Recent advances in seismic risk modelling

from spatial correlation to damage and loss dependence

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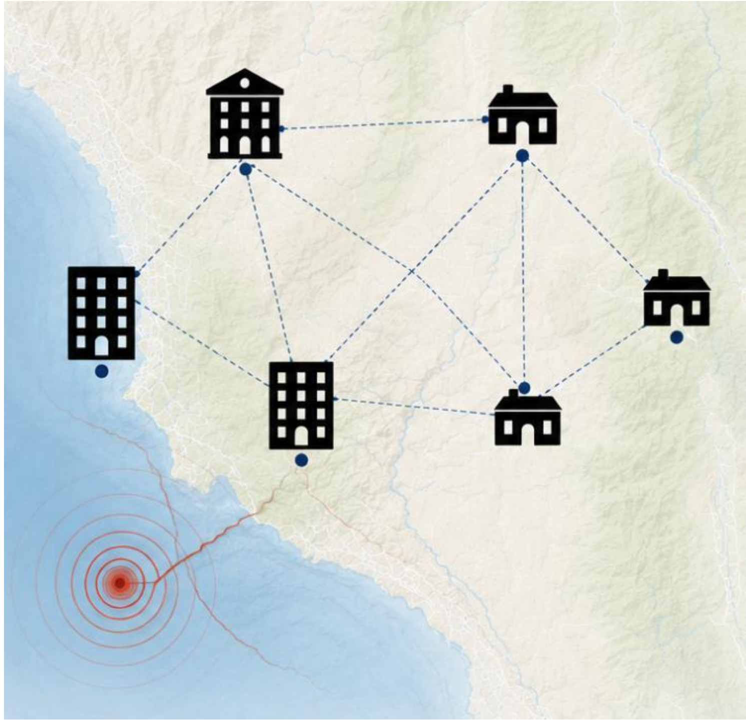
GEM CONFERENCE
FROM FAULTS TO FUTURE SCENARIOS

Challenges this talk seeks to address

1. How can seismic vulnerability of individual structures be more accurately captured?

2. How can this be practically implemented for an entire region?

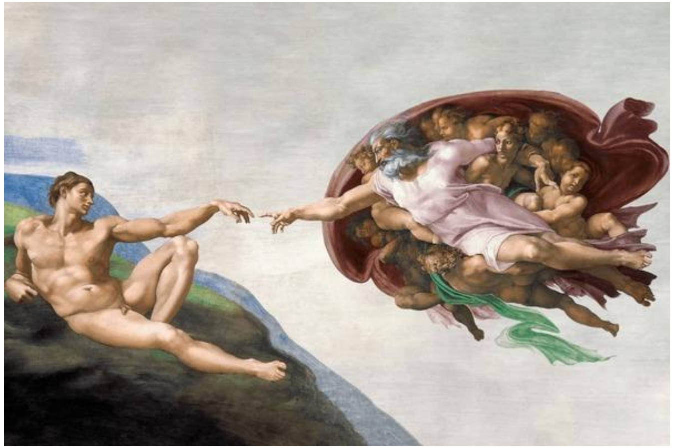
3. How does damage correlation between similar buildings affect portfolio loss estimates?

