UNIVERSITÀ DI TRENTO

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Introduction

Performance Based Earthquake Engineering

Ph.D. Student Chiara Nardin – M.Sc., Eng. in Civil Engineering

https://github.com/kia13nn/ISPS.git

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

PBEE: **P**erformance **B**ased **E**arthquake **E**ngineering

- Probabilistic framework for *(i)* assessing design, *(ii)* evaluation and *(iii)* planning of civil system.

- load-and-resistence-factor design (LRFD)

↕

performance based design (PBD):

3Ds – i.e. downtime, dollars, death

- 2 axes define the domain of acceptable system's response:

- System performance objectives
- Seismic hazard level, w.r.t. return periods

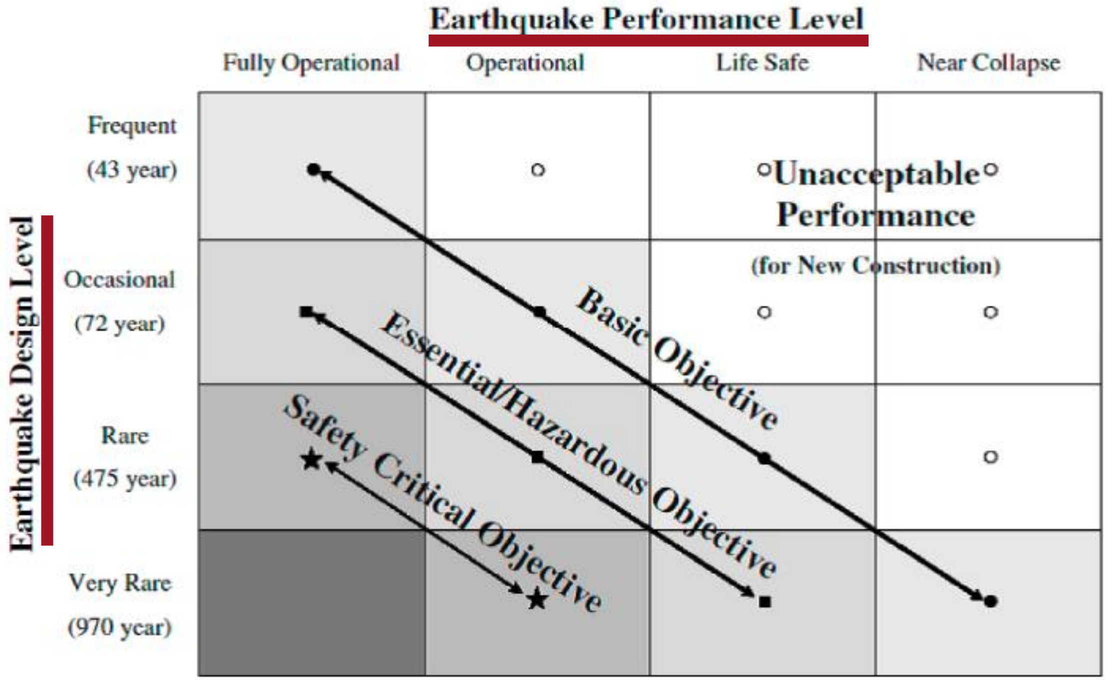


Fig.1 – PBEE concept: seismic performance objectives *vs* seismic hazard level. *©Poland et al.,(1995)-Vision 2000: Performance Based Earthquake Engineering of buildings. Structural Engineers Association of California, Sacramento, CA.*

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

The **PEER-PBEE** Framework

- PEER ~ Pacific Earthquake Engineering Research center – analytical approaches **based on total probability theorem** for the *yearly mean number of events of a selected decision variable*

$$IM \longrightarrow EDP \longrightarrow DM \longrightarrow DV$$

$$\lambda(dv) = \int_d \int_{edp} \int_{im} G(dv|d)|dG(d|edp)||dG(edp|im)||d\lambda(im)| \qquad (1)$$

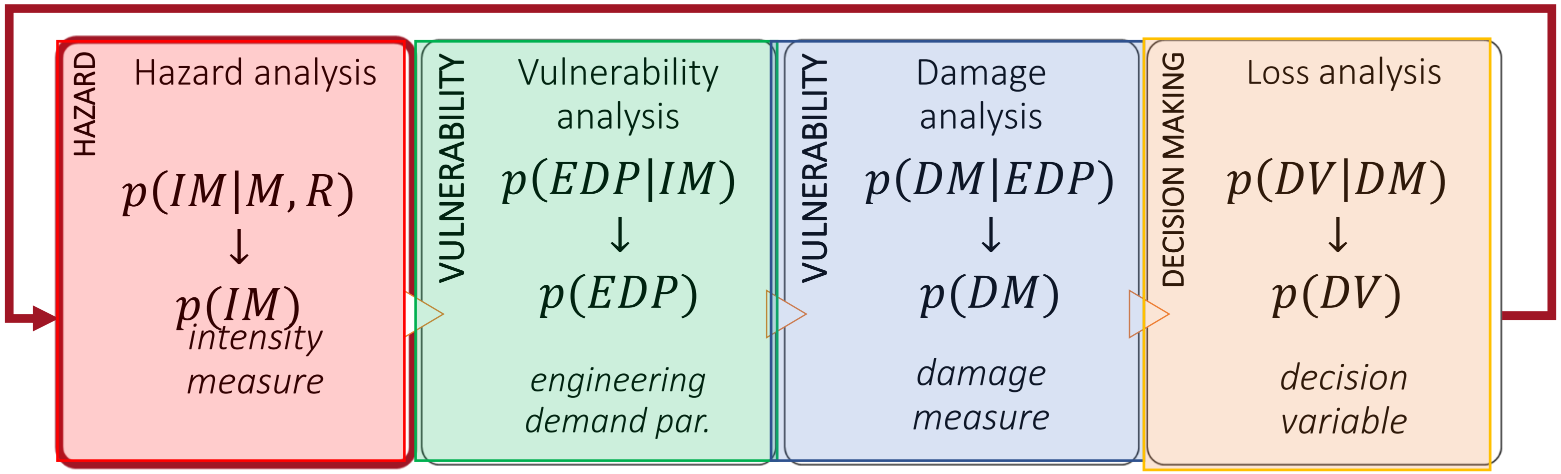
- with the underlying assumptions of:

  - Markovian structure → $DV \perp\!\!\!\perp EDP, IM | DM = dm$; $DM \perp\!\!\!\perp IM | EDP = edp$;
  - No-aging effects on structures;
  - Poisson's processes → memoryless seismic events.

UNIVERSITÀ DI TRENTO

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

The **PEER-PBEE** Framework



$$\boxed{IM} \longrightarrow \boxed{EDP} \longrightarrow \boxed{DM} \longrightarrow \boxed{DV}$$

(i) hazard analysis

(ii) fragility analysis

(iii) damage analysis

(iv) loss analysis

$$\lambda(dv) = \int_d \int_{edp} \int_{im} \boxed{G(dv|d)} \boxed{|dG(d|edp)|} \boxed{|dG(edp|im)|} \boxed{|d\lambda(im)|}$$

Trento, 02 December 2020
Ph.D. Student: *Chiara Nardin*
chiara.nardin@unitn.it

The **PEER-PBEE** Framework

$$IM \longrightarrow EDP \longrightarrow DM \longrightarrow DV$$

$$\lambda(dv) = \int_d \int_{edp} \int_{im} G(dv|d)|dG(d|edp)||dG(edp|im)||d\lambda(im)|$$

where

– im is an intensity measure (e.g., peak ground acceleration, spectral acceleration, etc.);

– edp is an engineering demand parameter (e.g., interstorey drift);

– d is a damage measure (e.g., minor, medium, extensive, collapse);

– dv is a decision variable (e.g., monetary losses, fatalities, etc.);

– $\lambda(x)$ is the mean annual rate of events exceeding a given threshold for a given variable x;

– $G(y|x) = P(Y \geq y|X = x)$ is the conditional complementary cumulative distribution function (CCDF)

UNIVERSITÀ DI TRENTO

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Probabilistic Hazard Analysis

