Practical solutions to hazard-consistent ground motion record selection for fragility and response hazard curves' computation

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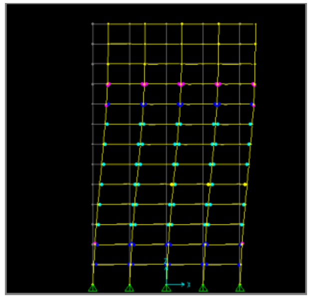
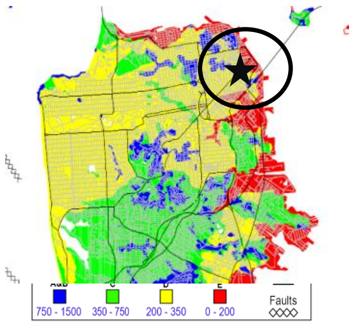
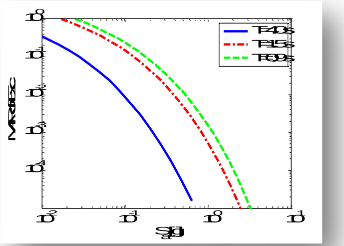
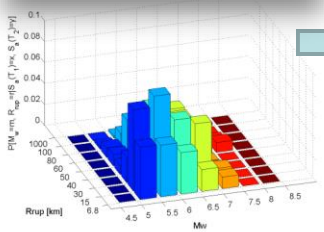
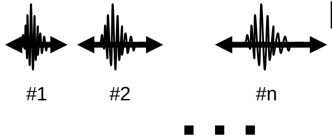
Typical Steps of a Seismic Risk Assessment of a Single Structure at a Given Site





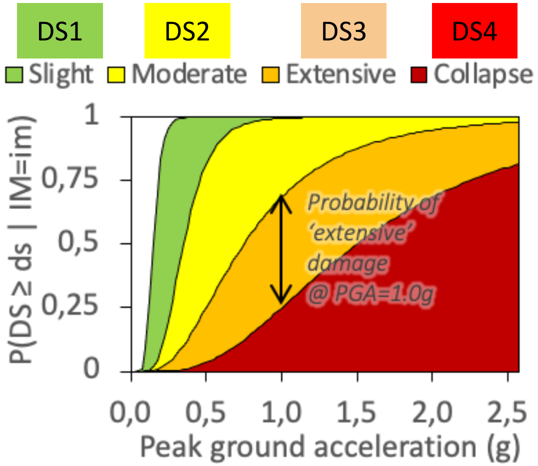






Incremental Dynamic Analysis
Multiple Stripe Analysis

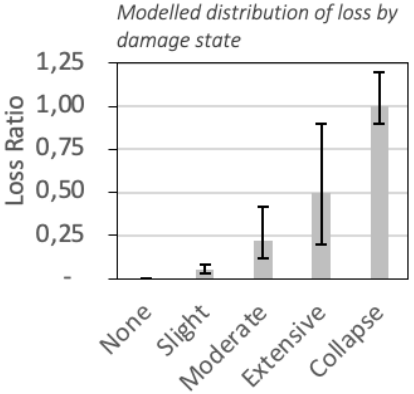
Fragility curves



Damage States Definition

+

Consequence functions



Consequence Function

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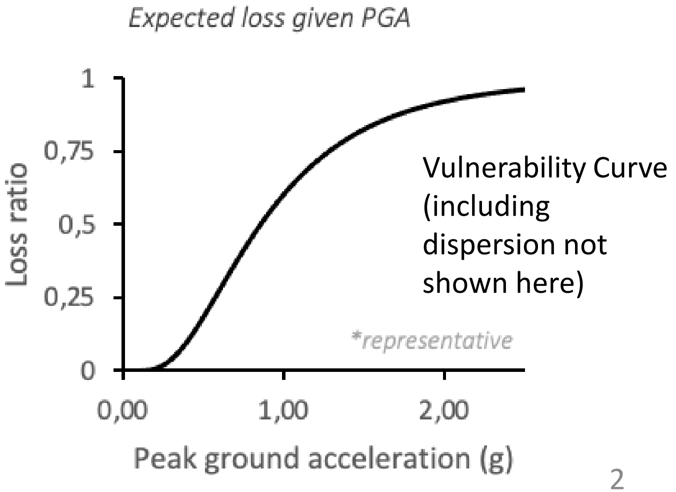


Performance Based Earthquake Engineering: Important Technicalities

$$\lambda(DV) = \int\int\int G(DV|DM)\ dG(DM|EDP)\ dG(EDP|IM)\ d\lambda(IM)$$

- 4) Loss Analysis — $G(DV|DM)$
- 3) Engineering Evaluation - Fragility — $dG(DM|EDP)$
- 2) Response/demand Analysis — $dG(EDP|IM)$
- 1) Scalar hazard — $d\lambda(IM)$

Cornell and Krawinkler, 2000

IM= Ground Motion Intensity Measure

EDP= Engineering Demand Parameter

DM=Damage Measure

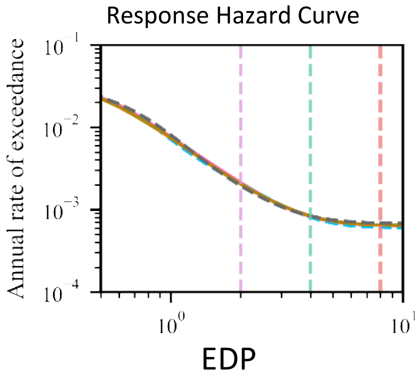
DV=Decision variable

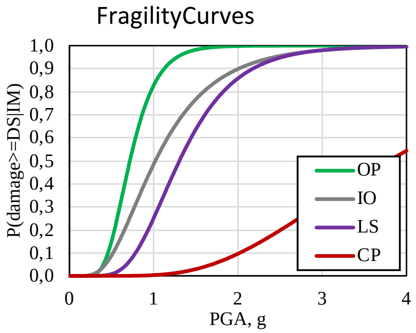
If we are only interested in annual rate of exceedance of response parameters, $\lambda(EDP)$, associated with onset of given limit states, then:

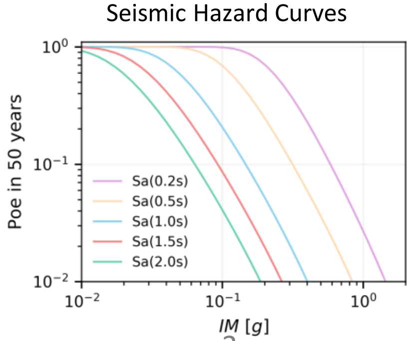
$$\lambda(EDP > y) = \sum_{all\ IMs} P(EDP > y|IM, M, R, \theta)P(IM, M, R, \theta) \approx \sum_{all\ IMs} P(EDP > y|IM)P(IM)$$

The EDP value y can be associated to

- ❑ Onset of loss of functionality
- ❑ "Life safety"
- ❑ Collapse capacity



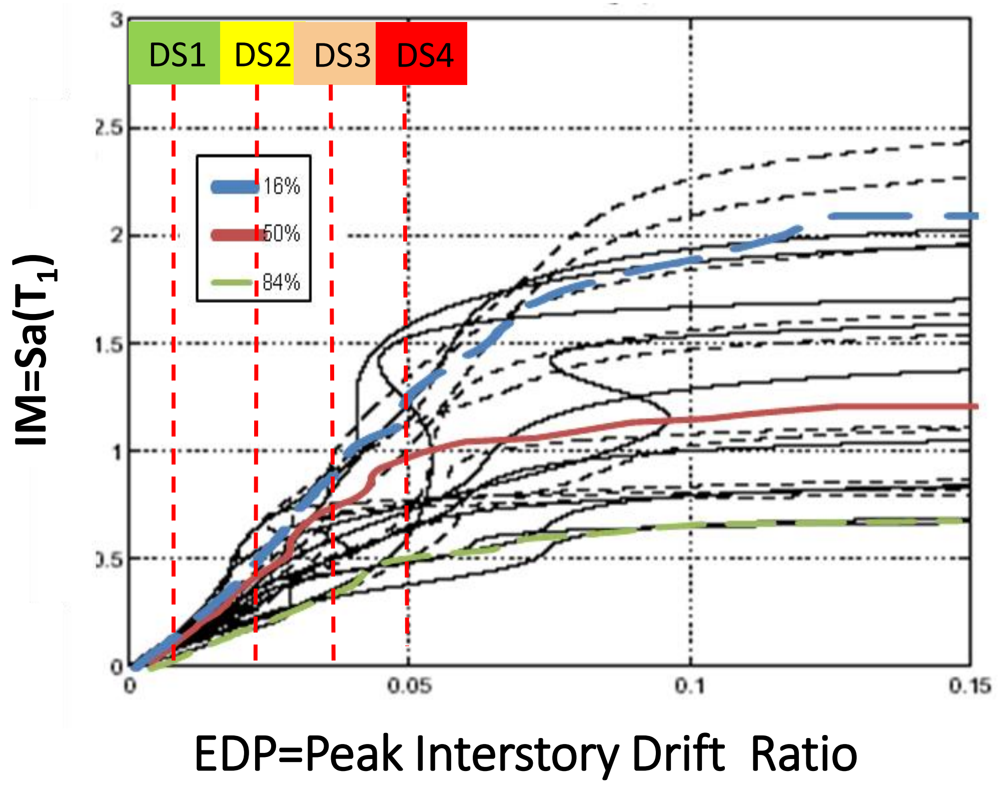




How are fragility curves usually (analytically) developed?