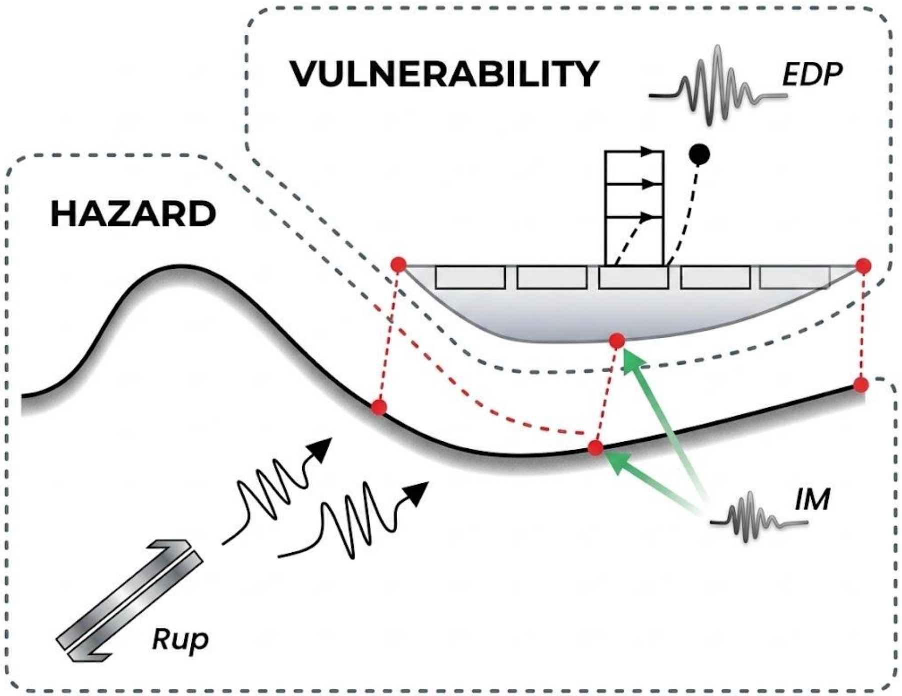


1. How can seismic vulnerability of individual structures be more accurately captured?

Intensity measures

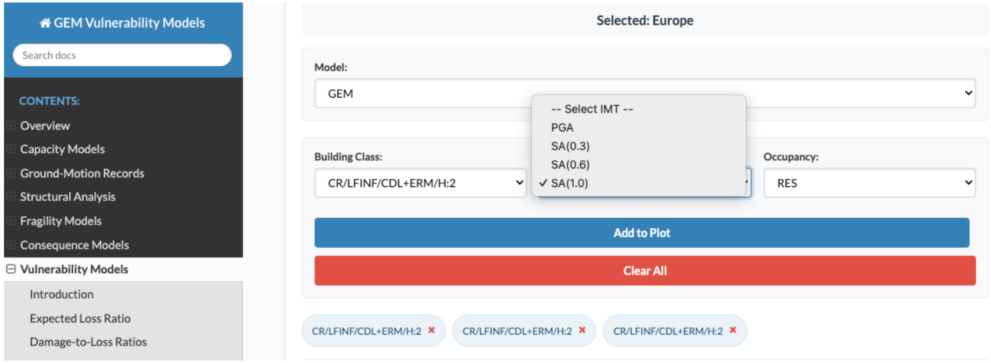
- IMs are the interface variable between seismic hazard and vulnerability



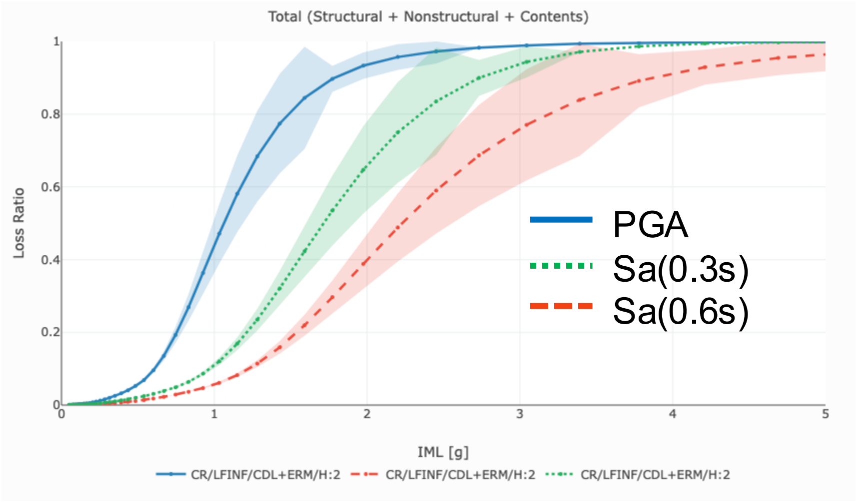


Intensity measures

- Practice has maintained Sa(T) and PGA as reference IMs for vulnerability models
- ESRM20 adopted PGA, Sa(0.3s), Sa(0.6s) and Sa(1s)
- Average spectral acceleration has 10-15 years of research demonstrating its benefits across a range of structural typologies and seismic scenarios



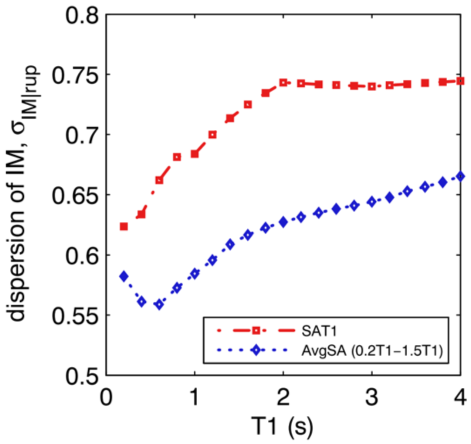
https://docs.openquake.org/vulnerability/vulnerability_models.html



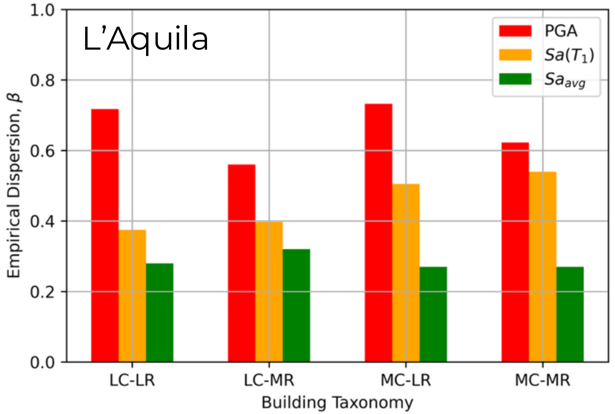
Reduced uncertainty

- Compared with Sa(T), the average spectral acceleration (Sa_{avg}(T) but also written as AvgSA) has lower dispersion for **both hazard** **<u>and</u>** **vulnerability**

Lower GMM dispersion



Lower empirical fragility function dispersion



Kohrangi et al. (2017) DOI:10.1002/eqe.2876
Nafeh O'Reilly (2024) DOI: 10.1007/s10518-024-01955-4

