

Physics-based Simulations and Statistical Approaches to Reduce Uncertainty in PSHA

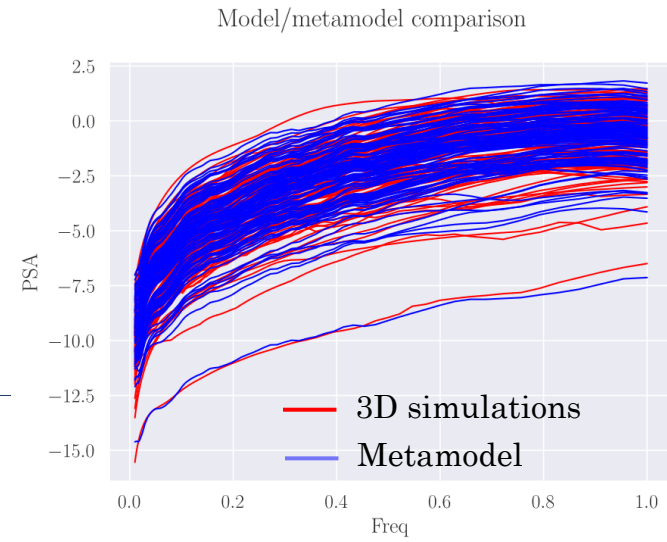
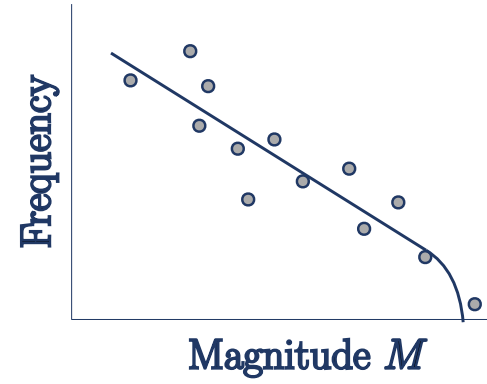
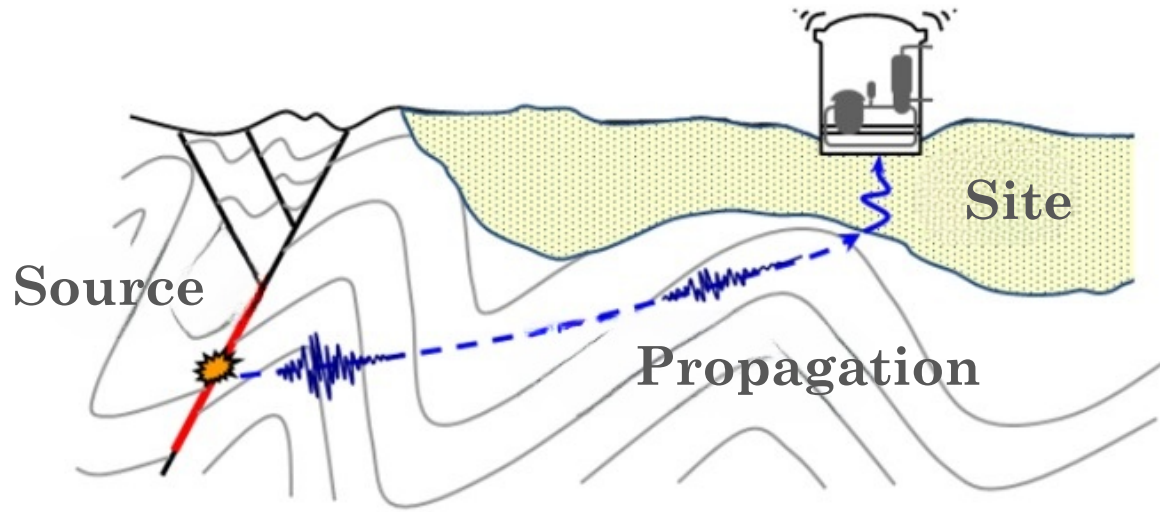
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DOE/NRC Natural Phenomena Hazards Meeting

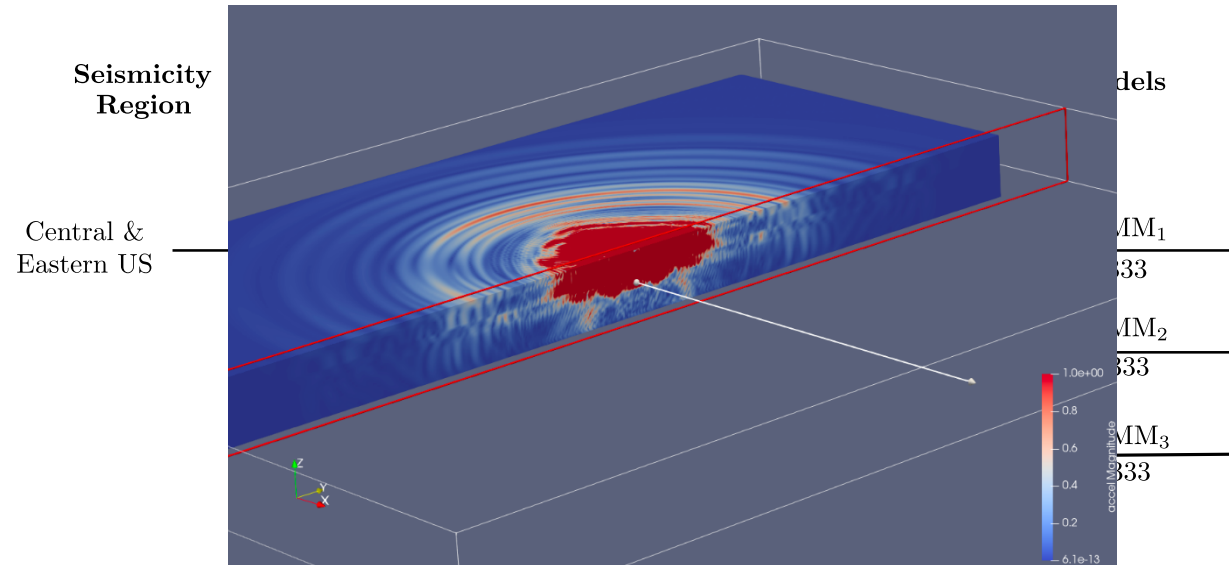


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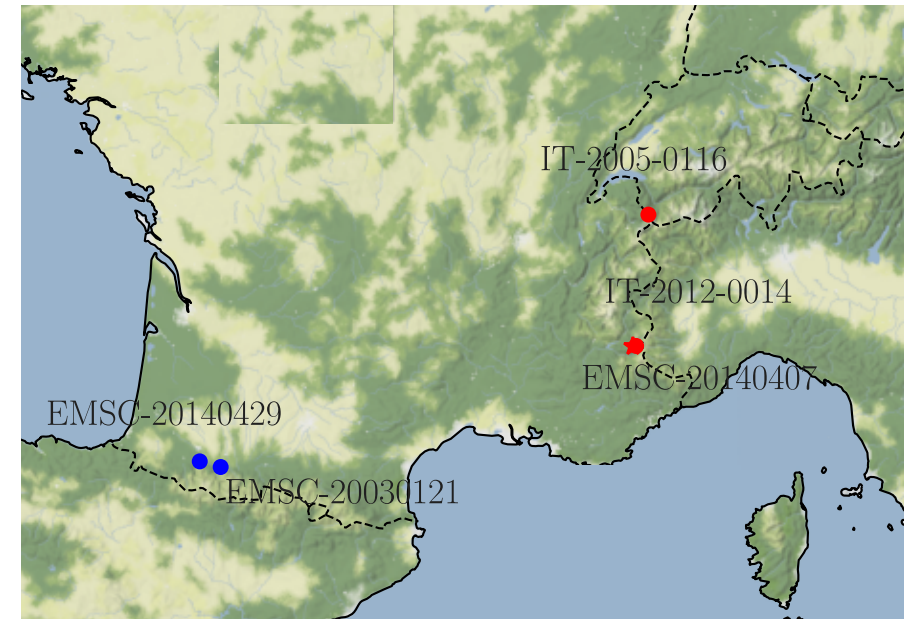
1. Source Model Characterization
2. Ground Motion Model Characterization
3. PSHA Logic Tree / Model Selection



*PSHA – Probabilistic Seismic Hazard Analysis

Low-to-moderate Seismicity

- Magnitude – [4, 5]
- Epicentral distance – 100 km
- *Focal mechanism (strike, dip, rake)*
- *Seismic moment (M_0)*



Event ID	Mw	Focal Depth	Stations
IT-2005-0116	4.5	2.4	24
IT-2012-0014	4.1	10.4	19
EMSC-20140407	4.7	11.1	30
EMSC-20140429	4.2	12.7	7
EMSC-20030121	4	2	5

Inputs for seismic source modeling

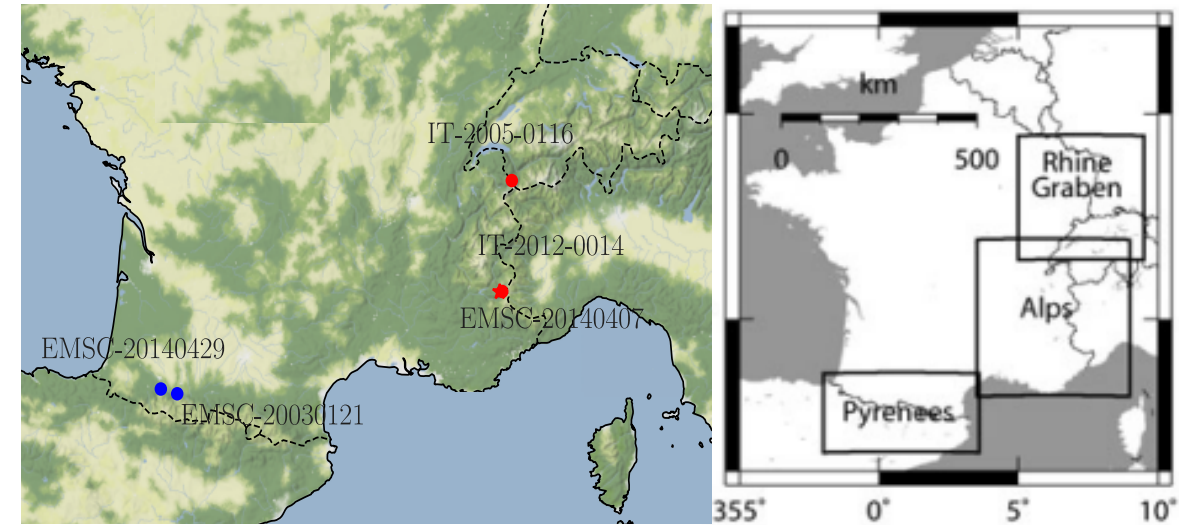
- ⇒ Epicenter location, fault mechanism, slip displacement, and area of fault rupture

Inputs for soil/rock modeling

- ⇒ Shear wave velocity, density, Poisson ratio

Uncertainty

- ⇒ Shear wave velocity (V_s) – [1000, 3500] m/s
- ⇒ Density – [1500, 2500] kg/m³
- ⇒ Strike, dip, and rake (2 combinations)



Drouet et al. (2010)

Assumed Input Values

- ⇒ Shear wave velocity, $V_s = 1000 \text{ m/s} - 3500 \text{ m/s}$
- ⇒ Density, $\rho = 1500 \text{ kg/m}^3 - 2500 \text{ kg/m}^3$
- ⇒ Poissons ratio, $\nu = 0.25$
- ⇒ Cutoff frequency, $f = 1 \text{ Hz}$
- ⇒ Homogeneous Domain