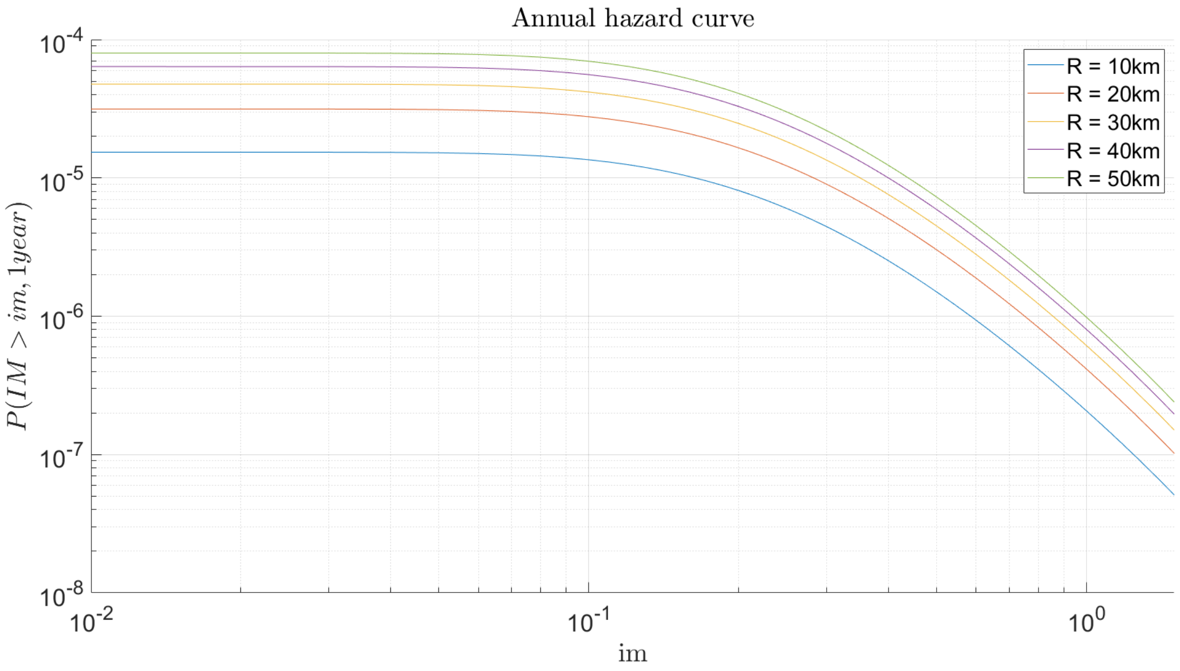
Formulation and MatLab Computation

Ph.D. Student Chiara Nardin – M.Sc., Eng. in Civil Engineering

https://github.com/kia13nn/ISPS.git

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 4: Hazard Computation



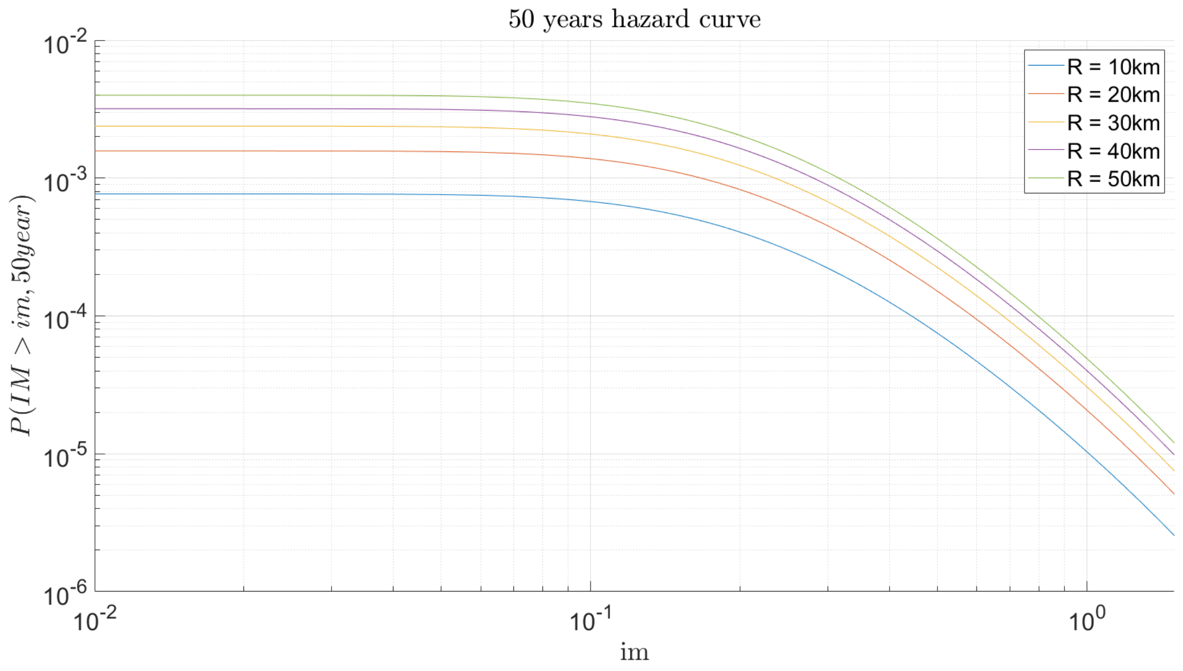
Goal and results

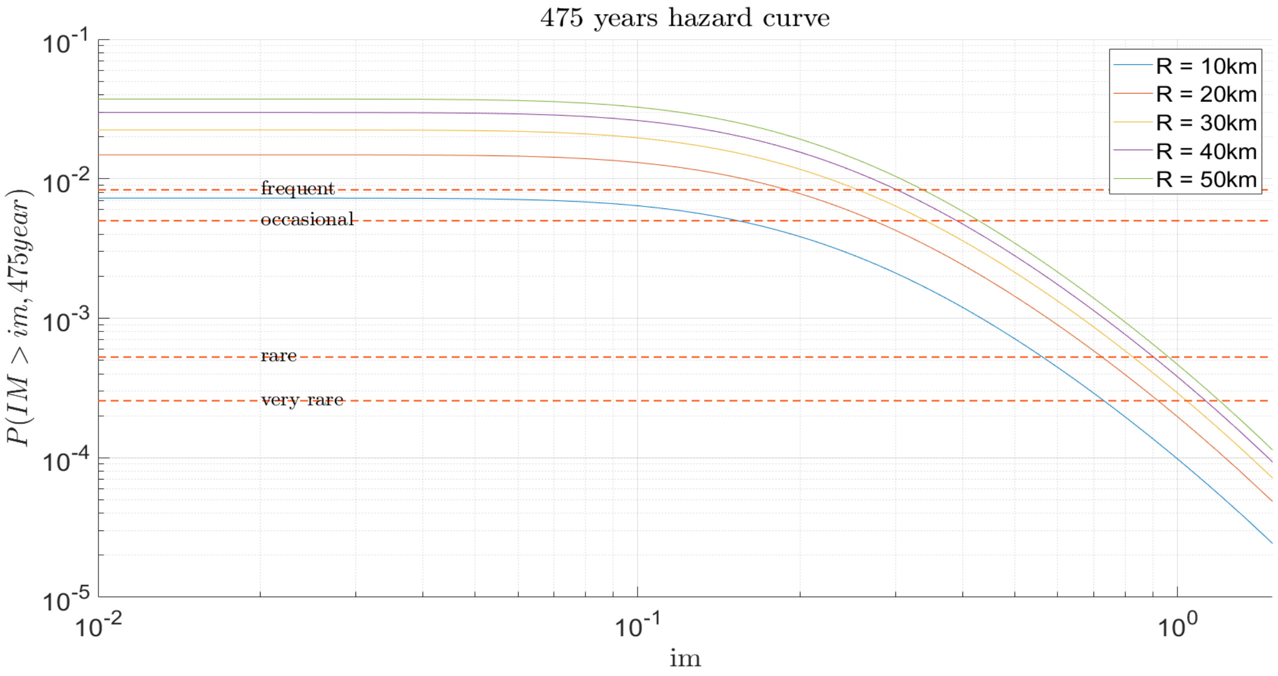
Through the scheme depicted in *(1)*, compute:

- the annual hazard curve for each fault;
- the 50 years hazard curve for each fault;
- the 475 years hazard curve for each fault

for the highlighted seismic site.

Step 4: Hazard Computation





UNIVERSITÀ
DI TRENTO

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Fragility Analysis

Formulation and MatLab Computation

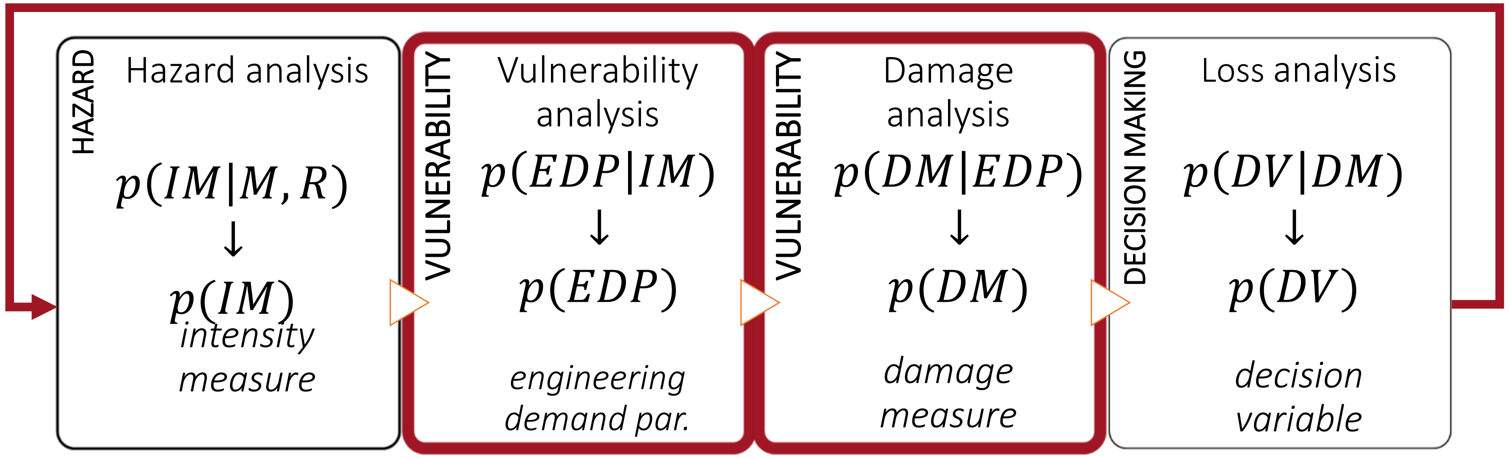
Ph.D. Student Chiara Nardin – M.Sc., Eng. in Civil Engineering

https://github.com/kia13nn/ISPS.git

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Fragility Analysis

Fragility (or Vulnerability) Analysis is the second step of the PBEE-PEER framework



Useful definitions:

seismic fragility function := the conditional probability of an event (e.g. a defined limit/damage state) given the observation of an intensity measure which describe the seismic event.

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Fragility Analysis

VULNERABILITY

Vulnerability analysis

$p(EDP|IM)$

$\downarrow$

$p(EDP)$

engineering demand par.

VULNERABILITY

Damage analysis

$p(DM|EDP)$

$\downarrow$

$p(DM)$

damage measure

The fragility curve is defined as the conditional probability of failure of a structure, or its critical components, at given values of seismic intensity measures (*IMs*).

$$\lambda(dv) = \sum_d \int_{edp} \int_{im} G(dv|d) P(d|im) |d\lambda(im)|$$

In practice, a fragility curve is calculated as the conditional probability that the damage measure (D) exceeds a critical threshold, for a given seismic IM.

$$P\ (D > d_{threshold}\ |\ IM = im)$$

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Fragility Analysis

VULNERABILITY

Vulnerability analysis

$$p(EDP|IM)$$
$$\downarrow$$
$$p(EDP)$$

engineering demand par.

