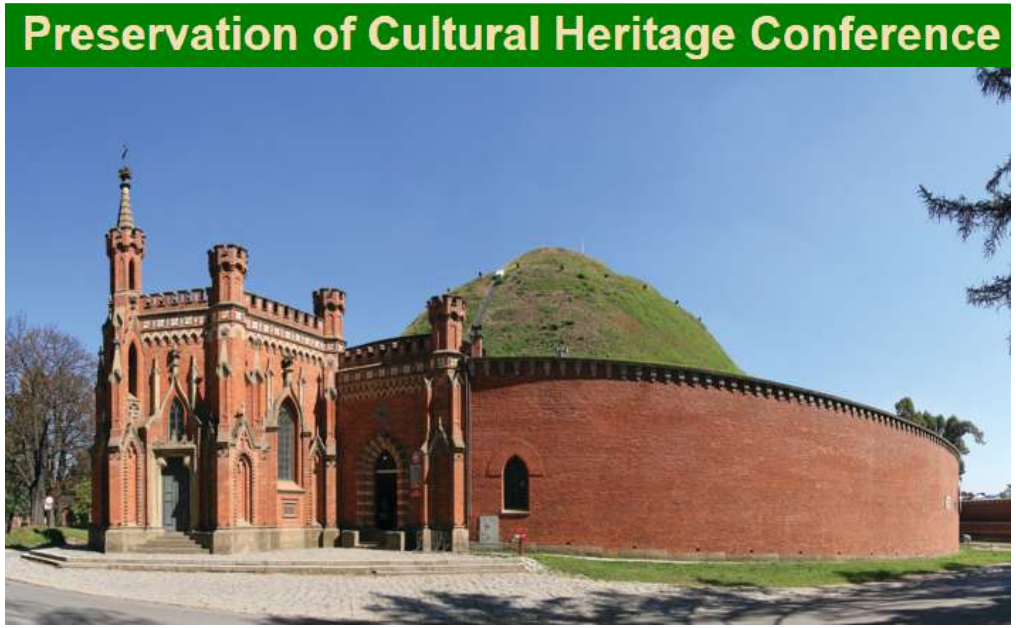


International Scientific Conference Preservation of Cultural Heritage
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REDUCING SEISMIC RISKS TO URBAN CULTURAL HERITAGE: IMPACT AND MITIGATION PLAN

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OBJECTIVE

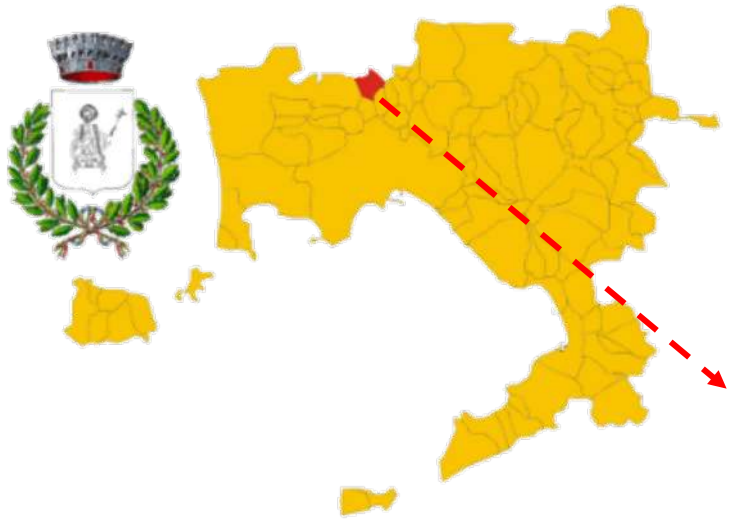
The proposed study aims to analyse a sub-urban sector of the historic centre of Sant'Antimo, located in the province of Naples, in order to assess the seismic vulnerability of the masonry building compounds and the expected damage scenarios

OUTLINE

1. **Structural and typological characterization**
2. **Seismic vulnerability assessment**
3. **Parametric damage scenarios and loss estimation**
4. **Conclusion**

1. Structural and typological characterization

Sant'Antimo is an Italian town with 33.905 inhabitants. It is sited 16 km far from the historical city of Naples.



- **The first urban nucleus of Sant'Antimo dates back since IV – III centuries BC.**
- **The built-up area of Sant'Antimo appears rather compact and expands radially.**



- **The municipality is mainlycharacterized by the presence of aggregated masonry buildings that reflect the constructive characteristics of the site.**





1. Structural and typological characterization

The sub-sector under study is composed of 42 buildings erected in aggregate. According to the *Building Typology Matrix (BTM)*, they are classified as follows:

- Class M3.3: masonry structures with composite steel and hollow tile floors (in 36% of the cases);
- Class M3.4 masonry structures with reinforced concrete floors and roofs (in 64% of the cases).

Investigated urban area



Main construction details

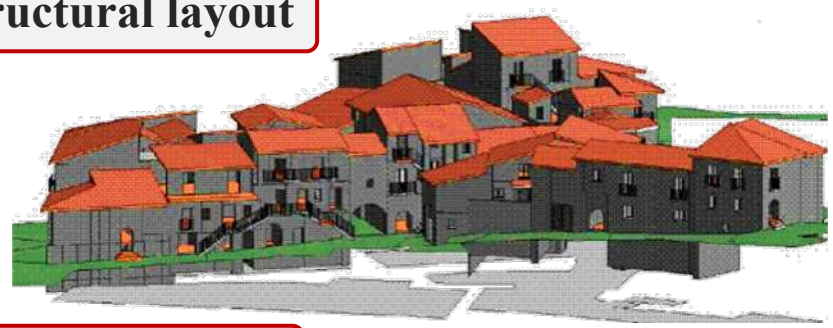
- Floors: deformable with no ring beams or tie-rods;
- Roof : r.c without tie-rods;
- Masonry: tuff stones with t=65 cm;
- Number of floors: 3 with interstory height of 3,50 m;
- Physical state: medium quality.

1. Structural and typological characterization

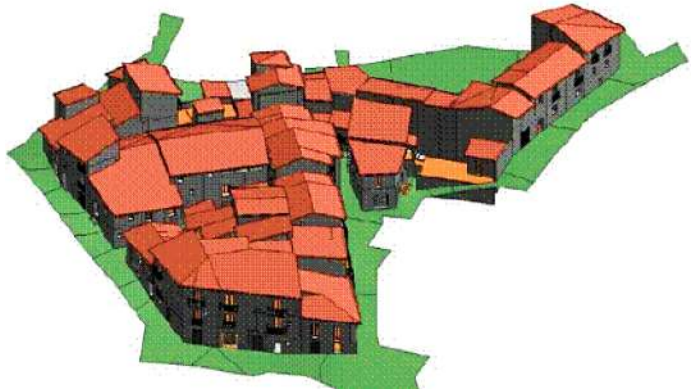
The masonry buildings sample, generally leading towards aggregates in the historical centres, is very often characterised by a static inadequacy mainly due to an obsolete construction technique that does not guarantee appropriate safety standards.