Derived Quantities

- ⇒ Shear Modulus, $G = V_s^2 \rho$
- ⇒ Elastic modulus, $E = 2G(1 + \nu)$
- ⇒ p-wave speed, $V_p = \sqrt{E/\rho}$
- ⇒ Rupture area*, $M_W = 4.07 + 0.98 \log(A)$
- ⇒ Slip displacement = $\frac{M_o}{GA}$

Event: IT-2005-0116

Design of Experiment values for V_s , ρ , and fault mechanism

V_s (m/s)	ρ (kg/m ³)	strike	dip	rake
3456	1514	54	77	-151
3012	2024	54	77	-151
2845	1868	317	61	-15
2599	2206	317	61	-15
2303	2193	317	61	-15
2003	1952	317	61	-15
1918	1794	54	77	-151
1541	2374	54	77	-151
1271	2497	54	77	-151
1005	1611	317	61	-15

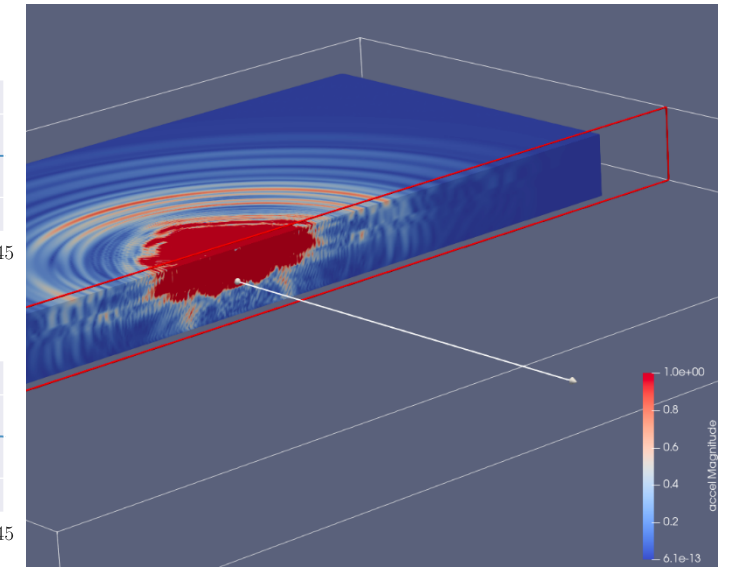
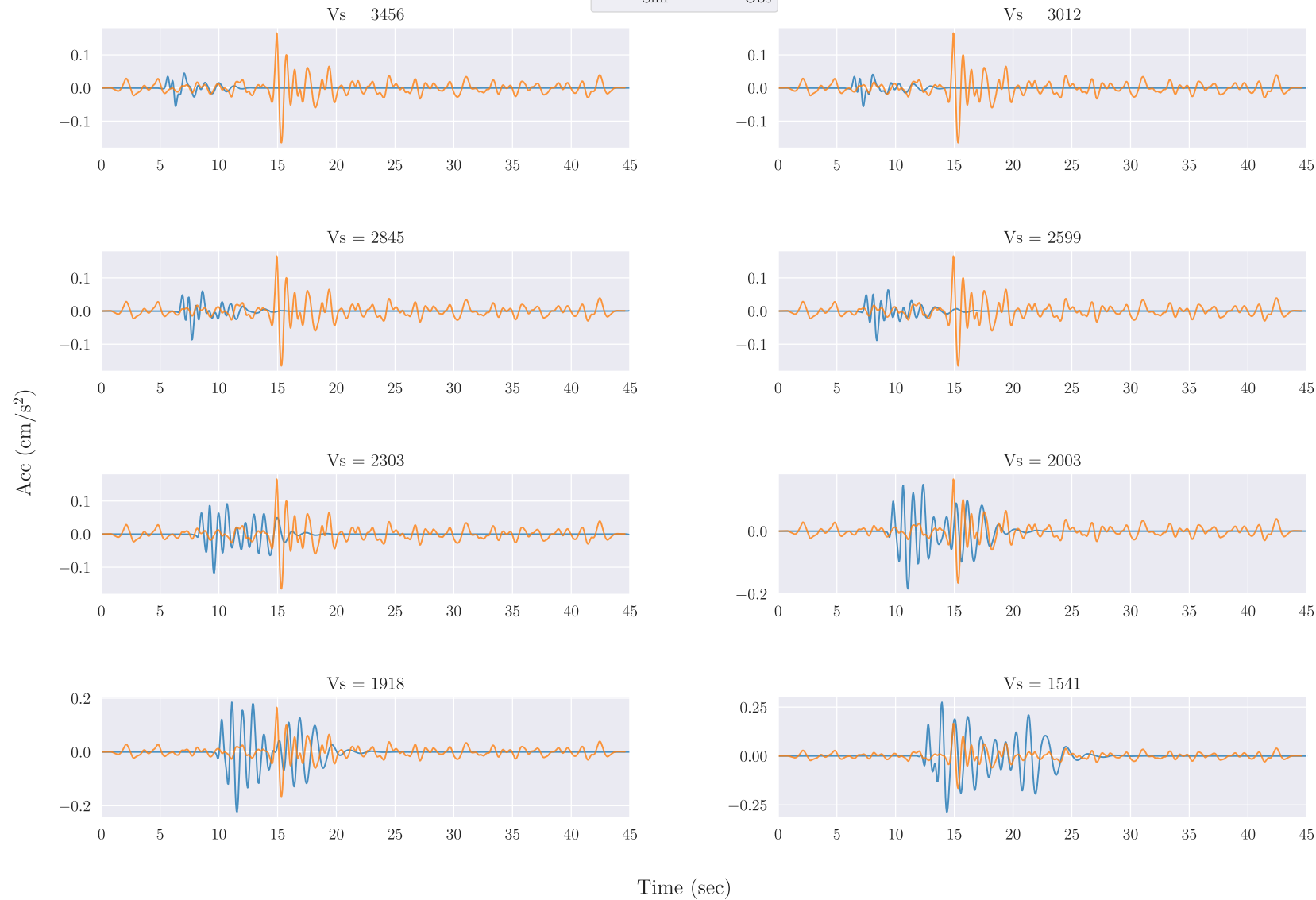
- ⇒ 1500 CPUs, 200 GB RAM, 40 hours wall time
- ⇒ Domain – Focal depth, Epicentral distance
- ⇒ EQ Duration – 30~70 sec

Event ID	Mw	Focal Depth	Stations	Runs	Records
IT-2005-0116	4.5	2.4	24	8	192
IT-2012-0014	4.1	10.4	19	5	95
EMSC-20140429	4.2	12.7	7	4	28
EMSC-20140407	4.7	11.1	30	6	180
EMSC-20030121	4	2	5	8	40
Total			85		535

Event: IT-2005-0116

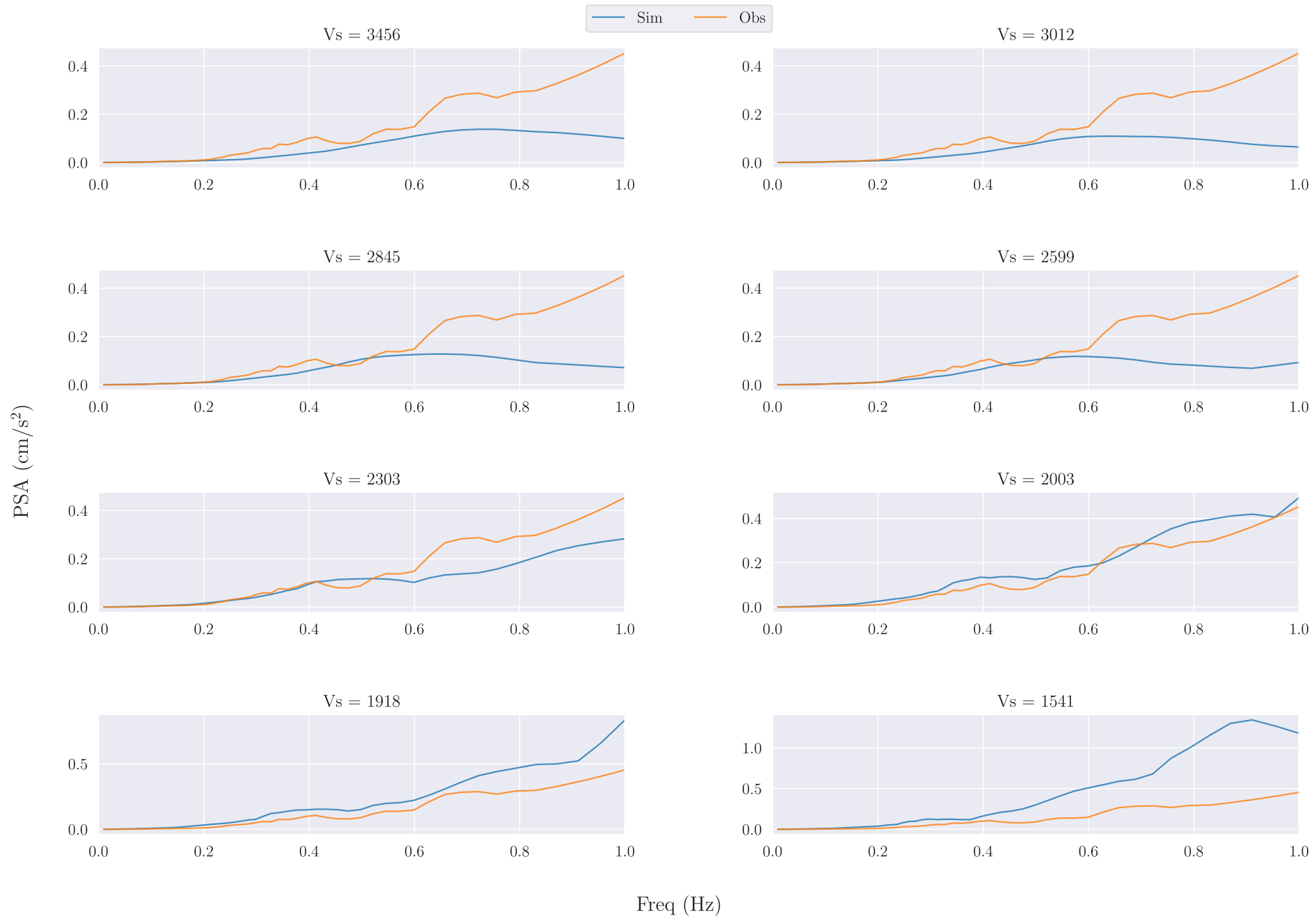
SDIF (R = 35 km)

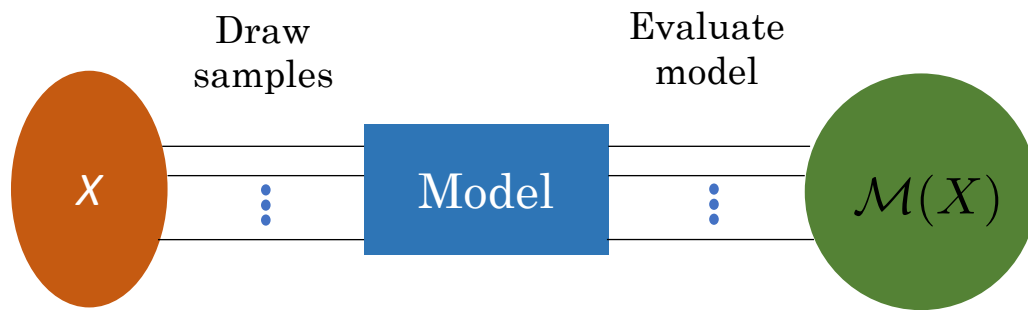
— Sim — Obs



PSA Comparison

SDIF (R = 35 km)



