ln\left[\overline{PSA}_{obs}(T)\right] - ln\left[\overline{PSA}_{GRA_j}(T)\right]$$





1-D soil response models at KiK-net sites

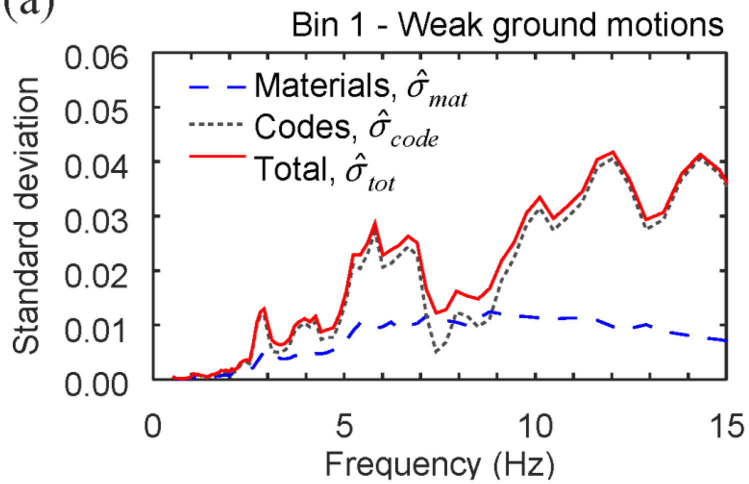
- ☐ **Variabilities in material curves and GRA methods (codes)**

The “mean” standard deviation across model predictions for each bin of ground motions:

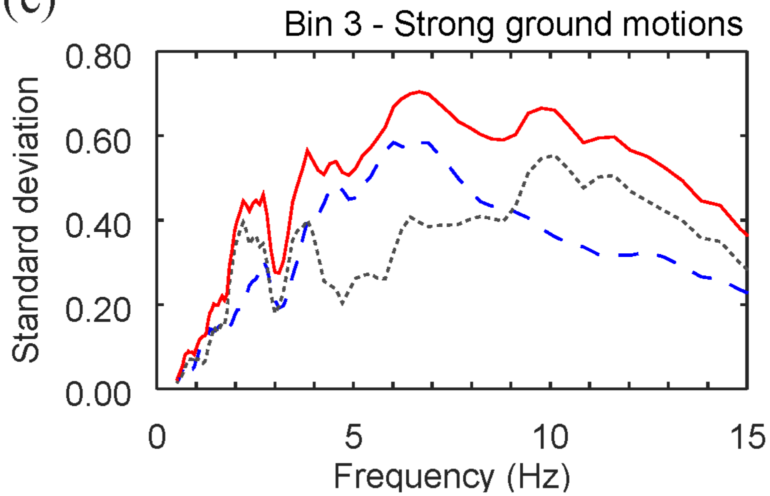
$$\hat{\sigma}_{tot} = \sqrt{\hat{\sigma}_{mat}^2 + \hat{\sigma}_{code}^2}$$

where $\hat{\sigma}_{mat}$ and $\hat{\sigma}_{code}$ denote the standard deviation terms associated with the mean material predictions $\hat{y}_{mat,i}$ and the mean code predictions $\hat{y}_{code,j}$.

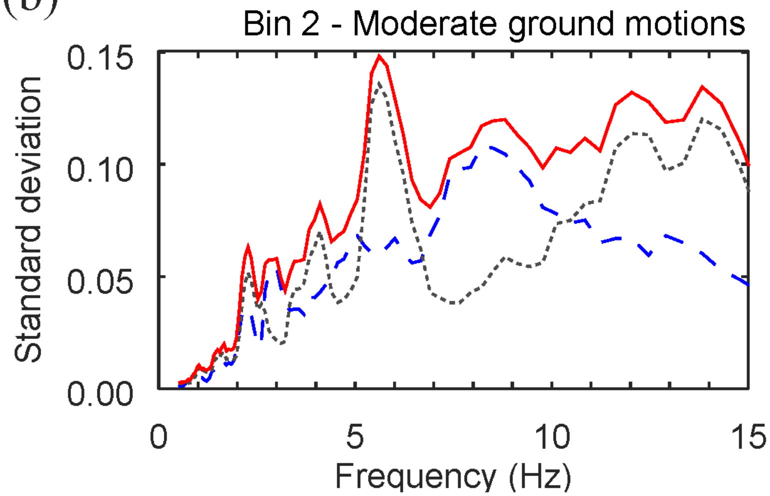
(a)



