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The seismic risk of code-conforming structures: what damages and where.

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**Professor of earthquake engineering and structural dynamics*

Bucharest – Romania, June 15 2017

Part I – What damage is expected to code-conforming structures?

The RINTC project (implicit risk of new structures)

1. Evaluate the annual rate (probability) of failure (damage or collapse) for the buildings designed according to the current Italian seismic code (NTC ’08, based on EUROCODE 8).

2. Five structural tipologies were considered: masonry, reinforced and precast concrete, steel, and base-isolated buildings.

3. Five sites in Italy were considered (and two soil classes A and C according to EUROCODE 8).

4. The structures were designed for the significant damage and damage-limitation limit states according to the most common methods in professional practice.

5. The failure rate was evaluated by integrating the hazard curves with the results of non-linear (multi-stripe) dynamic analysis, according to a state-of-the art approach in research of performance-based earthquake engineering.

6. The following uncertainties were considered: those related to hazard and to the *record-to-record variability* of the structural response, and (for selected cases) the uncertainty in structural modeling.

Working group

1. **Coordinators, seismic input and failure rate evaluation: I. Iervolino (Unina), P. Bazzurro (IUSS);**
2. **Masonry buildings: G. Magenes and A. Penna (Unipv), S. Lagomarsino (Unige), F. Da Porto (Unipd);**
3. **Reinforced concrete buildings: P. Franchin and F. Mollaioli (Unirm), A. Masi (Unibas), E. Spacone (Unich), G. Magliulo and G. Verderame (Unina);**
4. **Precast concrete buildings: G. Magliulo (Unina), R. Nascimbene (EUC.);**
5. **Steel buildings: R. Landolfo (Unina), A. Dall'Asta (Unicam);**
6. **Base-isolated buildings: D. Cardone and Felice Ponzo (Unibas), A. Dall'Asta (Unicam).**

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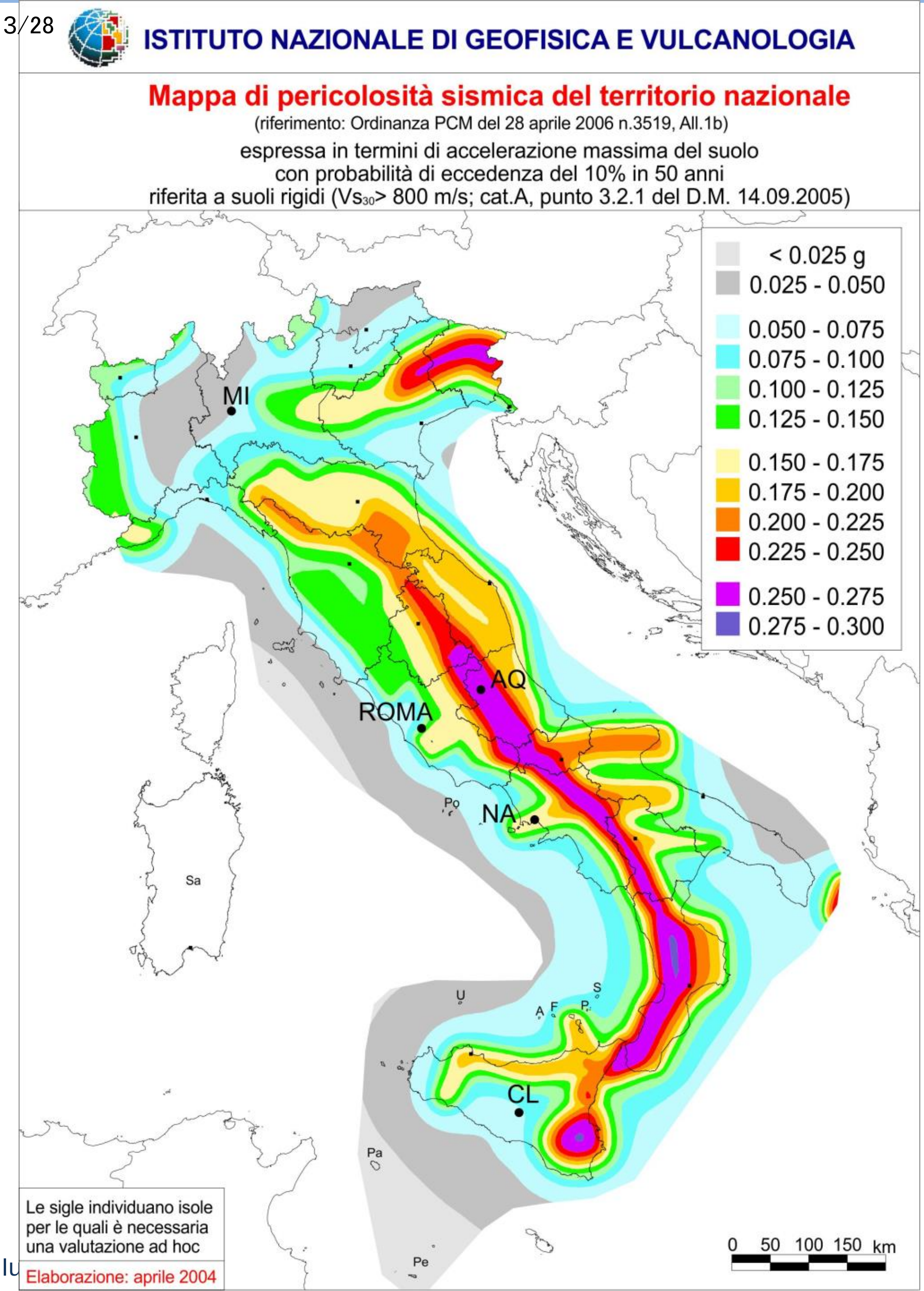
IUSS Scuola Universitaria Superiore Pavia
Sapienza Università di Roma
Università degli Studi Basilicata
Università degli Studi di Padova
Università di Camerino
Università degli Studi di Pavia



The considered sites span different hazard levels according to the official design hazard map of Italy.

City	PGA (475) [g] (Soil A)	PGA (475) [g] (Soil C)	Seismic zone
Milan	0.0495	0.0743	IV
Caltanissetta	0.0762	0.11428	III-b
Rome	0.1204	0.1806	III--a
Naples	0.1668	0.24338	II
L'Aquila	0.2607	0.3451	I

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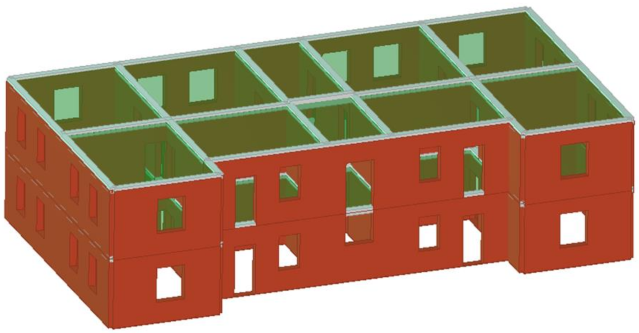
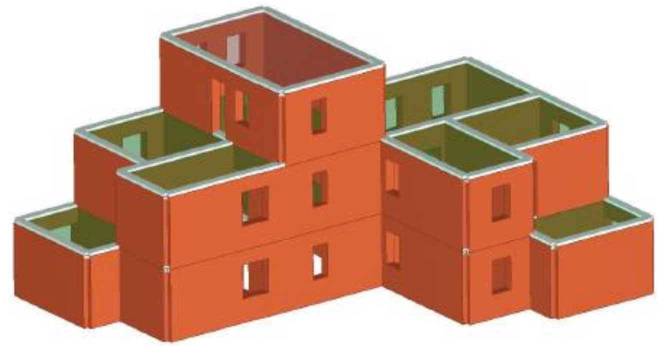
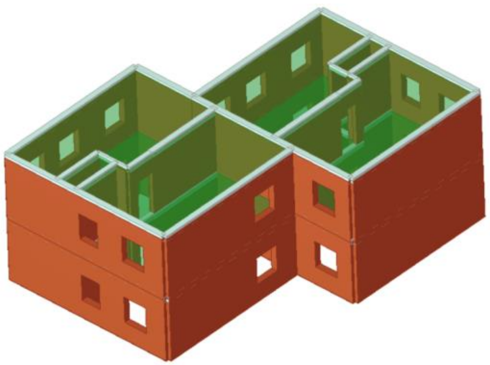
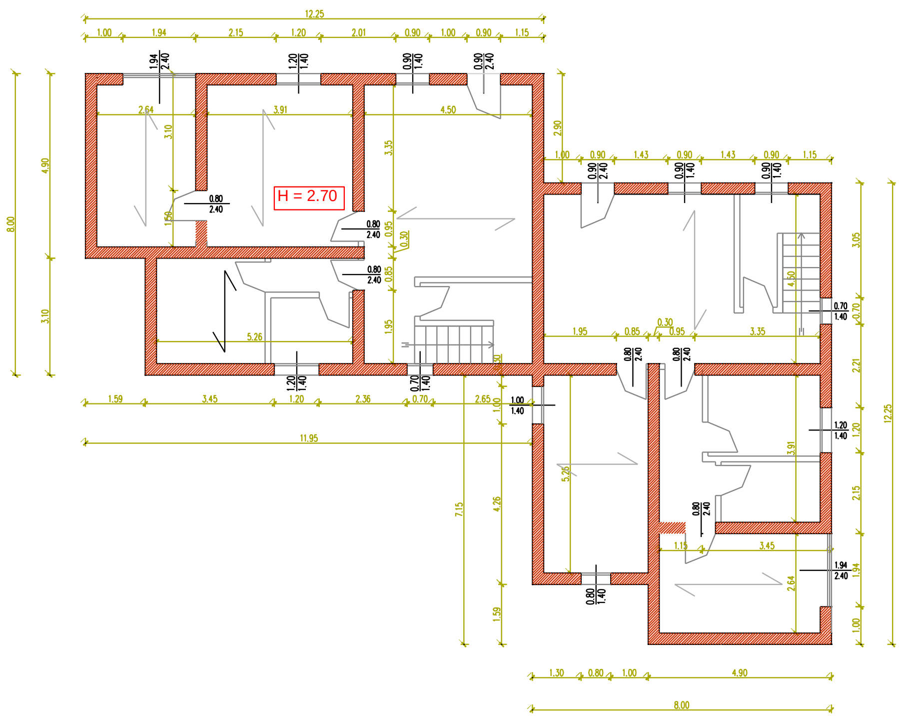
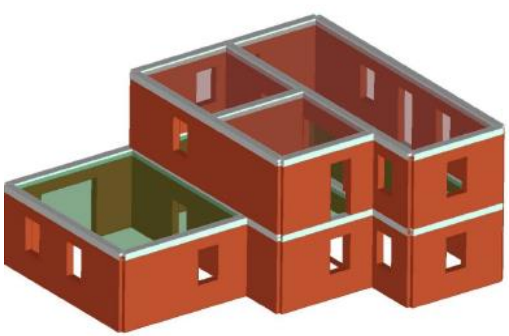
Masonry buildings











