Interdisciplinary Workshop on Management of Earthquake Risks

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DAMAGE ASSESSMENT OF CURRENT BUILDINGS AT TERRITORIAL SCALE:

A MECHANICAL MODEL CALIBRATED ON A MACROSEISMIC VULNERABILITY MODEL

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5th Framework European Commission Project

An advanced approach to earthquake risk scenarios with applications to different European towns

The aim of the projects was to develop <u>a comprehensive modular methodology</u> to create earthquake scenarios and risk analysis, concentrating on the <u>distinctive features of the European cities with regard to current and historical buildings</u>

Exposure | Hazard | Vulnerability | Specific Cost

⇩

The proposal for vulnerability methods within the modular methodology targeted by the Risk-UE project, had to respect the requirements of the others work-packages

EXPOSURE

❑ *A typological classification system has been assumed judged to account for and to represent the characteristic features of the European building typologies*

Unreinforced Masonry	
M1	Rubble stone
M2	Adobe (earth bricks)
M3	Simple stone
M4	Massive stone
M5	U Masonry (old bricks)
M6	U Masonry - r.c. floors

Reinforced/confined masonry	
M7	Reinforced/confined masonry

Reinforced Concrete	
RC1	Concrete Moment Frame
RC2	Concrete Shear Walls
RC3	Dual System

❑ *The different availability of data has been considered*

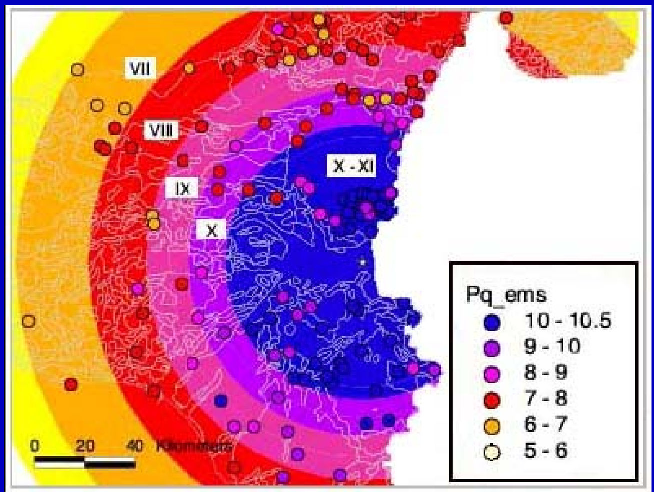
Level 0 Number of buildings and statistical knowledge of the main features

Level 1 Existing database with information non specifically surveyed for vulnerability purposes.

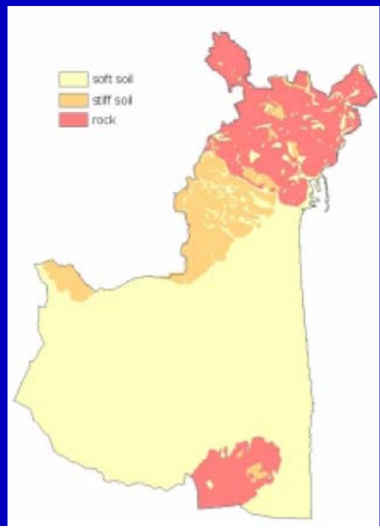
Level 2 Detailed information about the typology and the geometrical, structural and technological features from a survey specifically devoted to the vulnerability assessment

HAZARD

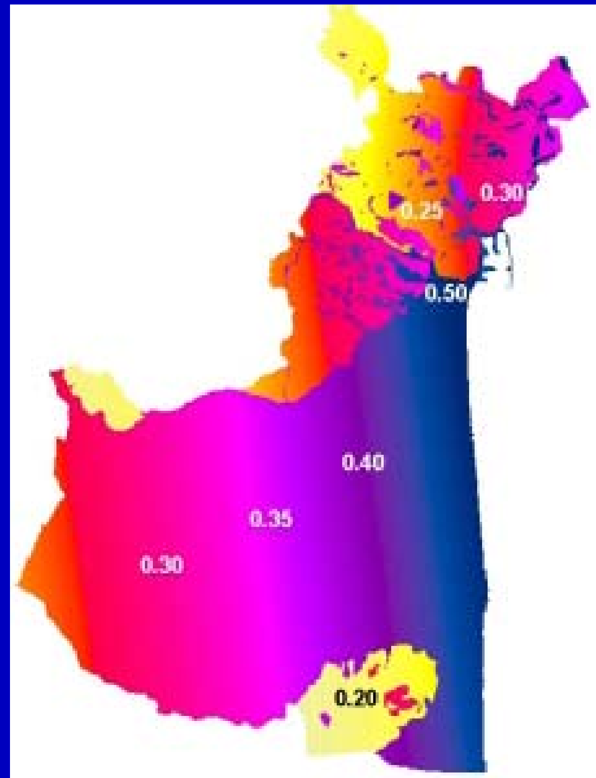
Hazard scenarios implemented both in terms of macroseismic intensity and in terms of physical parameters (e.g. PGA peak ground acceleration and response spectra)



EMS intensity distribution for the 1693 earthquake, derived with the attenuation relation of Grandori et al. (1991)



three ground profile classes



PGA[g] values for 1693 event

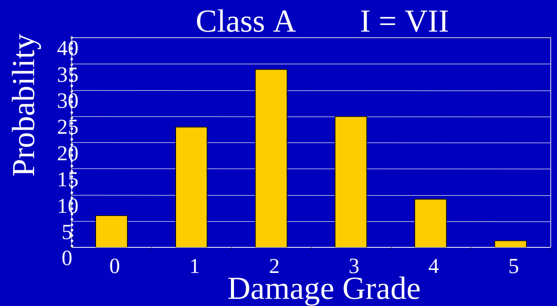
VULNERABILITY

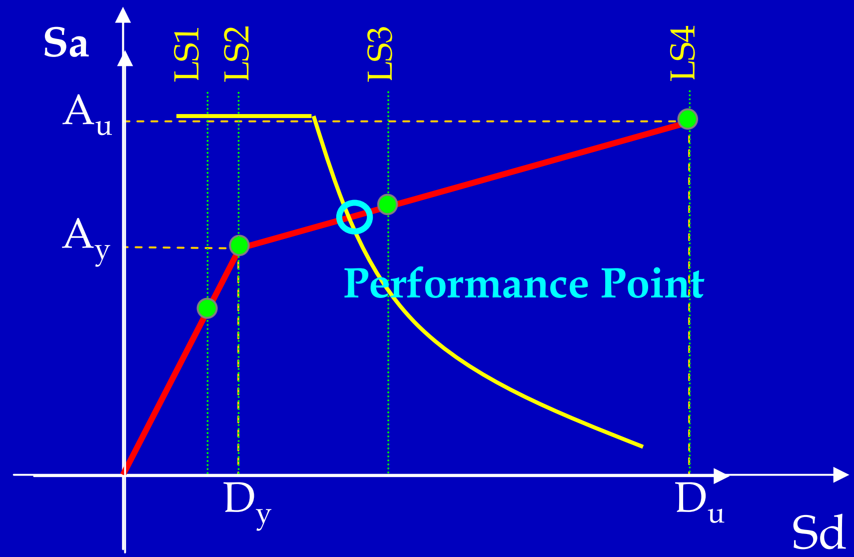
The state of the art in the field of seismic vulnerability approaches, available for Europe at the starting date of the project , classified vulnerability methods depending on their genesis

Observational methods:
DPM (Damage Probability Matrix), based on observed vulnerability. Implicitly contained in the macroseismic scale definition
Seismic input:
Intensity
Damage rapresentation:
Observed damage 5 damage grades: D1 - D5

Mechanical methods:
Capacity Spectrum Method: vulnerability represented by building capacity curve; demand-capacity comparison ⇒ performance evaluation
Seismic input:
ADRS – Acceleration Displacement Response Spectra
Damage representation:
4 Damage Limit States (performance levels)

	V	VI	VII	VIII	IX	X
0	0,90	0,18	0,06	1,5E03	5,4E05	2,7E06
1	0,092	0,37	0,23	2,0E02	1,6E03	1,6E04
2	0,038	0,296	0,34	0,108	2,0E02	3,9E03
3	7,6E05	0,117	0,25	0,287	0,12	4,6E02
4	7,8E07	0,023	9,2E02	0,38	0,38	0,28
5	3,2E09	0,0018	1,3E02	0,20	0,47	0,67





Non-linear equivalent s.d.o.f. structure Capacity Curve

Acceleration-Displacement Response Spectrum

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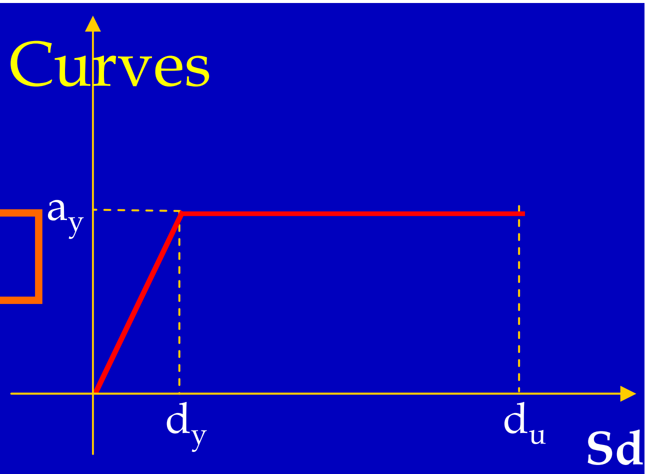
- The macroseismic method was originally developed by the authors (Giovinazzi and Lagomarsino, 2004) from the definition provided by the European Macroseismic scale EMS-98 (Grunthal, 1998)

- A capacity spectrum-based method was proposed, with capacity curves specifically definided for the European building typologies

The proposed vulnerability methods have been compared and cross-validated

Mechanical Method: Capacity Curves

- ❑ Mechanical Models on prototype buildings
  - Pushover Analyses
  - Simplified Models



- T Fundamental period [s]
- a_y Yield strength [g]
- μ Ductility Capacity

The Capacity Curve parameters have been evaluated on the basis of factors able to identify the Building Typology with regard to:

Geometrical features	*Technological features*	*Dynamic behaviour*
N - Floor Number	τ_K characteristic shear strength	m modal mass coefficient
h inter-story height	γ material density	Γ modal participation factor
α, β_T resistant area	q m^2 floor load	δ_u ultimate drift

Mechanical Method: Capacity Curves

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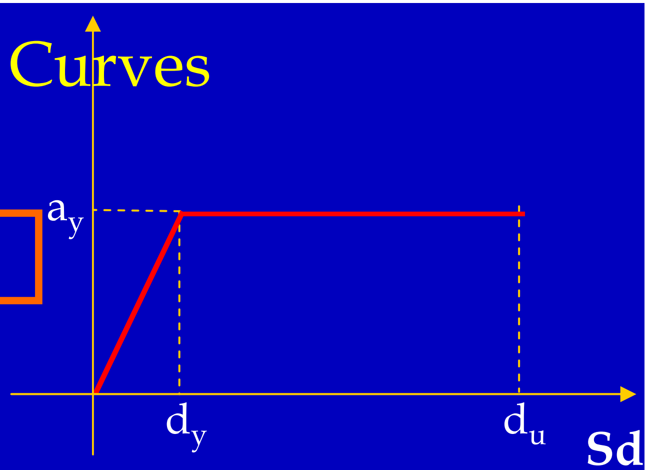


- T Fundamental period [s]
- a_y Yield strength [g]
- μ Ductility Capacity

T True fundamental period

$$T = \theta \cdot h^{\frac{3}{4}}$$

θ Defined for each typology

a_y Yield strength

soft-story collapse

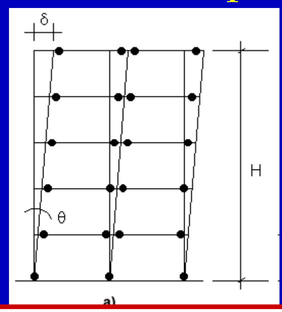
friction neglected

$$a_y = \frac{F}{mM}$$

$$a_y = \frac{0.5\tau_k \alpha \beta_T \xi}{m\left(Nq + \gamma\alpha h \sum_i^N \beta_i\right)}$$

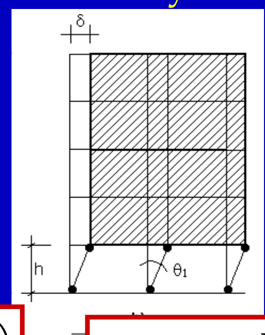
d_u ultimate displacement

uniform collapse



$$d_u = \delta_u \cdot h + d_y\left(1 - \frac{\Gamma}{N}\right)$$

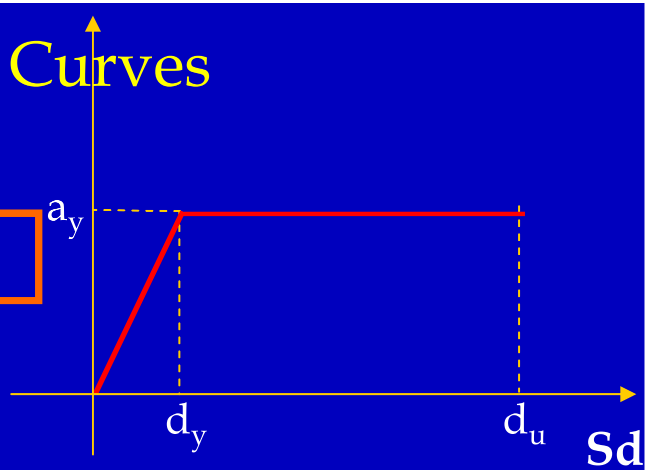
soft-story collapse



$$d_u = \delta_u \cdot \frac{Nh}{\Gamma}$$

Mechanical Method: Capacity Curves

- Mechanical Models on prototype buildings
  - Pushover Analyses
  - Simplified Models



- Derived from seismic design codes (for designed buildings)

- T Fundamental period [s]
- a_y Yield strength [g]
- μ Ductility Capacity

a_y yield strength

$$a_y = \frac{F_D}{mM}$$

$$F_D = \left[\frac{S_{ae}(T)}{q}\right]\frac{\gamma_m}{\alpha}$$

redundancies and conservatism in design and true strength of materials have to be considered

T true fundamental period

$$T = C_t \cdot h^{\frac{3}{4}}$$

C_t =0.075 moment resistant concrete frame

C_t =0.085 moment resistant steel frame

C_t =0.05 other structures

μ ductility   q Behaviour factors

$$\mu = 1 + (q-1)\frac{T_C}{T} \quad T < T_C$$

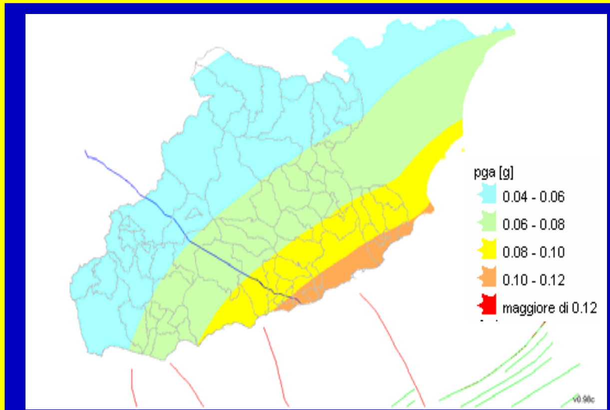
$$\mu = q \quad T > T_C$$

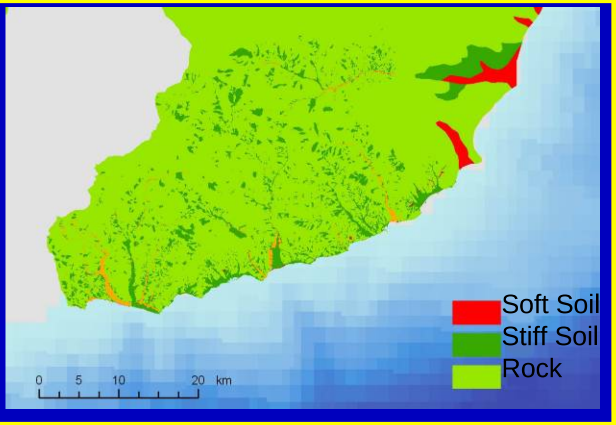
	Regular Structures		Irregular Structures	
	DCH	DCM	DCH	DCM
RC1	4.5	3.15	3.6	2.52
RC2	4	2.8	3.2	2.24
RC3	4	2.8	3.2	2.24

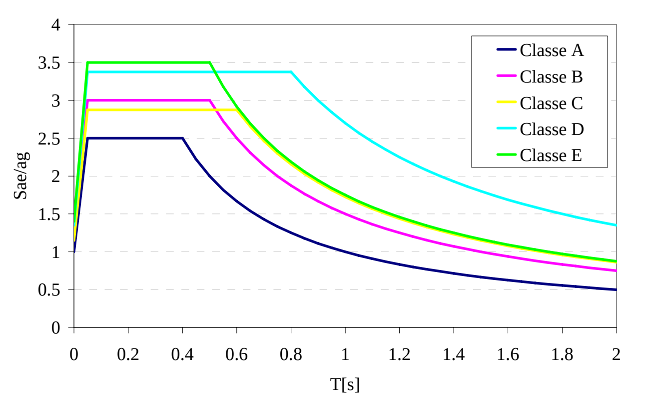
Mechanical Method: Hazard Description

The use of simplified mechanical approach in the framework of a seismic risk analysis requires an hazard description in terms of an elastic response spectra $S_{ae}(T)$ with a characteristic period T_C separating the periods of almost spectral acceleration ($T<T_C$) by the almost constant spectral velocity range ($T>T_C$).

- ❑ Anchoring to hazard analysis, provided in terms of peak ground acceleration a_g predefined spectral shapes related to the local soil conditions.







