Nationwide investigation of systematic site effects in New Zealand: Residual analysis of physics-based ground motion simulations

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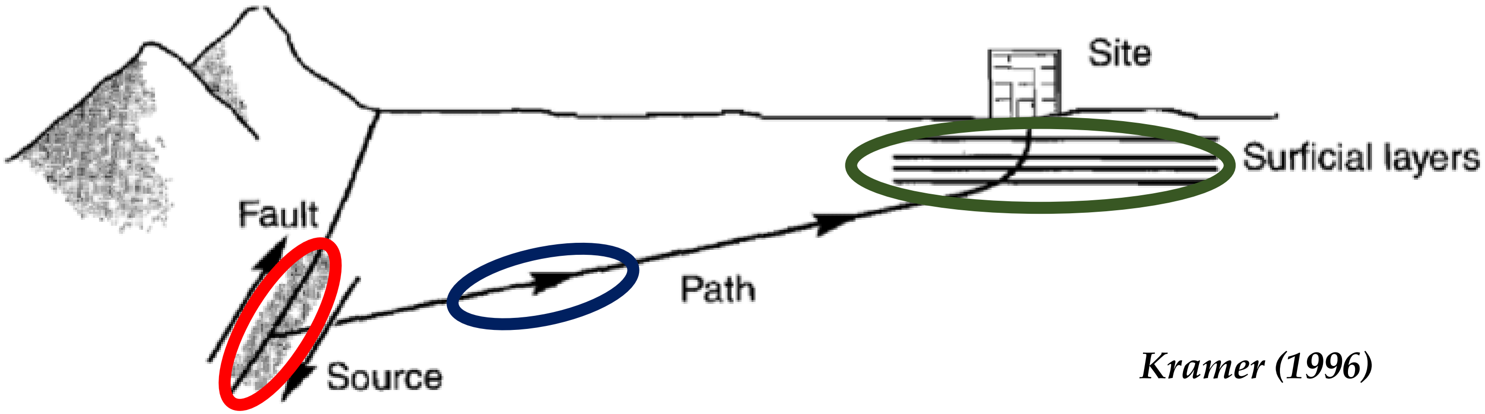
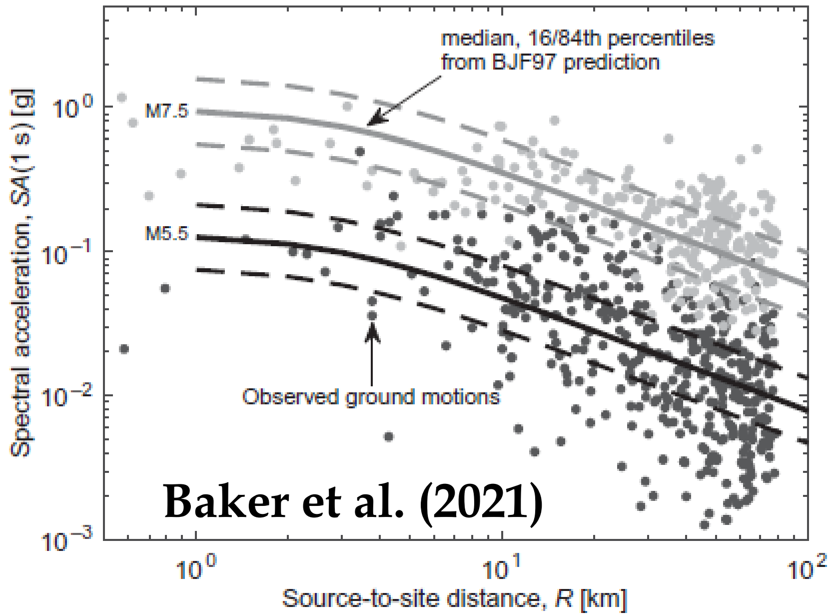
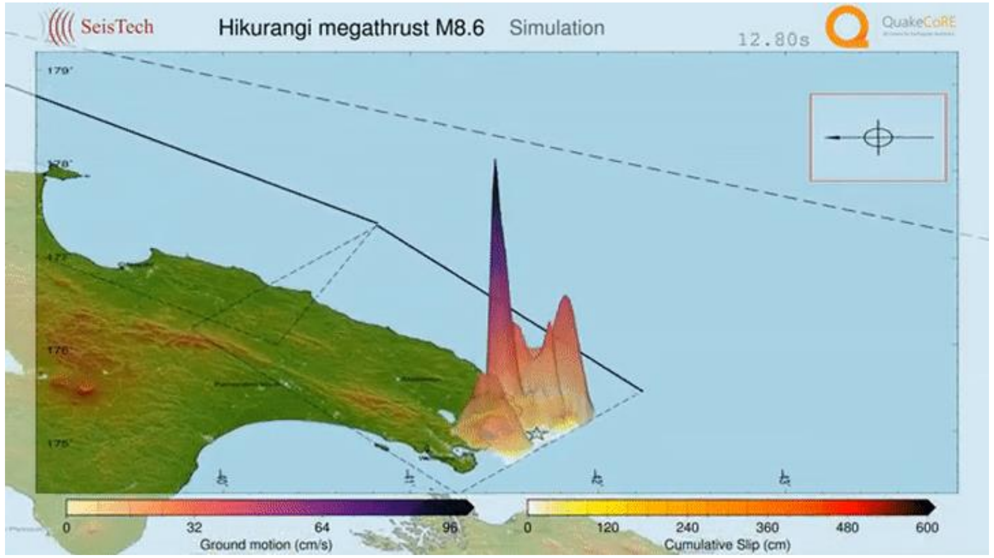
DT1 Meeting
28 March 2024

Ground motion modelling



Kramer (1996)

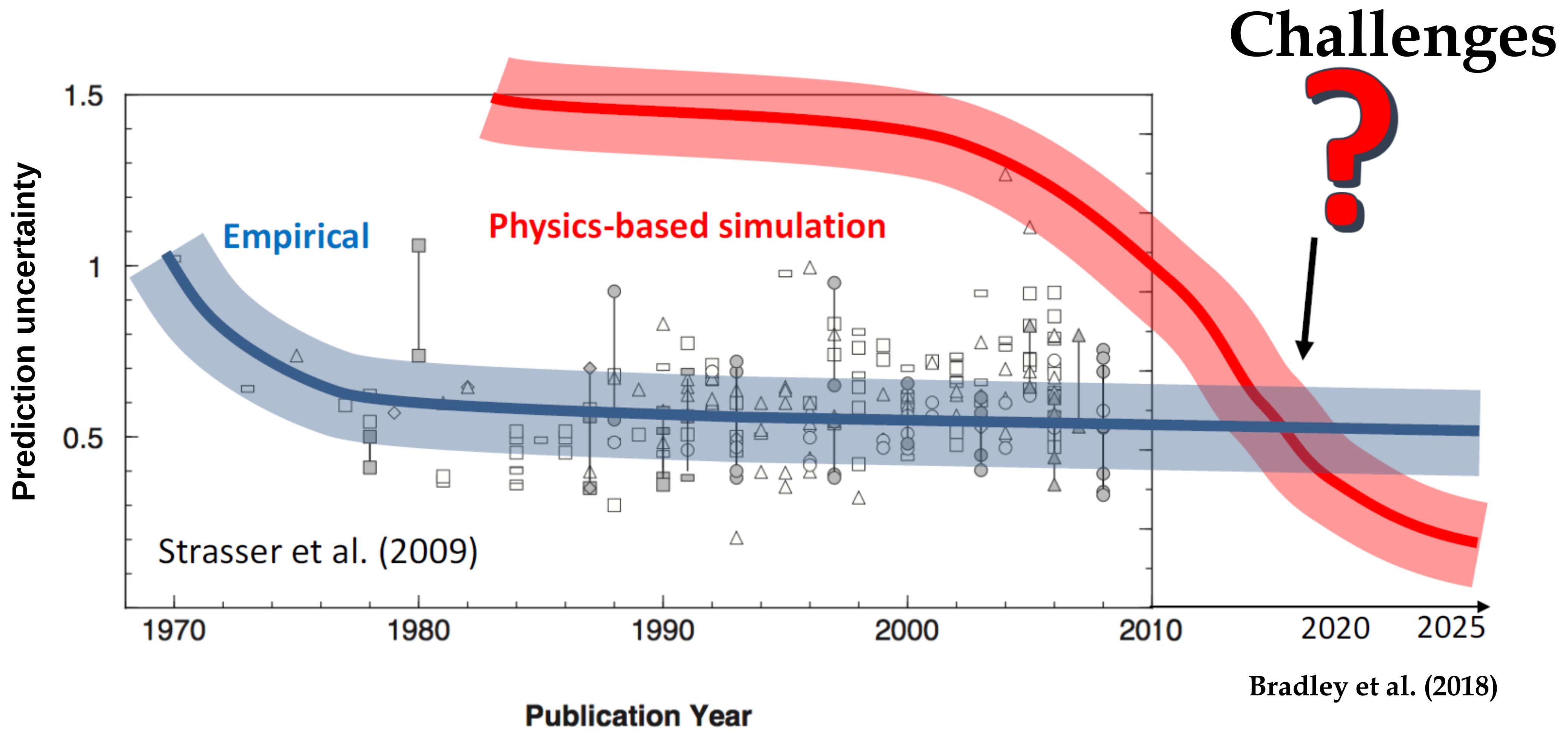




Empirical ground-motion models (GMMs)

Physics-based GMMs

Predictive capability over time



Validation

Validation study	Number of events	Magnitude range	Region
Lee et al. (2022)	479	$3.5 \leq M \leq 5.0$	New Zealand
Lee et al. (2020)	148	$3.5 \leq M \leq 5.0$	Canterbury (NZ)
de la Torre et al. (2020)	11	$4.7 \leq M \leq 7.1$	Christchurch (NZ)
Taborda et al. (2016)	30	$3.5 < M < 5.5$	Southern California
Maufroy et al. (2016)	19	$2.7 \leq M \leq 4.6$	Mygdonian basin (Greece)
Goulet et al. (2015)	12	$4.6 \leq M \leq 7.22$	US & Japan
Dreger et al. (2015)	7	$5.89 \leq M \leq 7.22$	US & Japan
Graves and Pitarka (2010)	4	$6.49 \leq M \leq 7.16$	California

Hybrid broadband ground motion simulations

Graves & Pitarka (2010, 2015, 2016) Methodology

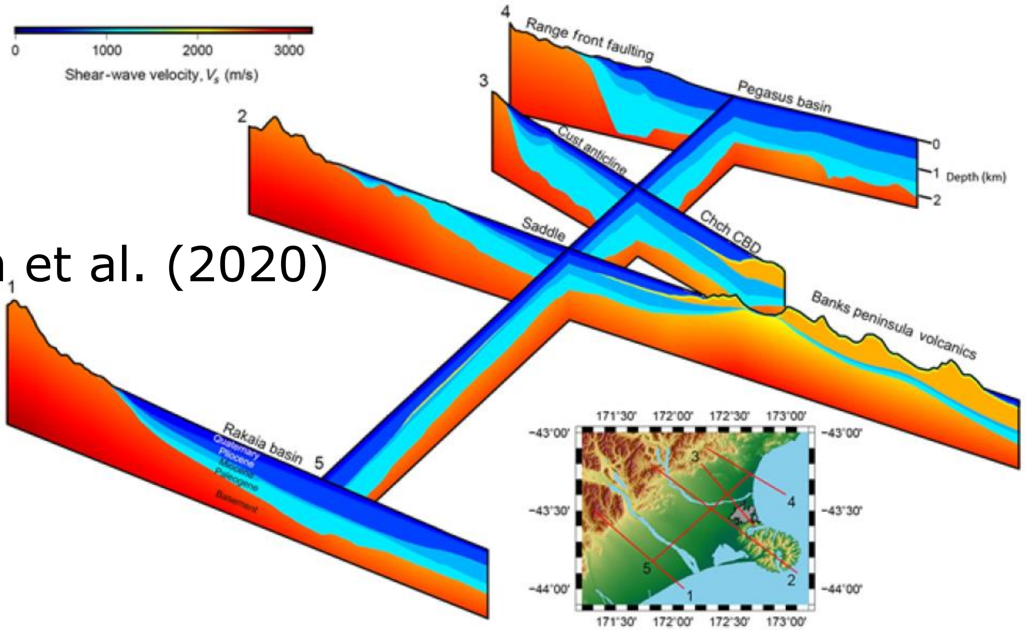
1 Hz transition

Low frequency (LF) ⟷ **High frequency (HF)**

3D wave propagation approach

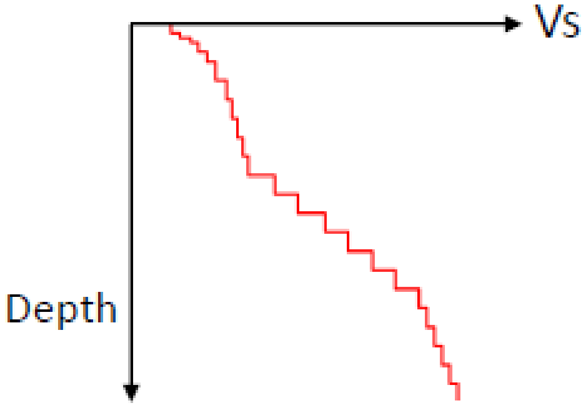
New Zealand Velocity Model (NZVM)

Thomson et al. (2020)



1D simplified physics

Regional V_S profile - crustal amplification



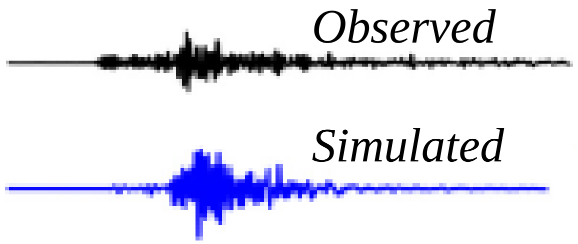
V_{S30} based site amplification adjustment (CB14) – shallow site amplification

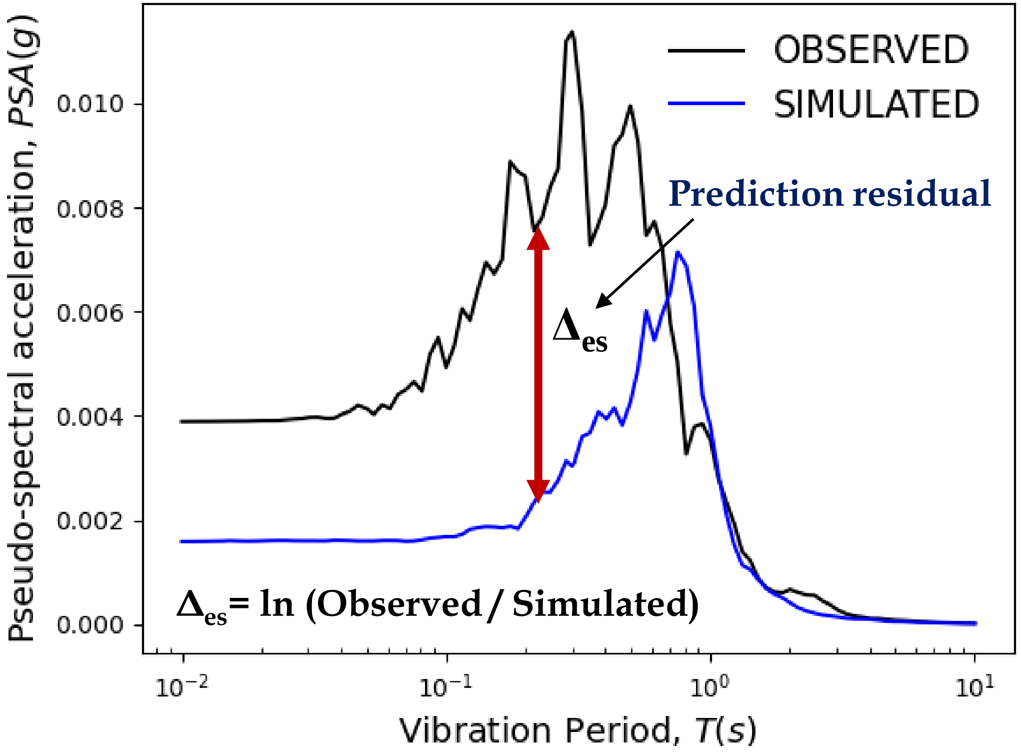
Grid spacing = 100 m

Minimum shear wave velocity = 500 m/s

Validation methodology: Residual analysis

TEPS (Te Papa Museum)





