Ground motion model (GMM) for directional inelastic spectral displacements

Savvinos Aristeidou[1], *Gerard J. O'Reilly*[1], *Karim Tarbali*[2]

1 – Scuola Universitaria Superiore IUSS Pavia, Pavia, Italy

2 - University of Paris-Saclay, CentraleSupelec, Gif-sur-Yvette, France

IUSS
Scuola Universitaria Superiore Pavia

ROSE
Centre for Training and Research on Reduction of Seismic Risk

Introduction

- Intensity measure (IM) → links seismological conditions with engineering demands
- Ground motion models (GMMs) provide the probability distribution of an IM at a site, given underlying seismic hazard conditions
- Ground motions (GMs) can then be selected and scaled to match that IM distribution → and then use them for nonlinear response history analysis (NRHA) of structures
- Inelastic spectral displacement (Sd_i) can be an effective IM, under certain conditions
- Novel horizontal component definition for Sd_i: *RotD50* and *RotD100*
  - ‘*RotDnn*’ denotes the nnth percentile of IM from all rotation angles sorted by amplitude
  - ‘D’ denotes that it’s dependent on the vibration period
- $Sd_{\mathrm{i,RotD100}}/Sd_{\mathrm{i,RotD50}}$ can be a more informative directionality measure, extended from $Sa_{\mathrm{RotD100}}/Sa_{\mathrm{RotD50}}$ which is the most common measure of GM directionality
- This $Sd_{\mathrm{i,RotD100}}/Sd_{\mathrm{i,RotD50}}$ can be also considered as a secondary IM

Luco and Cornell (2007) ***Boore (2010)*** ***Shahi and Baker (2014)***

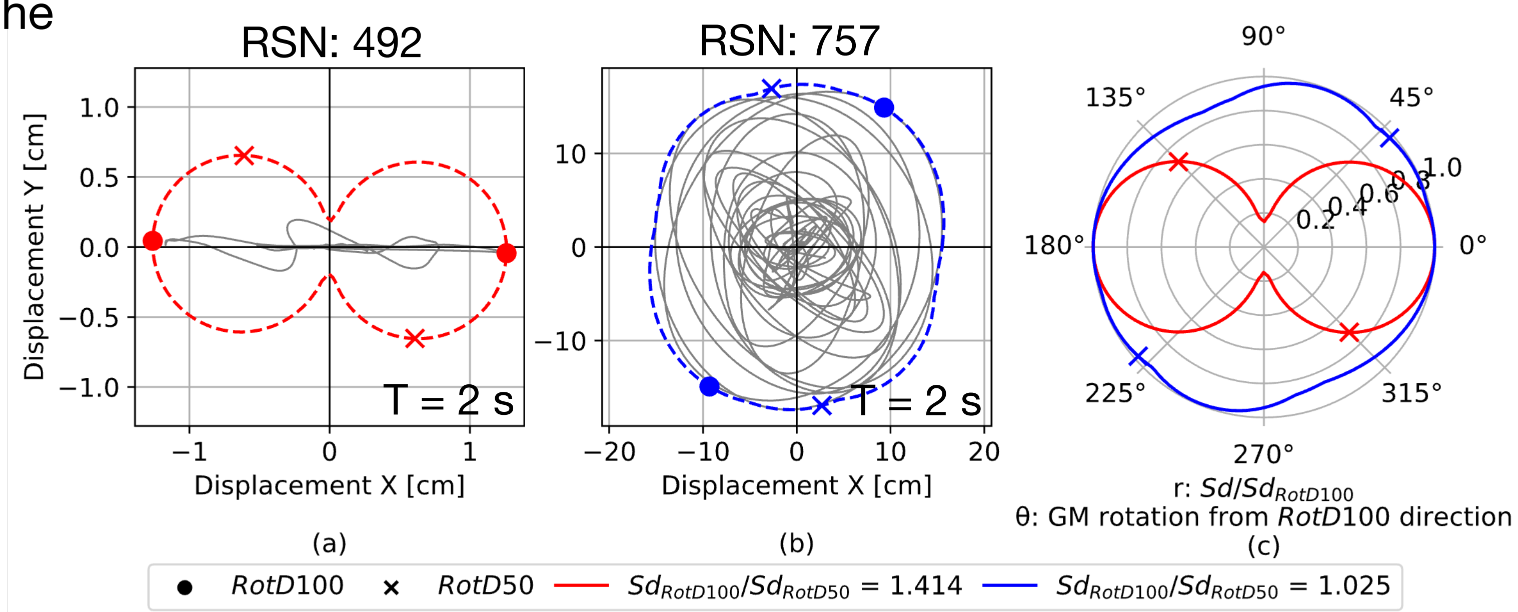
Ground motion directionality

- GMs include three translational and three rotational components (total: 6 components)
- Typically, rotational components are neglected, and vertical component receives much less attention than the horizontal ones
- Need to account for horizontal shaking in all orientations: when selecting and scaling GMs (with an IM that accounts for that), but also when applying them to structures
- Traditionally, the geometric mean of the IMs in each recorded direction was used, but orientation-dependent
- Commonly preferred orientation-independent definitions: *RotD50* and *RotD100*.