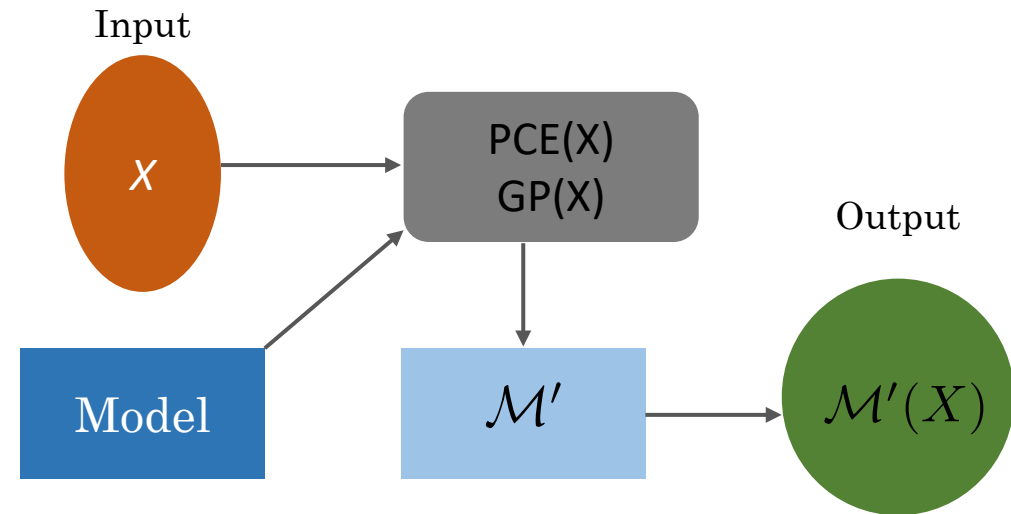


Polynomial Chaos Expansion (PCE)

$$Y = \sum_{k=0}^N a_k \Phi_k(\mathbf{X})$$

Where:

- Y is the output response.
- \mathbf{X} is a vector of uncertain parameters.
- a_k are expansion coefficients.
- $\Phi_k(\boldsymbol{\xi})$ are orthogonal polynomials.
- N is the order of the expansion.

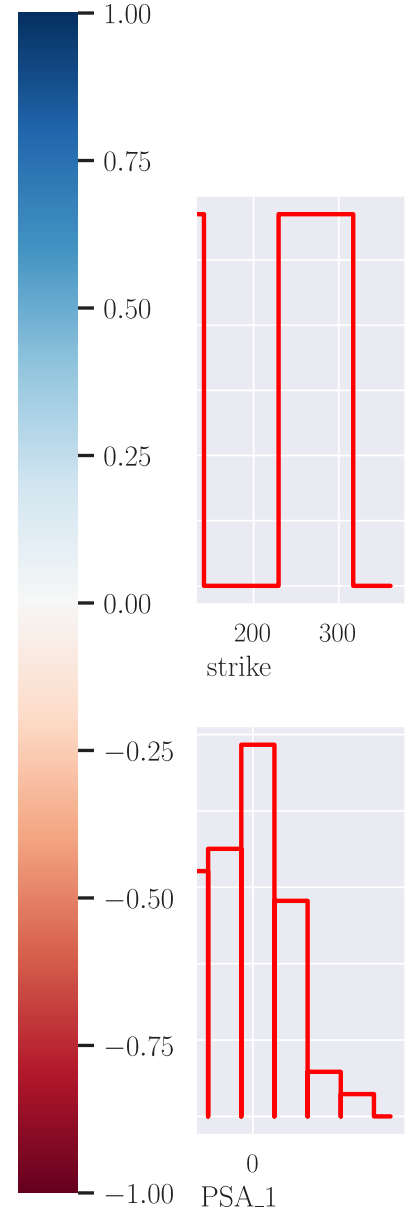
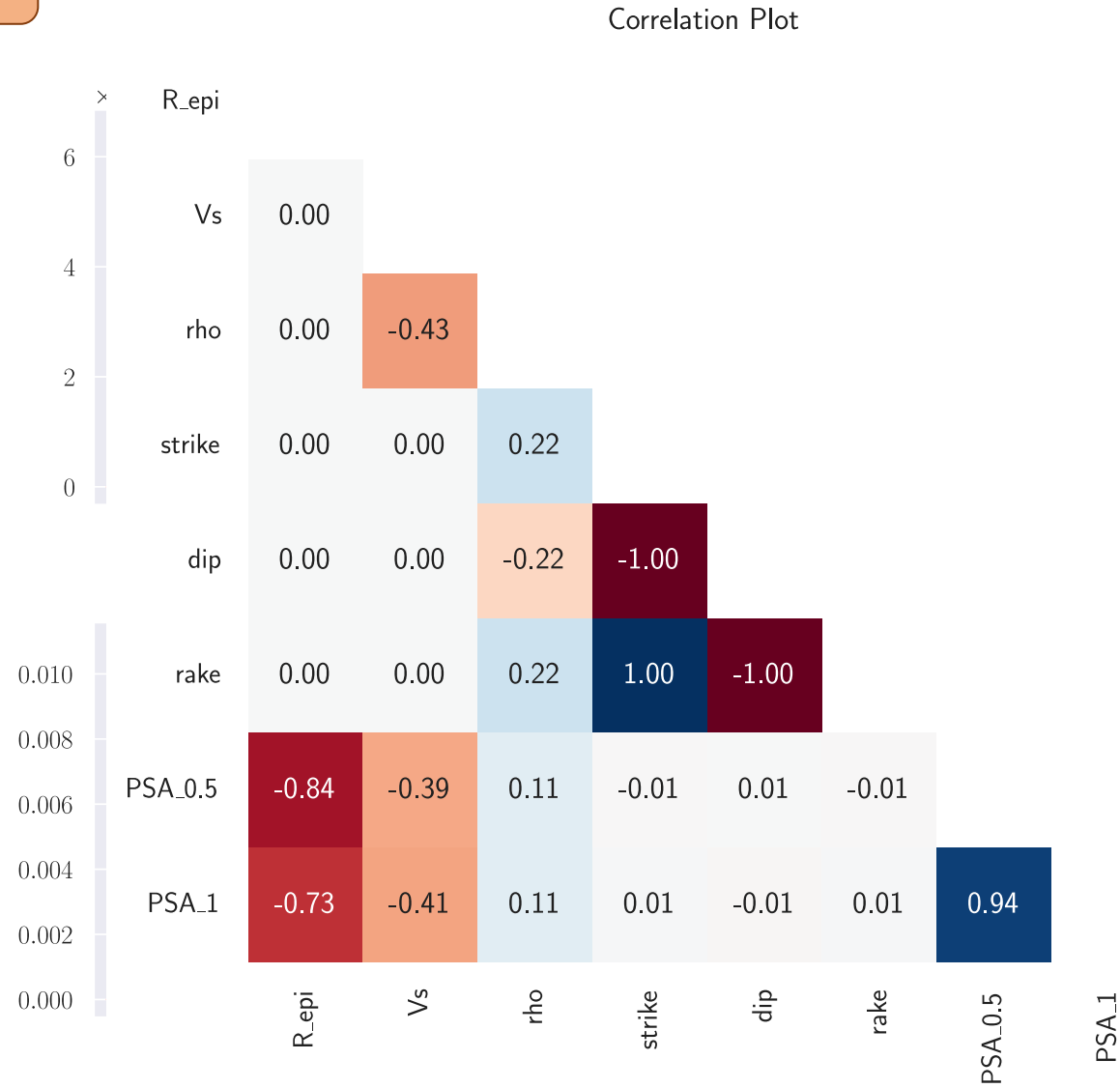
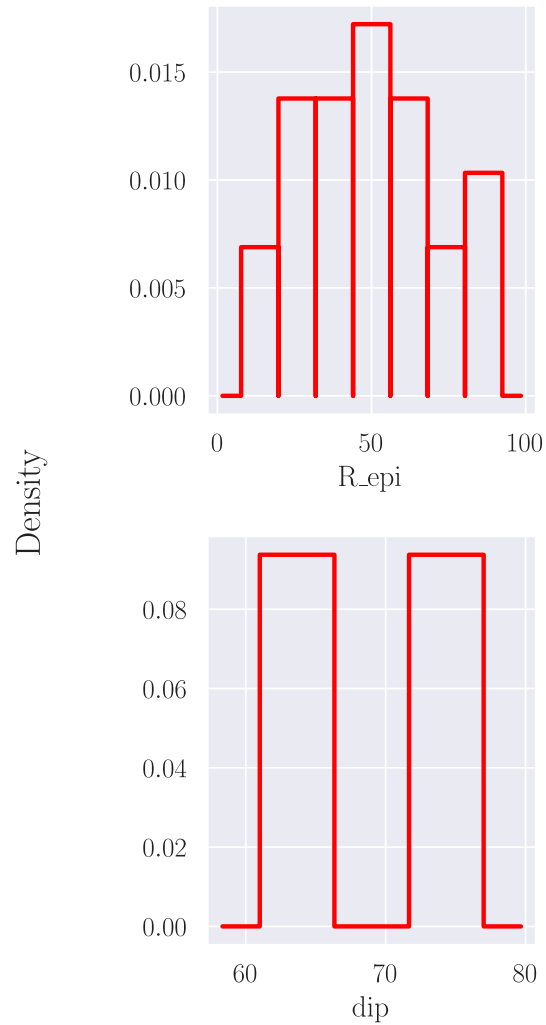


Gaussian Process (GP) or Kriging

$$Y = \beta^T f(\mathbf{X}) + \sigma^2 Z(\mathbf{X}, w)$$

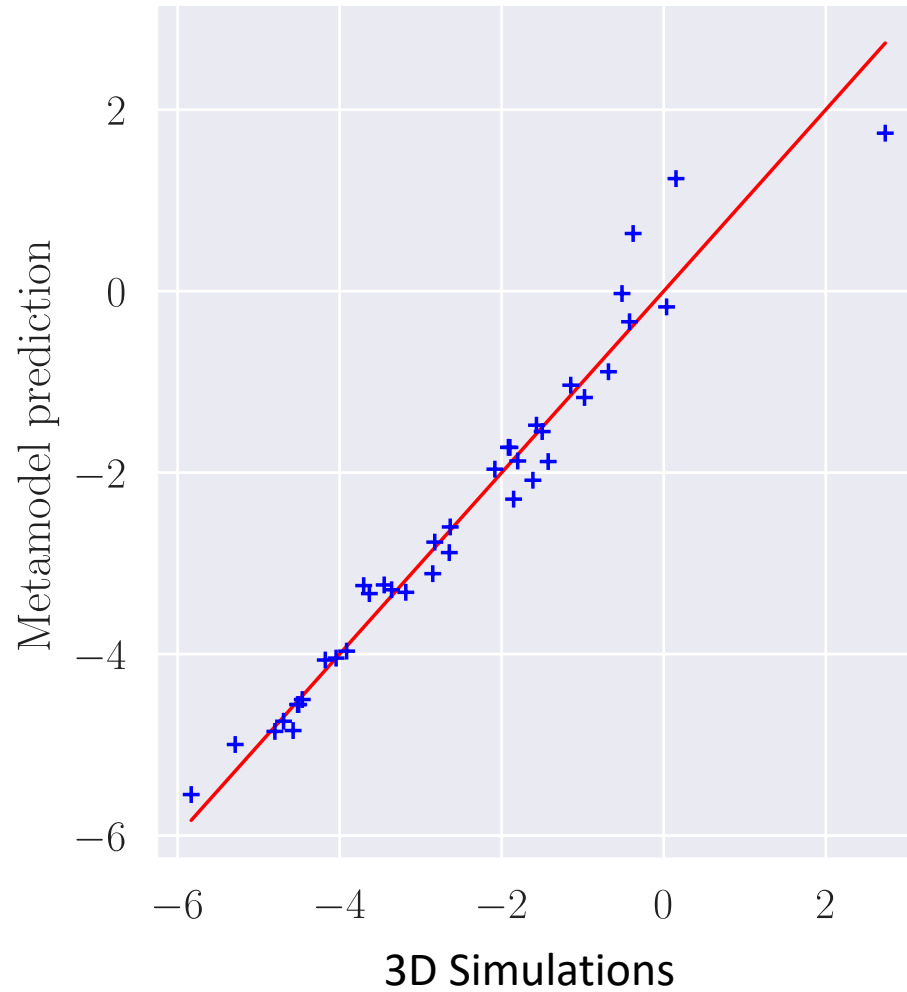
- $\beta^T f(\mathbf{X})$ is the mean value (trend) of the GP.
- σ^2 is the constant variance.
- $Z(\mathbf{X}, w)$ is a zero-mean unit-variance.