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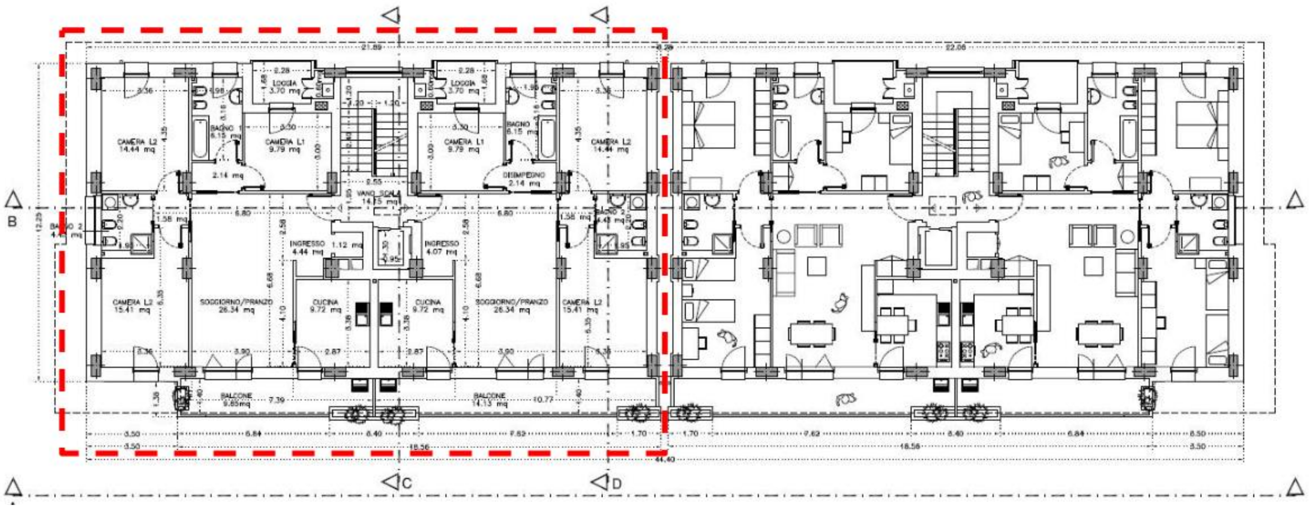
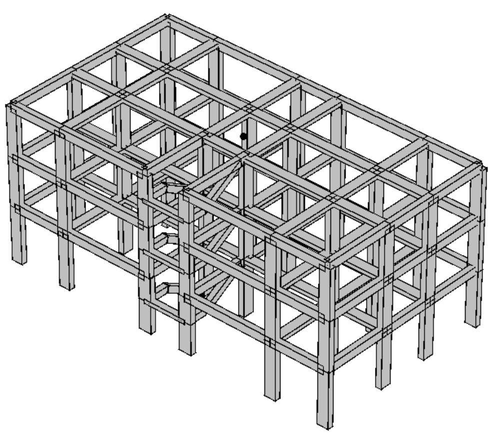
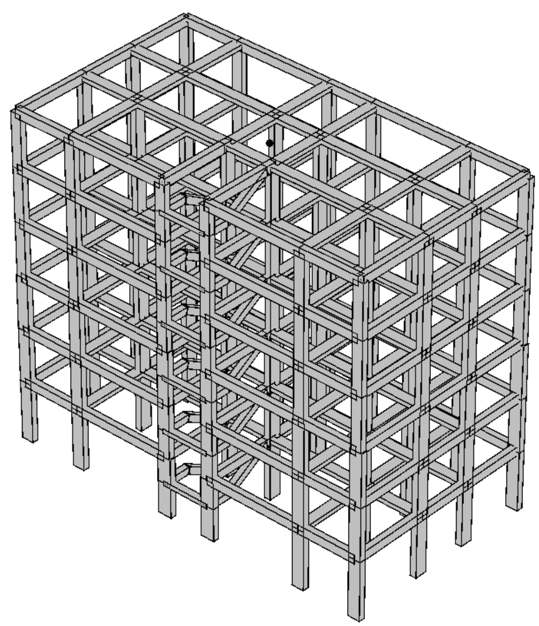
Reinforced concrete buildings (1)

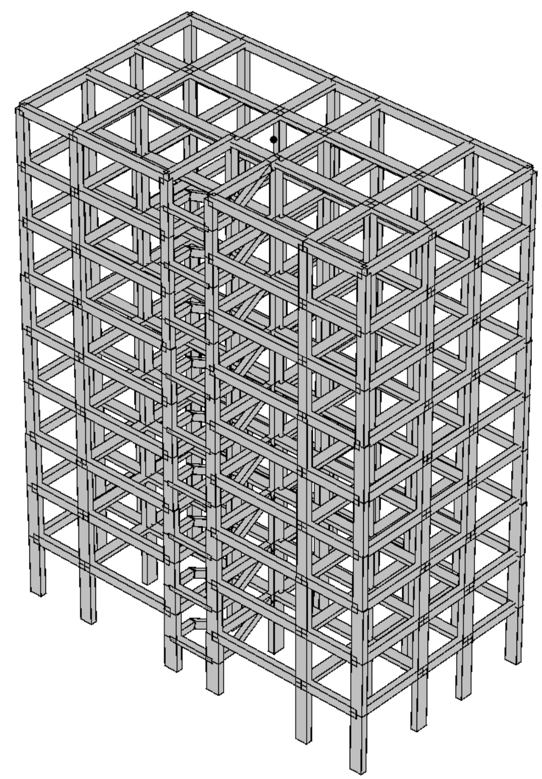


Building use: residential
Number of stories: 3 – 6 – 9 stories
Story height: 3.05m (1st story 3.4m)

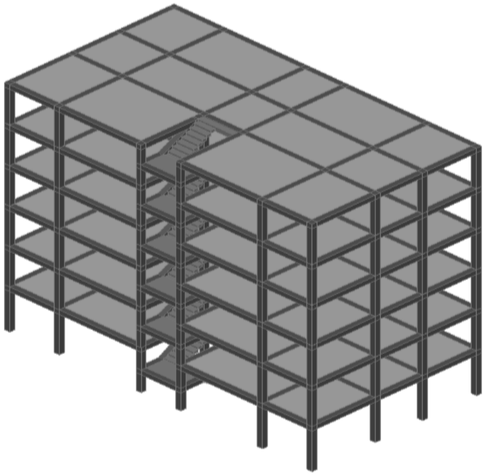
Floor area: 252m^2
Roof type: flat
Staircase type: knee beam

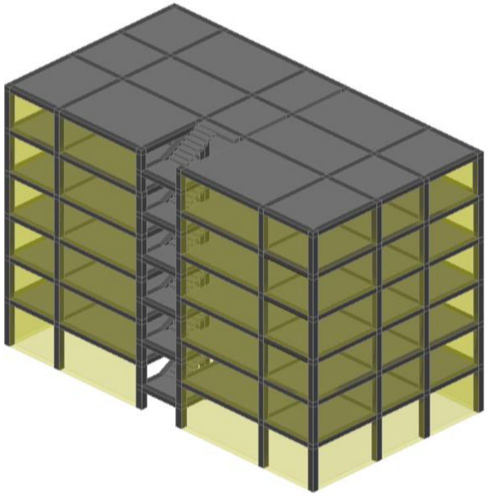


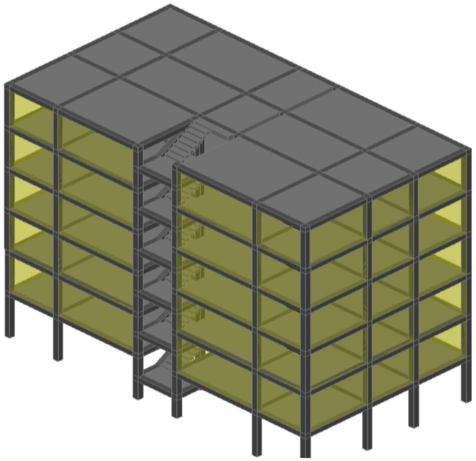


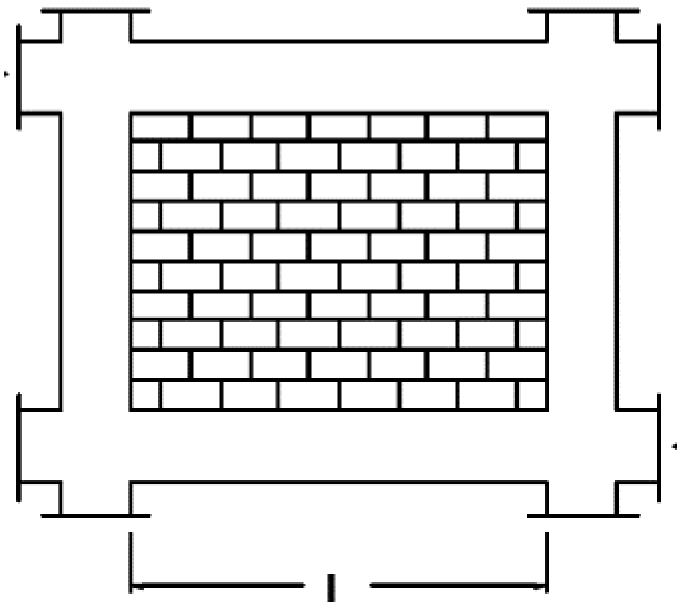


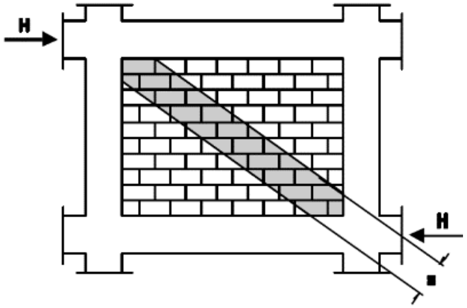
Reinforced concrete buildings (2)

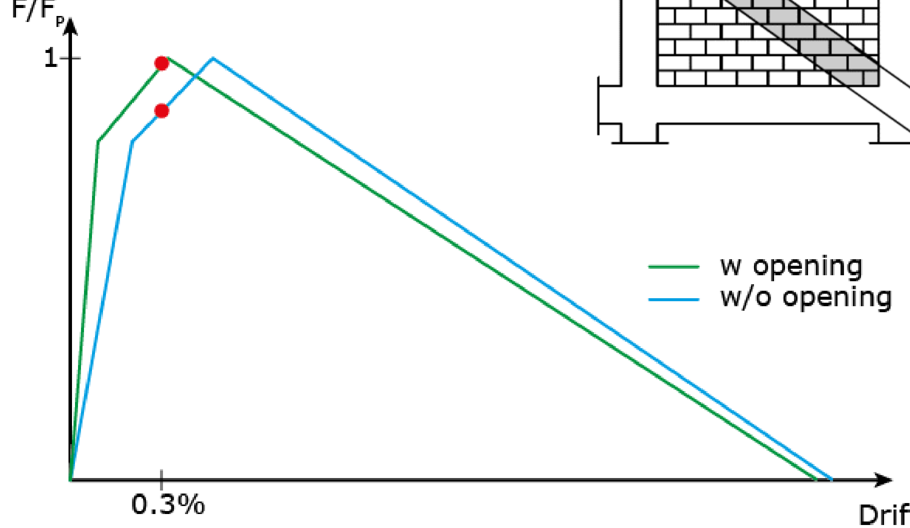












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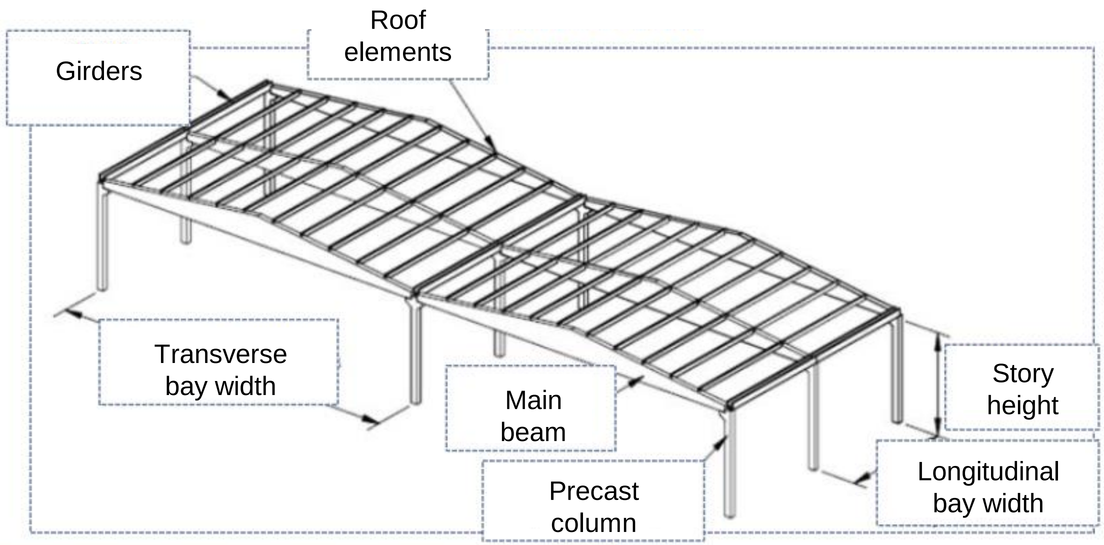
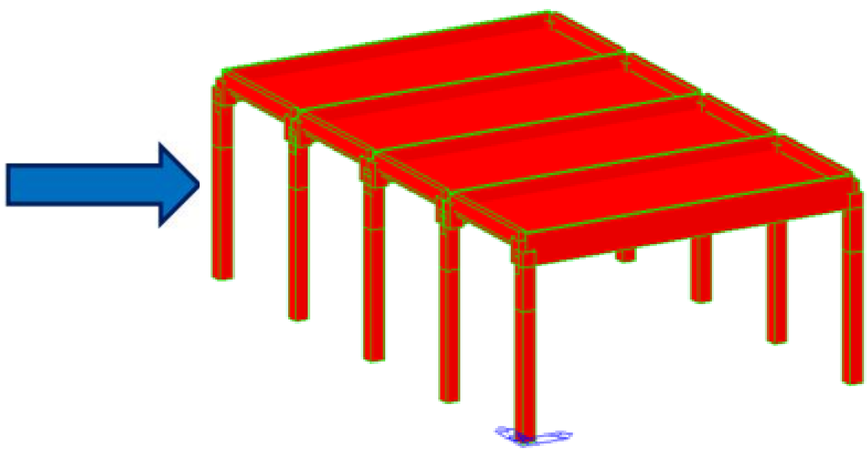
Industrial precast buildings



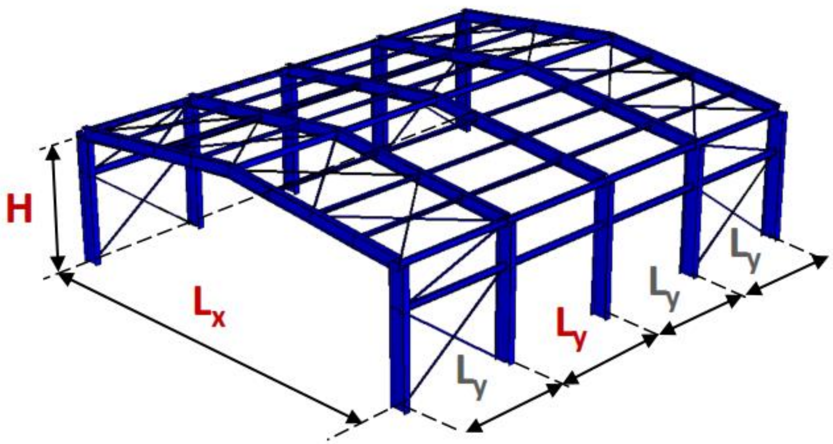
Geometrical variables:

- 2 column heights
- 2 pairs of longitudinal and transverse spans: 15m and 6m, 20m and 8m.



