  

1st SHORT COURSE ON MULTIHAZARD FOR EXTREME EVENTS:
Fires, Explosions, Floods, Earthquakes,
University of Cagliari (Italy), 17th – 20th September 2019

Multihazard of Cultural Heritage

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Cagliari - September 17, 2019

Co-Sponsored by:

Cultural heritage

Italy is a country with **very wide cultural heritage** *in terms of «monuments, settlements, historical sites with aesthetic, archeological, scientific and anthropologic value»*
(Unesco, 1972)

47 *sites defined as «world heritage» (4.7%, 1st worldwide country)*

46.9% *of the national territory is part of protected areas*

100.000 *historical buildings (33.3 every 100 km^2)*
(Ministry of Cultural Heritage - MiBACT, 2012)

Multi-hazard prevention

- *Aimed at the* **mitigation** *of* **multi-hazard consequences** *in terms of*
  - *life loss*
  - *damage*
  - *activities interruption*
  - *direct and indirect economical and social loss*
- **Lower expenses** *with respect to those necessary after strong events (rehabilitation, reconstruction)*

- **Cultural heritage** — **historical value**, **cultural value**, **identity value** — **priceless!**

Multi-hazard prevention and historical/monumental buildings

Combine SAFETY and PRESERVATION needs

- *Generally the capacity against hazards is much lower than the demand*
  old design concepts were not focusing on natural/anthropic hazards
- *Priority to identification and intervention on the most critical situations*
- *Due to preservation needs*
  no invasive rehabilitation actions are viable,
  large increase of capacity against hazards cannot be obtained easily

In general, an higher risk level is accepted with respect to ordinary constructions, due to need to respect and preserve the cultural heritage

Multi-hazard prevention and historical/monumental buildings

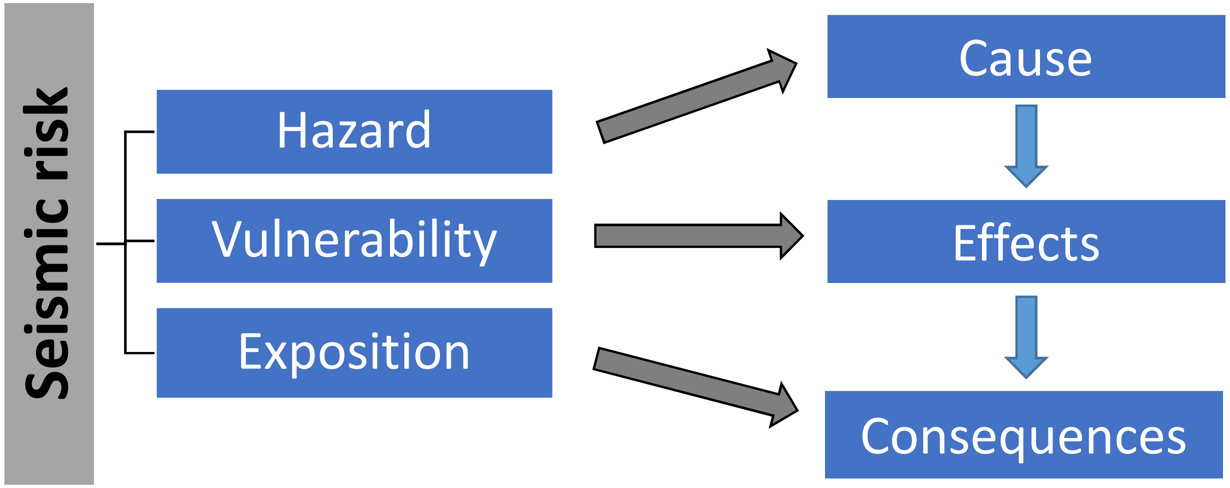
HIGH LEVEL OF COMPLEXITY *related to:*

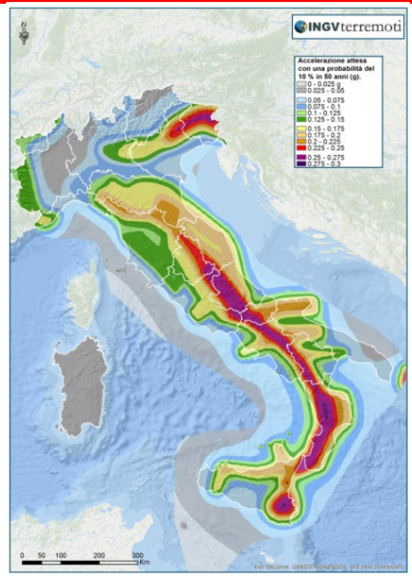
- **Complex structural typologies**
  subsequent construction phases during centuries
  inserted within the urban structure
  use of different materials (masonry, wood, steel, etc.)
- **Multidisciplinary approach**
  need for different expertises (architectural, engineering, historical, artistic, archeological…)
- **Complexity of the masonry material**
  composite nature
  difficulties in the analytical and numerical modeling
- **No invasive tests** *(preservation) that would be necessary for a comprehensive knowledge of the construction*
- *Need for* **'smart' interventions**, **respectful of the historical value** *of the construction*

- **Natural risk**
  - Seismic risk
    - earthquakes
    - tsunamis
  - Hydro-geological risk
    - landslides
    - floods
    - coastal erosion
  - Meteorological risk
    - rain
    - wind
    - hailstorm
    - snow
    - coastal storm
    - heatwave
- **Anthropic risk**
  - Industrial risk
    - chemical
    - important accidents
  - Environmental risk
    - pollution
  - Sanitary risk
    - epidemic
  - Wildfire
    - CO_2 emission

SEISMIC RISK

In the last three decades, Italy has been hit by about thirty earthquakes characterized by a magnitude higher than 5.0. Human lives and artworks have been lost as well as widespread damage has been observed in the built environment.