Event: IT-2005-0116

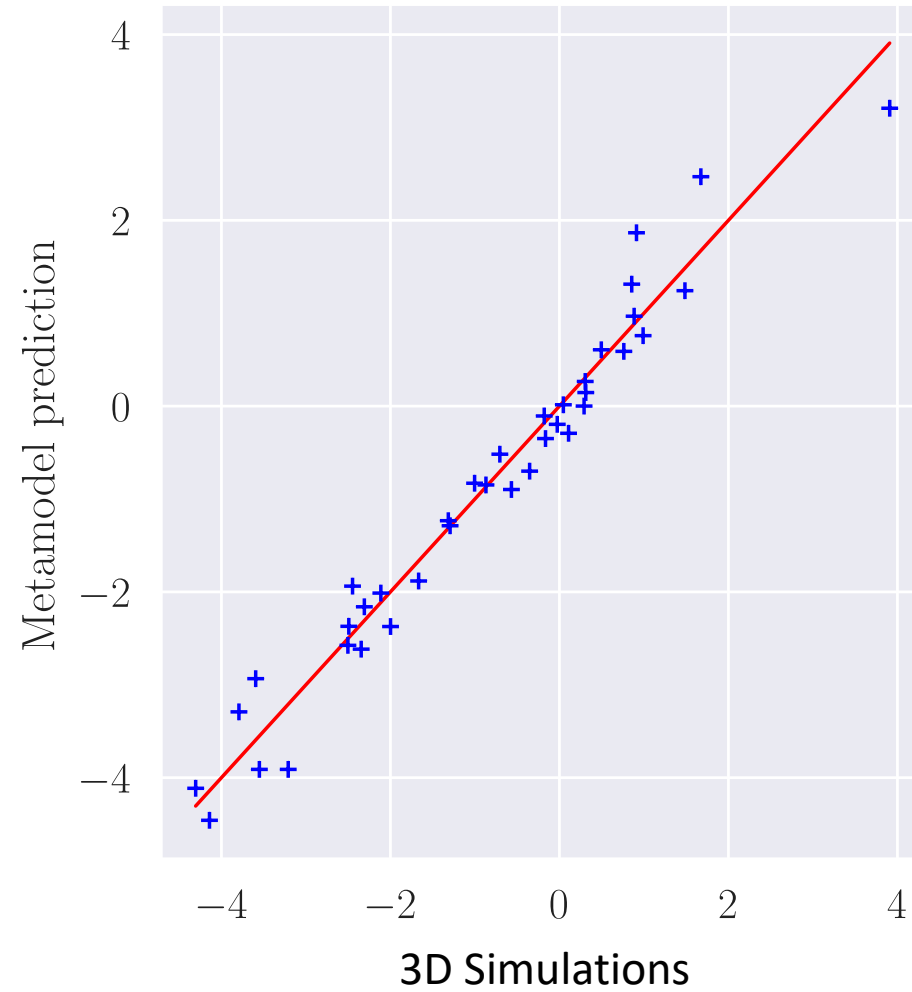


Kriging Validation

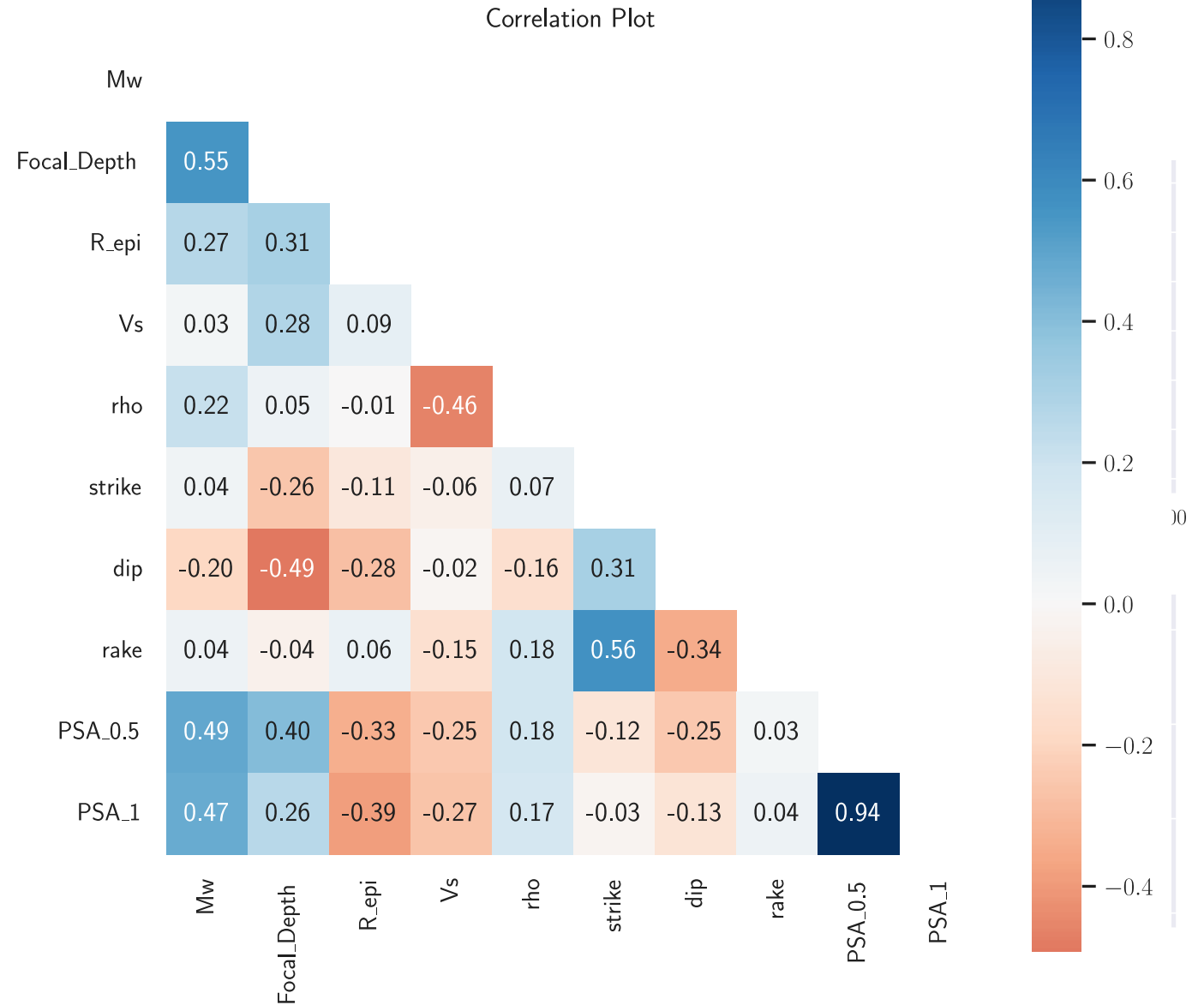
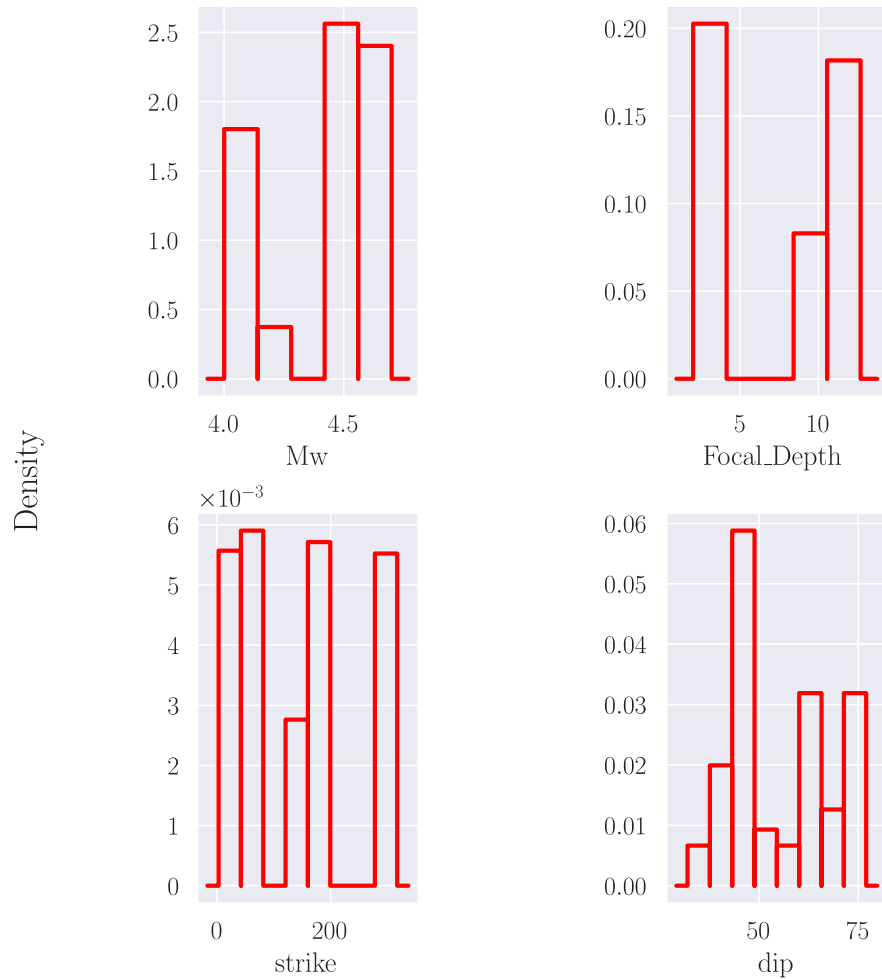
PSA_1: Q2 = 95.92 %