2. How can this be practically implemented for an entire region?

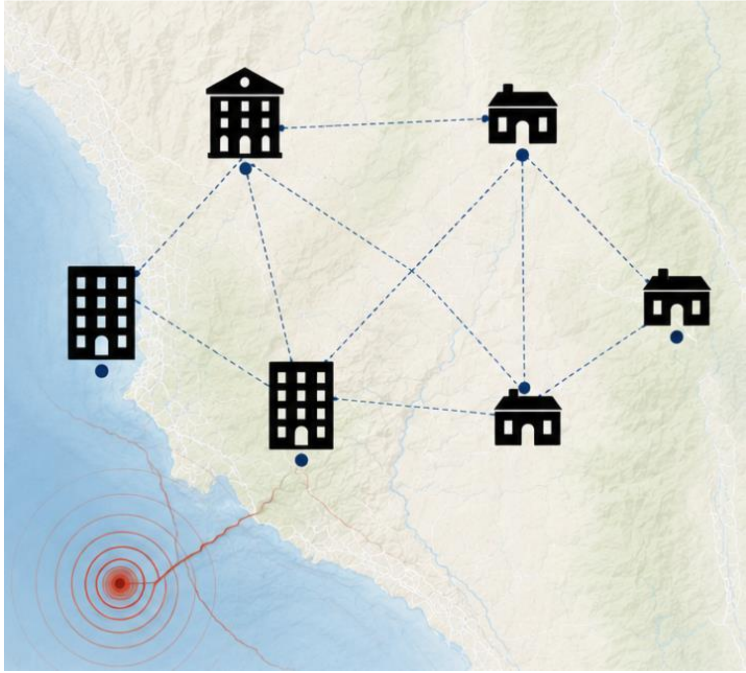
So what is the problem?

$$\ln \mathbf{IM}_i = \boldsymbol{\mu}_{\ln IM_i} + \underbrace{\delta b_i \cdot \tau_i \cdot \mathbf{1}}_{\boldsymbol{\delta B}} + \underbrace{\boldsymbol{\delta w}_i \cdot \phi_i}_{\boldsymbol{\delta W}}$$

- Vulnerability modelling research has identified a more accurate IM in $Sa_{avg}(T)$
- Lacks the hazard infrastructure to support its practical implementation in risk analysis
- Specifically, very few GMMs or spatial correlation models existed until recently

$$\boldsymbol{\mu}_{\ln IM_i} = [\mu_{\ln IM_{i,1}}, \ldots, \mu_{\ln IM_{i,M}}]^T$$

$$\Sigma = \underbrace{\tau_i^2 \cdot \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1 & \cdots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \cdots & 1 \end{bmatrix}}_{\text{between-event term}} + \underbrace{\phi_i^2 \cdot \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1M} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{M1} & \rho_{M2} & \cdots & \rho_{MM} \end{bmatrix}}_{\text{within-event term}}$$



Indirect methods

- Indirect methods were proposed based on existing GMMs for Sa(T) and relationship between them
- Different studies (e.g., Bianchini et al., 2009; Bojorquez and Iervolino, 2011; Kohrangi et al., 2017) proposed the aggregate GMM approach
- Heresi and Miranda (2021) developed the indirect spatial correlation model

Ground motion model

$$\mu_{\ln Sa_{avg}(T)|rup} = \frac{1}{N}\sum_{i=1}^{N}\mu_{\ln Sa(c_iT)|rup}$$

$$\sigma^2_{\ln Sa_{avg}(T)|rup} = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\rho_{\ln Sa(c_iT),\ln Sa(c_jT)}\sigma_{\ln Sa(c_iT)|rup}\sigma_{\ln Sa(c_jT)|rup}$$

Spatial correlation model

$$\rho_{\ln Sa_{avg}(T)_n,\ln Sa_{avg}(T)_m} = \frac{\frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\rho_{\ln Sa(c_iT)_n,\ln Sa(c_jT)_m}\sigma_{\ln Sa(c_iT)_n}\sigma_{\ln Sa(c_jT)_m}}{\sigma_{\ln Sa_{avg}(T)_n}\sigma_{\ln Sa_{avg}(T)_m}}$$

