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Empirical tsunami fragility modelling for hierarchical damage levels: application to damage data of the 2009 South Pacific and 2018 Sulawesi Palu Tsunamis

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Bayesian framework for empirical tsunami fragility parameter estimation and model selection for hierarchical damage levels

Hazard Curve

$$\lambda(IM > im)$$

$$\lambda(IM > im) = \sum_{i}^{N} \lambda_{M_{\min},i} \int_{s,m} P(IM > im \mid s, m)\, f_{s|M}(s \mid m)\, f_M(m)\, \mathrm{d}s\mathrm{d}m$$

IM ***(Intensity Measure)***

e.g., flow depth, momentum flux

Vulnerability Curve

$$G_{DV|IM}(dv \mid im) = \sum_{i=1}^{N_{DS}} G_{DV}(dv \mid DS_i)\, P(DS_i \mid im)$$

$$P_{DS|IM}(DS_i \mid im)$$

(Fragility Function)

DM ***(Damage Measure)***

e.g., damage states

$$G_{DV|DS}(dv \mid DS)$$

(Consequence Function)

DV ***(Decision Variable)***

e.g., fatalities, loss

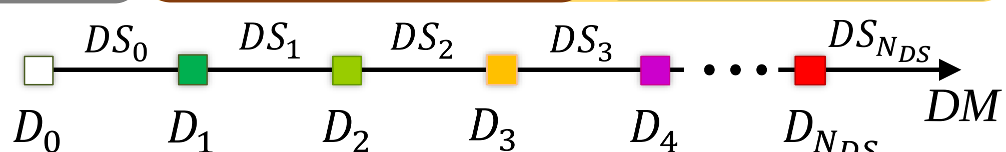
Risk Curve

$$\lambda(DV > dv)$$

$$\lambda(DV > dv) = \int_{im} G_{DV|IM}(dv \mid im) \left|\mathrm{d}\lambda(IM > im)\right|$$

Risk

e.g., AAL, LEC



- Assessing tsunami fragility and the related uncertainties is crucial in the evaluation of incurred losses. Empirical fragility modelling is based on observed tsunami intensity and damage data.
- Fragility curves for hierarchical damage levels are distinguished by their laminar shape; that is, the curves should not intersect. However, this condition is not satisfied automatically.
- We present a workflow and a tool for hierarchical fragility modelling, uncertainty propagation, and fragility model selection Using a Bayesian updating approach based on an adaptive MCMC simulation technique.
- We infer fragility model parameters and carry out model selection for a set of fragility curves for mutually exclusive and collectively exhaustive damage states.

Fragility assessment for hierarchical damage states

$$P\left(DS_j \mid IM_i\right)=P\left[\left(D<D_{j+1}\right)\cdot\left(D\geq D_j\right)\mid IM_i\right]$$

$$=\underbrace{\left[1-P\left(D\geq D_{j+1}\mid D\geq D_j, IM_i\right)\right]}_{\text{Conditional Fragility}}\cdot \overbrace{P\left(D\geq D_j \mid IM_i\right)}^{\text{Recursive Formulation}}$$

Definition of viable fragility models

$$\pi_{ij}=\pi_j\left(IM_i\right)=\begin{cases}\left(1+\exp(-l_{ij})\right)^{-1} & \text{logit} & \mathbb{M}_1\\ \Phi\left(l_{ij}\right) & \text{probit} & \mathbb{M}_2\\ 1-\exp\left(-\exp(l_{ij})\right) & \text{cloglog} & \mathbb{M}_3\end{cases}$$

$$P\left(DS_j \mid IM_i\right)=\boxed{\left[1-\pi_{ij}\right]}\cdot P\left(D\geq D_j \mid IM_i\right)$$

$$l_{ij}=\alpha_{0,j}+\alpha_{1,j}\ln IM_i$$

- The vector of fragility model parameters $\boldsymbol{\theta}=[\alpha_{0,1},\alpha_{1,1},\alpha_{0,2},\alpha_{1,2},\ldots,\alpha_{0,NDS-1},\alpha_{1,NDS-1}]$

Calculation of Likelihood and Bayesian inference for fragility parameters

$$p(\mathbf{D}\mid\boldsymbol{\theta}_k,\mathbb{M}_k)=\prod_{j=0}^{N_{DS}}\prod_{i=1}^{n_{CL,j}}P\left(DS_j \mid IM_i\right)$$

$$\underbrace{p\left(\boldsymbol{\theta}_k \mid \mathbf{D},\mathbb{M}_k\right)}_{\text{posterior}}=\frac{\boxed{p\left(\mathbf{D}\mid\boldsymbol{\theta}_k,\mathbb{M}_k\right)}\,p\left(\boldsymbol{\theta}_k\mid\mathbb{M}_k\right)}{\int_{\Omega_{\boldsymbol{\theta}_k}}\boxed{p\left(\mathbf{D}\mid\boldsymbol{\theta}_k,\mathbb{M}_k\right)}\,p\left(\boldsymbol{\theta}_k\mid\mathbb{M}_k\right)d\boldsymbol{\theta}_k}=C^{-1}\underbrace{p\left(\mathbf{D}\mid\boldsymbol{\theta}_k,\mathbb{M}_k\right)}_{\text{likelihood}}\,\underbrace{p\left(\boldsymbol{\theta}_k\mid\mathbb{M}_k\right)}_{\text{prior}}$$

Model selection

$$P\left(\mathbb{M}_k \mid \mathbf{D}\right)=\frac{\boxed{p\left(\mathbf{D}\mid\mathbb{M}_k\right)}\,P\left(\mathbb{M}_k\right)}{\sum_{k=1}^{N_{\mathbb{M}}}p\left(\mathbf{D}\mid\mathbb{M}_k\right)P\left(\mathbb{M}_k\right)}$$