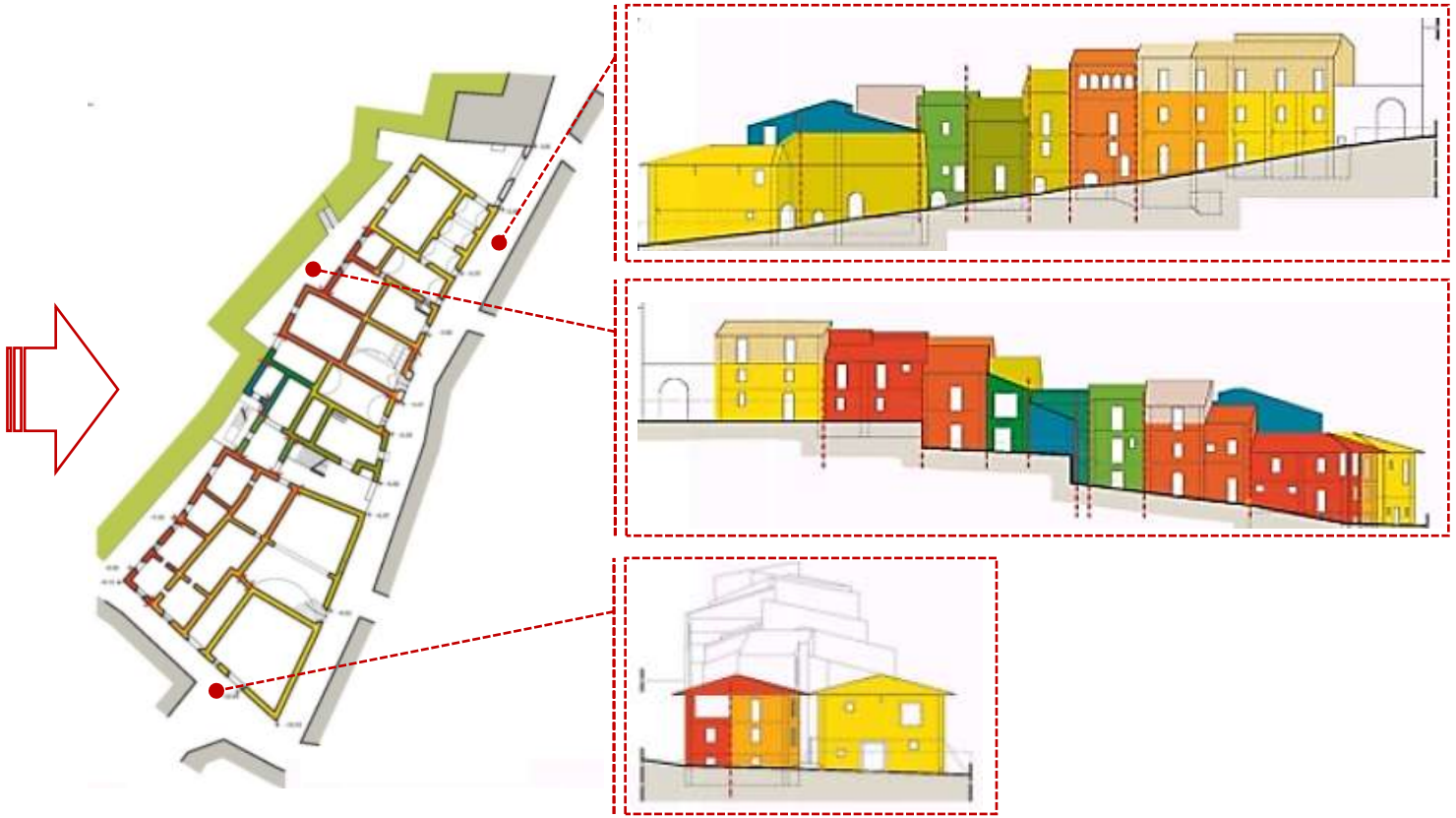
- **An aggregate can be understood as a non-homogeneous set of buildings (structural units), interconnected to each other with a more or less structurally effective connections, which can interact under seismic actions.**

Structural layout



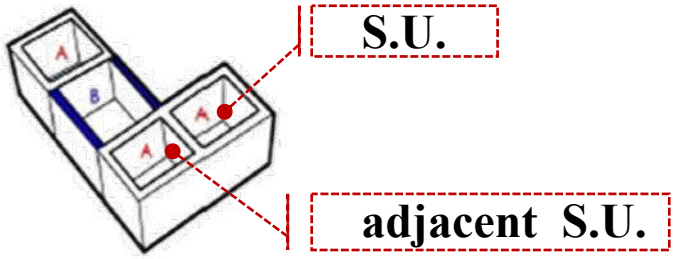
Global view



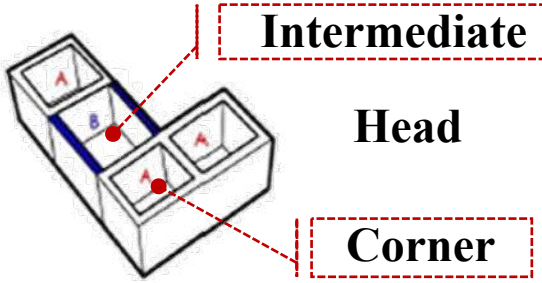


Within the aggregates it is possible to identify different structural units (S.U.) distinguishable from the others by at least one of the following characteristics, that identify a distinct dynamic behavior:

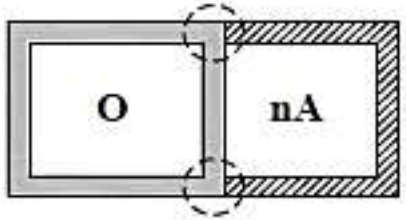
Structural Units (S.U.)



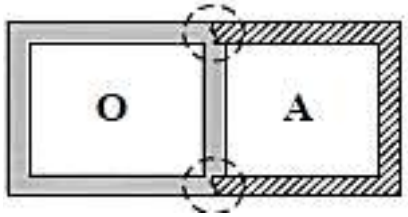
S.U. Position



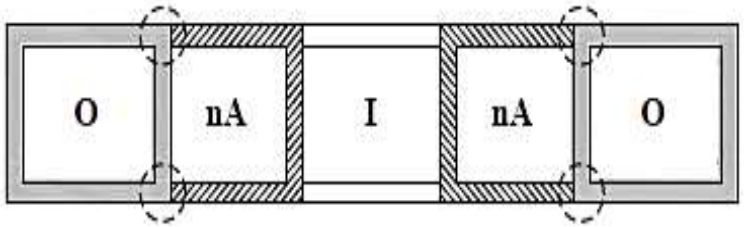
Lack of connections



Effective connections



Presence of arches on the S.U.



Vulnerability factors

- Type of construction;
- Different heights;
- Presence of planimetric irregularity;
- Lack of connections;
- Presence of arches/vaults;
- Heterogeneous materials;
- Age of construction.

These factors increase the vulnerability of the aggregate.

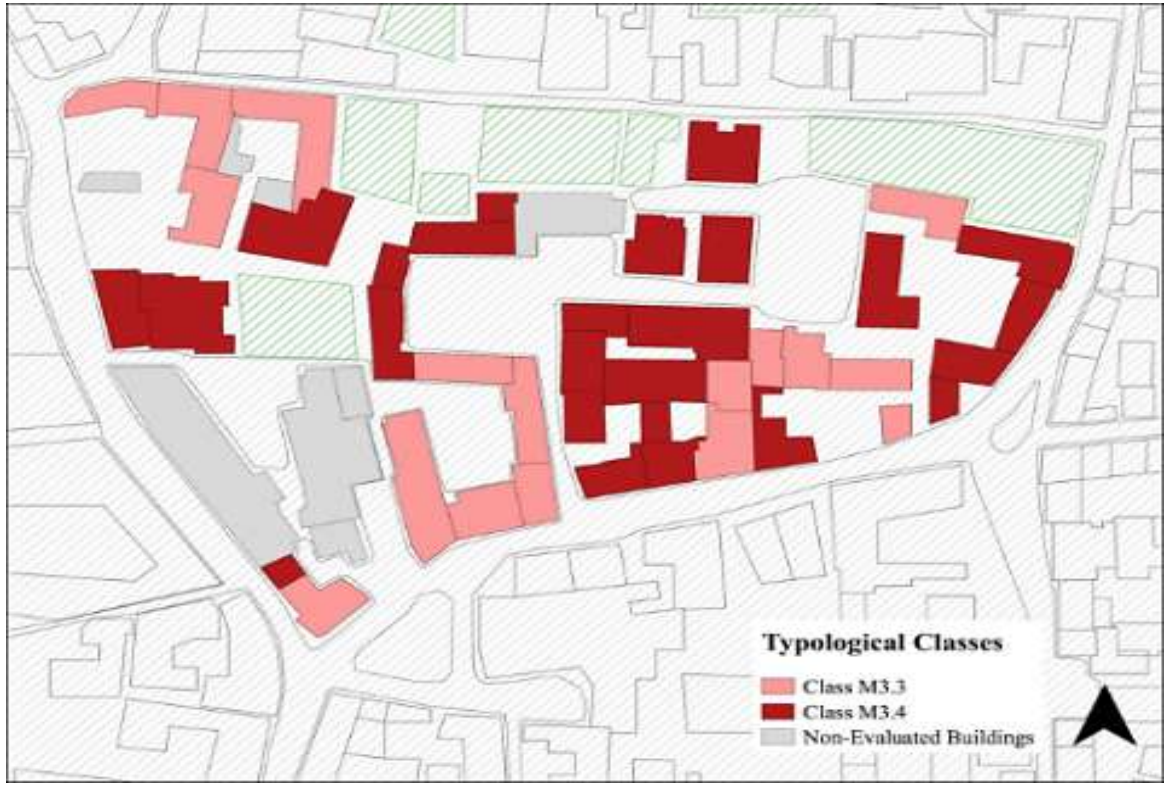
1. Structural and typological characterization