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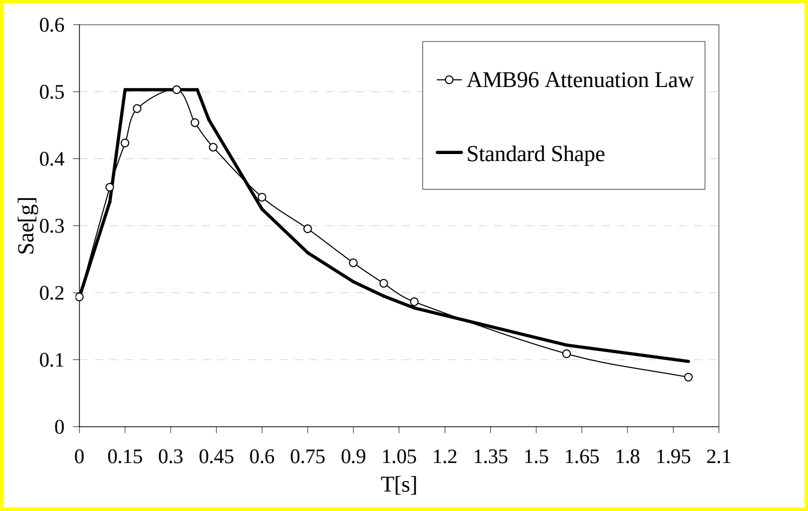
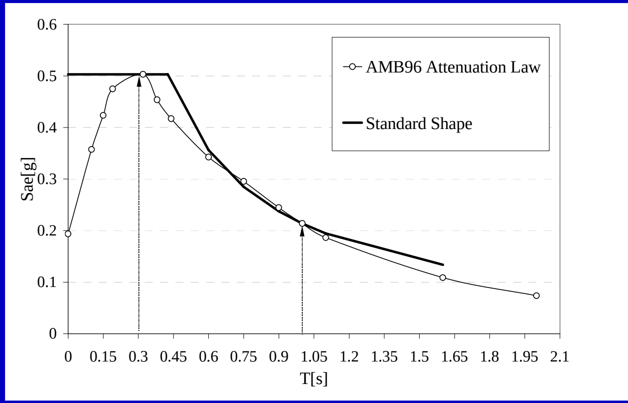
- ❑ Anchoring to hazard analysis, provided in terms of peak ground acceleration a_g predefined spectral shapes related to the local soil conditions.
  - ❑ Fitting response spectra discrete values with a standard spectral shape.





$$S_{ae}(T) = \begin{cases} S_{ae(T=0.3)} & 0 \le T \le T_C \\ S_{ae(T=0.3)} \dfrac{T_C}{T} & T_C < T \le T_D \end{cases}$$

$$A_{PE} = \frac{1}{2}\sum_{i=1}^{n-1}(S_{ae(T_{i+1})} + S_{ae(T_i)})(T_{i+1} - T_i)$$

$$T_C = \frac{S_{ae(T=1)}}{S_{ae(T=0.3)}}$$

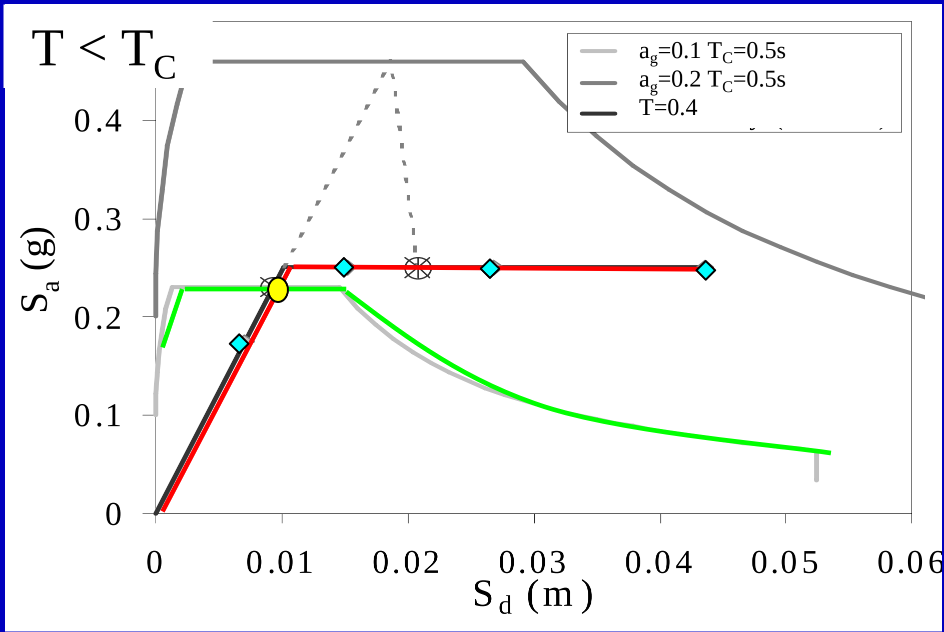
$$A_{SS} = 0.075(S_{ae(T=0)} + S_{ae(T=0.15)}) + \left(T_C - 0.15\right)S_{ae_{max}} + \left(\ln(2) - \ln(T_C)\right)T_C S_{ae_{max}}$$

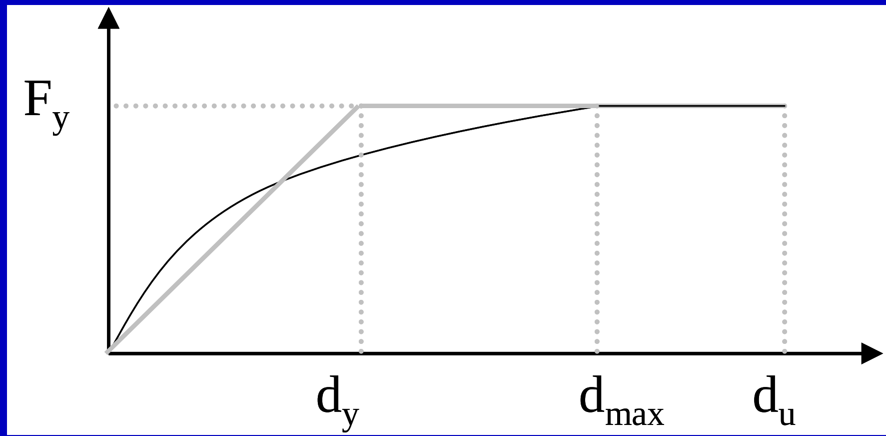
Mechanical Method: performance point evaluation

A seismic demand reduction is performed in order to take into account the inelastic behaviour of the building

- INELASTIC SPECTRA

Easier and the more direct. It has to be preferred to overdamped spectra dealing with Bilinear Capacity Curves





$$S_{d*} = \begin{cases} \left[1 + \left(\frac{S_{ae}}{a_y} - 1\right)\frac{T_C}{T}\right] d_y & T < T_C \text{ and } q > 1 \\ \frac{S_{ae}}{a_y} d_y & T_C \le T < T_D \text{ or } q \le 1 \\ S_{ae}\frac{(T_D)T_D^2}{4\pi^2} & T \ge T_D \end{cases}$$

$$S_{d,1} = 0.7 d_y$$

$$S_{d,2} = 1.5 d_y$$

$$S_{d,3} = 0.5(d_y + d_u)$$

$$S_{d,4} = d_u$$

Mechanical Method: fragility curves and damage distributions

Hazard: a_g

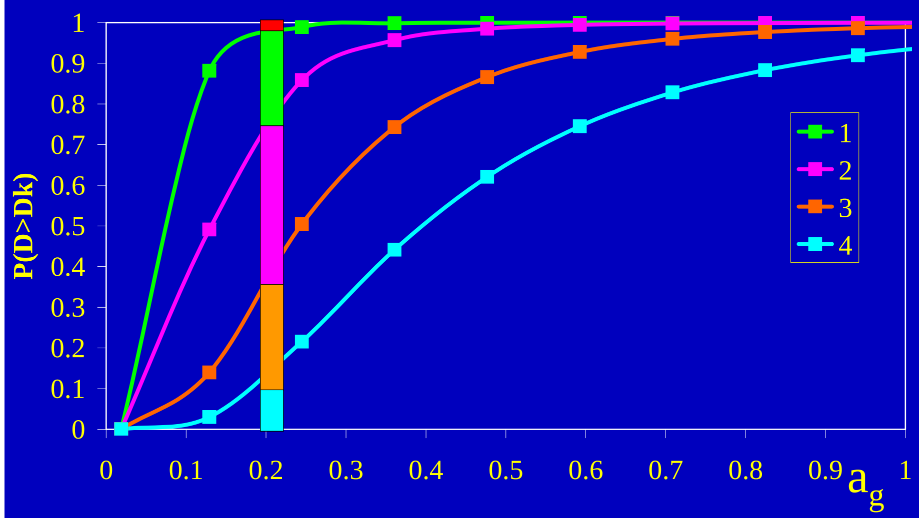
Site Effects: T_C, s

Vulnerability : ay,T,.µ

⇨ Performance Point S_{d*}

$$S_{d,1} = 0.7 d_y$$
$$S_{d,2} = 1.5 d_y$$
$$S_{d,3} = 0.5(d_y + d_u)$$
$$S_{d,4} = d_u$$

FRAGILITY CURVES



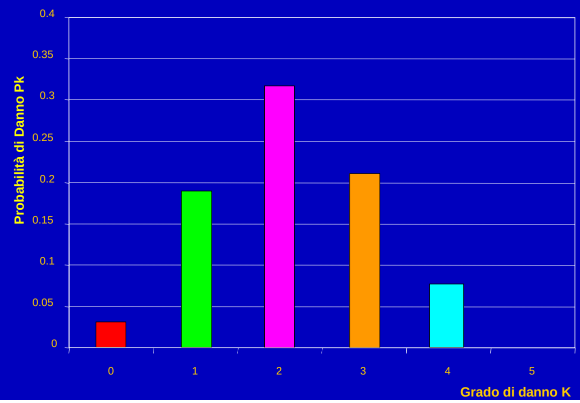
DAMAGE DISTRIBUTION

$$P_{k=1\div3} = P\left[D_k \middle| S_{d^*}\right] - P\left[D_{k+1} \middle| S_{d^*}\right]$$

$$P_0 = 1 - P\left[D_1 \middle| S_{d^*}\right]$$

$$P_4 = P\left[D_4 \middle| S_{d^*}\right]$$

$$P\left[D_k \middle| S_{d*}\right] = \Phi\left[\frac{1}{\beta_k}\ln\left(\frac{S_{d*}}{S_{d,k}}\right)\right]$$



Mechanical Method: consequences estimation

Consequences on buildings	Damaged buildings	**100%** of buildings suffering $\mathbf{D_3}$ **60%** of buildings suffering $\mathbf{D_2}$
	Unfit for use buildings	**100%** of buildings suffering $\mathbf{D_4}$ **40%** of buildings suffering $\mathbf{D_3}$
	Collapsed buildings	**100%** of buildings suffering $\mathbf{D_5}$
Consequences on people	Homeless	**100%** of people living in **Unfit for use buildings** + **70%** of people living in **Collapsed buildings**
	Dead people and heavy injured	**30%** of people living in **Collapsed buildings**

Economic losses are measured in terms of the damage factor (DF), defined as the ratio between the repair cost and the reconstruction cost (corresponding to the building value)

DF_1	DF_2	DF_3	DF_4	DF_5
0.01	0.1	0.35	0.75	1

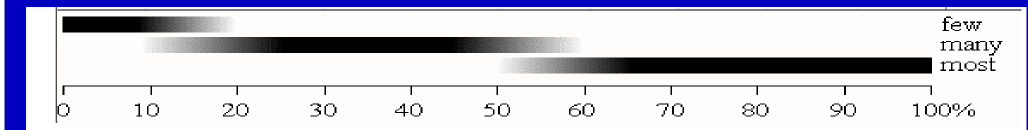
$$MDR = DF = \frac{\text{Repair Cost}}{\text{Building Value}}$$

Macroseismic Method - EMS 98 Macroseismic Scale

Six vulnerability classes (from A to F) of decreasing vulnerability: A, B and C classes of ordinary buildings designed without explicit control of seismic resistance; D, E and F classes of buildings with levels of progressively increasing protection.

Class A					
Damage grade	1	2	3	4	5
Intensity					
V	Few				
VI	Many	Few			
VII			Many	Few	
VIII				Many	Few
IX					Many
X					Most
XI					All
XII					

The meaning of the adjectives ("few", "many", "most") used for the description of the frequencies of damaged buildings, is qualitatively suggested by the scale in a graphical fuzzy manner



A discrete five damage grade scale Dk k=1÷5)

GRADE 1: Negligible to slight damage

GRADE 2: Moderate damage

GRADE 3: Substantial to heavy damage

GRADE 4: Very heavy damage

GRADE 5: Destruction

Macroseismic Method – Damage Probability Matrices

- The complete description of the damage distribution has been obtained via a linguistic extension, according to two different criteria.

	Class B					
	D_0	D_1	D_2	D_3	D_4	D_5
V	All-few	Few	none	none	none	none
VI	Most-8/3few	Many	Few	none	none	none
VII	3few	many	Many	Few	none	none
VIII	few	2few	many	Many	Few	none
IX	none	few	2few	many	Many	Few
X	none	none	few	3few	many	Many
XI	none	none	none	few	2few	Most

1) the scale explicitly gives the frequencies of grades of greater damage, thus the linguistic frequency "none" (i. e. numerically 0) is here assumed, for all higher grades of damage.

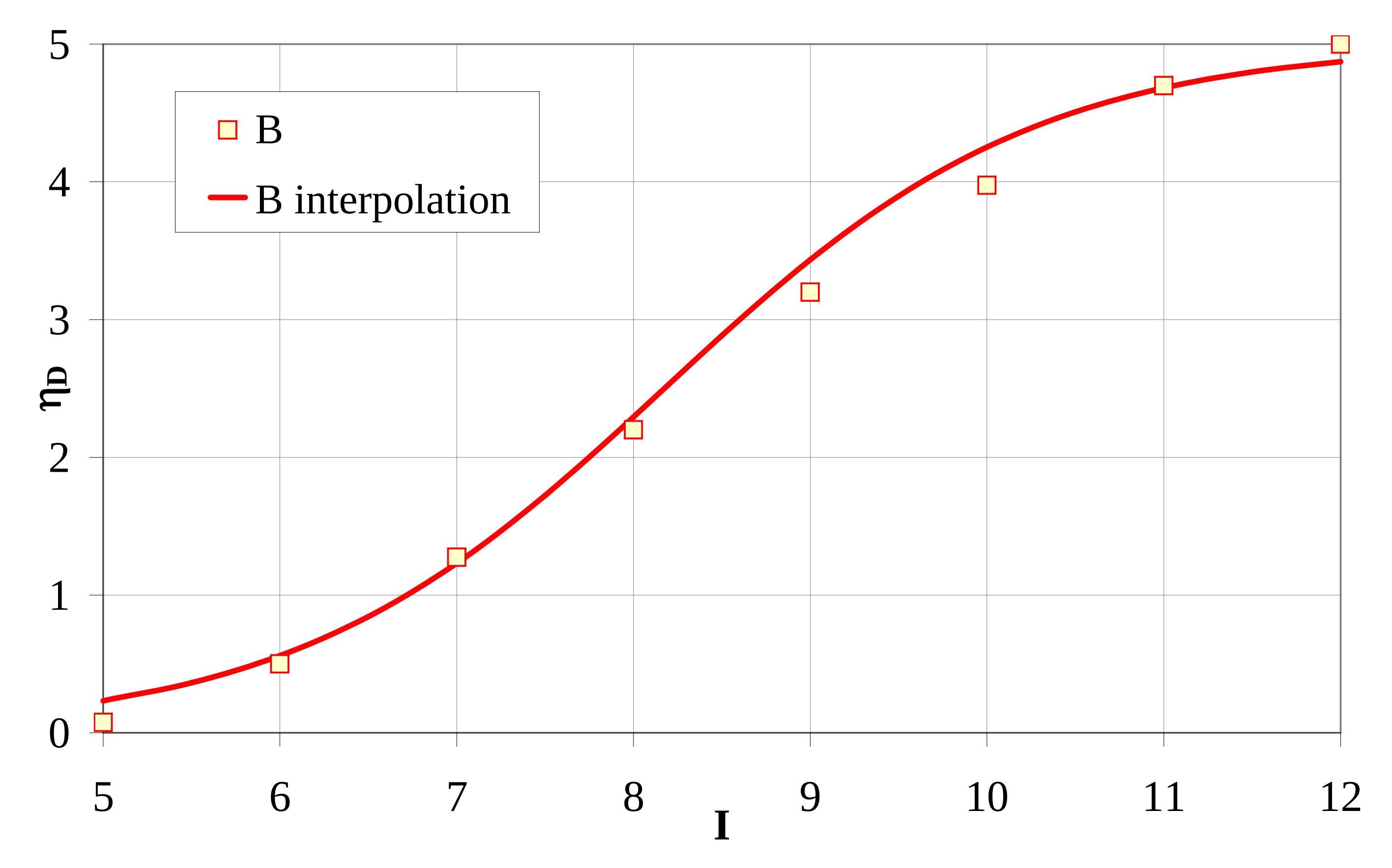
2) for lower grades, the extension of every row has been performed in such a way that the sum of the expected white percentages should be in any case equal to 100 .

	0	1	2	3	4	5	μ_D	σ_D
V	92.5	7.5	0	0	0	0	**0.08**	**0.26**
VI	57.5	35	7.5	0	0	0	**0.50**	**0.63**
VII	22.5	35	35	7.5	0	0	**1.28**	**0.89**
VIII	7.5	15	35	35	7.5	0	**2.20**	**1.03**
IX	0	7.5	15	35	35	7.5	**3.20**	**1.03**
X	0	0	7.5	22.5	35	35	**3.98**	**0.94**
XI	0	0	0	7.5	15	77.5	**4.70**	**0.60**

Few	7.5
Many	35
Most	77.5

Macroseismic Method – Vulnerability Curves

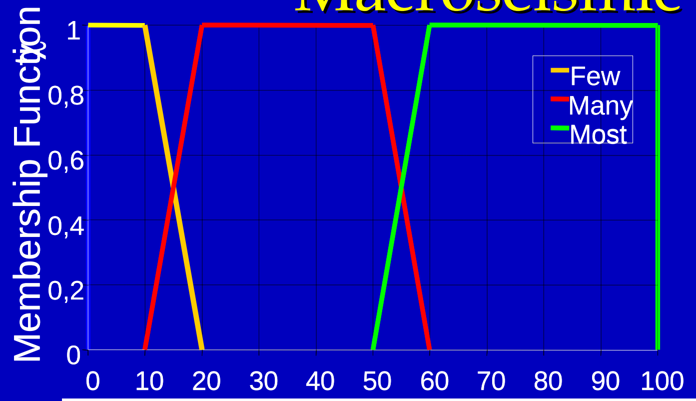
I	μ_D	σ_D
5	0.08	0.26
6	0.50	0.63
7	1.28	0.89
8	2.20	1.03
9	3.20	1.03
10	3.98	0.94
11	4.70	0.60
12	5	0

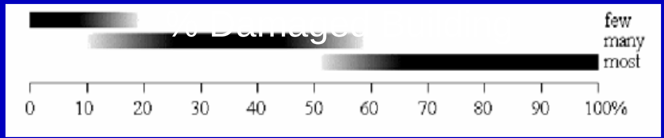


$$\mu_D = 2.5 \cdot \left[1 + \tanh \left(\frac{I + 6.25 \cdot V - 13.1}{Q} \right) \right]$$

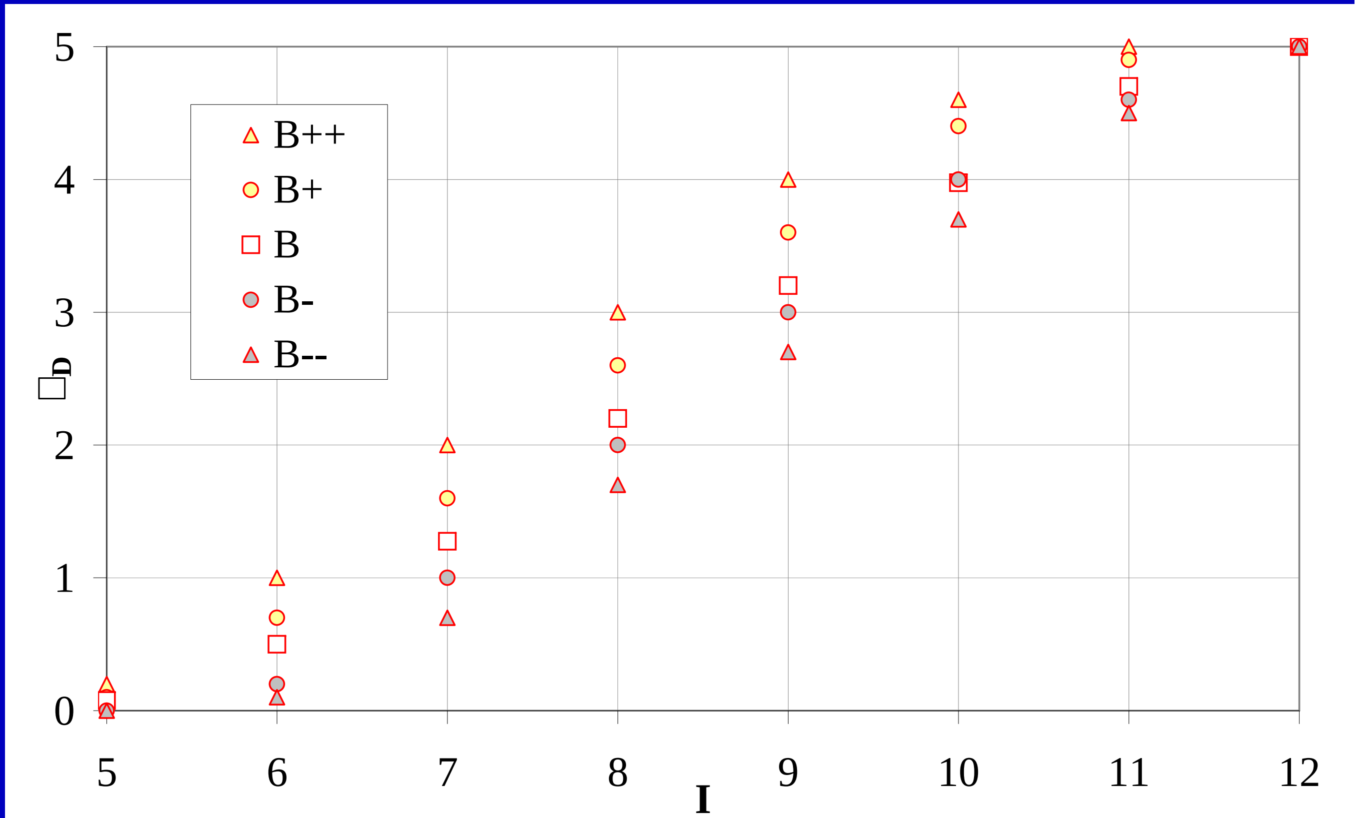
The macroseimic intensity is regarded as a continuous parameters