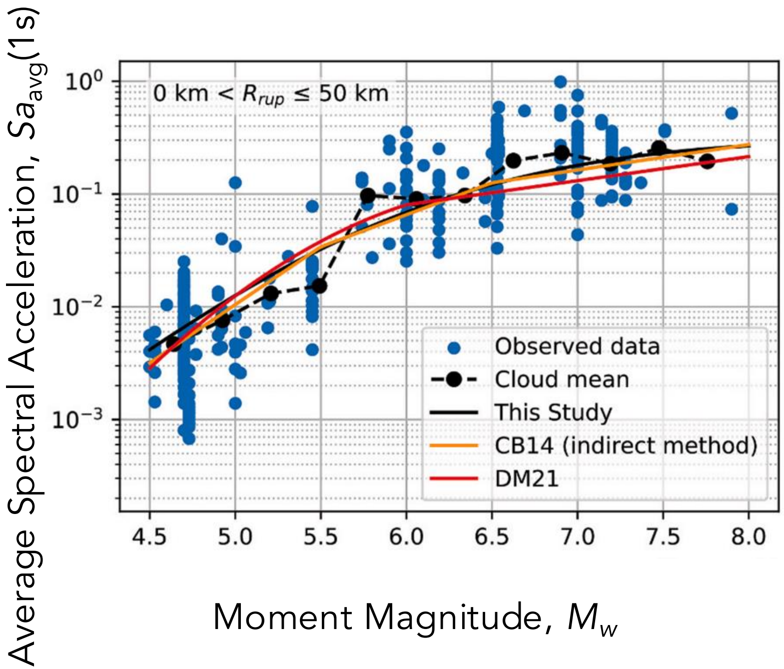
Direct solutions for GMM

$$\ln \mathbf{IM}_i = \boldsymbol{\mu}_{\ln IM_i} + \underbrace{\boldsymbol{\delta b}_i \cdot \tau_i \cdot \mathbf{1}}_{\boldsymbol{\delta B}} + \underbrace{\boldsymbol{\delta w}_i \cdot \phi_i}_{\boldsymbol{\delta W}}$$

- Direct model developed for $Sa_{avg}(T)$ and many other next-generation IMs
- Allows for ground motion record selection for single site analysis and generation of GMFs

Available!

Savvinos Aristeidou



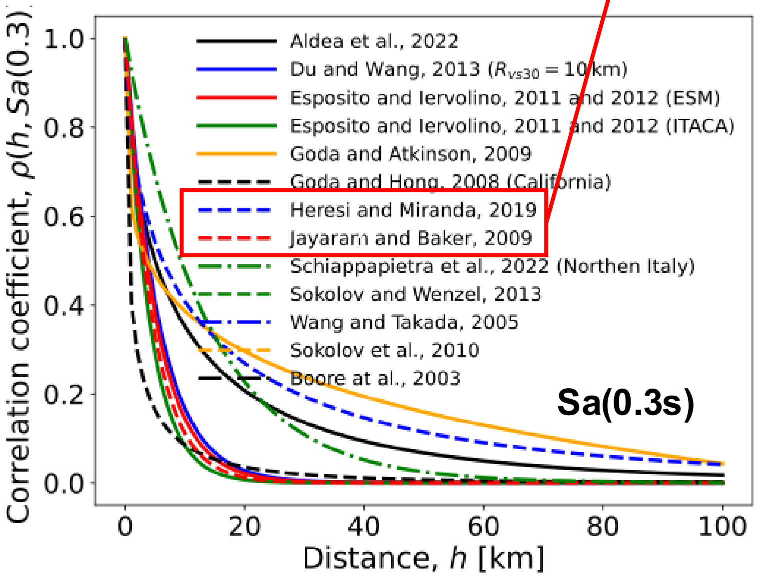
Aristeidou, S et al. (2024) DOI:10.1016/j.soildyn.2024.108851

Direct solutions for spatial correlation

- This led to the development of a direct spatial correlation model for $Sa_{avg}(T)$
- Developed using principal component analysis (PCA)
- Considerably faster to use compared to indirect formulation

Vítor Monteiro

GitHub

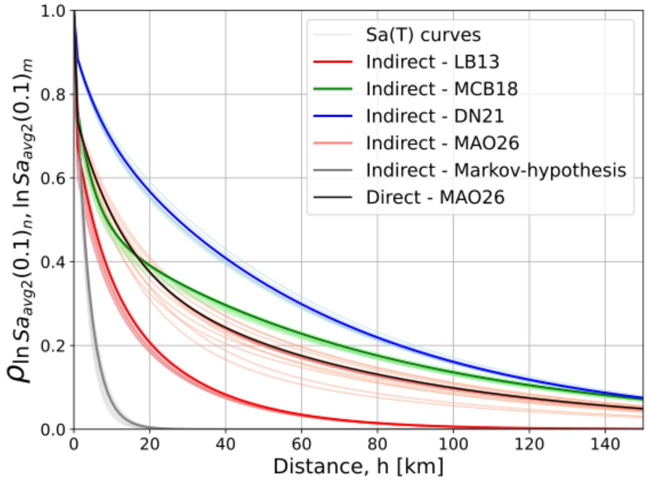


Monteiro VA, Aristeidou S & O'Reilly GJ (2026) DOI: 10.1002/esp4.70076

Direct versus indirect?

$$\rho_{\ln Sa_{avg}(T)_n, \ln Sa_{avg}(T)_m} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} [\rho^B_{i,j}\tau_i\tau_j + \rho^W_{i,j,n,m}\phi_i\phi_j]}{\sum_{i=1}^{N} \sum_{j=1}^{N} [\rho^B_{i,j}\tau_i\tau_j + \rho^W_{i,j,0}\phi_i\phi_j]}$$