$$IM_{GM} = \left(IM_x \times IM_y\right)^{0.5}$$

$$IM_{RotD50} = \underset{\theta}{\mathrm{median}}[IM(\theta)]$$

$$IM_{RotD100} = \max_{\theta}[IM(\theta)]$$

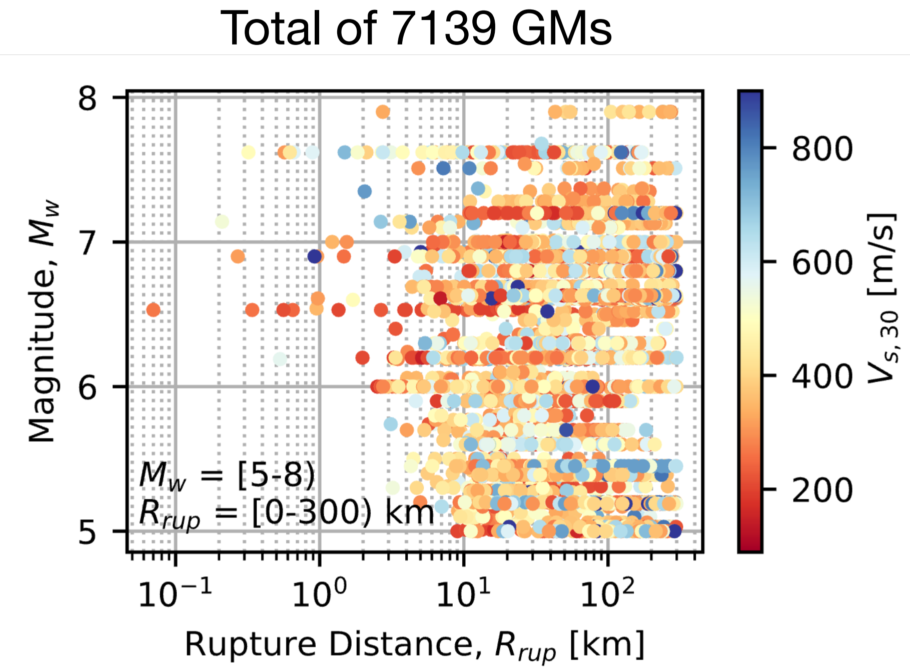


Baker, Bradley & Stafford (2021) – Section 4.2.6

Methodology

NGA-west2 database

GM filtering: **$M_w \geq 5$ & $R_{rup} \leq 300$ km**



Total of 7139 GMs

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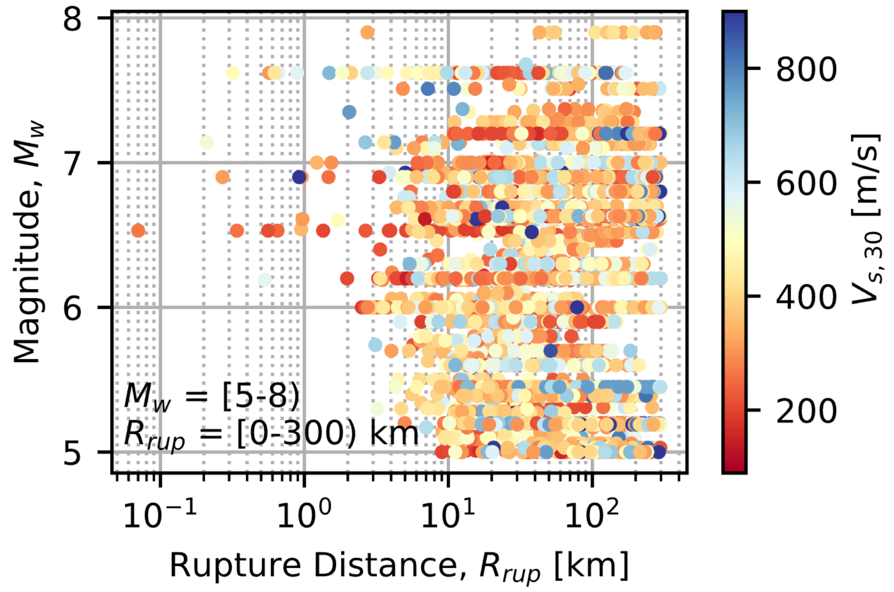
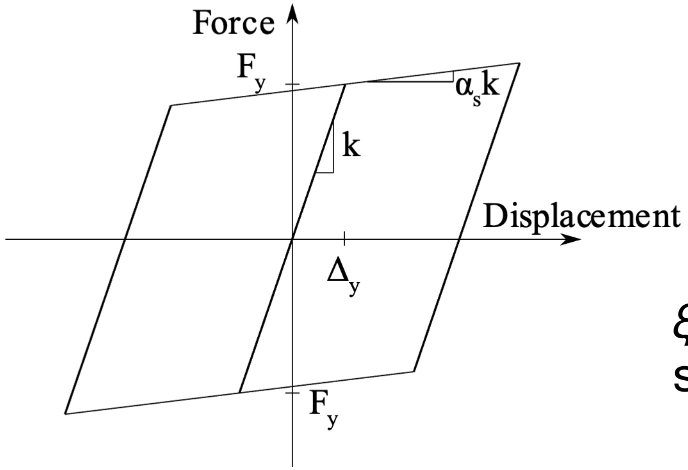
Definition of SDOF system characteristics