Macroseismic Method – Vulnerability Curves

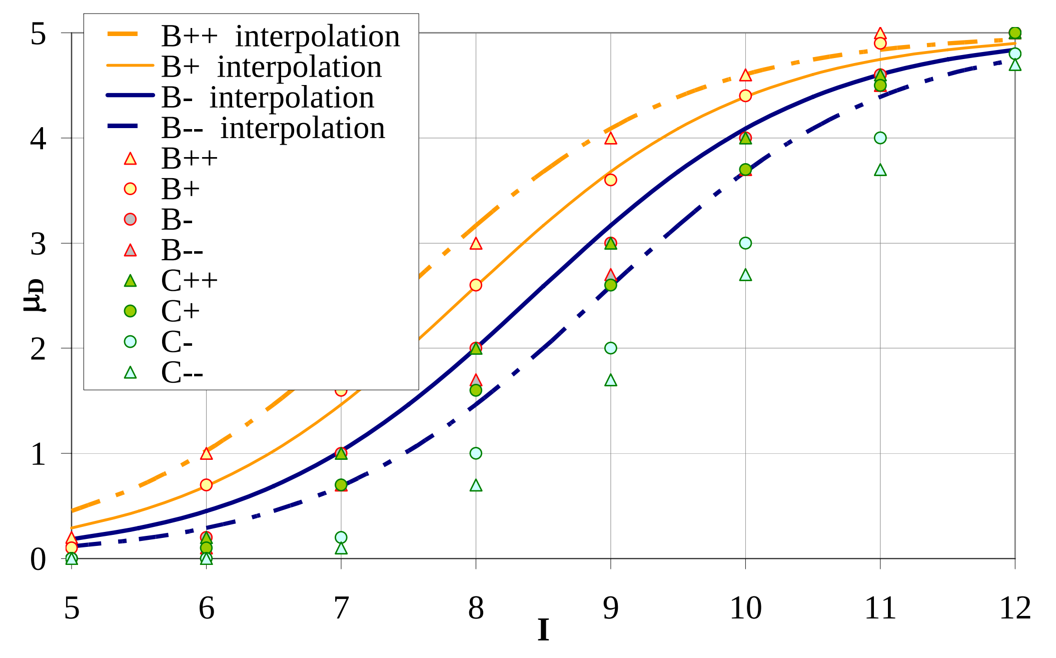




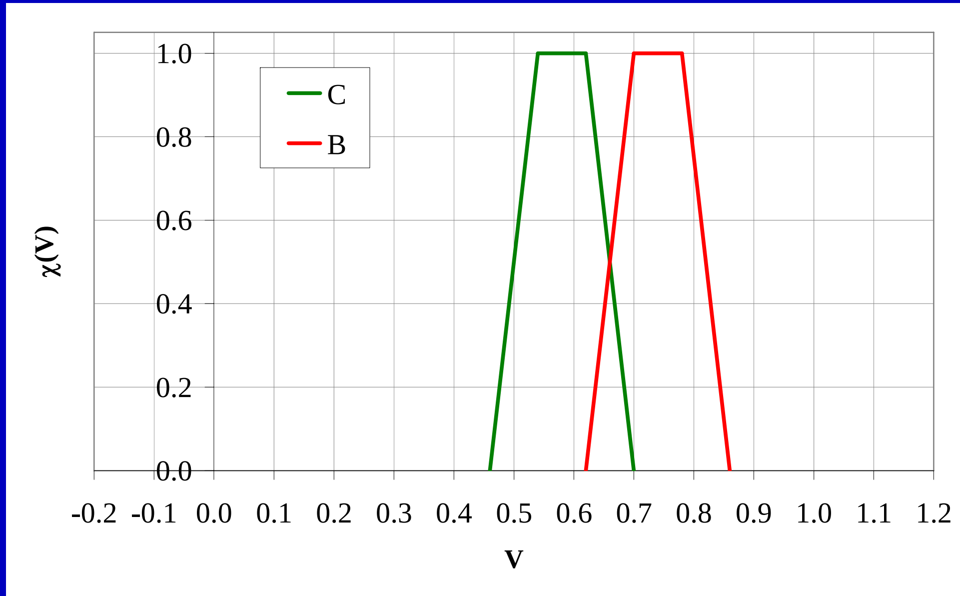
α-cuts	Label	few	many	most
α=0 (upper bound)	++	20	60	100
α=1 (upper bound)	+	10	50	100
α=0.5 (mean value)		7.5	35	77.5
α=1 (lower bound)	-	0	20	60
α=0 (lower bound)	--	0	10	50



Macroseismic Method – Vulnerability Curves



$$\mu_D = 2.5 \cdot \left[1 + \tanh \left(\frac{I + 6.25 \cdot V - 13.1}{Q} \right) \right]$$



Macroseismic Method – Vulnerability Curves

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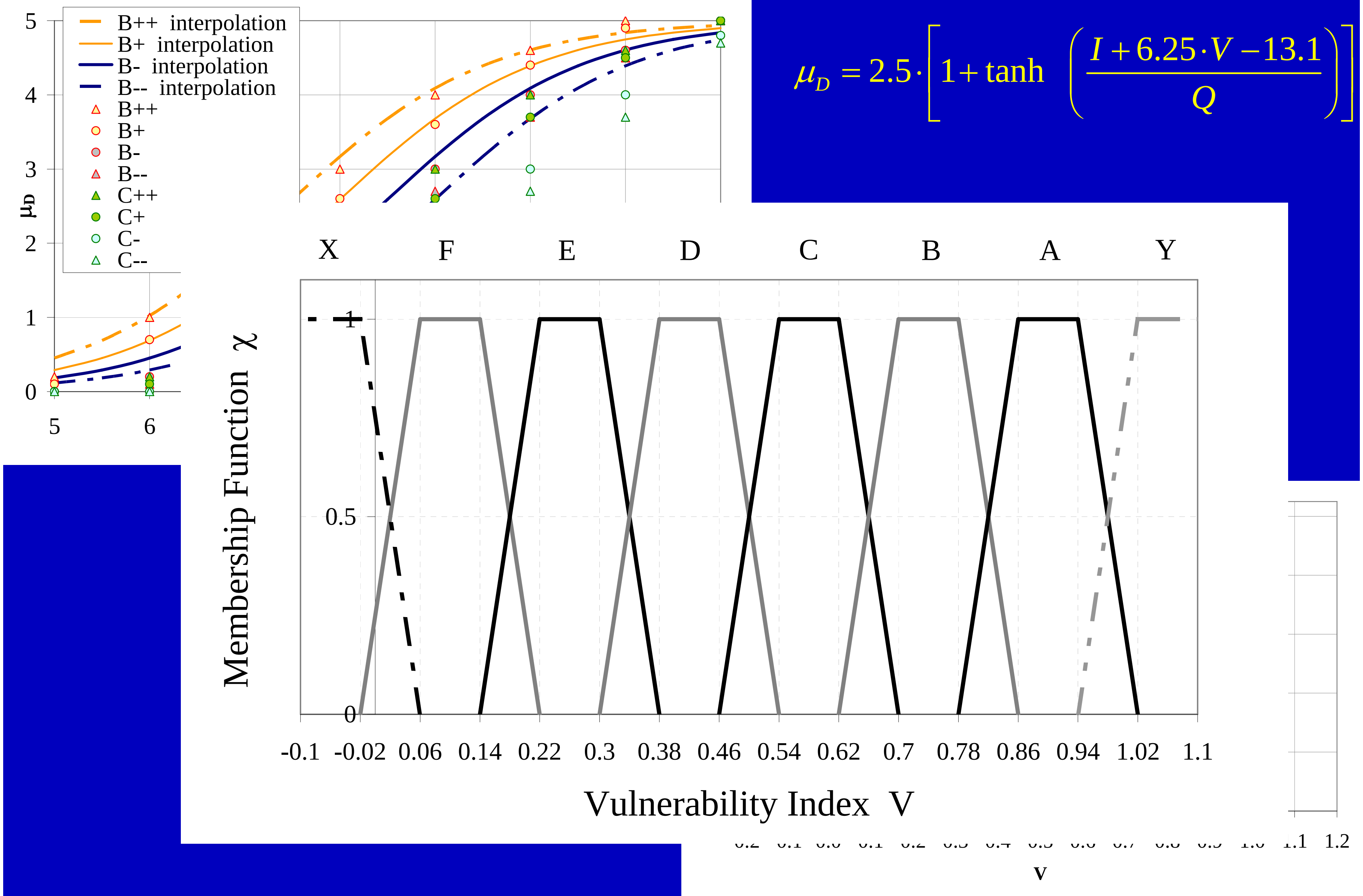
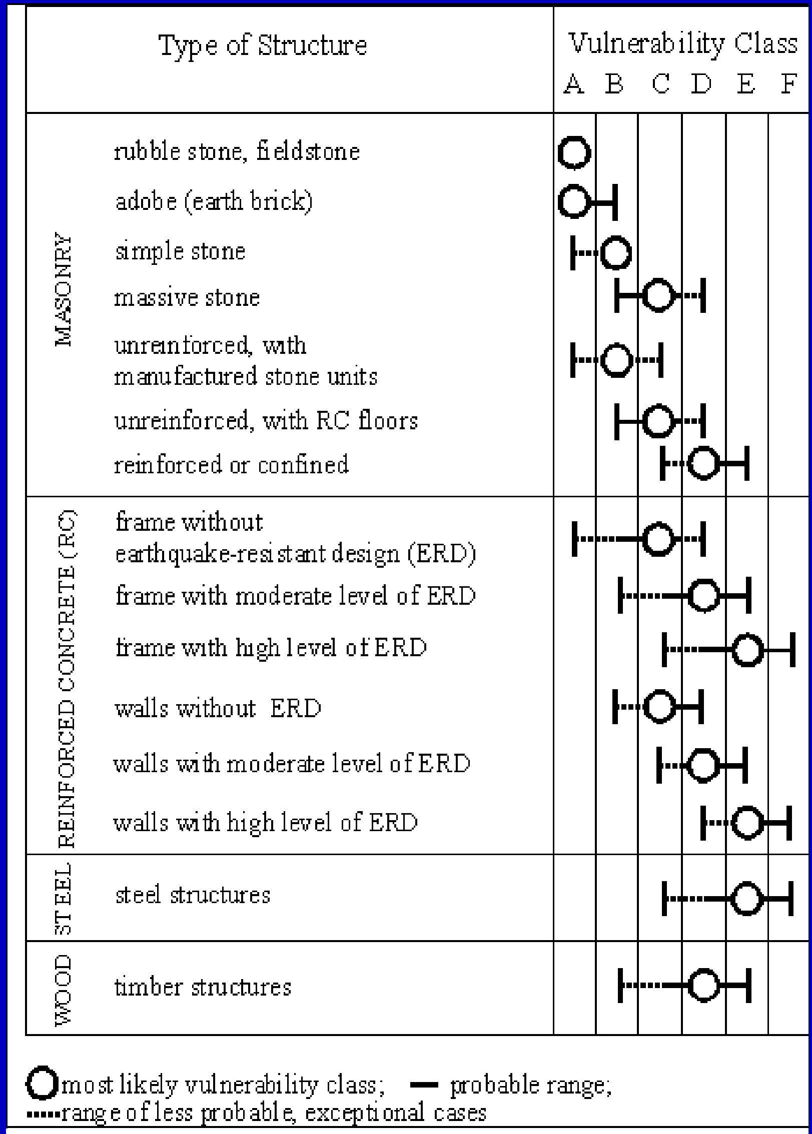


Macroseismic Method for Building Typologies



EMS-98 provide the information about the prevalent vulnerability class (“most likely”) and in case point out the “probable” and the “less probable, exceptional”

The information at the basis of the EMS-98 Vulnerability Table, describing the distribution in terms of vulnerability classes Cj (j 0 1 to 6) for each building typology Ti, can be interpreted as a distribution of relative frequencies:

Less Probable	Few	7.5
Probable	3 Few	22.5
Most Likely		

Typologies		Building type	V^-	V	V^+
Masonry	M1	Rubble stone	0.81	0.873	0.98
	M2	Adobe (earth bricks)	0.687	0.84	0.98
	M3	Simple stone	0.65	0.74	0.83
	M4	Massive stone	0.49	0.616	0.793
	M5	U Masonry (old bricks)	0.65	0.74	0.83
	M6	U Masonry - r.c. floors	0.49	0.616	0.79
	M7	Reinforced /confined masonry	0.33	0.451	0.633
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)	0.49	0.644	0.8
		Frame in r.c. (moderate E.R.D.)	0.33	0.484	0.64
		Frame in r.c. (high E.R.D.)	0.17	0.324	0.48
	RC2	Shear walls (without E.R.D)	0.367	0.544	0.67
		Shear walls (moderate E.R.D.)	0.21	0.384	0.51
		Shear walls (high E.R.D.)	0.047	0.224	0.35

$$V = V^* + \Delta V_m + \Delta V_r + \Delta V_s$$

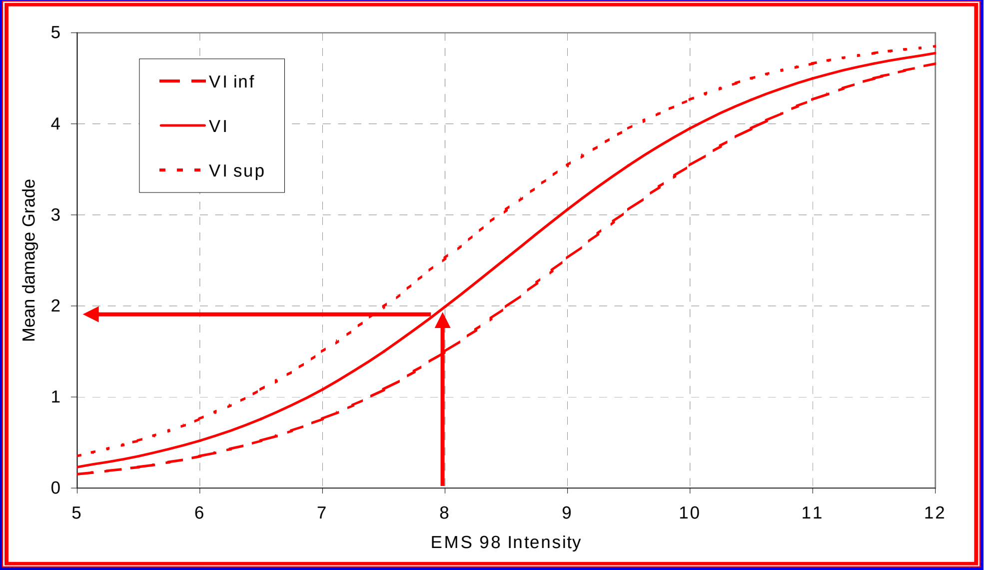
Macroseismic Method: fragility curves and damage distributions

Hazard: I

Site Effects: ΔV

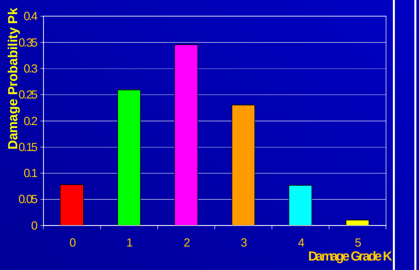
Vulnerability: V and Q

$$\mu_D = 2.5 \cdot \left[1 + \tanh \left(\frac{I + 6.25 \cdot V - 13.1}{Q} \right) \right]$$



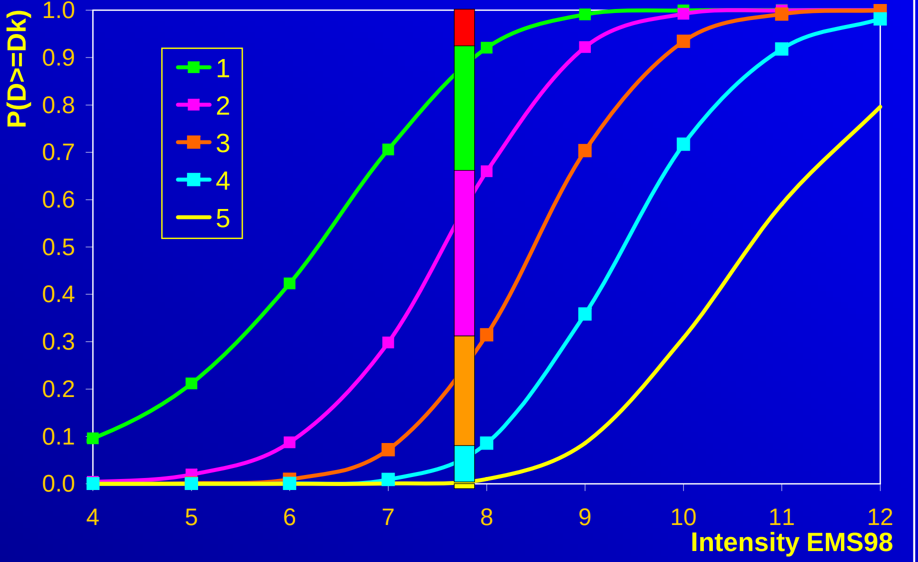
Damage Distribution

$$P_k = \frac{5!}{k!\,(5-k)!} \left(\frac{\mu_D}{5} \right)^k \left(1 - \frac{\mu_D}{5} \right)^{5-k}$$