PSA_0.5: Q2 = 96.01 %

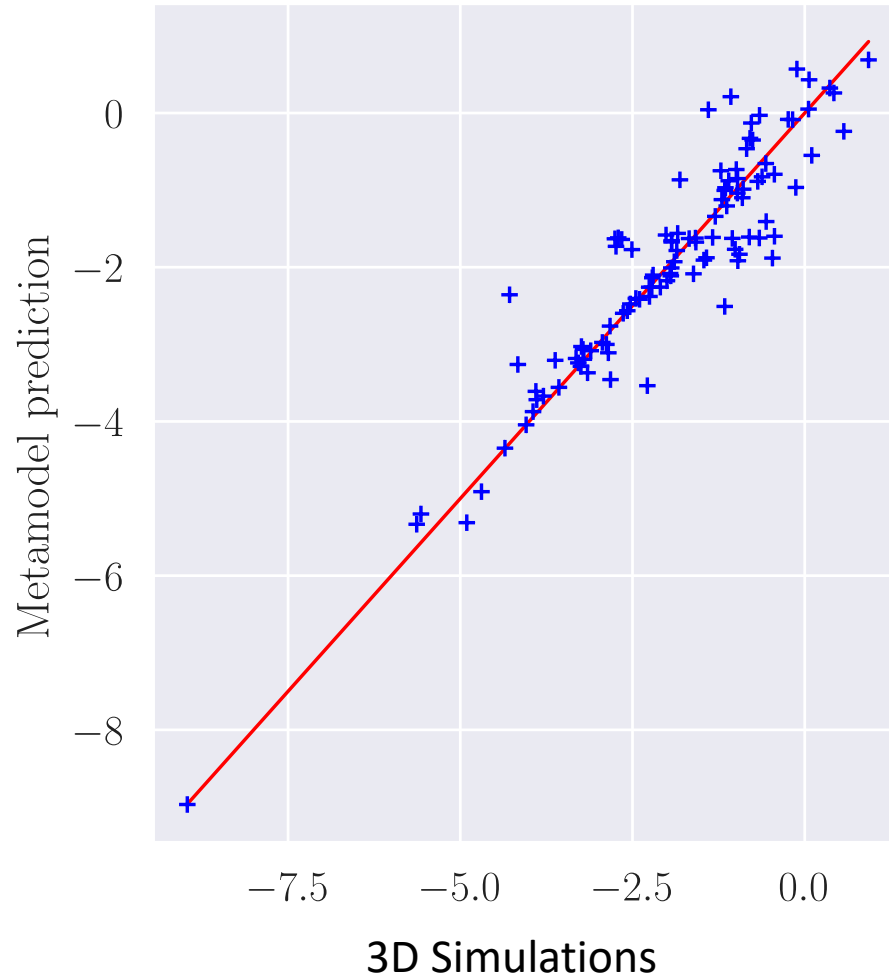


Complete Dataset

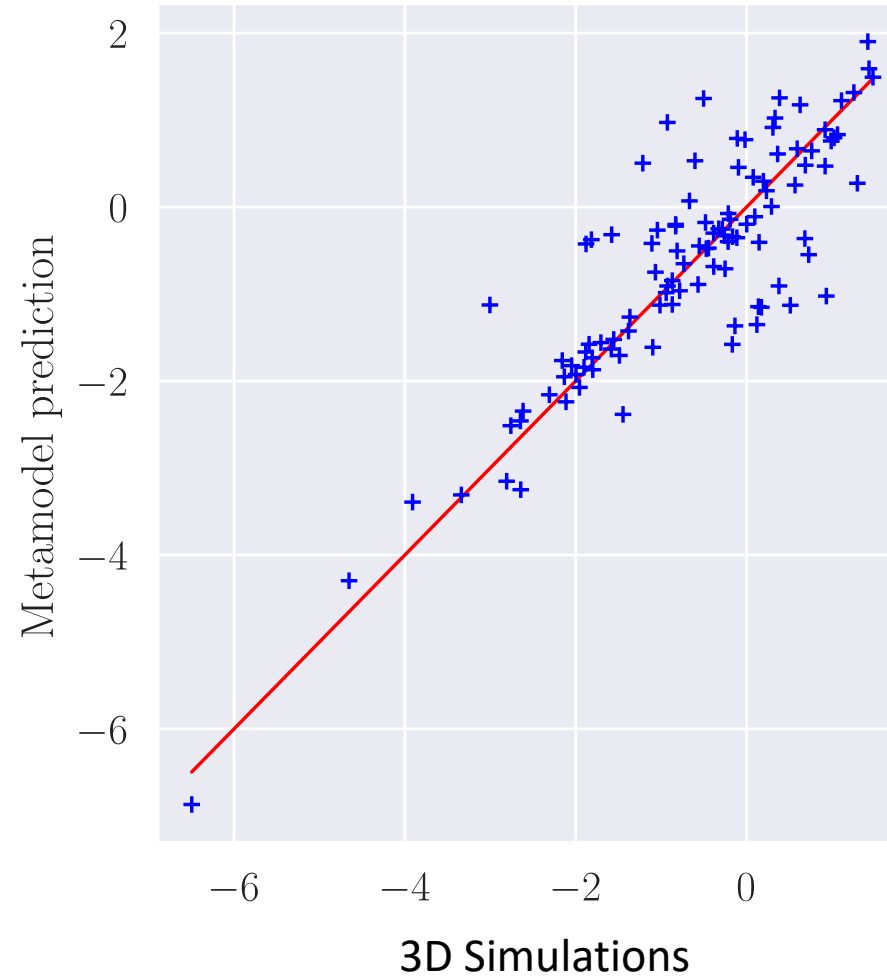


Kriging Validation

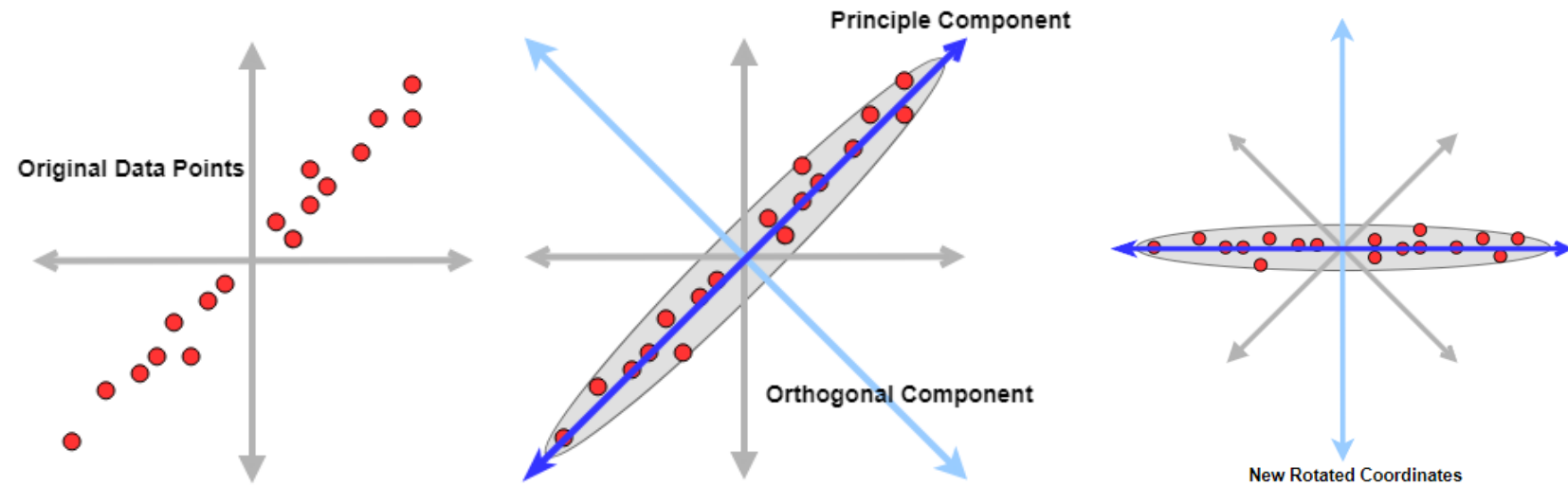
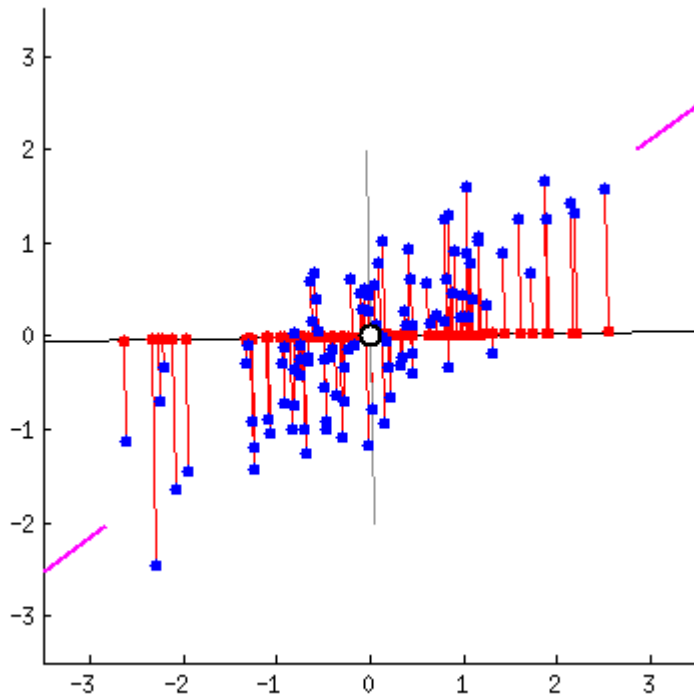
PSA_1: Q2 = 86.57 %