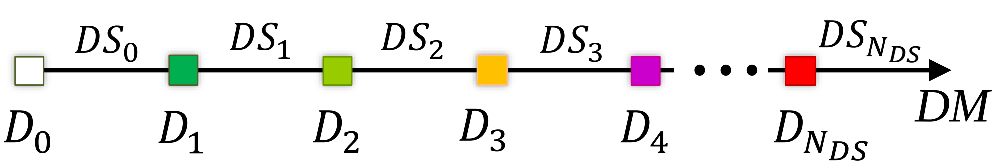
$$\ln\left[p\left(\mathbf{D}\mid\mathbb{M}_k\right)\right]=\underbrace{\int_{\Omega_{\boldsymbol{\theta}_k}}\ln\left[p\left(\mathbf{D}\mid\boldsymbol{\theta}_k,\mathbb{M}_k\right)\right]p\left(\boldsymbol{\theta}_k\mid\mathbf{D},\mathbb{M}_k\right)d\boldsymbol{\theta}_k}_{\text{Term 1}}-\underbrace{\int_{\Omega_{\boldsymbol{\theta}_k}}\ln\left[\frac{p\left(\boldsymbol{\theta}_k\mid\mathbf{D},\mathbb{M}_k\right)}{p\left(\boldsymbol{\theta}_k\mid\mathbb{M}_k\right)}\right]p\left(\boldsymbol{\theta}_k\mid\mathbf{D},\mathbb{M}_k\right)d\boldsymbol{\theta}_k}_{\text{Term 2}}$$

Evidence | Likelihood | Information gain

Building Class	Tsunami Event	Total Number of Data Points	Number of Damage Levels/total number of damage levels defined N_{DS}
Brick masonry residential, 1 storey	South Pacific 2009	120	5/5
Timber residential	South Pacific 2009	23	3/5
Non engineered masonry, unreinforced with clay brick, 1 storey	Sulawesi (Palu) 2018	279	2/3
Non engineered masonry, unreinforced with clay brick, 2 storey	Sulawesi (Palu) 2018	37	2/3
Non engineered light timber	Sulawesi (Palu) 2018	14	2/3

Damage Level		Damage level description
D_0	None	no damage
D_1	Light	non-structural damage
D_2	Minor	significant non-structural damage, minor structural damage
D_3	Moderate	significant structural and non-structural damage
D_4	Severe	irreparable structural damage, will require demolition
D_5	Collapse	complete structural collapse
		South Pacific 2009 Reese et al. 2011

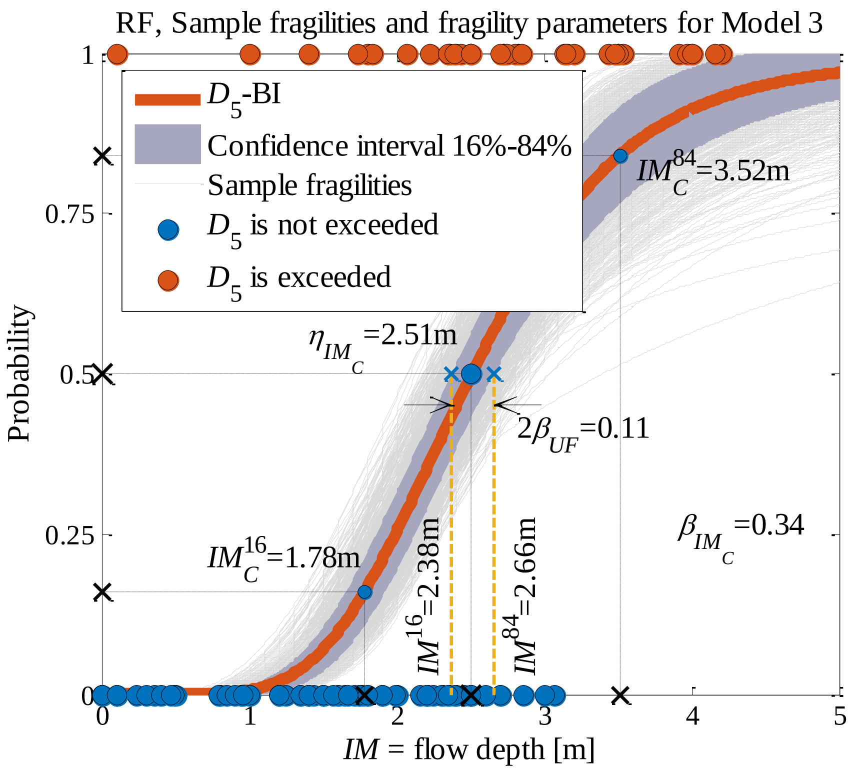
Damage Level		Damage level description
D_0	None	no damage
D_1	Repairable	Partial damage, repairable
D_2	Unrepairable	Partial damage, unrepairable
D_3	Complete	Complete structural collapse
		Sulawesi 2018 Paulik et al. 2019