Numbering map



- **Investigated building: 42**

Typological classes



- **Class M3.3: 36% of the cases**
- **Class M3.4: 64% of the cases**

For seismic vulnerability assessment a Vulnerability Index Method (V.I.M.) based on the form proposed by *Formisano et al. (2010)* has been used:

Parameter	Class score (*s*)				Weight (*w*)
	A	B	C	D	
1. Organization of vertical structures	0	5	20	45	1
2. Nature of vertical structures	0	5	25	45	0.25
3. Location of the building and type of foundation	0	5	25	45	0.75
4. Distribution of plan resisting elements	0	5	25	45	1.5
5. In-plane regularity	0	5	25	45	0.5
6. Vertical regularity	0	5	25	45	0.5÷1
7. Type of floor	0	5	15	45	0.75÷1
8. Roofing	0	15	25	45	0.75
9. Details	0	0	25	45	0.25
10. Physical conditions	0	5	25	45	1
11. Presence of adjacent buildings with different height	-20	0	15	45	1
12. Position of the building in the aggregate	-45	-25	-15	0	1.5
13. Number of staggered floors	0	15	25	45	0.5
14. Structural or typological heterogeneity among adjacent structural units	-15	-10	0	45	1.2
15. Percentage difference of opening areas among adjacent facades	-20	0	25	45	1

Vulnerability index (Iv) $$I_V = \sum_{i=1}^{15} S_i \times W_i$$

- S_i are the scores associated with vulnerability classes (from A, better, to D, worst);
- W_i are the weights associated to each parameters.

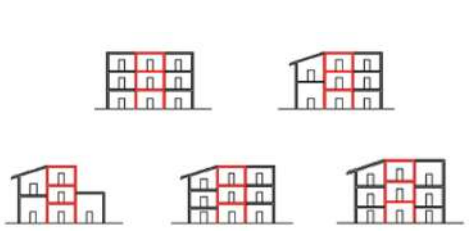
- **The first 10 parameters are based on the form proposed by Benedetti & Petrini (isolated buildings);**
- **The 5 additional parameters take into account the effects of mutual interaction between structural units in aggregate.**

PARAMETER 11

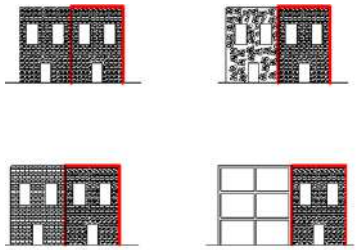


PARAMETER 12

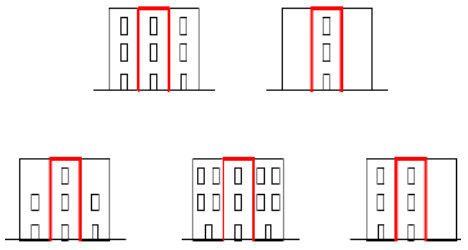
PARAMETER 13



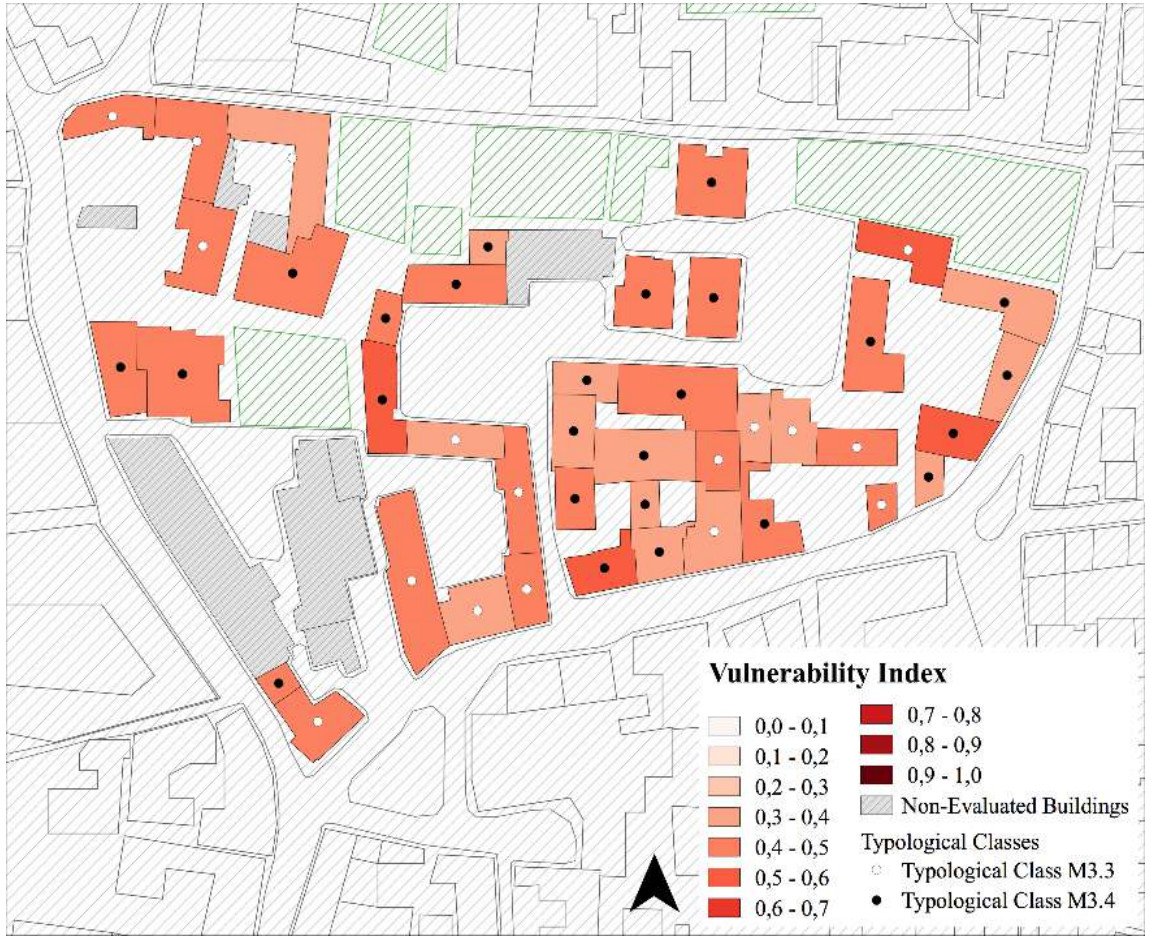
PARAMETER 14



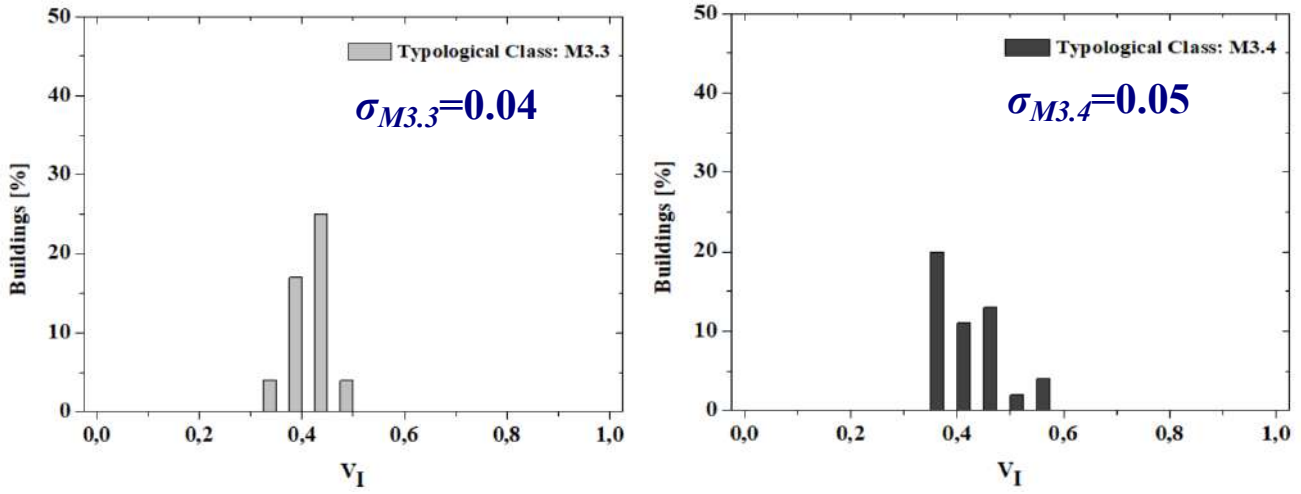
PARAMETER 15



Vulnerability distribution



Statistical distribution of the expected frequencies



- **M3.3: 25% of buildings have a vulnerability index of 0.45 and only 8% have an index of 0.35.**
- **M3.4: 20% of buildings have a vulnerability index of 0.35 and only 4% have a vulnerability index of 0.55.**

Typological vulnerability curves provide the probability to exceed a specific damage grade as a function of macroseismic intensity (I_{EMS-98}).