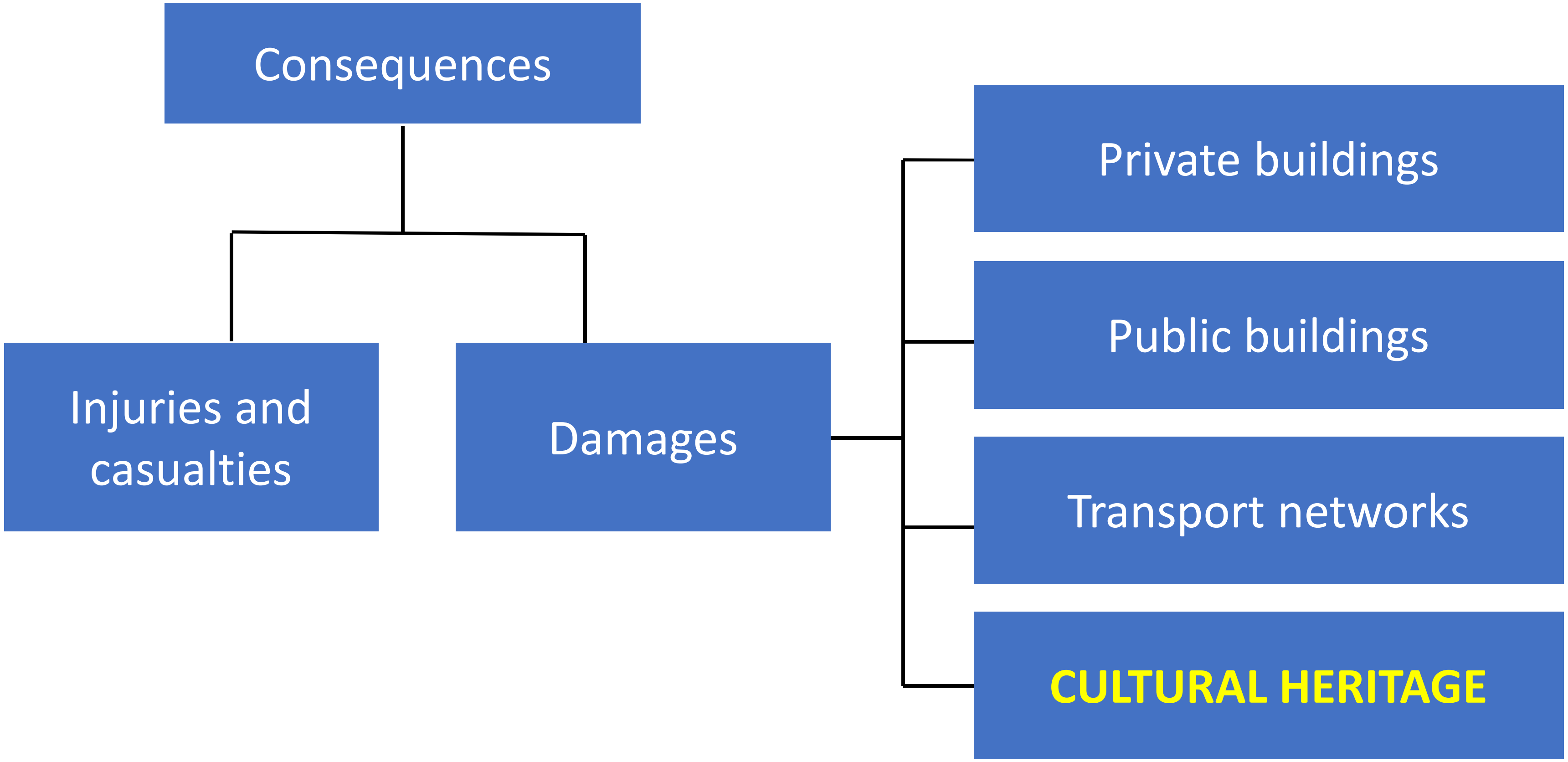




Seismic hazard in a given region is quantified through the mean annual frequency that a certain seismic intensity measure (e.g., peak-ground acceleration) occurs.

Seismic vulnerability of a building or a group of buildings is defined as their proneness to experience damage in occurrence of a seismic event

Exposition accounts for the number of objects and people subjected to the seismic action, therefore tightly linked to the local socio-economic system and building environment characteristics


Consequences
Injuries and casualties
Damages
Private buildings
Public buildings
Transport networks
CULTURAL HERITAGE

Umbria-Marche earthquake

(September 26, 1997)