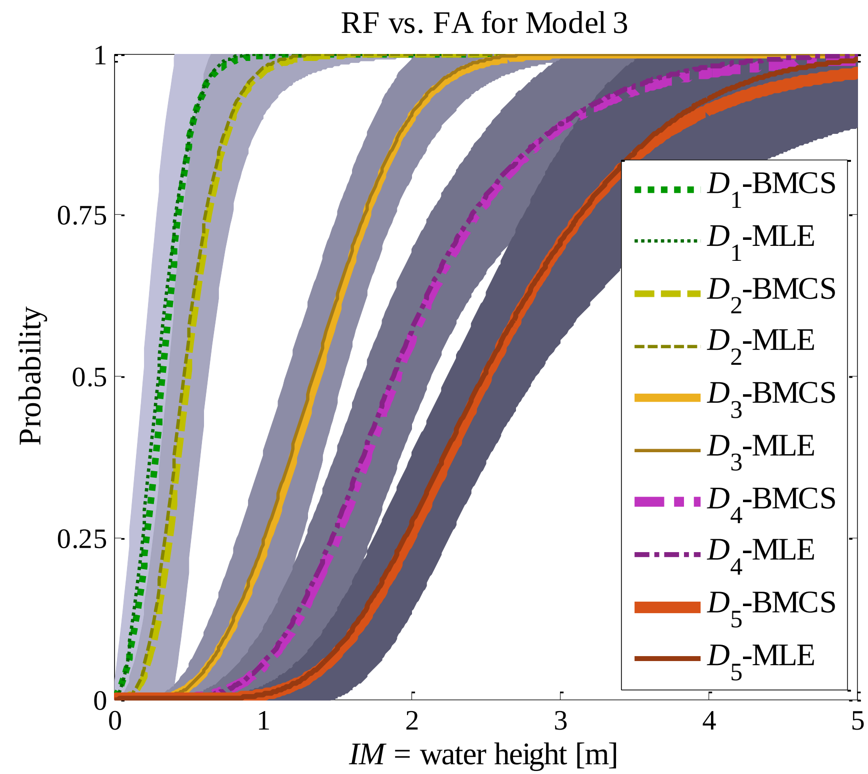


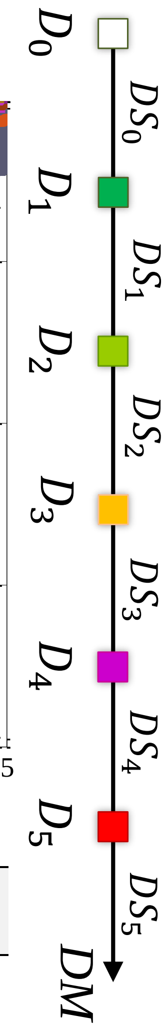
Reese, S., Bradley, B. A., Bind, J., Smart, G., Power, W., & Sturman, J. (2011). Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. *Earth-Science Reviews*, *107*(1-2), 156-173.

Paulik, R., Gusman, A., Williams, J. H., Pratama, G. M., Lin, S. L., Prawirabhakti, A., ... & Suwarni, N. W. I. (2019). Tsunami hazard and built environment damage observations from Palu City after the September 28 2018 Sulawesi earthquake and tsunami. *Pure and Applied Geophysics*, *176*(8), 3305-3321.

Fragility assessment for *brick masonry residential, 1 storey*
South Pacific Tsunami 2009

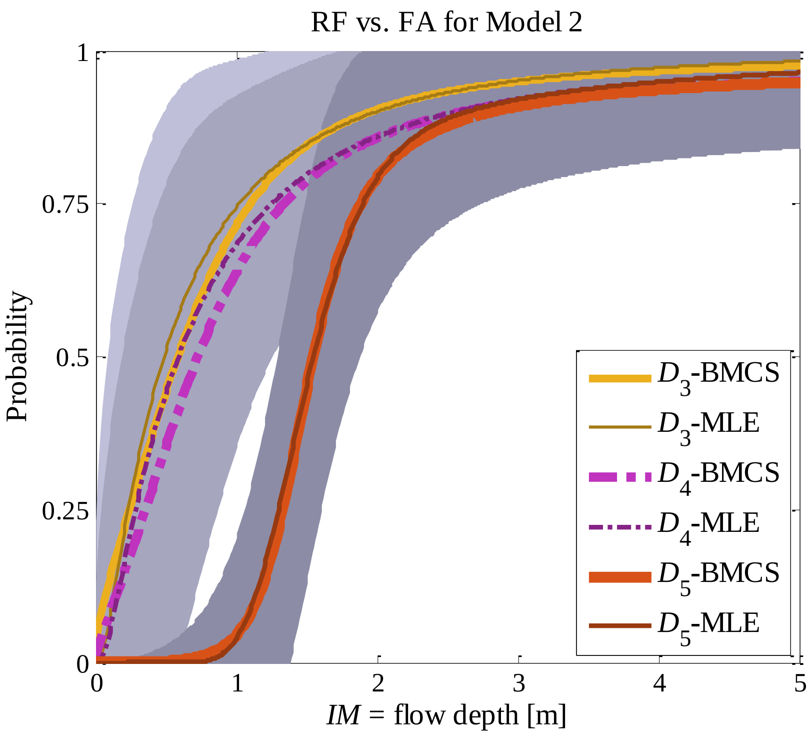


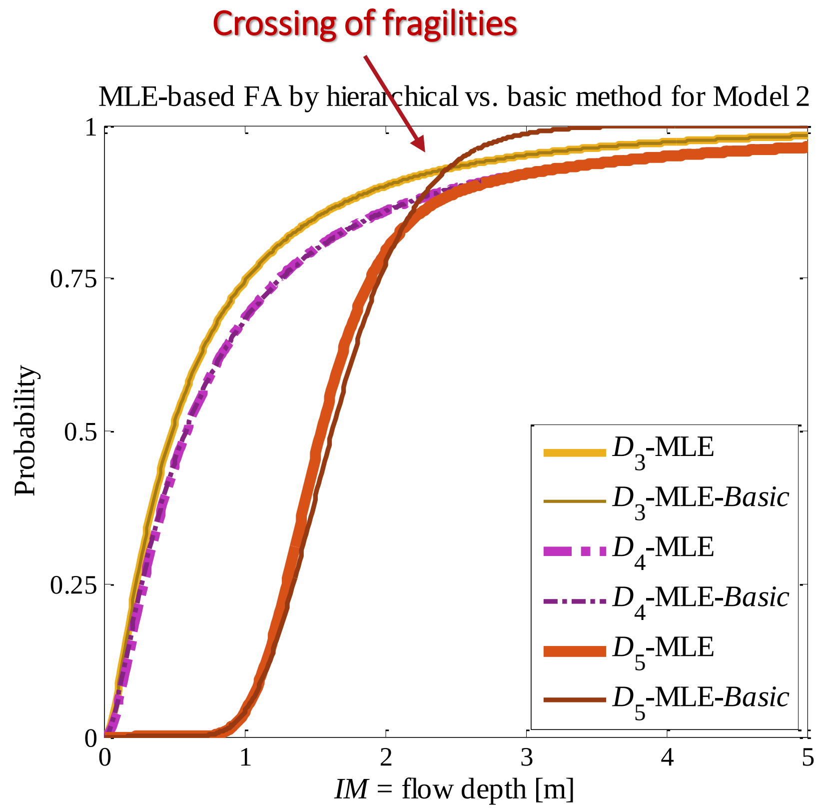


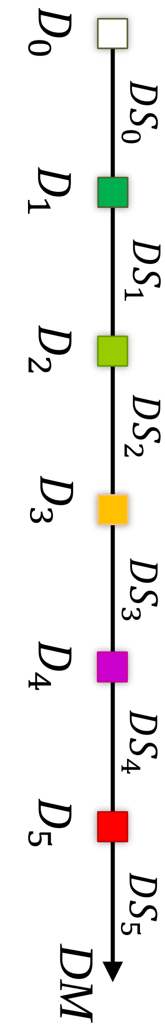


Model Class	*Term* 1: Average Data Fit	*Term* 2: Information Gain	Log-Evidence	Posterior Probability of each model
$\mathbb{M}_1$	-124.2898	17.3825	-141.6723	0.058
$\mathbb{M}_2$	-123.1298	17.9314	-141.0612	0.107
$\mathbb{M}_3$	-120.6051	18.4015	-139.0066	0.835