They are functions of:

- Normalized vulnerability index (V_I);
- Hazard, expressed in terms of macroseismic intensity (I_{EMS-98});
- Global ductility factor (Q), equal to 2.3 (buildings).

Normalized V.I., V_I

$$V_I = \left[\frac{I_V - \left(\sum_{i=1}^{15} S_{min} \times W_i \right)}{\left| \sum_{i=1}^{15} \left[(S_{max} \times W_i) - (S_{min} \times W_i) \right] \right|} \right]$$

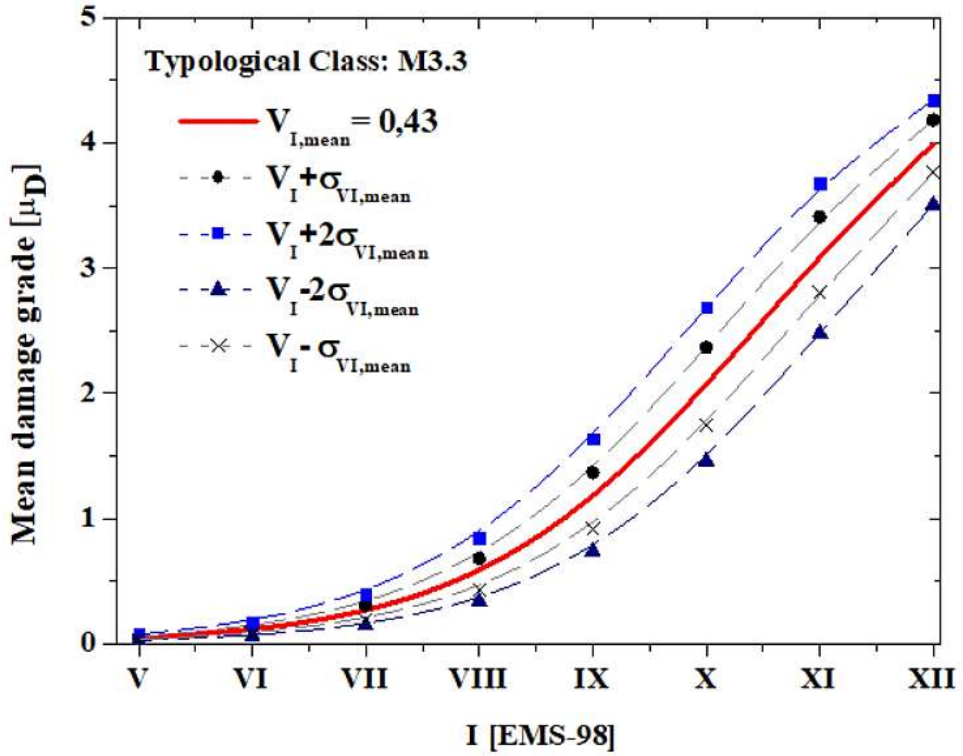
Damage level [DL]

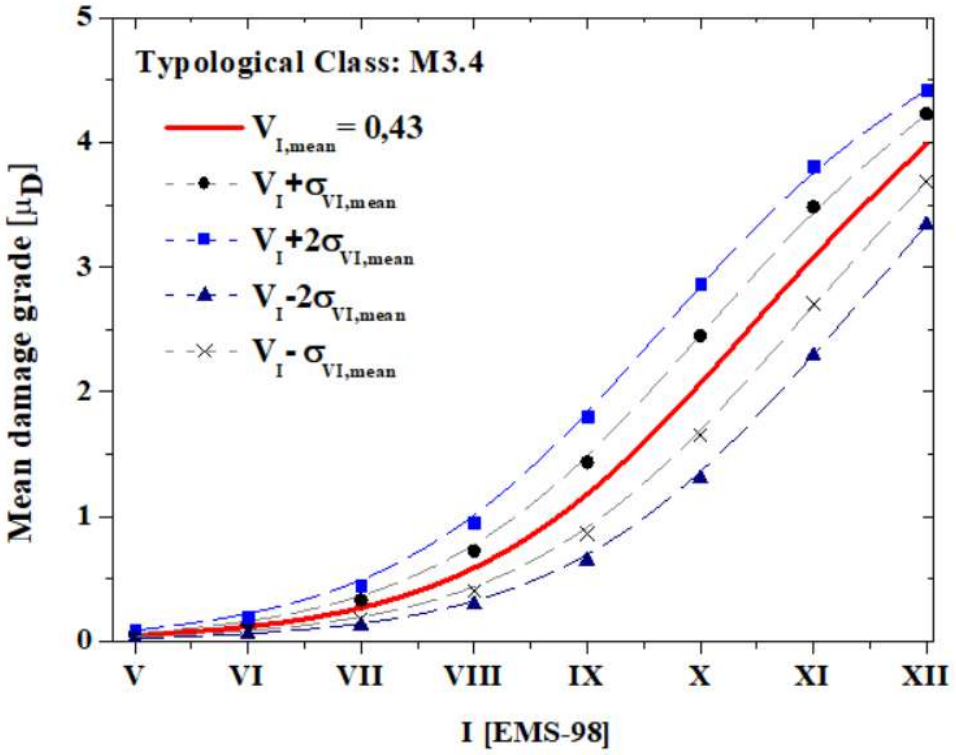
Mean damage range $[\mu_D]$	Damage State $[D_i]$	Damage level [DL]
0÷0,5	D0	No damage
0,5÷1,5	D1	Moderate damage
1,5÷2,5	D2	Substantial damage
2,5÷3,5	D3	Significant damage
3,5÷4,5	D4	Partial collapse
4,5÷5	D5	Collapse

Mean damage grade, μ_D

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

Continuous distribution of mean typological vulnerability curves





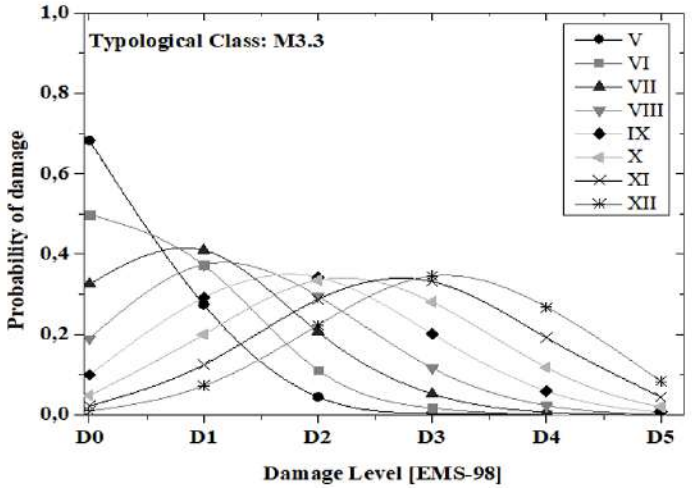
In order to quantify the distribution of seismic damage in a discrete form, damage thresholds, DG_k (K_i= 1 ÷ 5), are defined.

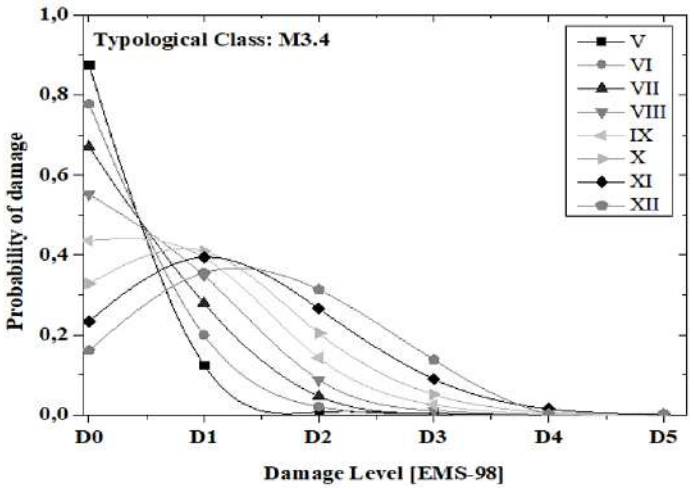
The applied method is based on the *binomial probability mass function* (PMF).