Industrial steel buildings

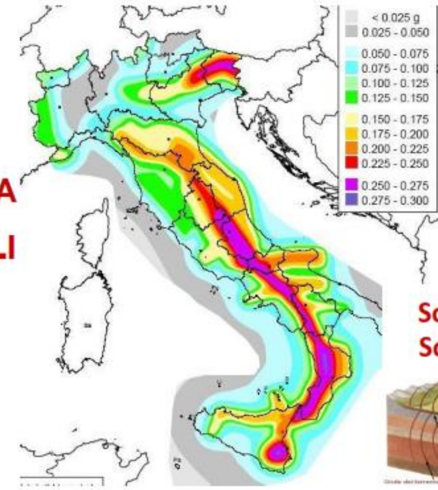
Geometric parameters
Global geometry of building



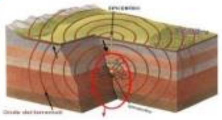
Transverse direction
1) Lx = 20m, H = 6m
2) Lx = 30m, H = 9m

Longitudinal direction
1) Ly = 6m
2) Ly = 8m

Localizzazione
Azioni sulle costruzioni: Neve,Vento, sisma



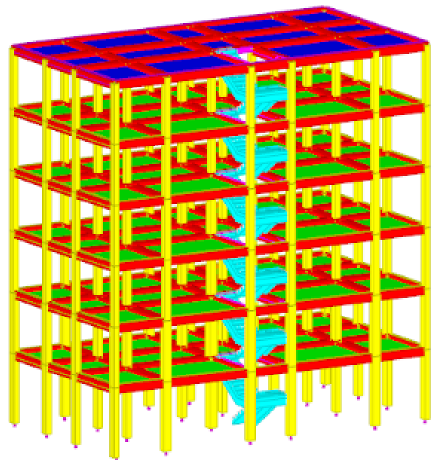
Sottosuolo A
Sottosuolo C

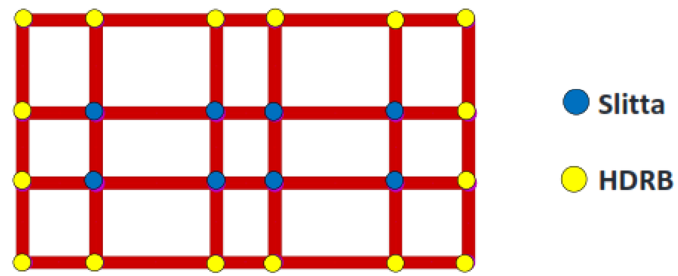


	Neve	Vento	Sisma		
Sito	q_s [kN/m^2]	q_v [kN/m^2]	$a_{g,SLV}$	$a_{g,SLD}$	**Cat. sottosuolo**
Milano	1.20	0.39	0.050	0.024	sottosuolo A sottosuolo C
L'Aquila	1.31	0.61	0.261	0.104	sottosuolo A sottosuolo C
Napoli	0.48	0.46	0.168	0.060	sottosuolo A sottosuolo C

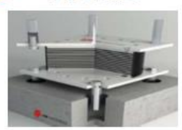
Base-isolated buildings

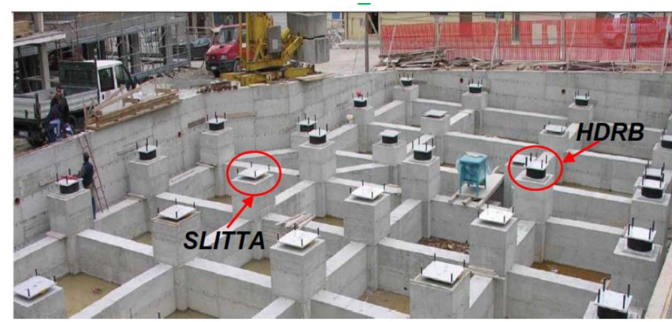
	dispositivi	T_{is} (s)
Elastomeric isolators	n.18 SI-S 600/128 n.6 700/130	2,04
	n. 16 SI-S 550/154 n.8 600/150	2,46
Elastomeric Isolators and sledges	n. 16 SI-S 650/180 n. 8 slitte	2.84
	n. 16 SI-S 600/152 n. 8 slitte	2.84
	n. 16 SI-S 600/176 n. 8 slitte	3.04
	n. 16 SI-S 700/180 n. 8 slitte	2.66
Friction pendulum	n. 24 dispositivi R=3100	2.49
	n.24 dispositivi R=3700	3.37





HDRB





SLITTA

HDRB

Sinoptic table of analyzed cases

			MI	CL	RM	NA	AQ
Reinforce concrete 42 cases	RC	*Soil A*	---	---	---	---	9-story (BF/PF/IF)
		Soil C	3/6/9-story (BF/PF/IF)	6-story (BF/PF/IF)	6-story (BF/PF/IF)	3/6/9-story (BF/PF/IF) ModUnc	3/6/9-story (BF/PF/IF)
Masonry 49 cases	URM	*Soil A*	2/3-story, regular	2/3-story, regular	2/3-story, regular ModUnc	2/3-story, regular/irregular	2/3-story, regular ModUnc
		Soil C	2/3-story, regular	2/3-story, regular	2/3-story, regular/irregular	2/3-story, regular/irregular	2/3-story, regular/irregular
Precast concrete 24 cases	PRC	*Soil A*	1-story, geometry 1/2/3/4	---	---	1-story, geometry 1/2/3/4	1-story, geometry 1/2/3/4
		Soil C	1-story, geometry 1/2/3/4	---	---	1-story, geometry 1/2/3/4	1-story, geometry 1/2/3/4
Steel 24 cases	S	*Soil A*	1-story, geometry 1/2/3/4	---	---	1-story, geometry 1/2/3/4	1-story, geometry 1/2/3/4
		Soil C	1-story, geometry 1/2/3/4	---	---	1-story, geometry 1/2/3/4	1-story, geometry 1/2/3/4
Base-isolated 11 cases	BI	*Soil A*	---	---	---	---	---
		Soil C	---	---	---	---	6-story, HDRB/HDRB+Slider/DCFP (11

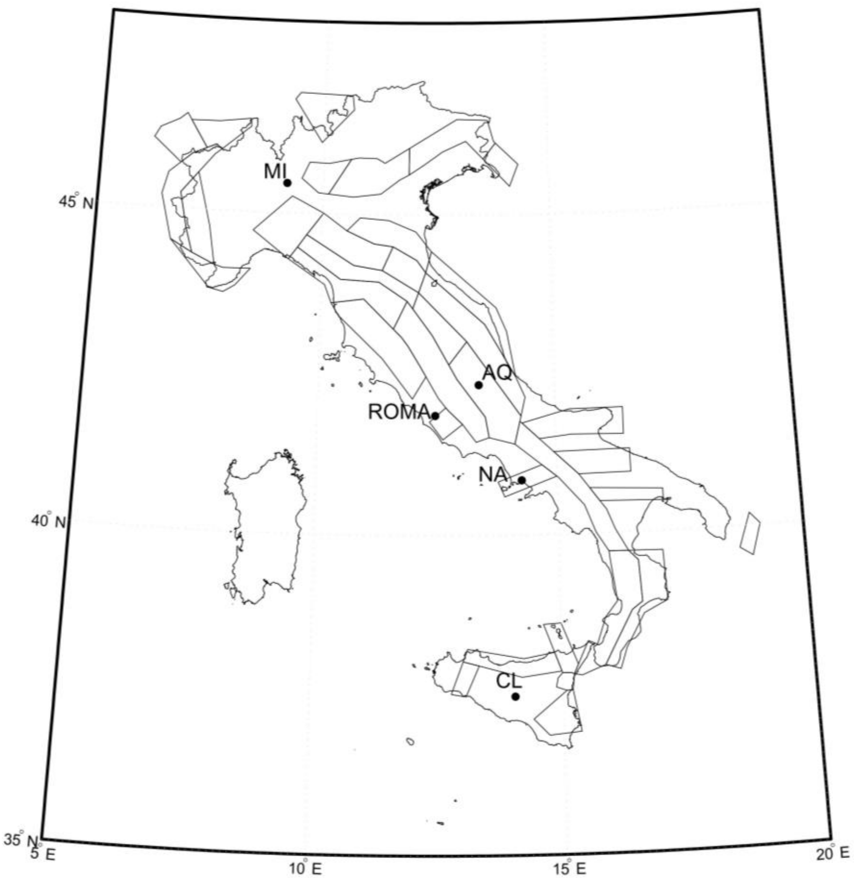
Total rate

GMPE

Annual rate of exceedance

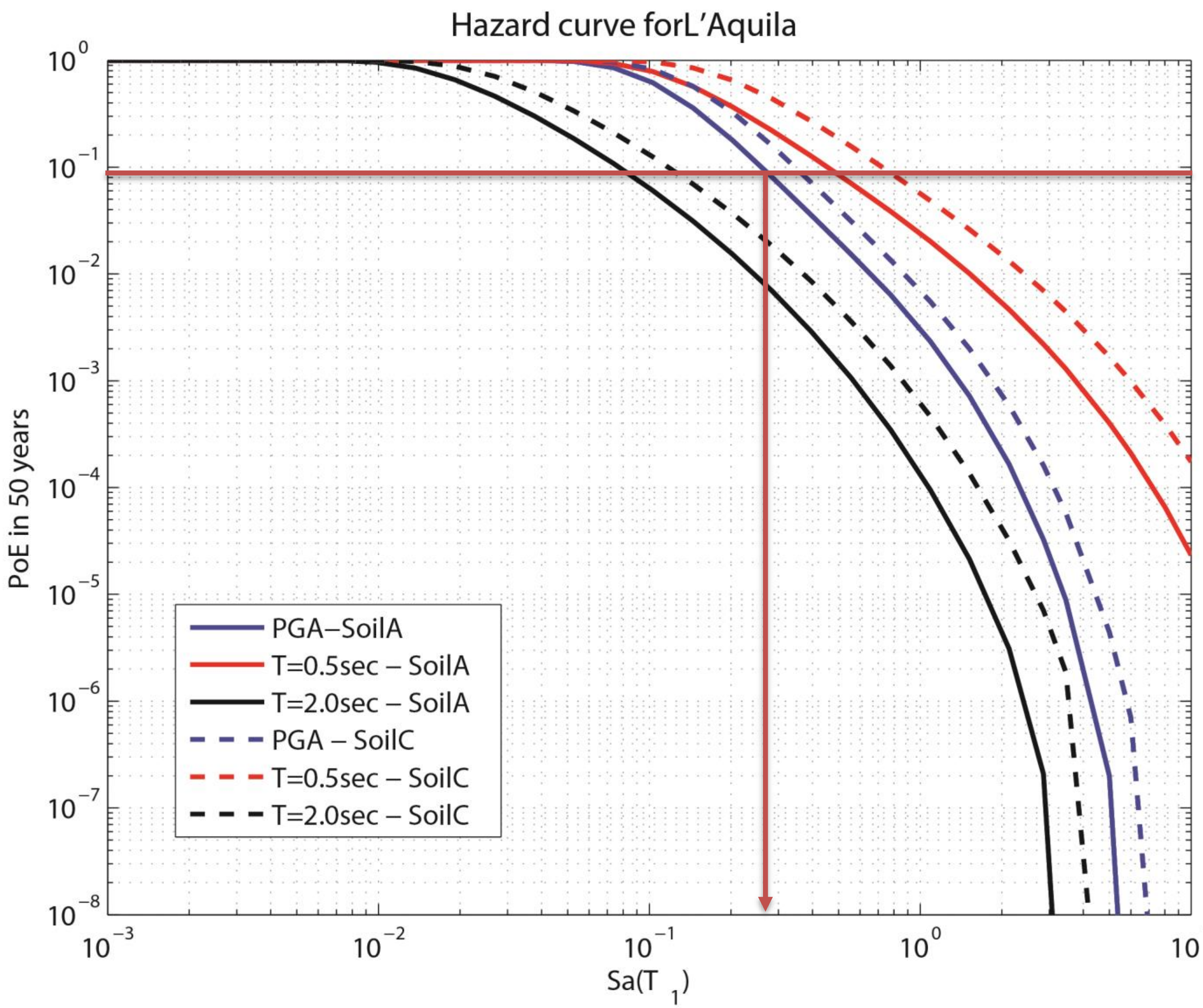
$$\lambda_{im} = \nu \cdot \iint_{m,r} P\left(IM > im \mid m,r\right) \cdot f_{M,R}\left(m,r\right) \cdot dr \cdot dm$$