Fragility assessment for *Timber residential, South Pacific Tsunami 2009*

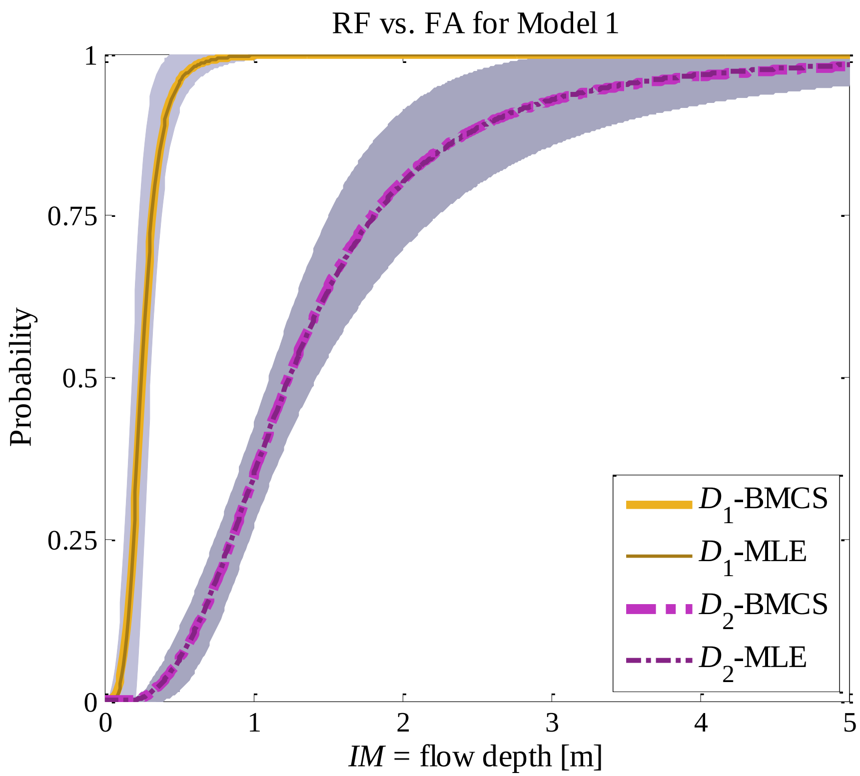


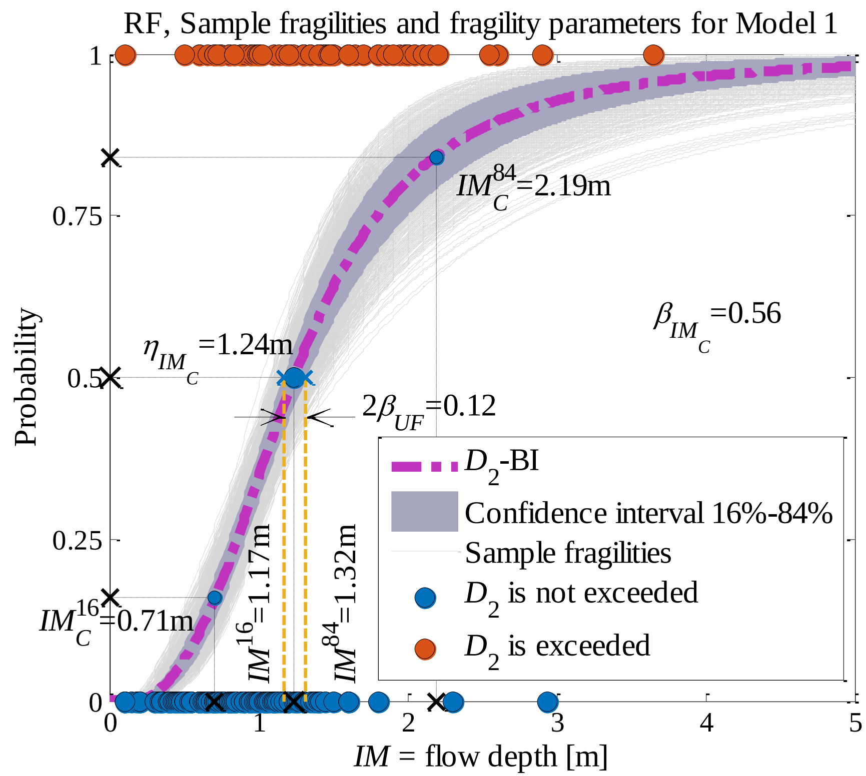


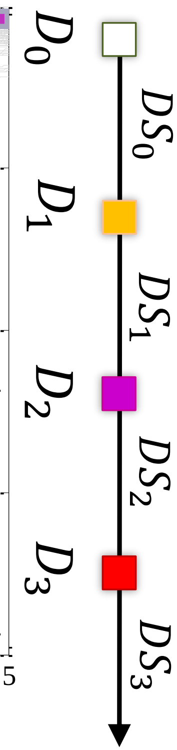


Model Class	*Term* 1: Average Data Fit	*Term* 2: Information Gain	Log-Evidence	Posterior Probability of each model
$\mathbb{M}_1$	-19.3442	5.3210	-24.6631	0.30
$\mathbb{M}_2$	-19.2930	5.0772	-24.3702	0.41
$\mathbb{M}_3$	-18.5401	6.1717	-24.7117	0.29

Fragility assessment for *Non engineered masonry, unreinforced with clay brick*, 1 storey, Sulawesi Palu Tsunami 2018