Fragility Curves

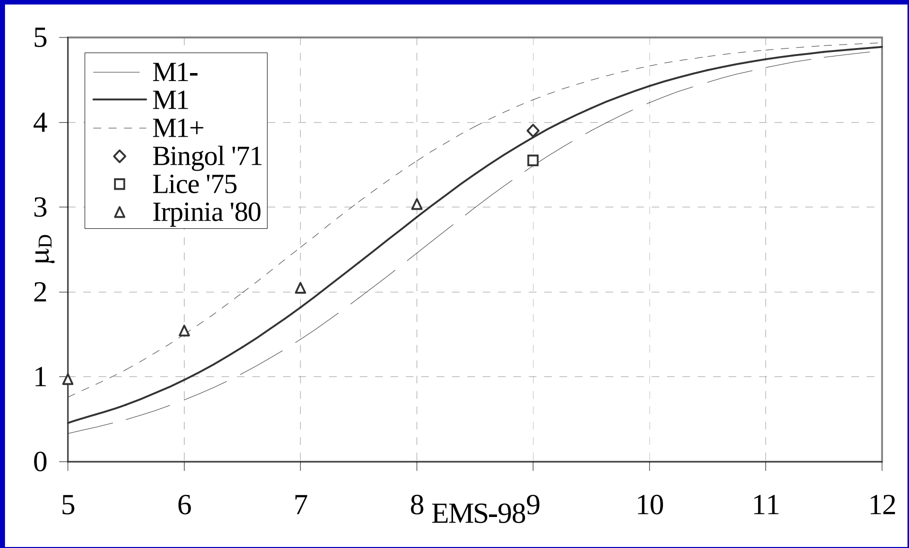
$$P(D \geq D_k) = \sum_{j=k}^{5} P_j$$

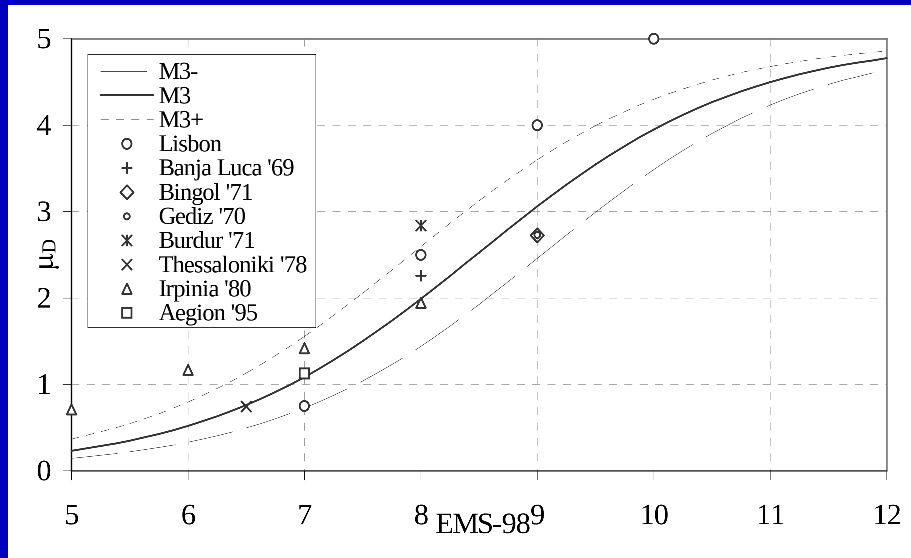


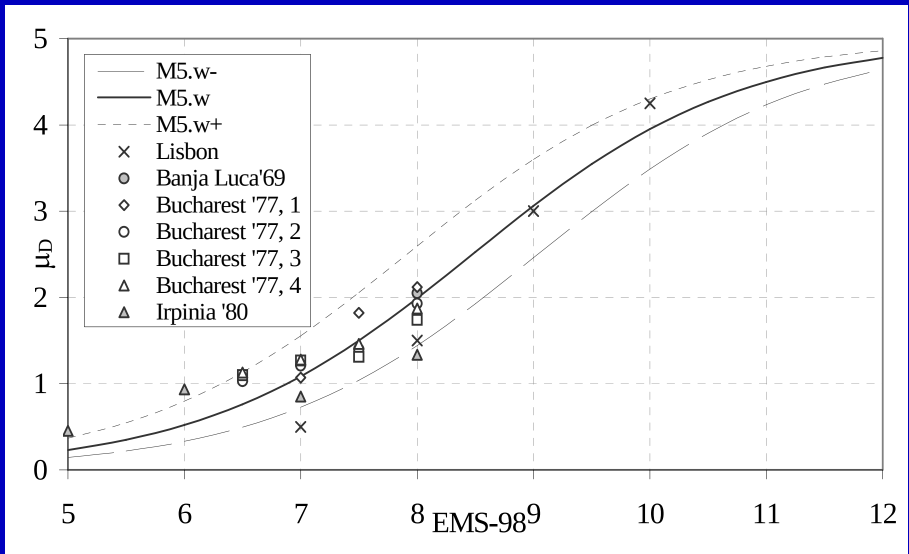
Macroseismic Method: validation

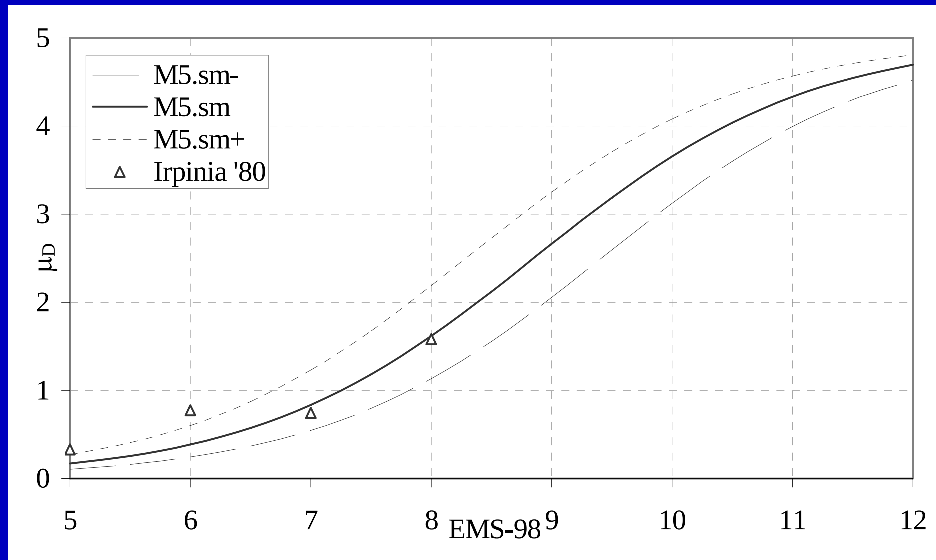
Observed Damage Data

Different European regions



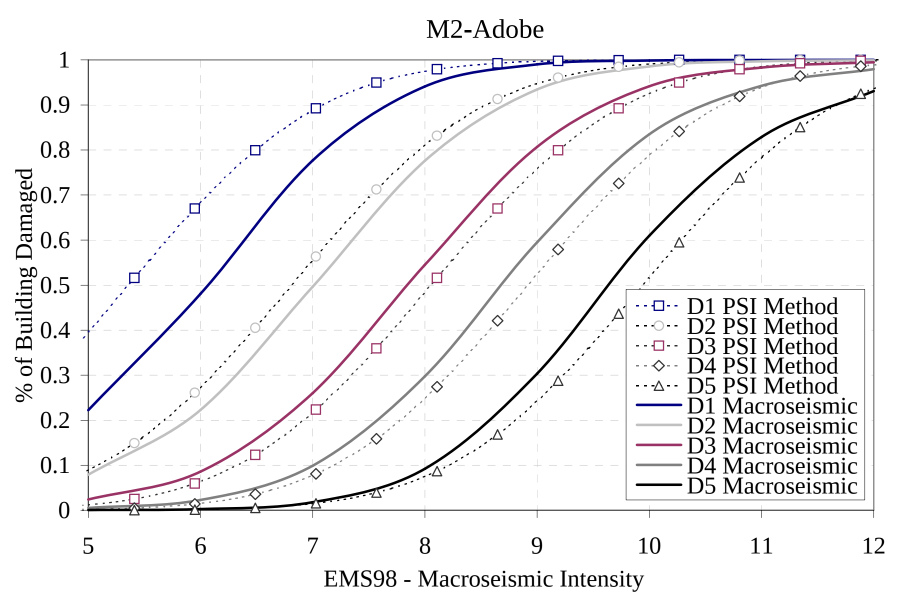


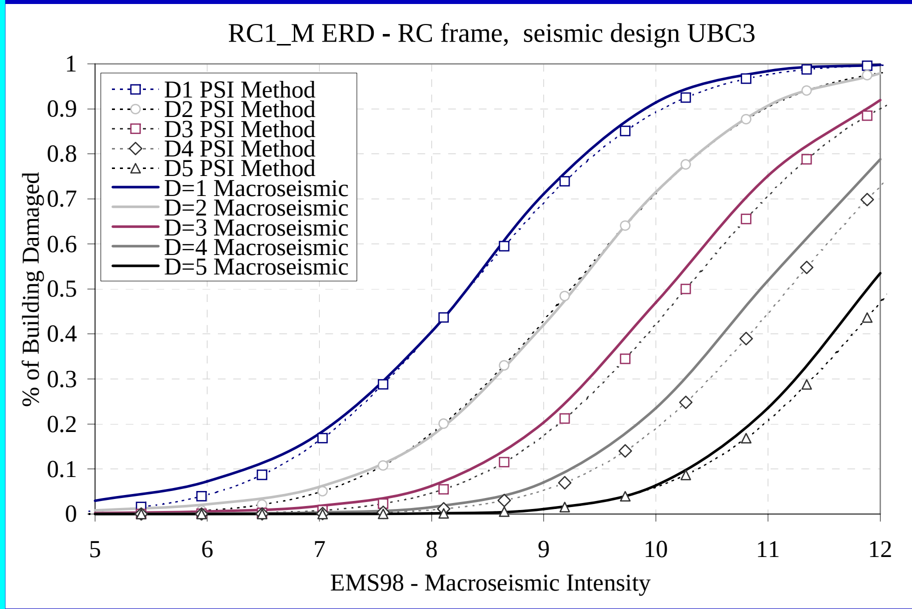


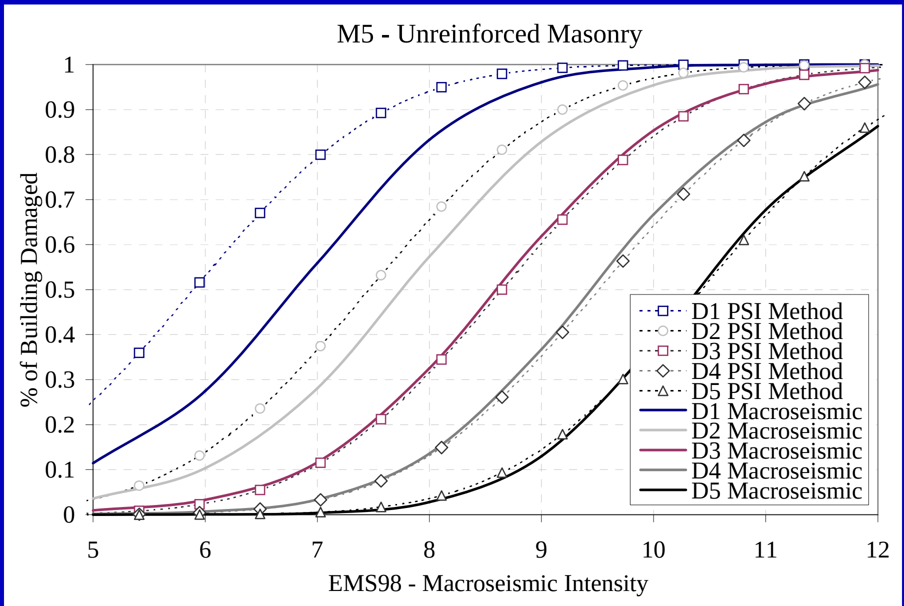


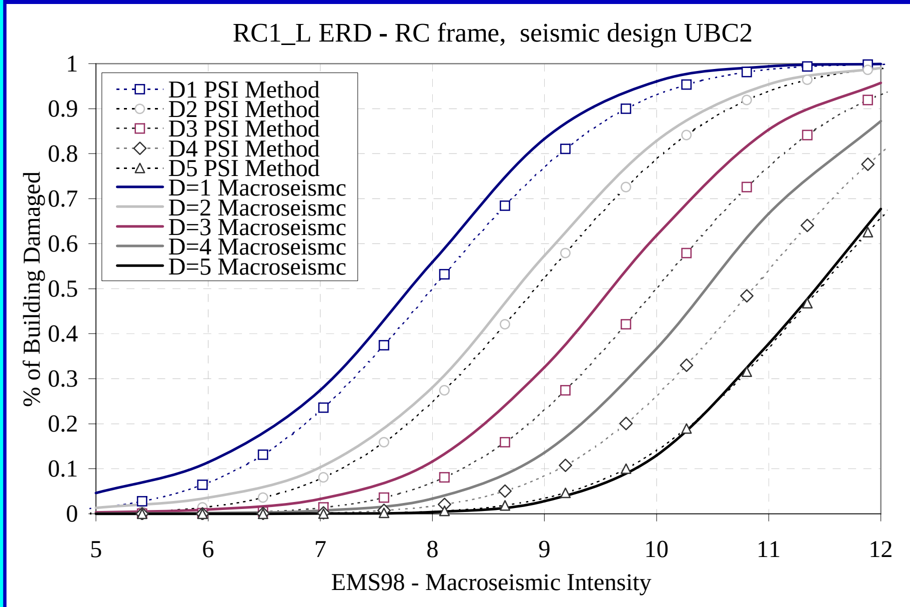
Macroseismic Method : validation

PSI Vulnerability Method (COBURN & SPENCE, 2002)





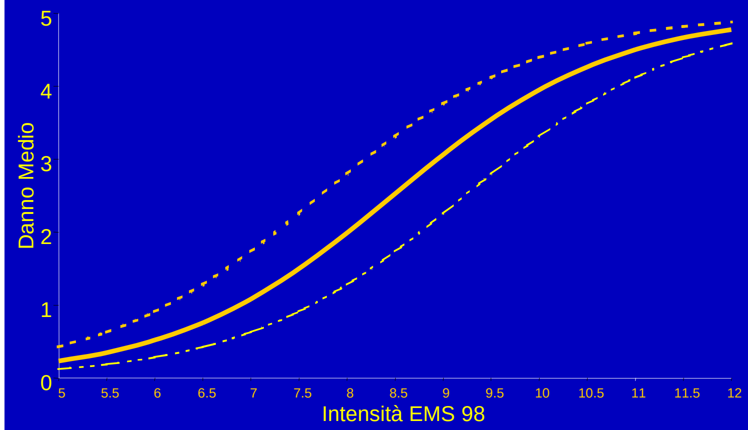




Macroseismic Mechanical Methods: equivalent approaches

Macroseismic Approach

- V Vulnerability Index
- Q Ductility Index



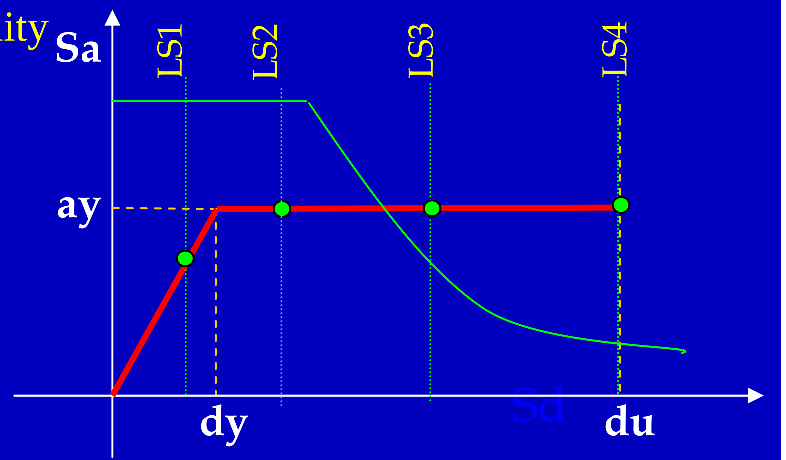
Macroseismic Intensity

I_1=f(V,Q) ----$\mu_{D,1}$ t.c. $P(D_1)=0.5$

I_4 =f(V,Q) --- $\mu_{D,4}$ t.c. $P(D_4)= 0.5$

Mechanical Approach

- T Fundamental period
- a_y Yielding strength
- μ, Ductility



Peak Ground Acceleration

$a_{g,1}$=f(s, T_c, A_y , T) -------- $S_{d*} = S_{d1}$

$a_{g,4}$=f(s, T_c, A_y , T, μ) --- $S_{d*} = S_{d4}$

$$a_g = c_1 c_2^{(I-5)}$$

$$T < T_C \quad \begin{cases} a_y = 1.43 s c_1 c_2^{(8.1-6.25V-0.95Q)} \\ \mu = 1 - \dfrac{T_C}{T} + 0.7 \dfrac{T_C}{T} c_2^{1.35Q} \end{cases}$$

$$T \geq T_C \quad \begin{cases} a_y = 1.43 s c_1 c_2^{(8.1-6.25V-0.95Q)} \dfrac{T_C}{T} \\ \mu = 0.7 c_2^{1.35Q} \end{cases}$$

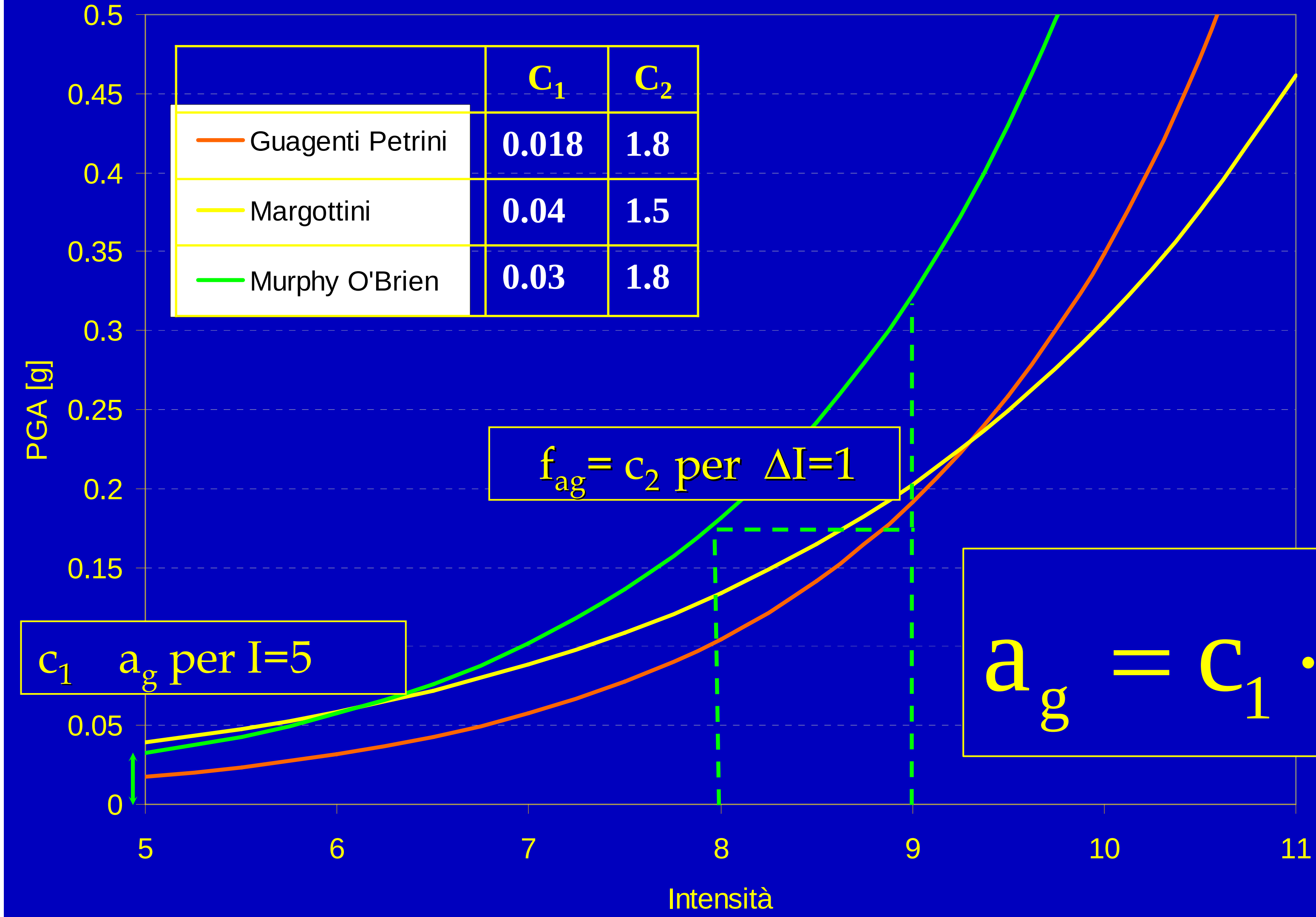
$$T < T_C = \begin{cases} V = \dfrac{1}{6.25} \cdot \left[8.1 - 0.95 \cdot Q - \ln_{c_2} \left(\dfrac{a_y}{1.43 \cdot s \cdot c_1} \right) \right] \\ Q = \dfrac{1}{1.35} \cdot \ln_{c_2} \left[\left(\mu - 1 + \dfrac{T_C}{T} \right) \cdot \dfrac{\cdot T}{0.7 \cdot T_C} \right] \end{cases}$$

$$T \geq T_C = \begin{cases} V = \dfrac{1}{6.25} \cdot \left[8.1 - 0.95 \cdot Q - \ln_{c_2} \left(\dfrac{a_y}{1.43 \cdot s \cdot c_1} \cdot \dfrac{T}{T_C} \right) \right] \\ Q = \dfrac{1}{1.35} \cdot \ln_{c_2} \left(\dfrac{\mu}{0.7} \right) \end{cases}$$

Macroseismic Mechanical Methods: equivalent approaches

For the mechanical method a predefined spectral shape related to soil conditions is assumed

Correlation between intensity I and peak ground acceleration a_g.