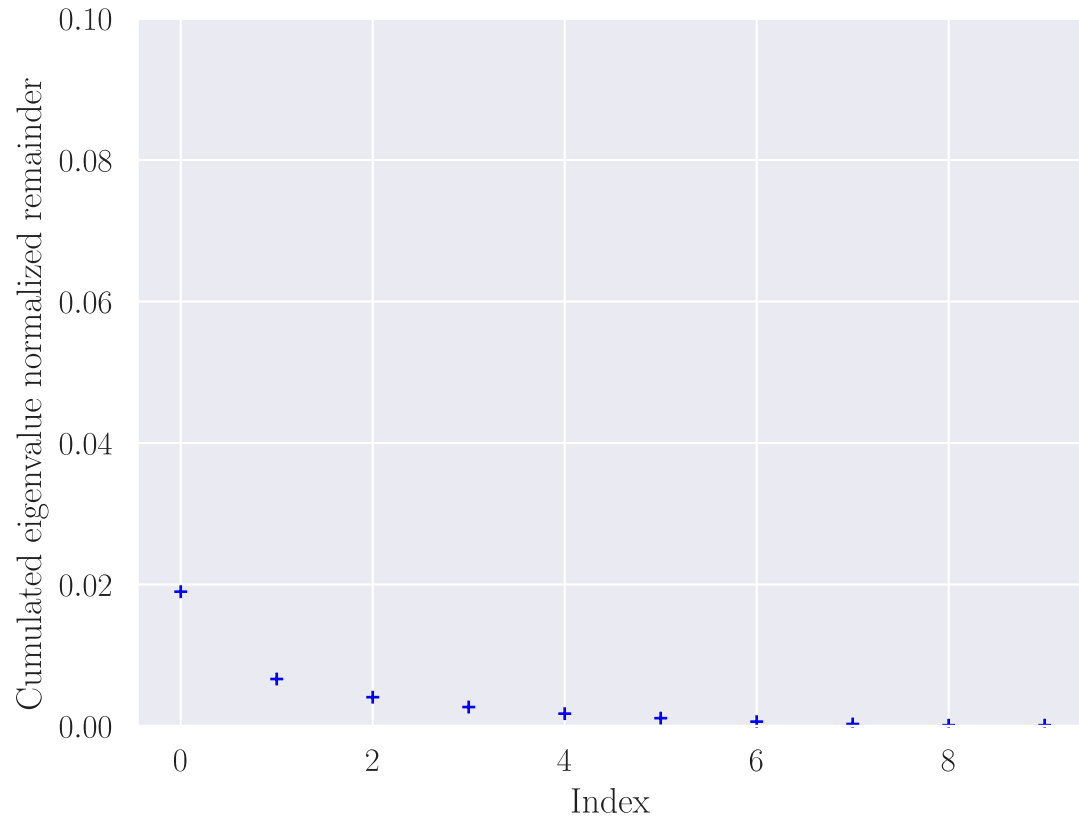
PSA_0.5: Q2 = 73.02 %



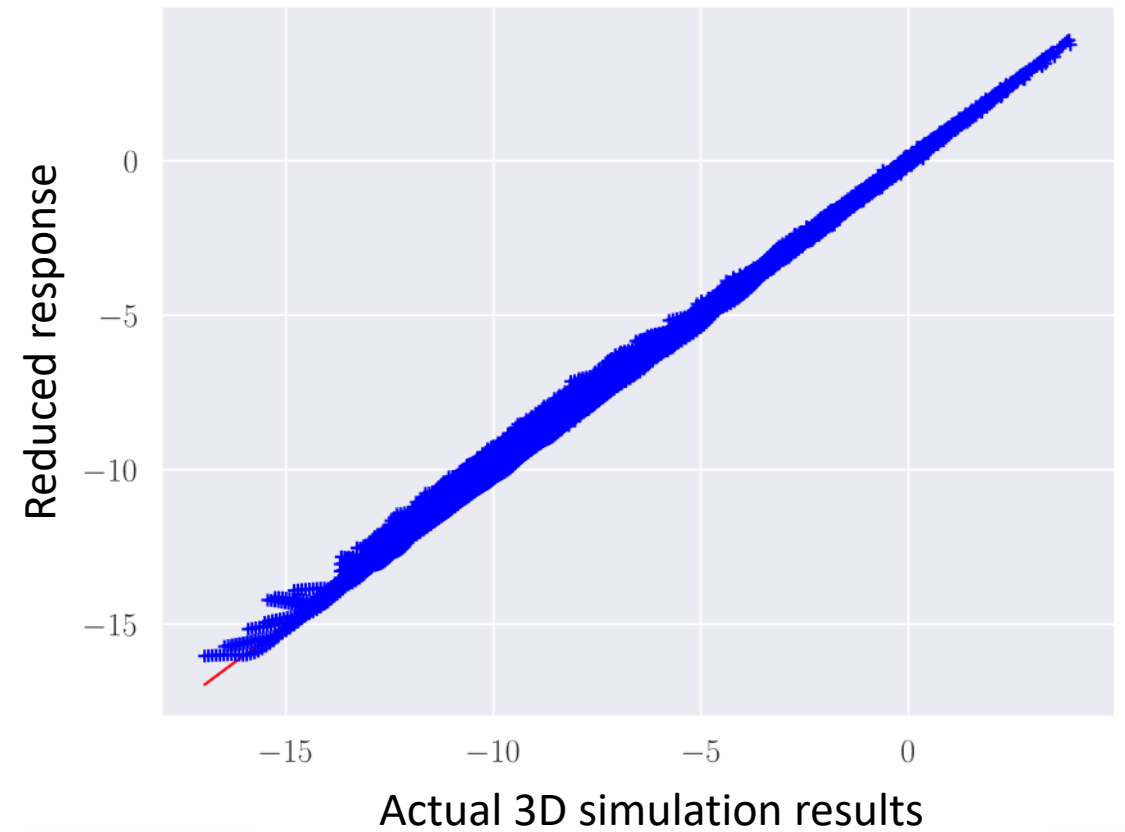
⇒ Identify the principal components along which the data is more relevant.



Karhunen-Loeve eigenvalues

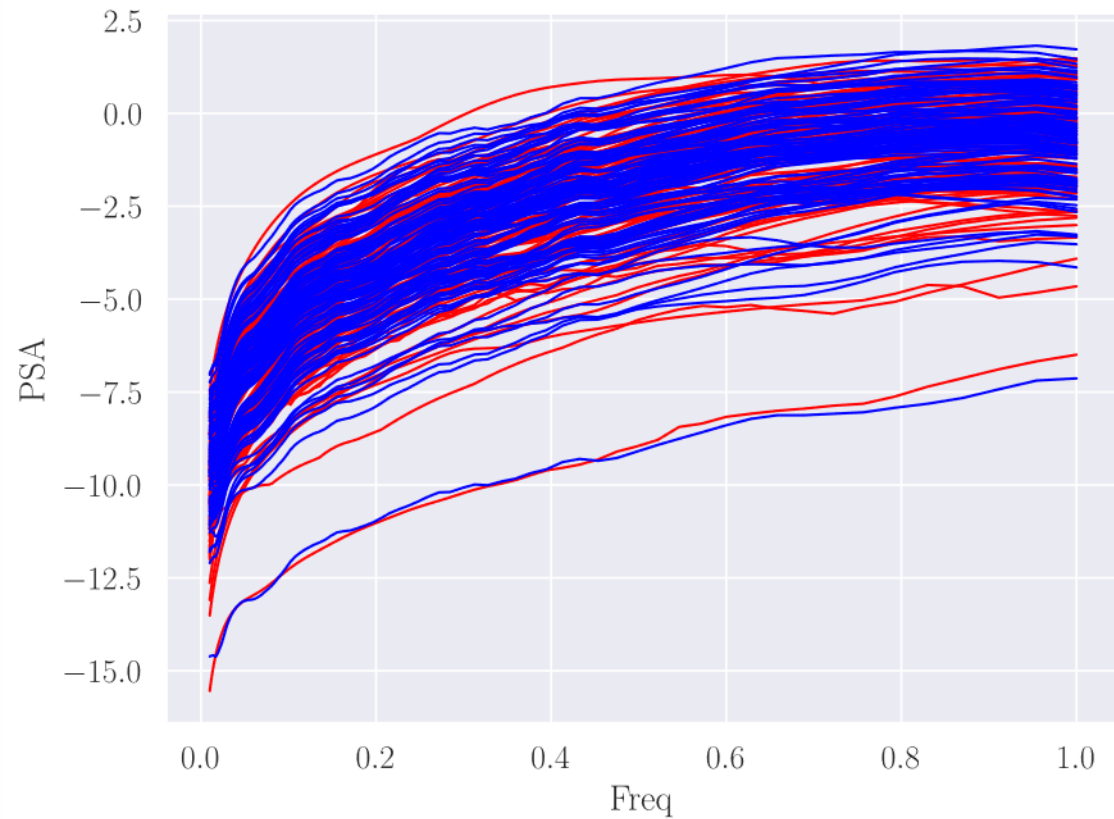


Karhunen-Loeve Validation



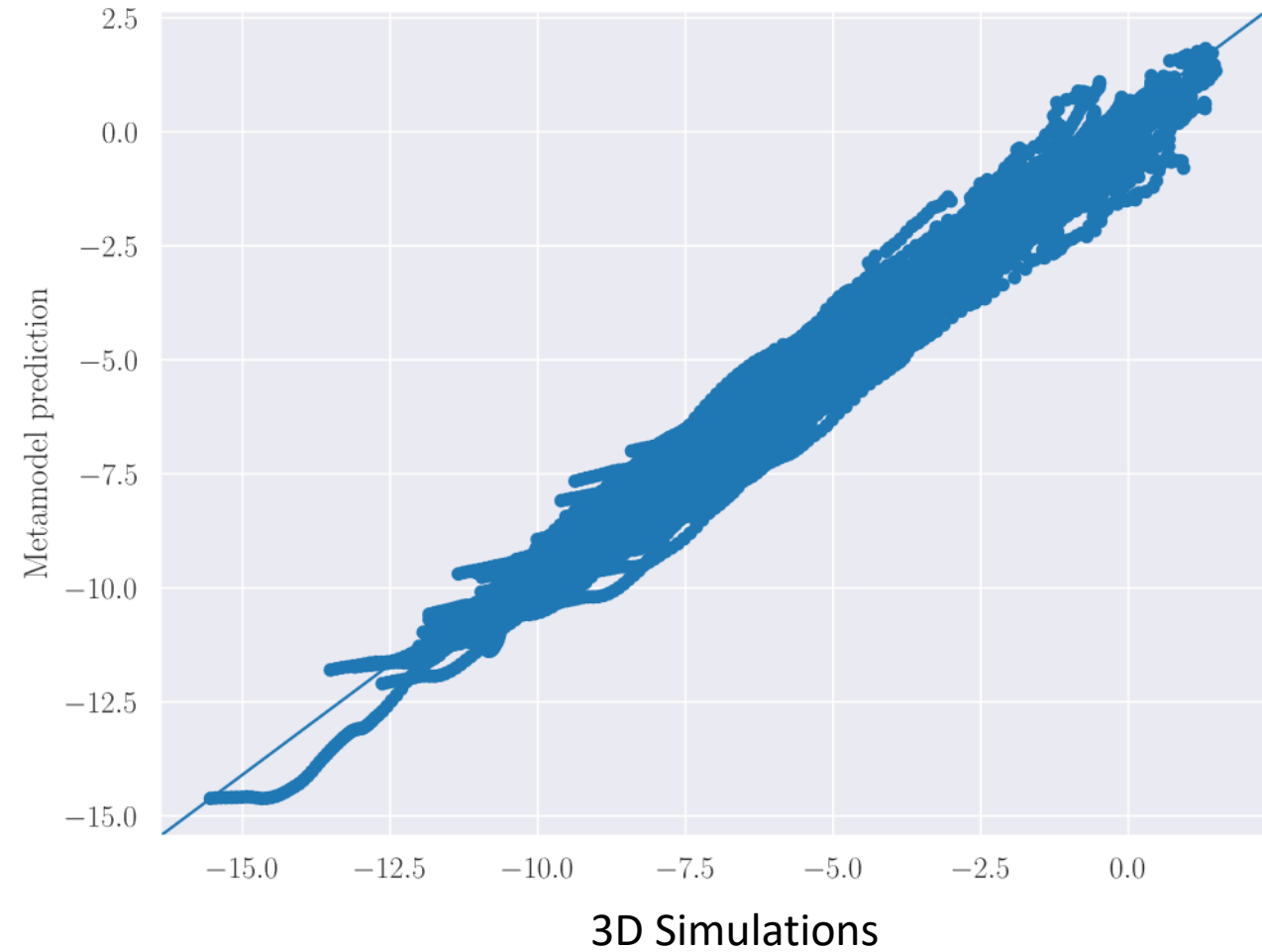
Selection ratio: 0.999361 (10 modes)

Model/metamodel comparison



- 3D simulations
- Metamodel

$Q2 = 97.99\%$



$$y^o = \zeta(\mathbf{X}^o) + \varepsilon$$

Displacement of a damped harmonic oscillator

Observed

$$y^o = Ae^{-\xi\sqrt{\frac{k}{m}}t} \sin\left(\sqrt{1-\xi^2}\sqrt{\frac{k}{m}}t\right)$$

$$A = 1, k = 6, m = 50 \times 10^{-3}$$

$$\xi = 0.2$$

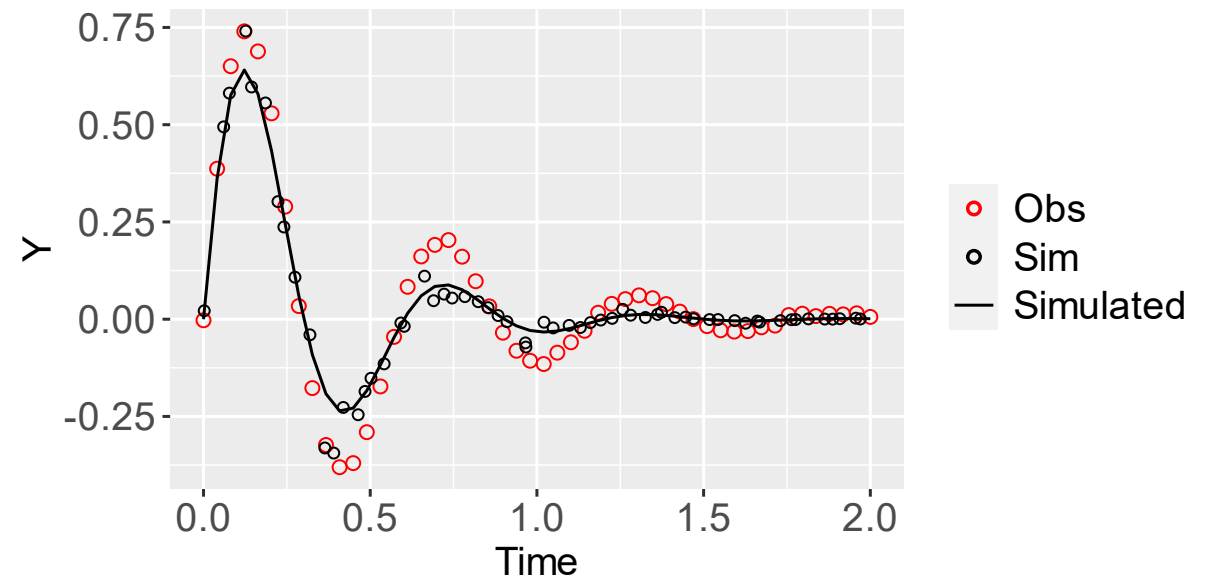
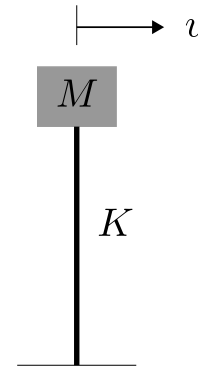
$$\mathbf{X}^0 = t$$