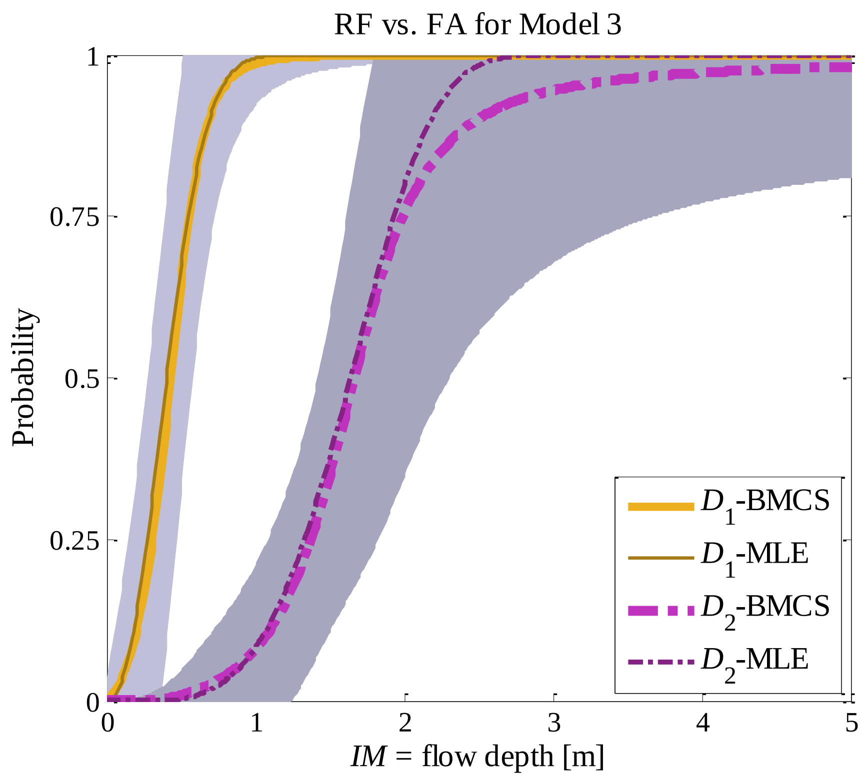


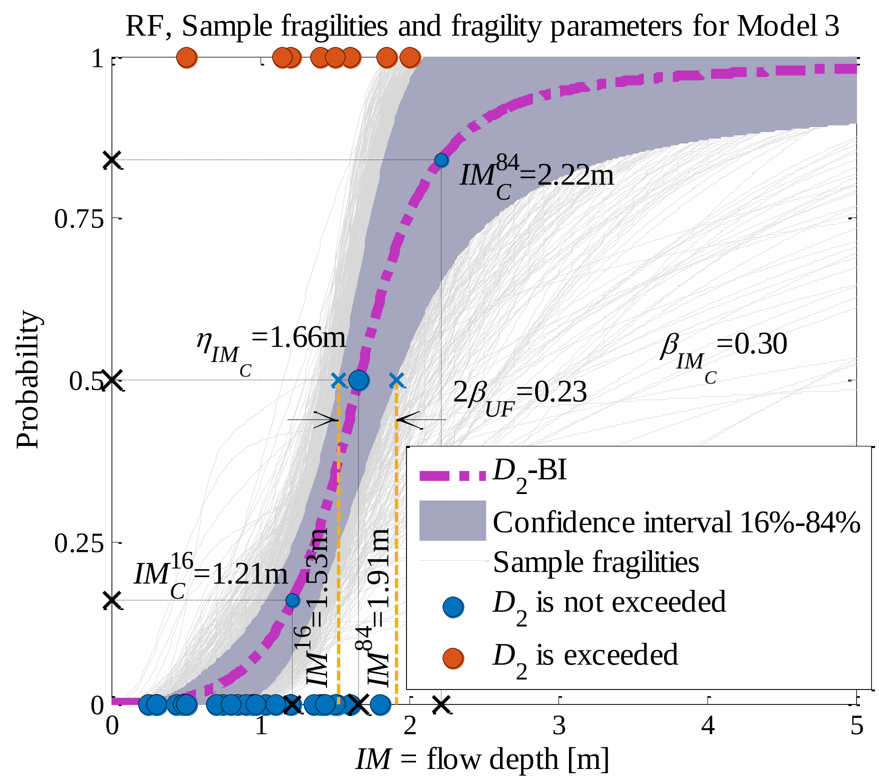


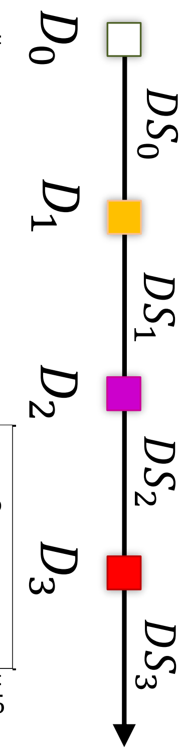


Model Class	*Term* 1: Average Data Fit	*Term* 2: Information Gain	Log-Evidence	Posterior Probability of each model
$\mathbb{M}_1$	-161.8184	7.0014	-168.8198	0.96
$\mathbb{M}_2$	-161.0047	12.0943	-173.0990	0.01
$\mathbb{M}_3$	-161.5005	10.7668	-172.2673	0.03

Fragility assessment for *Non engineered masonry, unreinforced with clay brick,* 2 *storey, Sulawesi Palu Tsunami 2018*