	C_1	C_2
Guagenti Petrini	0.018	1.8
Margottini	0.04	1.5
Murphy O'Brien	0.03	1.8

$$\Delta I = \frac{\ln f_a}{\ln c_2}$$

$$f_{a_g} = c_2^{\Delta I}$$

$$a_g = c_1 \cdot c_2^{(I-5)}$$

Macroseismic Mechanical Methods: equivalent approaches

The macroseimic and the mechanical models provide comparable results

The cross validation between the macroseimic and the mechanical-based methods allow improvements for both

THE MECHANICAL MODEL

- The reliability of assumed force-based capacity curves can be cross-validated on the basis of real observed damage data
- Possible over or under estimation of the building capacity due to element that have not been accounted for (i.e, non structural elements, further design safety coefficients) can be noticed and reduced by the comparison with the macroseismic approach

THE MACROSEISMIC MODEL

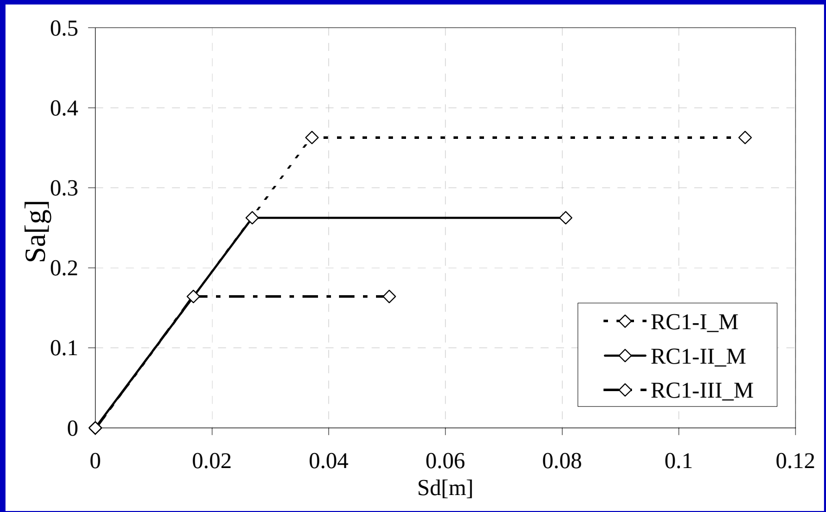
- *Behavior modifier* and values of the *ductility indexes* Q for the definition of the macroseismic method can be derived
- Refinements in the definition of the mechanical model based on numerical/experimental analysis results can be directly implemented ("translated") into the equivalent macroseismic model

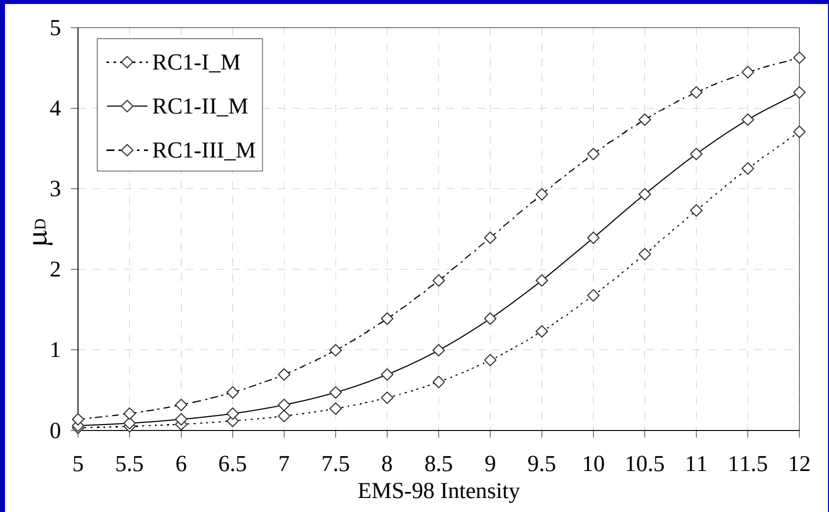
Macroseismic Mechanical Methods: equivalent approaches

RC1 – Concrete Moment Frame

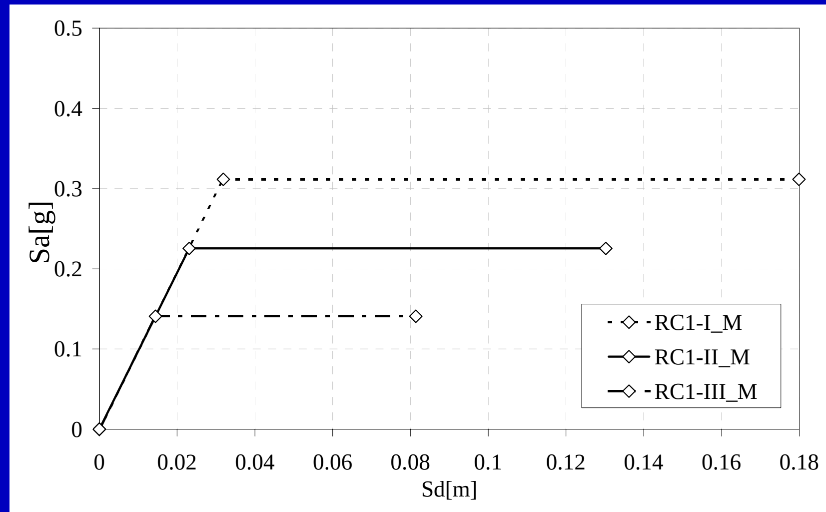
Different Levels of Earthquake Resistant Design

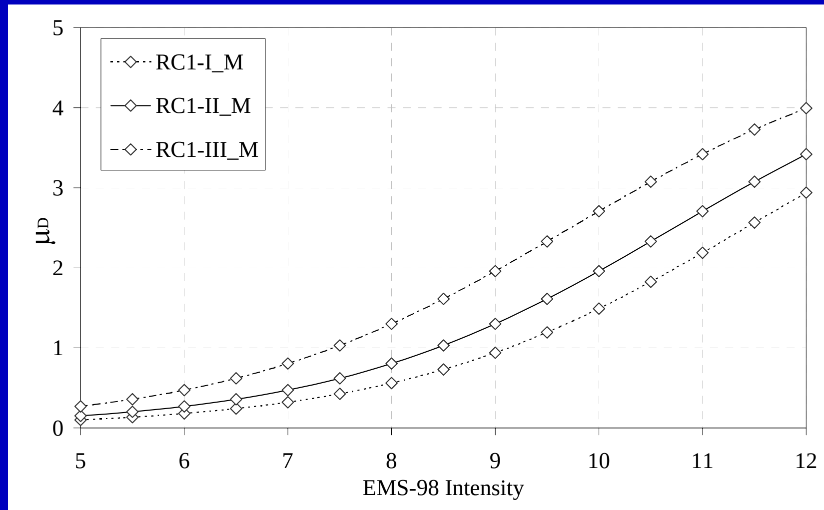
WCD without Ductility Class





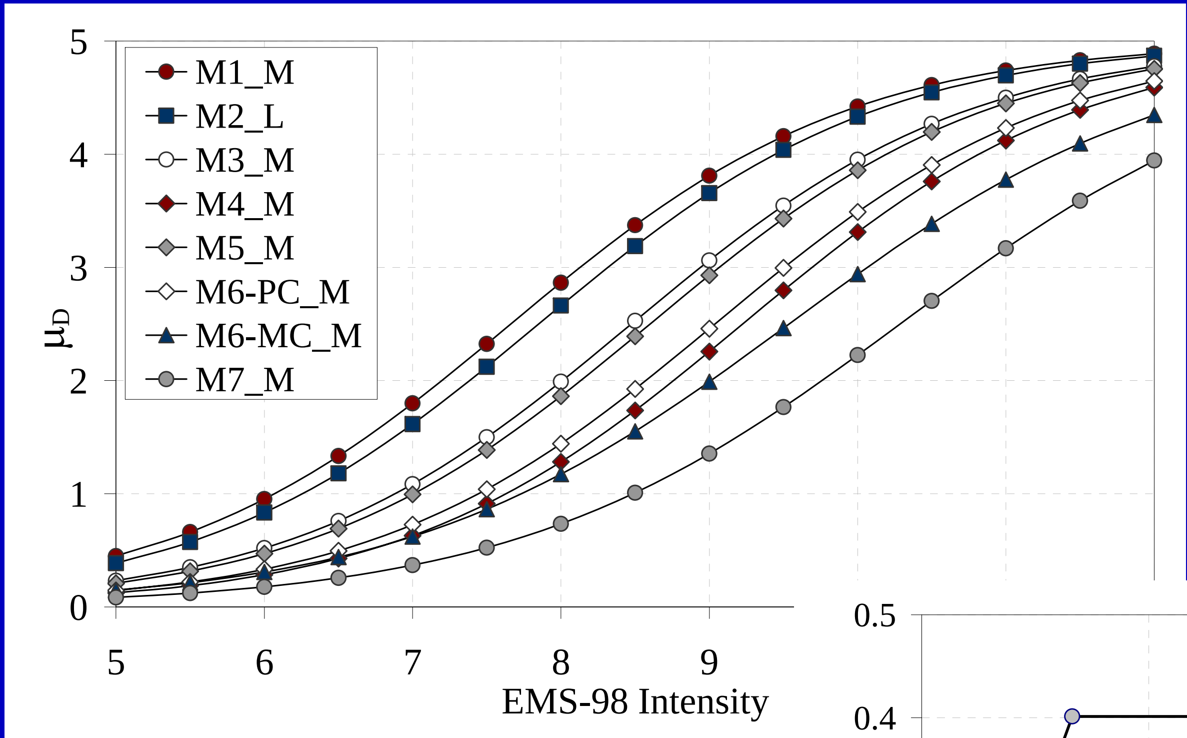
HCD high Ductility Class

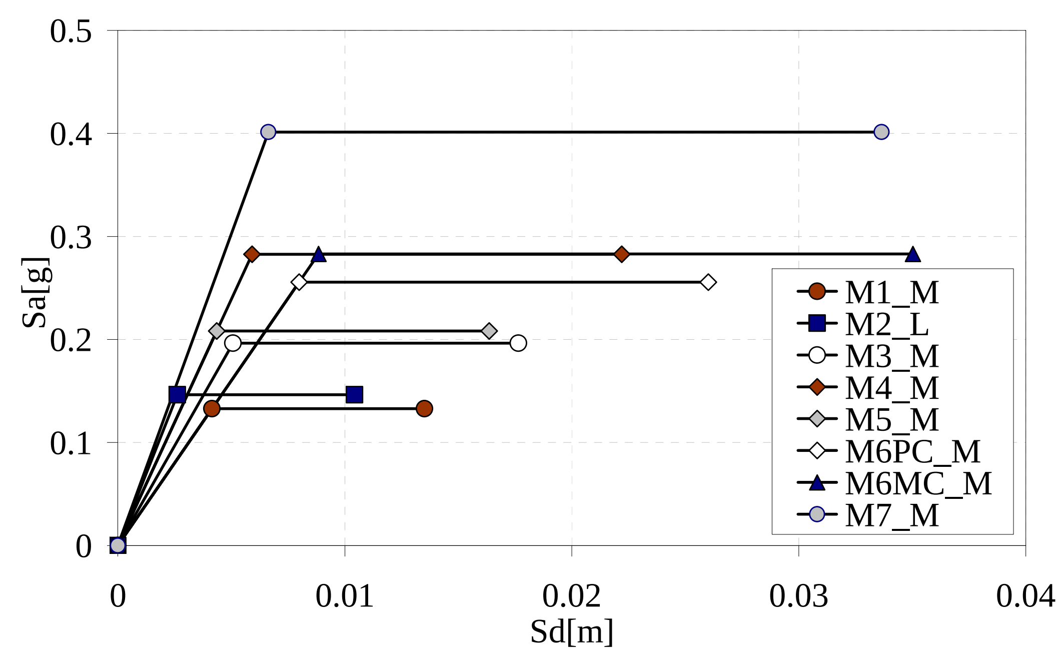




Macroseismic Mechanical Methods: equivalent approaches

MASONRY BUILDING TYPOLOGYS



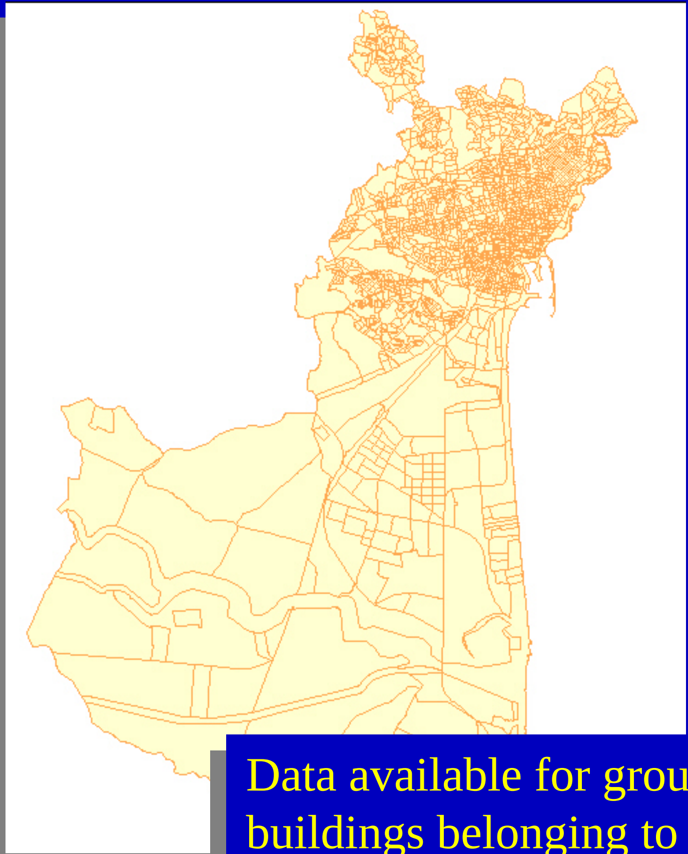


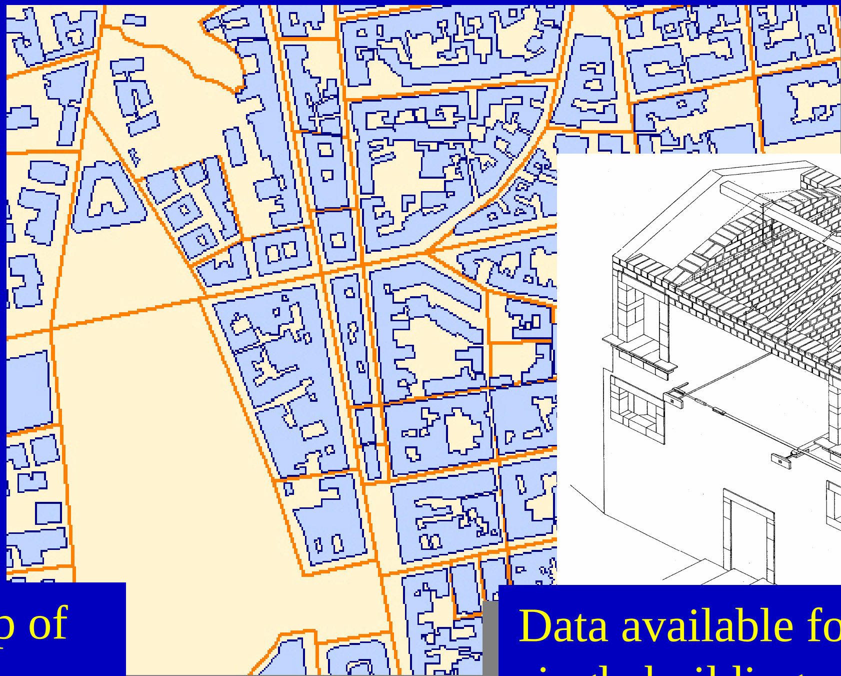
Assumed I-a_g correlation (c1=0.03, c2=1.6) in the hypothesis to refer to rock soil condition (TC=0.4 s=2.5)

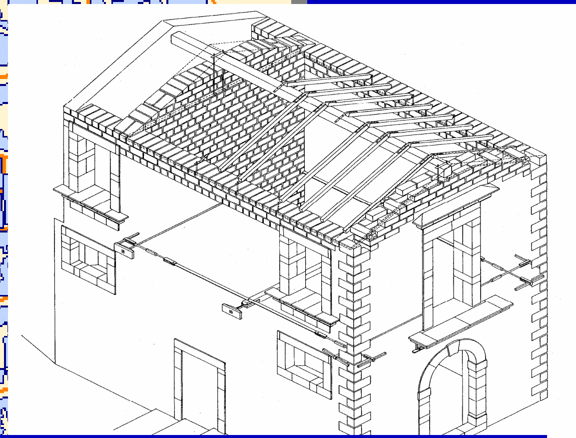
	BTM	V	Q	T	a_y	μ	d_y	d_u
M1	M1_L	0.79	2.3	0.211	0.168	4.79	0.0019	0.0089
	M1_M	0.87	2.3	0.355	0.133	3.25	0.0042	0.0135
	M1.w_L	0.77	2.3	0.211	0.178	4.79	0.0020	0.0094
	M1.w_M	0.85	2.3	0.355	0.141	3.25	0.0044	0.0143
	M1.v_L	0.87	2.3	0.211	0.132	4.79	0.0015	0.0070
	M1.v_M	0.95	2.3	0.355	0.105	3.25	0.0033	0.0107
	M2_L	0.84	2.3	0.268	0.146	3.98	0.0026	0.0104
M2	M2.w_L	0.82	2.3	0.268	0.155	3.98	0.0028	0.0111
	M2.v_L	0.92	2.3	0.268	0.116	3.98	0.0021	0.0082
M3	M3_L	0.66	2.3	0.192	0.248	5.17	0.0023	0.0117
	M3_M	0.74	2.3	0.322	0.196	3.48	0.0051	0.0176
	M3_H	0.82	2.3	0.437	0.142	3.00	0.0067	0.0202
	M3.w_L	0.64	2.3	0.192	0.263	5.17	0.0024	0.0124
	M3.w_M	0.72	2.3	0.322	0.208	3.48	0.0054	0.0187
	M3.w_H	0.80	2.3	0.437	0.151	3.00	0.0071	0.0214
	M3.v_L	0.74	2.3	0.192	0.196	5.17	0.0018	0.0093
	M3.v_M	0.82	2.3	0.322	0.155	3.48	0.0040	0.0140
	M3.v_H	0.90	2.3	0.437	0.112	3.00	0.0053	0.0160
	M3.sm_L	0.60	2.3	0.192	0.296	5.17	0.0027	0.0140
	M3.sm_M	0.68	2.3	0.322	0.234	3.48	0.0060	0.0210
	M3.sm_H	0.76	2.3	0.437	0.170	3.00	0.0080	0.0241

Vulnerability Methods Implementation for Catania Town

• DATA SPATIAL DISTRIBUTION







Data available for group of buildings belonging to census tracts

Data available for each single building

• DATA ORIGIN

Existing data base, with generic information
Data surveyed for vulnerability assessment

Macroseismic Method Implementation with statistical data available on census tracts

Structural Typology	Building Age	Floor Numbers	Structural Context	State of Maintenance
Masonry Reinforced Concrete Piloty Other Typologies	Age< 1919 1919 <= Age <= 1945 1946 <= Age <= 1960 1961 <= Age <= 1971 1972 <= Age <= 1981 Age > 1981	1 - 2 floors 3, 4 - 5 floors >6 floors	Isolated Building Aggregated Building	Good Bad

$$V_o^C = \sum_t p_t V^T{}_o \qquad \Delta V_m = \sum_k q_k \cdot V_{m,k}$$

		Masonry
Category	**Age**	V_0^c
I	<1919	**0.799**
II urban	1919-1945	**0.713**
II rural	1919-1945	**0.738**
III	1946-1971	**0.658**
IV	>1971	**0.616**

Macroseismic Method Implementation with statistical data available on census tracts

RISK-UE

Structural Typology	Building Age	Floor Numbers	Structural Context	State of Maintenance
Masonry Reinforced Concrete Piloty Other Typologies	Age< 1919 1919 <=Age<= 1945 1946 <=Age<= 1960 1961 <= Age<= 1971 1972 <= Age<=1981 Age > 1981	1 - 2 floors 3, 4 - 5 floors >6 floors	Isolated Building Aggregated Building	Good Bad