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

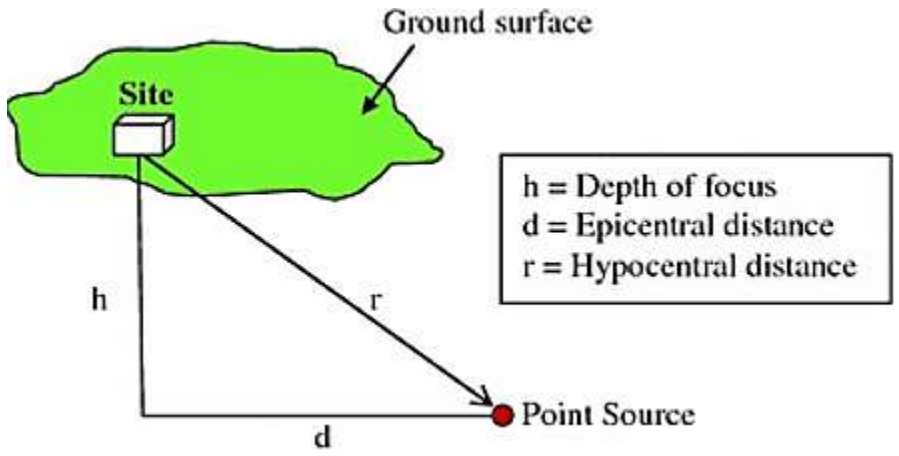
- μ_D: mean damage grade;
- K_i: damage level;
- P_k: damage probability.

Damage Probability Matrix (DPM)





The seismic attenuation laws allow to describe the ground motion (PGA or Intensitiy) as a function of other parameters (magnitude, epicentral distance and focal distance)



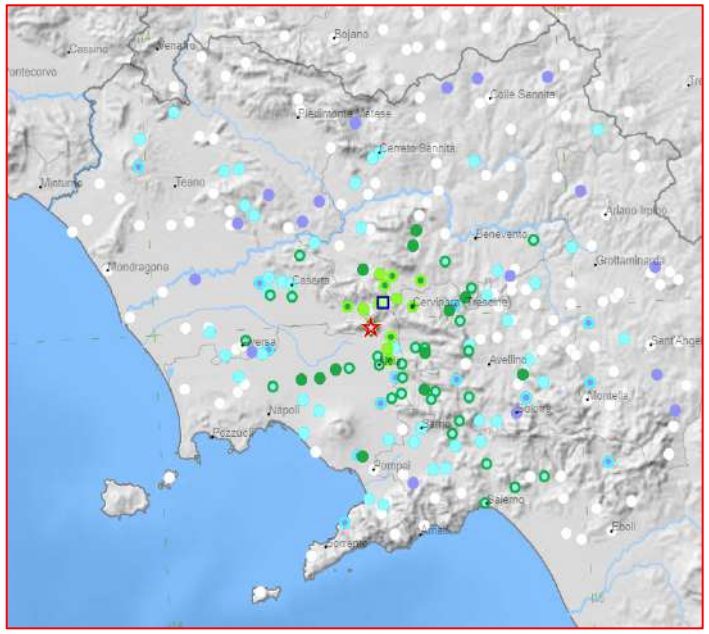
$$Y = f(M, R, source, soil, \varepsilon)$$

$$\ln Y = C_1 + C_2 M + C_3 M^{C_4} + C_5 \ln\sqrt{R^2 + h^2_0} + C_6\sqrt{R^2 + h^2_0}$$

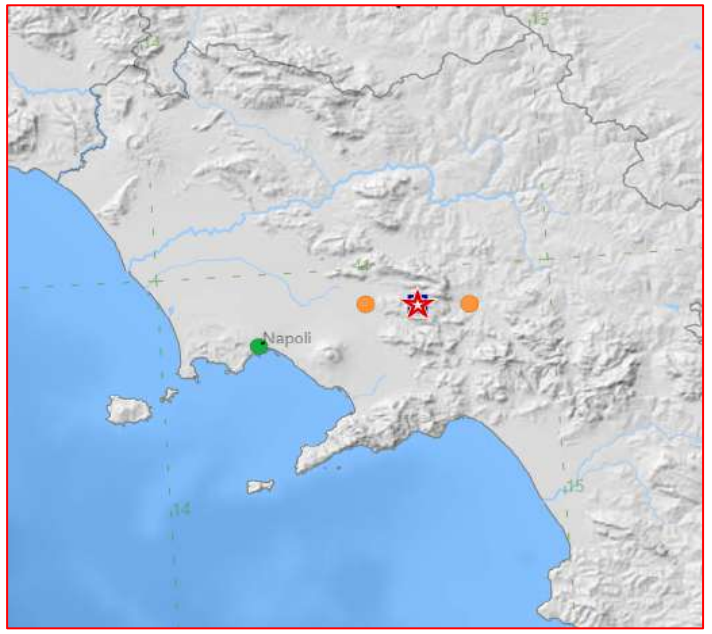
- **C1 is a term that reflects the unit of Y (i.e. PGA, Intensity);**
- **C2, C3 and C4 express the exponential relation between the magnitude and the energy released by the earthquake;**
- **C5 is related to the spreading of the energy;**
- **C6 represents the anelastic attenuation of the energy due to absorption or dissipation.**

For the evaluation of the damage scenarios, the DBMI15 - INGV has been used in order to select a set of moment magnitudes between 4 and 6 characterizing the seismicity of the area.

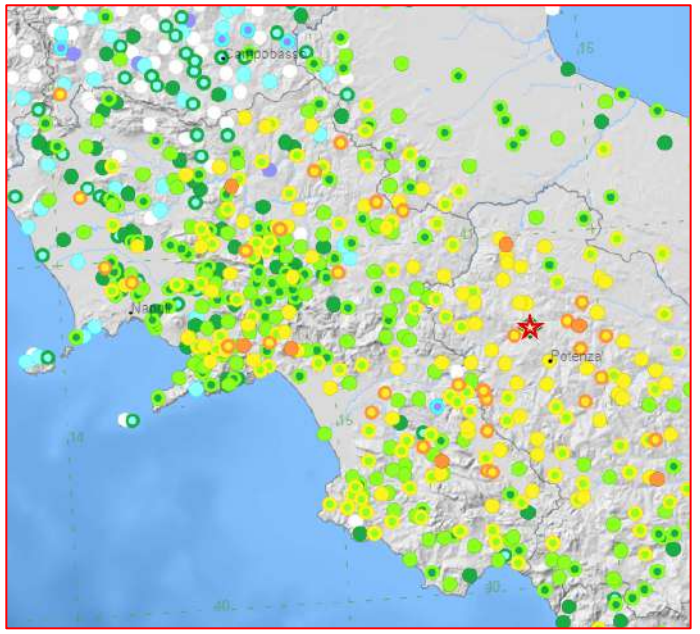
Historical Earthquakes



Area Nolana (2005)
M_w=4



Irpinia-Basilicata (1980)
M_w=5



Potentino (1990)
M_w=6

In terms of predictive analysis, a set of magnitude and site-source distances are defined.