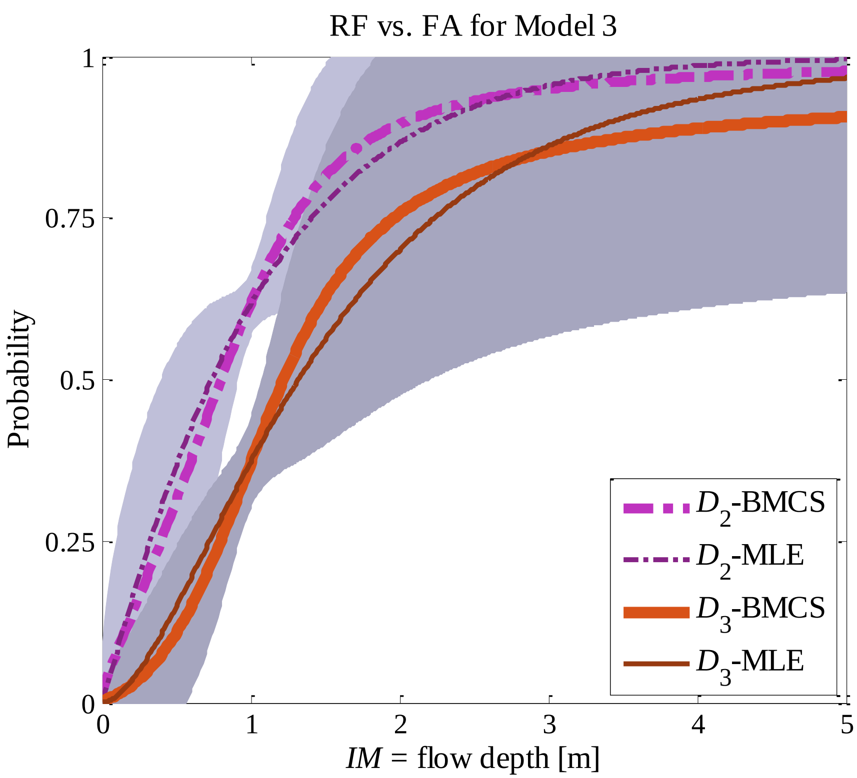


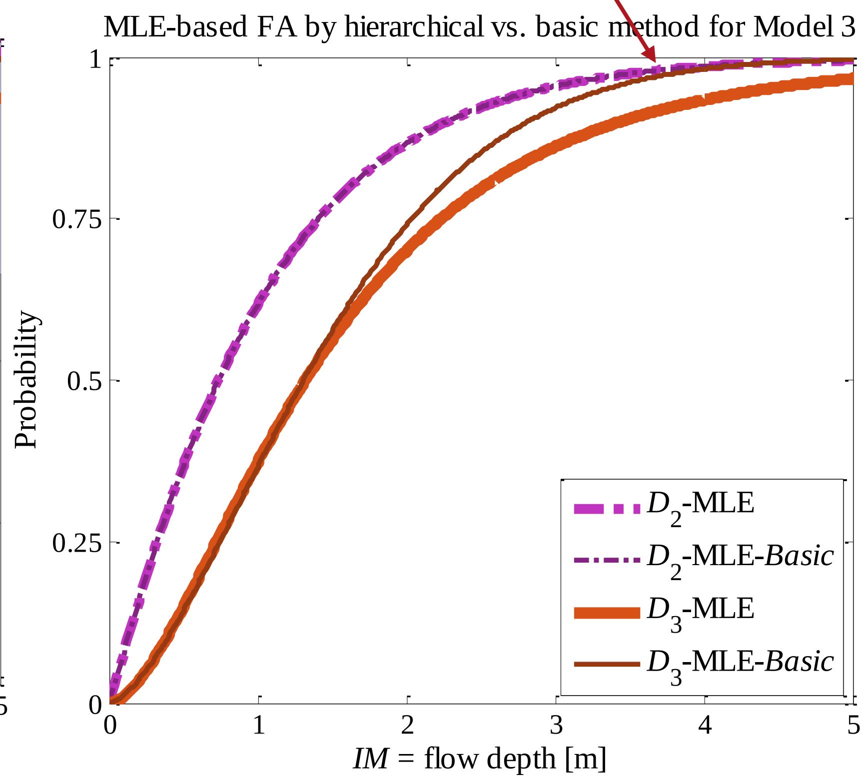


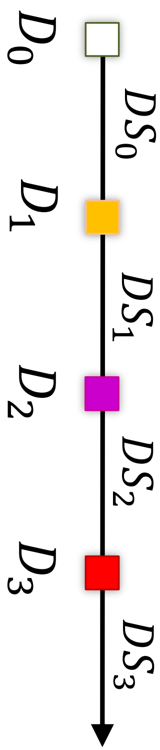
Model Class	*Term* 1: Average Data Fit	*Term* 2: Information Gain	Log-Evidence	Posterior Probability of each model
$\mathbb{M}_1$	-23.0250	4.4357	-27.4606	0.22
$\mathbb{M}_2$	-22.4372	4.8097	-27.2469	0.28
$\mathbb{M}_3$	-22.0454	4.6037	-26.6491	0.50

Fragility assessment for *Non engineered light timber, Sulawesi Palu Tsunami 2018*