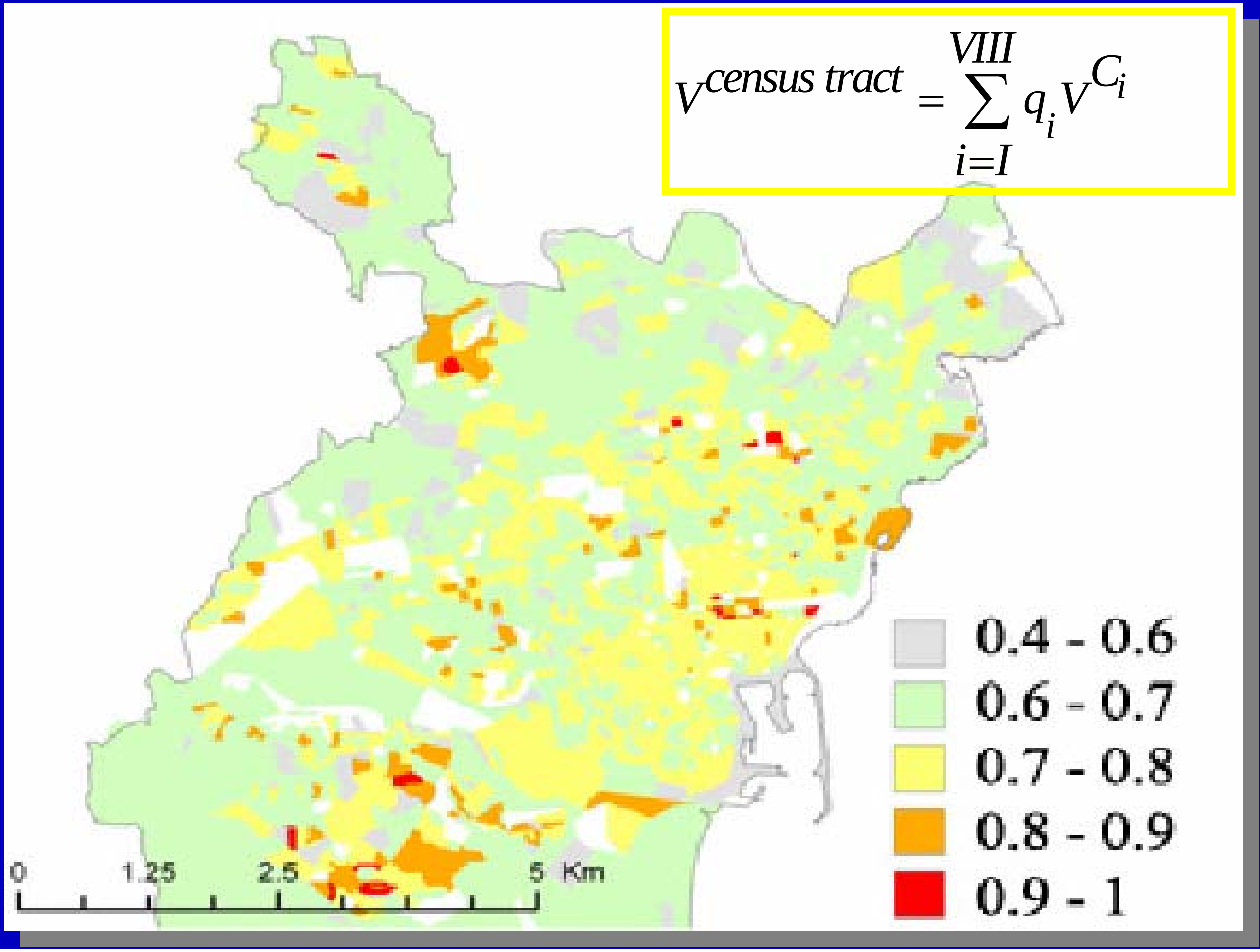
$$V_o^C = \sum_t p_t V^T_o \qquad \Delta V_m = \sum_k q_k \cdot V_{m,k}$$

Vulnerability Factors	Parameters	Masonry Categories			
		I	II	III	IV
State of Maintenance	Good	-0.04	-0.03	-0.02	-0.02
	Bad	+0.04	+0.03	+0.02	+0.02
Floor number	Low (1 - 2 floors)	-0.04	-0.04	-0.04	-0.04
	Medium (3, 4 - 5 floors)	0	0	0	0
	High (> 5 floors)	+0.04	+0.04	+0.04	+0.04
Aggregate building	Isolated building	-0.02	-0.02	-0.02	-0.02
	Aggregated building	+0.02	+0.02	+0.02	+0.02
Earthquake Resistant Design	-	0	0	0	-0.08

Macroseismic Method Implementation with statistical data available on census tracts

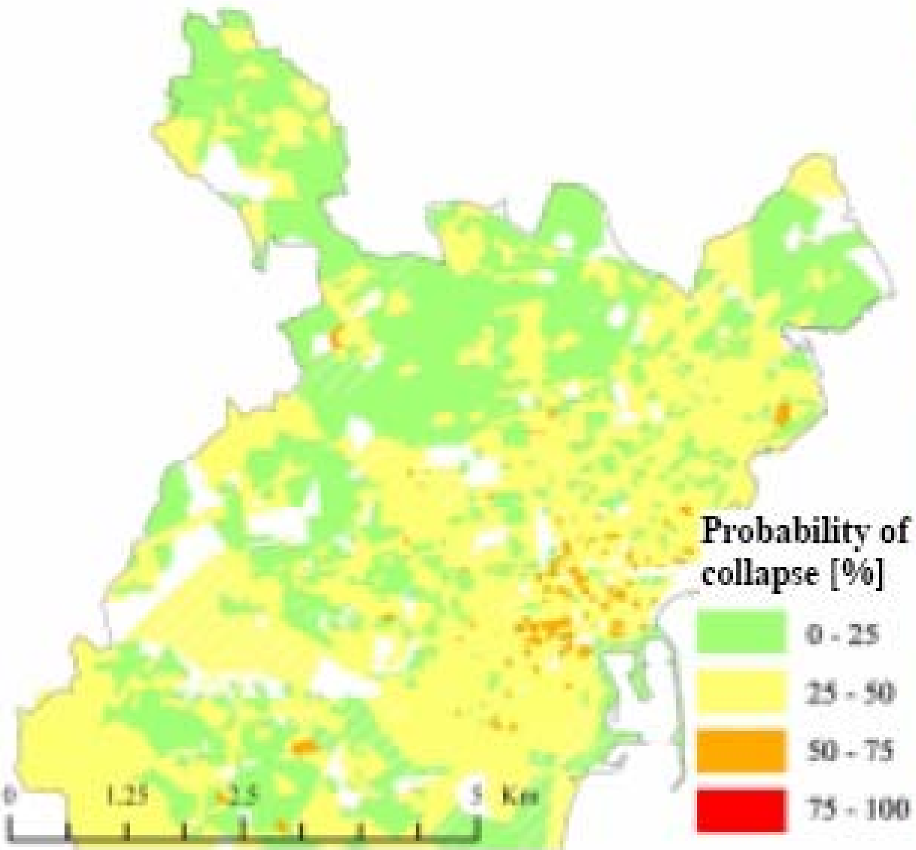
$$V = V^* + \sum_k q_k \Delta V_m + \sum_k r_k \Delta V_r + \sum_{j=1}^{3} \sum_{S=B}^{E} m_j \Delta V_{s_{M,j}} + \sum_{j=1}^{3} \sum_{S=B}^{E} rc_j \Delta V_{s_{RC,j}}$$

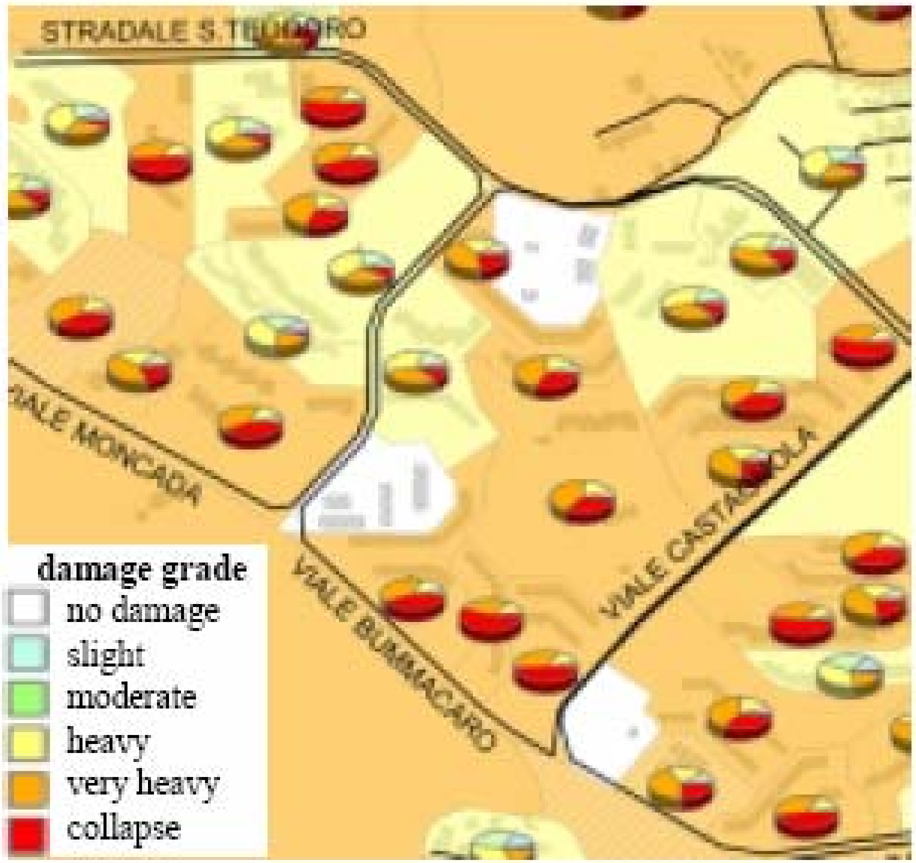
$$V^{census\ tract} = \sum_{i=I}^{VIII} q_i V^{C_i}$$



Macroseismic Method Implementation with statistical data available on census tracts

$$V = V^{*} + \sum_{k} q_k \Delta V_m + \sum_{k} r_k \Delta V_r + \sum_{j=1}^{3} \sum_{S=B}^{E} m_j \Delta V_{s_{M,j}} + \sum_{j=1}^{3} \sum_{S=B}^{E} rc_j \Delta V_{s_{RC,j}}$$





Macroseismic and mechanical methods implementation with specific surveyed data available for each single building

V_0 Typological Vulnerability Index

ΔV_m Behaviour Modifier Factor

	Vertical Structures	*Horizontal Structures*	*Age*	*Subsequent Intervention*
M1	A-E-T			
M2	B-C-F			
			<1945	
M3	D-G			
M4	L-M- H- I	A-B		
	L-M- H- I		<1919	
M5	L-M	F-G		
M6	L-M- H- I	C-D		
	L-M		<1945	
M7	L-M- H- I			
	H- I			
	L-M		>1946	
			>1946	

Example of quick survey form
Aggregate code
Building code
House number
Number of floors
H_{MAX}
H_{MIN}
Use (residential, production..)
Age
Subsequent intervention
Vertical structure type
Horizontal structure type
Roof structure type
Connection between structural elements
Non structural elements
Building condition

Macroseismic and mechanical methods implementation with specific surveyed data available for each single building

V_0 Typological Vulnerability Index

ΔV_m Behaviour Modifier Factor

Vulnerability Factors	Parameters	
State of preservation	Good maintenance Bad maintenance	-0,04 +0.04
Number of floors	Low (1 or 2) Medium (3, 4 or 5) High (6 or more)	-0.02 +0.02 +0.06
Structural system	Wall thickness Distance between walls Connection between walls (tie-rods, angle bracket) Connection horizontal structures-walls	-0,04 ÷ +0,04
Soft-story	Demolition/ Transparency	+0.04
Plan Irregularity	…	+0.04
Vertical Irregularity	…	+0.02
Superimposed floors		+0.04
Roof	Roof weight + Roof Thrust Roof Connections	+0.04
Retrofitting interventions		-0,08 ÷ +0,08
Aseismic Devices	Barbican, Foil arches, Buttresses	
Aggregate building: position	Middle Corner Header	-0.04 +0.04 +0.06
Aggregate building: elevation	Staggered floors Buildings of different height	+0.02 -0,04 ÷ +0,04
Foundation	Different level foundation	+0.04

Example of quick survey form
Aggregate code
Building code
House number
Number of floors
H_{MAX}
H_{MIN}
Use (residential, production..)
Age
Subsequent intervention
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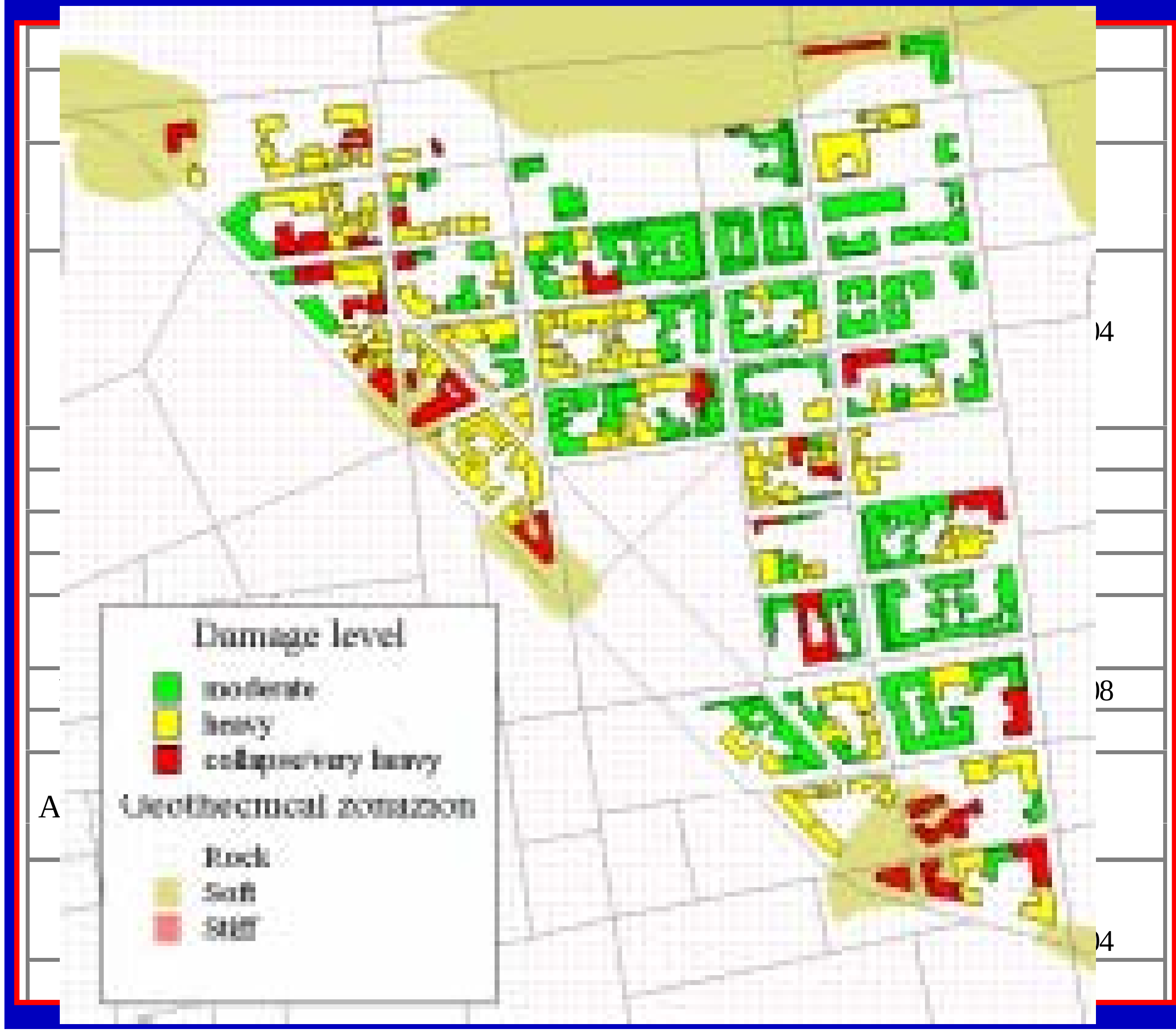
Macroseismic and mechanical methods implementation with specific surveyed data available for each single building

V_0 Typological Vulnerability Index

ΔV_m Behaviour Modifier Factor



Example of quick survey form
Aggregate code
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H_{MIN}
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Vertical structure type
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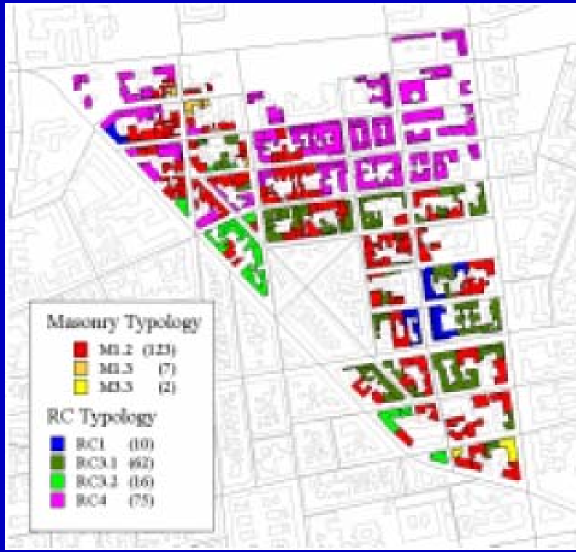
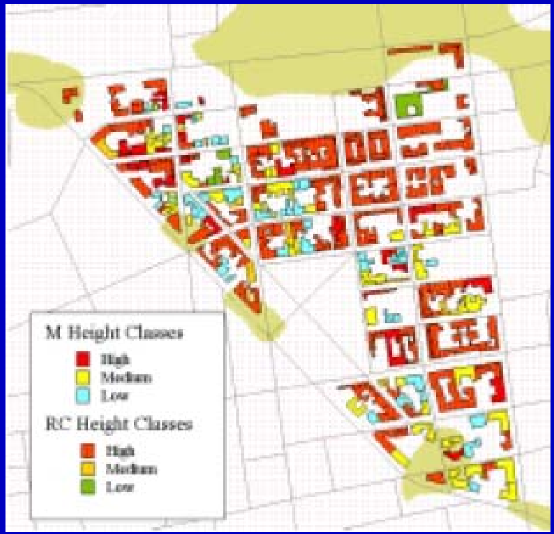
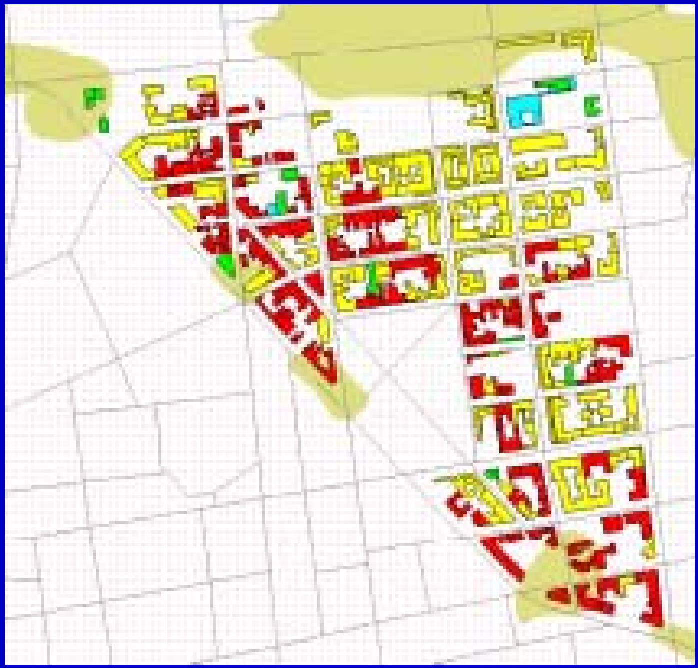
Mechanical methods implementation with specific surveyed data available for each single building





Identification of building type and height for the Catania test zone



Distribution of average damage level

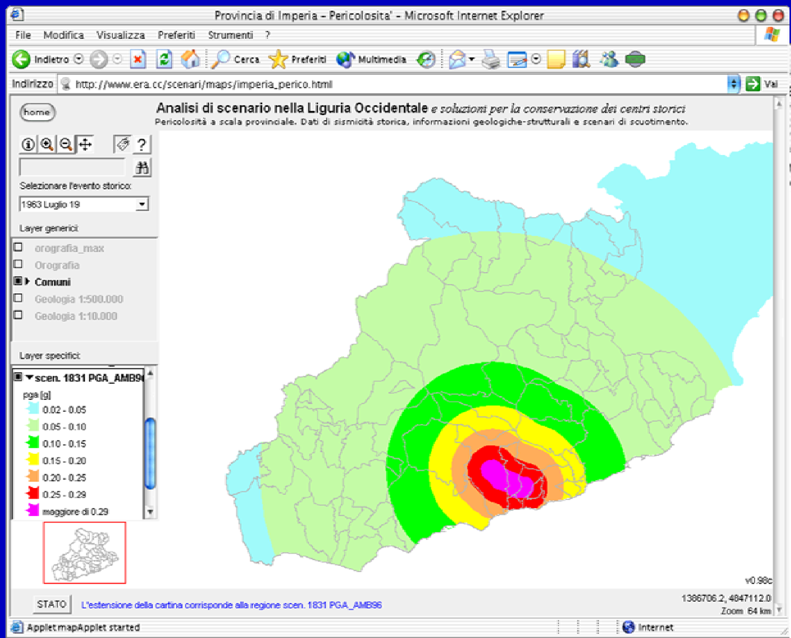
Italian National research project "Earthquake scenario in Western Liguria, Italy, and strategies for the preservation of historic centres"