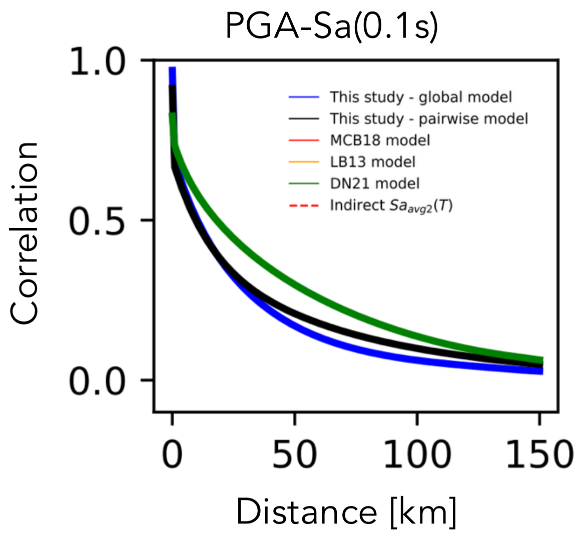
- Monteiro and O'Reilly (2026) extended this indirect spatial correlation model to separate between- and within-event residuals
- Compared it to a direct model and found it works reasonably well
- Accumulates errors in aggregation and is much slower to implement on a regional scale



Monteiro VA & O'Reilly GJ (2026) DOI: 10.1002/esp4.70049

Inclusion of cross-IM spatial correlation

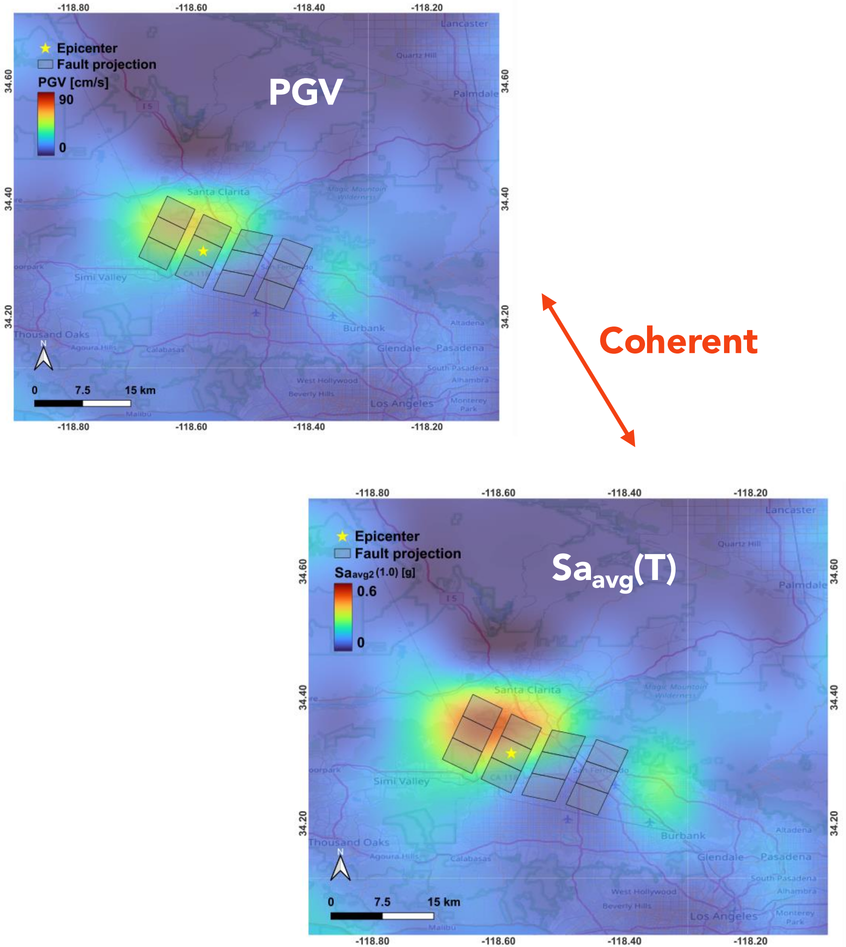
- In the process, a cross-IM spatial correlation model was developed for many IMs
- This tackled other practical issues where spatial correlation models:
  - Correlating IM_1 to IM_1
  - Correlating IM_1 to IM_2 ⟵ **Seldom available**



Monteiro VA, Aristeidou S & O'Reilly GJ (2026) DOI: 10.1002/esp4.70076

Advantages offered

- IMs like $Sa_{avg}(T)$ can be efficiently implemented on a regional scale
- Multiple IMs can be collectively simulated in ground motion fields (GMFs)
- Vector-IM fragility and vulnerability models can be used