Total of 7139 GMs





$$F_y = \frac{m \times Sa_{RotD100}}{R}$$

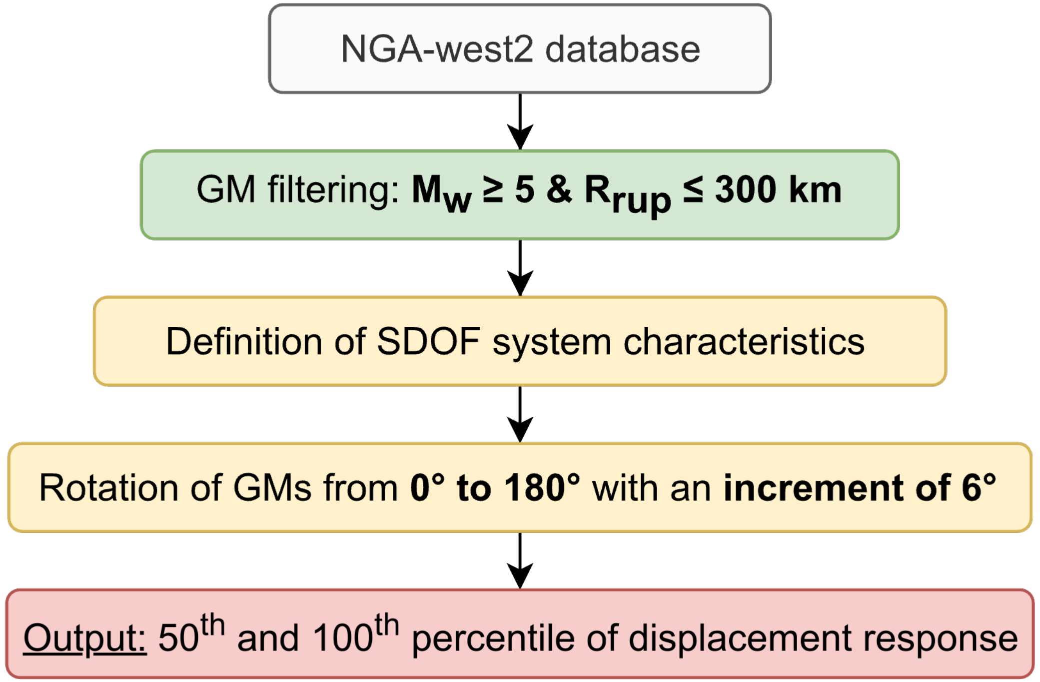
$$a_s = 3\ \%$$

ξ = 5% tangent-stiffness proportional

T = [0.04, 0.06, 0.1, 0.2, 0.3, 0.5, 0.75, 1, 1.5, 2, 3, 4, 5] s

R = [1.5, 2, 3, 4, 6]

Methodology



NGA-west2 database

GM filtering: $\mathbf{M_W \geq 5}$ **&** $\mathbf{R_{rup} \leq 300}$ **km**

Definition of SDOF system characteristics

Rotation of GMs from **0° to 180°** with an **increment of 6°**

<u>Output:</u> 50th and 100th percentile of displacement response

T = [0.04, 0.06, 0.1, 0.2, 0.3, 0.5, 0.75, 1, 1.5, 2, 3, 4, 5] s

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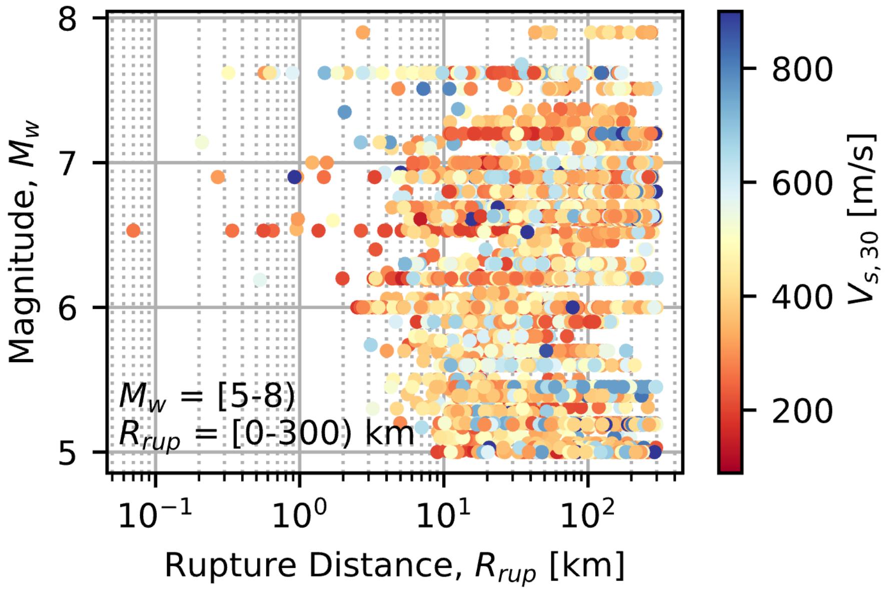