Magnitudo 6.0

CORRIERE DELLA SERA

TRE SCOSSE TREMENDE, CROLLATI INTERI PAESI, TERRORE. DANNI IRREPARABILI AL PATRIMONIO ARTISTICO

L'Italia colpita al cuore

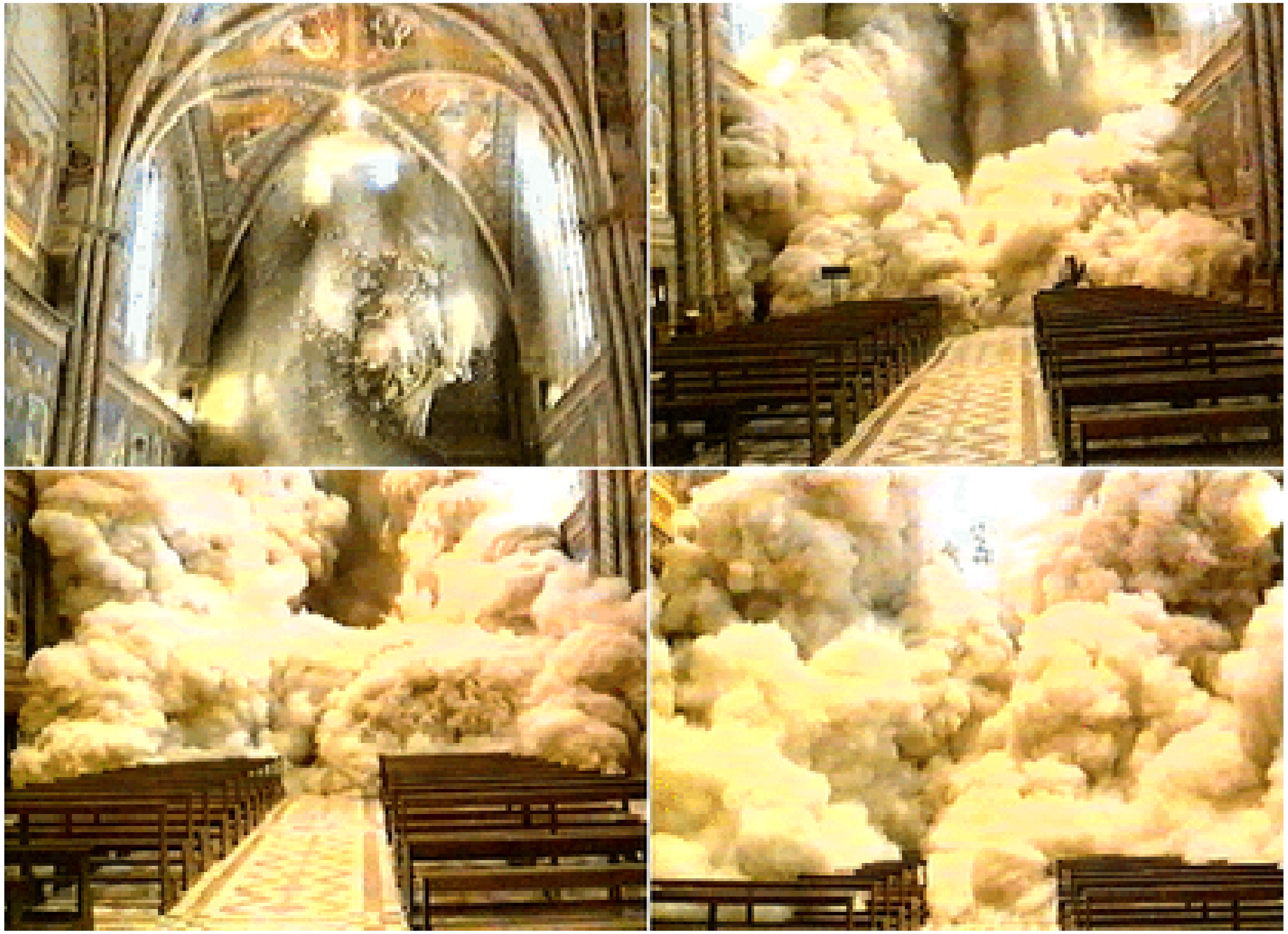
Il terremoto devasta Umbria e Marche: dieci morti, centinaia di feriti, migliaia i senzatetto

Crolla la volta della basilica di San Francesco ad Assisi, distrutti affreschi di Giotto e Cimabue

SOTTO LA POLVERE

SOTTOSCRIZIONE

Un aiuto subito



EARTHQUAKE RISK: recent italian earthquake

L'Aquila earthquake (April, 6 2009)

Magnitudo 6.1

CORRIERE DELLA SERA

Fondato nel 1876 www.corriere.it

Focus

Macerie e morte in Abruzzo

Sisma devastante: più di 150 vittime, 70 mila sfollati. Berlusconi: non vi abbandoniamo

LA TERRA IMPAZZITA E I GIURAMENTI MAI MANTENUTI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Oggi con il Corriere
Falcone e Borsellino Il coraggio e l'esempio
I RISCHI SISMICI SONO NOTI (E IGNORATI)
LE FATALITÀ PREVEDIBILI
di GIAN ANTONIO STELLA
Oltre cento scosse, la più forte di 5.9 gradi Richter. Lo sciame continua. Paura al Nord da Milano a Venezia
L'Emilia sfregiata dal terremoto
Crollano torri, rocche e chiese. Sette morti, emergenza per gli sfollati
Tra le vittime quattro operai del turno di notte travolti in fabbrica
di FRANCESCO ALBERTI e ANDREA PASQUALETTO
Giannelli
Finale Emilia annientata come L'Aquila
Radiografia di un disastro culturale
Perché trema la Pianura padana?
Il filmato dell'attentato di Brindisi. S'indaga nella scuola
«Ha guardato le ragazze e ha premuto il pulsante»
Lo strisciane
DOBBIAMO STARE INSIEME
di BEPPE SEVERGNINI
La Torre del Duecento che si è sbriciolata

Emilia earthquake (May, 20 2012)

Magnitudo 5.8

Central Italy earthquake (August 24, 2016)

Magnitudo 6.0

CORRIERE DELLA SERA

FONDATO NEL 1876

UN AIUTO SUBITO

Come effettuare i versamenti

Il territorio

24 AGOSTO 2016

Morti e paesi cancellati

Sisma devasta il Centro Italia, oltre 150 vittime. Trappola in un albergo

HYDRAULIC RISK

Both environmental and anthropic aspects influence the hydrogeological risk.