VULNERABILITY

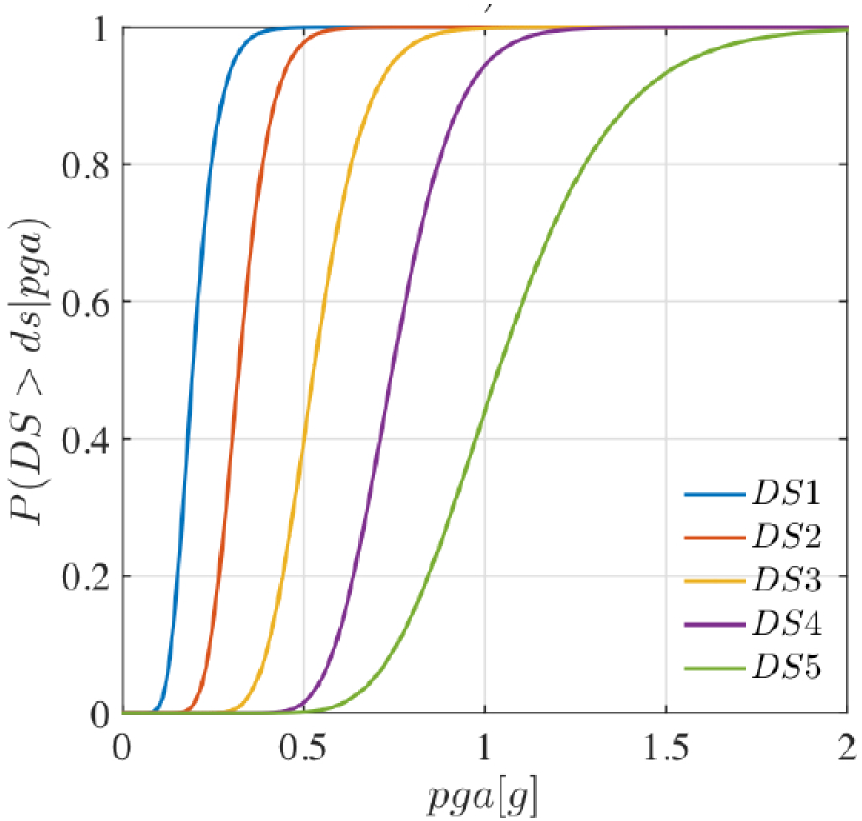
Damage analysis

$$p(DM|EDP)$$
$$\downarrow$$
$$p(DM)$$

damage measure

$$P\,(D > d_{threshold} \mid IM = im)$$

Fragility curves for different damage limit states or thresholds.



Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Fragility Analysis: key aspects

VULNERABILITY

Vulnerability analysis

$p(EDP|IM)$
$\downarrow$
$p(EDP)$

engineering demand par.

VULNERABILITY

Damage analysis

$p(DM|EDP)$
$\downarrow$
$p(DM)$

damage measure

INTENSITY MEASURE (*IM*)	DAMAGE STATE (*D*)
in terms of: • ***Efficiency***, i.e. variability of an *EDP* for a given *IM*; • ***Robustness***, i.e. efficiency between *IM-EDP* at different period ranges; • ***Practicality***, i.e. correlation to known and easy identifiable engineering quantities; • ***Sufficiency***, i.e. validity of *EDP*|*IM* as statistically independent from gm site characteristics; • ***Effectiveness***, i.e. ability to evaluate an analytical relation.	Should suit the specific structural problem → associate each damage state to a specific *EDP* • Categorical variables, i.e. D_0 *no damages* – D_1 *minor* – D_2 *moderate* – … – $D_f = C$ *collapse* ; • Probabilistic or deterministic relationship between *EDP* and *D*

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Class of fragilities

EMPIRICAL	ANALYTICAL	EXPERT OPINION	HYBRID
• by fitting a function to observational data from past earthquakes or lab tests ↕ collections pairs of level of excitation and categorical variables of damage or collapse	• by defining analytical structural model and analyzing its performance under different levels of the seismic hazard ↕ ***static***, i.e. hazard as response spectrum and push-over analysis *vs* ***dynamic***, i.e. collection of gms and simulations on FEM via NLA	• by polling one or more experts of the given structural asset ↕ to guess or estimate the failure probability for a given hazard level	• based on combination of the different methods

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Dynamic based fragility functions: steps

i) Definition of a numerical model: $y(t) = \mathcal{M}\left[\ddot{x}_g(t|IM = im); \boldsymbol{\theta}_{\mathcal{M}}(t)\right]$

ii) Selection of a suitable IM given the structure

iii) Selection of a suitable set of N gms for the location

iv) Selection of an EDP of interest

v) Definition of damage limit states D via EDP thresholds

vi) Scale each gm based on the given IM eventually until collapse → *a) Full IDA* / *b) Truncated IDA*

vii) Save each $[EDP \rightarrow D]$ threshold-im_n pair for each gm

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Computation of fragility function

Hp: - assume a *lognormal probability distribution* for the random variable IM associated with given D

FULL IDA	TRUNCATED IDA
∀ damage state → N results, since ∀ $IM_n = im_n$, $y(t)$ reached the given damage state	$\overline{IM}$ upper limit;

FULL IDA

∀ damage state → N results, since ∀ $IM_n = im_n$,
$y(t)$ reached the given damage state

$$P(D > d | IM = im) = \Phi\left(\frac{\ln(im_n) - \hat{\mu}}{\hat{\sigma}}\right)$$

where $\Phi(\cdot)$ is the CDF of the normal distribution and

$$\hat{\mu} = \frac{1}{N}\sum_{n=1}^{N} \ln(im_n)$$

$$\hat{\sigma} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} (\ln(im_n) - \hat{\mu})^2}.$$

TRUNCATED IDA

$\overline{IM}$ upper limit;

a) data that causes collapse $n \in [1, \bar{N}]$,

b) data that do not cause collapse $n \in [\bar{N}+1, N]$

a) → $\underline{\mathcal{L}}(\mu, \sigma) \propto \prod_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n) - \mu}{\sigma}\right)$

b) → $\overline{\mathcal{L}}(\mu, \sigma) \propto \prod_{n=\bar{N}+1}^{N} \left[1 - \Phi\left(\frac{\ln(\overline{IM}) - \mu}{\sigma}\right)\right] = \left[1 - \Phi\left(\frac{\ln(\overline{IM}) - \mu}{\sigma}\right)\right]^{N-\bar{N}}$

a)+b) →

$$\mathcal{L}(\mu, \sigma) = \underline{\mathcal{L}}(\mu, \sigma)\overline{\mathcal{L}}(\mu, \sigma) =$$

$$= \prod_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n) - \mu}{\sigma}\right)\left[1 - \Phi\left(\frac{\ln(\overline{IM}) - \mu}{\sigma}\right)\right]^{N-N}$$

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Computation of fragility function

TRUNCATED IDA

The likelihood for the entire set of data

$$\mathcal{L}(\mu,\sigma) = \underline{\mathcal{L}}(\mu,\sigma)\overline{\mathcal{L}}(\mu,\sigma) = \prod_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n)-\mu}{\sigma}\right)\left[1-\Phi\left(\frac{\ln(\overline{IM})-\mu}{\sigma}\right)\right]^{N-\overline{N}} \tag{1}$$

And the log likelihood

$$\ln \mathcal{L}(\mu,\sigma) = \sum_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n)-\mu}{\sigma}\right) + (N-\overline{N})\left[1-\Phi\left(\frac{\ln(\overline{IM})-\mu}{\sigma}\right)\right] \tag{2}$$

Estimation of parameters by optimization

$$[\hat{\mu},\hat{\sigma}] = \underset{\mu,\sigma}{\mathrm{argmin}}[-\ln \mathcal{L}(\mu,\sigma)].$$

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Computation of fragility function

For a generic $f(x;\boldsymbol{\theta})$

$$\mathcal{L}(\boldsymbol{\theta}) = \prod_{n=1}^{\bar{N}} f\left(im_n;\boldsymbol{\theta}\right)\left[1 - F(\overline{IM};\boldsymbol{\theta})\right]^{N-\bar{N}}$$

And the log likelihood

$$\ln \mathcal{L}(\boldsymbol{\theta}) = \sum_{n=1}^{\bar{N}} f\left(im_n;\boldsymbol{\theta}\right) + (N - \bar{N})\left[1 - F(\overline{IM};\boldsymbol{\theta})\right]$$

Estimation of parameters by optimization

$$\hat{\boldsymbol{\theta}} = \underset{\boldsymbol{\theta}}{\operatorname{argmin}}[-\ln \mathcal{L}(\boldsymbol{\theta})]$$

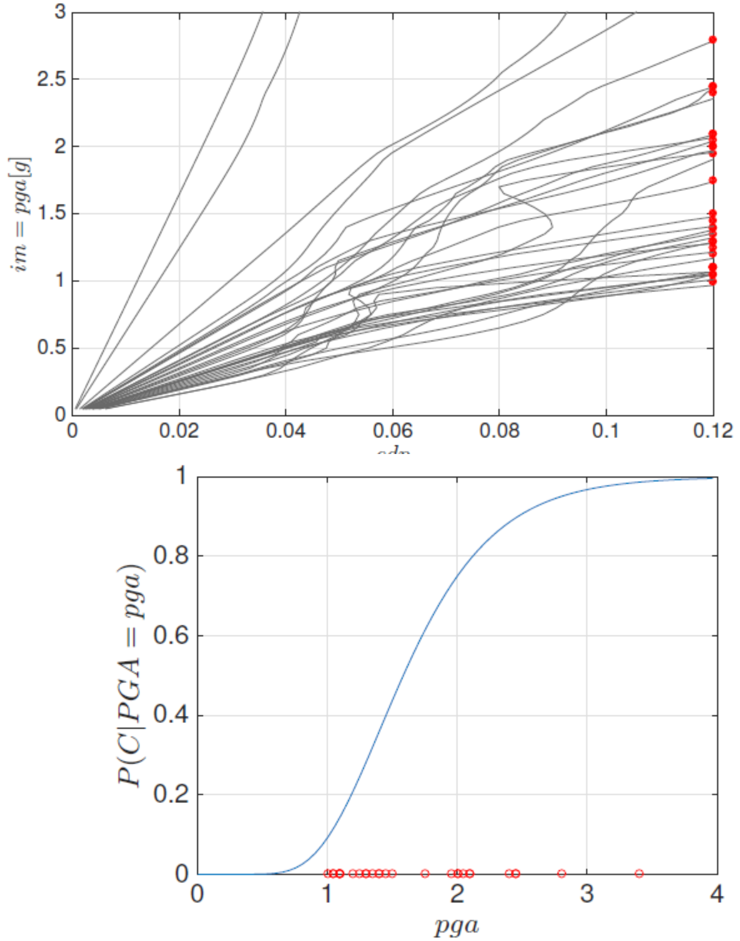


Fig.1 – Fragility function computed via IDA, see Broccardo, M. (2018) *Probabilistic seismic risk analysis for civil systems*, Lecture Notes.