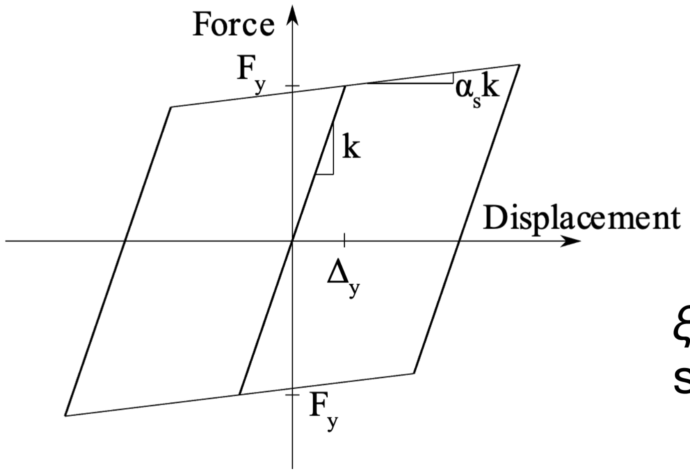

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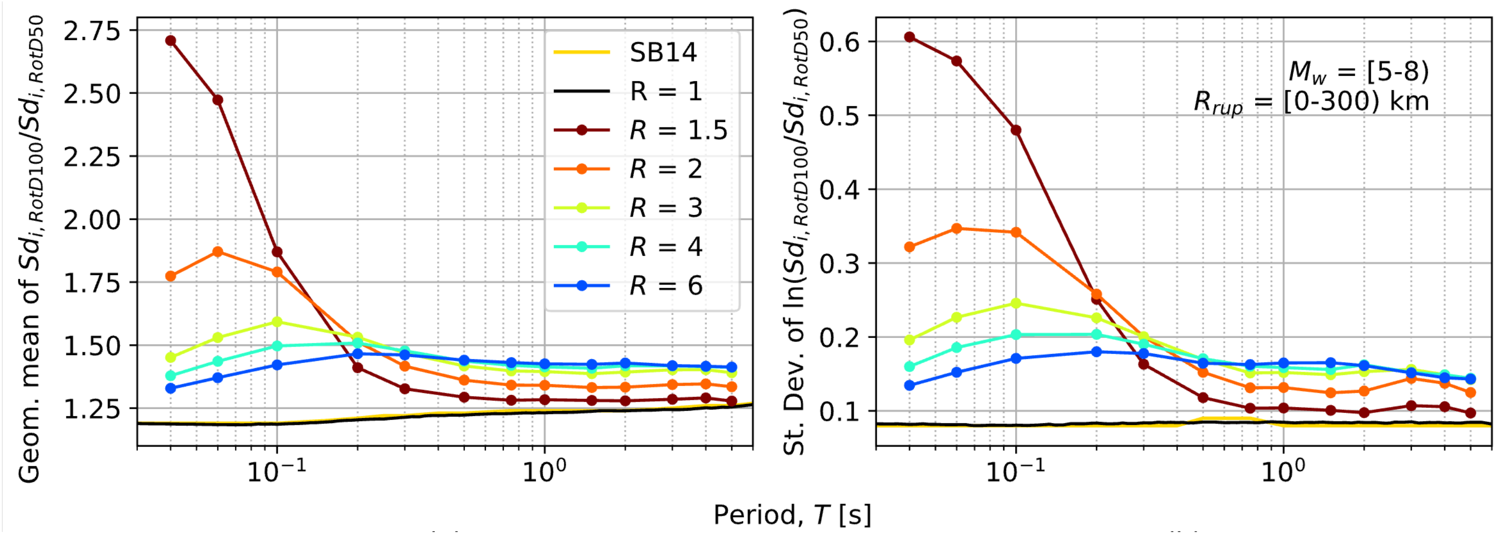
Directionality model for inelastic displacements



R = 2

T [s]	τ	φ	σ	$\ln(Sd_{i,RotD100}/Sd_{i,RotD50})$	$Sd_{i,RotD100}/Sd_{i,RotD50}$
0.04	0.099	0.306	0.321	0.651	1.917
0.06	0.079	0.334	0.344	0.679	1.973
0.1	0.044	0.333	0.336	0.581	1.788
0.2	0.040	0.249	0.252	0.397	1.487
0.3	0.023	0.196	0.197	0.339	1.404
0.5	0.012	0.150	0.150	0.307	1.360
0.75	0.006	0.130	0.130	0.295	1.343
1	0.007	0.130	0.130	0.292	1.339
1.5	0.011	0.122	0.123	0.284	1.328
2	0.009	0.125	0.125	0.287	1.333
3	0.021	0.137	0.138	0.291	1.338
4	0.019	0.130	0.131	0.292	1.339
5	0.015	0.121	0.122	0.287	1.332

Shahi and Baker (2014) → Directionality model for $Sa_{\mathrm{RotD100}}/Sa_{\mathrm{RotD50}}$

Aristeidou, Tarbali, and O'Reilly (2023) → Directionality model for $Sd_{\mathrm{i,RotD100}}/Sd_{\mathrm{i,RotD50}}$

Functional form of GMM

$$\ln \underbrace{Y_{i,j}}_{Sd_{i,RotD50} \text{ or } Sd_{i,RotD100}} = a + F_M + F_D + F_{sof} + F_s + F_{basin} + \eta_i + \varepsilon_{i,j}$$

a: Model scaling coefficient

$\mathbf{F_M}$: Magnitude scaling term

$\mathbf{F_D}$: Distance attenuation term

$\mathbf{F_{sof}}$: Style of faulting term

$\mathbf{F_s}$: Site amplification term

$\mathbf{F_{basin}}$: Basin effects correction term

$\boldsymbol{\eta_i}$: inter-event residual

$\boldsymbol{\varepsilon_{i,j}}$: intra-event residual

Predictor seismological parameters:

$\boldsymbol{M_w}$: Moment magnitude

$\boldsymbol{R_{rup}}$: Rupture distance

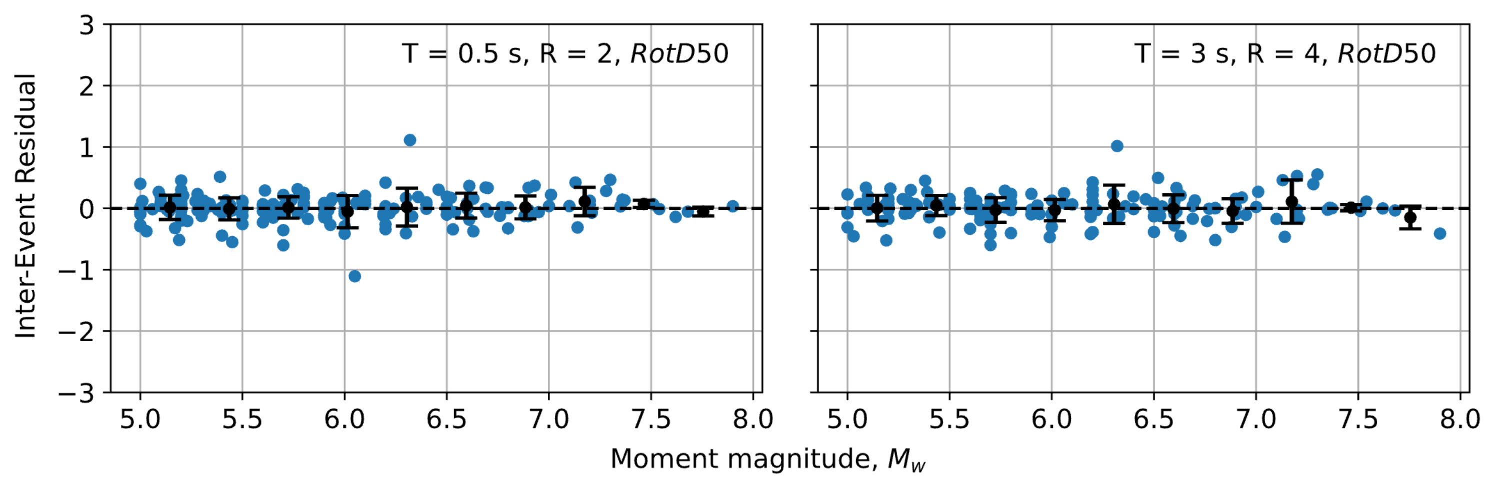
Fault mechanism: Discretised into 3 faulting styles: strike-slip, normal and thrust fault