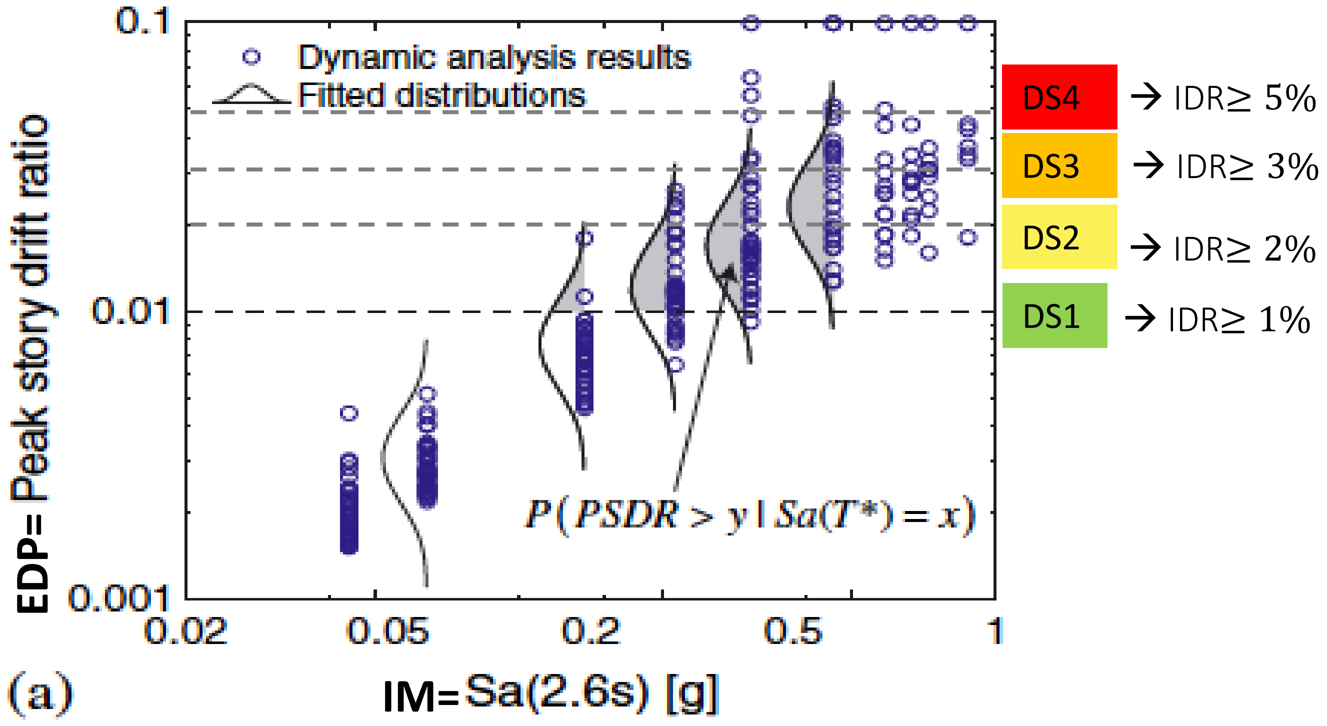
1. **Incremental Dynamic Analysis (IDA)**

   Single set of records selected without any particular attention to the seismic hazard at the site under consideration



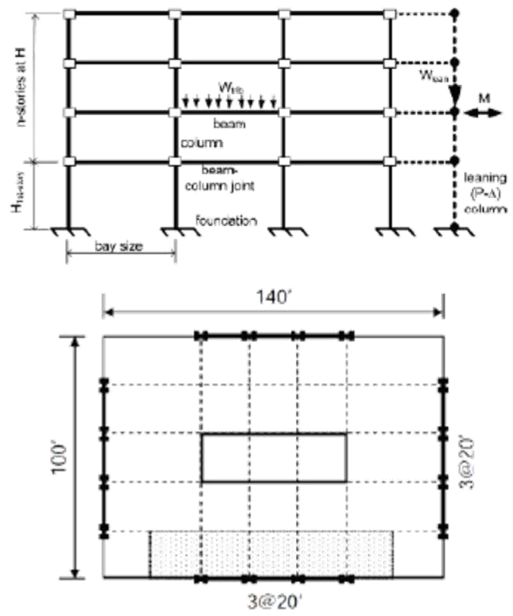
2. **Multiple Stripe Analysis (MSA)**

   Different set of hazard-consistent records selected for each stripe



Why all this fuss about hazard consistency? The tale of a 3 identical buildings…

- Three identical buildings: one in Istanbul, one in Ankara and one in Erzincan
- Hazard is different at the three sites $\lambda(EDP > y) \approx \sum_{all\ IM} P(EDP > y \mid IM)P(IM)$
- Are responses of the three identical buildings equal for the same level of IM?

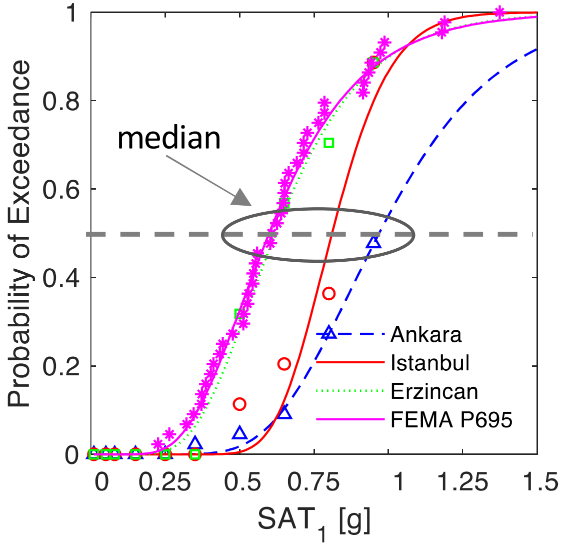


(excerpted from Kohrangi et al. 2017)

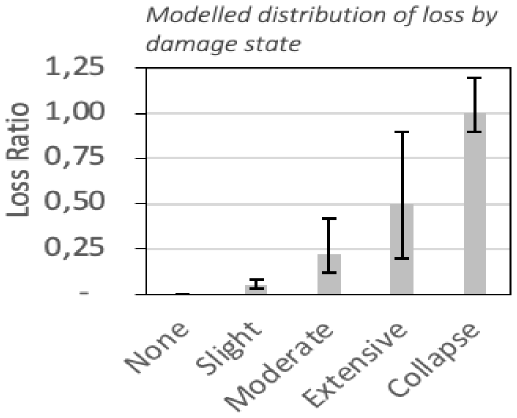
The seismogenic environment around the site affects the fragility and vulnerability curves

- Two alternative approaches:
  - Hazard-consistency enforced via site-specific Conditional Spectrum CS with IM=Sa(T1) + MSA
  - Hazard inconsistent (beyond IM= Sa(T1)): set of 22 pairs of motions from FEMA P695 + IDA

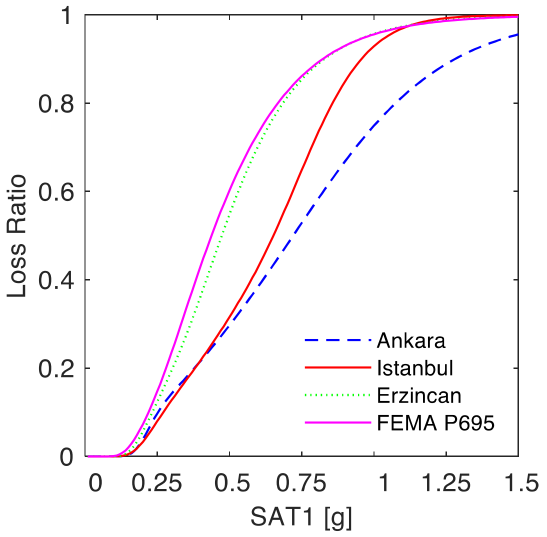
Fragility Curves



Consequence functions



Vulnerability Curves



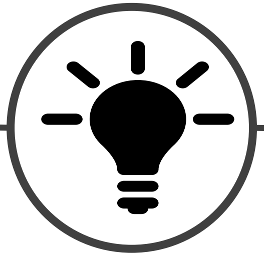
Fragility/vulnerability curves very different for same building!

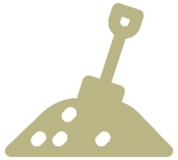
So it matters... But what is hazard consistency?

Geologist and Seismologist: use GMs from EQs with M and R and rupture mechanisms such as those that can occur in the region

Layman in utopia: just use ground motions recorded at the site in past earthquakes

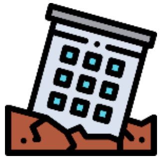
Seismologist-Engineer-Physicist: use appropriate synthetic GMs





Geotechnical engineer: use ground motions recorded on soil conditions identical or at least similar to those at the site

Engineer-seismologist: use GMs that have the "right" probabilistic distribution of all IMs that affect the structural response

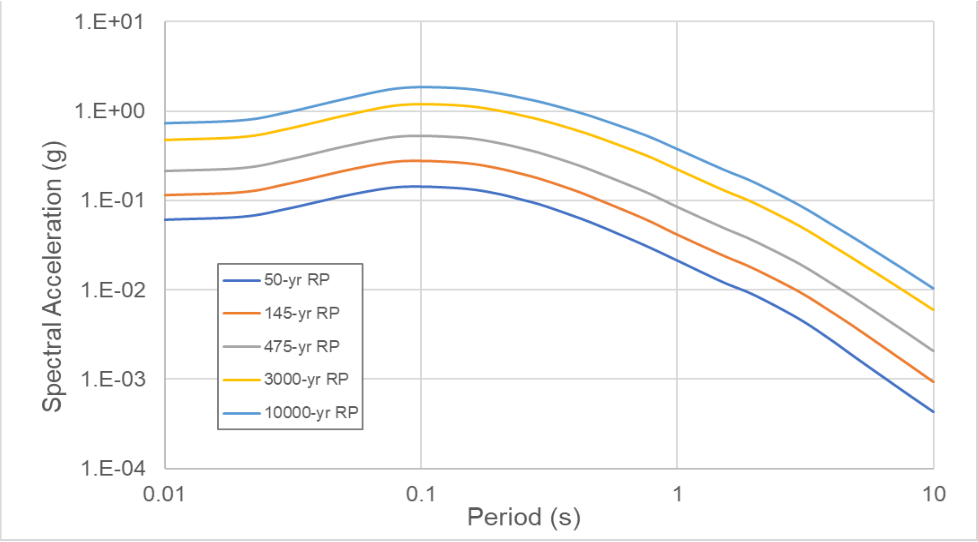


Structural engineer: you all are right. Do whatever you want provided that the distribution of my EDP is not distorted