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Fragility Analysis

Formulation and MatLab Computation

Ph.D. Student Chiara Nardin – M.Sc., Eng. in Civil Engineering

https://github.com/kia13nn/ISPS.git

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

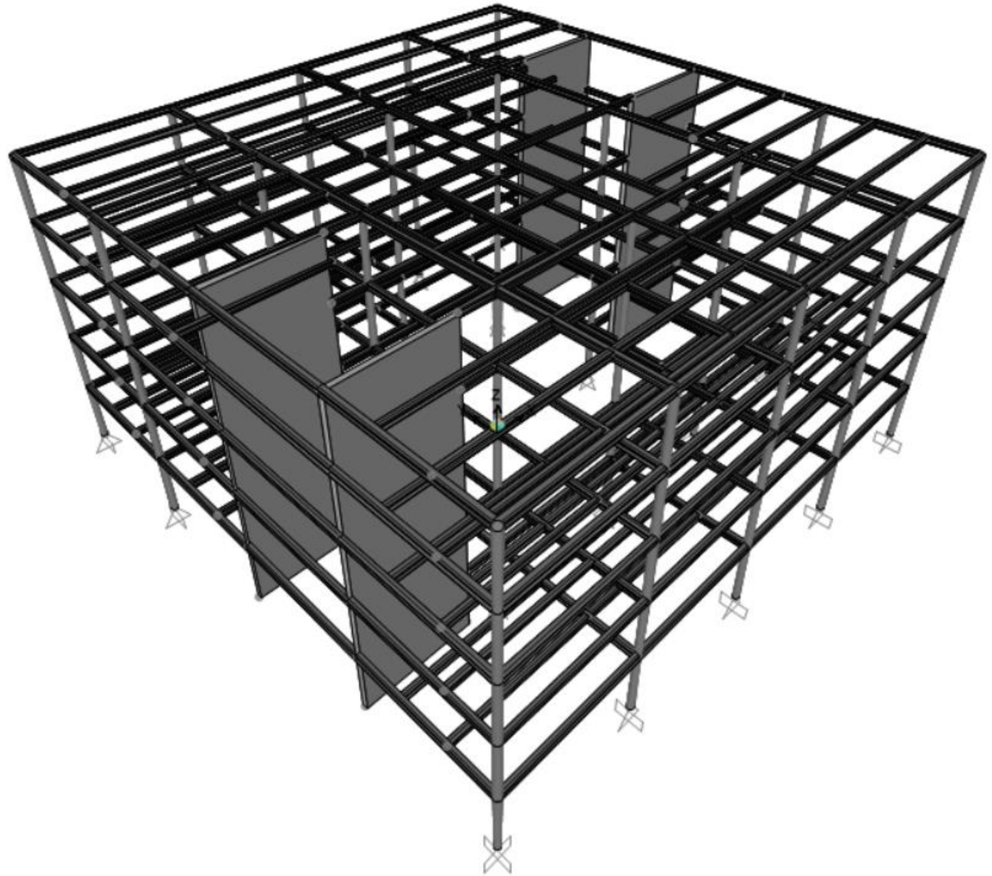
Goal: to perform fragility analysis

Given the provided set of ground motions, perform a classical and truncated incremental dynamic analysis (*IDA*) and determine fragility curves for:

- ATTEL – moment resistant frame (*MRF*);
- ATTEL – braced frame (*BF*)

by considering both

- Linear elastic behaviour
- Bouc – Wen model for hysteresis

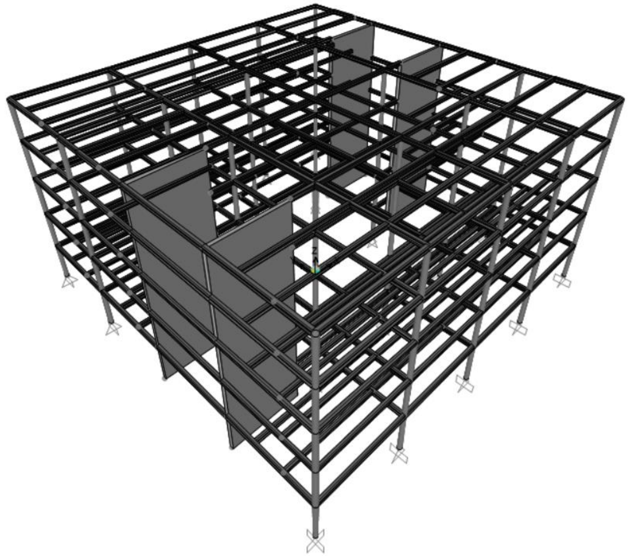


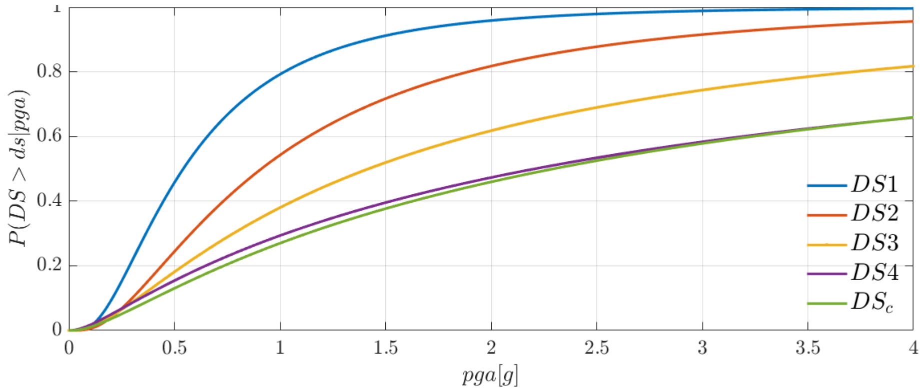
3D model of the case study ATTEL – SERA project.

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Main steps:

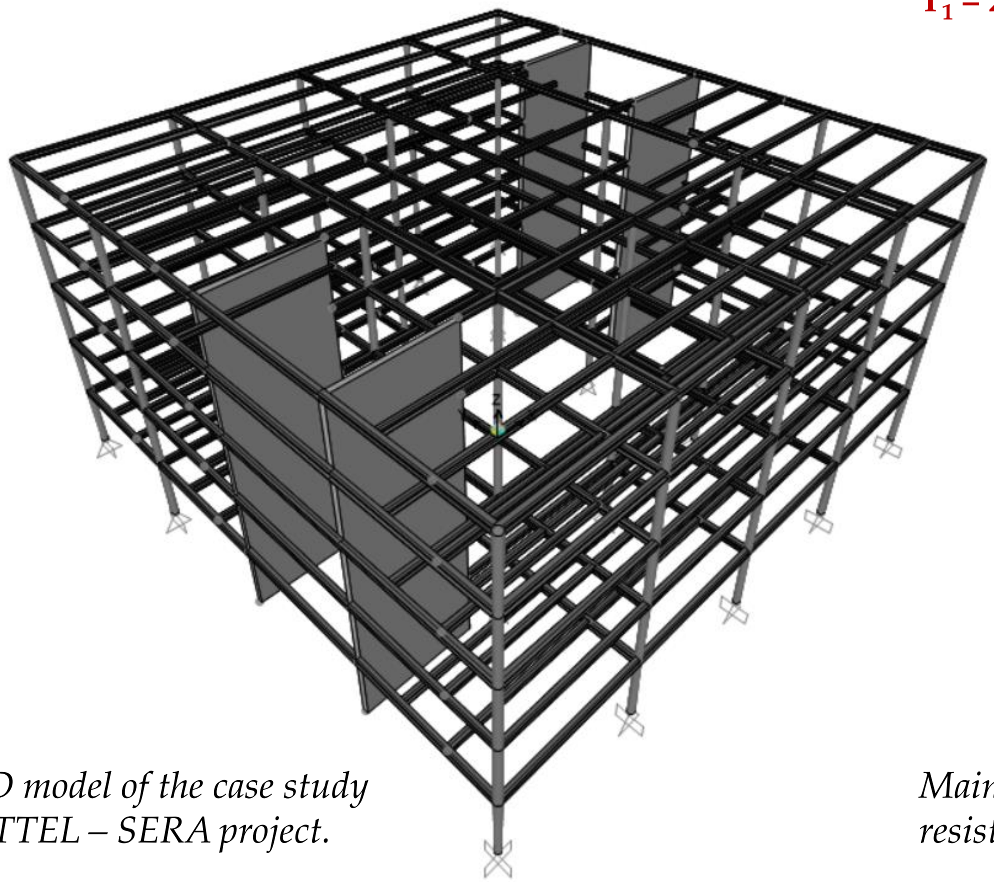
1) Definition of the numerical model
2) Input and *IM* selection
3) Definition of *damage limit states* and reference *EDP*
4) Performing non-linear time histories analysis (IDA, truncated IDA, cloud, MSA …)
5) Collecting results pairs and computing fragility