Environmental aspects
- water action
- adverse weather conditions

Anthropic aspects
- uncontrolled urbanization
- deforestation
- slope and river maintenance

HYDRAULIC RISK

The hydraulic risk represents the probability of damages into the system given a certain flood

The damages in the system can be produced by two mechanisms:

- **overflow**, which occurs when the riverbank is not able to stem the flood wave;
- **riverbank collapse**, which represents a settlement in the riverbank due to the flood wave.

Hydraulic risk

- **Hazard**: mean annual frequency that a certain flood intensity measure (e.g., water level) occurs
- **Exposition**: number of objects and people subjected to the flood action
- **Vulnerability**: proneness of the system to manifest damage in occurrence of a flood event

FLOOD RISK: Florence flood (1966)

Date: November 4, 1966

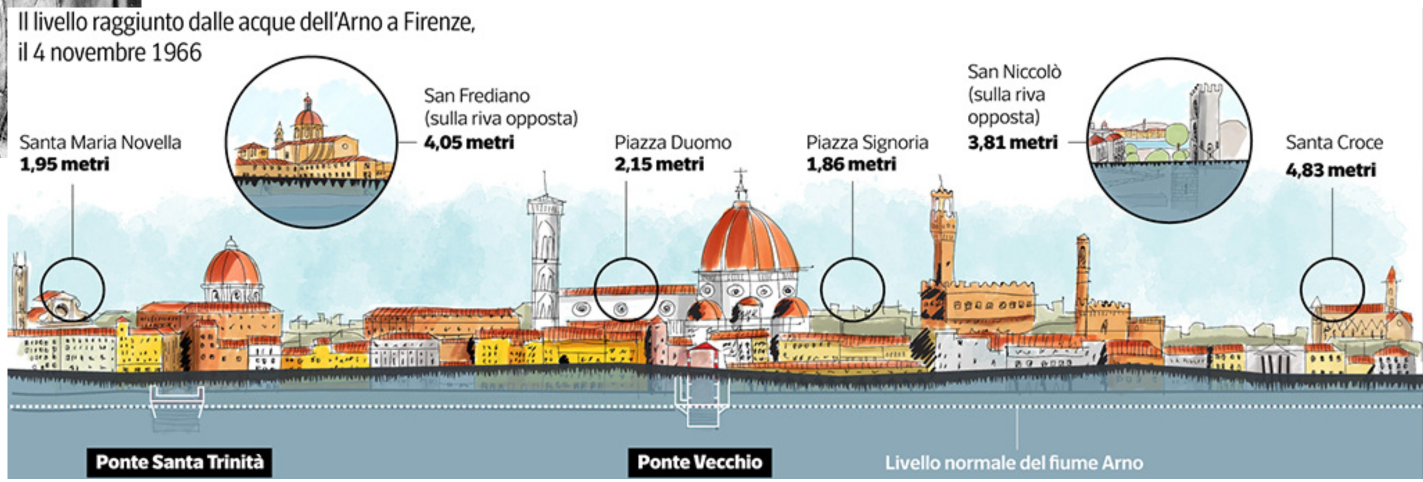
Deaths: 35

Other data:

- Florence was invested by 80 millions of cubic meters of water
- 4000 homeless families

The water level reached about 5 meters

Water level on the Baccio Bandinelli chorus near Duomo



UNA CITTA' COLPITA NEL CUORE DEL SUO PATRIMONIO CULTURALE

SI CALANO NEL BUIO DELLA MELMA PER AMORE DI LIBRI E DI FIRENZE

Giovani e stranieri fanno catena per strappare al fango opere preziose - Duecento volontari alla Biblioteca Nazionale - L'esperimento degli essiccatoi agricoli - Le drammatiche condizioni dell'Archivio di Stato e del Gabinetto Vieusseux - Gravissimi danni alle case editrici e alle librerie del centro - Occorrono carta assorbente, velina e borotalco, ma soprattutto braccia, per arrestare la muffa