$\boldsymbol{V_{s,30}}$: Time-averaged soil shear-wave velocity to 30 m depth

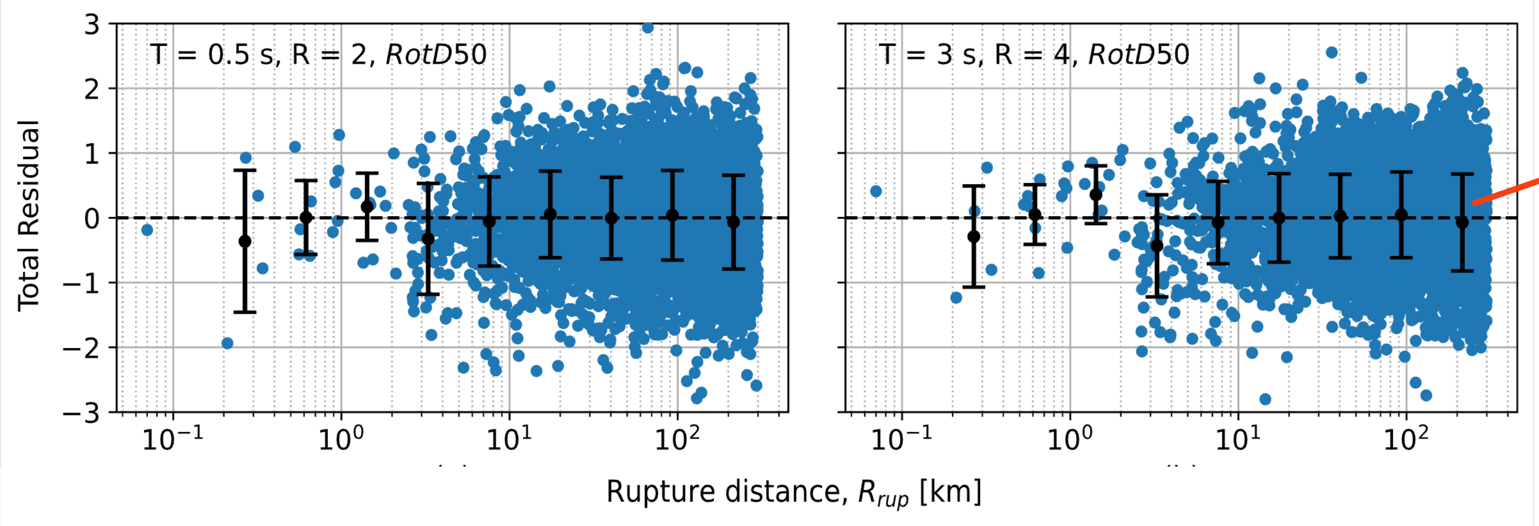
$\boldsymbol{Z_{2.5}}$: Depth to the 2.5 km/s shear-wave velocity horizon (basin proxy)

18 model coefficients calibrated for each elastic vibration period, ***T***, and strength ratio, ***R***

GMM performance



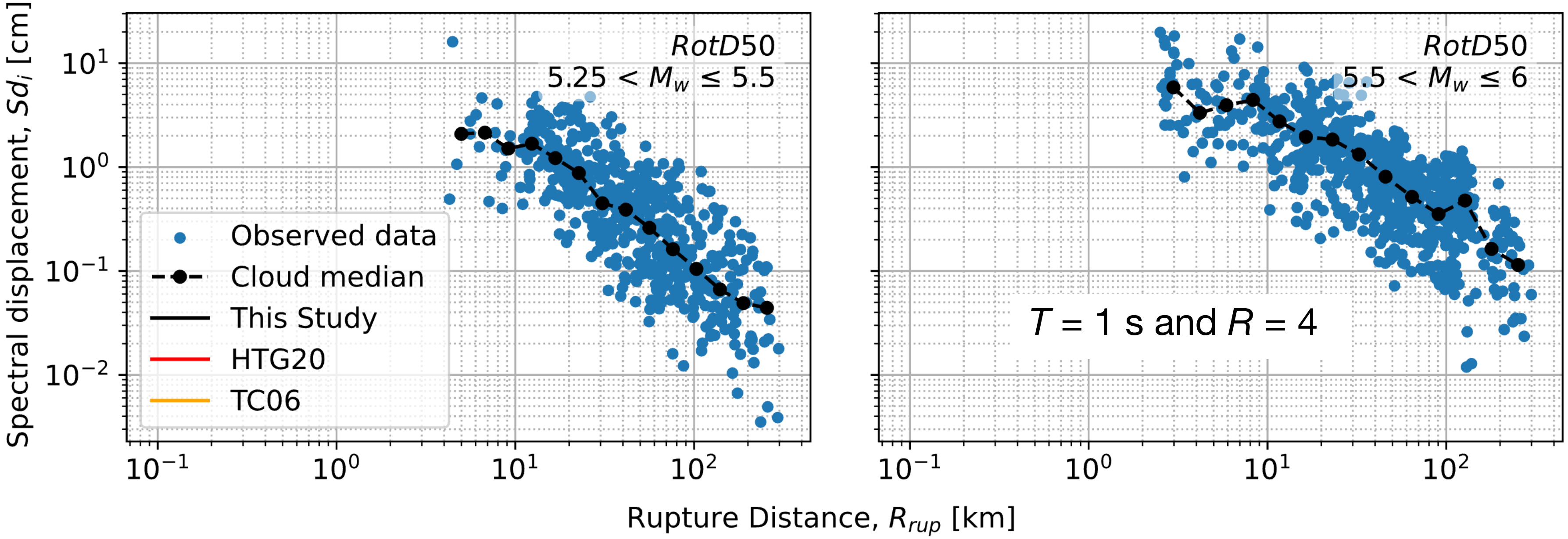
- Residual definition: difference between ‘observed empirical data’ and model predictions
- No apparent bias is present
- **R^2 ≈ 0.8** for most *T* and *R* cases