Crossing of fragilities

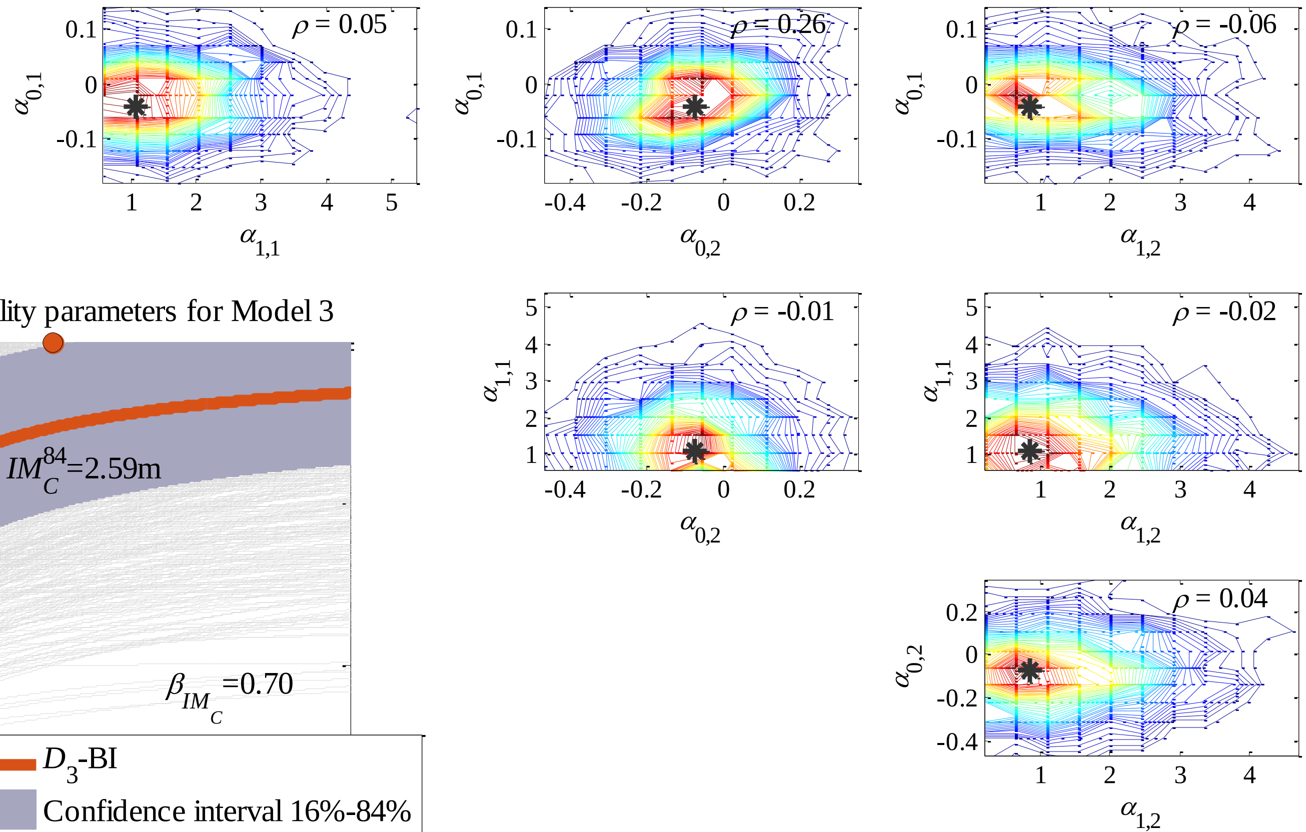


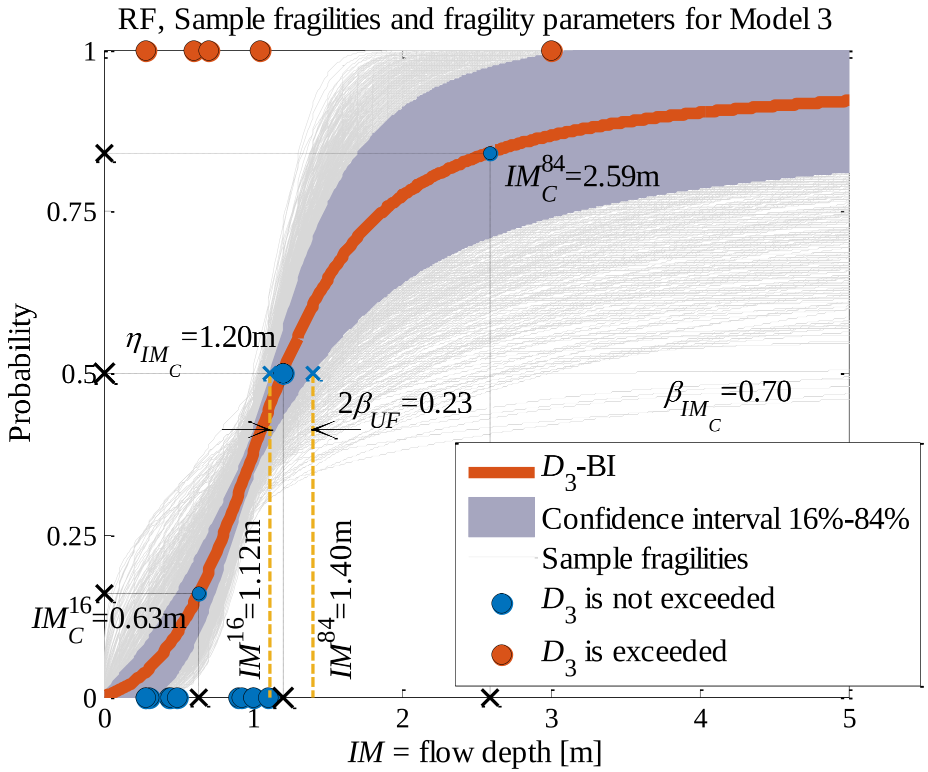


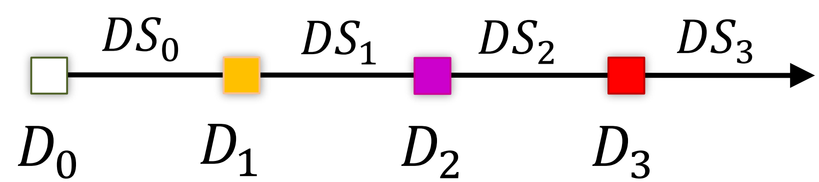


Model Class	*Term* 1: Average Data Fit	*Term* 2: Information Gain	Log-Evidence	Posterior Probability of each model
$\mathbb{M}_1$	-14.5461	1.1062	-15.6523	0.23
$\mathbb{M}_2$	-14.5717	1.1770	-15.7487	0.21
$\mathbb{M}_3$	-13.8229	0.9391	-14.7619	0.56

Fragility assessment for *Non engineered light timber, Sulawesi Palu Tsunami 2018*