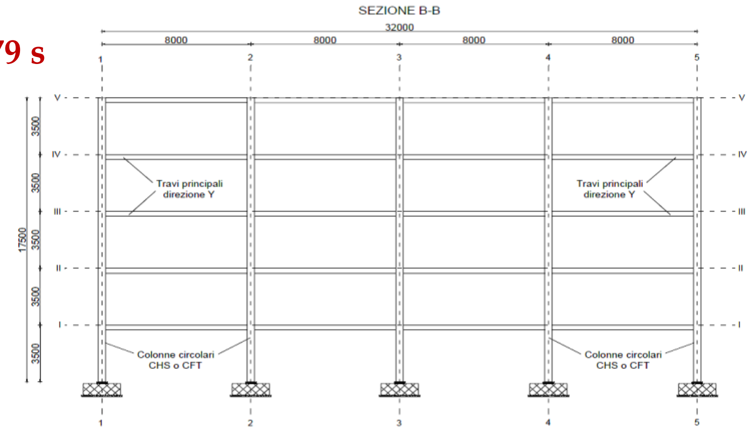
Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 1: the case study ATTEL[(1)]

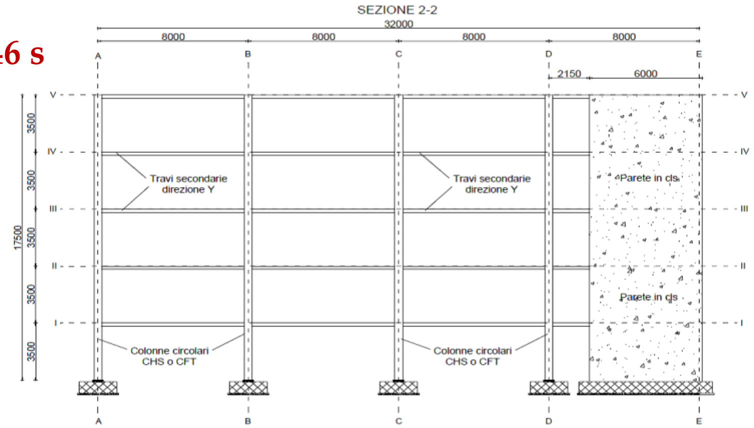


3D model of the case study ATTEL – SERA project.

$T_1 = 2.79$ s

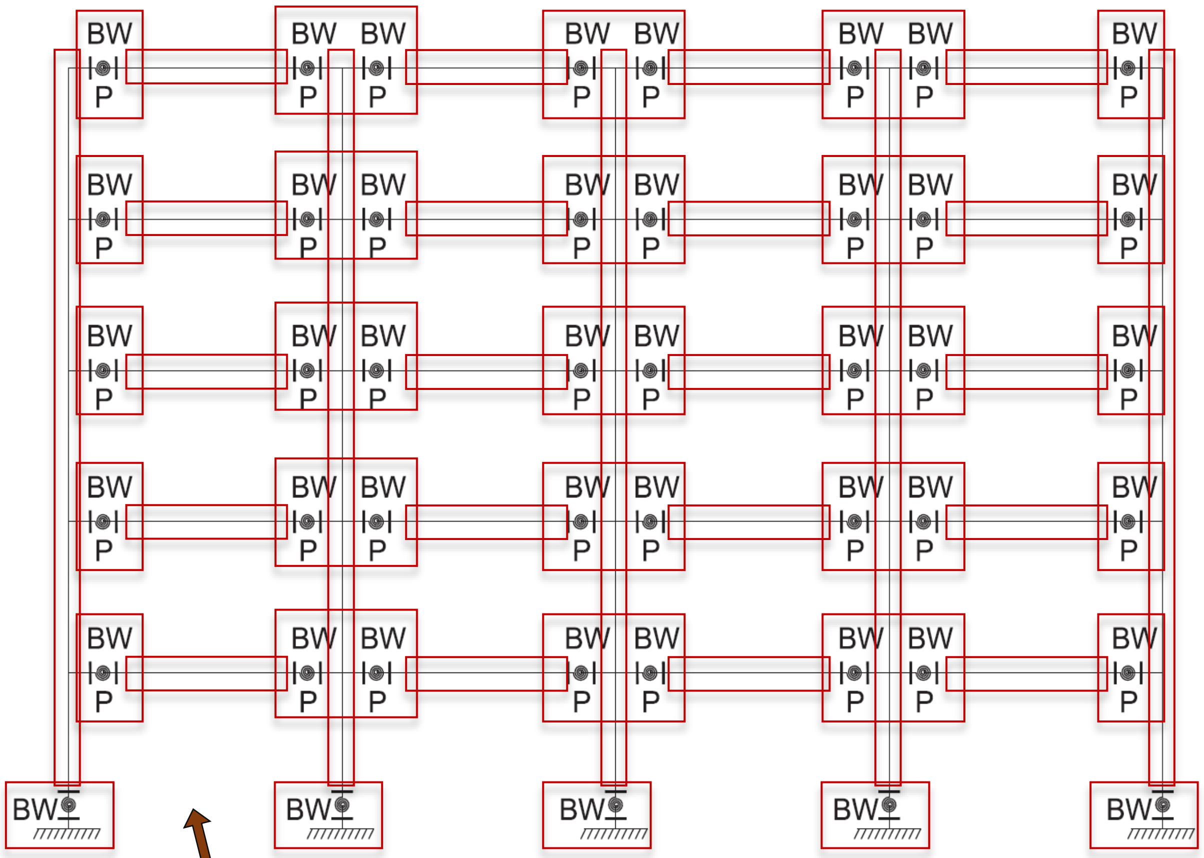


$T_1 = 0.46$ s



Main sections of the moment resistent frame and the braced one.

[1]BURSI, PUCINOTTI, TONDINI, ZANON, Tests and model calibration of high strength steel tubular beam-to-column and column-base composite joints for moment-resisting structures, Earthquake Engineering and Structural Dynamics, (2015).



Model of the structure in OpenSees.

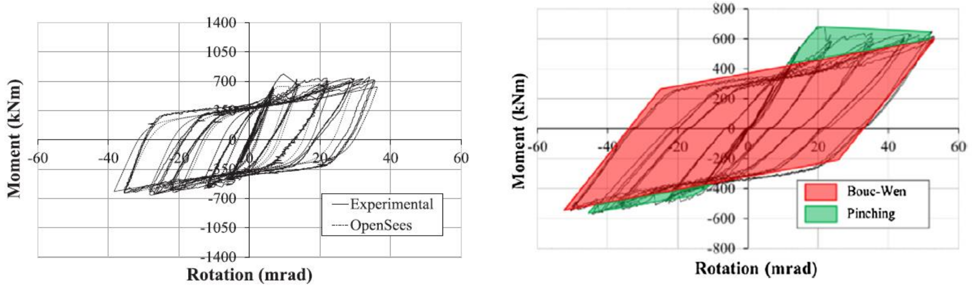
Designed according to EC8 and modelled in OS:

- beam and column elements with linear elastic behavior

  `elasticBeamColumn`

- mechanical nonlinearities

  `uniaxialMaterial BoucWen`
  `uniaxialMaterial Pinching4`
  `uniaxialMaterial Parallel`

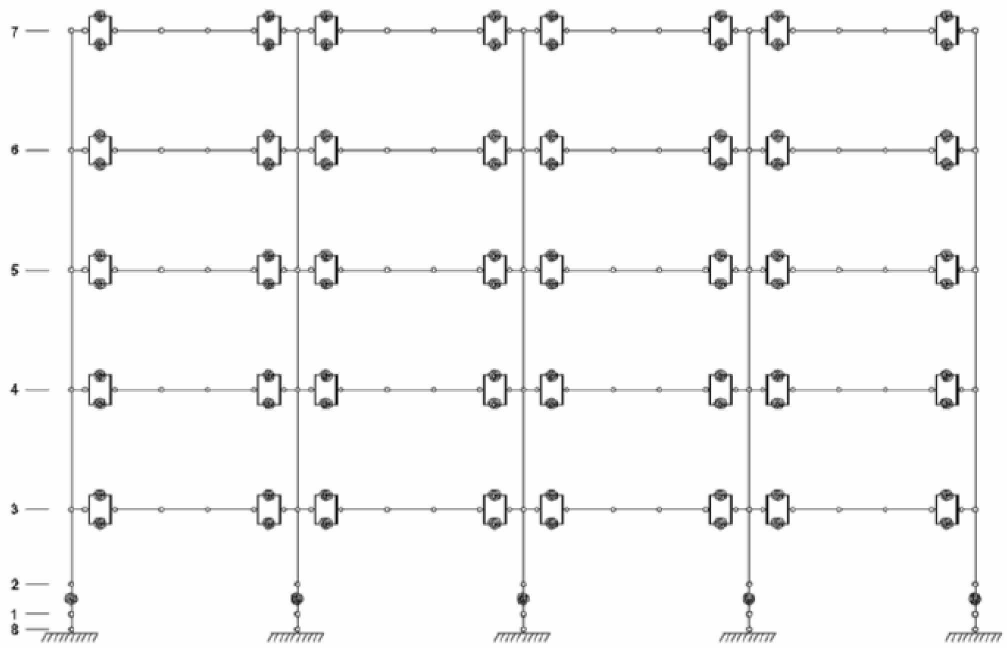


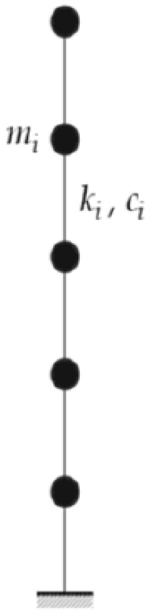
`e uniaxialMaterial Parallel $matBoucWen $matPinching $Iz $transfTag`

Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

High number of analysis for seismic simulations →

- to reduce computational burden
- to reduce required simulation times



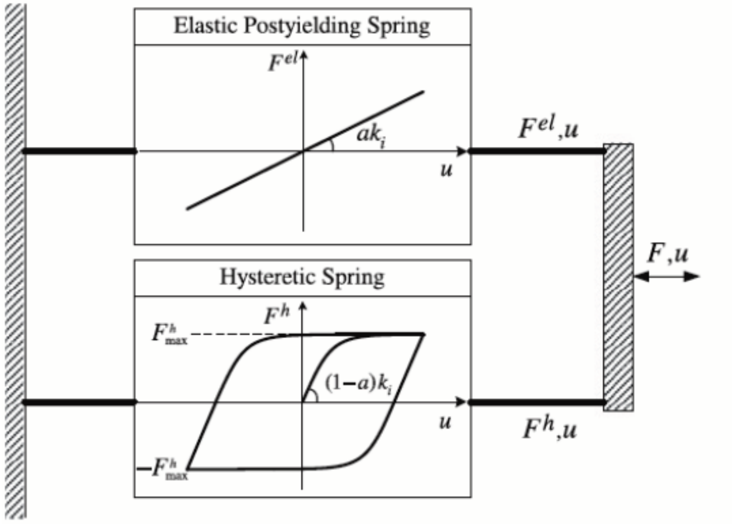


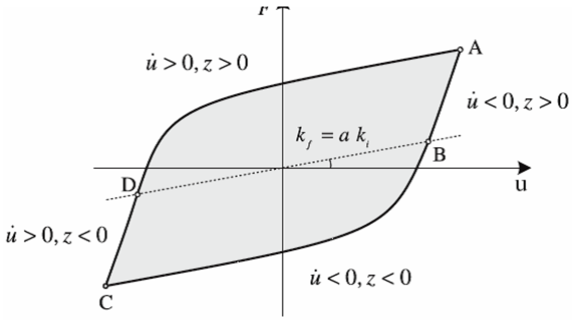
Calibration oriented to correspondence of:

- main periods
- modes of vibrating
- dissipative behavior

high fidelity model in *OpenSees - OS* → simplified model MDOF in *MATLAB® - ML*

Trento, 02 December 2020
Ph.D. Student: *Chiara Nardin*
chiara.nardin@unitn.it





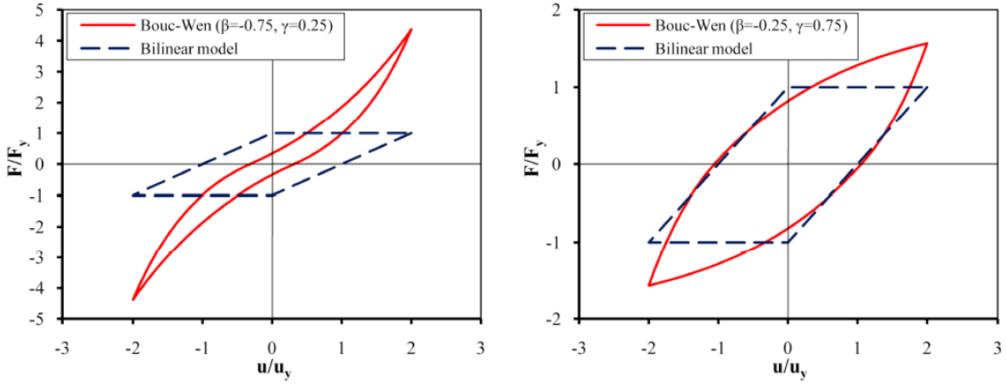
Hysteretic model of Bouc Wen.

Hysteretic model of Bouc Wen

$$m\ddot{u}(t) + c\dot{u}(t) + F_s(t) = F(t)$$

$$F_s(u(t),\dot{u}(t),z(t)) = F_{el}(t) + F_h(t) = \alpha\, k_i\, u(t) + (1-\alpha)\, k_i\, z(t)$$

$$\dot{z} = \frac{A\dot{u} - \{\beta\,|\,\dot{x}\,|\,z\,|\,z\,|^{n-1} + \gamma\dot{u}\,|\,z\,|^{n}\}\,\nu}{\eta}$$



Formulation of the problem and examples of hysteretic cycles.

UNIVERSITÀ DI TRENTO

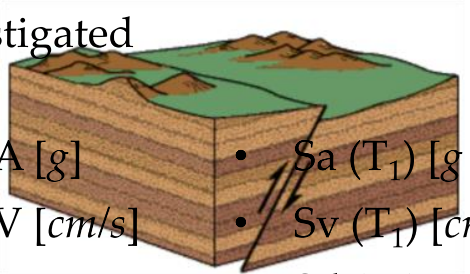
Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

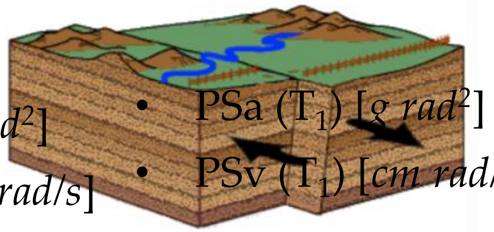
Step 2: input and *IM* selection

Dataset NGA-WEST 2 → *206 ground motions*

main features
- crustal earthquakes
- $M_w > 6$
- $R_{rup} > 10$ km
- $V_{s30} > 600$ m/s

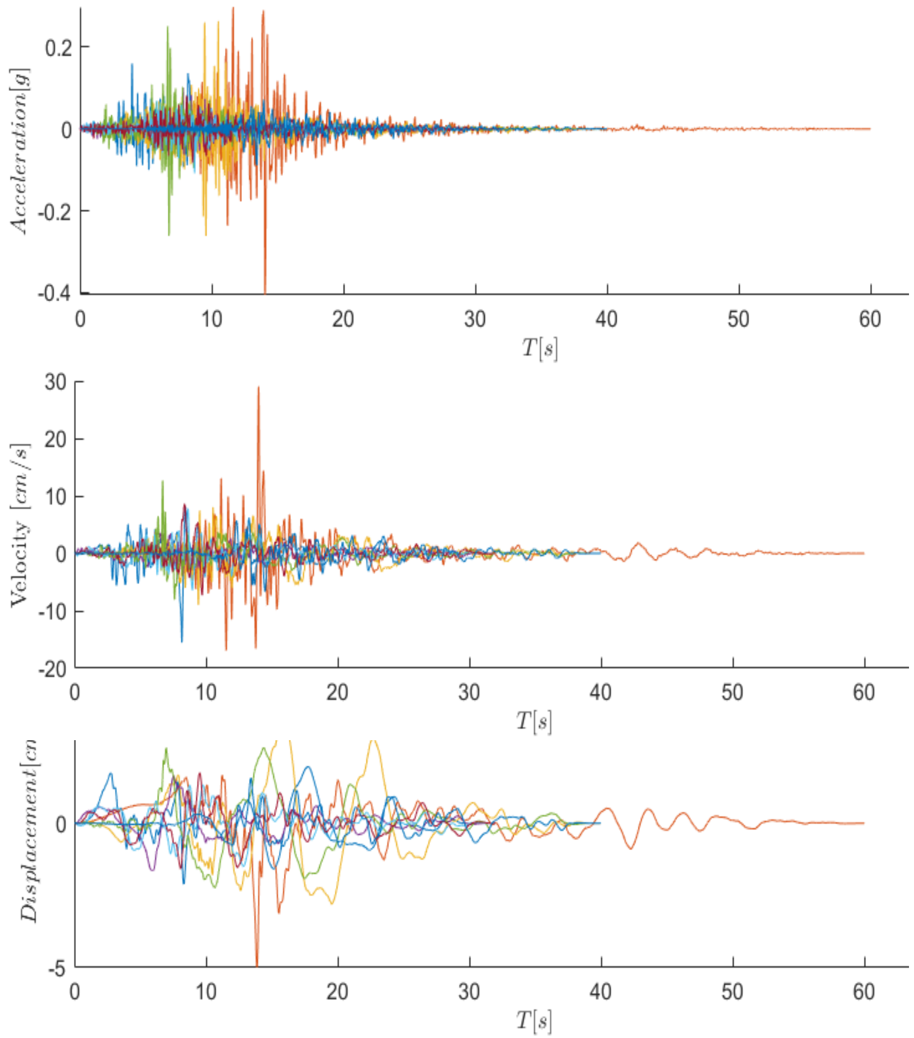
fault mechanism
- *reverse REV*
- *strike slip SS*