Binned mean residual values
± 1 standard deviation

Comparison with other studies

- Only a few available models that have strength ratio, *R*, as input. A few of them have ductility demand, *μ*, or strength coefficient, C_y
- Two models from the literature were compared herein
- Median prediction of the proposed GMM matches well the cloud median



T = 1 s and *R* = 4

Huang, Tarbali and Galasso (2020): HTG20 ***Tothong and Cornell (2006): TC06***

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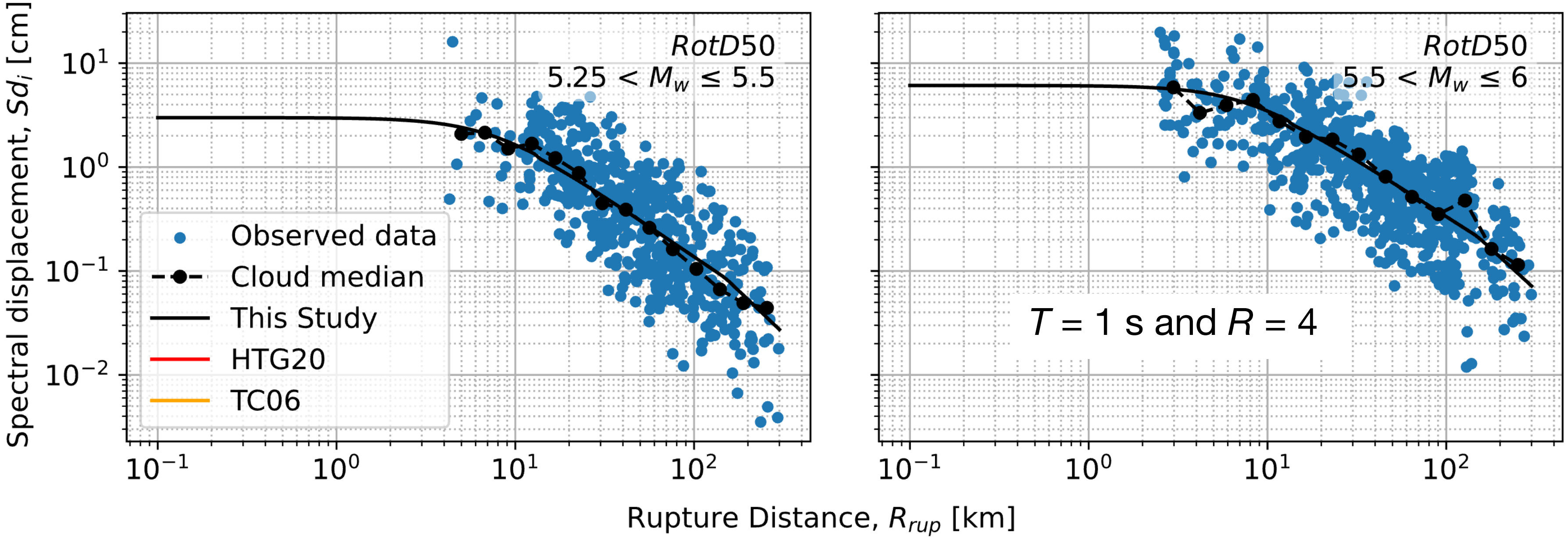

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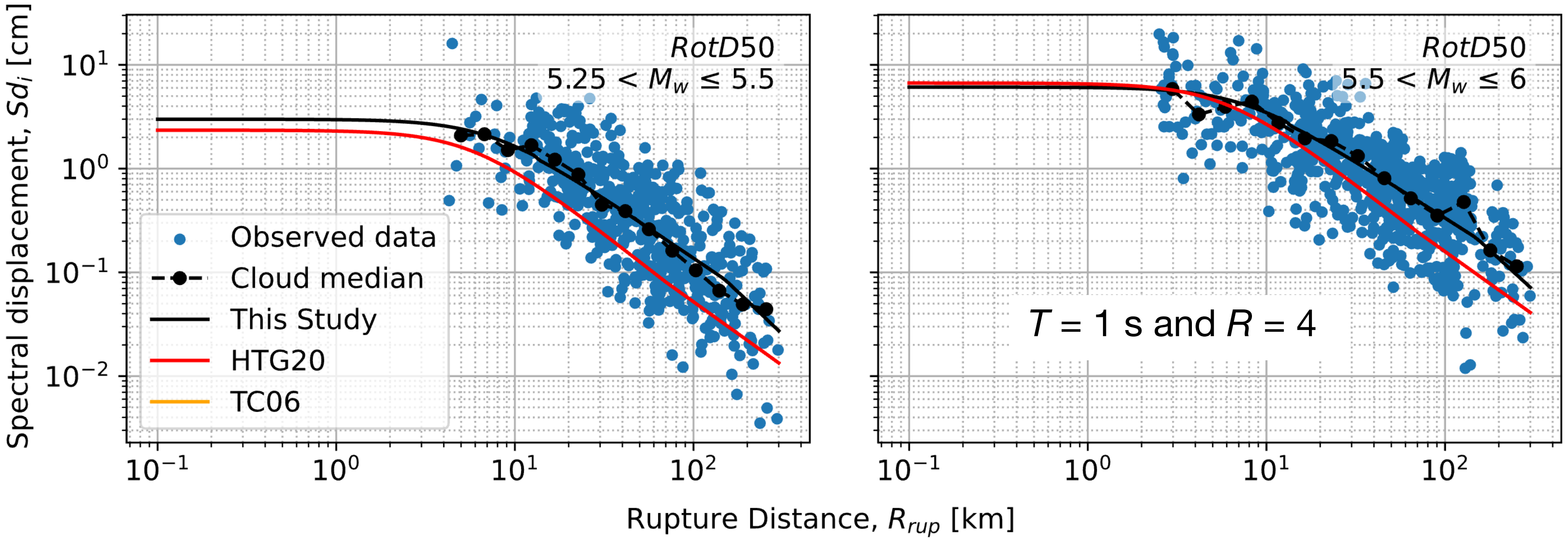