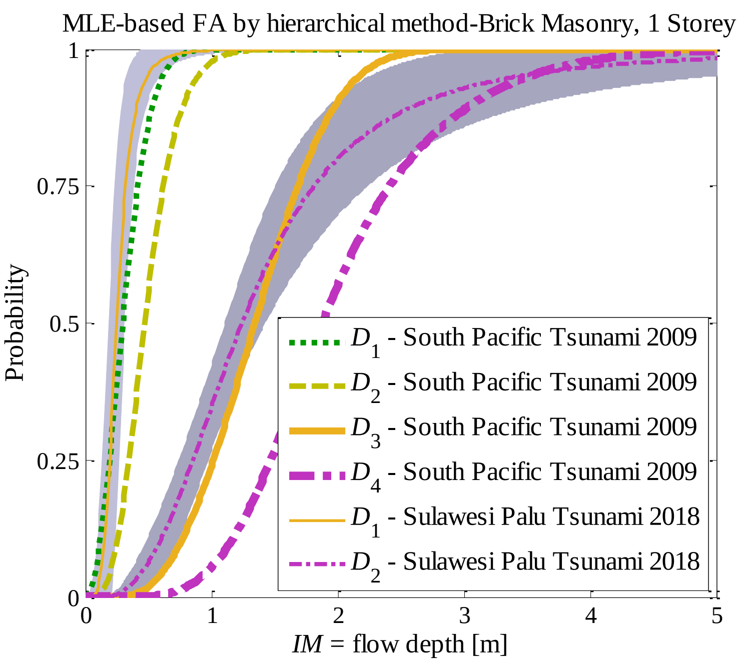




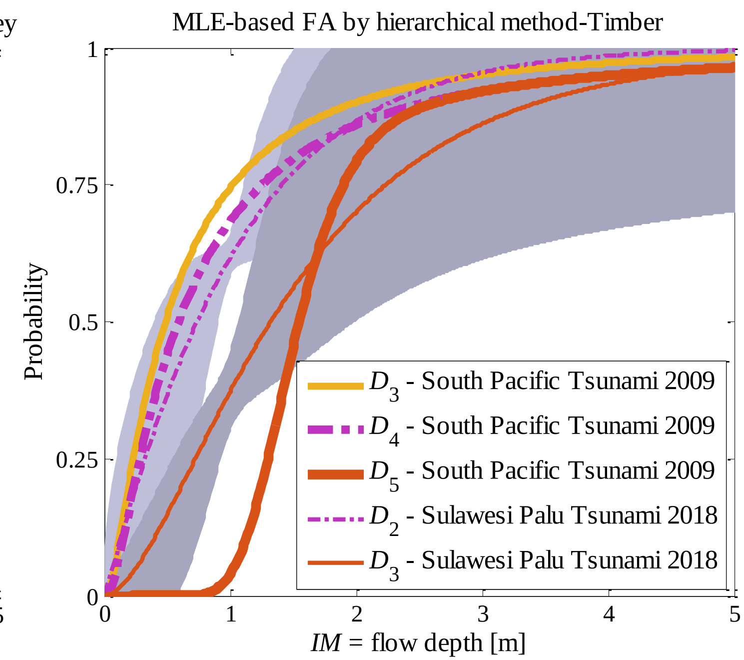


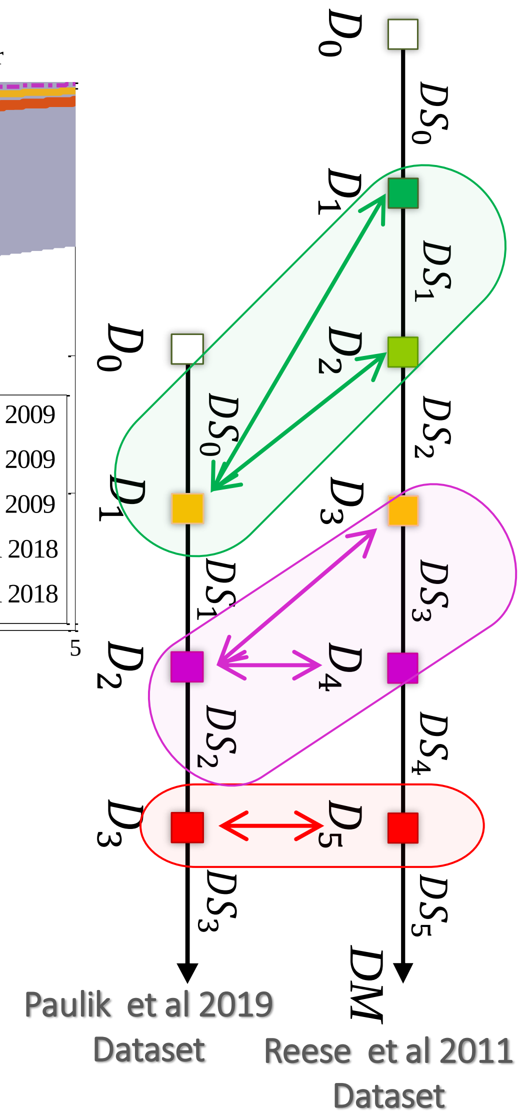
Discussion: Harmonization across different taxonomies and damage scales

Brick Masonry, 1 Storey



Timber





Taxonomy	Location
Brick masonry residential, 1 storey	South Pacific Tsunami 2009
Non engineered masonry, unreinforced with clay brick, 1 storey	Sulawesi Palu Tsunami 2018
Timber residential	South Pacific Tsunami 2009
Non engineered light timber	Sulawesi Palu Tsunami 2018

- We provide a workflow and tool that can fit fragility curves to a set of hierarchical damage levels in an ensemble manner. This tool is based on prescribed fragility models and ensures the hierarchical relation between the damage levels.

- This workflow is very robust to cases where few data points are available. This tool provides confidence bands for the fragility curves and performs model selection among a set of viable link functions for generalized regression.

- We have applied this workflow to building damage data available from two different tsunamis, namely, South Pacific 2009 (Samoa and American Samoa Islands) and Sulawesi (Palu) 2018.

- We have demonstrated how the fragility curves derived based on the two datasets can be harmonized (they are based on two different damage scales).

- The workflow is available as a software tool:
  eurotsunamirisk/computeFrag: v.2021.08.06b-alpha (v.2021.08.06b-alpha)
  ETRiS - European Tsunami Risk Service, https://doi.org/10.5281/zenodo.5167276

Thank you for your kind attention!

Pre-print available at:

Jalayer, F., Ebrahimian, H., Trevlopoulos, K., and Bradley, B.: *Empirical tsunami fragility modelling for hierarchical damage levels: An application to damage data of the 2009 South Pacific tsunami*, EGUsphere [preprint] https://doi.org/10.5194/egusphere-2022-206, 2022.

The workflow is available as a software tool:

eurotsunamirisk/computeFrag: v.2021.08.06b-alpha (v.2021.08.06b-alpha)

ETRiS - European Tsunami Risk Service, https://doi.org/10.5281/zenodo.5167276