- 1500 artworks damaged
- 1 million books submerged

Baptistery doors

Cimabue Christ in Santa Croce church

Santa Croce square


Firenze - 1966

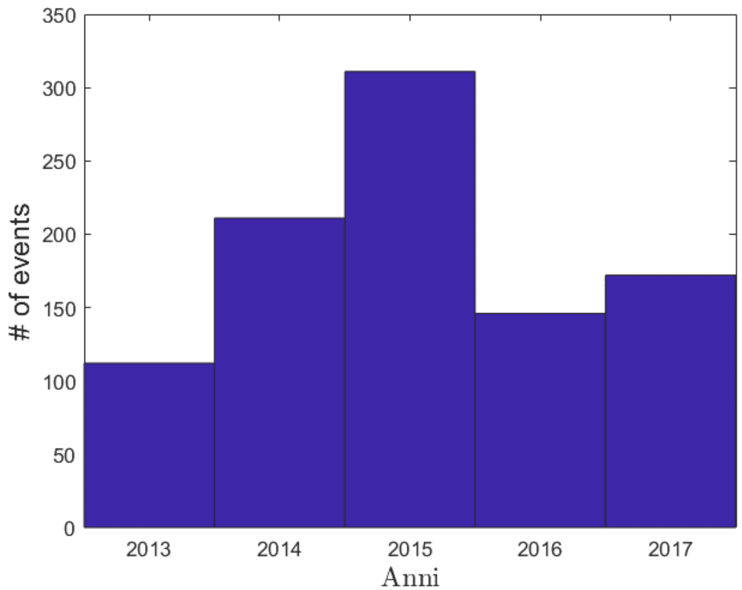

Valtellina - 1987

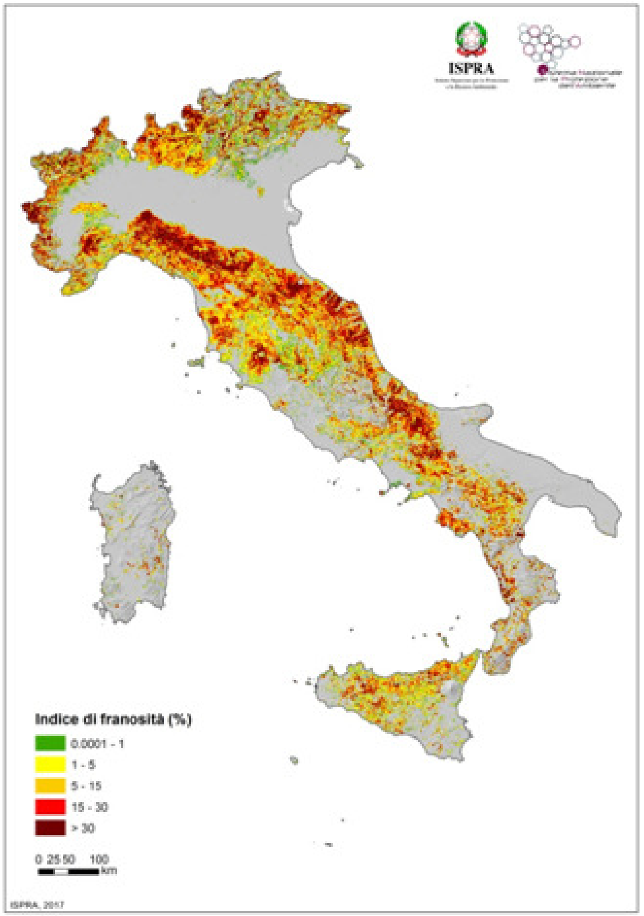

Piemonte - 1994


Genova - 2011

LANDSLIDE

Italy is one of the European Countries mainly hit by landslides: 620808 landslides over an area of 23700 km^2 (7.9% of the national territory) from 1116 to 2017 ("Inventario dei Fenomeni Franosi in Italia", http://www.progettoiffi.isprambiente.it).





LANDSLIDE RT ‘Piano Assetto Idrogeologico’ CLASSIFICATION

- **Active landslide**: continuous or discontinuous movement.
- **Quiescent landslide**: discontinuous movement; the causes of the landslide are still present
- **Inactive landslide**: not reactivable since the ground was stabilized by natural or artificial methods; the causes of the landslide are no more present

A DEFINITION FOR THE LANDSLIDE HAZARD

Hazard assessment

- Spatial location — Where?
- Frequency of occurrence — When? How often?
- Typological forecast — Expected phenomenon and evolution?
- Intensity or magnitude — How big? How fast?

$$H = f\,(F;I)$$

F = frequency, I = intensity

(Panizza, 2001)

LANDSLIDE RISK: the Agrigento landslide

GIORNALE DI SICILIA

Dopo la disastrosa frana che ha sconvolto la città le migliaia di senza tetto e gli abitanti dei quartieri rimasti indenni temono nuovi slittamenti del terreno

SU AGRIGENTO INCOMBE LA PAURA

Il culto di Mammona

Un netturbino, dando tempestivamente l'allarme, ha forse evitato che si lamentassero vittime - L'intero fianco della collina si è spostato verso il basso - Case distrutte, altre lesionate e in pericolo - Il disperato esodo dai quartieri pericolanti

Il disastro poteva essere evitato?