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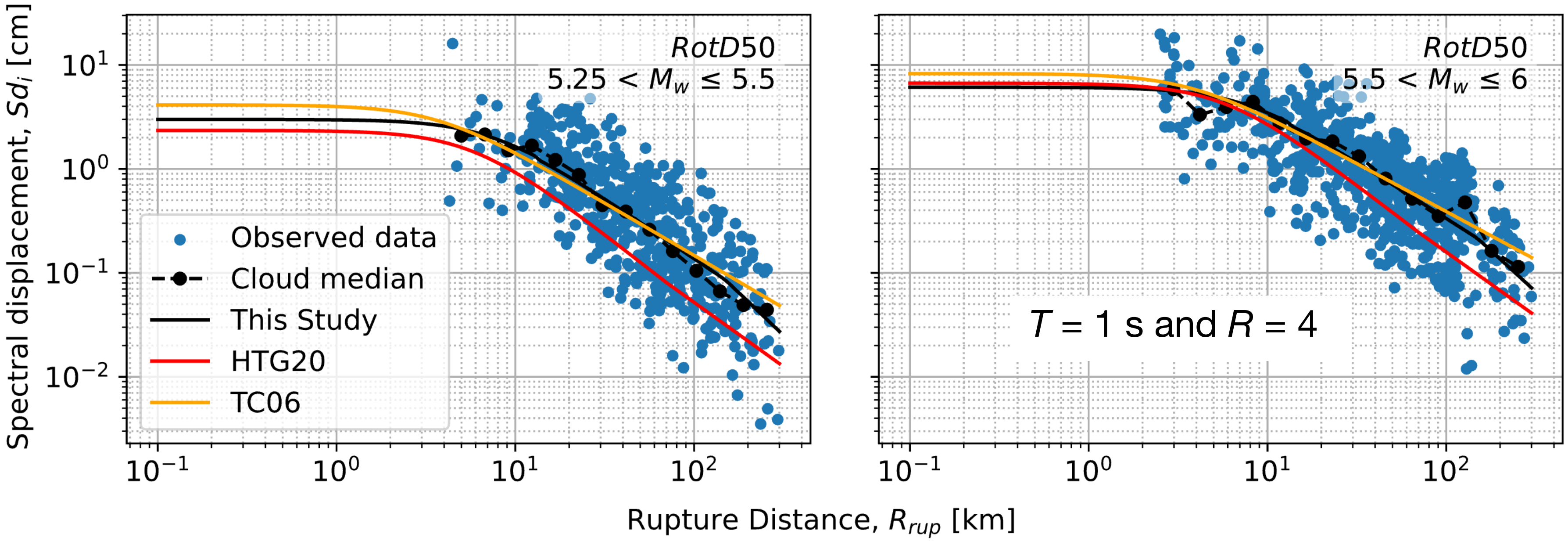

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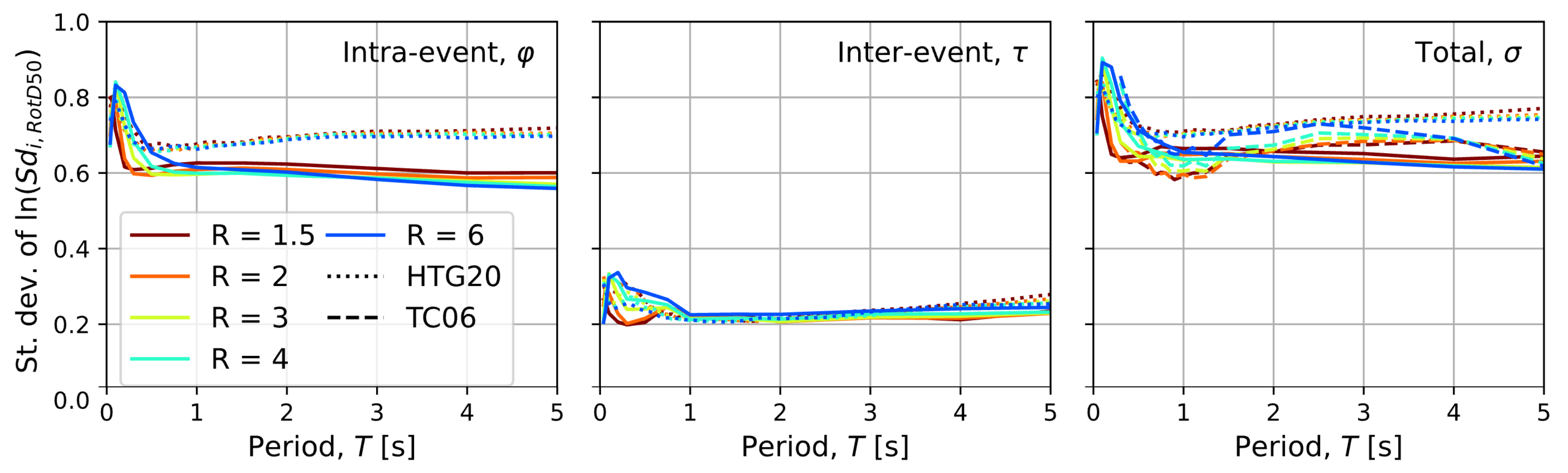
Tothong and Cornell (2006): TC06