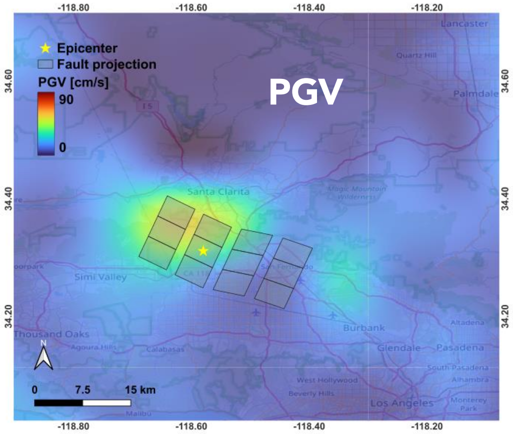


Monteiro VA, Aristeidou S & O'Reilly GJ (2026) DOI: 10.1002/esp4.70076

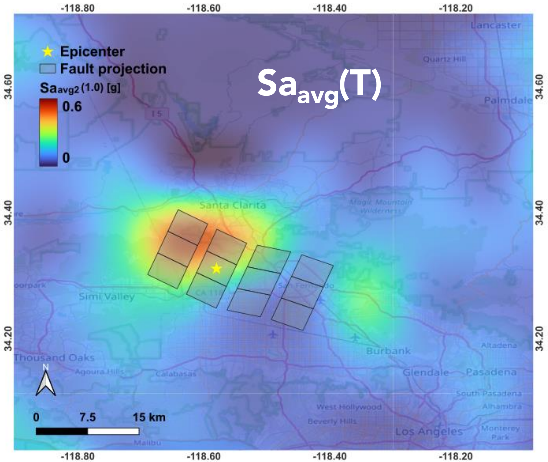
Advantages offered

- The PCA-based model is <u>**much faster**</u>
- The Cholesky factorisation scales as $O(N^3)$ so for m locations and n IMs:
  - **LMC/MT:** one $(mn) \times (mn)$factorization $\rightarrow \frac{1}{3}(mn)^3$FLOPS
  - **PCA:** PCs $n \times n$factorizations $\rightarrow \text{PCs} \cdot \frac{1}{3} n^3$FLOPS

Coming soon!



Coherent



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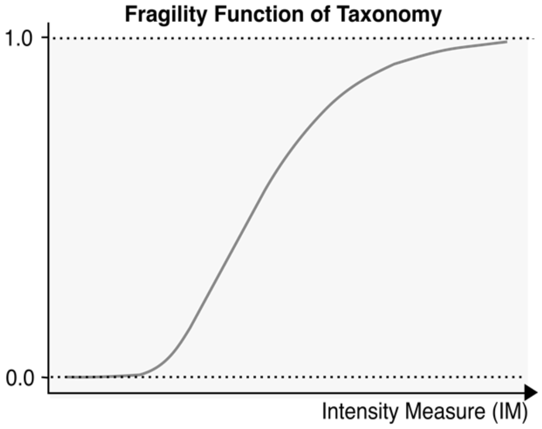
3. How does damage correlation between similar buildings affect portfolio loss estimates?

Damage correlation in scenario assessment

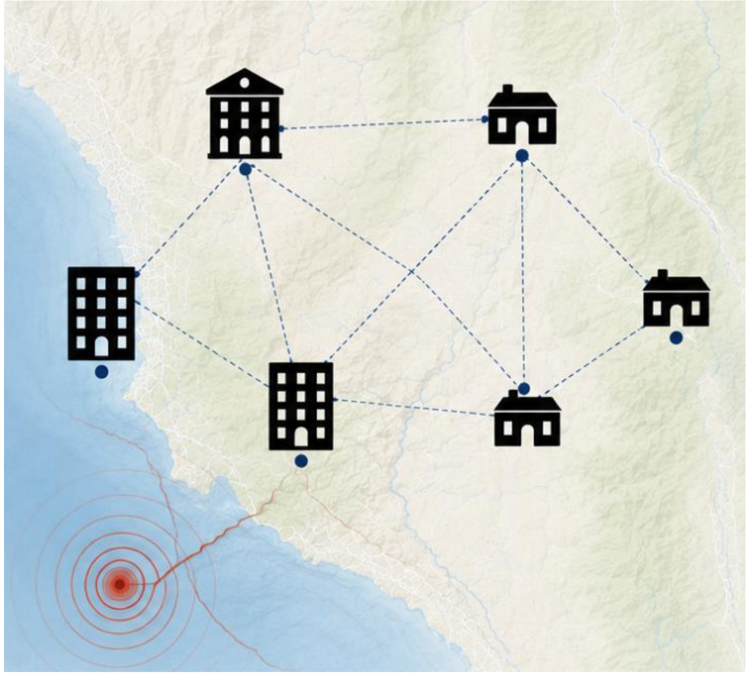
- Structures constructed in the same region were likely designed and constructed with **similar characteristics** resulting in them having **similar strengths or deficiencies**
- Does this impact damage scenarios and losses?

Damage correlation in scenario assessment

- For the simple case of collapse assessment, how can this be considered
- Assume all buildings have the same fragility and the GMF is constant (just for illustration)



Tomas Mejia



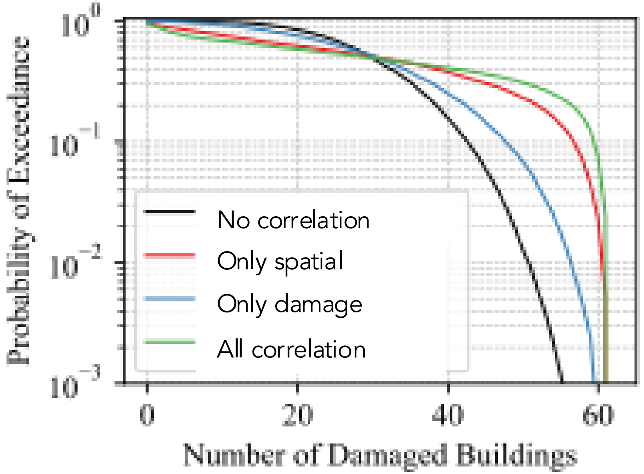
Damage correlation in scenario assessment