Le impressionanti rivelazioni dell'ing. Rizzica, ex membro

OGGI

SI ABOLISCE IL DELITTO D'ONORE

IN LIBERTÀ GLI ACCUSATI DEL DELITTO DI PETRALIA

"NETTURBINI" A PALERMO TRE CONSIGLIERI COMUNALI

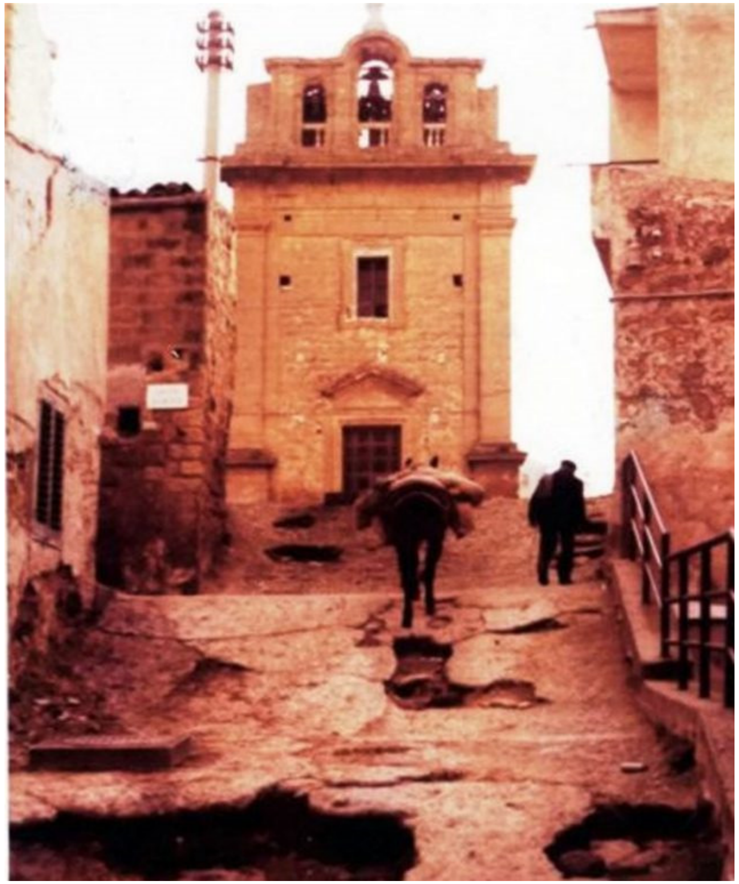
LA VERGOGNA DEGLI 'AZZURRI' ELIMINATI DAI MONDIALI

LA LEGA NON RATIFICA GLI ACQUISTI DEL PALERMO

Date: July 19, 1966

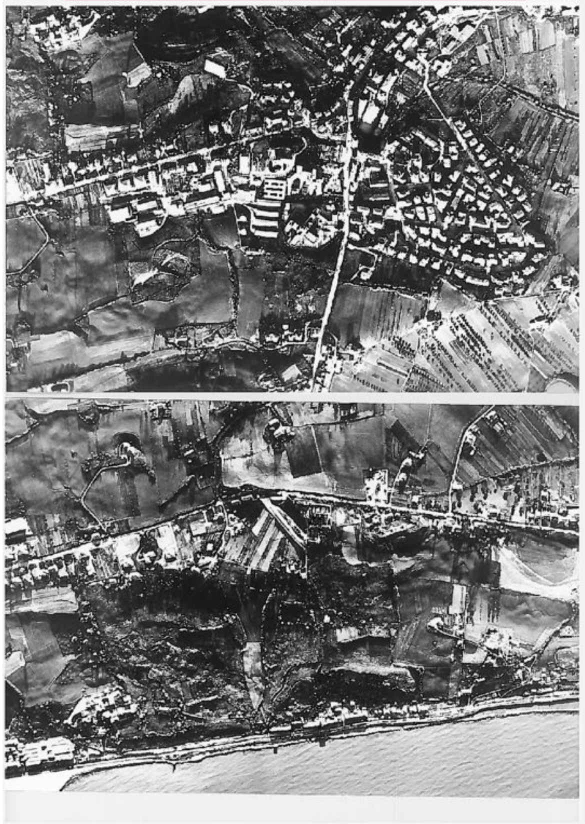
Other data:

- 20 hectares of ground slided
- 4 buildings collapsed
- 7000 homeless

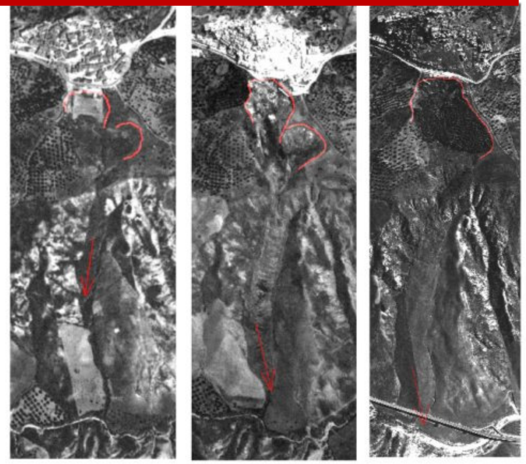


San Michele cathedral completely destroyed

Ancona

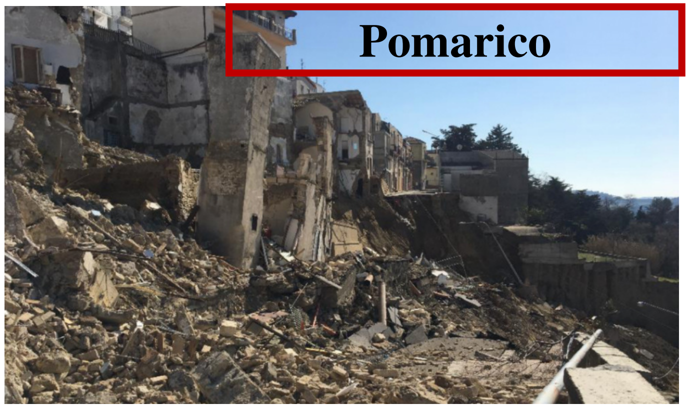


Craco 1955 1972 1997



Agrigento

Pomarico



EARTHQUAKE-INDUCED LANDSLIDES

Besides producing additional casualties and damages, earthquake-induced landslides can slow down or even prevent the rescue opertations. They are also characterized by a sudden detachment of the ground mass.