$$\lambda(EDP > y) \approx \sum_{all\ IM} P(EDP > y \mid IM) P(IM)$$

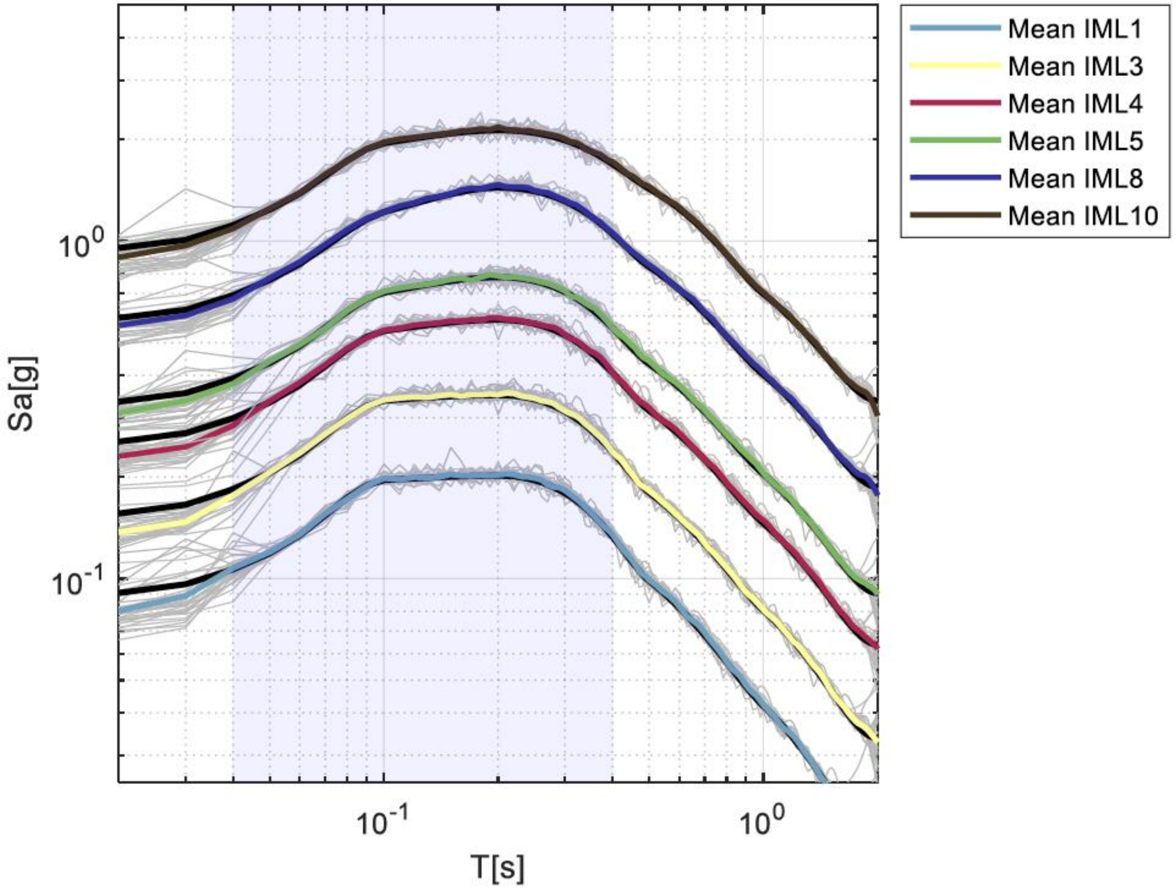
How has Hazard Consistency been historically enforced?

The Uniform Hazard Spectrum (UHS)



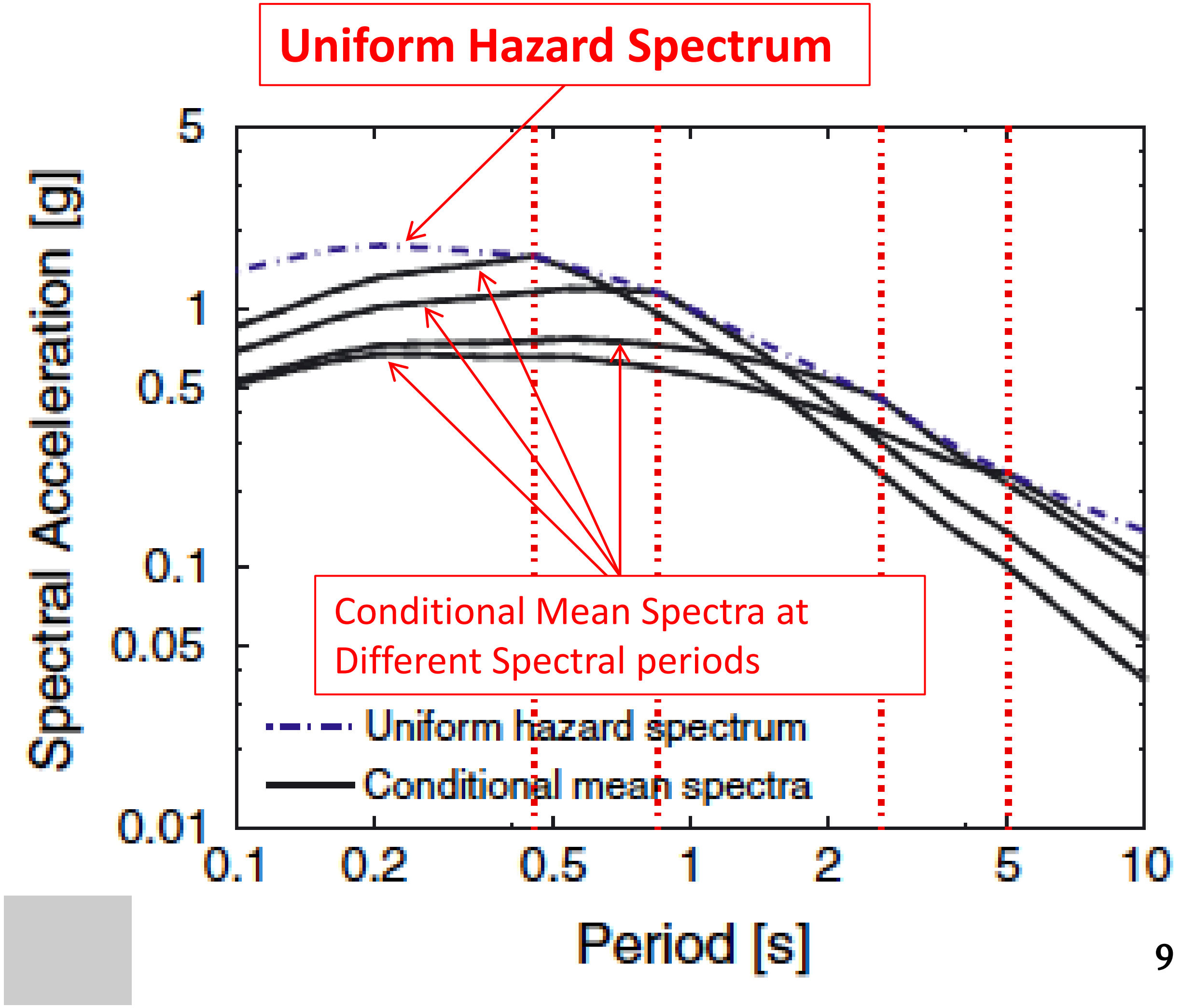
UHS already contain record-to-record response spectrum variability! Avoid double counting and remove peaks and valleys → spectrum compatible ground motions