IMs investigated

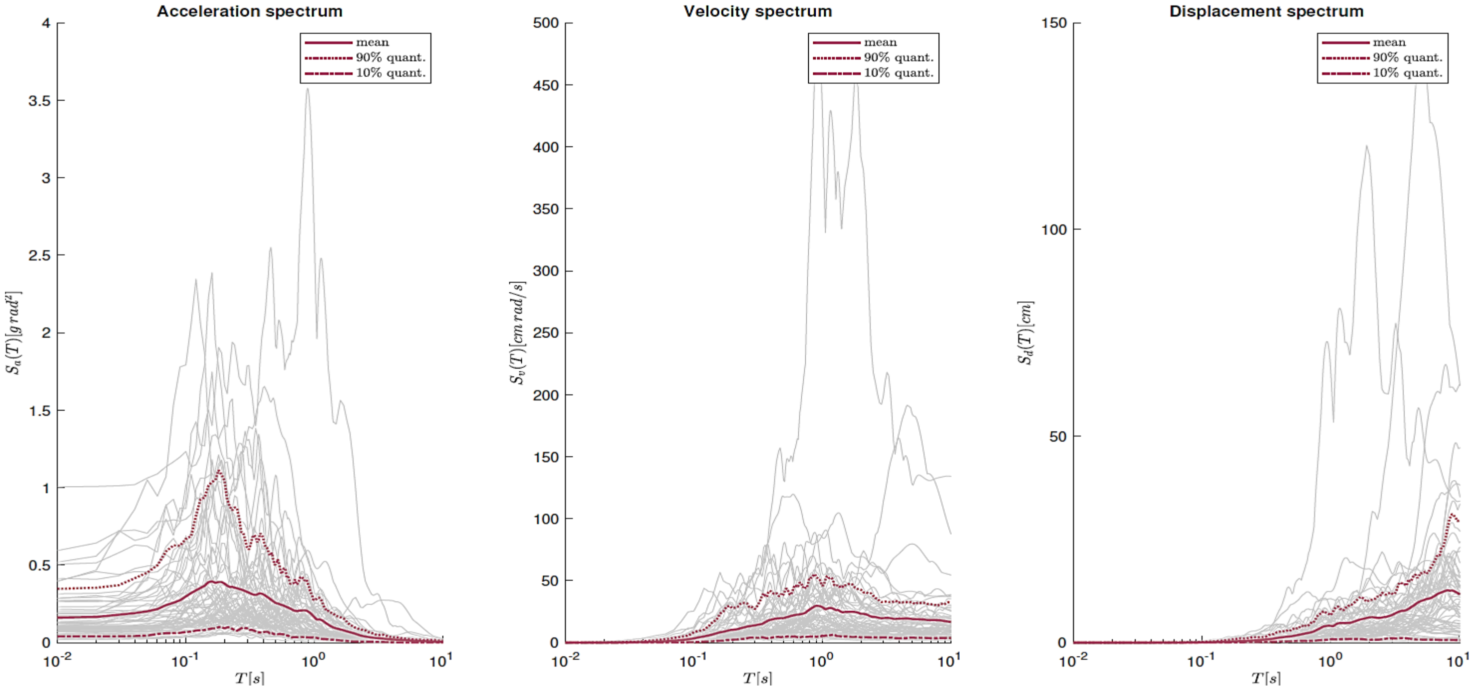
- PGA [*g*]
- PGV [*cm/s*]
- PGD [*cm*]
- Sa (T_1) [*g rad*^{2}]
- Sv (T_1) [*cm rad/s*]
- Sd (T_1) [*cm*]
- PSa (T_1) [*g rad*^{2}]
- PSv (T_1) [*cm rad/s*]



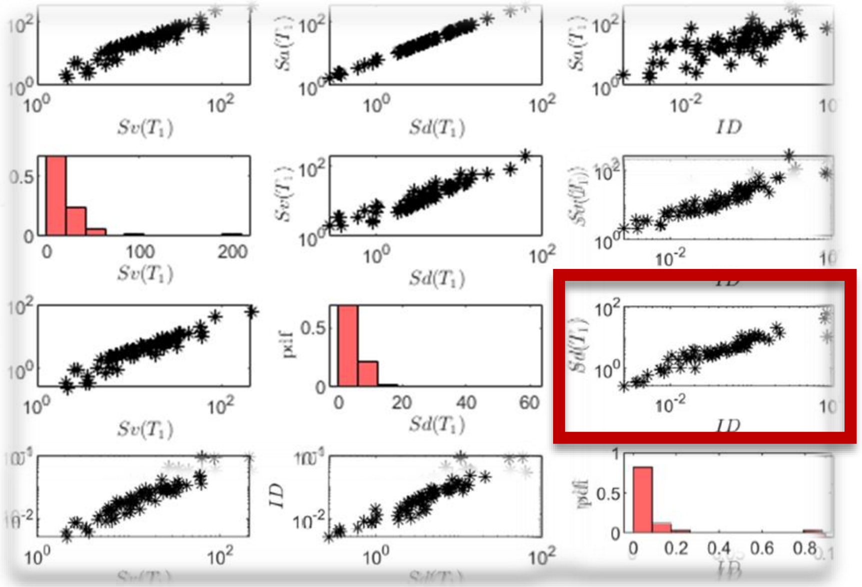
Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 2: input and *IM* selection

1) Data exploration of recorded gms
2) Scatter plot and statistic tools to evaluate proper *IM*



Acceleration, velocity and displacement response spectra with mean value, 10-th and 90-th quantile.



Scatter plot for correlation.

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 2: input and *IM* selection

Codes:

```
%% Ground motions
Ground_motions = load('accelrot_cellarray.mat');
%
NN = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 19, 21, 23, 24,...
    25, 26, 28, 29, 30, 31, 32, 33, 34, 36, 37]; % number ID of the SS ground motions
DT = [0.01 , 0.01 , 0.005, 0.005, 0.005, 0.005, 0.02 , 0.02, 0.02, 0.01,...
    0.01 , 0.01 , 0.02 , 0.02 , 0.02 , 0.02 , 0.02 , 0.02, 0.01, 0.01,...
    0.005, 0.005, 0.005, 0.005, 0.02 , 0.005, 0.005, 0.01, 0.01, 0.01,...
    0.01 , 0.005, 0.005, 0.02 , 0.005, 0.01 , 0.01]; % integration time step
```

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 3: Definition of *damage limit states* and reference *EDP*

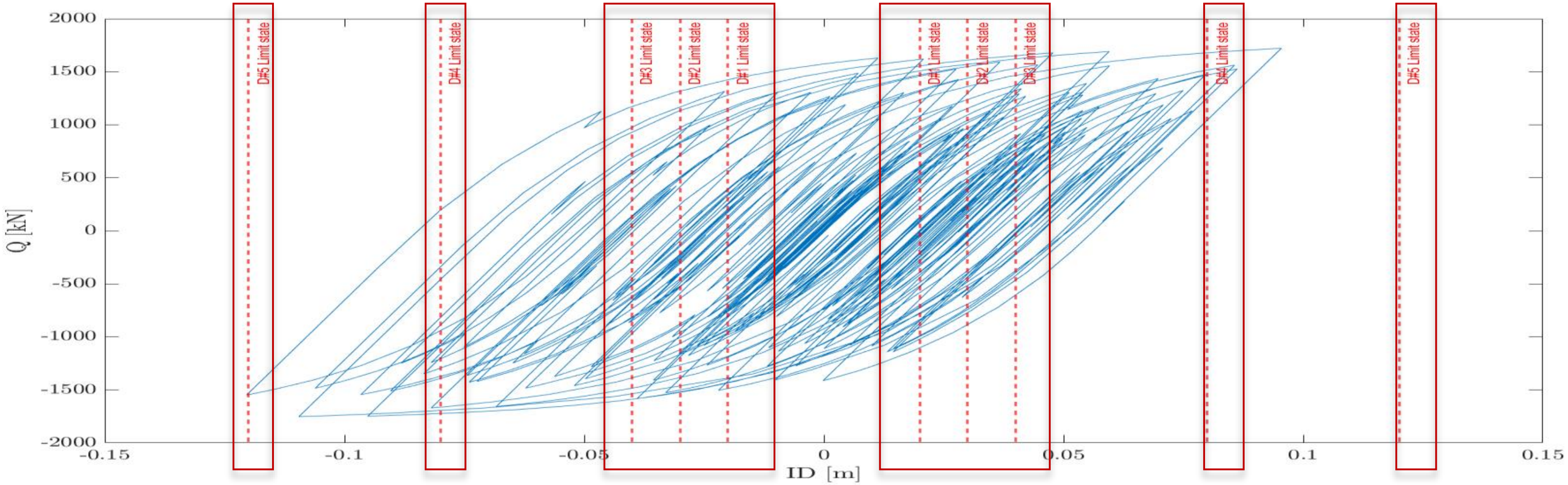
MRF

		Structural Performance Levels			
		Collapse Prevention	**Life Safety**	**Service**	**Immediate Occupancy**
Drift	[%]	5%	2,50%	1%	0,70%
	[m]	0,175	0,088	0,035	0,025

BF

		Structural Performance Levels			
		Collapse Prevention	**Life Safety**	**Service**	**Immediate Occupancy**
Drift	[%]	2,00%	1,00%	0,50%	0,30%
	[m]	0,07	0,035	0,0175	0,0105

Document *FEMA 356 - Prestandard and Commentary for the Seismic Rehabilitation of Buildings; Table C1-3 - Structural Performance Levels and Damage.*



Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 3: Definition of *damage limit states* and reference *EDP*

Codes:

```
%% MDOF Properties
% Choose between the structural system
MDOF_properties_BW_MRF
MDOF_properties_BW_BF
% and  between linear or hysteretic behaviour
%% Structural behaviour
System_type = 'le'; % 'bw'
% bw = bouc-wen
% le = linear elastic
```

```
…
%% Limit States
LS = [0.50 0.75 1 2 3]*4/100;
for ls_i = 1:numel(LS)
ls_val = LS(ls_i)
Main_IDA_o_t
ls_i = ls_i + 1;
end
```

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 4: Performing non-linear time histories analysis

Codes:

```
 %% Initial condition
Mat.dFe=zeros(Mat.NDOF,numel(a_g_norm));    % Preallocation for the load for the time series
a_g = a_g_norm*scale;                        % Scaled ground motion
Mat.Fe=Mat.M*Mat.r'*a_g'*g;
%% Computation response
[HistVarBw]=ResponceMDF_Bw(Mat);
edp = max(abs(HistVarBw.eps(1,:)));
EDP(i) = edp; %store the EDP for each time history analysis
SCALE(i) = scale; %store the scale factor for each time history analysis…
```

UNIVERSITÀ DI TRENTO

Trento, 02 December 2020
Ph.D. Student: *Chiara Nardin*
chiara.nardin@unitn.it

Step 5: Computing fragilities

$$\mathcal{L}(\mu,\sigma) = \underline{\mathcal{L}}(\mu,\sigma)\overline{\mathcal{L}}(\mu,\sigma) = \prod_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n)-\mu}{\sigma}\right)\left[1-\Phi\left(\frac{\ln(\overline{IM})-\mu}{\sigma}\right)\right]^{N-\bar{N}} \quad (1)$$