- Uses Gaussian Copulas to handle structure-to-structure correlation of damage states

$$\Phi[\Phi^{-1}(p_a), \Phi^{-1}(p_b); \delta_{a,b}]$$

- Case study implementation for a city in Italy
- Examined number of damaged buildings for a scenario earthquake

Number of buildings	No spatial or damage correlation	Spatial correlation only	Damage correlation only	All correlation considered
40	16%	38%	25%	40%
45	6%	31%	15%	36%
50	1%	23%	7%	31%



Mejia T & O'Reilly GJ (2026) DOI: 10.1002/eqe.70069

Damage correlation in scenario assessment

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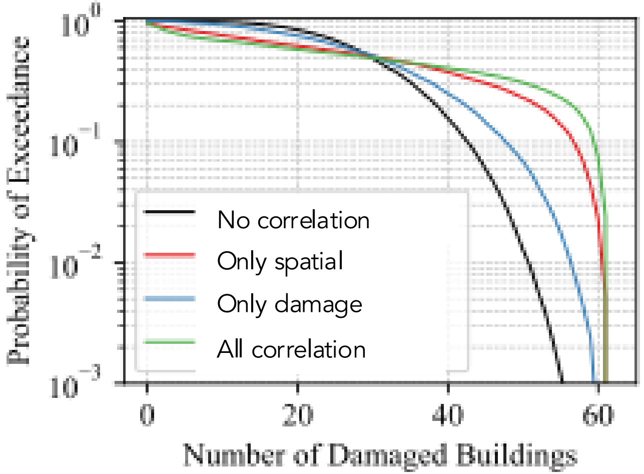

Mejia T & O'Reilly GJ (2026) DOI: 10.1002/eqe.70069

Potential caveats of DS-based approach

- Extending this to a general regional scale approach using damage states becomes tricky
- For T taxonomies with M buildings each, and assuming all buildings have K damage states, we need KMT intra-DS models and $((KMT)^2 - KMT)/2$ inter-DS models to construct the covariance matrix
- Computational infrastructure would need to be updated alongside the correlation model creation