Spectrum compatible records

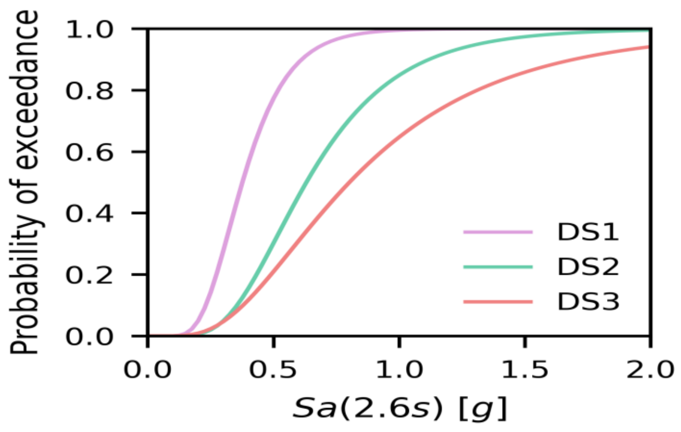


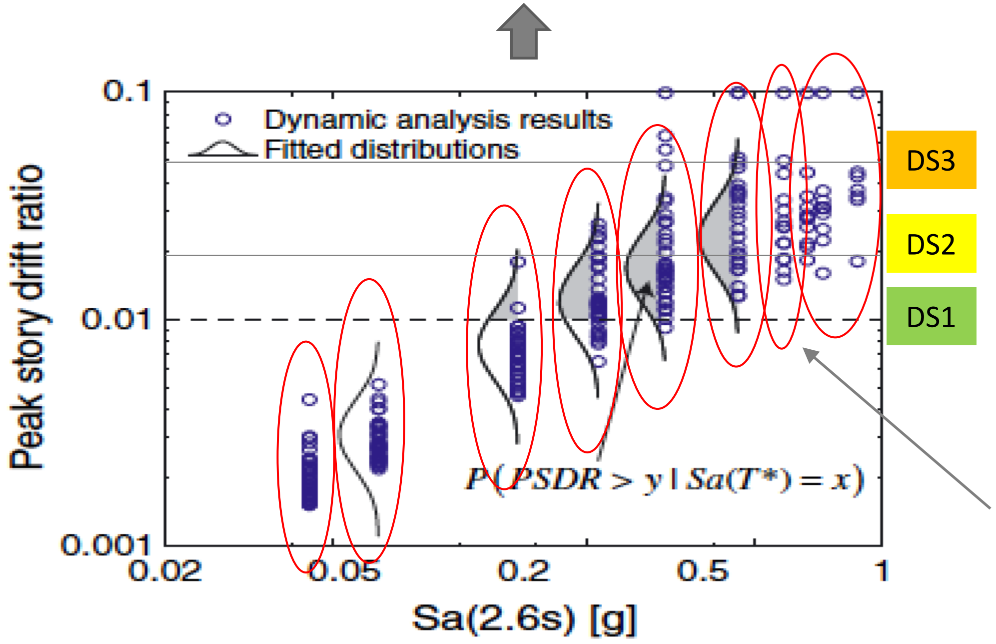
If UHS too wide use CMS…

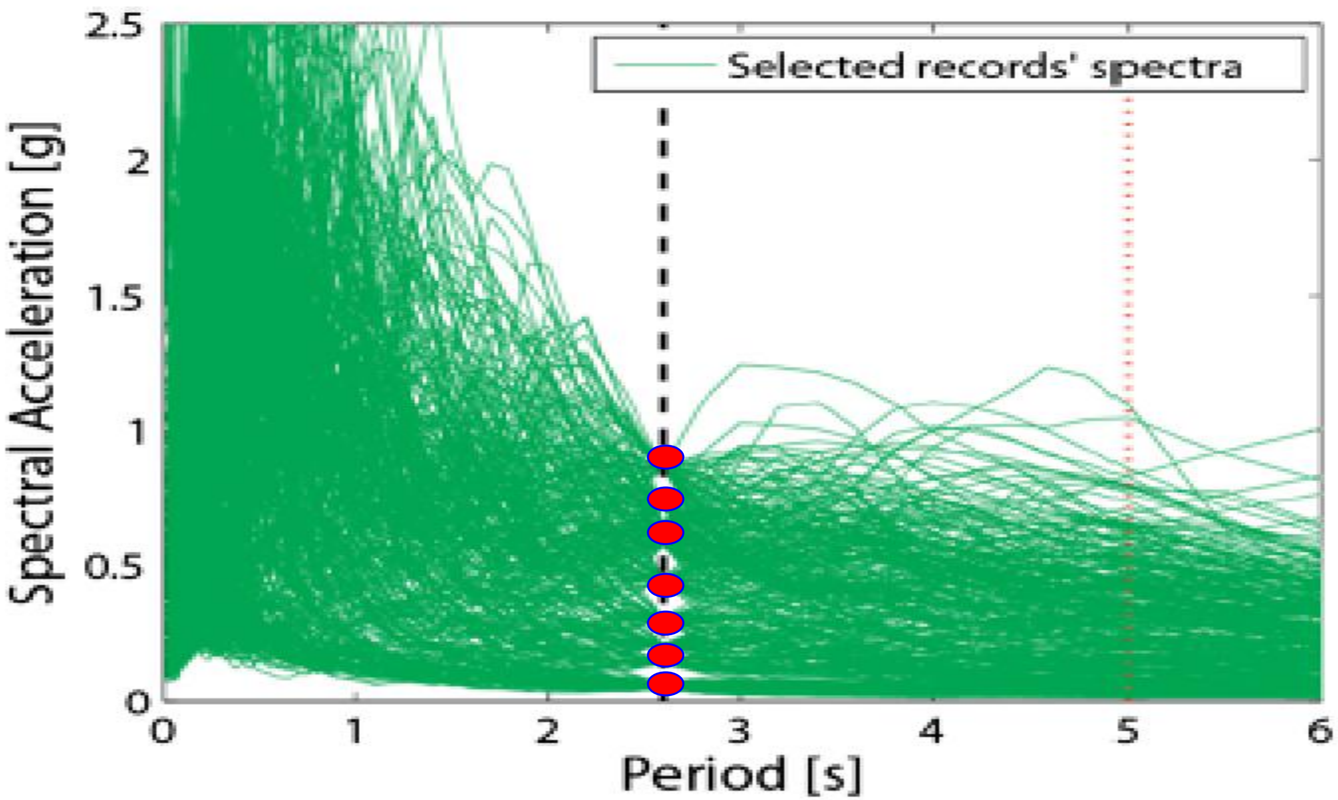
UHS is an Envelope of Conditional Mean Spectra (CMS) at Oscillator Periods



If CMS has no variability → use Conditional Spectrum…







Threshold for
a given DS

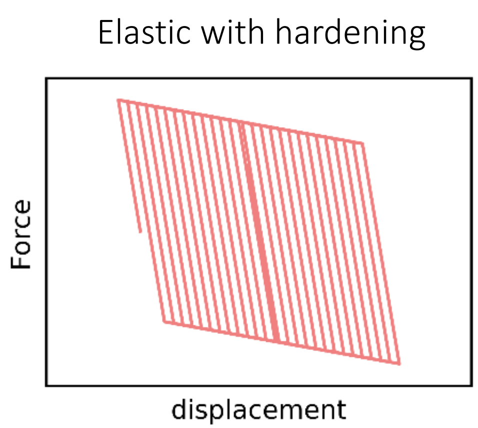
Excerpted from:
Lin, Haselton
and Baker, 2013

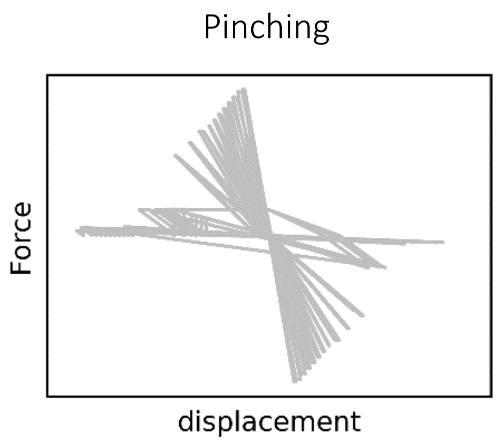
Do we have all these real ground motions to choose from?

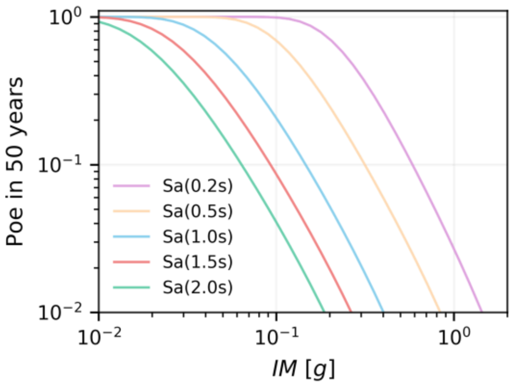
NO – Scaling and Mixing soils needed

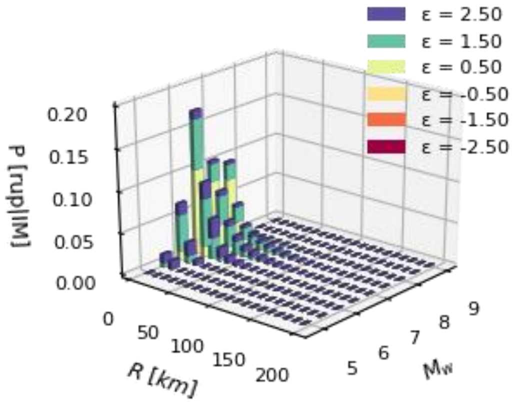
Do we bias the response?

- Extensive set of tests;
  - Five SDOFs (0.2s,0.5s,1.0s,1.5s,2.0s) with two material models:
    - ✓ elastio-plastic with hardening
    - ✓ pinching with degradation);
  - Rock Site in Perugia, Central Italy (Vs_{30}=800 m/s);
  - PSHA and hazard disaggregation using OpenQuake;
  - SHARE area source model + Boore and Atkinson (2008) GMPE









(excerpted from de Quevedo Iñarritu et al. 2023)

Effects of scaling and different soil conditions on fragility curves

- Ground motions DB used: ESM, NGA and GNS;
- Ground motions were classified in different groups:

<u>For assessing effect of soil sites</u>:

- Rock Vs30 (RV): Vs30>800 m/s;
- Soil Vs30 (SV): Vs30<400 m/s;
- Rock Complex (RC): using proxy-based methods;
- Soil Complex (SC): using proxy-based methods (Lanzano, 2019).

<u>For assessing the effect of scaling:</u>

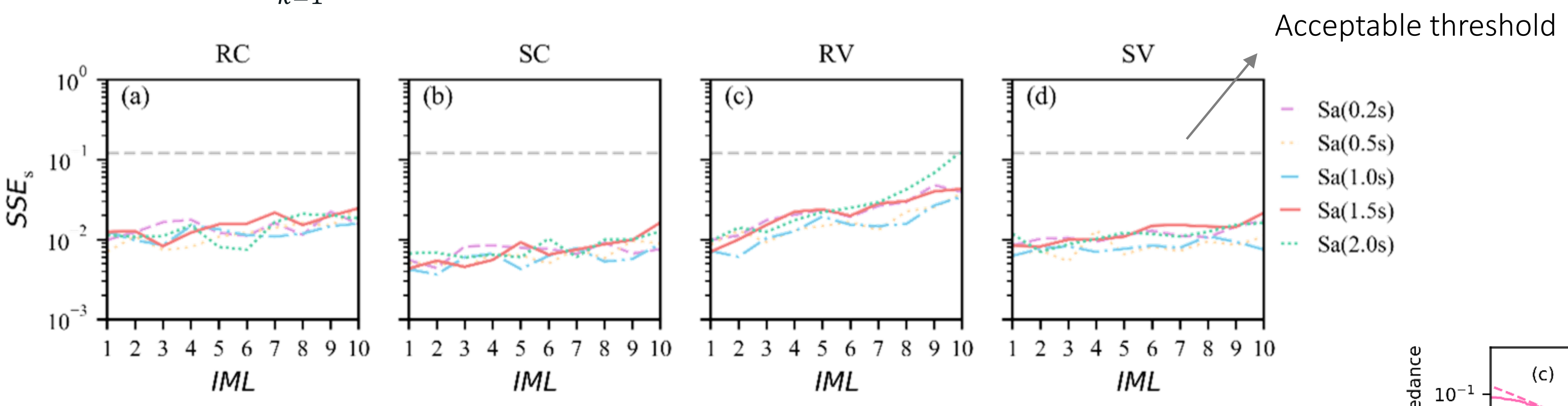
- Low scaling factor (LSF) – [1, 2]
- High scaling factor (HSF) – [7, 10]

- We used CS(SaT_1)-based MSA with 10 IM levels ranging between 0.2% poe in 50 years (RP = 25000 years) to 70% poe in 50 years (RP = 40 years) and sets of 40 records per IM level;

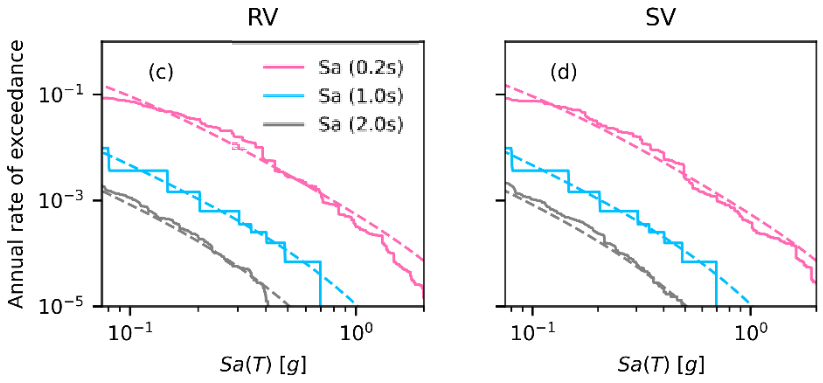
Does the use of CS-consistent ground motions that are either amplitude-scaled or recorded on different soil bias the fragility curve estimates?