Distribution of source characteristics



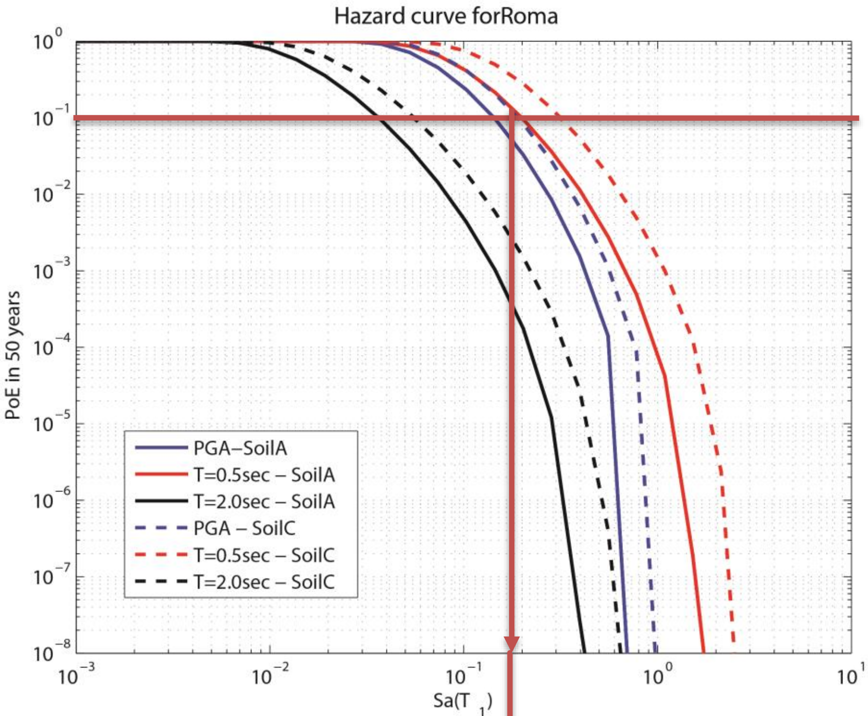
Site	Soil A	Soil C
MI	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.0s)$, $Sa(T=1.5s)$, $Sa(T=2.0s)$	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.0s)$, $Sa(T=1.5s)$, $Sa(T=2.0s)$
CL	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.5s)$	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.5s)$
RM	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.5s)$	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.5s)$
NA	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.0s)$, $Sa(T=1.5s)$, $Sa(T=2.0s)$	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.0s)$, $Sa(T=1.5s)$, $Sa(T=2.0s)$
AQ	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.0s)$, $Sa(T=1.5s)$, $Sa(T=2.0s)$	$Sa(T=0.15s)$, $Sa(T=0.5s)$, $Sa(T=1.0s)$, $Sa(T=1.5s)$, $Sa(T=2.0s)$, $Sa(T=3.0s)$

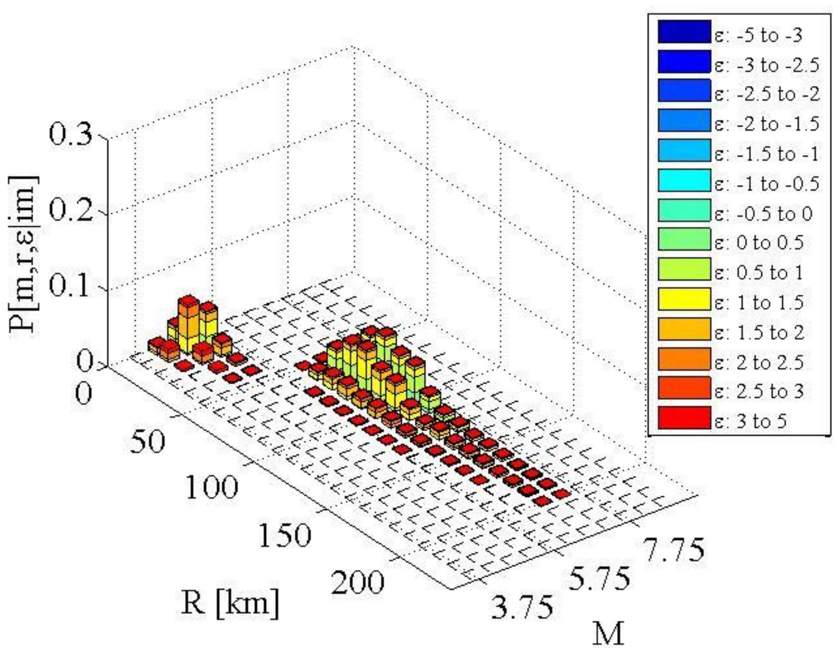
$$T_R = \{10, 50, 100, 250, 500, 1000, 2500, 5000, 10000, 100000\}$$


Hazard curve forL'Aquila
PoE in 50 years
Sa(T 1)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
PGA–SoilA
T=0.5sec – SoilA
T=2.0sec – SoilA
PGA – SoilC
T=0.5sec – SoilC
T=2.0sec – SoilC

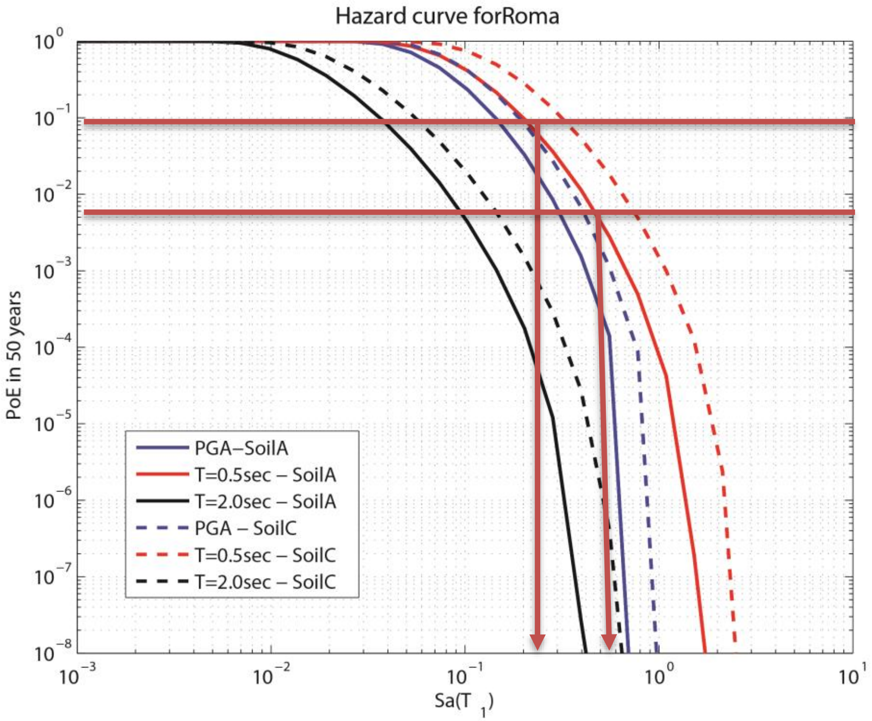
Disaggregation: what pairs of magnitude and distance are most likely to cause the exceedance of a certain acceleration?

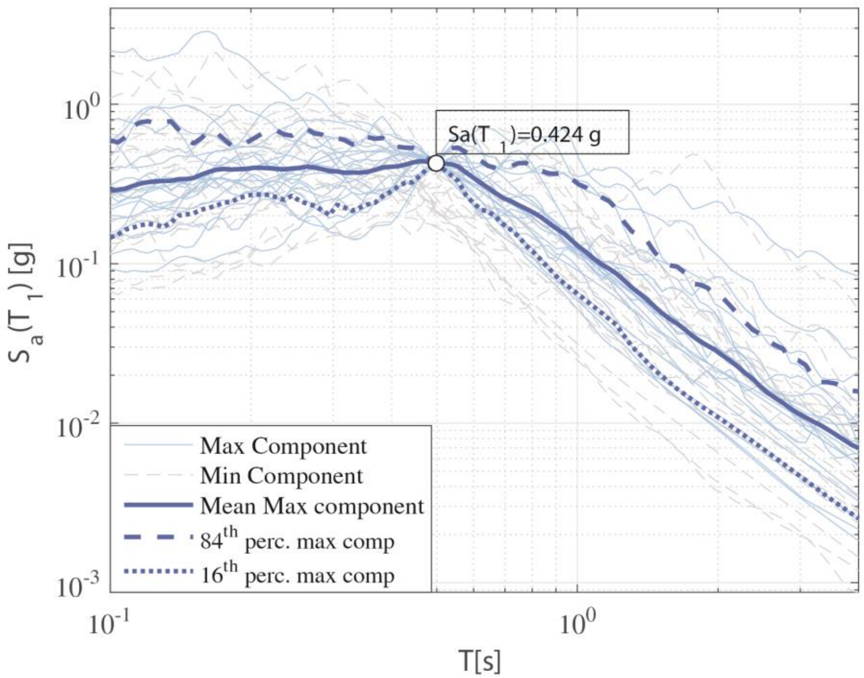
$$f_{M,R|IM>im}(m,r)=\frac{\nu\cdot P(IM>im\,|\,m,r)\cdot f_{M,R}(m,r)}{\lambda_{im}}$$





Input for non-linear dynamic analysis (accelerograms) selected according to the Conditional Spectrum Method: i.e., compatible with the spectrum of earthquakes that have the intensity measure of interest