Variability in the GMM

- The proposed model gives lower standard deviations for most periods when comparted to TC06 and HTG20
- *RotD50* component slightly reduces the dispersion in comparison to the arbitrary component used by TC06 and to the geometric mean used by HTG20
- HTG20: difference mainly due to intra-event, which is a product of considering spatial correlation



Inter- and intra-event residuals mutually independent

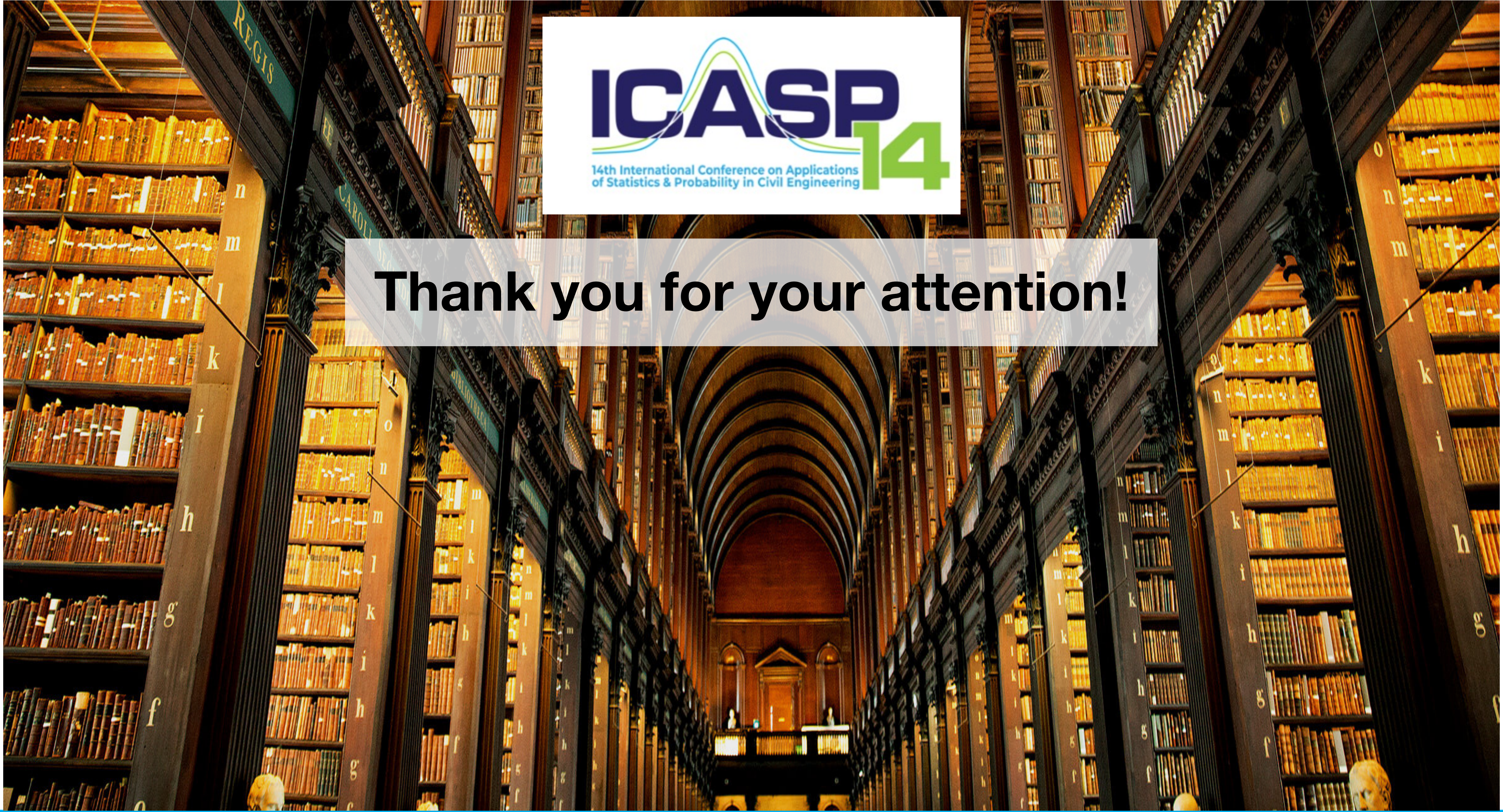
$$\sigma = \sqrt{\tau^2 + \varphi^2}$$

Beyer and Bommer (2006) ***Jayaram and Baker (2010)***

Conclusions

- GMM developed to estimate the *RotD50* and *RotD100* horizontal component of Sd_i from shallow-crustal earthquakes
- Used substantially large dataset of GMs from NGA-West2 database
- Does not require any auxiliary elastic GMM to predict the median and dispersion of inelastic displacements
- Range of applicability: $5 < \boldsymbol{M}_{\mathbf{w}} \leq 8$; $0 < \boldsymbol{R}_{\mathbf{rup}} \leq 300$ km; $90 \leq \boldsymbol{V}_{\mathbf{s,30}} \leq 1300$ m/s; $0.04 \leq \boldsymbol{T} \leq 5$ s; $1 \leq \boldsymbol{R} \leq 6$; tectonically active shallow crustal regions
- Model exhibits good performance and reasonably low dispersions, compared to similar models available in literature, and they are not sensitive to the level of non-linear demand
- Proposed directionality models based on Sd_i, given in the journal paper, can be used
- Directionality can be also estimated from the GMM itself, using the different available horizontal component definitions

- ***Aristeidou, S., K. Tarbali, and G. J. O'Reilly. 2023. "A ground motion model for orientation-independent inelastic spectral displacements from shallow crustal earthquakes." Earthq. Spectra, 0 (0): 1–23. https://doi.org/10.1177/87552930231180228.***
- ***Aristeidou, S., G. J. O'Reilly. 2023. "Exploring the use of orientation-independent inelastic spectral displacements in the seismic assessment of bridges." Under review.***



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