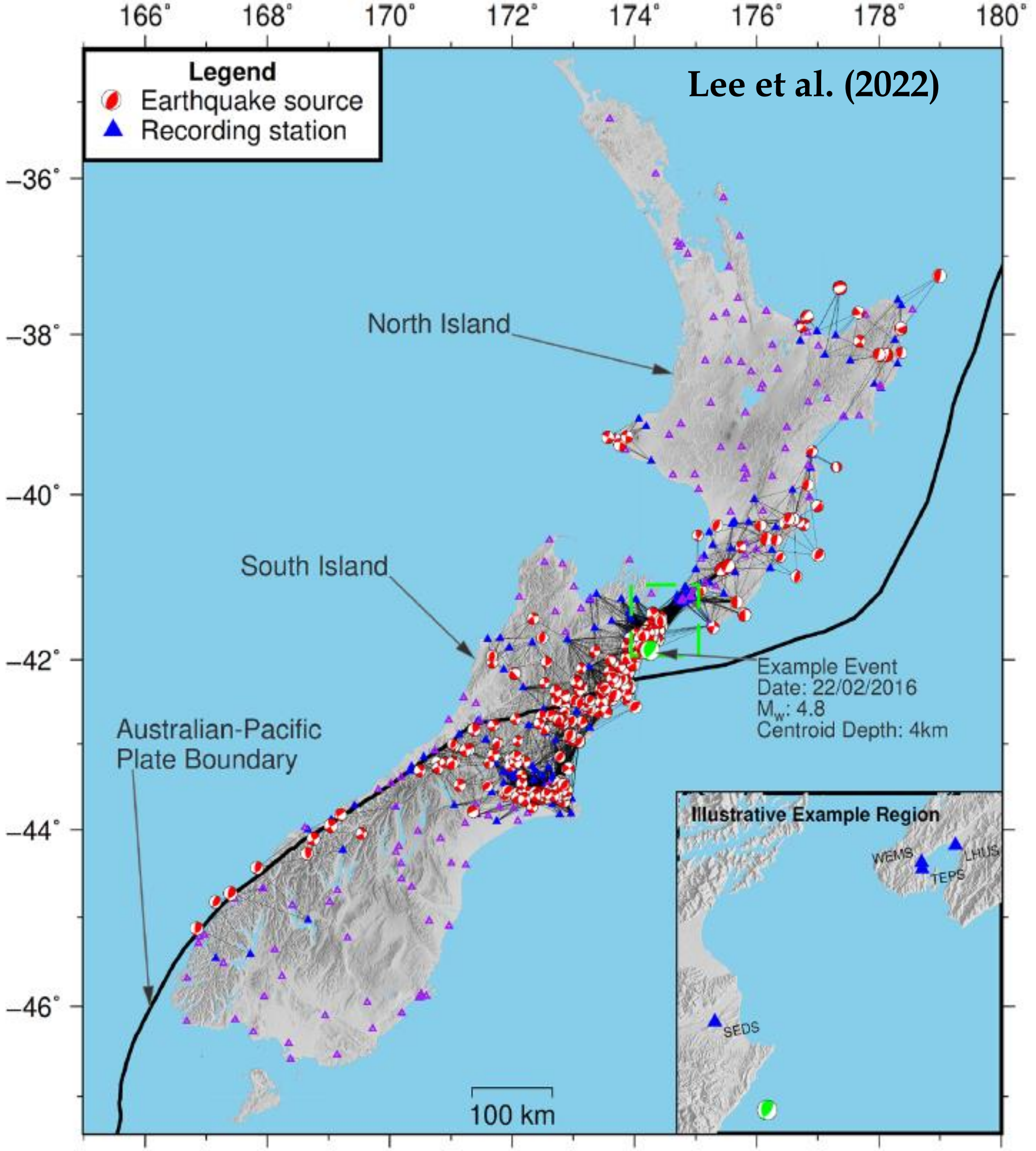
$$\Delta_{es} = a + \delta B_e + \boxed{\delta S2S_s} + \delta W^0_{es}$$

Model bias — ***Source term*** — ***Site term*** — ***Remaining residual***

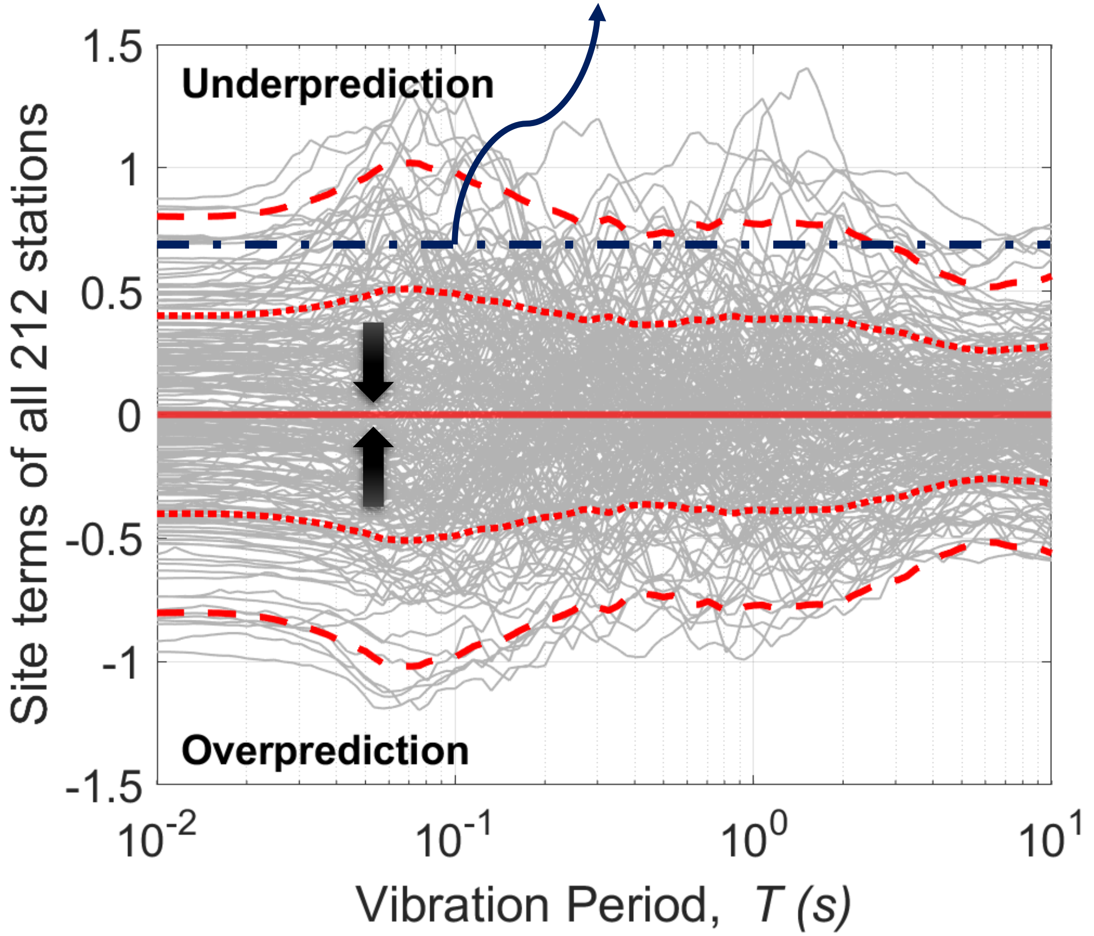
Mixed-effects regression

Observed and simulated ground motion dataset

479 small magnitude crustal events | **212** sites



exp(0.7) ~ A factor of 2!!!!

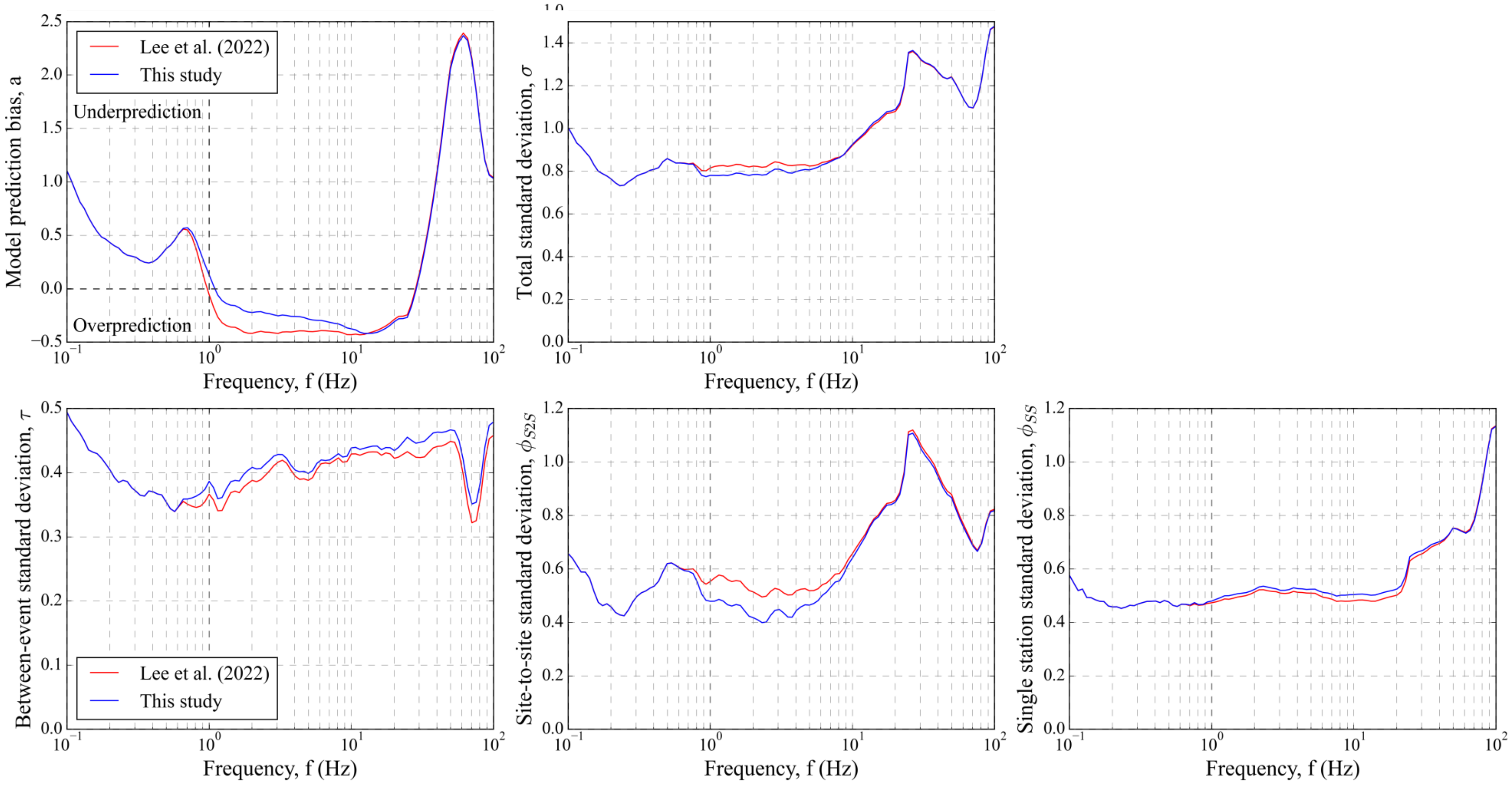


Different variety of site effects 'missing'

Research questions

- Which geographic *regions* and *sites* have predictions from simulations that significantly deviate from observations and why ?
- How can the *systematic site effects* be examined, which represents different 'missing' wave propagation phenomena governing site response?
  - Can an *optimum categorization* of sites be obtained which represents different types of site effects?
  - How much *uncertainty* in the site-to-site residuals is reduced using this categorization?
  - How can the *attributes* that *influence* these site residuals be identified ?
- Which *improvements* identified can be seamlessly integrated into the simulation workflow ?

V_{S30} model sensitivity - Overall results

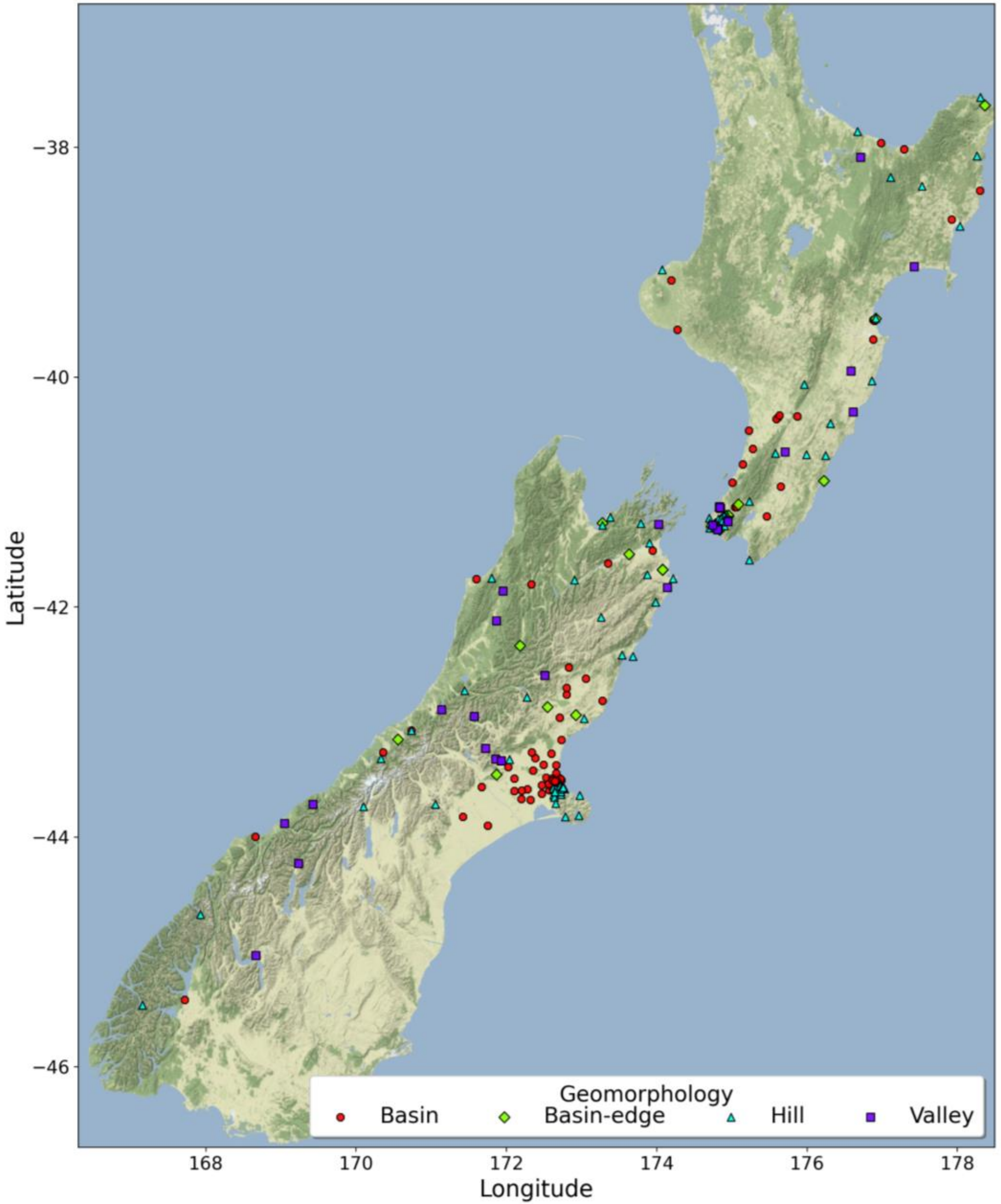


- V_{S30} is a significant contributor to model prediction bias and uncertainty
- Large portion of model uncertainty comes from different variety of site effects