Seismic attenuation law in term of macroseismic intensity

$$I_{EMS-98} = 1,45 \cdot M_w - 2,46 \ln(R) + 8,166$$

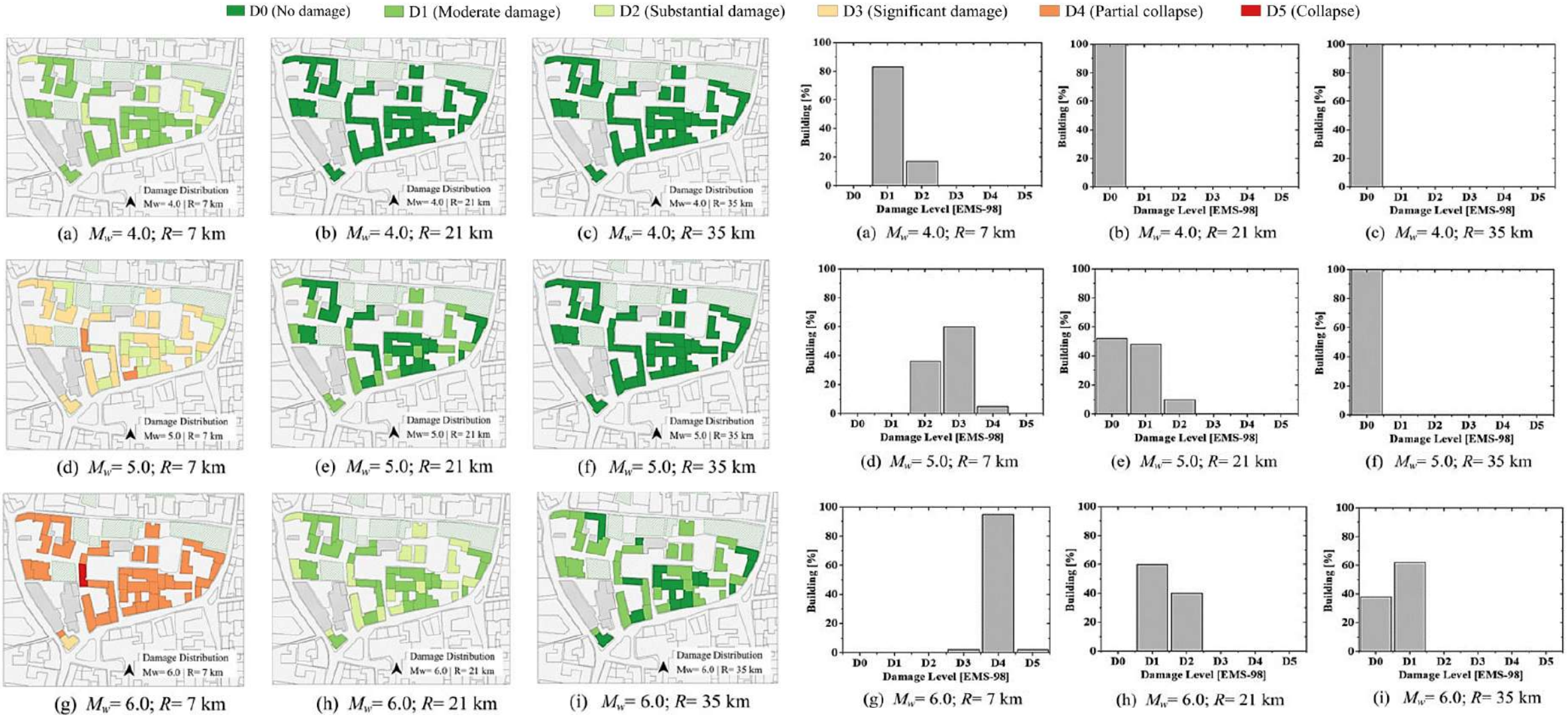
$$R = \sqrt{d^2 + h^2_f}$$

- I_{EMS-98} = the macroseismic intensity according to EMS-98 scale;
- M_W = the moment magnitude;
- R= the site-source distance.

Parametric damage scenarios: in order to characterize the seismicity of the area varying the input parameters.

Epicentral distance, R [km]	M_w=4.0	M_w=5.0	M_w=6.0
	Macroseismic Intensity, I_{EMS-98}		
7	IX	VI	V
21	XI	VIII	VII
35	XII	IX	VIII

Parametric damage scenarios



(a) M_w= 4.0; R= 7 km (b) M_w= 4.0; R= 21 km (c) M_w= 4.0; R= 35 km

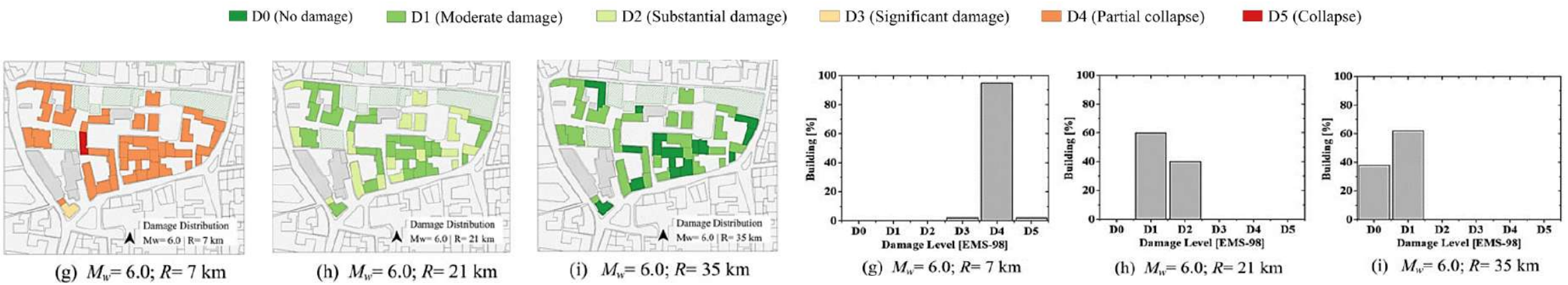
(d) M_w= 5.0; R= 7 km (e) M_w= 5.0; R= 21 km (f) M_w= 5.0; R= 35 km

(g) M_w= 6.0; R= 7 km (h) M_w= 6.0; R= 21 km (i) M_w= 6.0; R= 35 km

Parametric damage scenarios

The level of damage mainly depends on the distance of the site from the seismogenic source. In fact, it is possible to note that, when increasing the epicentral distance, the expected damage tends to decrease.

Worst-case scenario

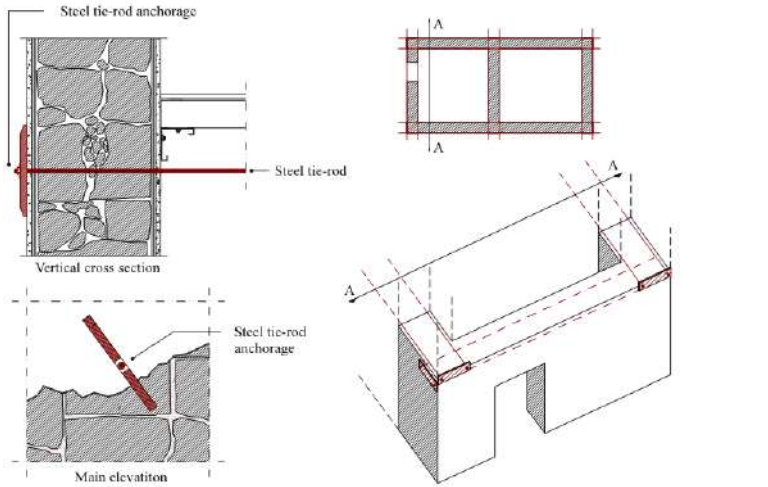


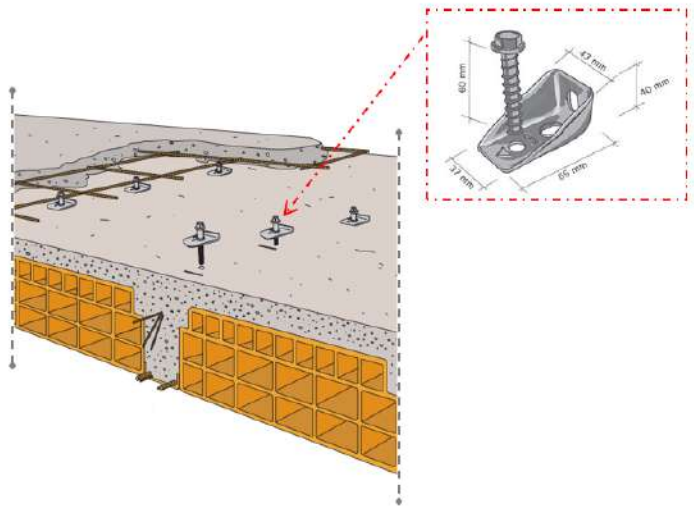
(g) M_w= 6.0; R= 7 km (h) M_w= 6.0; R= 21 km (i) M_w= 6.0; R= 35 km

(g) M_w= 6.0; R= 7 km (h) M_w= 6.0; R= 21 km (i) M_w= 6.0; R= 35 km

- M_w=6.0 and R=7 km (I_{EMS-98}= V): it is expected that 80% of the buildings reach damage level D4.
- M_w=6.0 and R=21 km (I_{EMS-98}= VII): it is expected that 58% of the buildings reach damage level D1 and 42% D2.
- M_w=6.0 and R=35 km (I_{EMS-98}= VIII): it is expected that 62% of the buildings reach damage level D1 and 38%, D0.