- The goodness of fit to the target spectrum is evaluated based on the SSE_s value

$$SSE_s = \sum_{k=1}^{p}\left[\left(m_{lnIM_k} - \mu_{lnIM_k}\right)^2 + w\left(s_{lnIM_k} - \sigma_{lnIM_k}\right)^2\right]$$

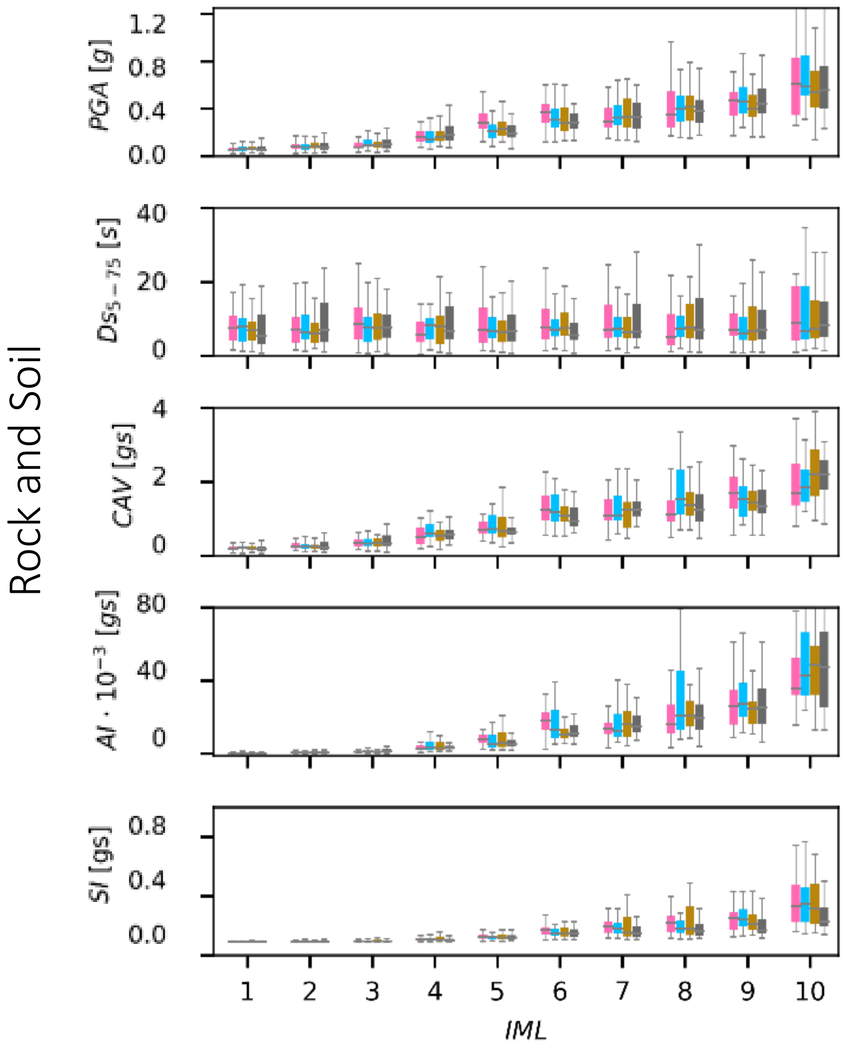


- Hazard consistency verification for the CS(Sa(1.0s))-selected records



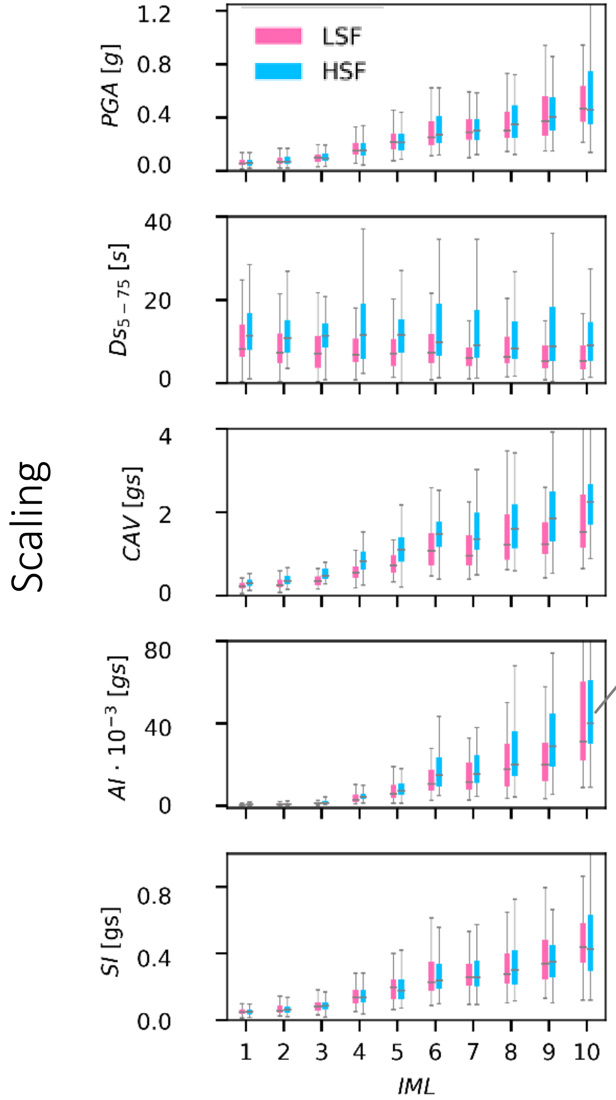
(excerpted from de Quevedo Iñarritu et al. 2023)

Distributions of IMs of CS-based rock/soil and scaled motions are very similar



(excerpted from de Quevedo Iñarritu et al. 2023)

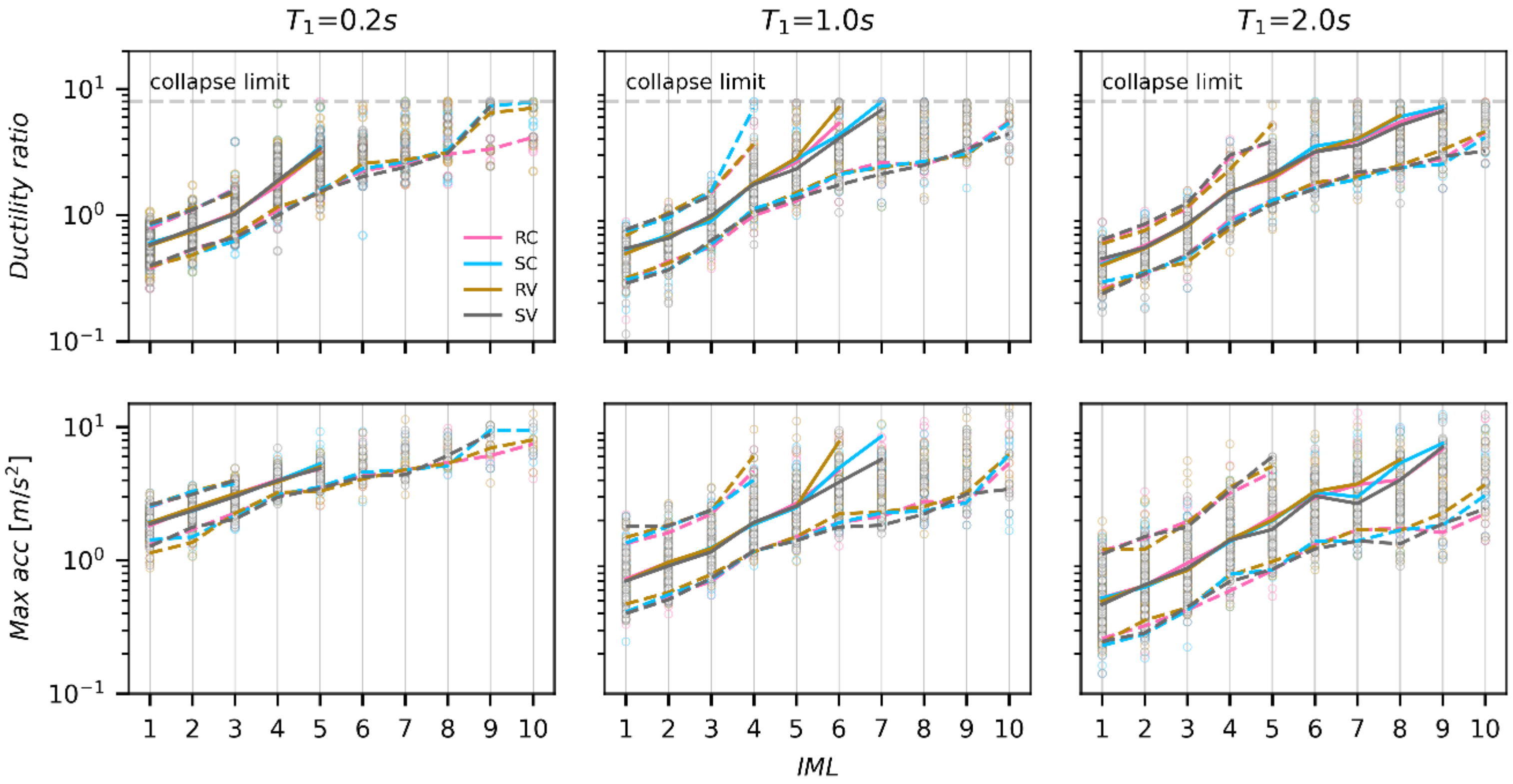
Statistically significant difference only in few cases, for higher intensity levels