A famous example occurred the 18th January 2017 in Rigopiano (Italy)

Before the event

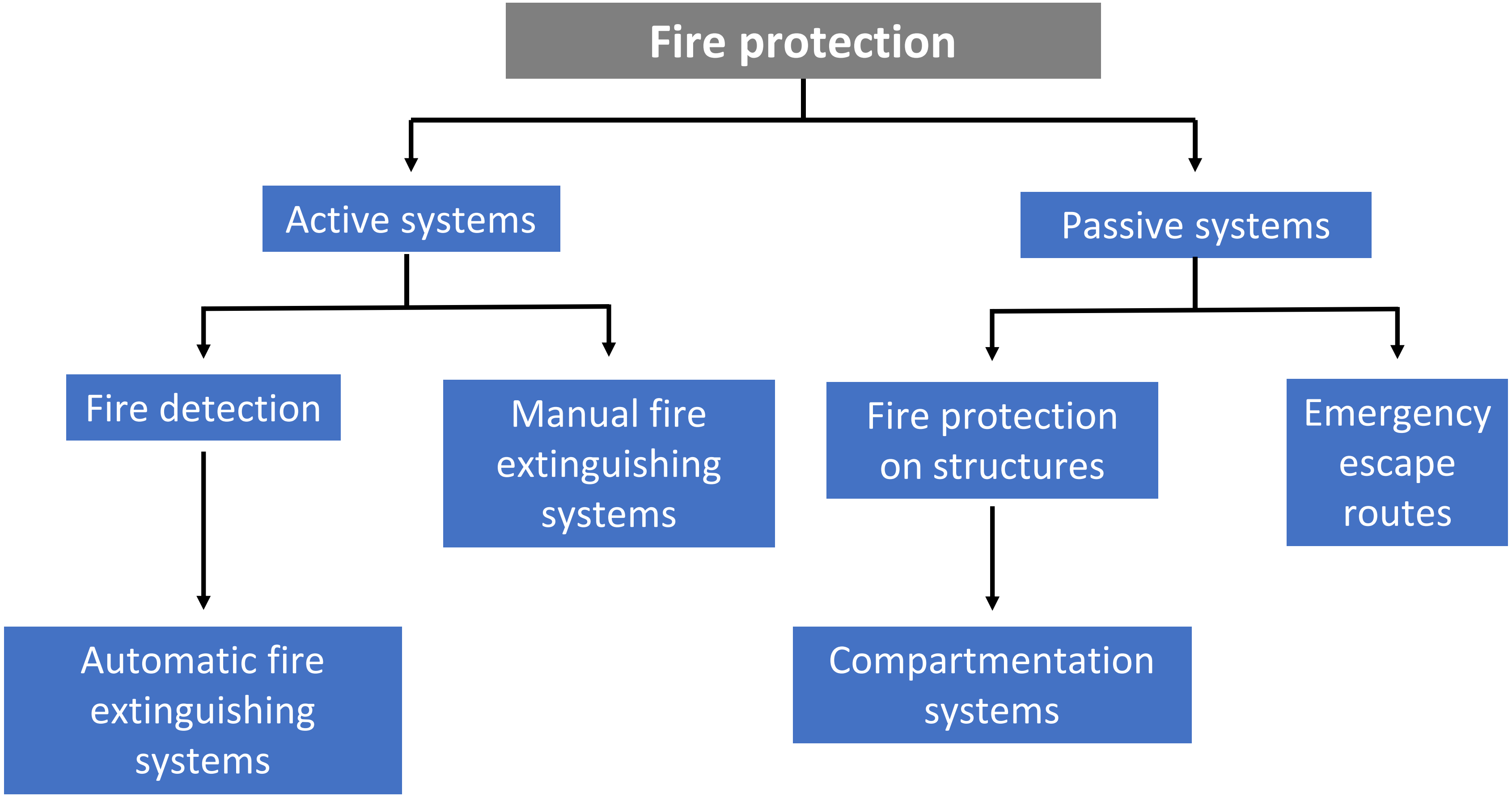
After the event

FIRE RISK

Fire risk is commonly subdivided in:

- **Low fire risk**: working places where low-flammable substances are present and it is unlikely the spread of the flames.
- **Medium fire risk**: working places where flammable substances are present and there is a limited possibility of spread of the flames.
- **High fire risk**: working places where high-flammable substances are present and there is a significant probability of spread of the flames.

FIRE PROTECTION STRATEGIES



SOURCES OF FIRE VULNERABILITY IN HISTORICAL BUILDINGS

Single building scale
- High density of wood elements
- No active protection systems
- No compartmentation systems

Local (Urban aggregate) scale
- Storage area of inflammable substances
- No active protection systems
- No compartmentation systems
- Eccessive rescue time

All these sources of vulnerability were present in the Notre-Dame de Paris Cathedral!

FIRE RISK: Notre-Dame de Paris fire

Underestimation of the vulnerability to fire attack of the attic

The New York Times

Notre-Dame's Safety Planners Underestimated the Risk, With Devastating Results

PARIS — The architect who oversaw the design of the fire safety system at Notre-Dame acknowledged that officials had misjudged how quickly a flame would ignite and spread through the cathedral, resulting in a much more devastating blaze than they had anticipated.

The system was based on the assumption that if the cathedral ever caught fire, the ancient oak timbers in the attic would burn slowly, leaving ample time to fight the flames, said Benjamin Mouton, the architect who oversaw the fire protections.

A 31-Minute Gap

The response to the Notre-Dame fire wasted critical minutes before the fire department was alerted, safety experts said.

6:20 P.M. **FIRST ALARM** When the alarm sounded, a fire security agent alerted church employees. A church guard then climbed a steep staircase to assess the attic before the fire department could be notified.