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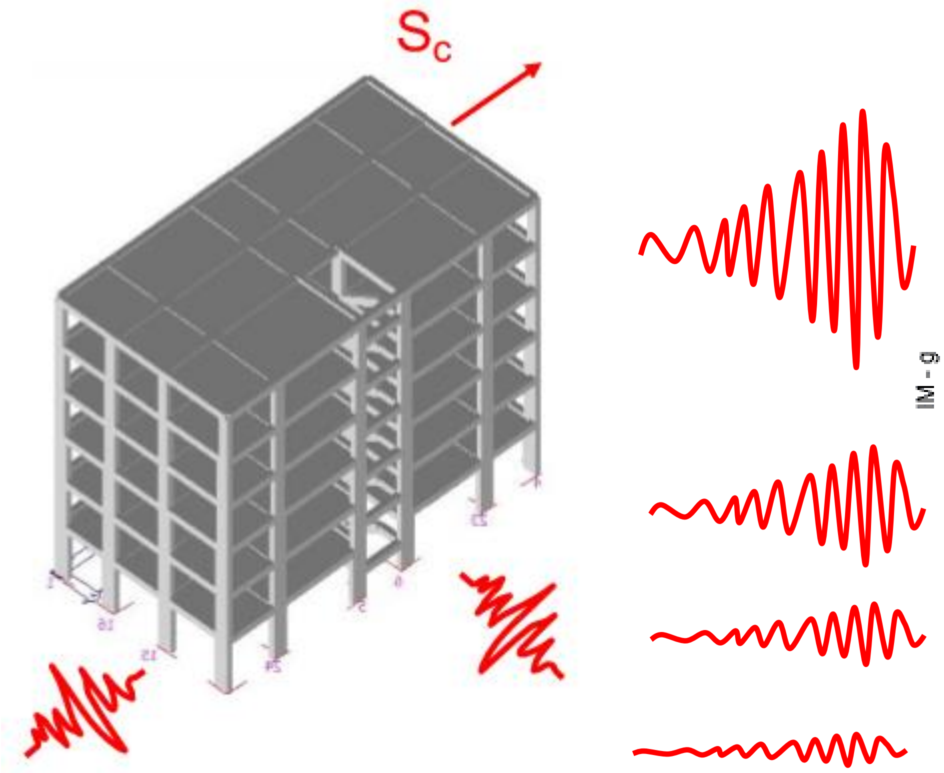
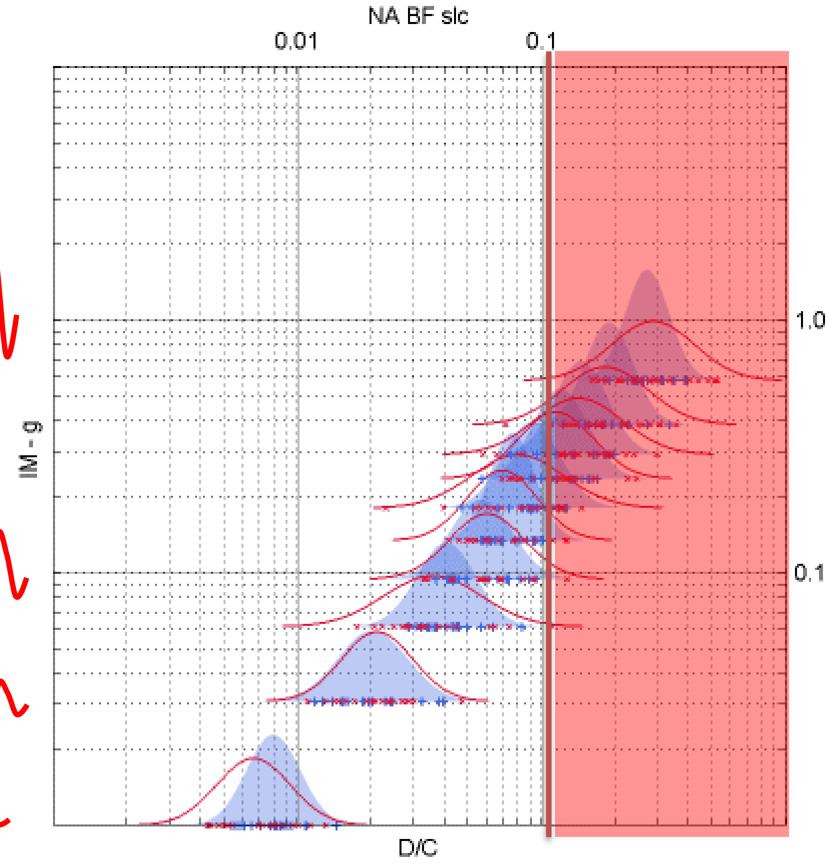
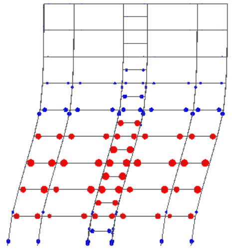
Analyses (multi-stripe) of structural response







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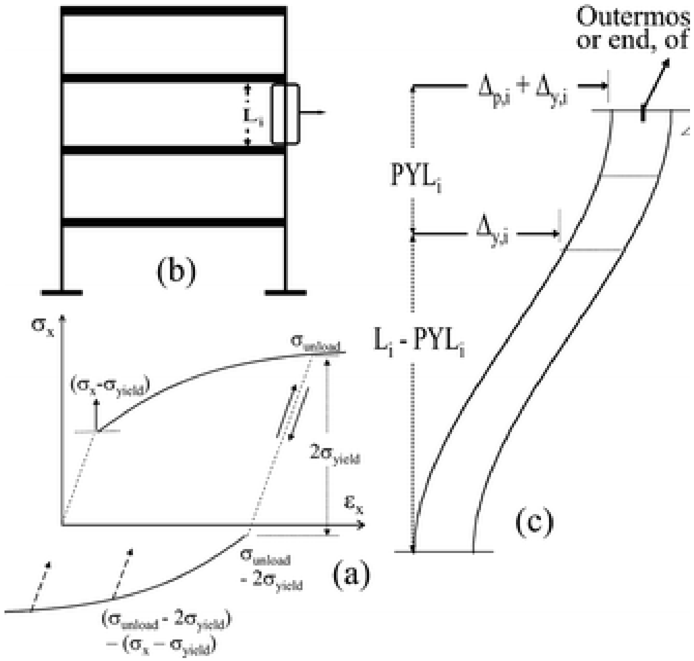
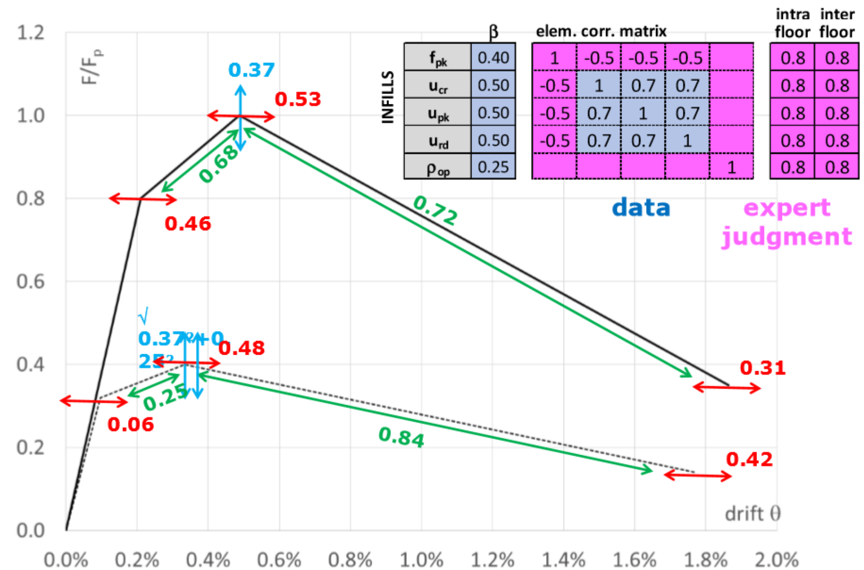
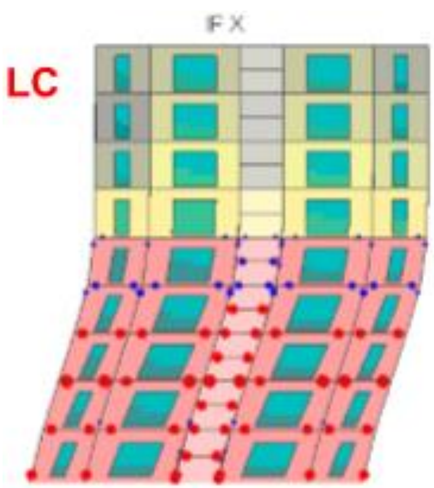
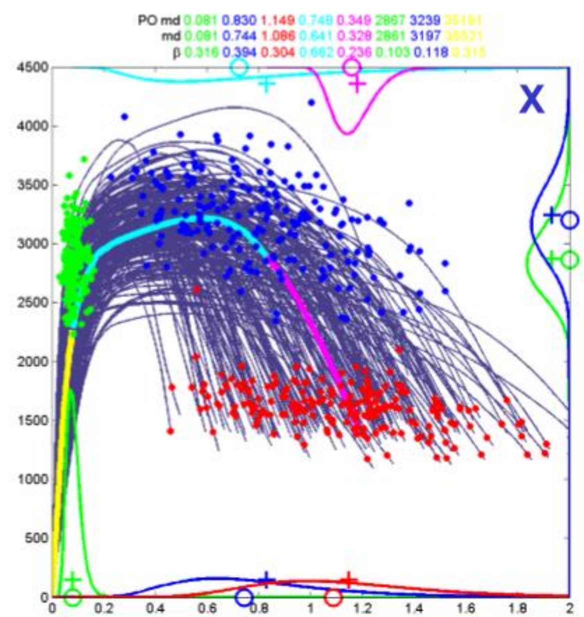
Model uncertainties









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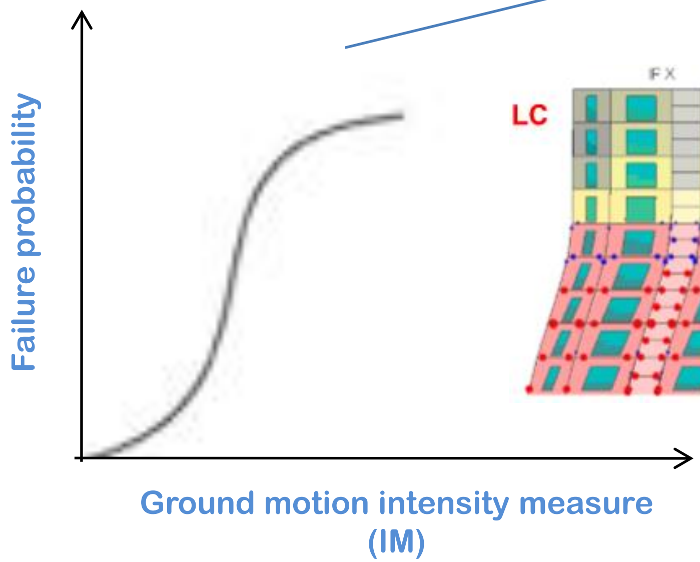
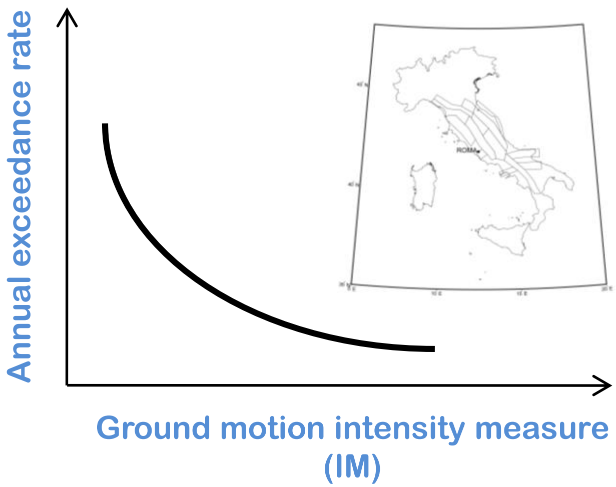
Performance-based earthquake engineering framework (PBEE)

Annual failure rate $$\lambda_f = \int_{im} P\left[f \,|im \right] \cdot \left| d\lambda_{im} \right|$$