Categorization of sites based on Geomorphology

Province	Des	no.	No. of sites
Basin	Basi		429
Basin edge	Alo		72
Valley	“Sm stru		172
Mountain/hill	Site sedi havi		329

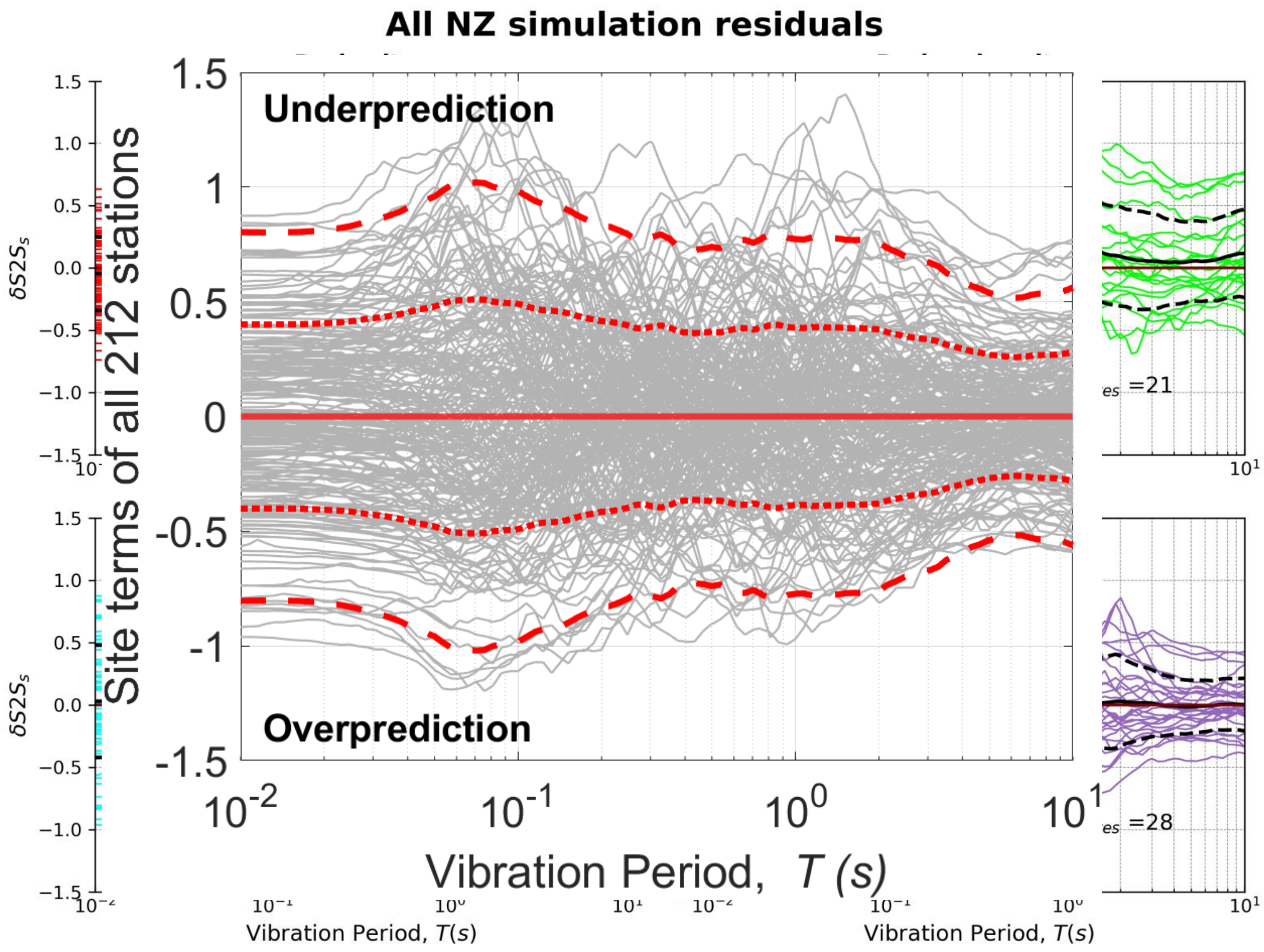
[a]Basin edge defined visu



Nweke et al. (2022)

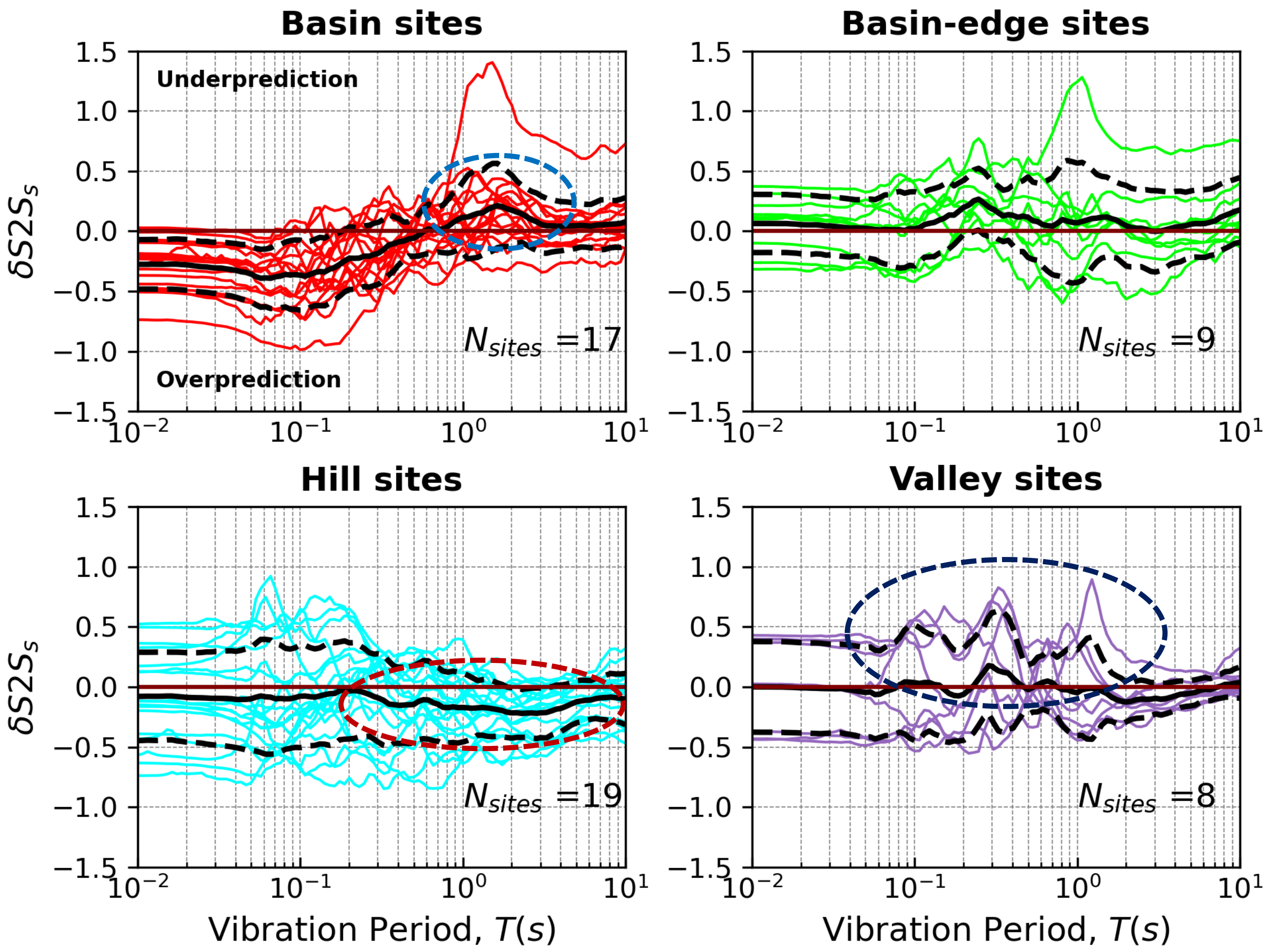
212 total sites
92 basin (43.4%)
21 basin-edge (9.9%)
71 hill (33.5%)
28 valley (13.2%)

Examination 1: Geomorphological categorization



Examination 1: Wellington region

- **Underpredicted** in the moderate periods and overpredicted at short periods
- Basin model **not refined**



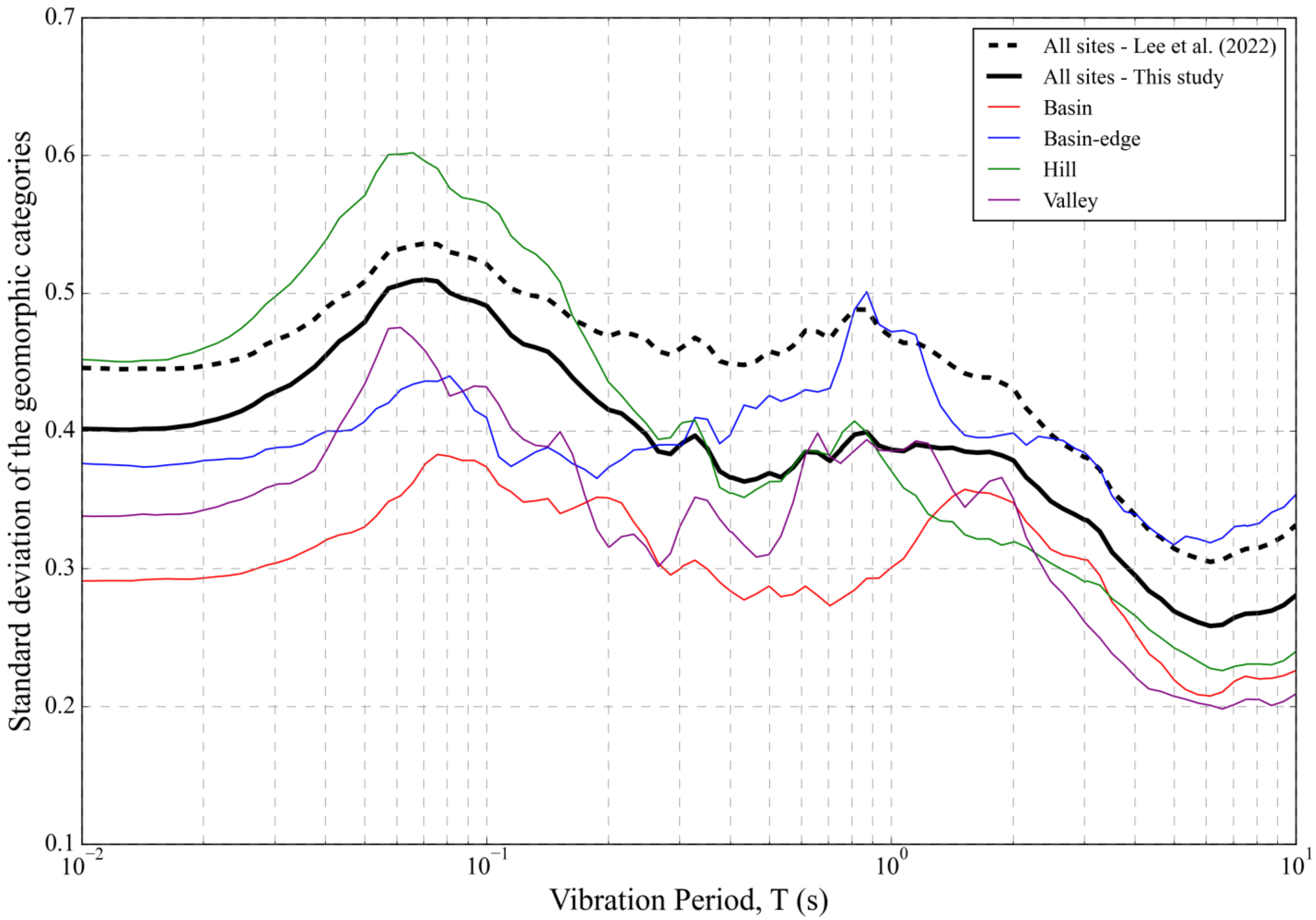
- Complex mechanism of these sites isn't yet understood

- Variability among hill sites

- Valleys are **small basins;** don't **show up** in simulations
- **Narrow period** range with a large residual
- High std. dev.

Tiwari et al. (2023)

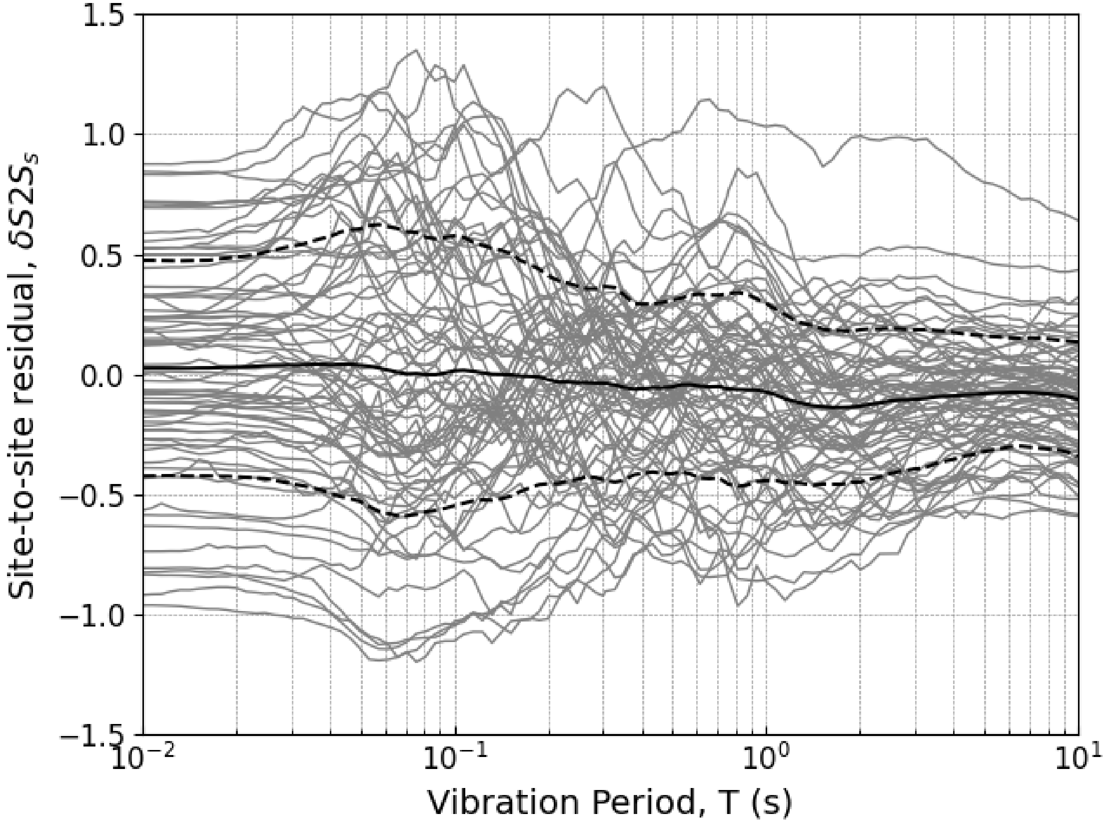
Examination 1: Geomorphological categorization