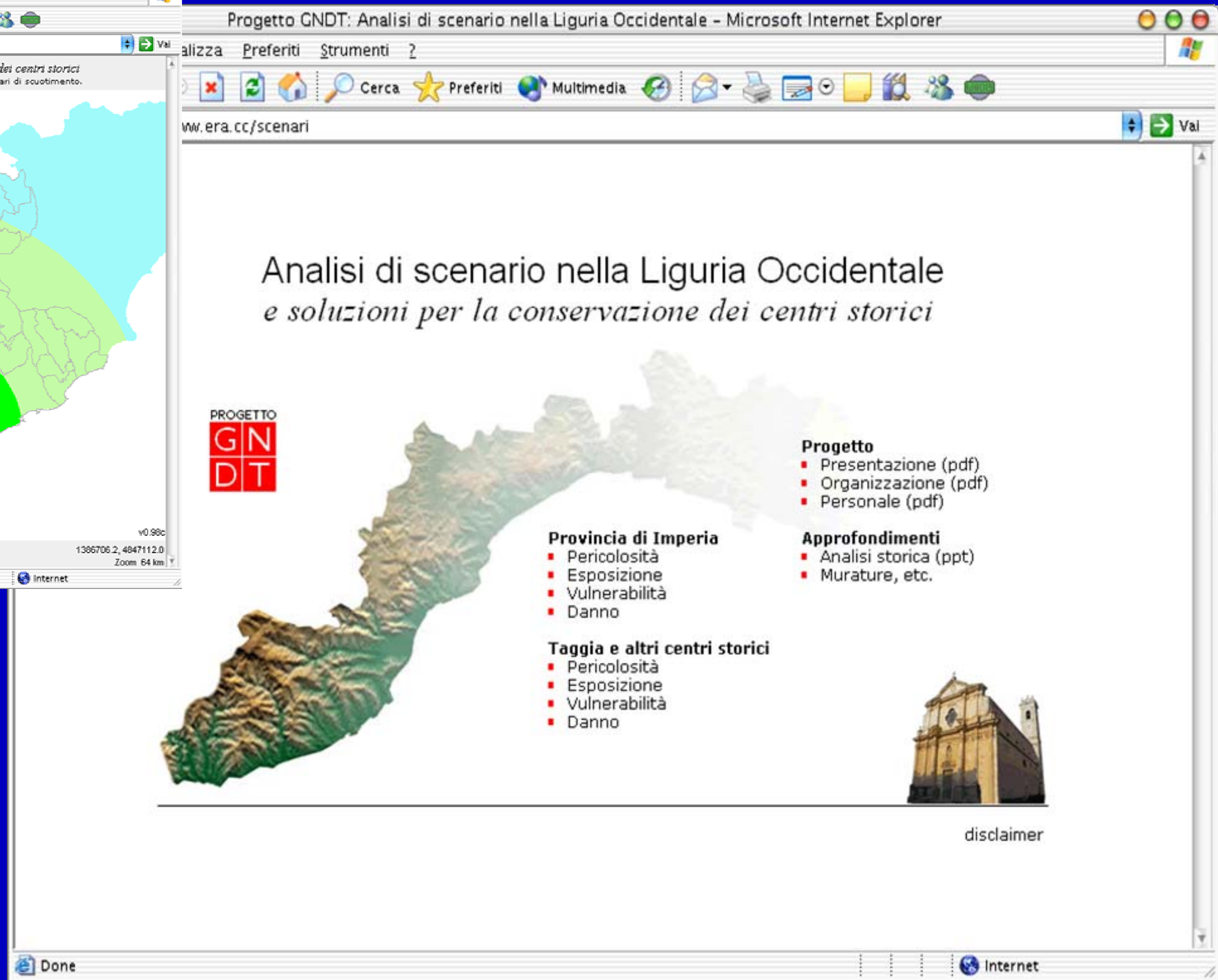
Civil Protection Department

National Institute for Geophysics and Vulcanology

National Group for the Defense from Earthquakes

http://adic.diseg.unige.it/gndt-liguria





Data and results of each steps have are available on the WEB

Simulation of Western Liguria - 23 February 1887 earthquake

Macroseismic Scenario

	1887 - Macroseimic			
CONSEQUENCES ON BUILDINGS	*Masonry*	*R.c.*	*All*	*%*
Unfit for use building	3775	563	4337	**8.8**
Collapsed Building	208	15	223	**0.5**
CONSEQUENCES ON PEOPLE	*Mason*		*All*	*%*
People requiring short term shelter	10317		17017	**8.1**
Dead and severely injured people	182	71	253	**0.1**

0.2%

Mechanical Scenario

	1887 - Mechanical			
CONSEQUENCES ON BUILDINGS	*Masonry*	*R.c.*	*All*	*%*
Unfit for use building	4706	1102	5808	**11.8**
Collapsed Building	530	69	599	**1.2**
CONSEQUENCES ON PEOPLE	Masonry	R.c.	All	%
People requiring short term shelter	14150		25477	**12.1**
Dead and severely injured people	552		801	**0.4**

0.6%

	Number				Percentage	
	All	R.c.	Masonry		Rc	M
Number of Buildings	49372	17733	31639		36%	64%
Number of Hinabitants	211349	126616	84733		60%	40%

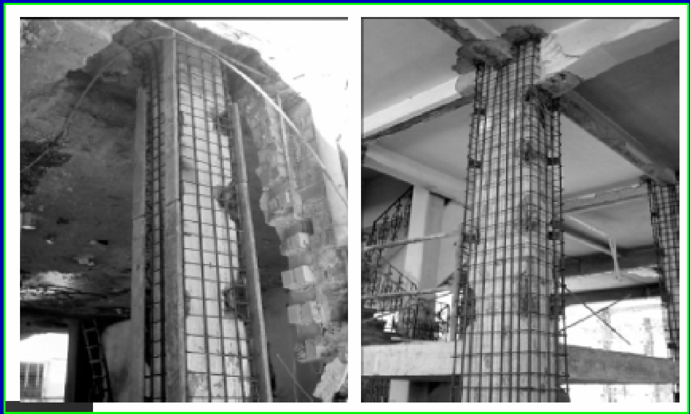
- 509 dead over a population of 49.000 people (thus 1% of the whole population)
- 212 people dead because of the roof collapse of the church in Baiardo
- **0.6% of the population inside ordinary buildings**

Alternative retrofit solutions and strategies for pre'70 R.C. buildings

Retrofit Solutions:

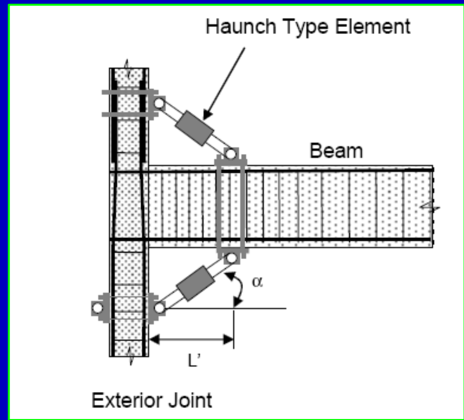
- **<u>Conventional Techniques</u>**

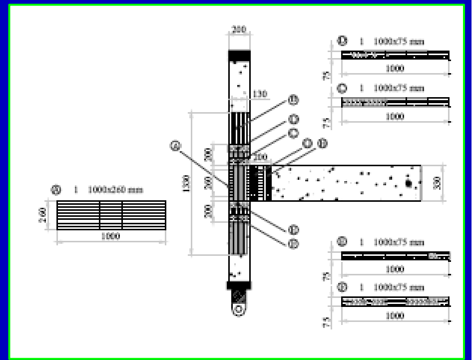
- braces
- jacketing or infills



- **<u>More recent approaches</u>**

- supplemental damping devices
- advanced materials (FRP, SMA)
- diagonal metallic haunches





TARGETED OBJECTIVES

- ***<u>MULTI – LEVEL RETROFIT</u>***

alternative objectives targeted in terms of hierarchy of strength within the beam-column-joint

<u>Total Retrofit</u> i.e. full upgrade by protecting all joint panel zones

<u>Partial Retrofit</u> i.e. partial upgrade by protecting exterior joints

- ***<u>SELECTIVE UPGRADING</u>***

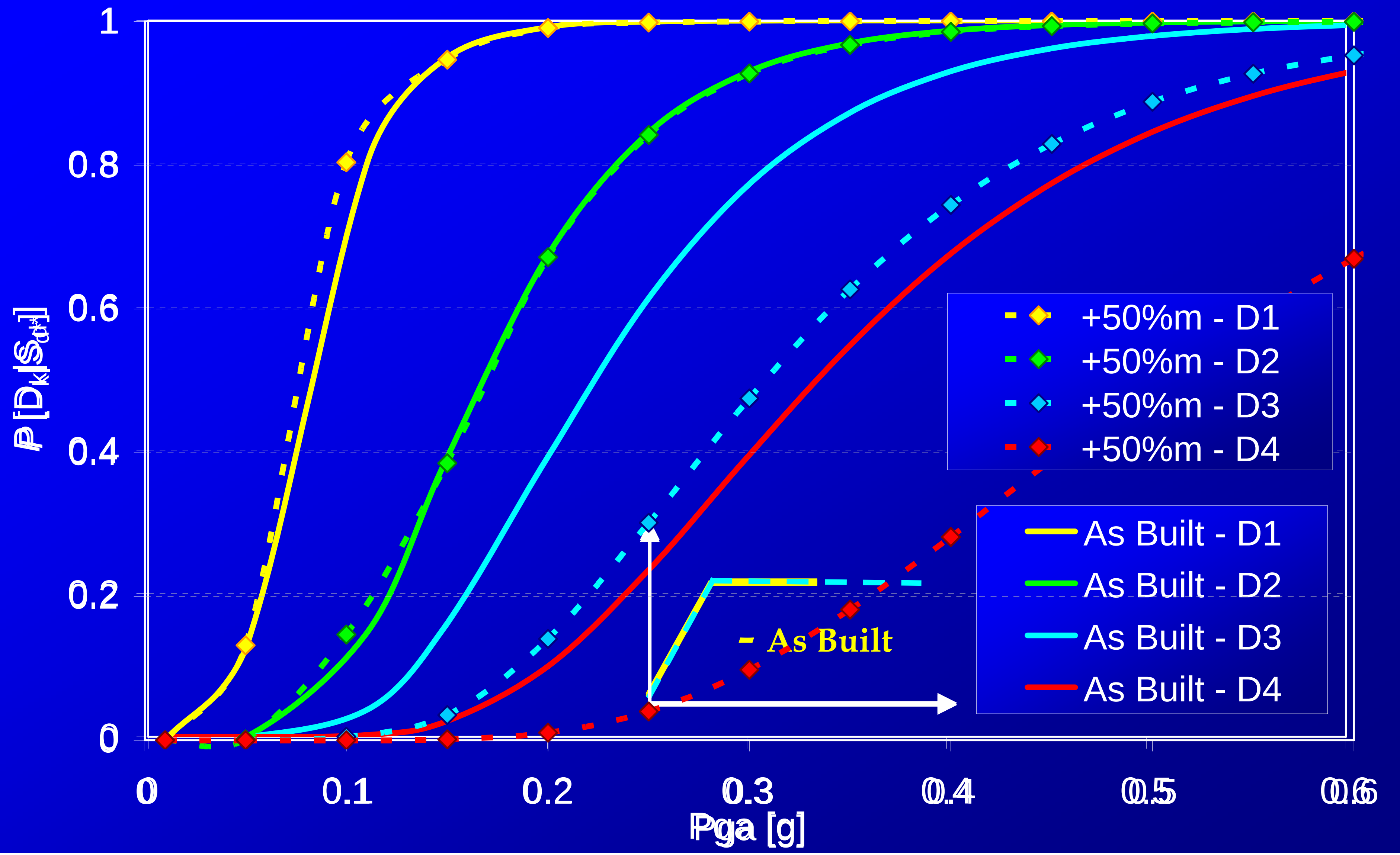
Independently upgrades stiffness, strength or ductility-only of a single member

- ***<u>SELECTIVE WEAKENING</u>***

Re-enhancing strength and dissipation capacity

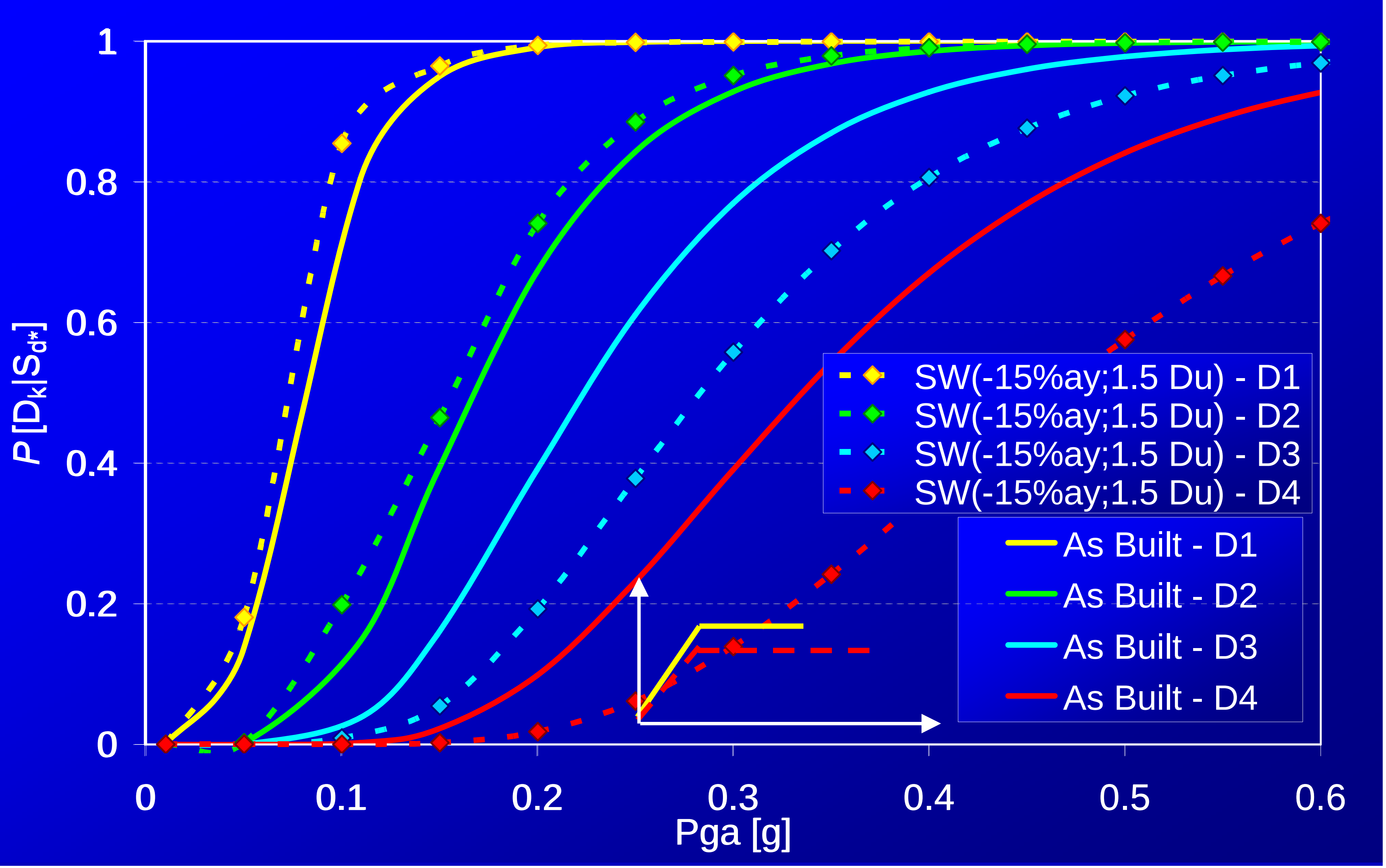
Representation of alternative retrofitting strategies within the proposed vulnerability methods

SELECTIVE UPGRADE ***Ductility Only***

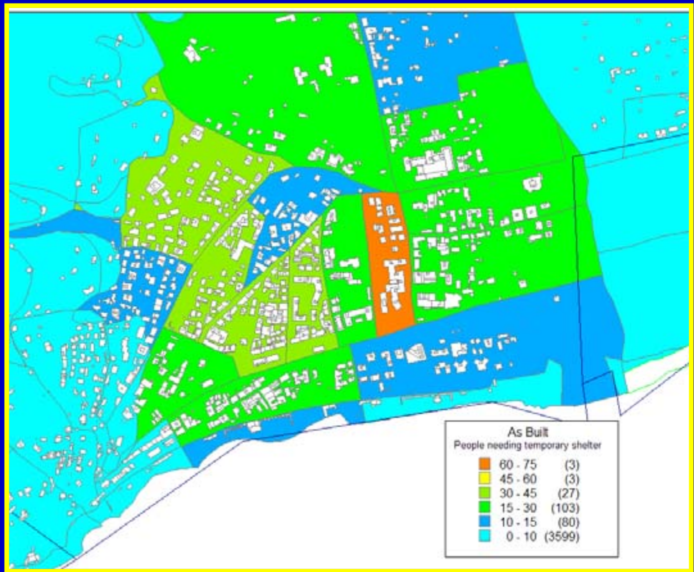


Representation of alternative retrofitting strategies within the proposed vulnerability methods

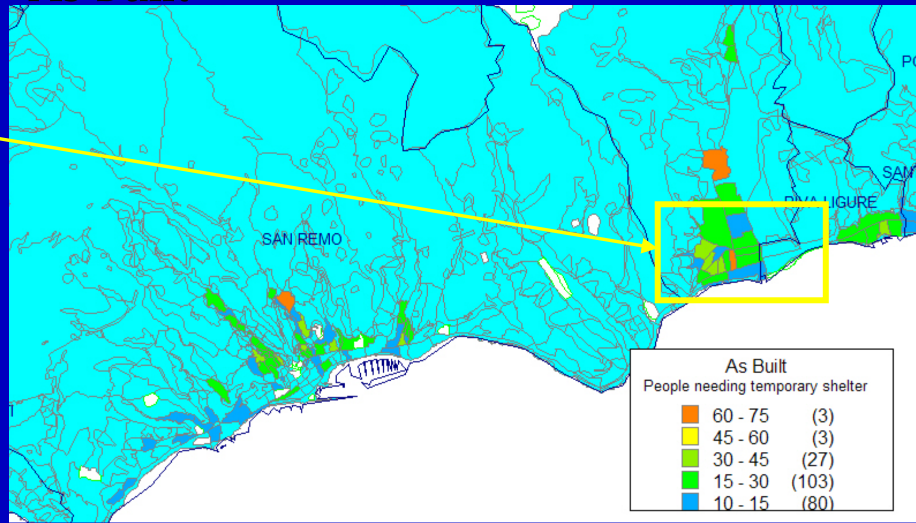
SELECTIVE WEAKENING



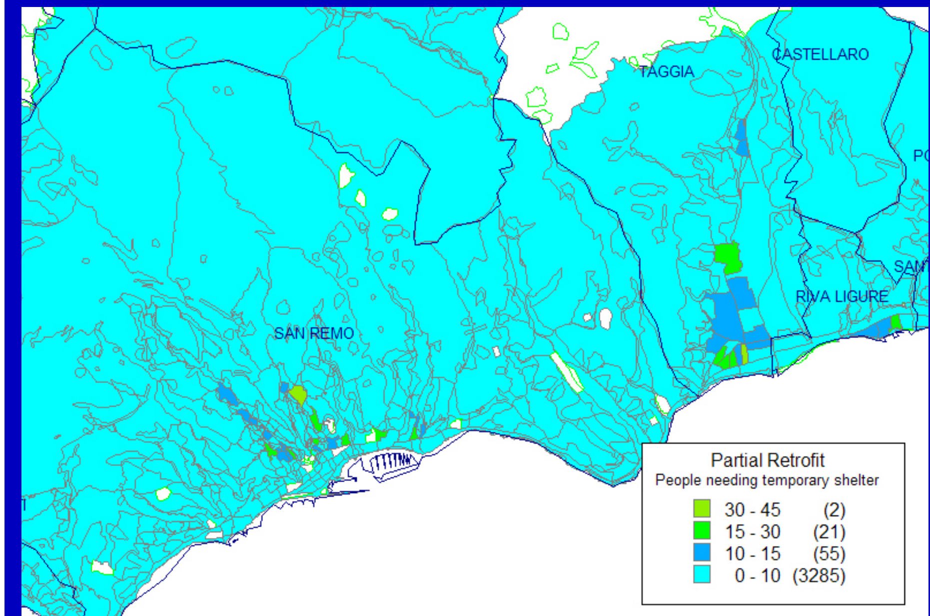
Damage SCENARIO: people needing temporary shelter