Fragility

Hazard

Truncation of hazard curves and the effect on the calculation of failure rates

$$T_R = \{10, 50, 100, 250, 500, 1000, 2500, 5000, 10000, \boxed{100000}\}$$

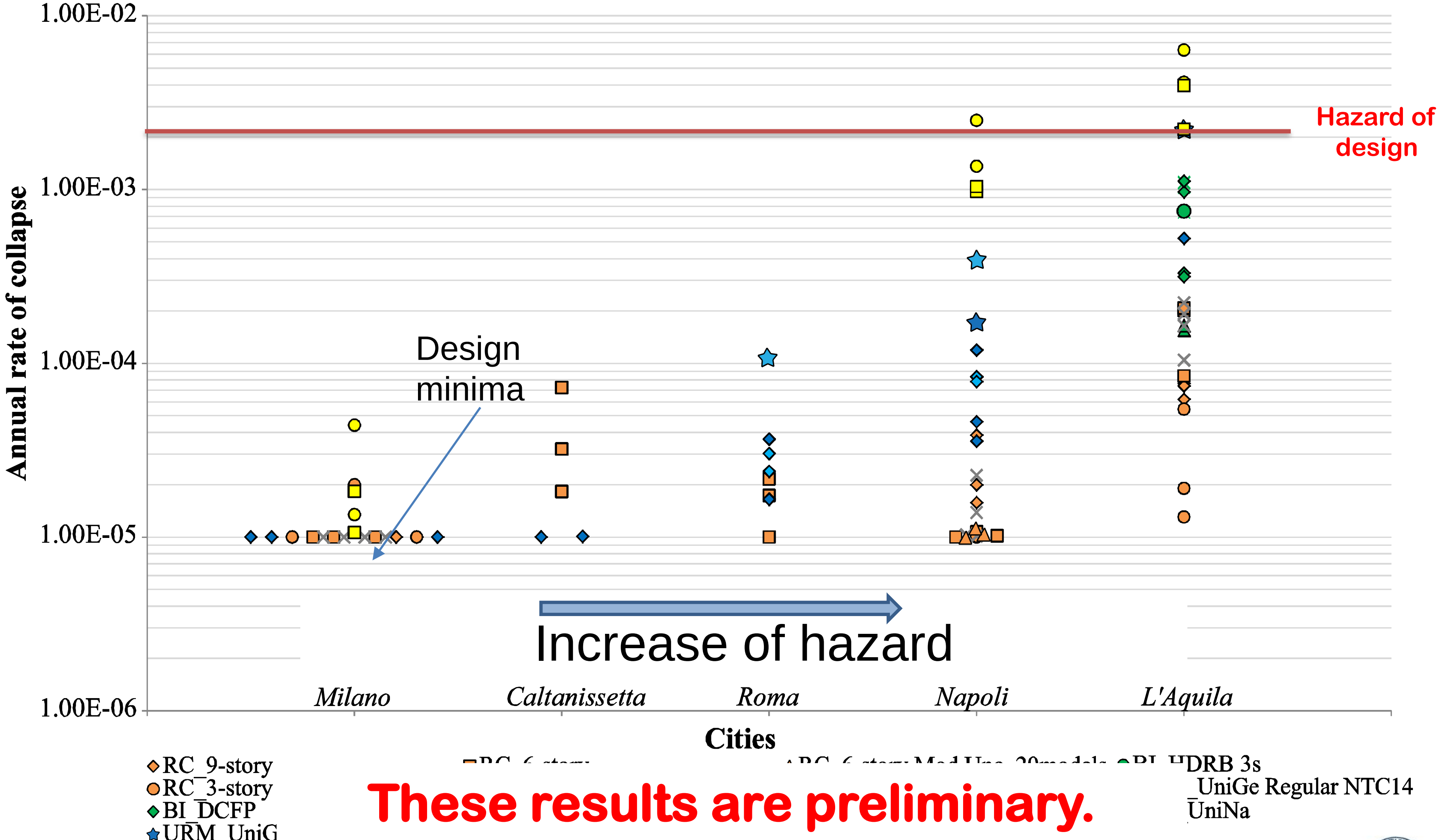
Structural failure certainly happens beyond the IM (intensity) corresponding to the maximum return period available in hazard curves. This selection implicitly means that the calculated rate is larger than the actural failure rate.

$$\lambda_f = \int_0^{IM_{T_R^*}} P\left[failure \middle| IM = x \right] \cdot \left| d\lambda_{IM}(x) \right| + \int_{IM_{T_R^*}}^{+\infty} 1 \cdot \left| d\lambda_{IM}(x) \right|$$

$$= \int_0^{IM_{T_R^*}} P\left[failure \middle| IM = x \right] \cdot \left| d\lambda_{IM}(x) \right| + 10^{-5}$$

Exceedance rate of the acceleration beyond which the hazard was not computed.

Collapse rates on soil C (10^{-5} values are upper bounds)



These results are preliminary.

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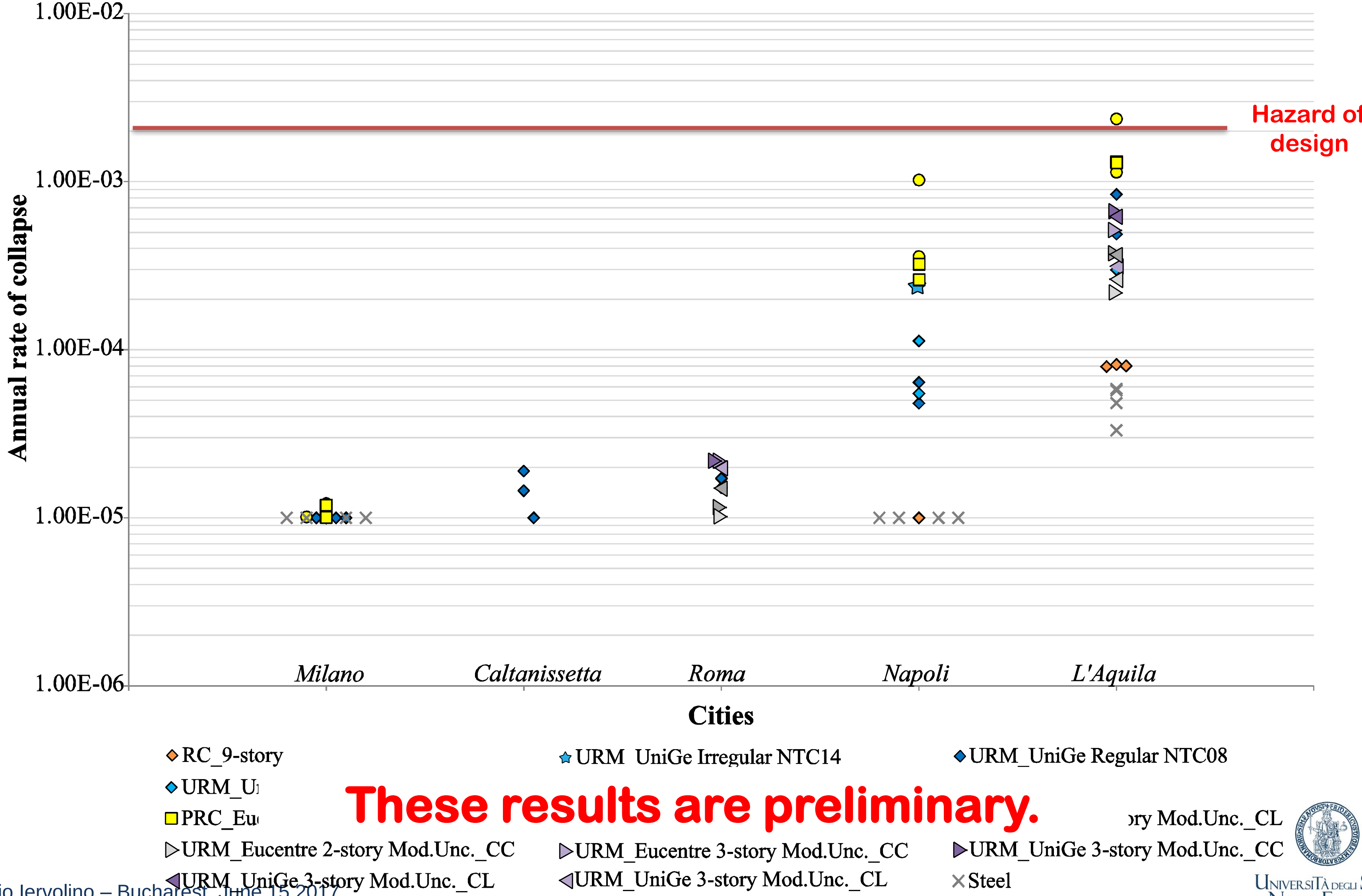
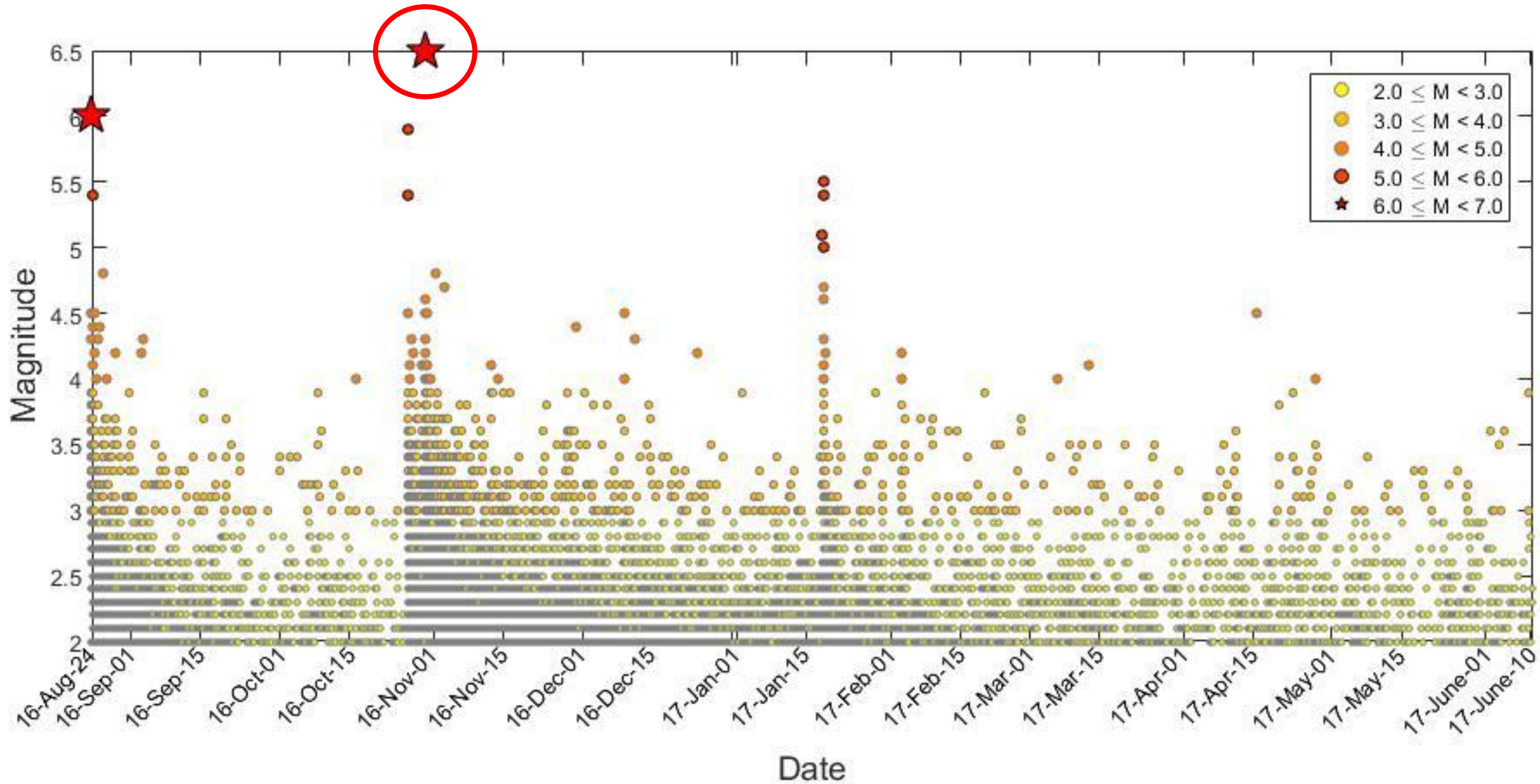
Collapse rates on soil A (10^{-5} values are upper bounds)



These results are preliminary.

Part II – Where damage are expected?

The 2016-2017 central Italy seismic sequence



12000+ M>2 earthquakes between August 24 2016 and June 10 2017.