Statistically significant differences for some IMs

Effect of soil characteristics of CS-based ground motions on Structural response

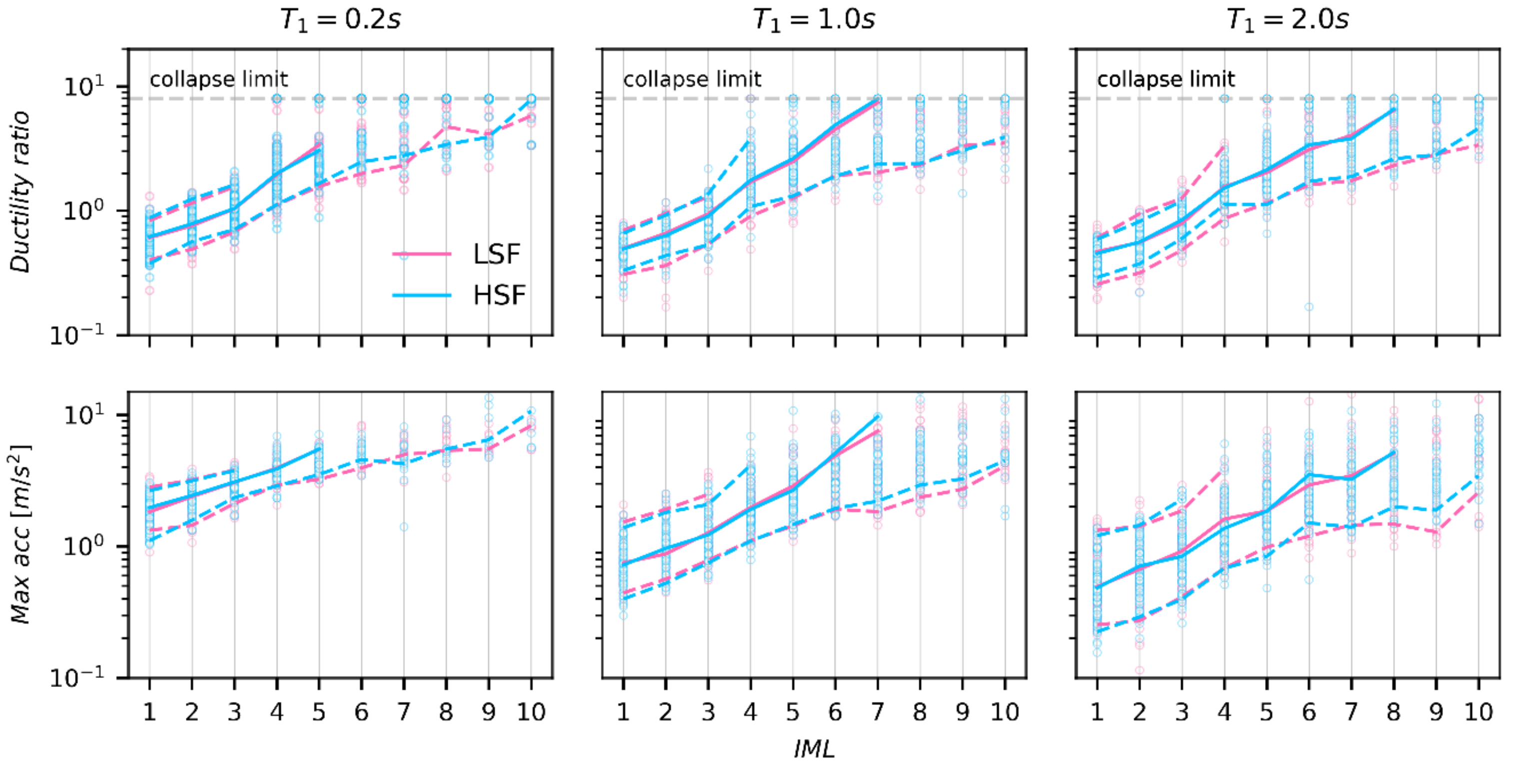
- Results shown for the pinching SDOFs but similar for the elastoplastic ones
- The median response in solid line while 5th and 95th percentiles in dashed lines



(excerpted from de Quevedo Iñarritu et al. 2023)

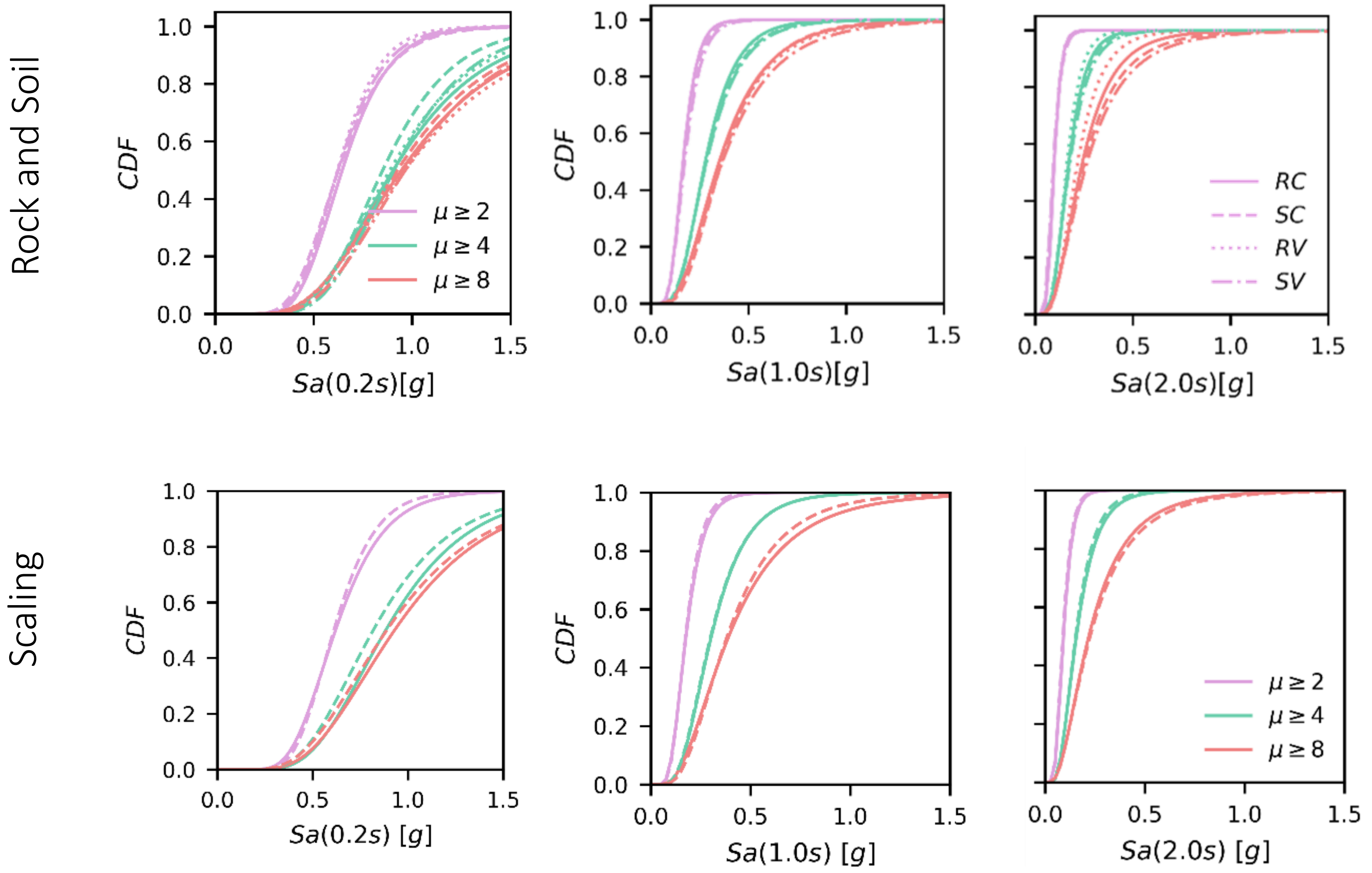
Effect of CS-based scaled accelerograms on structural response

- Results shown for the pinching SDOFs but similar for the elastoplastic ones
- The median response in solid line while 5th and 95th percentiles in dashed lines



(excerpted from de Quevedo Iñarritu et al. 2023)