$$
\Sigma_X = \begin{bmatrix}
\multicolumn{2}{c}{\text{DS}_1} & \cdots & \multicolumn{2}{c}{\text{DS}_k} \\
\text{Tax. 1} & \cdots\ \text{Tax. T} & & \text{Tax. 1} & \cdots\ \text{Tax. T} \\
\{\text{B}_a \cdots \text{B}_b\} & \{\text{B}_x \cdots \text{B}_y\} & & \{\text{B}_a \cdots \text{B}_b\} & \{\text{B}_x \cdots \text{B}_y\} \\
\begin{bmatrix} \delta^{1,1}_{a,a} & \cdots & \delta^{1,1}_{a,b} \\ \vdots & \ddots & \vdots \\ \delta^{1,1}_{b,a} & \cdots & \delta^{1,1}_{b,b} \end{bmatrix} &
\begin{bmatrix} \delta^{1,1}_{a,x} & \cdots & \delta^{1,1}_{a,y} \\ \vdots & \ddots & \vdots \\ \delta^{1,1}_{b,x} & \cdots & \delta^{1,1}_{b,y} \end{bmatrix} & \cdots &
\begin{bmatrix} \delta^{1,k}_{a,a} & \cdots & \delta^{1,k}_{a,b} \\ \vdots & \ddots & \vdots \\ \delta^{1,k}_{b,a} & \cdots & \delta^{1,k}_{b,b} \end{bmatrix} &
\begin{bmatrix} \delta^{1,k}_{a,x} & \cdots & \delta^{1,k}_{a,y} \\ \vdots & \ddots & \vdots \\ \delta^{1,k}_{b,x} & \cdots & \delta^{1,k}_{b,y} \end{bmatrix} \\
(\text{sym}) &
\begin{bmatrix} \delta^{1,1}_{x,x} & \cdots & \delta^{1,1}_{x,y} \\ \vdots & \ddots & \vdots \\ \delta^{1,1}_{x,y} & \cdots & \delta^{1,1}_{y,y} \end{bmatrix} & \cdots &
\begin{bmatrix} \delta^{1,k}_{x,a} & \cdots & \delta^{1,k}_{x,b} \\ \vdots & \ddots & \vdots \\ \delta^{1,k}_{y,a} & \cdots & \delta^{1,k}_{y,b} \end{bmatrix} &
\begin{bmatrix} \delta^{1,k}_{x,x} & \cdots & \delta^{1,k}_{x,y} \\ \vdots & \ddots & \vdots \\ \delta^{1,k}_{y,x} & \cdots & \delta^{1,k}_{y,y} \end{bmatrix} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
(\text{sym}) & (\text{sym}) & \cdots &
\begin{bmatrix} \delta^{k,k}_{a,a} & \cdots & \delta^{k,k}_{a,b} \\ \vdots & \ddots & \vdots \\ \delta^{k,k}_{a,b} & \cdots & \delta^{k,k}_{b,b} \end{bmatrix} &
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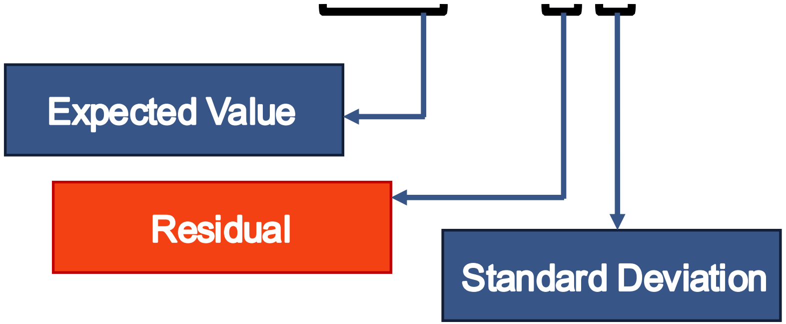
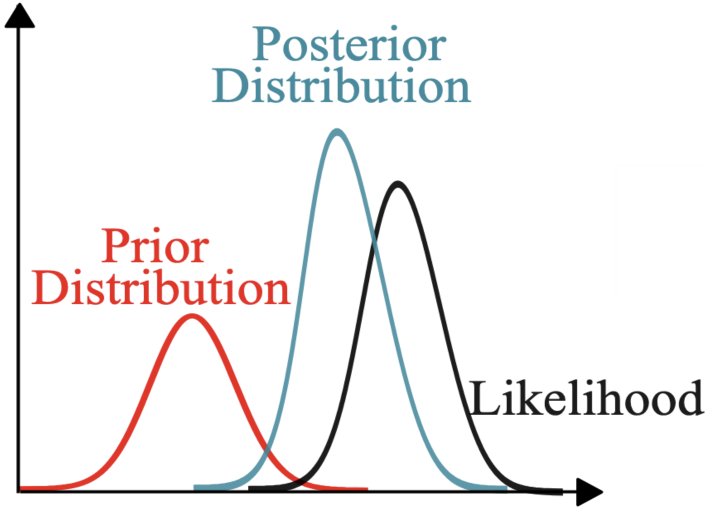
(\text{sym}) & (\text{sym}) & \cdots & (\text{sym}) &
\begin{bmatrix} \delta^{k,k}_{x,x} & \cdots & \delta^{k,k}_{x,y} \\ \vdots & \ddots & \vdots \\ \delta^{k,k}_{y,x} & \cdots & \delta^{k,k}_{y,y} \end{bmatrix}
\end{bmatrix}
$$

Alternative procedures

- Instead of sampling DSs, sample EDPs instead
- Correlate the residuals of the obtained EDPs
- The result could be updated with real observations from instrumented buildings

$$\ln(EDP)\,|\,\ln(im) = \mu_{EDP|IM} + \varepsilon \,.\, \sigma$$





Sources of damage correlation (ongoing)

- Consequence similarity can arise for different reasons
- These may relate to:
  - Similarity in dynamic characteristics of structures
  - Common structural construction deficiencies

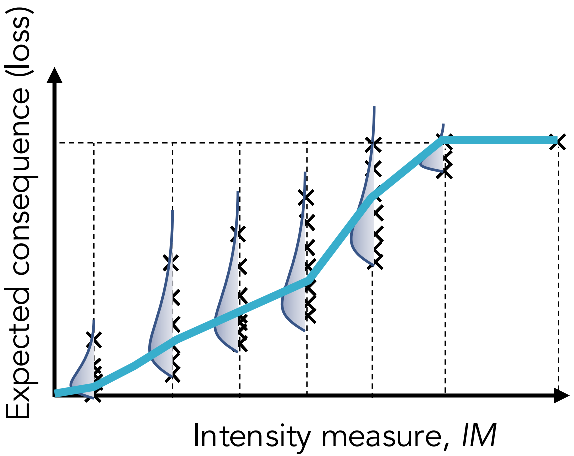
$$\sigma_{tot}^2 = \underbrace{\sigma_d^2}_{\text{Dynamic}} + \underbrace{\sigma_c^2}_{\text{Construction deficiences}}$$

- It is analagous to how between-event and within-event correlations are handled in seismic hazard
- <u>Question</u>: is the correlation dependent on the intensity measure used? ← **Spoiler: Yes!**

Extension to loss and vulnerability (ongoing)

- This same concept can be extended to the vulnerability curve showing the **expected loss**

$$Loss|\ln(IM) = \mu_{Loss|IM} + \varepsilon \;.\; \sigma$$



- The correlation between losses (or damage or EDP previously) can analysed analytically and validated empirically using field data

- The is no effect of the damage correlation in the expected loss but there should be in the total loss or distribution tails

THANK YOU!

June 23 – 25, 2026
University of Zagreb, Croatia

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