Simulated

$$\eta(\mathbf{X}^o, \boldsymbol{\theta}) = Ae^{-\xi\sqrt{\frac{k}{m}}t} \sin\left(\sqrt{1-\xi^2}\sqrt{\frac{k}{m}}t\right)$$

$$\mathbf{X}^0 = t, \boldsymbol{\theta} = (\xi)$$

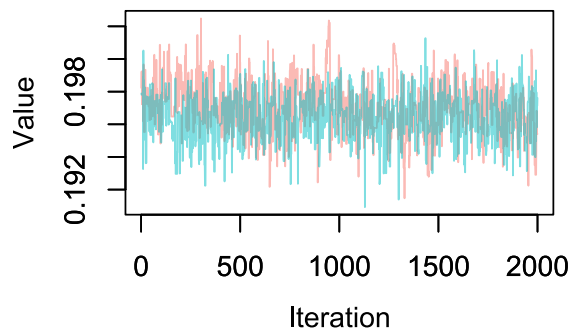
$$\xi \sim \mathcal{N}(0.3, 0.05)$$



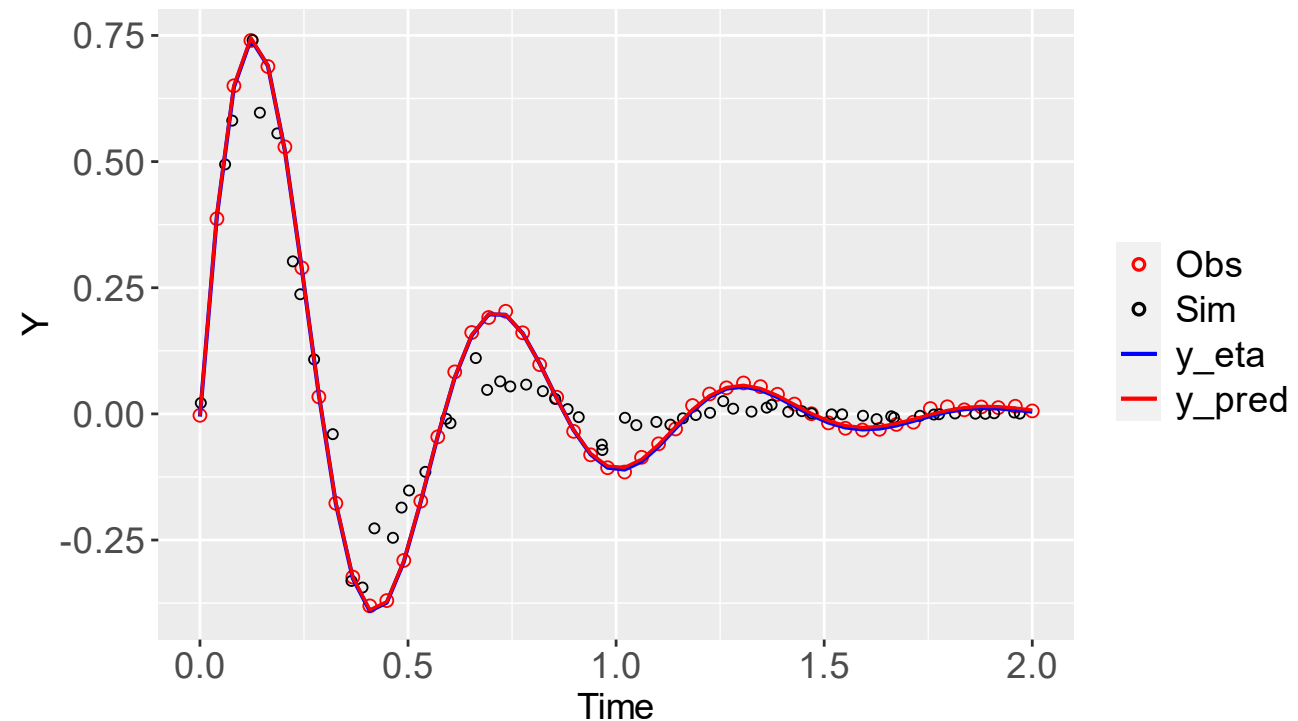
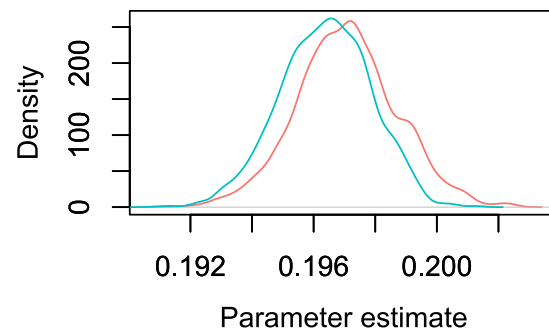
⇒ The discrepancy function has no effect.

Posterior distribution of ξ

Trace



Density



True value $\xi = 0.2$

$$\begin{aligned}
 \mathbf{y}^o &= \zeta(\mathbf{X}^o) + \varepsilon \\
 &= \eta(\mathbf{X}^o, \boldsymbol{\theta}^*) + \varepsilon && \Leftarrow \mathcal{M}_1 \\
 &= \eta(\mathbf{X}^o, \boldsymbol{\theta}^*) + \delta(\mathbf{X}^o) + \varepsilon && \Leftarrow \mathcal{M}_2
 \end{aligned}$$

Displacement of a damped harmonic oscillator

Observed

$$y^o = Ae^{-\xi\sqrt{\frac{k}{m}}t} \sin\left(\sqrt{1-\xi^2}\sqrt{\frac{k}{m}}t + \frac{\pi}{2}\right)$$

Adding phase term

$$A = 1, k = 6, m = 50 \times 10^{-3}$$

$$\xi = 0.2$$

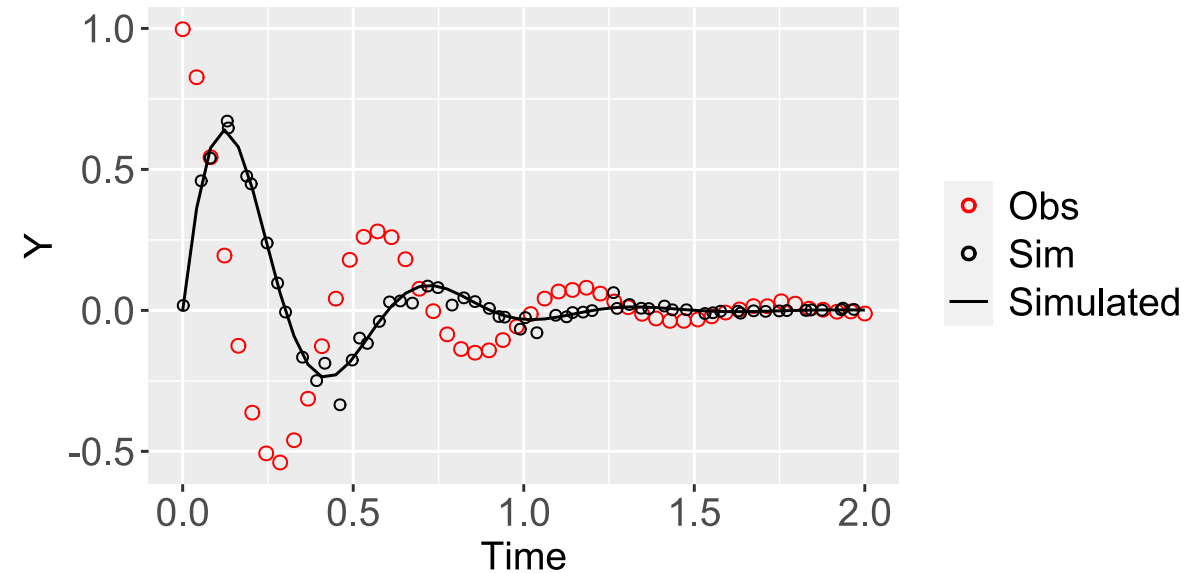
$$\mathbf{X}^0 = t$$

Simulated

$$\eta(\mathbf{X}^o, \boldsymbol{\theta}) = Ae^{-\xi\sqrt{\frac{k}{m}}t} \sin\left(\sqrt{1-\xi^2}\sqrt{\frac{k}{m}}t\right)$$

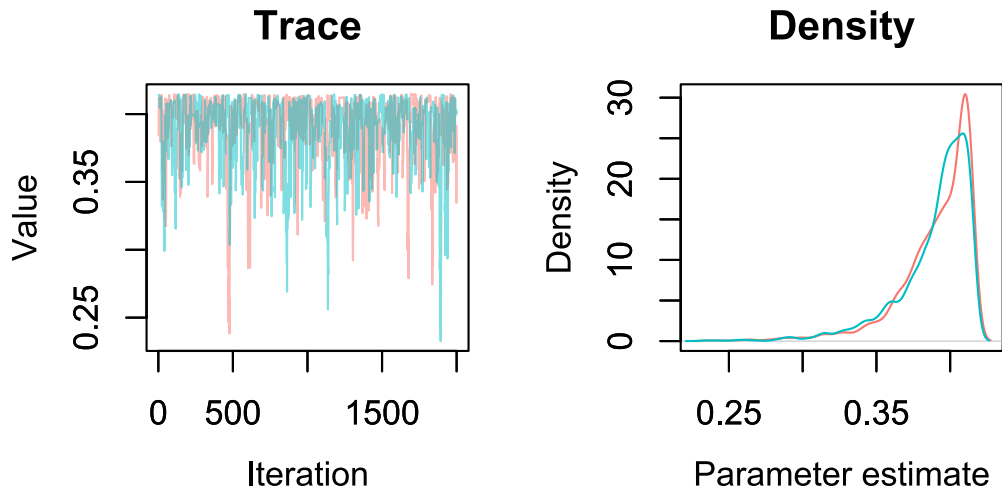
$$\mathbf{X}^0 = t, \boldsymbol{\theta} = (\xi)$$