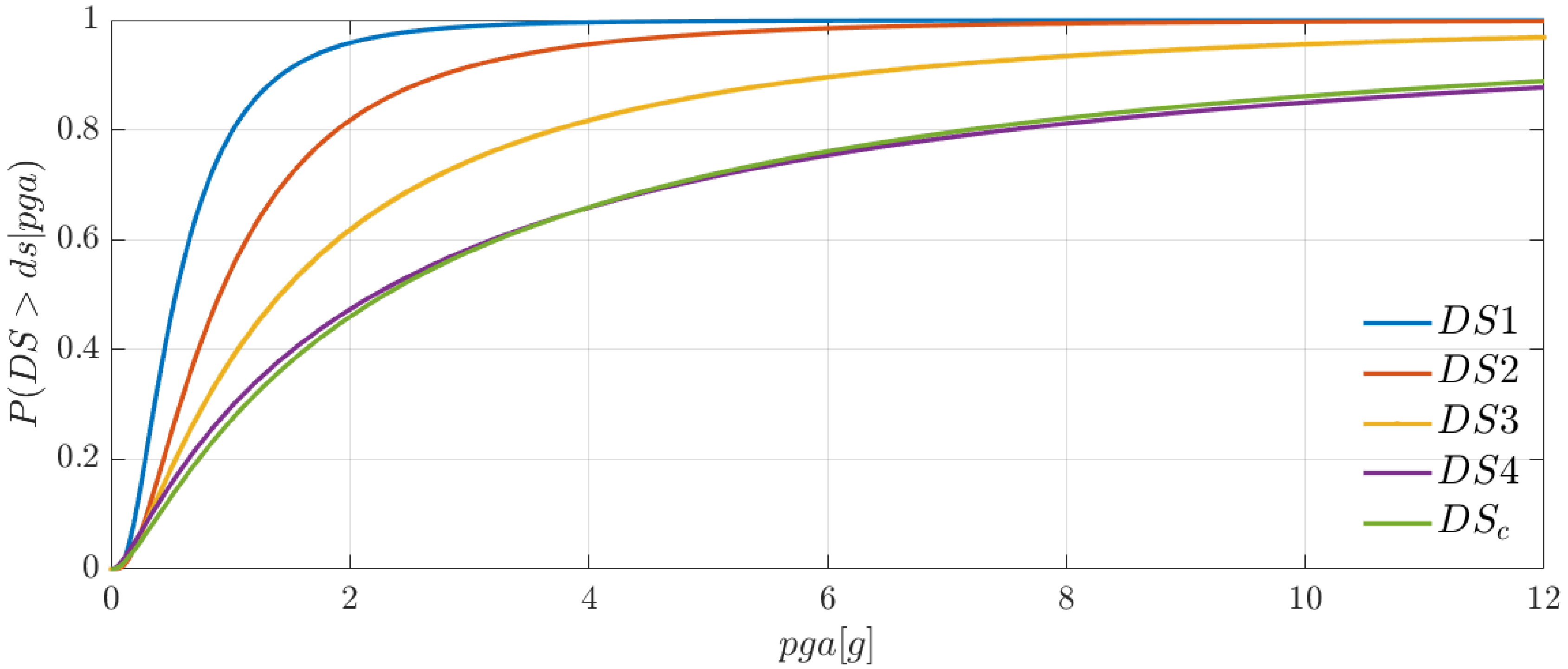
$$\ln\mathcal{L}(\mu,\sigma) = \sum_{n=1}^{\bar{N}} \varphi\left(\frac{\ln(im_n)-\mu}{\sigma}\right) + (N-\bar{N})\left[1-\Phi\left(\frac{\ln(\overline{IM})-\mu}{\sigma}\right)\right] \quad (2)$$

<u>Codes:</u>

```
 %% Untruncated IDA
[parmhat,parmci] = lognfit(IM_t_c ,0.01);
mu_IDA = parmhat(1);
sigma_IDA = parmhat(2);
%% Truncated IDA
IM_max = 2.2;
IM_trunc = IM_t_c(IM_t_c < IM_max); % take only the results with IM < IM_max
eq_over = sum(IM_t_c >= IM_max);    % number of analyses reached IM_max without collapsing
% Maximum likelihood fit, using equation (1) and (2) of previously slides
[mu_IDA_t, sigma_IDA_t ] = truncated_ida(IM_trunc, IM_max, eq_over);
```

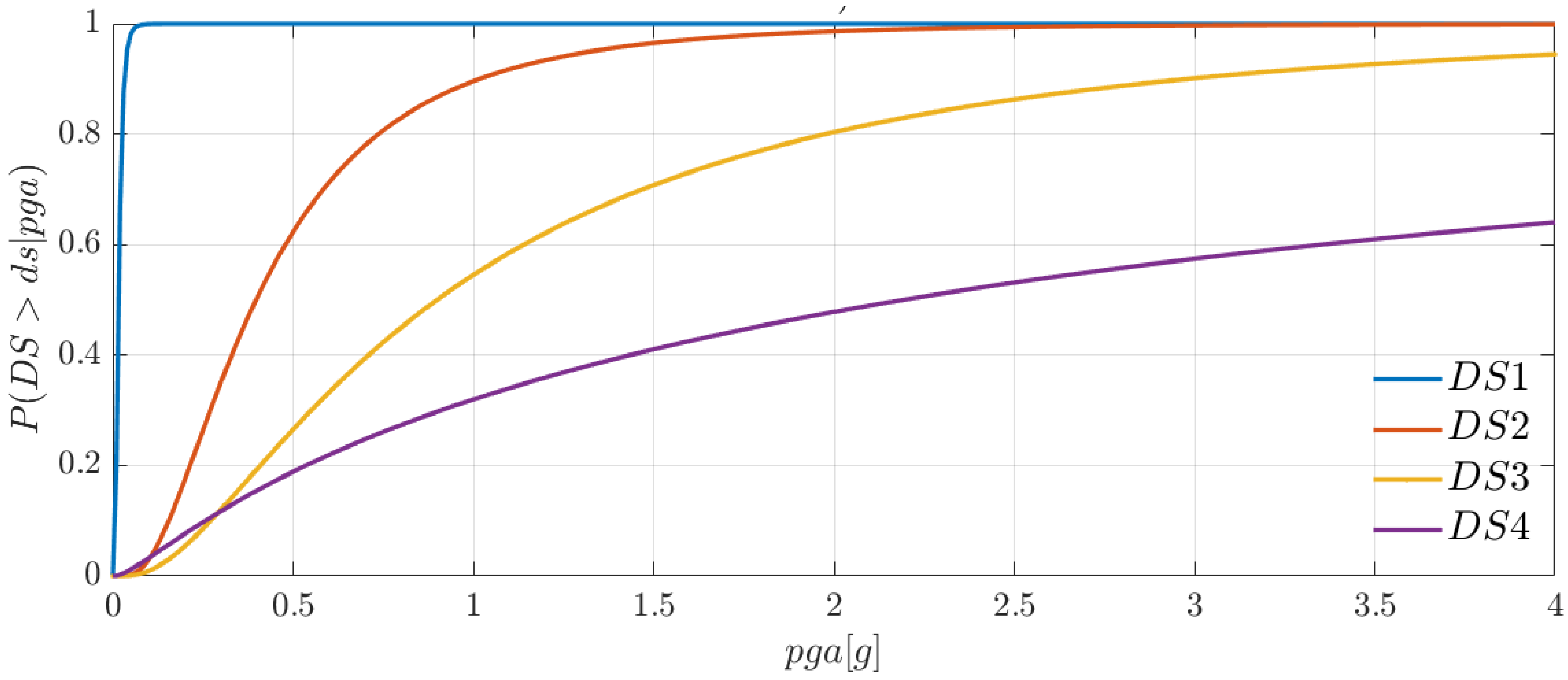
Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 5: Computing fragilities - Results



Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Step 5: Computing fragilities - Results



Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

References

Ph.D. Student Chiara Nardin – M.Sc., Eng. in Civil Engineering

https://github.com/kia13nn/ISPS.git

References:

- Baker J. W. (2008). *An Introduction to Probabilistic Seismic Hazard Analysis (PSHA)*, White Paper, Version 1.3, 72 pp.
- Kramer, S.L. (1996) *Geotechnical earthquake engineering*. Prentice Hall, Upper Saddle River, N.J.
- Wells, D.L. and Coppersmith, K.J. (1994) *New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement*. Bull. Seism. Soc. Am., 84, 974-1002.
- Cornell, C.A. (1968). *Engineering seismic risk analysis*, Bull. Seism. Soc. Am., 58, 1583-1606.
- Broccardo, M. (2018) *Probabilistic seismic risk analysis for civil systems*, Lecture Notes
- Stucchi M., Meletti C., Montaldo V., Akinci A., Faccioli E., Gasperini P., Malagnini L., Valensise G. (2004). *Pericolosità sismica di riferimento per il territorio nazionale MPS04*. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/sh/mps04/agKramer, S.L. (1996) Geotechnical earthquake engineering. Prentice Hall, Upper Saddle River, N.J.
- http://zonesismiche.mi.ingv.it/ → Italian database

References:

- Mackie, K & Stojadinovic, Bozidar. (2003). *Seismic Demands for Performance-Based Design of Bridges.*
- Bursi, Pucinotti, Tondini, Zanon, *Tests and model calibration of high strength steel tubular beam-to-column and column-base composite joints for moment-resisting structures*, Earthquake Engineering and Structural Dynamics, (2015).
- Broccardo, M. (2018) *Probabilistic seismic risk analysis for civil systems*, Lecture Notes
- Charalampakis, A. & Koumousis,V. (2010). *Parameters of Bouc–Wen Model Revisited*, Applied Mechanics.
- Haukaas, T. & Der Kiureghian, A. (2004). *Finite Element Reliability and Sensitivity Methods for Performance-Based Earthquake Engineering*, tech. rep., PEER - Pacific Earthquake Engineering Research Center.

Trento, 02 December 2020
Ph.D. Student: ***Chiara Nardin***
chiara.nardin@unitn.it

Thanks for the attention!

Ph.D. Student Chiara Nardin – M.Sc., Eng. in Civil Engineering

https://github.com/kia13nn/ISPS.git