Effect of soil characteristics and accelerograms' scaling on Fragility Curves

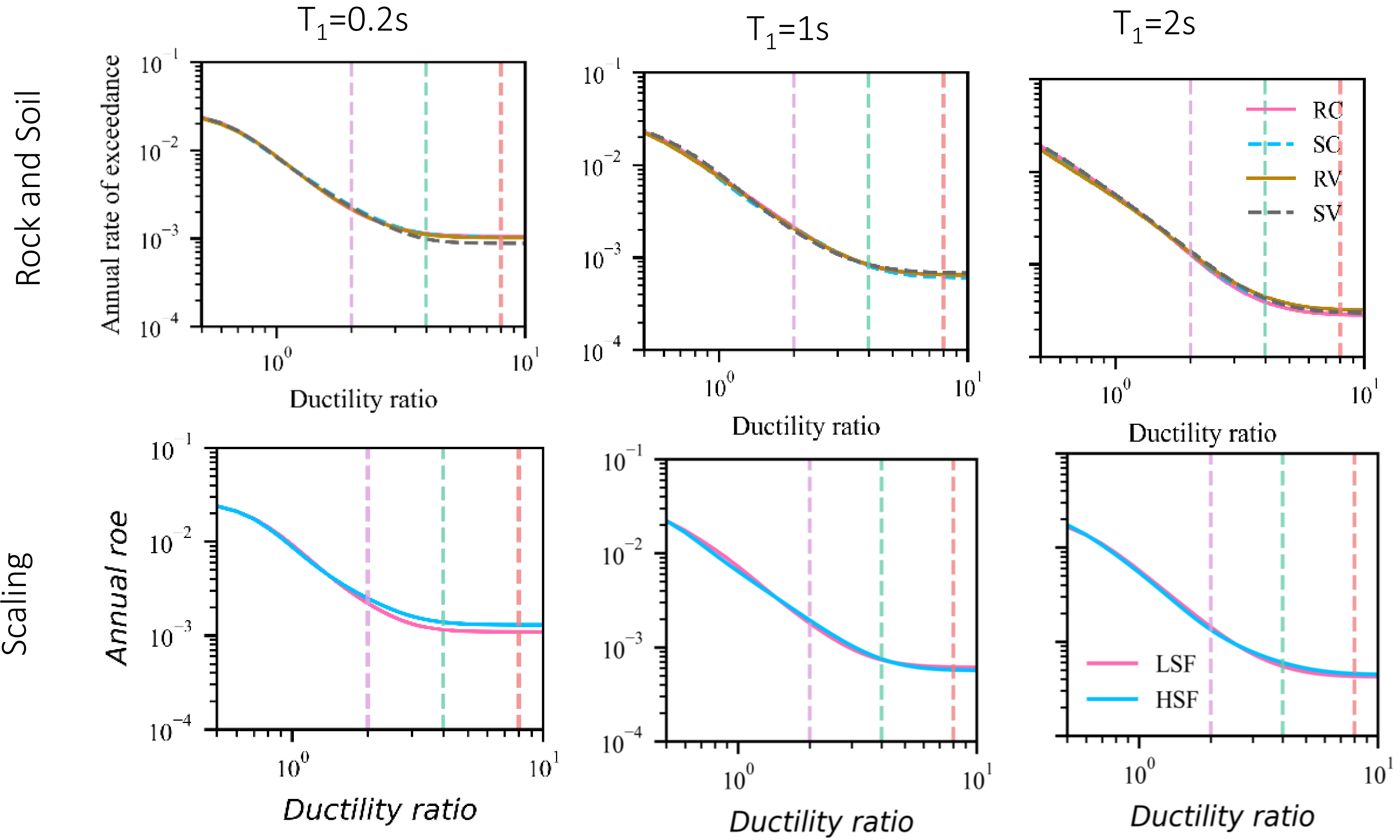


- Fragility curves for onset of damage (DS_1: μ=2) , moderate damage (DS_2: μ=4), and "collapse" (DS_3: μ=8)

- Dashed line is HSF and solid line is LSF

(excerpted from de Quevedo Iñarritu et al. 2023)

Effect of soil characteristics and accelerograms' scaling on Demand Hazard Curves



Negligible difference between the different groups;

Vertical lines correspond to the different damage states: DS1: μ=2, DS2: μ=4 and DS3: μ=8

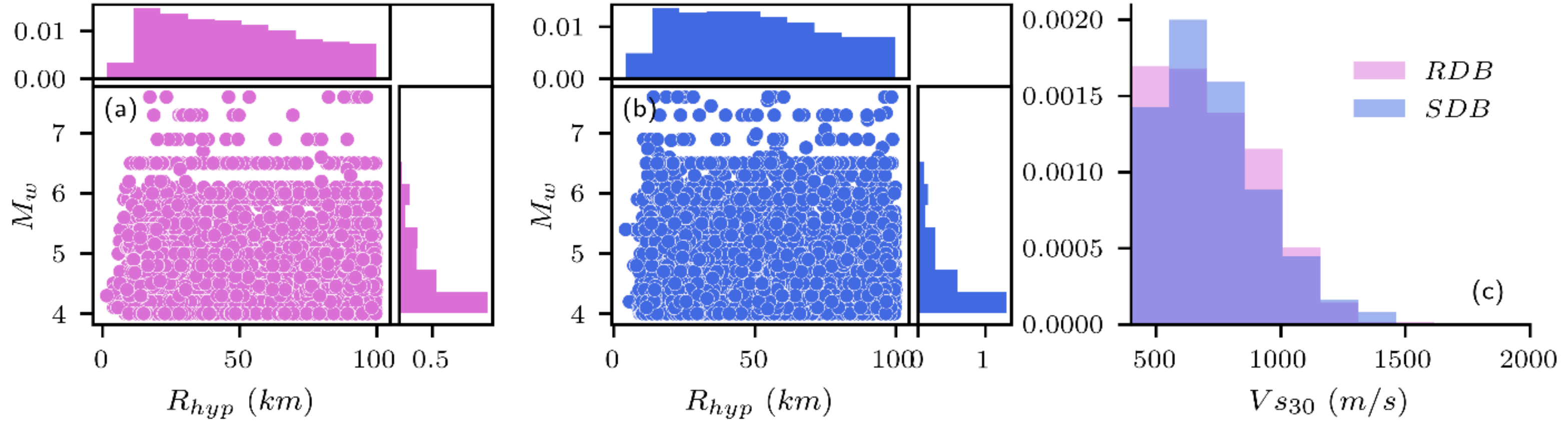
(excerpted from de Quevedo Iñarritu et al

Why not using synthetic ground motions instead?

- Simulated ground motions represent an attractive alternative to recorded ground motions especially for M,R scenarios of interest not densely represented in the DB.
- To evaluate the impact of considering synthetic ground motions, we compared two "equivalent" databases of about 7,000 records each
- Finite-source 3D stochastic ground motion simulation method used (originally proposed by Otarola and Ruiz, 2016, and improved by et al., 2022)

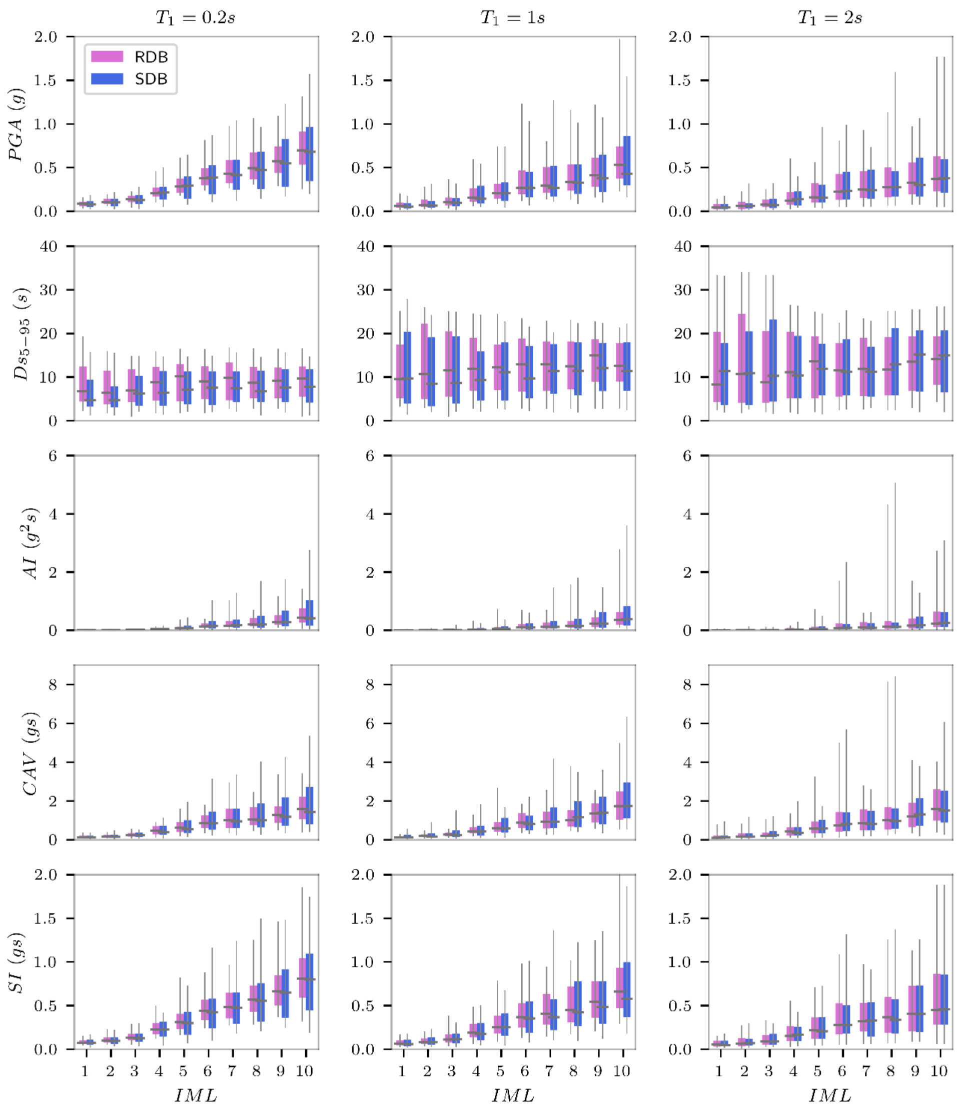
<u>Records selected from:</u>

- Simulated database (SDB)
- Reference database (RDB)