For risk mitigation, especially in areas with high population density, retrofit strategies are a solution to reduce the seismic emergency problem.





Steel tie-rods

This intervention technique consists in preparing steel tie-rods with a diameter 16 mm<Φ<20 mm, which are fixed by metal plates in order to guarantee a box behavior of the structure.

- **Guarantee an important constraint among walls.**

Floor shear connectors

The use of shear connectors and steel bar mesh allow to increase the floor strength and stiffness, through the increase of its height, to avoid the formation of cracks induced by the flexural regime.

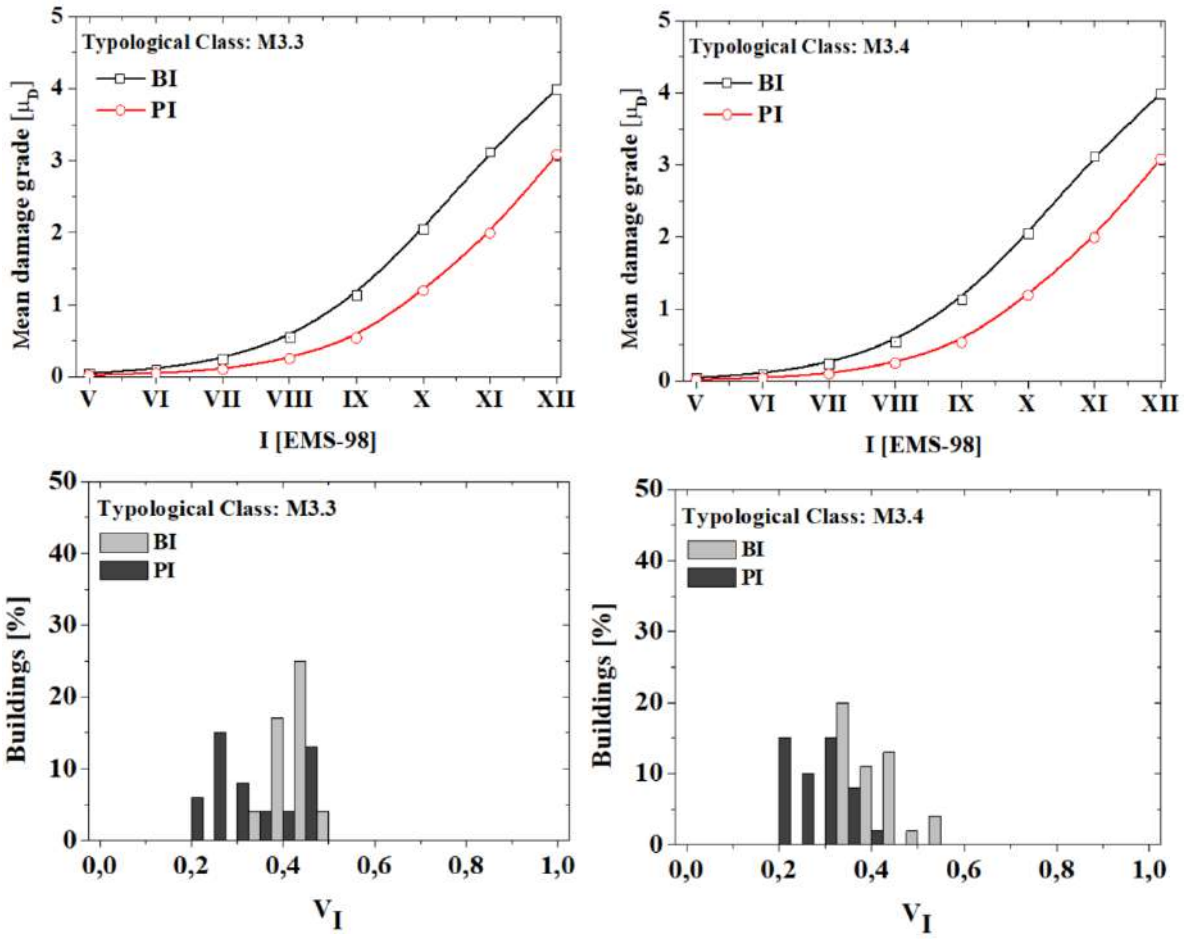
- **Guarantee a resistance increase, which is proportional to the increase of the floor height.**

3. Parametric damage scenarios and loss estimation

The proposed intervention techniques are applied to all buildings of the study area.

- In this case, the box behaviour is guaranteed by the steel tie-rods, while shear connectors and steel bar meshes increase the in-plane resistance of the existing floors.

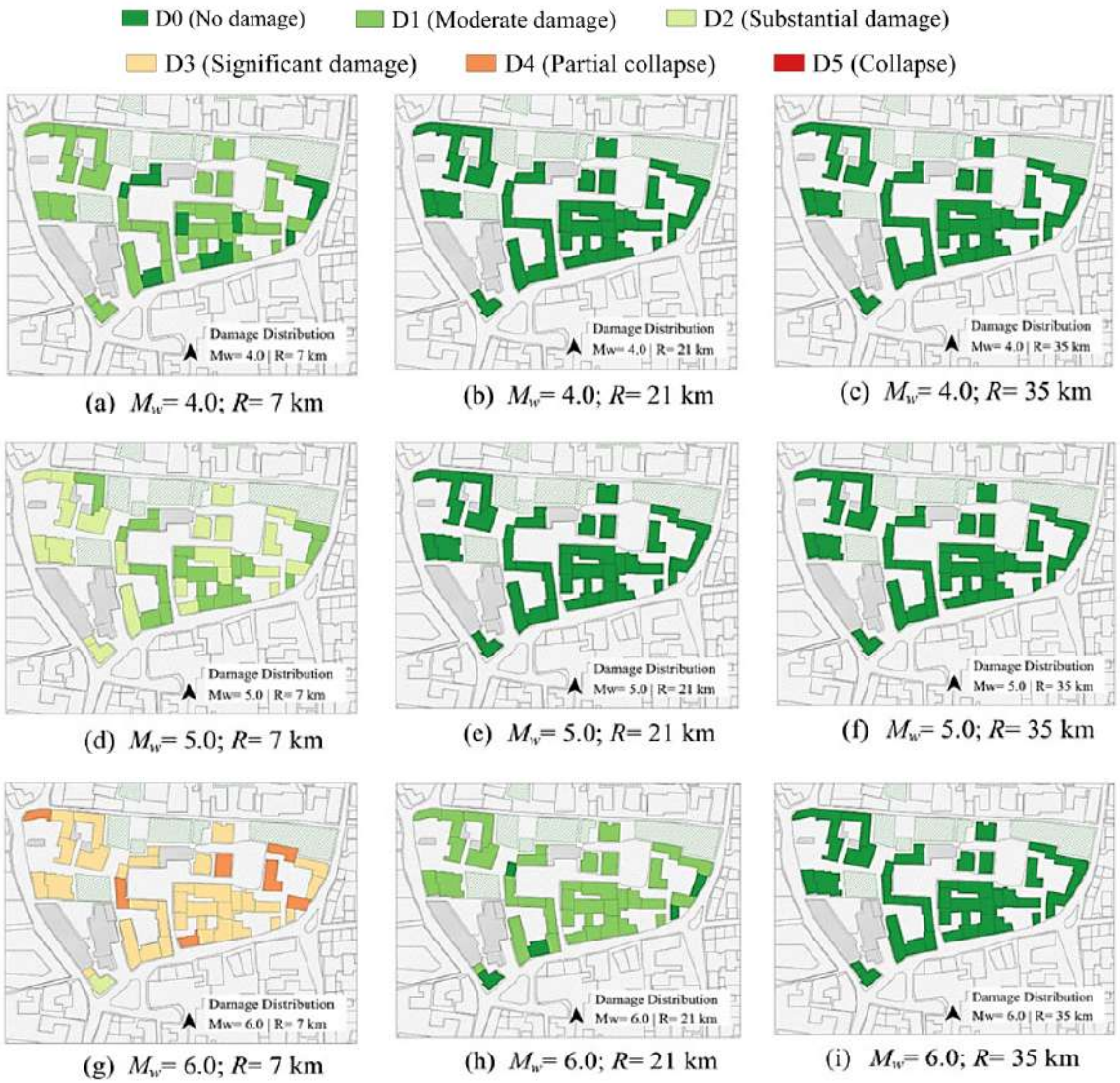
- In methodological terms, this can be done by reassessing the vulnerability classes, S_i, of the parameters that are related to those features, namely Parameter 1, which evaluates the organisation of the vertical structures, Parameter 7, which evaluates the horizontal diaphragms, and Parameter 8, which evaluates the roofing system.