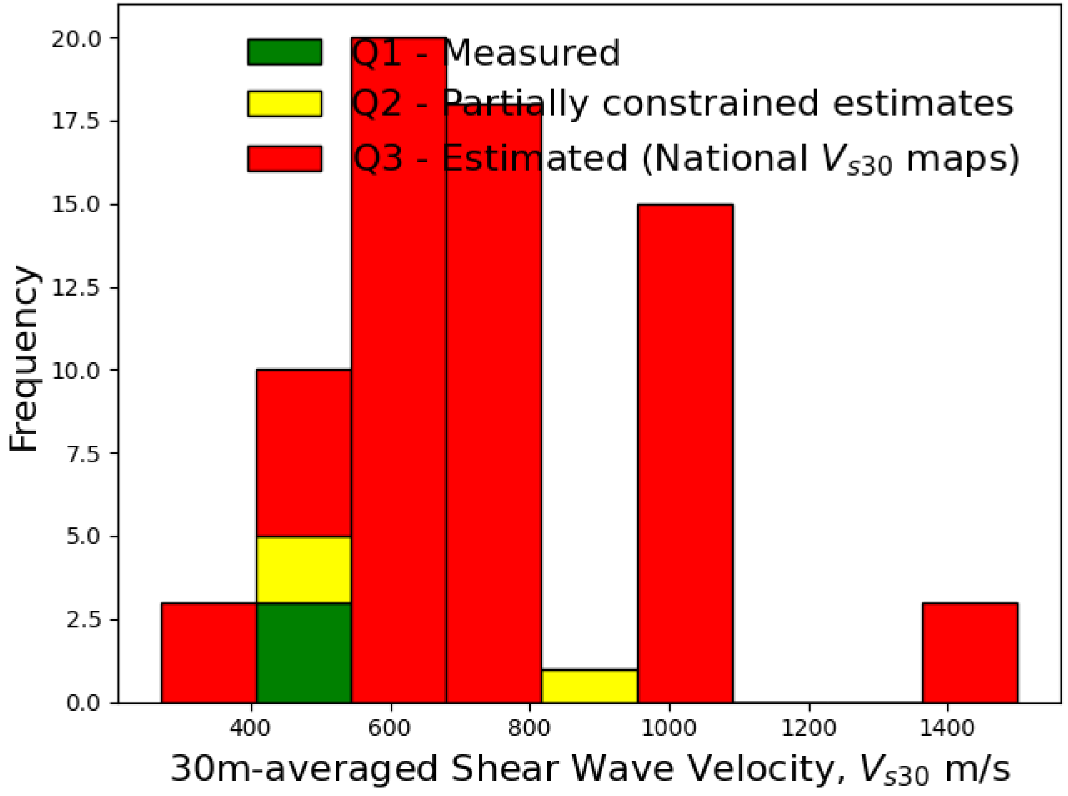


Hill/stiff rock sites contribute the most uncertainty to the current state of site response modelling

Site characterization of hill sites

70 hill sites

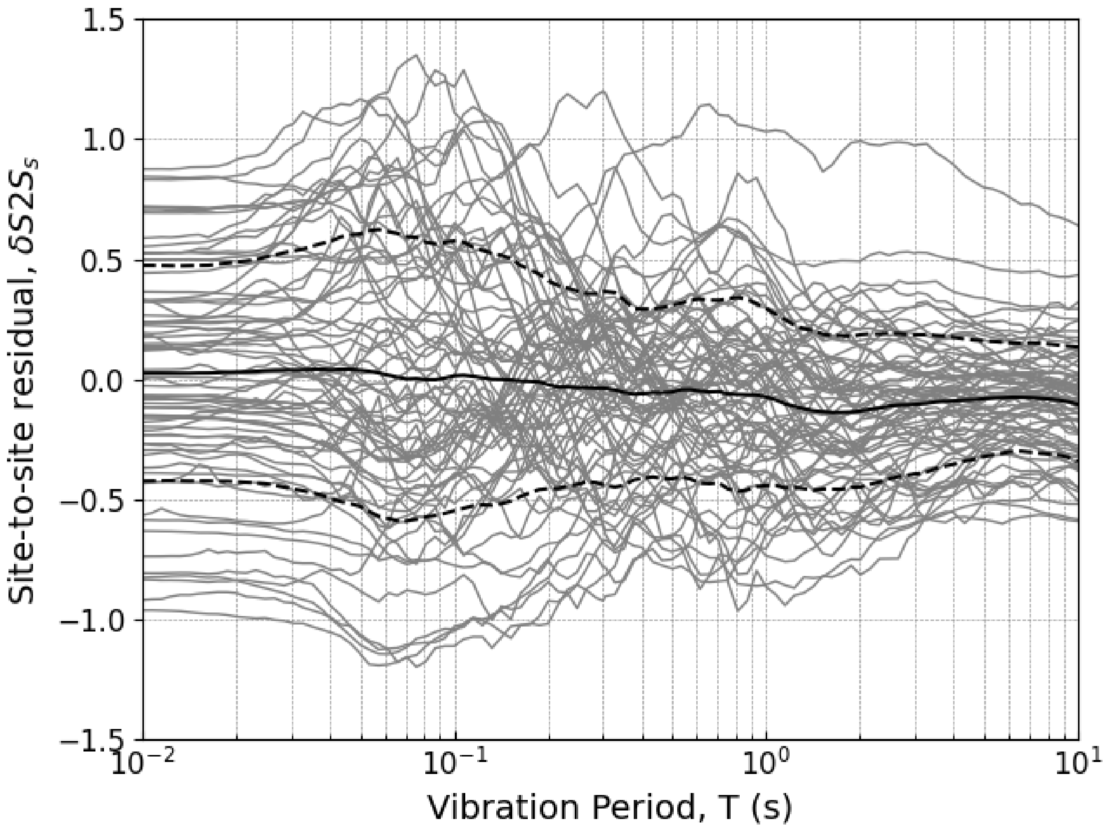


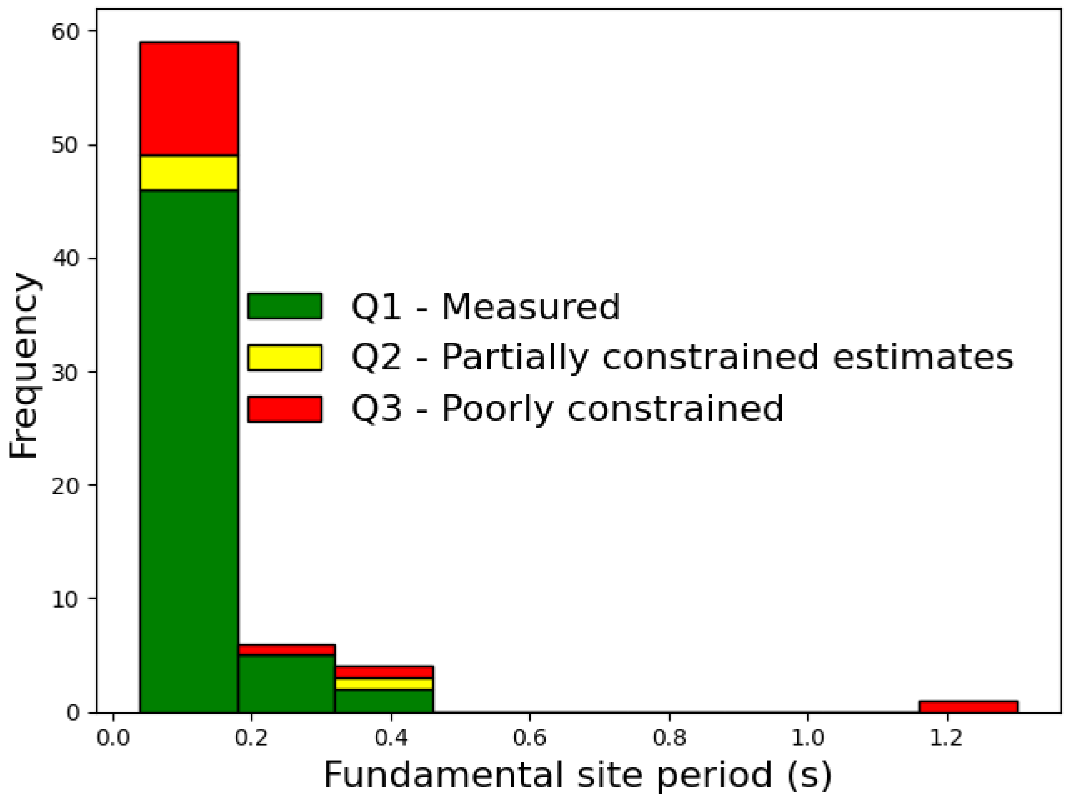


- Poor V_{S30} estimates at hill sites of NZ
- Large variability among V_{S30} estimates