$$\xi \sim \mathcal{N}(0.3, 0.05)$$

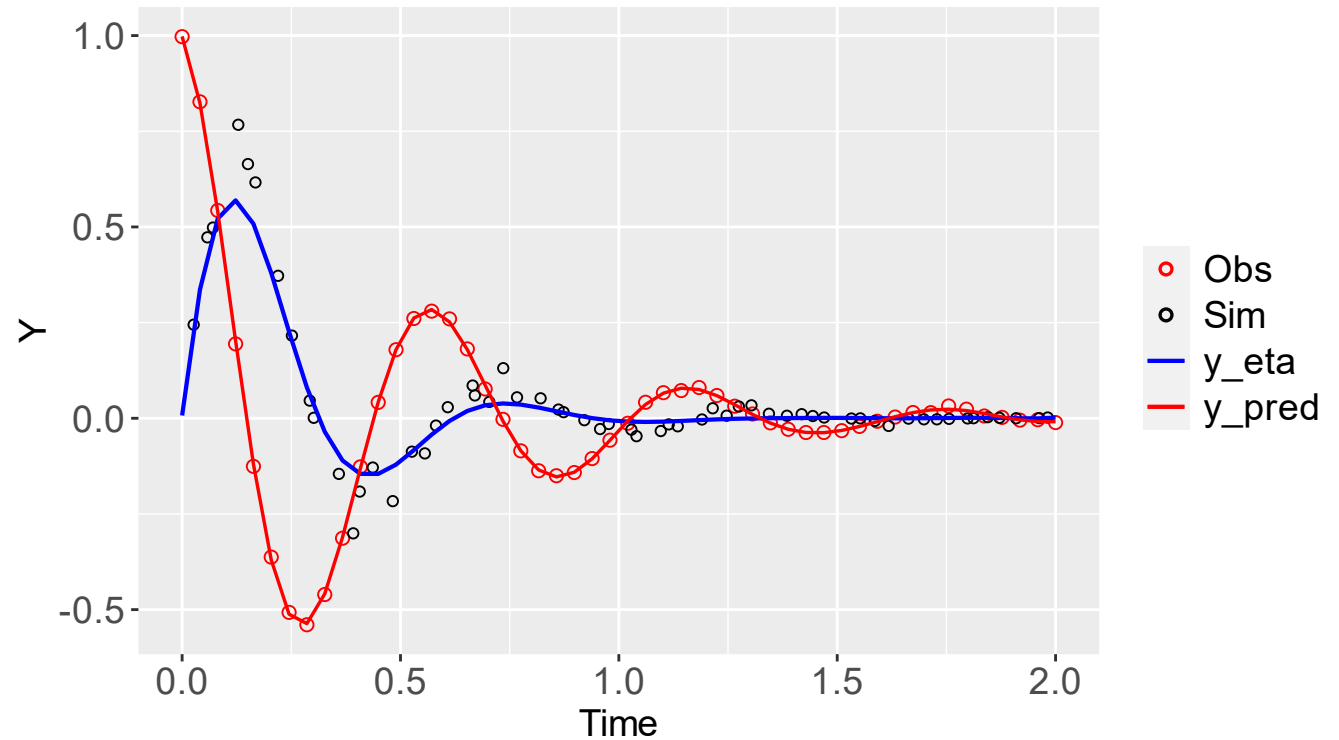


➡ The discrepancy function takes over post-calibration.

Posterior distribution of ξ



True value $\xi = 0.2$



$$\mathbf{y}^o = \zeta(\mathbf{X}^o) + \varepsilon$$

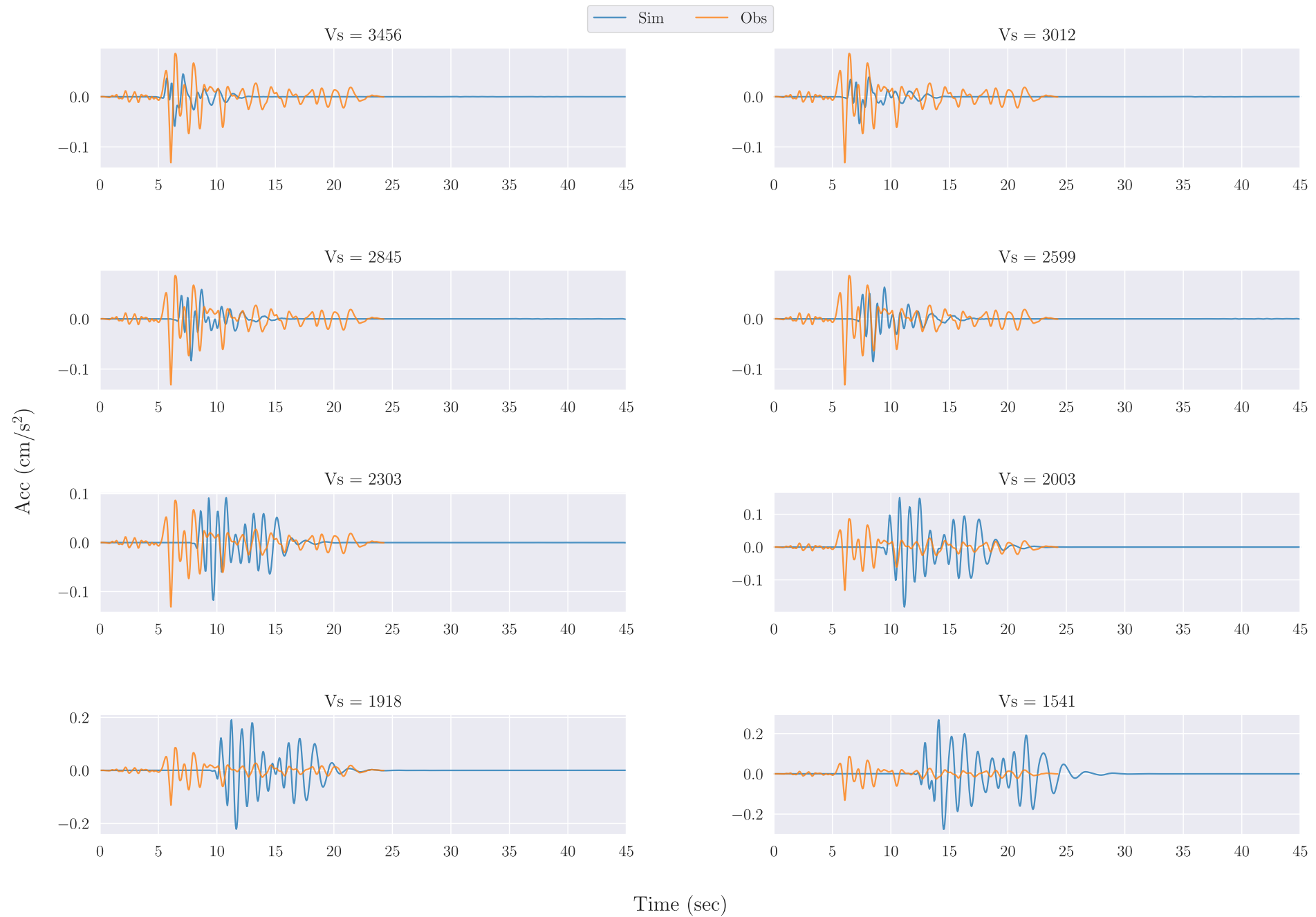
$$= \eta(\mathbf{X}^o, \boldsymbol{\theta}^*) + \varepsilon \quad \Leftarrow \mathcal{M}_1$$

$$= \eta(\mathbf{X}^o, \boldsymbol{\theta}^*) + \delta(\mathbf{X}^o) + \varepsilon \quad \Leftarrow \mathcal{M}_2$$

- ⇒ Mitigate conservatisms in seismic hazards, particularly relevant for nuclear facilities situated in low-to-moderate seismicity regions.
- ⇒ Physics-based simulations, while promising, demand substantial computational resources.
- ⇒ Novel PSHA methodology, integrating both physics-based simulations and statistical models.

Thank you!
Any Questions?

DIX (R = 35 km)



Time (sec)

Residual	0.067
R2	0.002

Q2 = 74.12%

Polynomial basis

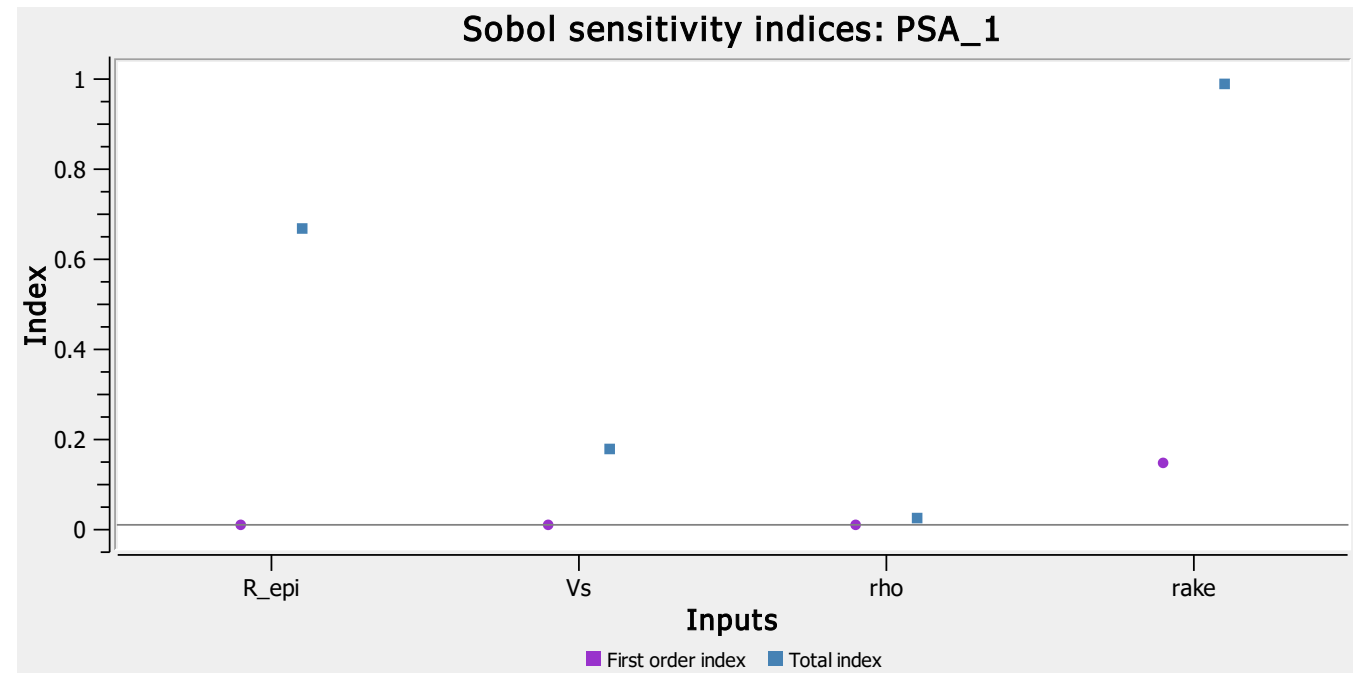
Dimension	4
Maximum degree	3
Full basis size	35
Truncated basis size	6

Moments estimates

Estimate	Value
Mean	-0.136
Variance	0.661
Standard deviation	0.813

Part of variance

Index	Multi-indices	Coefficient	Part of variance (Threshold : 1 %)
0	[0, 0, 0, 0]	-0.136	-
2	[1, 0, 0, 2]	-0.304	67.21%
3	[0, 1, 0, 2]	-0.666	17.21%
1	[0, 0, 0, 2]	-0.337	13.99%
4	[0, 0, 1, 2]	-0.101	1.53%
Sum			99.94%



Sobol Indices: variance-based sensitivity analysis.

First-order: sensitivity of output variance explained by effect of X_i alone.

Total-order: part of variance of Y explained by X_i and its interactions with other input variables.