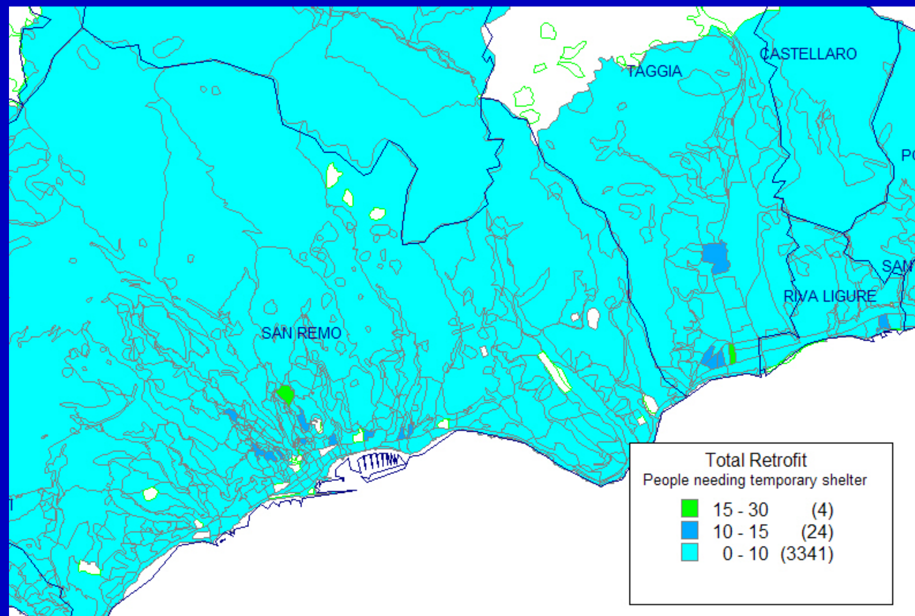
As Built



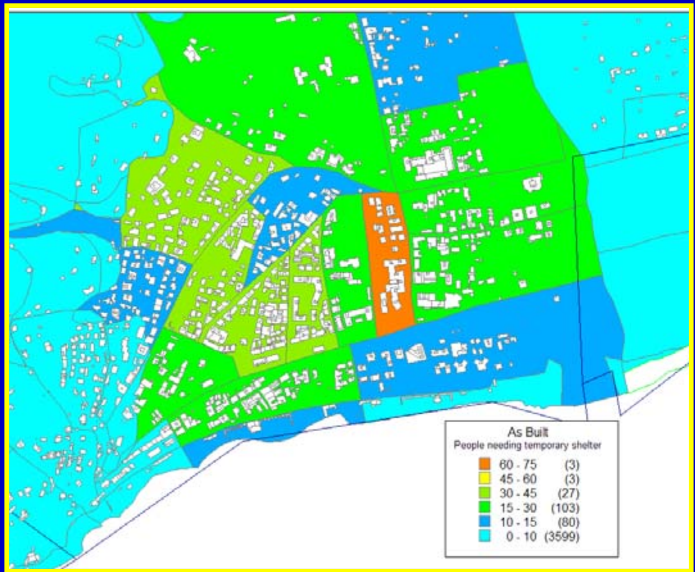
Partial Retrofit



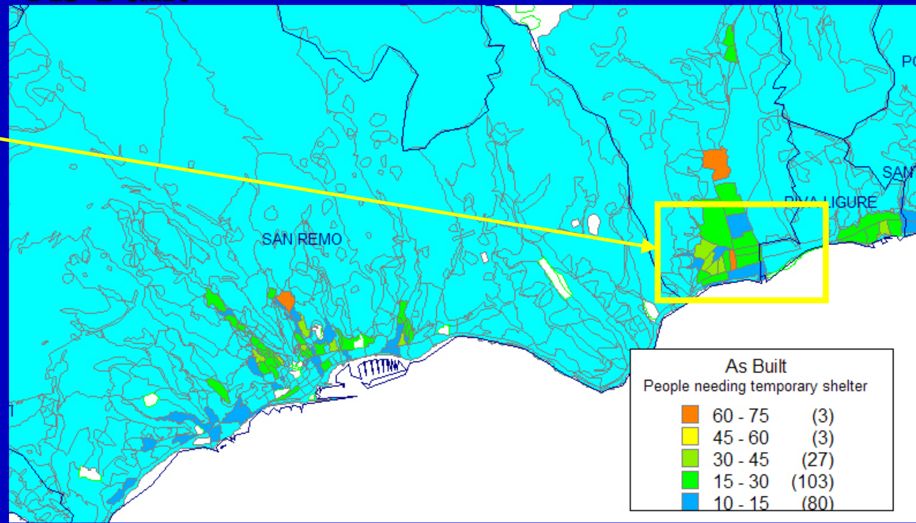
Total Retrofit



Damage SCENARIO: people needing temporary shelter



As Built



Partial Retrofit

Total Retrofit

Damage scenario for the 1887 event		**As Built**				**Partial Retrofit**	**Total Retrofit**
	Building Typology	*URM*		*R.C.*		*R.C.*	*R.C.*
	Class of Age	*All*	*<'71*	*'71-'81*	*<'71*	*<'71*	*<'71*
BUILDINGS	Unfit for use	3775	480	135	6	242	183
	Collapsed	208	15	3	0	4	2
PEOPLE	Requiring short term shelter	10317	6129	1118	89	2999	2182
	Casualties and severely injured	182	79	9	0	20	10

CONCLUSIONS

VULNERABILITY MODELS:

- Macroseismic Method derived from EMS-98 macroseismic scale
- Mechanical Method for non-designed masonry building typologies
  for designed reinforced concrete buildings
- Equivalent Macroseimic-Mechanical Approaches in order to reciprocally calibrate, to tune and to verify that reliable and comparable results are obtained with the two

DAMAGE SCENARIO:

- The methods can be employed either with properly surveyed data or with statistical existent data of different origin and quality
- A different uncertainty is associated with the vulnerability assessment and the consequent damage evaluation depending on the reliability of data available for the analysis
- Easy implementation in a GIS environment

RISK MITIGATION AND RISK ANALYSIS APPLICATIONS:

The use of these methods for risk mitigation purposes has become an effective tool

GNDT Project Earthquake Risk scenarios in Western Liguria and strategies for the preservation of historic centres

Risk-UE Project An advanced approach to earthquake risk scenarios with application to European towns

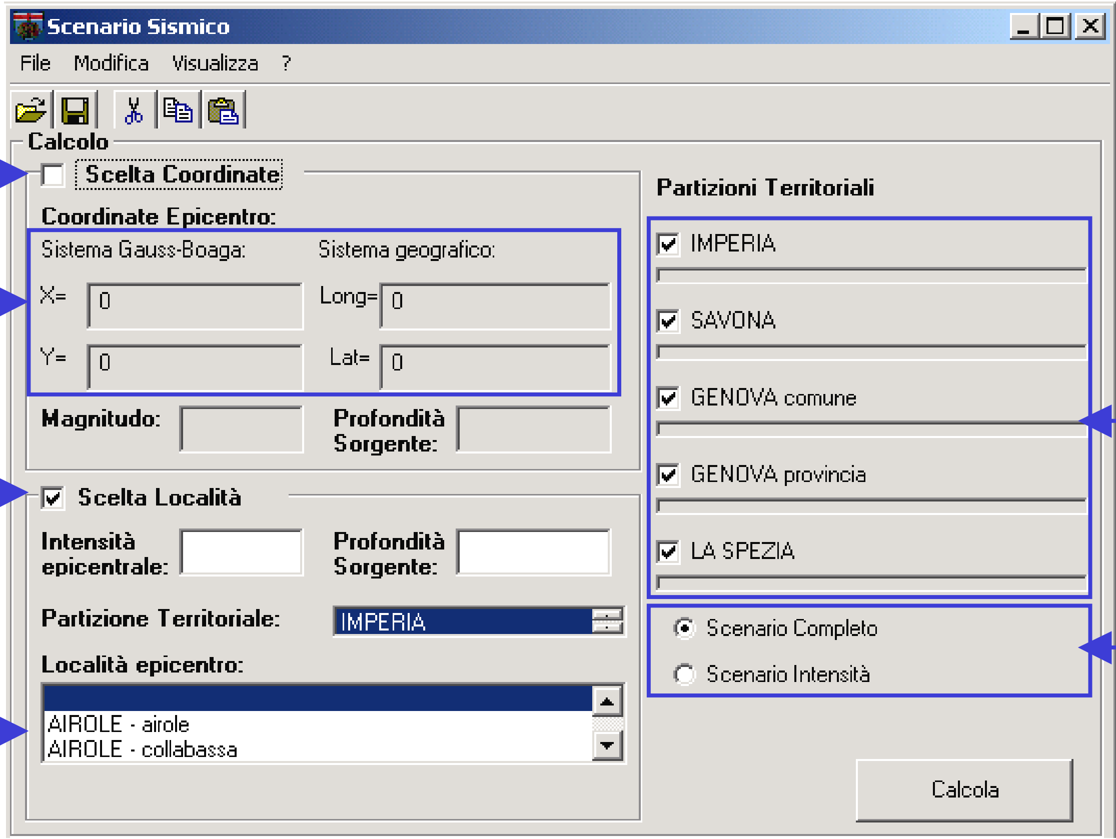
Munich-RE Reinsurance Company applications of the proposed methods for insurance and reinsurance industry

Real–time damage scenarios tool for Liguria Region Civil Protection Department

“Scenario Sismico”: a tool for real time damage scenarios

Scenario Sismico - Elaboration

Scenario Sismico - Visualisation



A) Epicentre coordinates:
- Gauss-Boaga
- Geographic reference

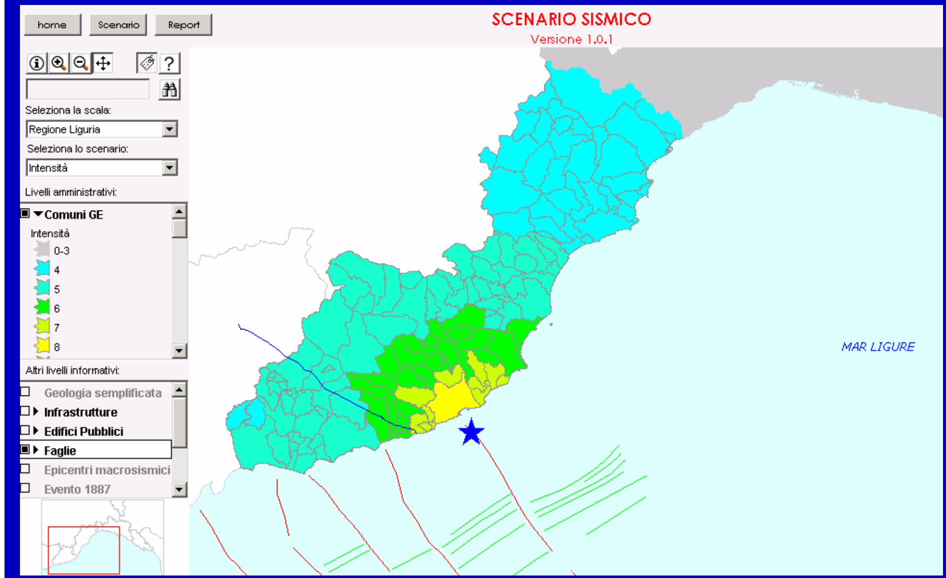
Options for the earthquake definition:
A) Epicentre coordinates
B) Epicentre located at urban level

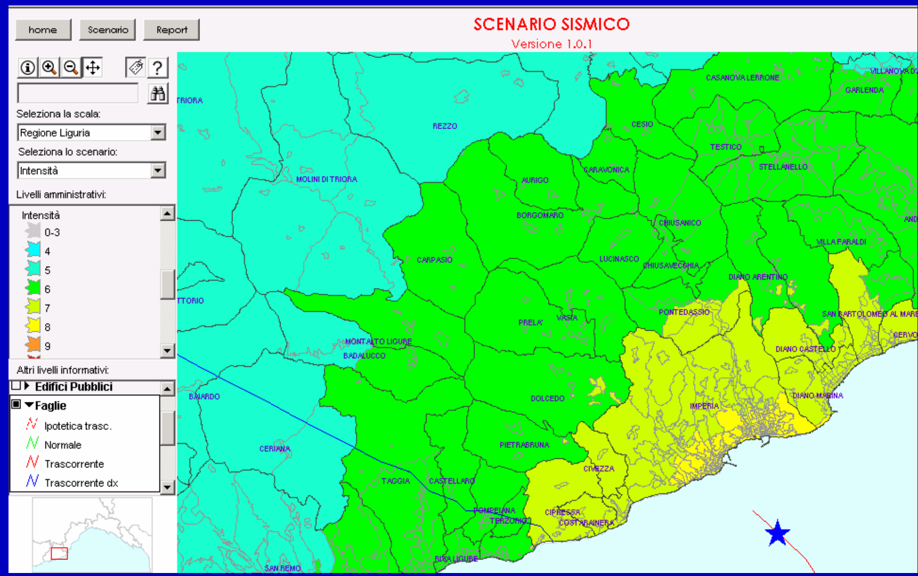
B) Urban epicentre

Selection of the administrative unit where the scenario is simulated

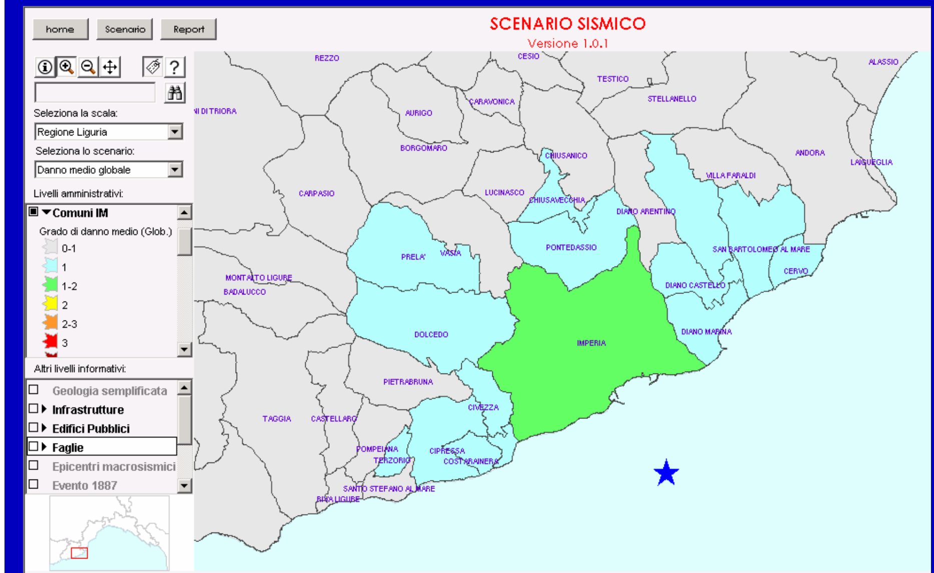
Options for the scenario:
- complete
- hazard

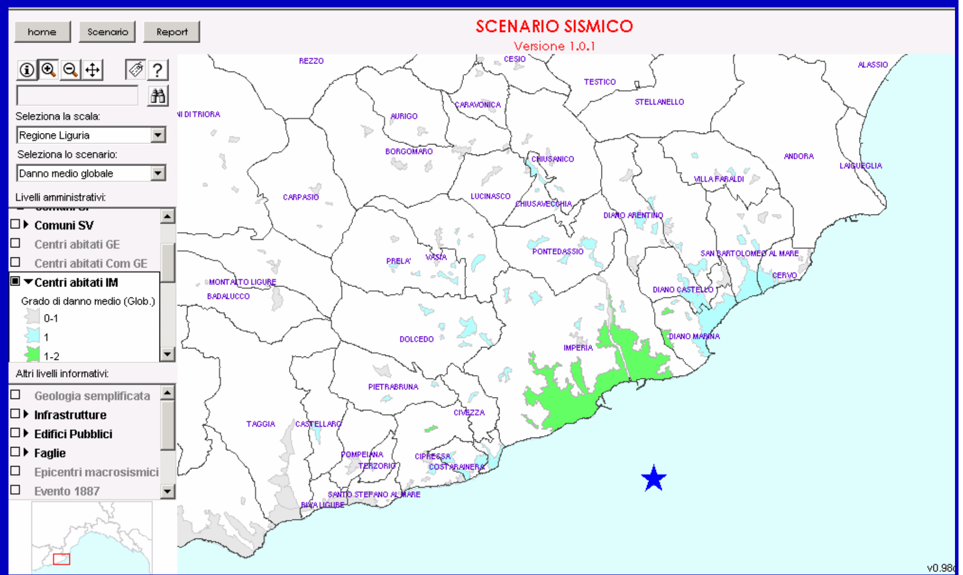
Macroseimic intensity hazard scenario



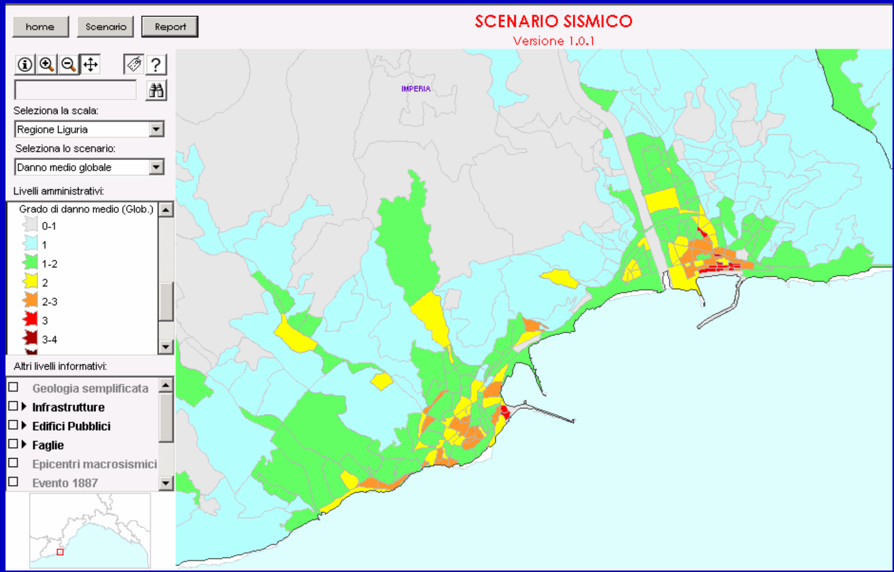


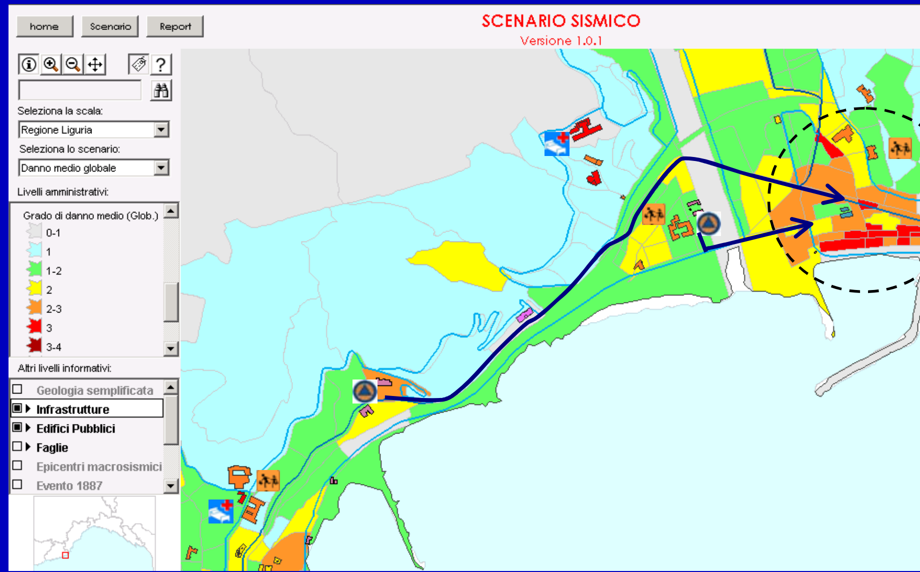
Damage scenario in terms of mean damage grade





Damage scenario and identification of routes suitable for reaching high affected areas





Consequence scenario at census tract level: a) homeless people and buildings suitable for providing a temporary shelter, b) casualties and health facilities