Site characterization of hill sites

70 hill sites

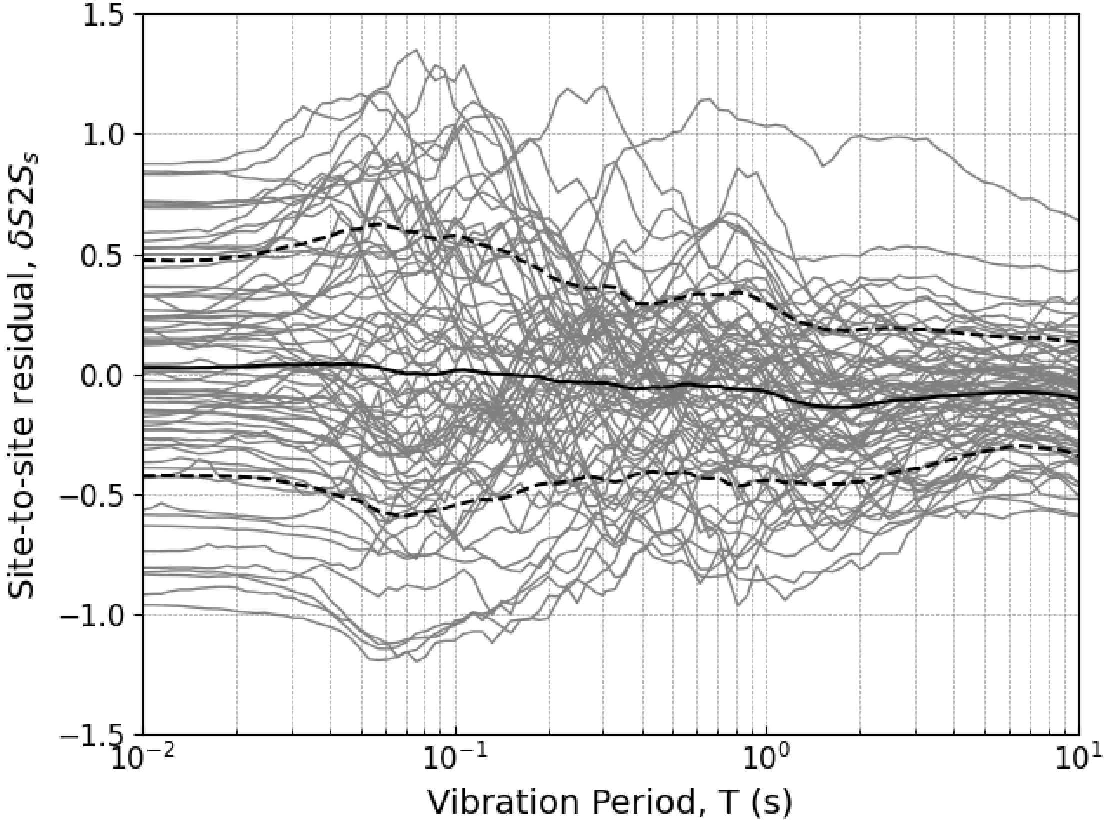


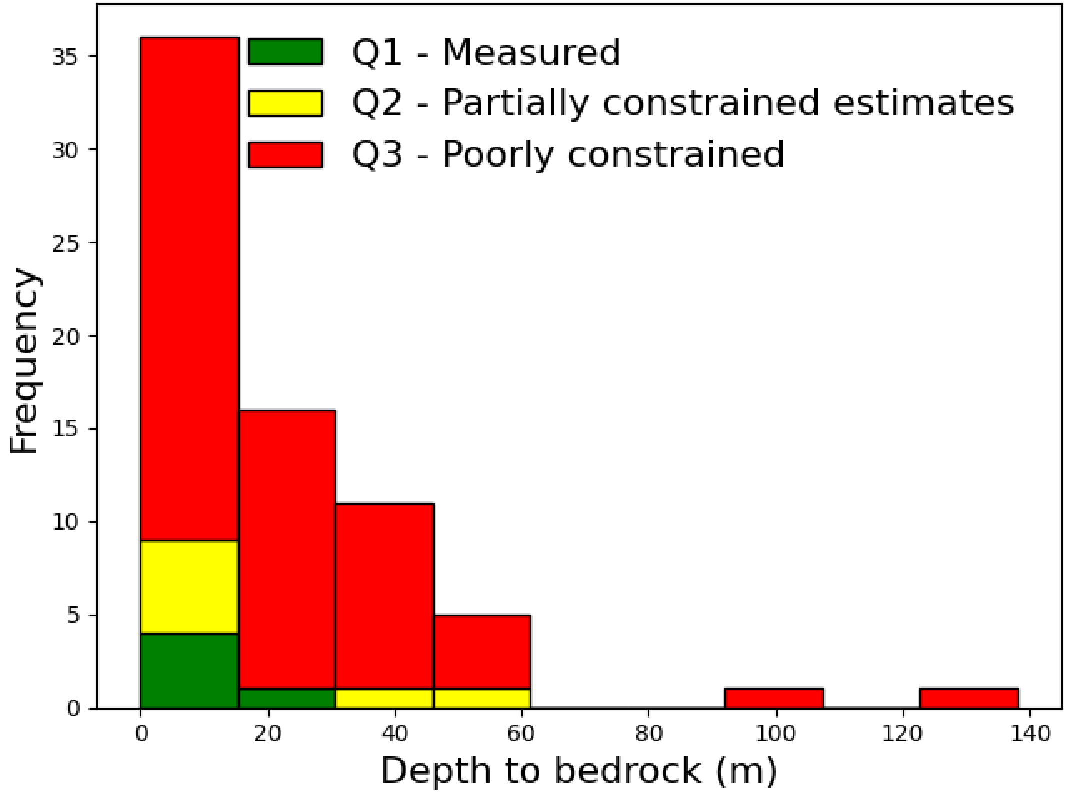


Well constrained T_0 estimates at hill sites of NZ

Site characterization of hill sites

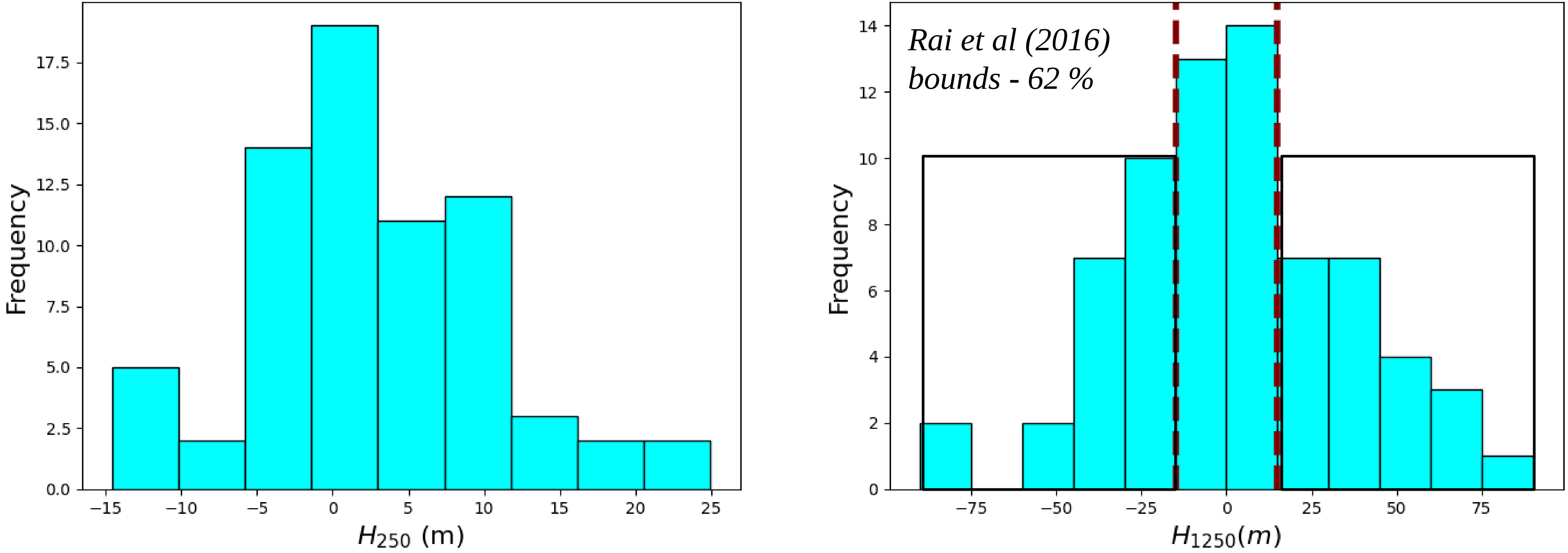
70 hill sites





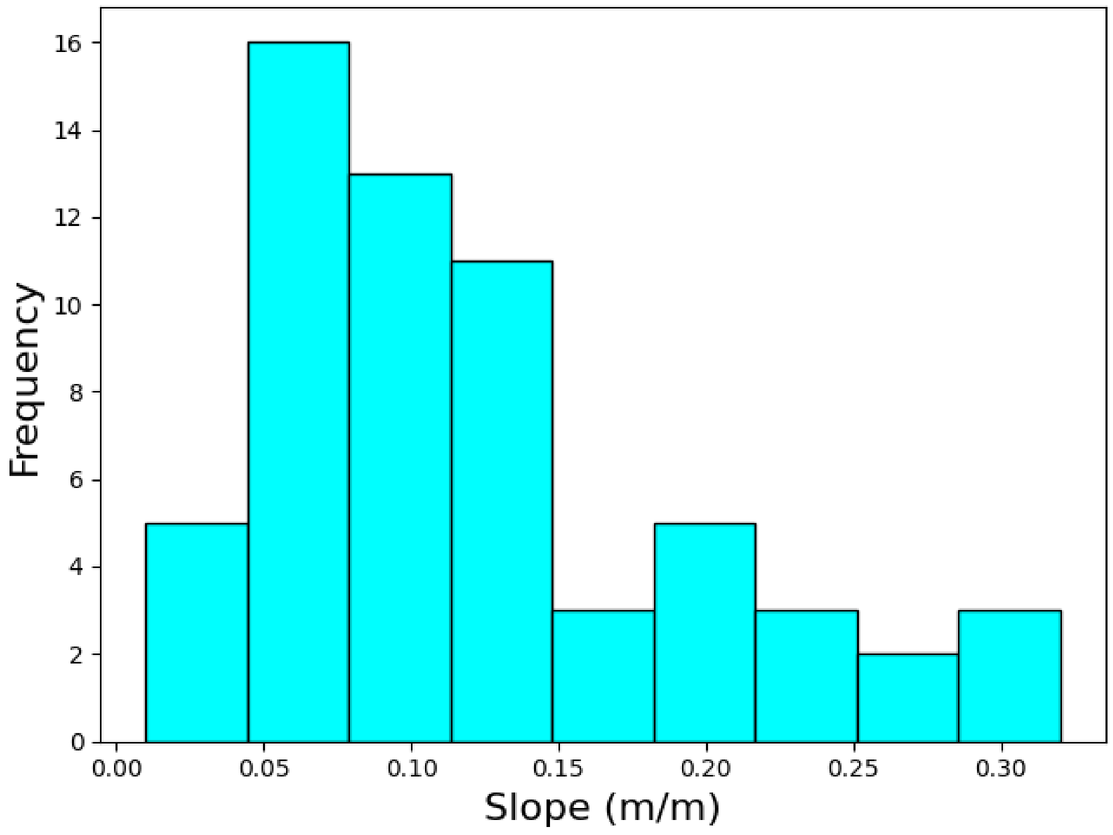
Poor $Z_{1.0}$ estimates at hill sites of NZ

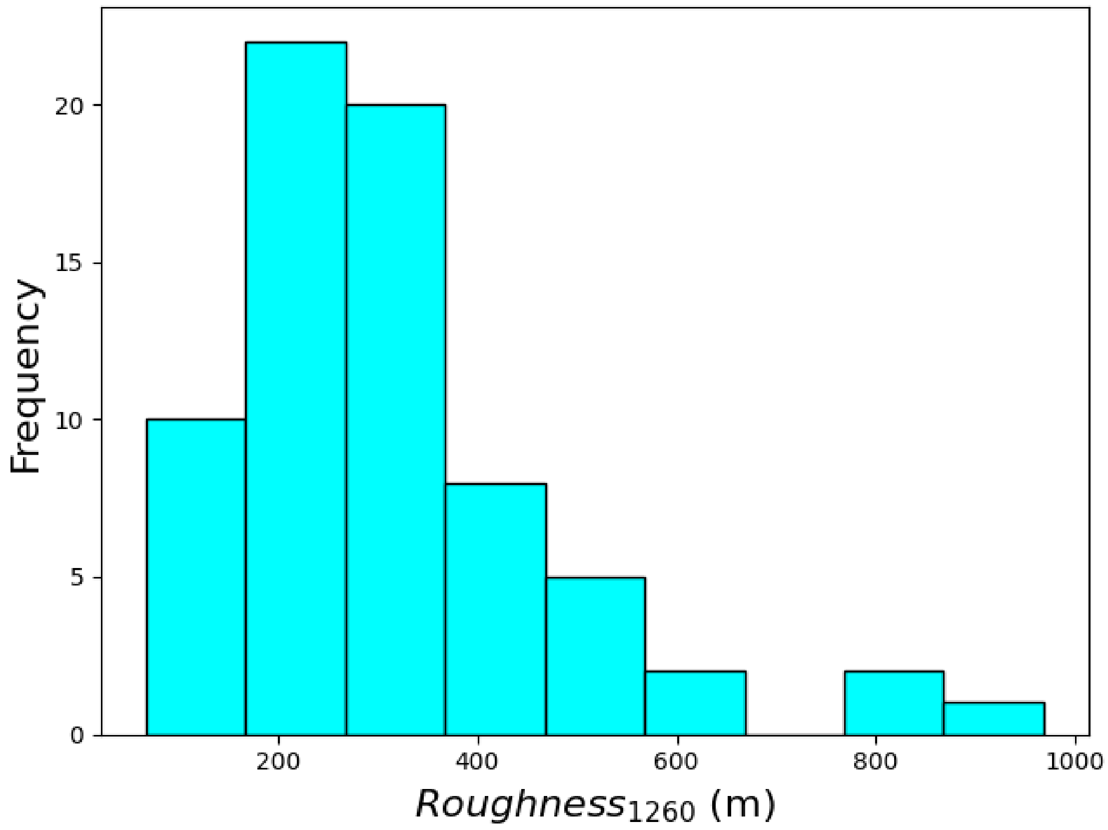
Site characterization of hill sites



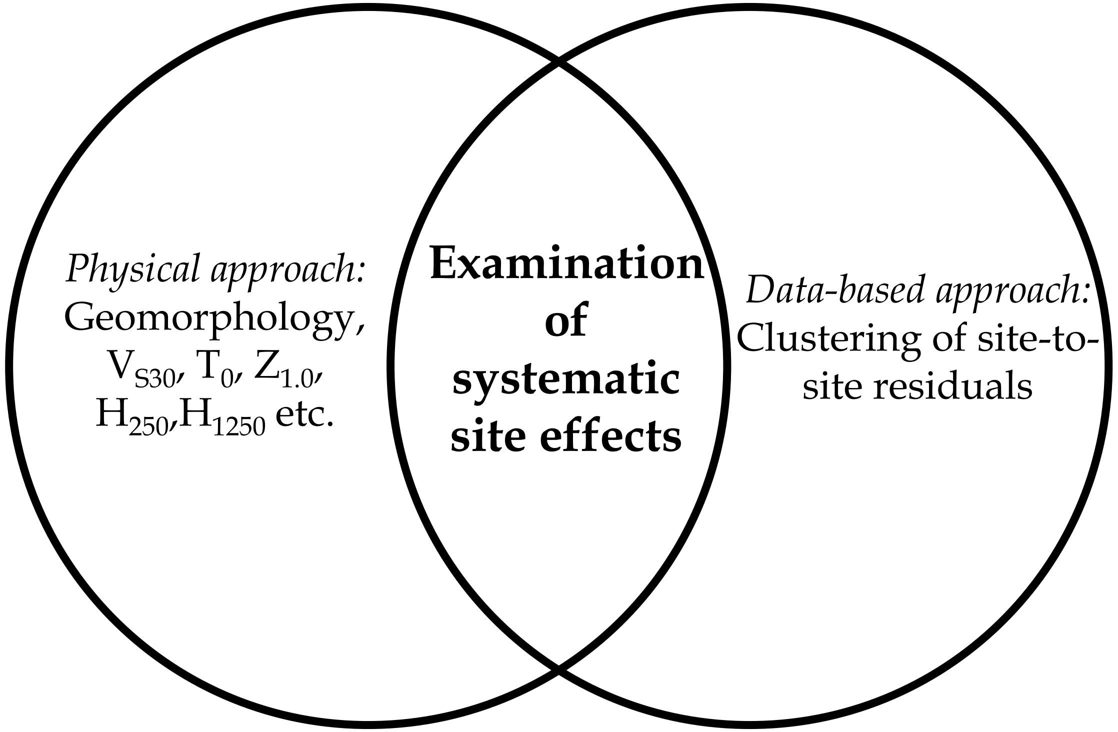
Large variability among the relative elevation parameters

Site characterization of hill sites

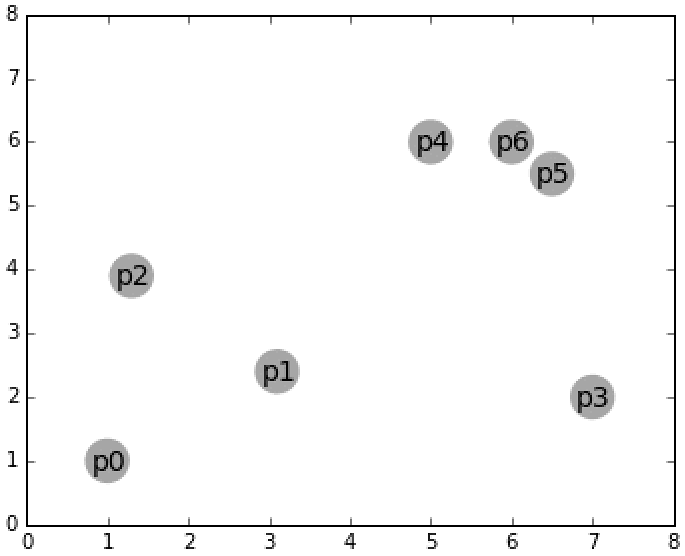




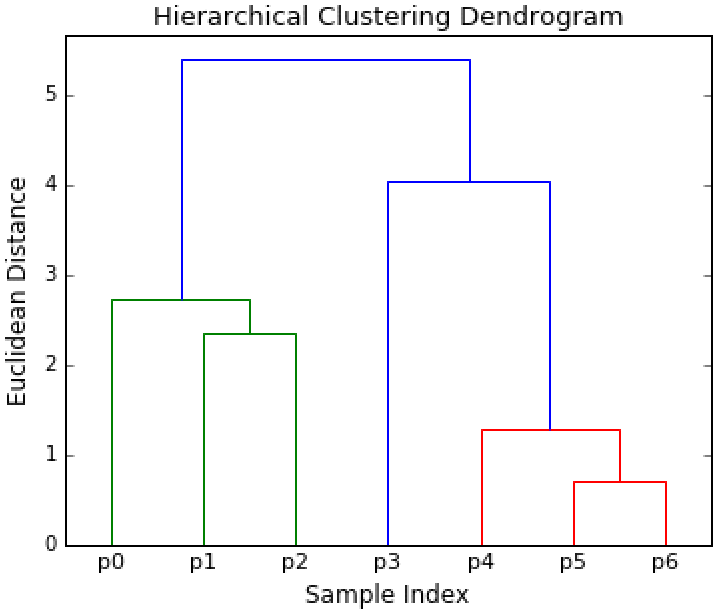
Large variability among most site characterization parameters of hill sites



Physical approach:
Geomorphology, V_{S30}, T_0, $Z_{1.0}$, H_{250},H_{1250} etc.
Examination of systematic site effects
Data-based approach:
Clustering of site-to-site residuals