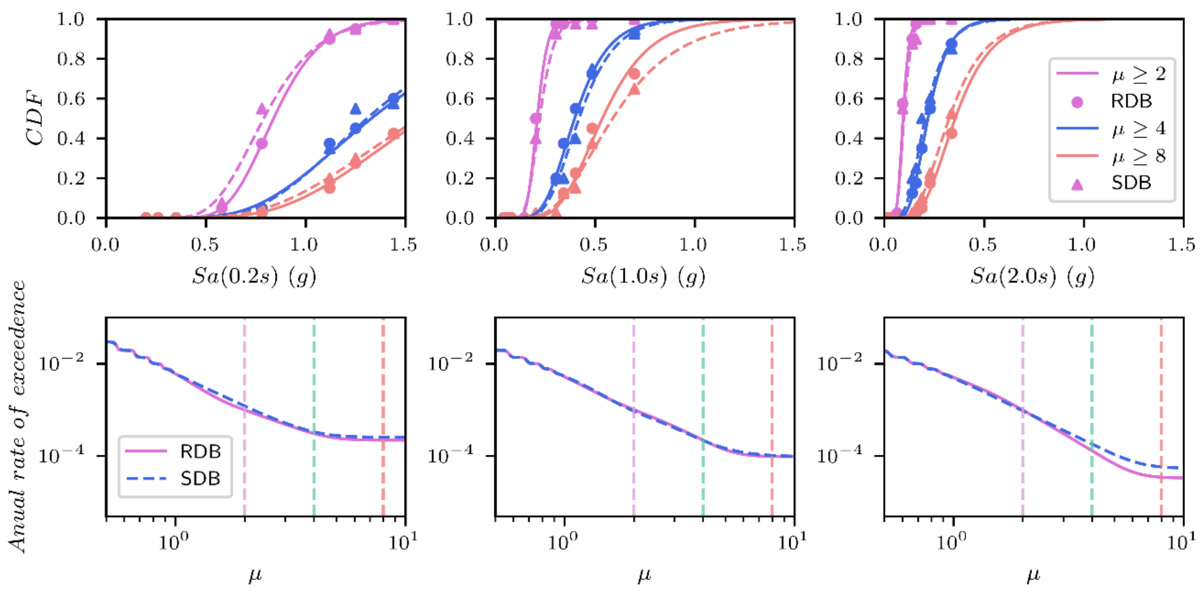
- SDB is designed to be statistically equivalent to the RDB in terms of causative parameters and site. <u>Calibrated to match the spectral content of the RDB up to $T_1 = 1.0s$.</u>

Distributions of IMs of CS-based real and synthetic motions are very similar



- Comparison of the distributions of IMs, computed from records CS-selected from the RDB and the SDB
- Good spectral match (considered in the calibration of the simulation technique)
- Differences in IMs related to duration (not directly considered in the calibration)

Any difference in the Fragility and Demand Curves based on real and synthetics?

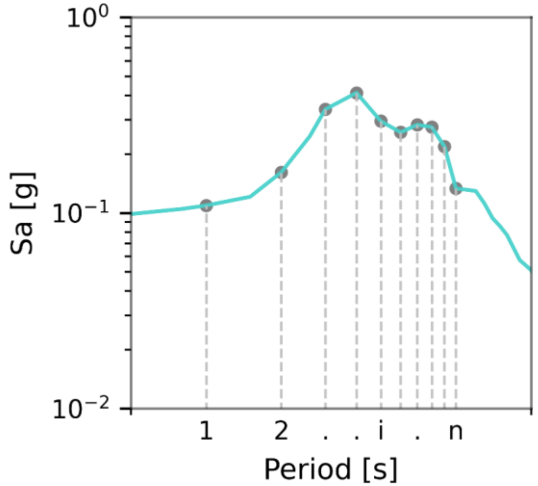


Results shown for the pinching model. Similar for elastoplastic

- Good match especially for lower severity damage states
- Extreme non-linear responses are caused by very severe ground motions not largely represented in either the simulation technique or the calibration procedure

Final alternative: Choosing a more sufficient IM* -- AvgSa and CS(AvgSa)

AvgSa definition

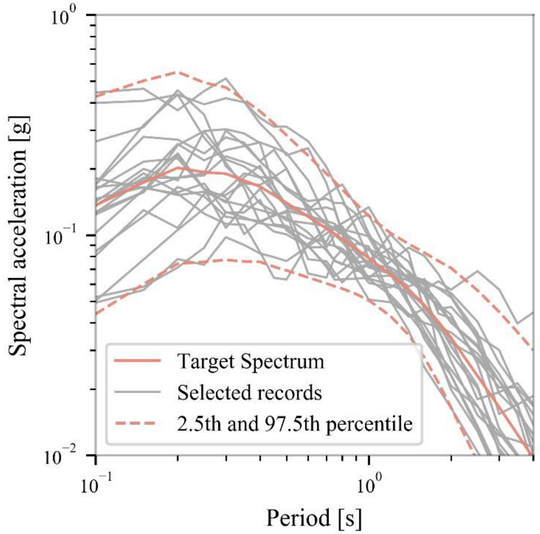


$$AvgSa = \left[\prod_{i=1}^{n} SaT_i\right]^{1/n}$$

$$\ln(AvgSa) = \frac{1}{n}\sum_{i=1}^{n} SaT_i$$

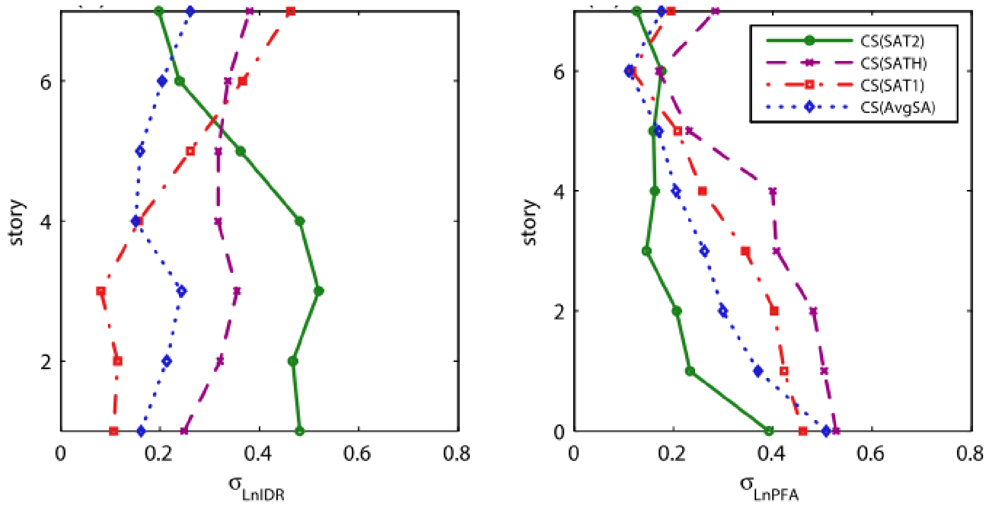
Record Selection

CS(AvgSa) definition



Some qualities of AvgSa

- Higher efficiency → low $\sigma_{ln(EDP|IM)}$
- More predictable → low $\sigma_{ln(IM|rup)}$
- No need for new GMPE



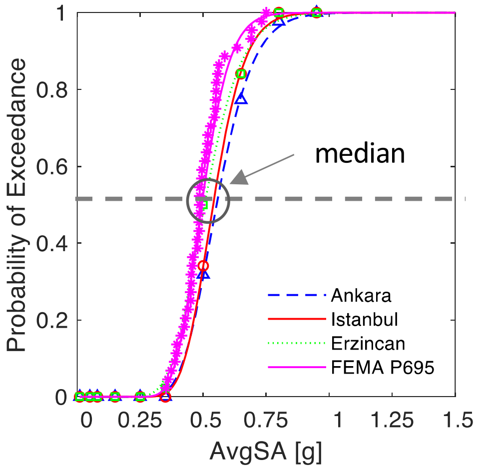
Excerpted from Kohrangi et al. (2017)

- Efficient predictor for different EDPs
- Efficient predictor at all IM levels
- Efficient predictor at different heights

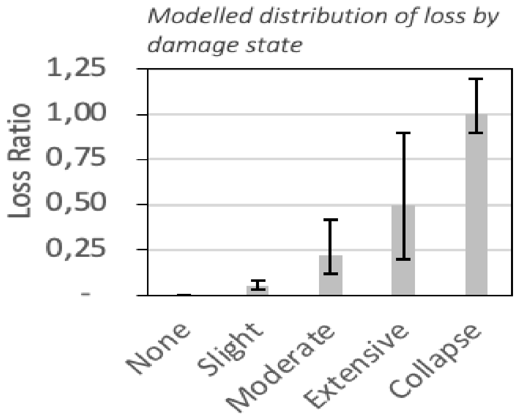
The tale of a 3 identical buildings in Turkey revisited…

- Again, two alternative approaches :
  - Hazard-consistency enforced via site-specific Conditional Spectrum CS with IM=AvgSa + MSA
  - Hazard inconsistent (beyond IM=AvgSa): set of 22 pairs of motions from FEMA P695 + IDA

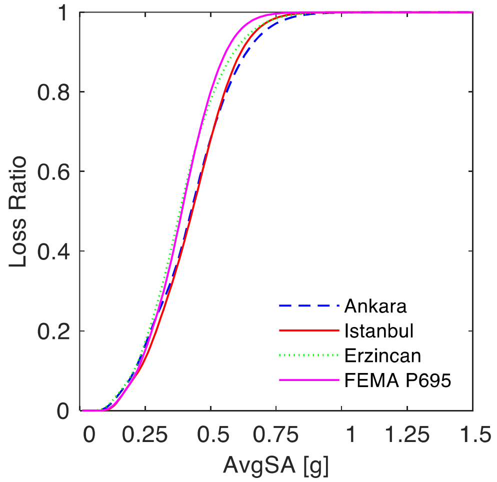
Fragility Curves



Consequence functions



Vulnerability Curves



Fragility/vulnerability curves very similar when “better IM” is used

Conclusions and Recommendations

- A careful, hazard-consistent ground motion selection for fragility/vulnerability curves development is essential if the chosen IM* is “insufficient” (e.g., Sa(T_1) for most buildings);
- To enable a good match of the CS (good consistency) the judicious use of scaled ground motions, ground motions recorded on soil conditions different than the target ones, and use of “realistic” synthetic ground motions is a viable option.
- To make ground motion selection less rigorous and still obtain high-fidelity fragility curves choice of a more sufficient IM* (e.g., AvgSa in some applications) is essential;
- If attention is paid neither the ground motion hazard consistency nor to the choice of a sufficient IM*, then analytically derived fragility curves become completely unreliable for site-specific risk assessment

THANK YOU!

Contact: paolo.bazzurro@iusspavia.it

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