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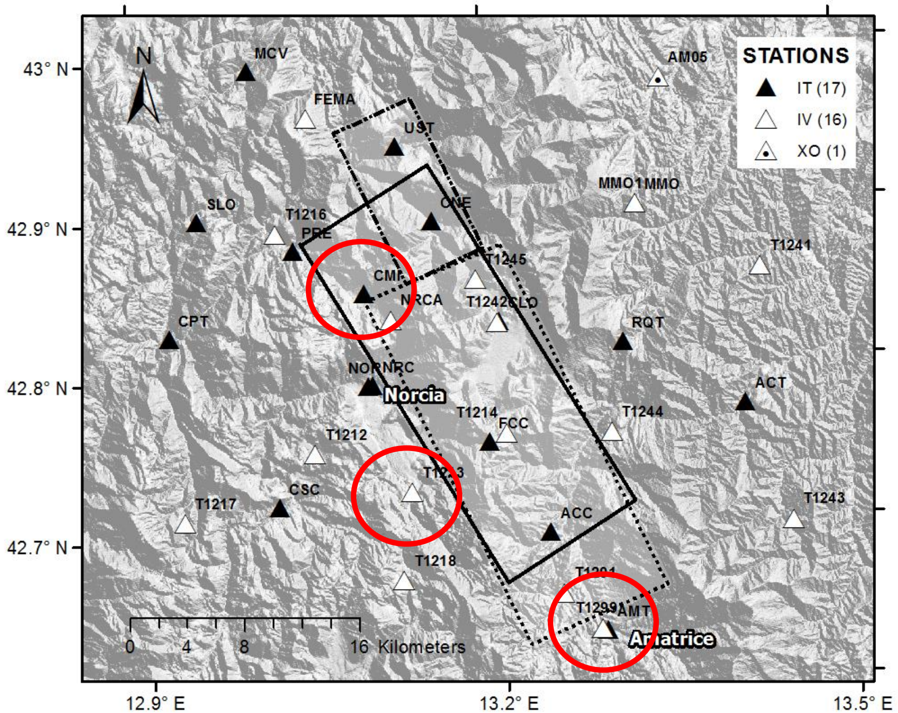
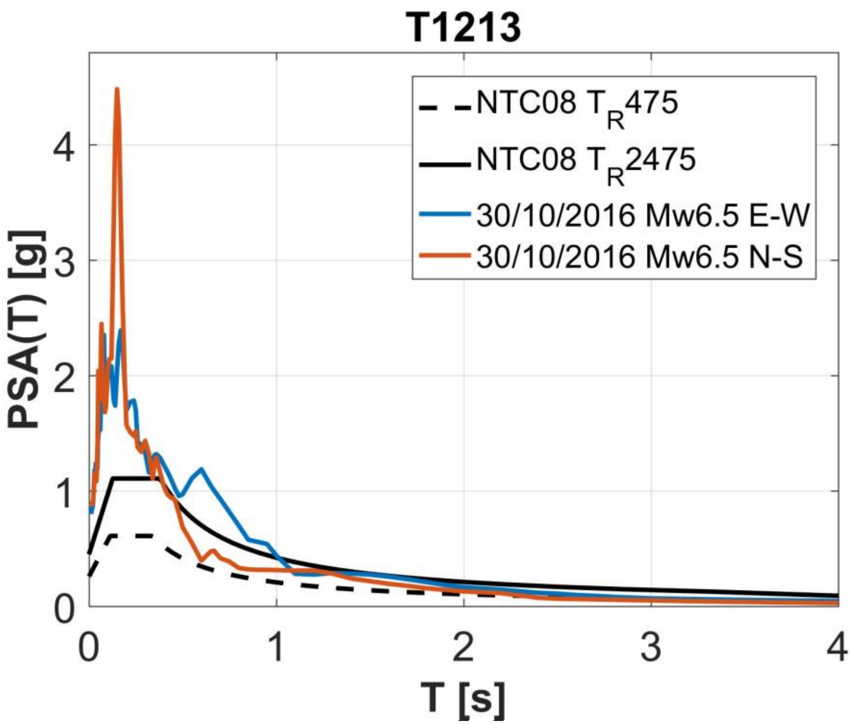
As seen in all the recent large earthquakes, as well as in the 2016 central Italy sequence, the spectra recorded spectra exceed those used for structural design.





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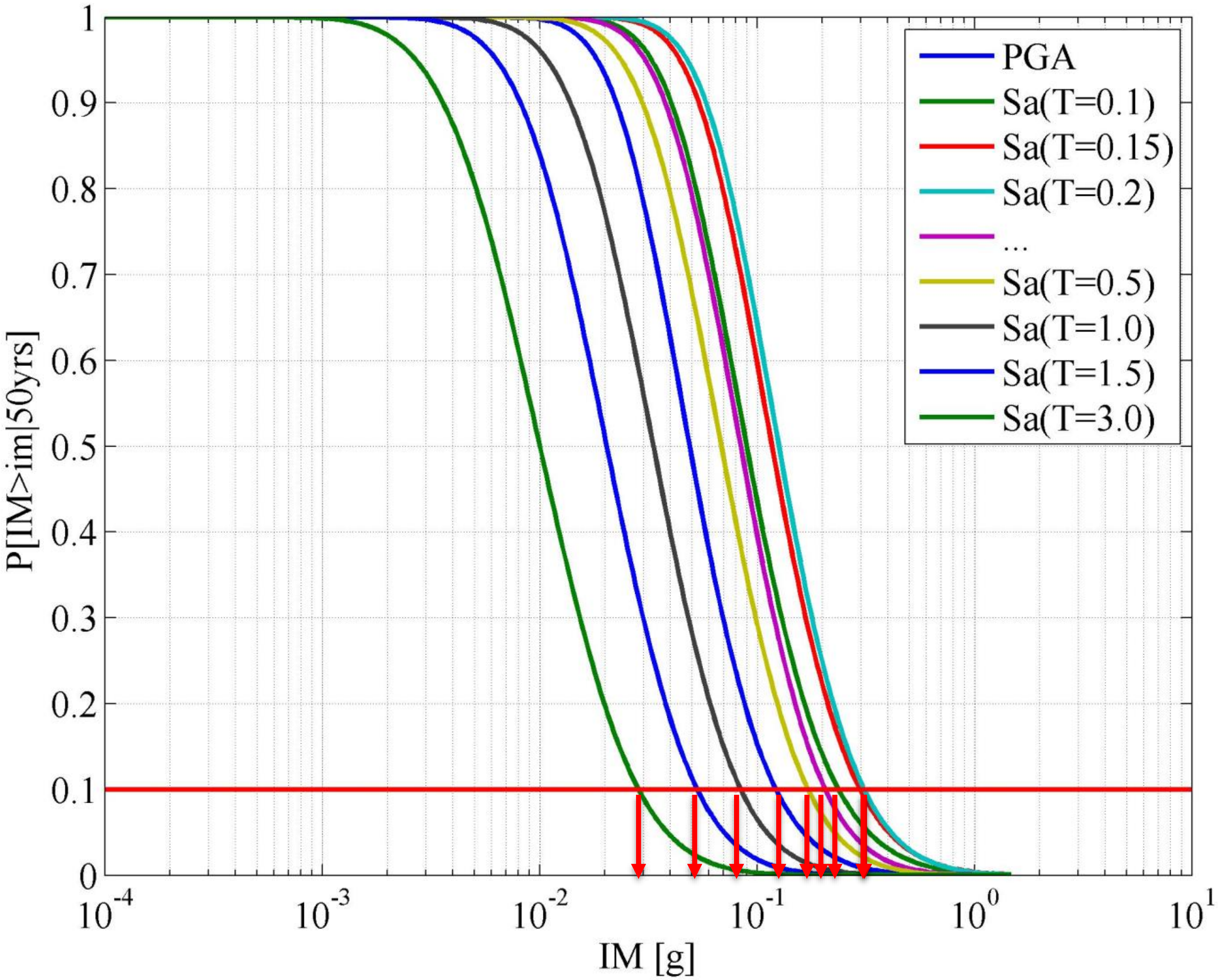
Uniform hazard spectra (1)



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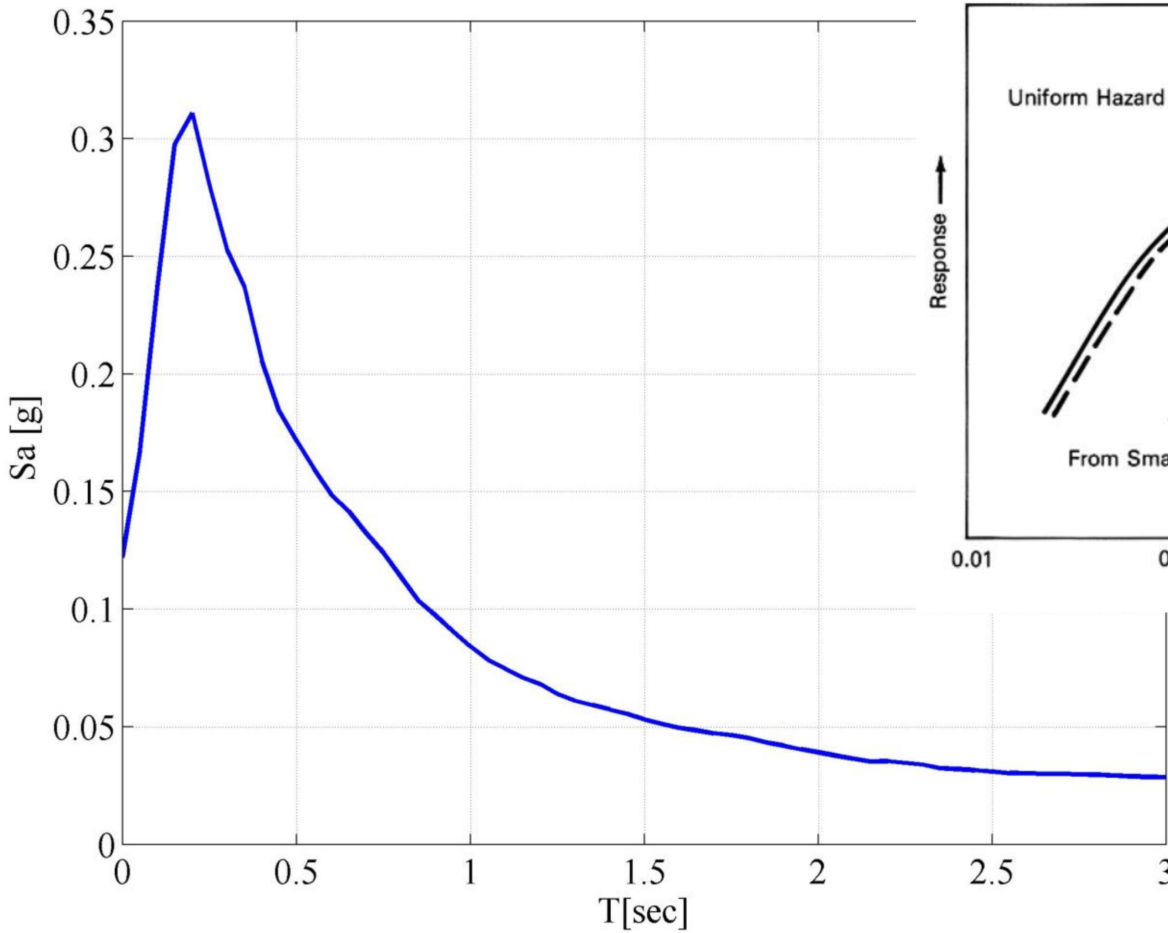
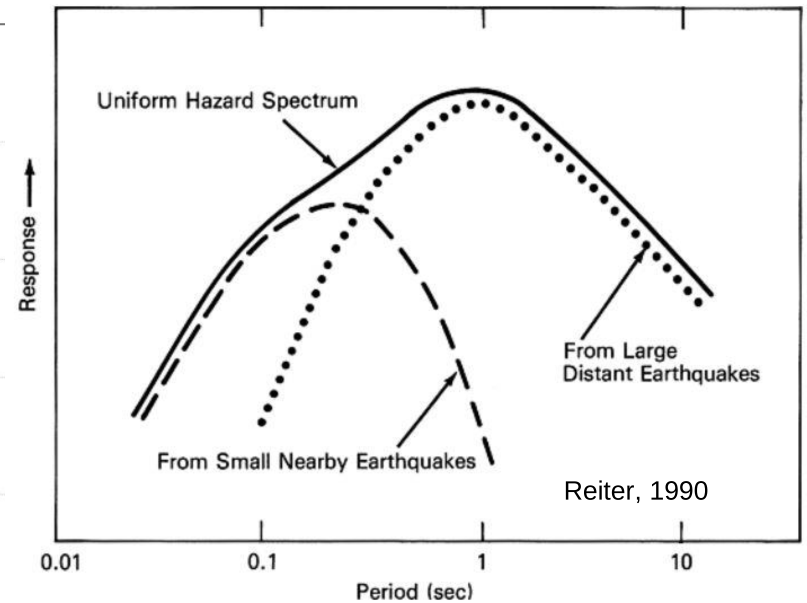
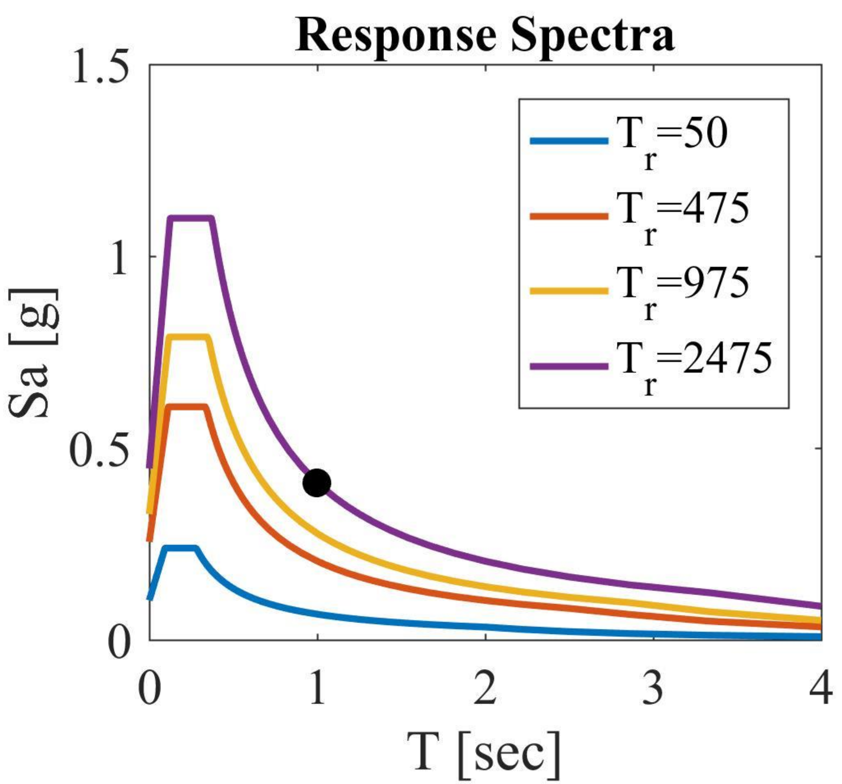
Uniform hazard spectra (2)