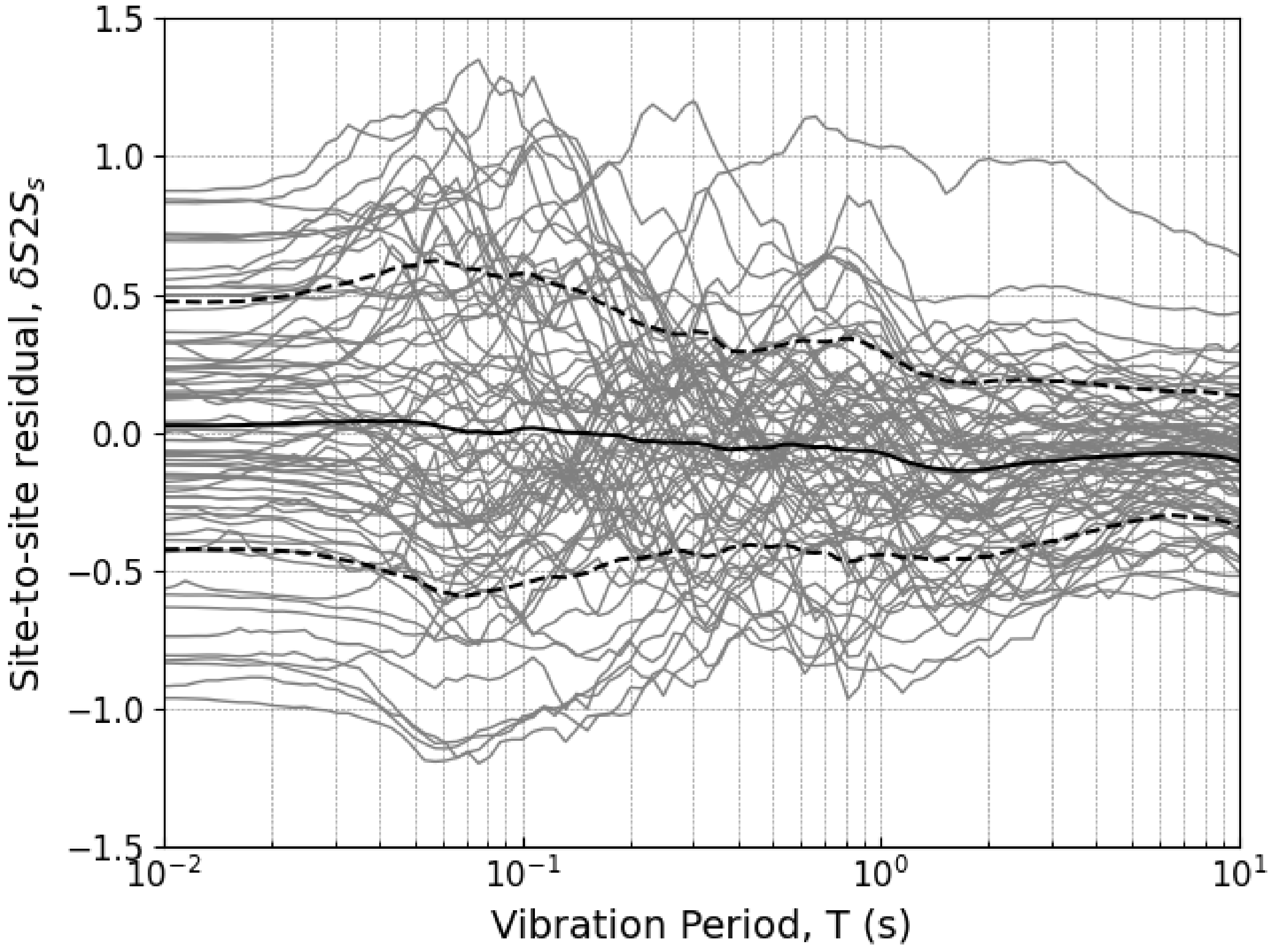


p0
p1
p2
p3
p4
p5
p6
0 1 2 3 4 5 6 7 8



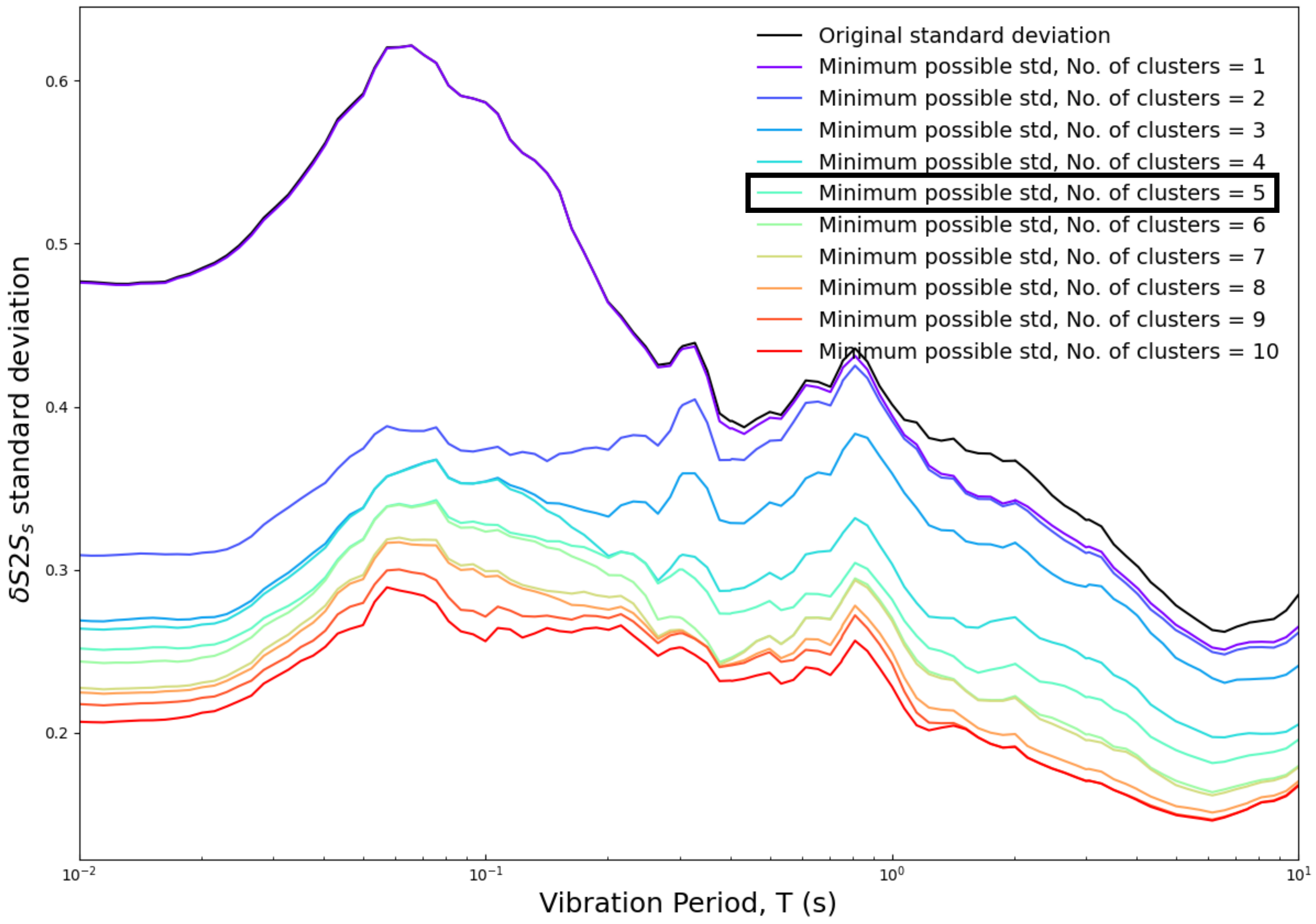
Hierarchical Clustering Dendrogram
Euclidean Distance
Sample Index
p0 p1 p2 p3 p4 p5 p6
0 1 2 3 4 5

Variability reduction among hill sites: Hierarchical Clustering



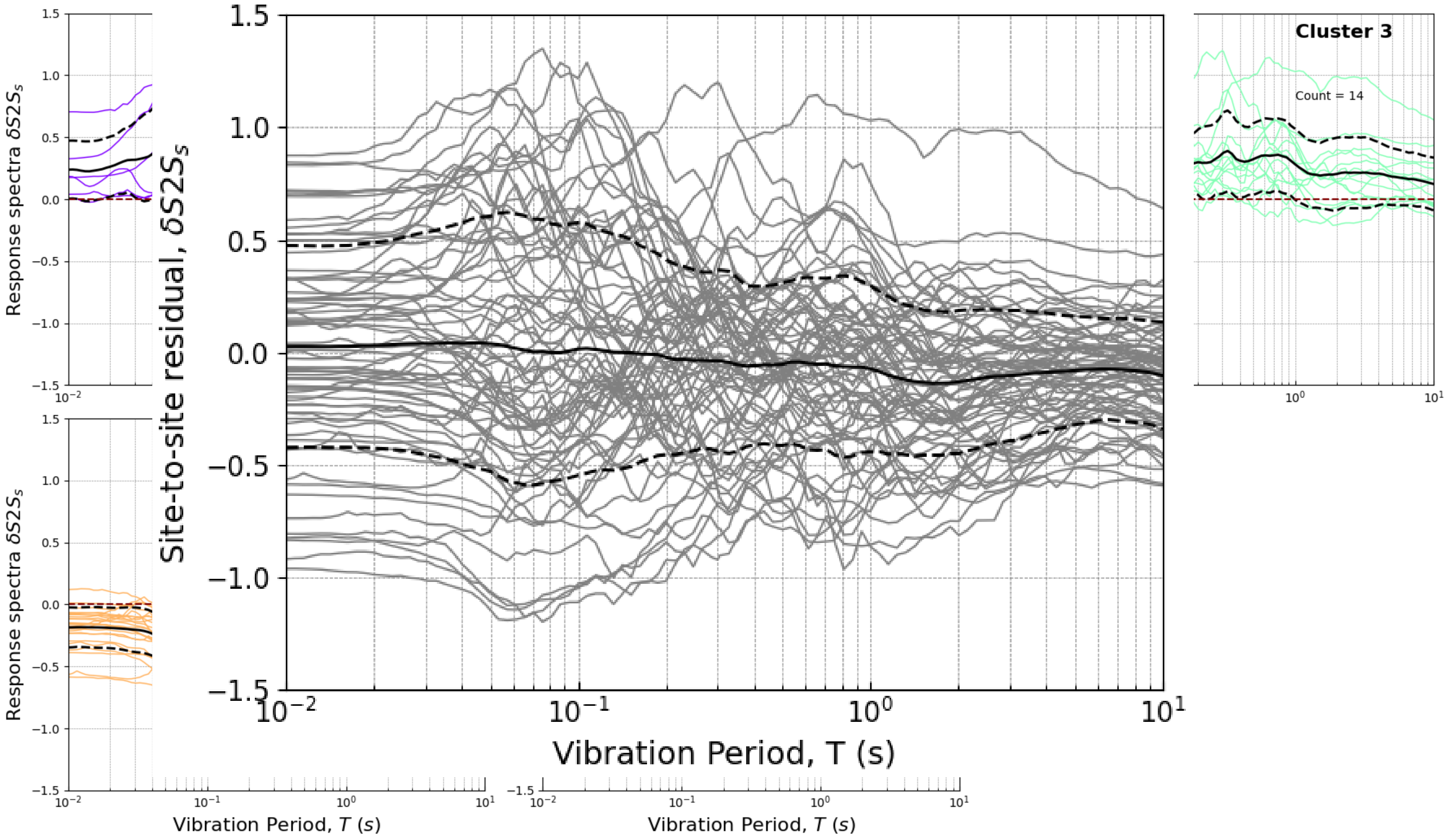
Objective: Understand different types of hill sites in order to reduce variability among them for ground motion prediction

Variability reduction among hill sites: Hierarchical Clustering

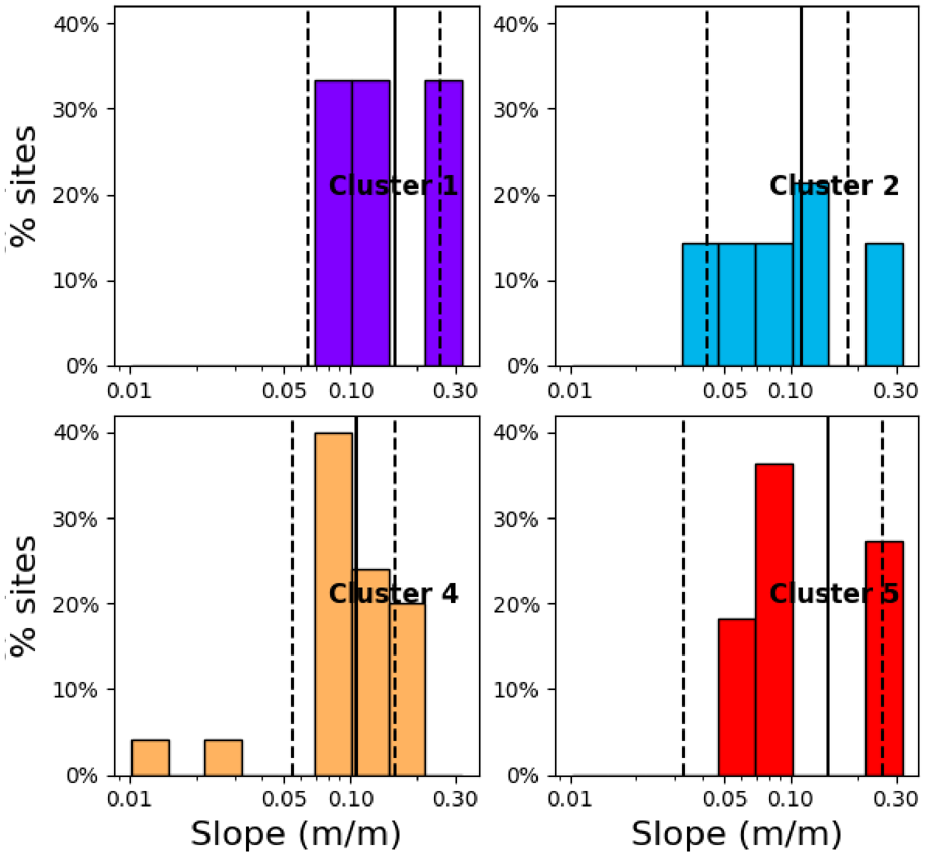


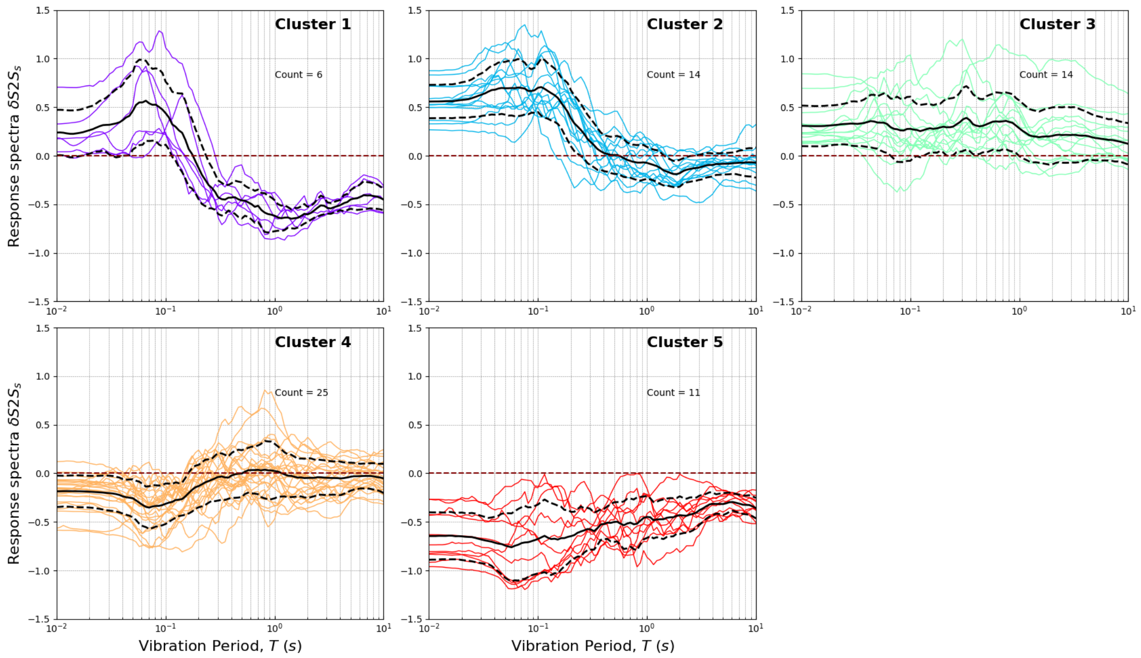
- Adjusted residual of a site = Original residual – Mean of the assigned cluster
- Minimum possible standard deviation = Std(Adjusted residuals)