(c)

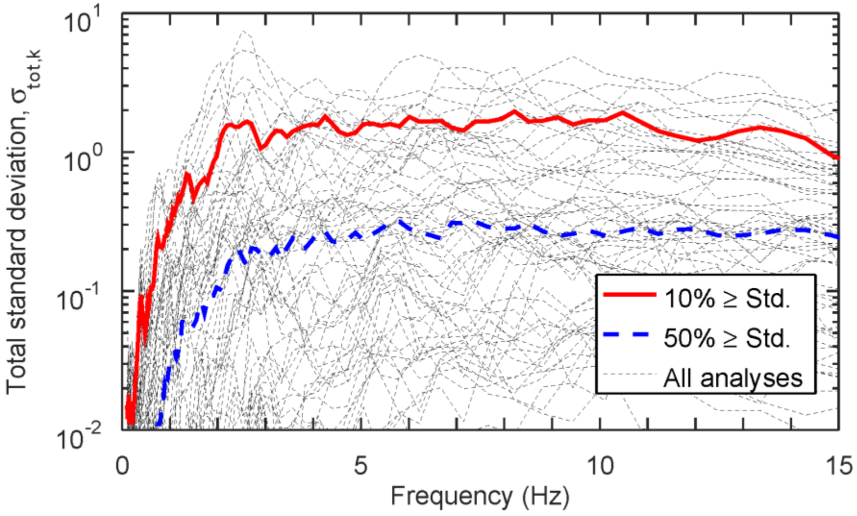


(b)



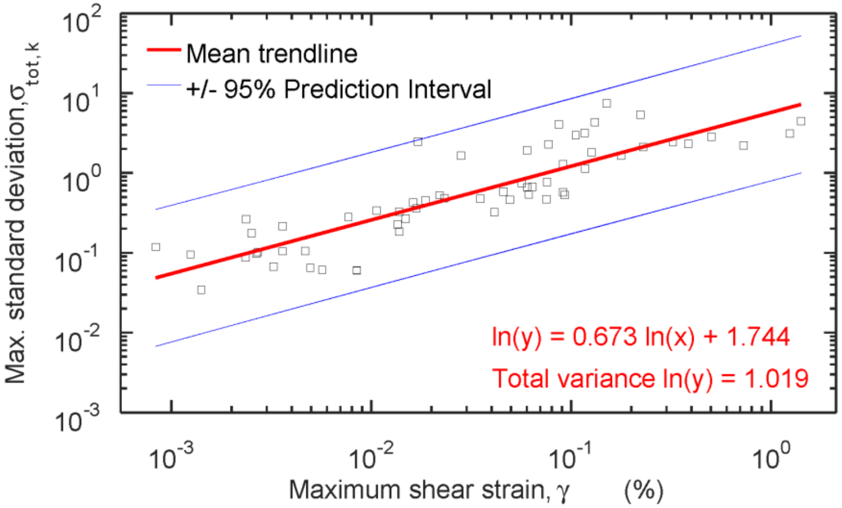
1-D soil response models at KiK-net sites

- ☐ **Total standard deviations across all models calculated for each of 60 ground motions:**



(a)

Standard deviation terms from soil model predictions plotted individually for each of 60 ground motions.



(b)

Variation of maximal standard deviations with respect to the peak shear strain amplitudes developed in soil models across all range of frequencies.

Conclusions

- ✓ A new FDEL method is proposed to address the overdamping observed in higher frequency components of ground motions predicted using the EL method.
- ✓ The proposed FDEL procedure can be employed over a range of ground motion intensities and soil conditions, which was problematic in previous FDEL methods.
- ✓ 1-D ground response predictions are highly sensitive to the choice of analysis methods and the parametrization of dynamic soil models using hyperbolic material curves.
- ✓ The model-to-model variabilities dramatically increase when considering higher ground motion intensities.
- ✓ A linear model regression was established between the maximum standard deviations and the peak shear strains developed within the soil profile.

Thank you !