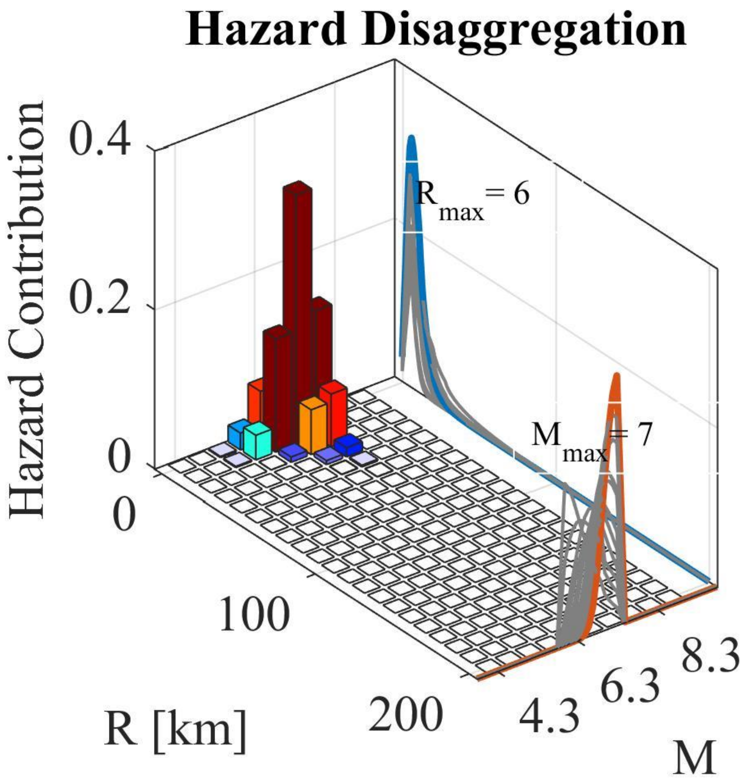




$$\lambda_{im} = \nu \cdot \iint_{m,r} P\left(IM > im \mid m,r\right) \cdot f_{M,R}\left(m,r\right) \cdot dr \cdot dm$$

Hazard disaggregazion in Norcia

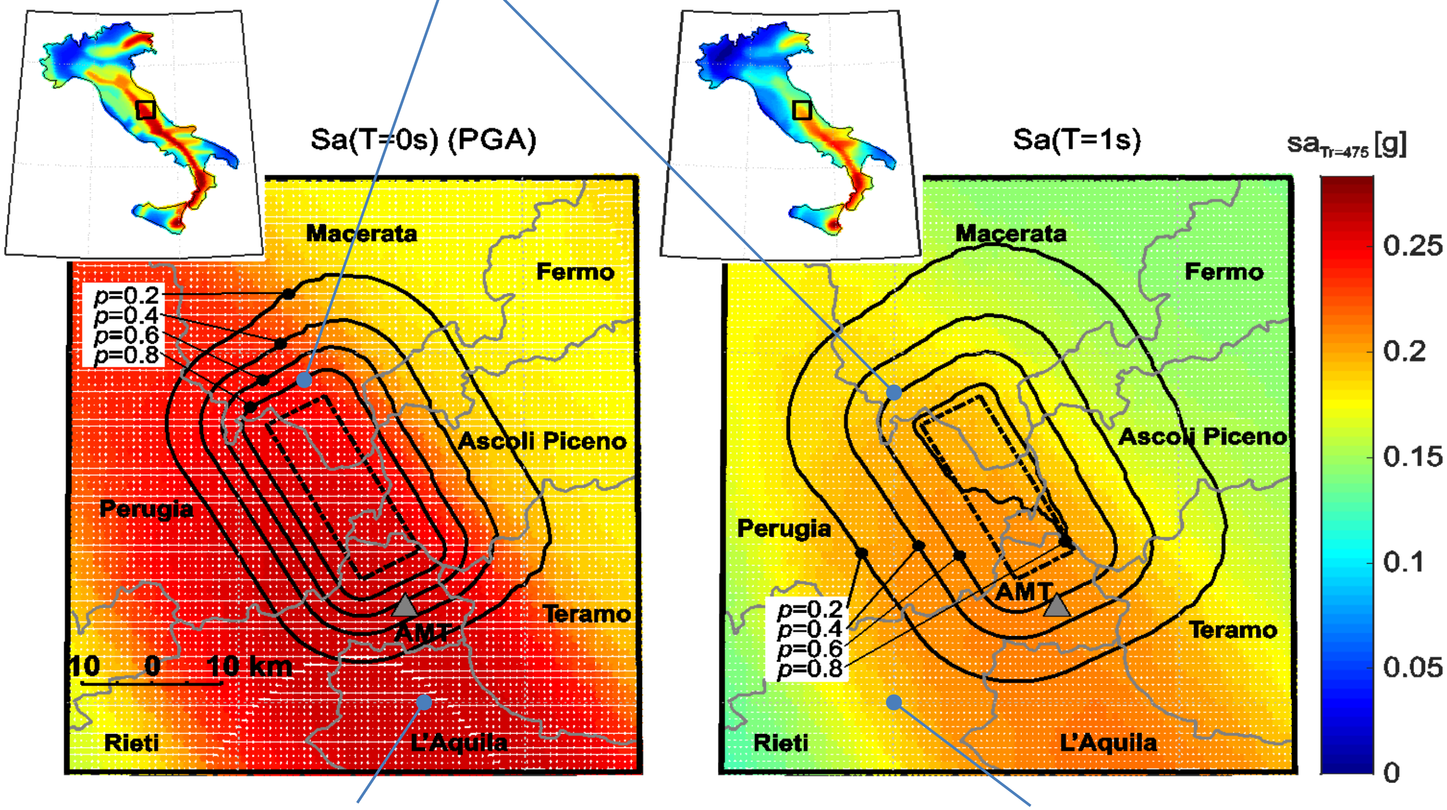




Because of the way design spectra are defined, the largest probability of exceedance must be in epicentral zone by relatively high magnitude earthquakes.

How likely was the exceedance of design accelerations in the epicentral area of the M6.5 earthquake?

$$p = P\left[Sa(T) > sa_{T_r=475} \middle| M = 6.5, R = r \right]$$



Design Sa(T=0s) (PGA) (475yr)

Design Sa(T=1s) (475yr)

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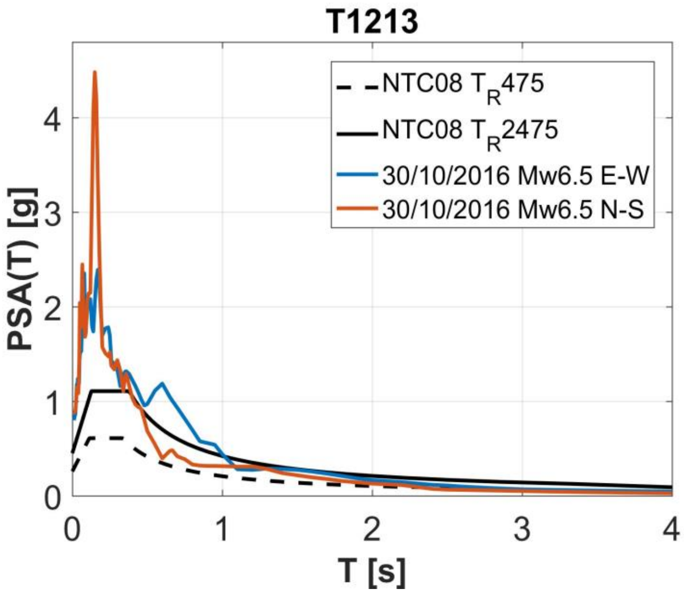
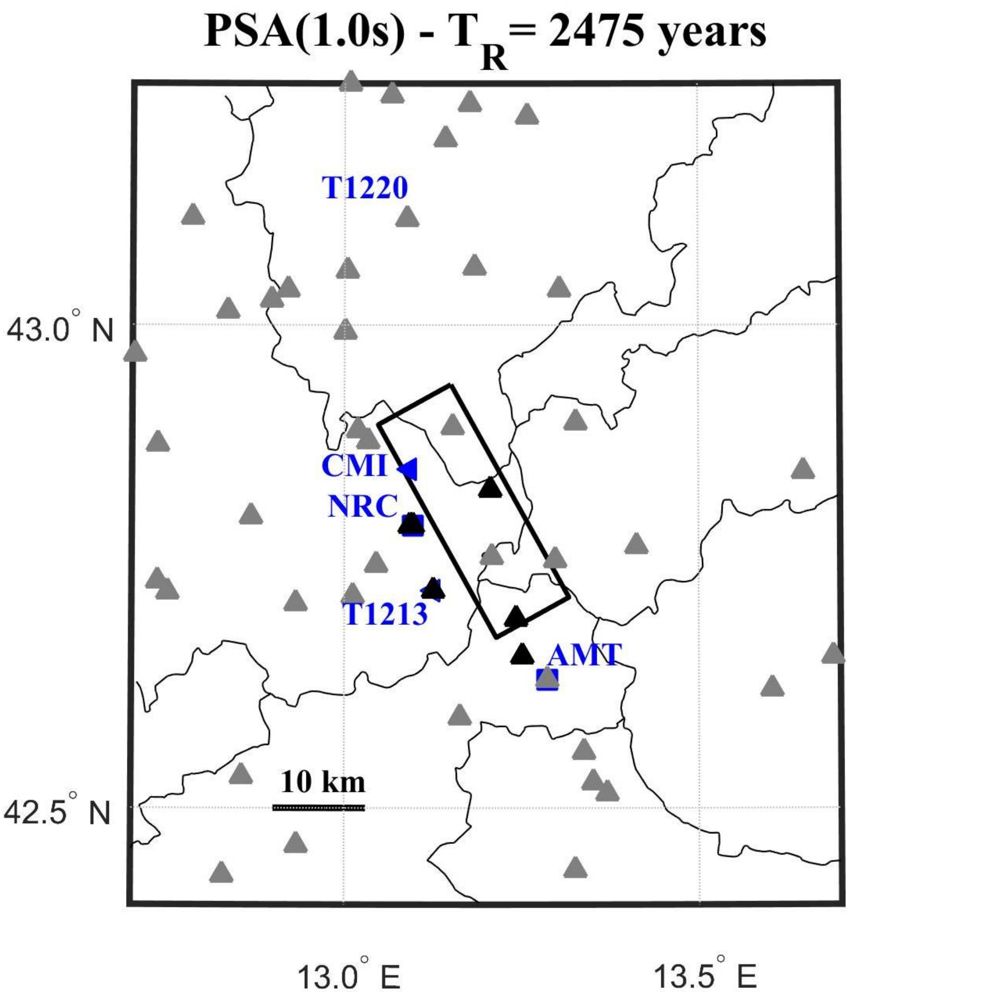
What if these expected events happened in the central Italy?

Disaggregation			
T [sec]	TR [years]	R [km]	M
PGA	475	5	5,6
PGA	2475	5	6,4
1,0	475	6	6,2
1,0	2475	6	7,0





Conclusive remarks

1. Damage expected for new structures:

   a) From the preliminary results of the firs two years of the RINTC project, the seismic risk of new structures was found to be not uniform between structural typologies.
   b) The risk does not seem to be uniform even for the same typology as the hazard at the site varies. In paticular, the risk tends to increase with the increase of hazard.
   c) In some cases, the failure rate was comparable or higher than the exceedance rate of the designed seismic intensity (spectral acceleration).
   d) However, the project is still on-going and **much work is still needed to consolidate these outcomes** that could be substantially revised in the future click here for details and references about the project].

2. Where damage expected for new structures:

   a) Because of the way the design spectra are defined, they do not protect for close earthquakes with relatively high magnitude. Protection for these earthquakes is ensured by the fact that it is rare that they will occurr close to the site.
   b) In the case of earthquakes with relatively rare magnitude, uniform hazard spectra are exceeded with very high probability in areas close to source.
   c) Damage to structures even designed according to the state-of the-art codes will continue to occur in the epicentral zone of relatively high magnitude events. (Yet much more limited damage with respect to low- or no-code structures.)

The seismic risk of code-conforming structures: what damages and where.

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