Variability reduction among hill sites: Hierarchical Clustering



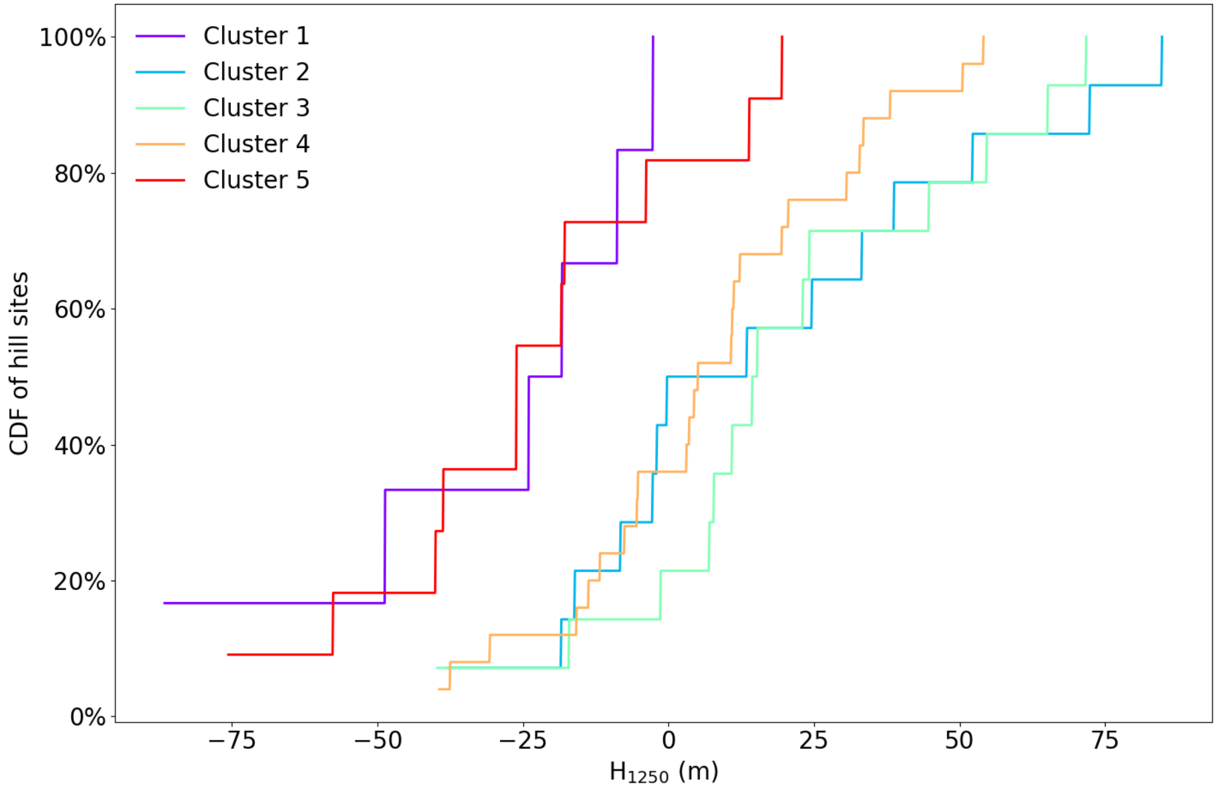
Variability reduction among hill sites: Hierarchical Clustering

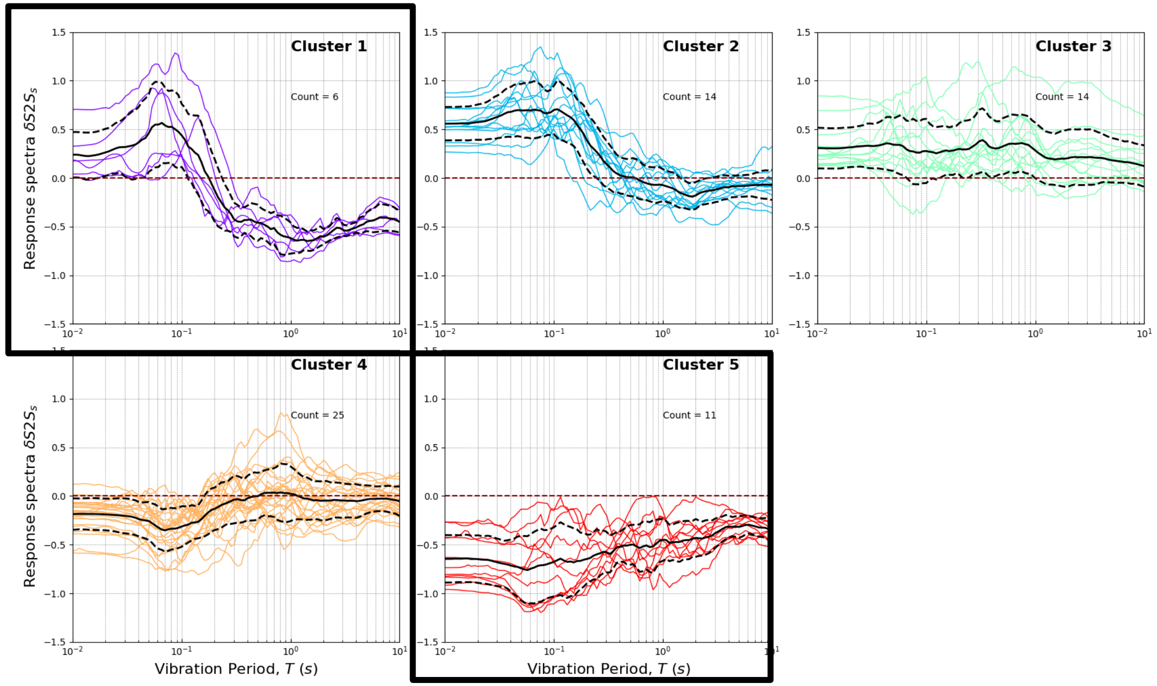




- V_{S30}, $Z_{1.0}$, $\delta Z_{1.0}$, Slope – a poor differentiator between clusters
  - T_0 – Clusters 1 and 2 have more weathered hill sites

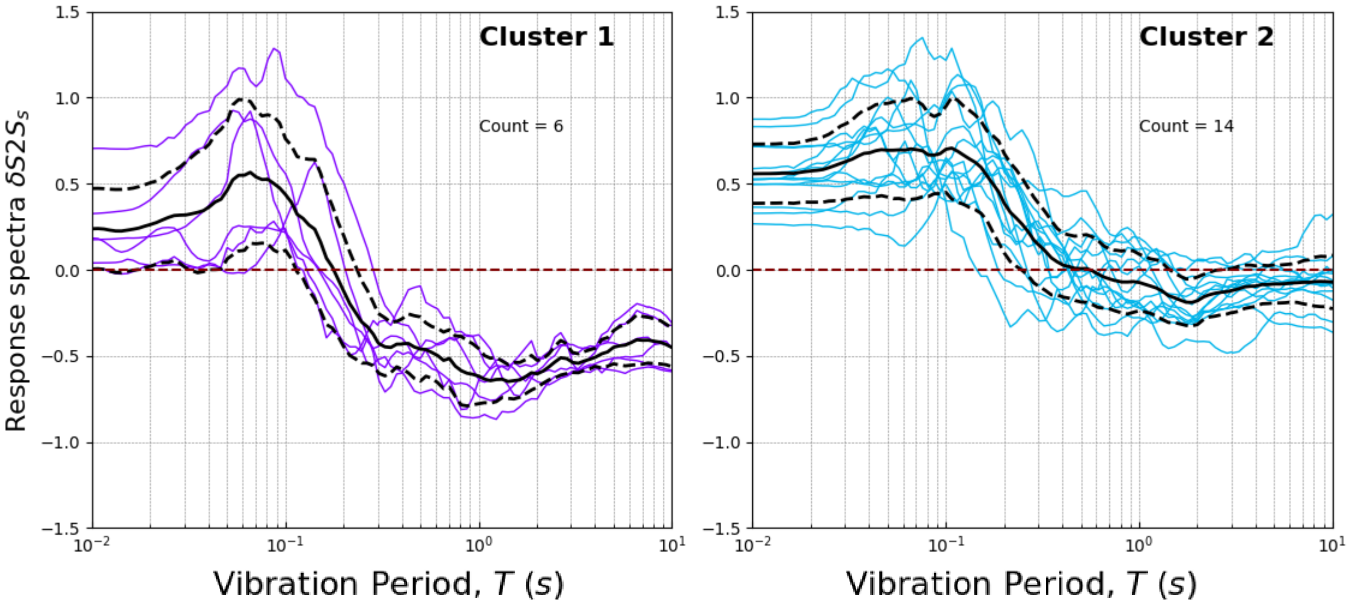
Variability reduction among hill sites: Hierarchical Clustering





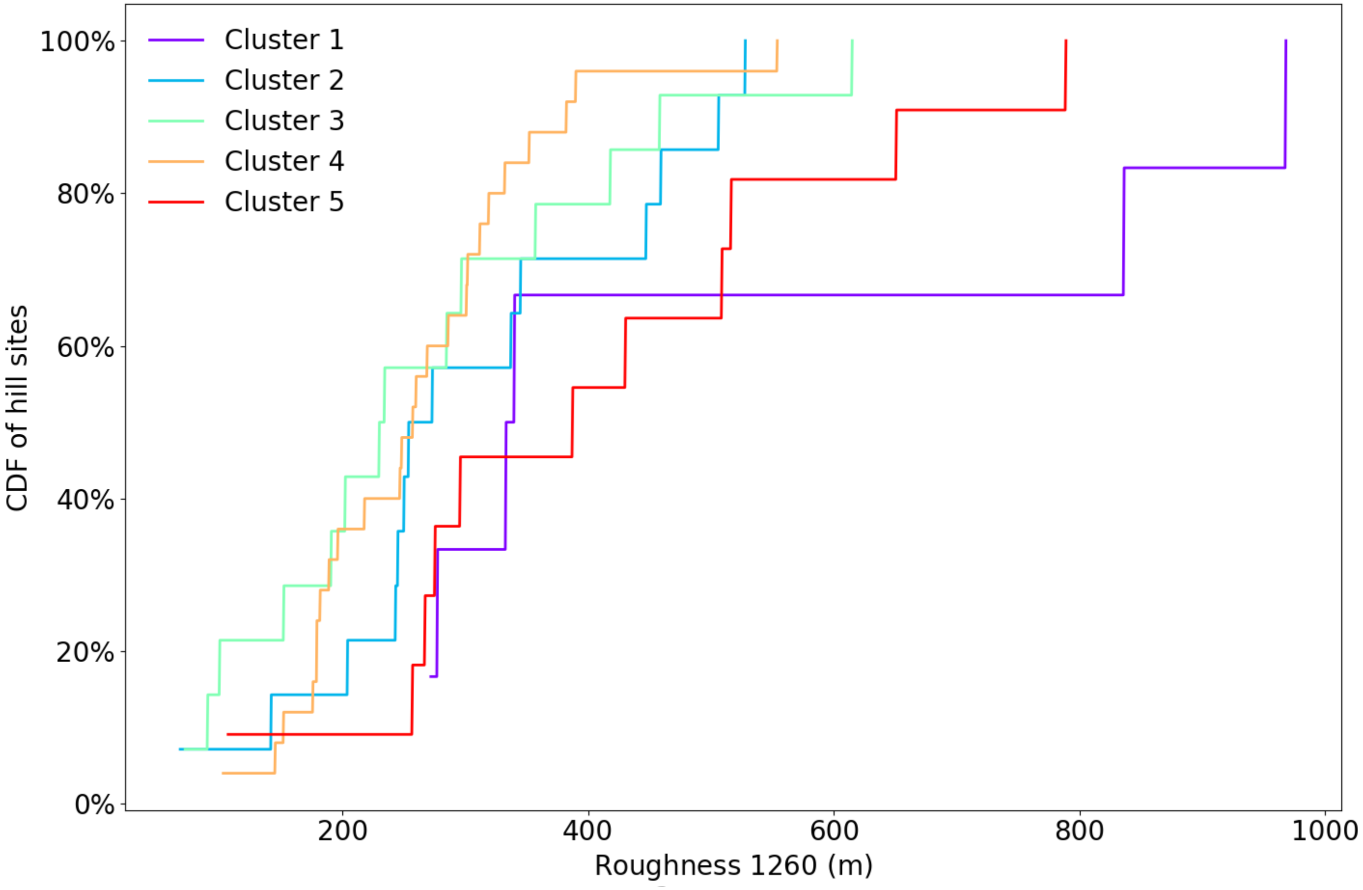
- Cluster 1 and Cluster 5 have negative values of relative elevation parameters – Lying near or on the toe of a hill
- Difference seen easier at higher scale i.e., H_{1250}

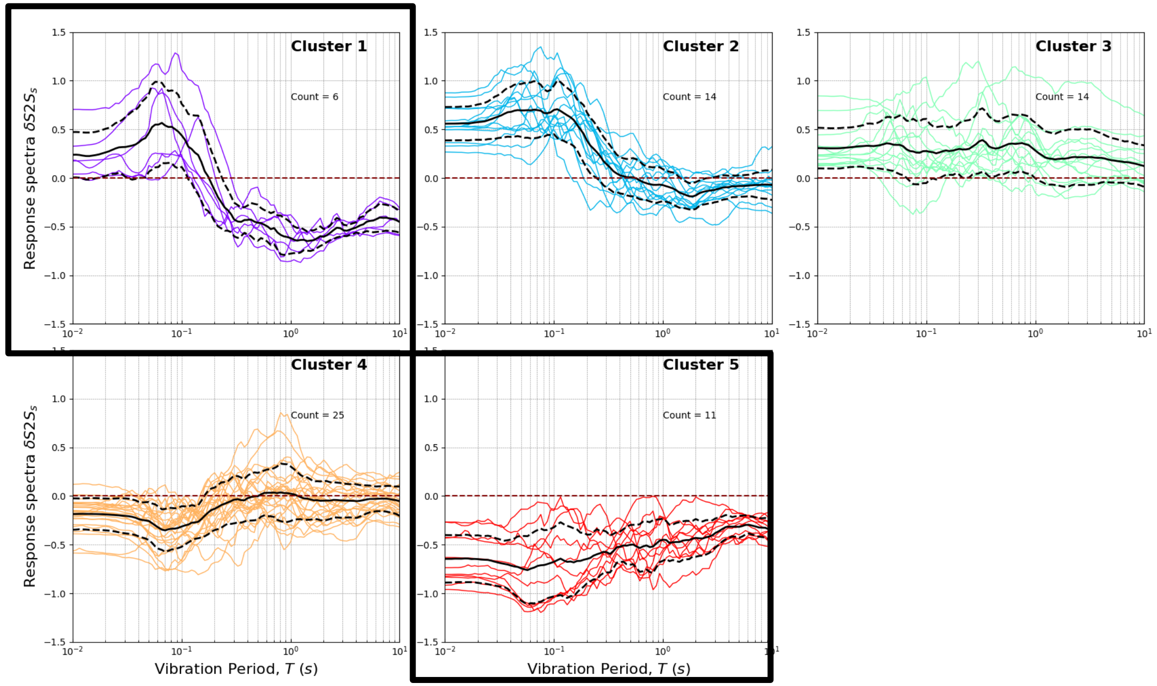
Variability reduction among hill sites: Hierarchical Clustering



- Cluster 1 and Cluster 2 difference – Possible topographic deamplification at longer periods not captured in simulations
- Cluster 2 have ~60 % Port Hills sites where BPV volcanics subregion is modelled (above travel-time tomography-based velocity model)

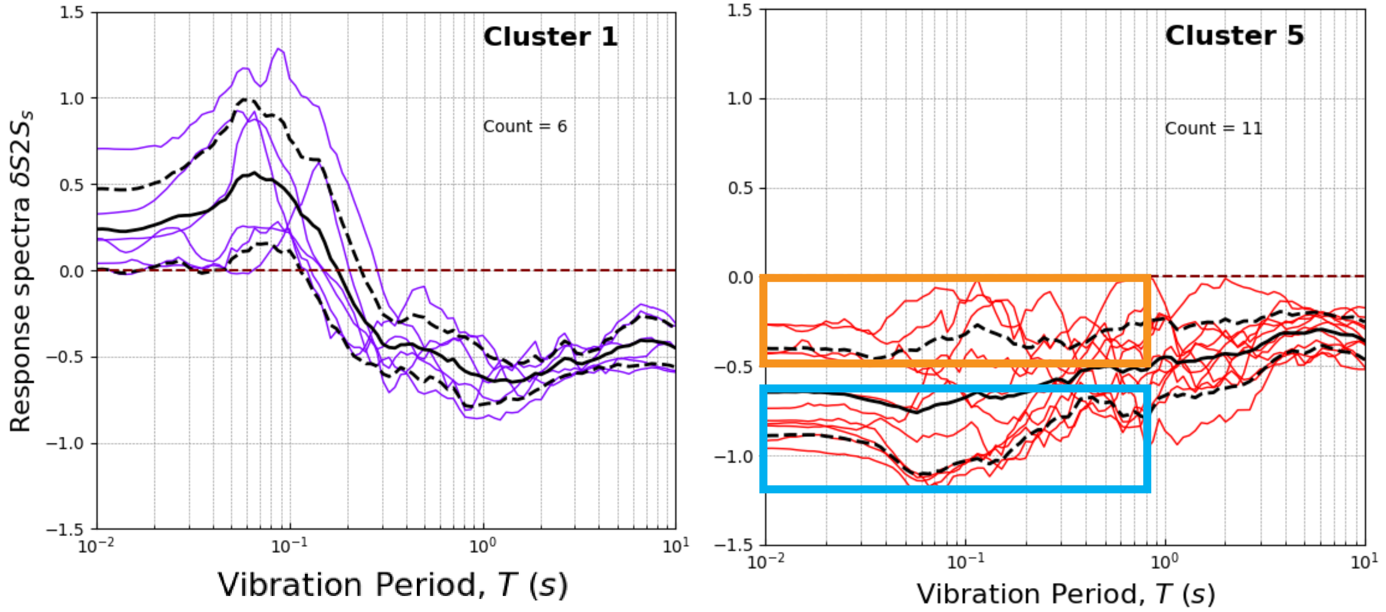
Variability reduction among hill sites: Hierarchical Clustering