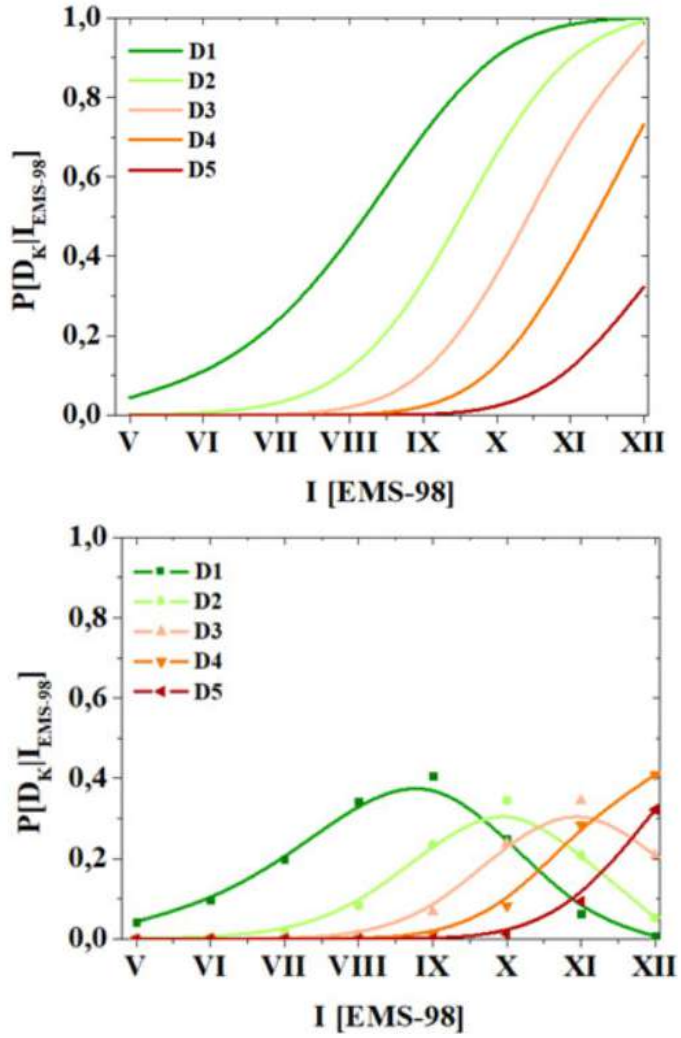
- The buildings are thus virtually retrofitted by upgrading the original vulnerability classes of these parameters to class B, in the case of P1 and P7, and A, in the case of P8, resulting in the reduction of their vulnerability indexes values and, therefore, the expected mean damage grade.

3. Parametric damage scenarios and loss estimation

Post-intervention scenarios



Typological fragility curves and damage distributions



3. Parametric damage scenarios and loss estimation

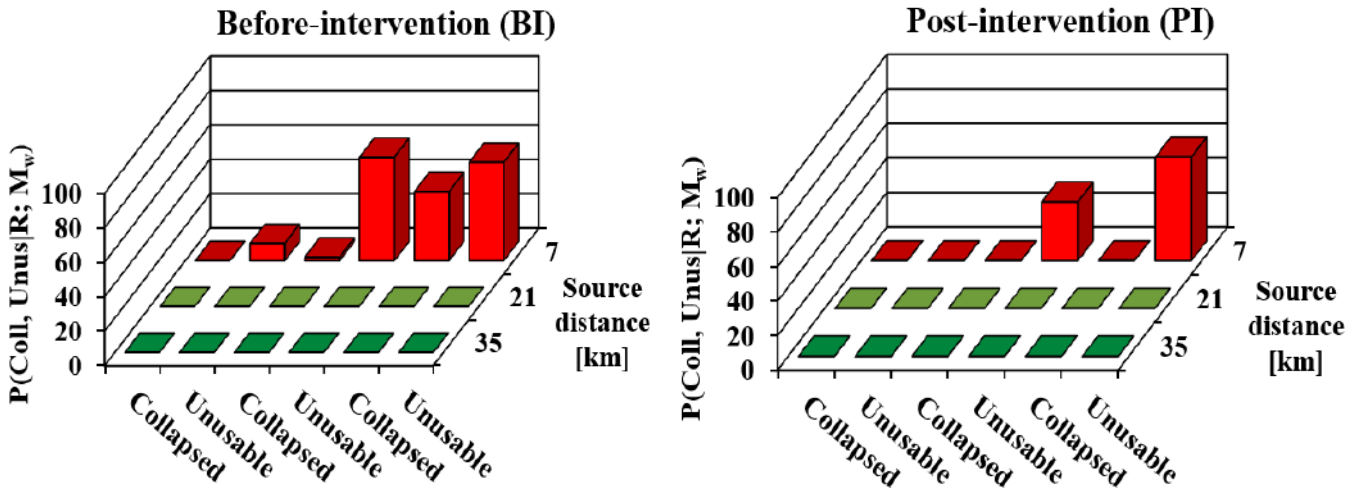
The consequences of seismic events in terms of collapse and unusable buildings are evaluated considering the empirical correlations below provided.

The estimation of unusable and collapsed buildings is a function of damage scenarios:

$$N_{coll.} = 100\%D5 + 40\%D4$$

$$N_{unus.} = 60\%D4 + 100\%D3 + 60\%D2$$

Source distance, R [km]	Number of collapsed and unusable buildings (BI)					
	M_w=4		M_w=5		M_w=6	
	Collapsed	Unusable	Collapsed	Unusable	Collapsed	Unusable
7	-	7 (10%)	2 (2%)	25 (60%)	17 (40%)	25 (60%)
21	-	-	-	-	-	-
35	-	-	-	-	-	-
Source distance, R [km]	Number of collapsed and unusable buildings (PI)					
	M_w=4		M_w=5		M_w=6	
	Collapsed	Unusable	Collapsed	Unusable	Collapsed	Unusable
7	-	-	-	14 (34%)	-	25 (60%)
21	-	-	-	-	-	-
35	-	-	-	-	-	-



Casualty rates (number of deaths and severely injured) and homelessness are evaluated according to the number of people living in the study urban area.

$$N_{m,r} = \frac{N_{Tot,res.}}{N_{bld}}$$

$$N_{died} = N_{m,r} \times N_{coll.}$$

$$N_{hmls} = N_{m,r} \times N_{unus.}$$

- $N_{m,r}$= average number of residents in the analysed area;
- $N_{Tot,res}$= total number of residents (142 from ISTAT);
- N_{bld}= total number of investigated buildings (42);
- N_{died}= total number of deaths;
- N_{hml}= total number of homelessness.

Source distance, R [km]	Number of casualties and homeless people (BI)					
	M_w=4		M_w=5		M_w=6	
	Death	Homeless	Death	Homeless	Death	Homeless
7	-	-	3 (2%)	92 (60%)	64 (40%)	87 (57%)
21	-	-	-	-	-	-
35	-	-	-	-	-	-
Source distance, R [km]	Number of casualties and homeless people (PI)					
	M_w=4		M_w=5		M_w=6	
	Death	Homeless	Death	Homeless	Death	Homeless
7	-	-	-	52 (34%)	10 (7%)	92 (60%)
21	-	-	-	-	-	-
35	-	-	-	-	-	-

4. Conclusion

The proposed study is a useful tool for the quick vulnerability assessment at urban scale considering the use of appropriate attenuation relationship and retrofitting strategies.

From results achieved, it is noted that:

- **The use of an appropriate vulnerability form is essential to consider the mutual interaction among S.U.**
- **The use of the seismic attenuation law allows to identify the worst case scenario in terms of expected damage.**
- **For risk mitigation, retrofit strategies have been used as solution to reduce the seismic emergency problem. The physical vulnerability is reduced of 39% considering the post-intervention strategies.**
- **The adoption of appropriate retrofitting systems reduces the possibility of structural collapse by 40%.**
- **Future Developments: extend the analysis to the whole Municipality considering the influence of local site effects and focal depths.**

THANKS FOR YOUR ATTENTION