- Cluster 1 and Cluster 5 have roughness higher than other clusters – difference seen easier at higher scales
- Roughness is correlated with high site terms (or site amplification from literature)
- Cluster 1 sites are generally ‘rougher’ at higher scales, Cluster 5 sites are generally ‘rougher’ at lower scales

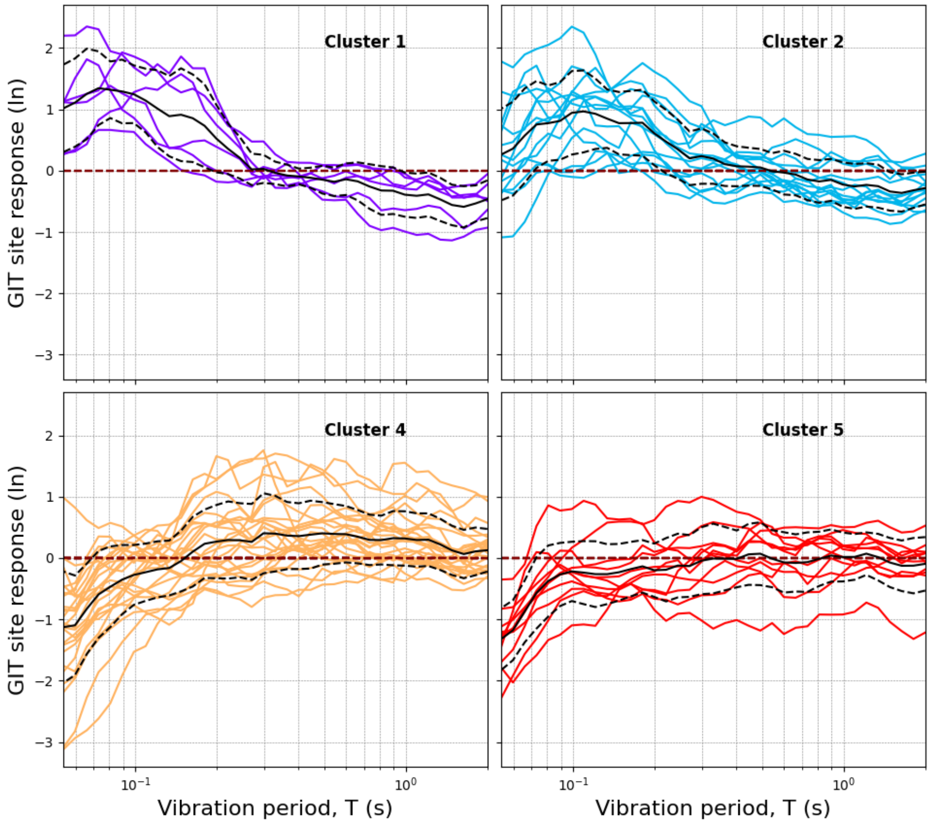
Variability reduction among hill sites: Hierarchical Clustering



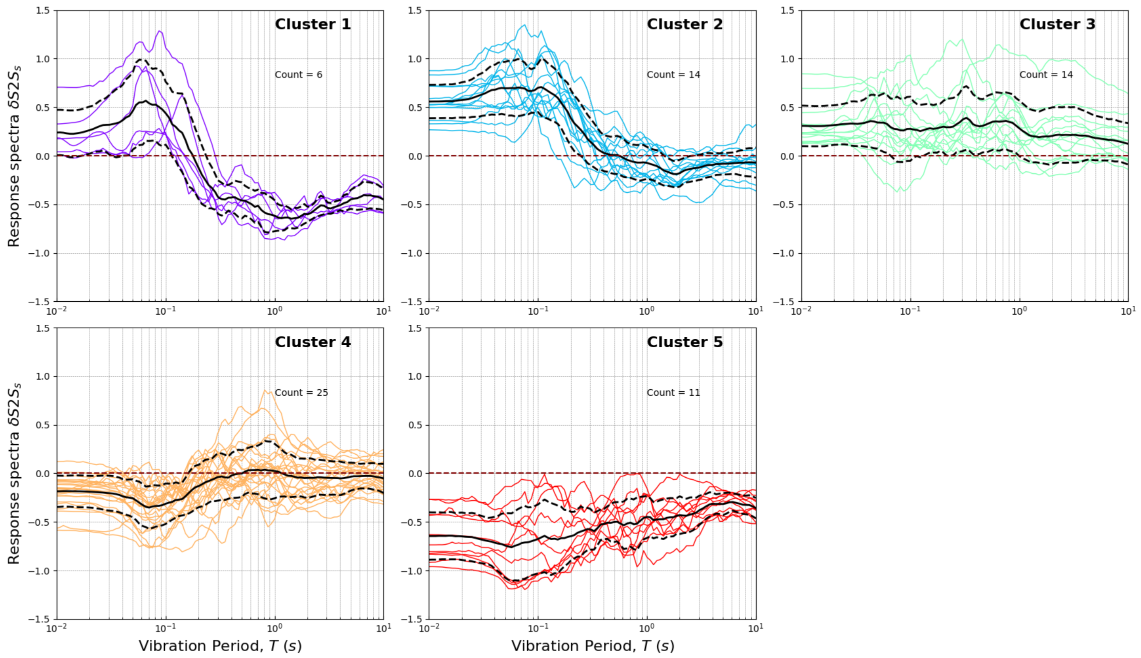
- Cluster 1 and 5 both lie on or near the toe of hill
- Cluster 1 sites are more weathered – Thin impedance contrast uncaptured by V_{S30} based prediction
- Cluster 5 can be further subdivided – the "less overpredicted" sites are rougher than "more overpredicted" sites
- Cluster 5 sites have low site response in general

Variability reduction among hill sites: Hierarchical Clustering

Zhu et al. (2024)



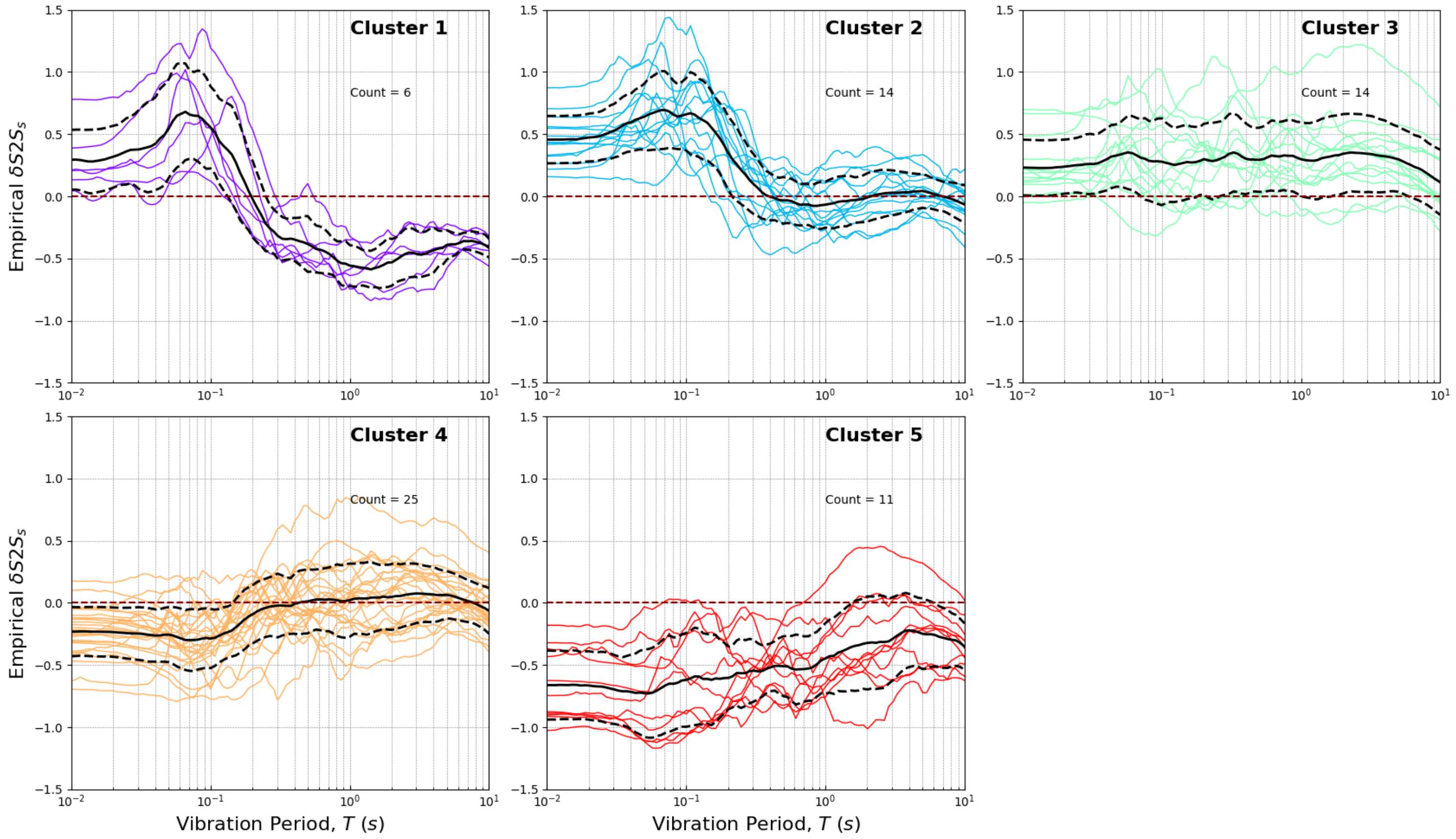
Current study – Physics based simulations



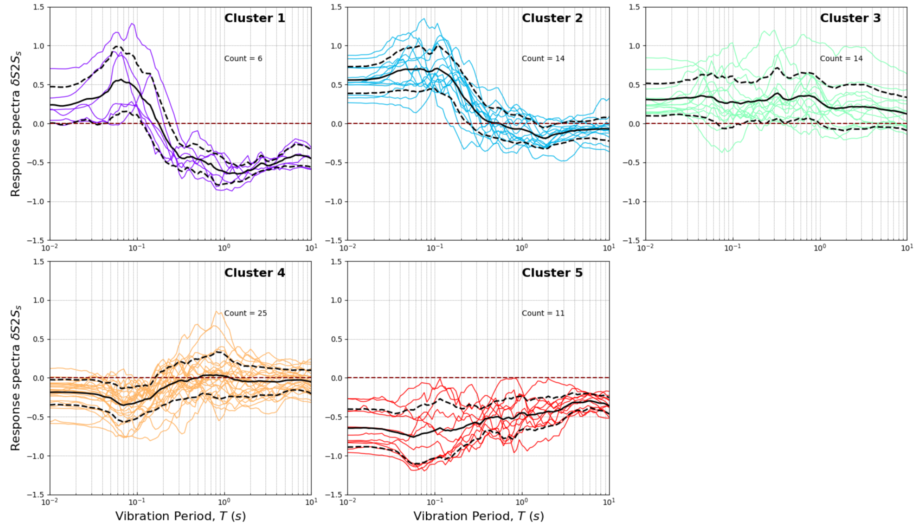
- Clusters 1, 2, and 5 have high/low site responses and only partially predicted well by V_{S30} based prediction
- Clusters 3 and 4 are generally appropriately predicted

Variability reduction among hill sites: Hierarchical Clustering

Bradley (2013) GMM empirical residuals

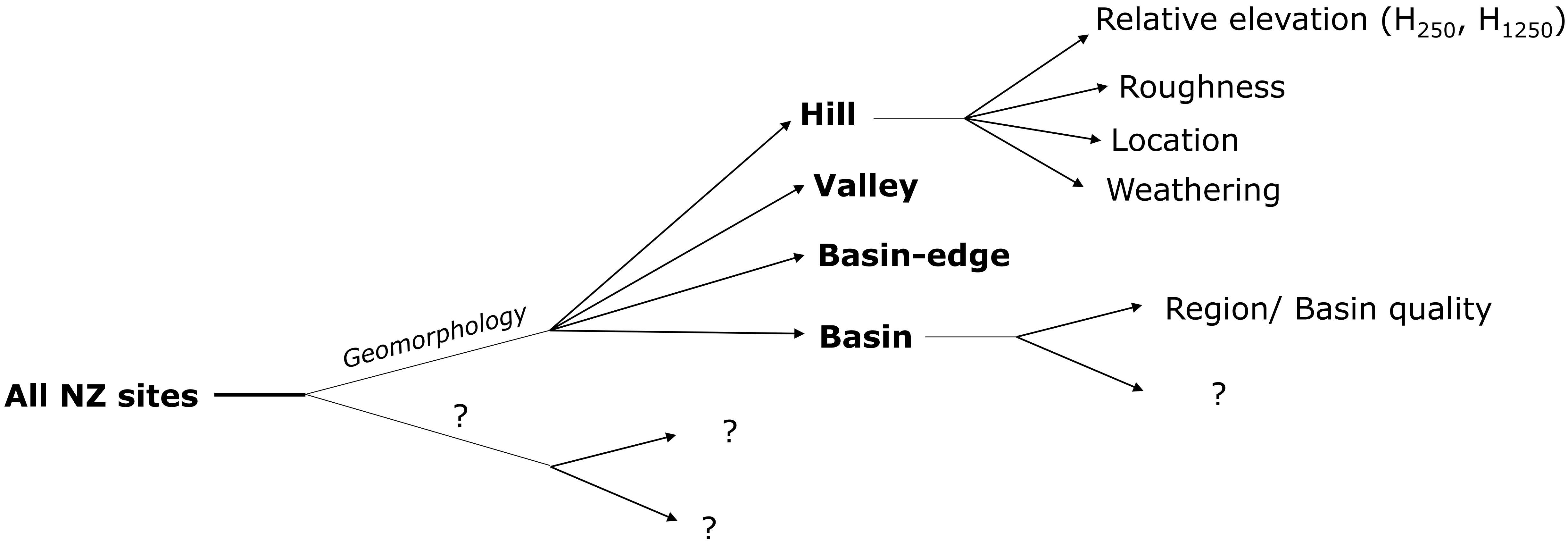


Current study – Physics based simulations



- Empirical site-to-site residuals are generally like site terms from physics-based simulations

Development of predictive model



Key points

1) Advancement of ground motion modelling is a **multidimensional iterative** problem
   i. Large portion of model uncertainty comes from different variety of **site effects**
   ii. Optimum categorization of sites, facilitating an understanding of various systematic site effects, is necessary.
2) Hill/stiff rock sites contribute the most uncertainty to the current state of site response modelling in ground motion simulations.
   i. Improved characterization of such hill sites (e.g., measured V_{S30}) is imperative.
3) Physical approaches (Geomorphic classification and sub-classification of sites, site characterization parameters, etc.) along with **data-based approaches** (such as clustering of site-to-site residuals) aids in understanding imprecisions in ground-motion modelling.

Te Hiranga Rū
NZ Centre for Earthquake Resilience
QuakeCoRE

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

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NSHM Call
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