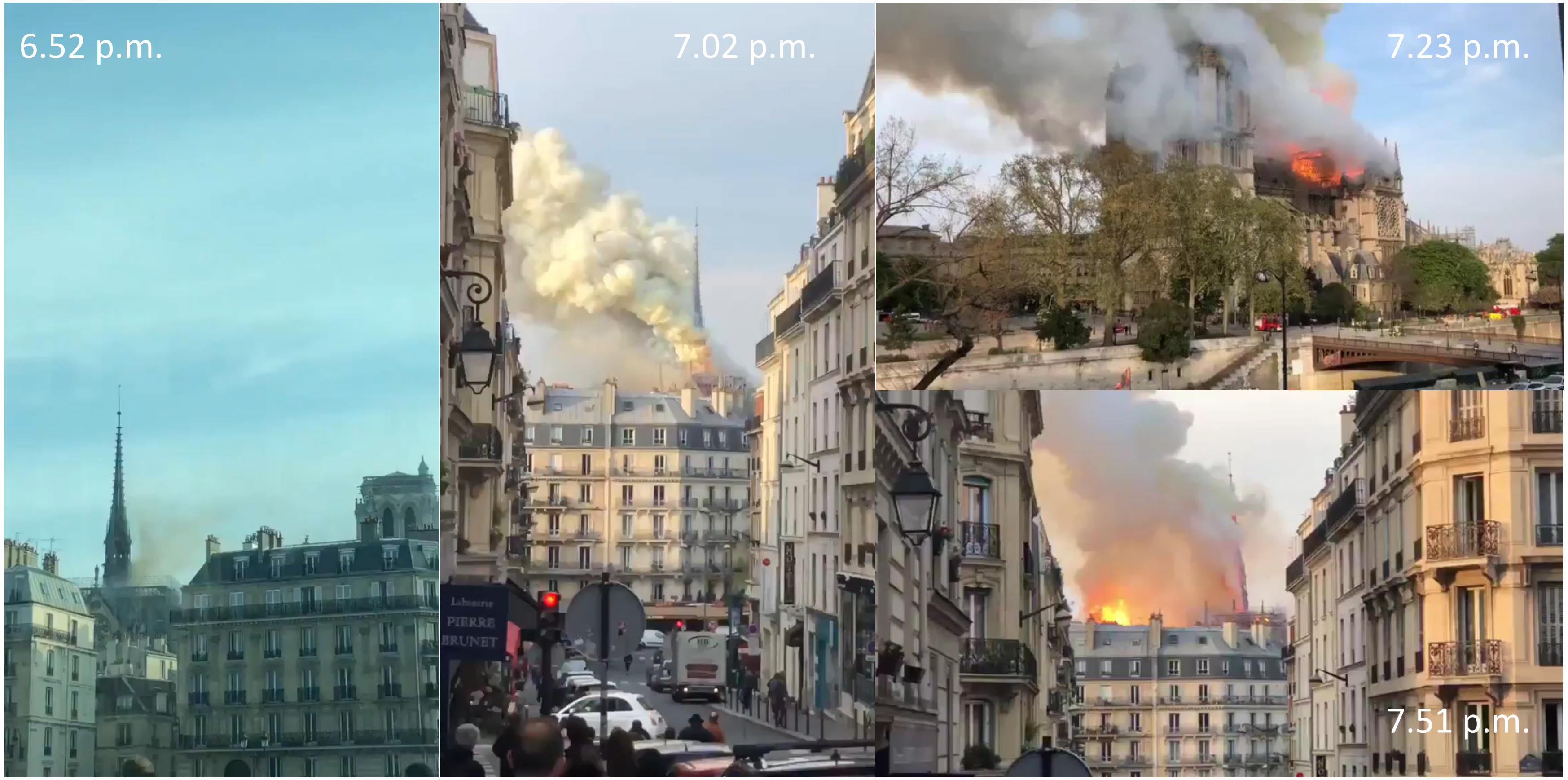
6:26 P.M. **6 minutes**
REACHES ATTIC The guard did not see a fire and returned to the ground with the all-clear.

6:43 P.M. **23 minutes**
SECOND ALARM Just as the cathedral was closing to the public for the day, a second alarm went off.

6:49 P.M. **29 minutes**
RETURN TO ATTIC Two church employees climbed back up the stairs, but the flames were too high to do anything. On their way down, they realized they had locked the door and had to go back to open it.

6:51 P.M. **31 minutes**
FIRE DEPARTMENT CALLED After more than a half-hour, the call finally went out to dispatch firefighters.

By Allison McCann and Elian Peltier



"Fire alarms in France never automatically alert the fire department…"

Delay in the fire response

20 more minutes: time from the moment the alarm sounded until firefighters could arrive and climb to the attic with hundreds of pounds of hoses and equipment to begin battling a fire

Fire design philosophy of historic structures is similar to that of the seismic design

- Even if no cost was spared, there was also a conservative approach to preserving the historic wooden structure in its pristine form

- The designers were determined not to alter the attic with protective measures like sprinklers or fire walls

Library of the Science Academy of Mosca 2015

Ruggi d’Aragona building (CS) 2017

San Francesco church in Castel Bolognese 2017



BLAST RISK: Ronan Point partial progressive collapse

CITY EDITION

THE GUARDIAN

Manchester Friday May 17 1968

Price 6d

Pound falls to lowest level

Pompidou's plea: 'Reject anarchy'

Flat victims may refuse to return

Hospital patient given a new lung

Oxford student inquiry

Sick pay changes dropped

Three killed in house fire

US forces lose 562 dead in a week

Miss Taylor buys £127,083 ring

Girl trapped in sand hopper

Adventure overseas competition

VIETNAM what will peace bring for the victims?

Footprint led to trapped miners

Ronan Point flats, Newham, yesterday (Picture by Peter Johns)

Date: May 16, 1968

Deaths: 4

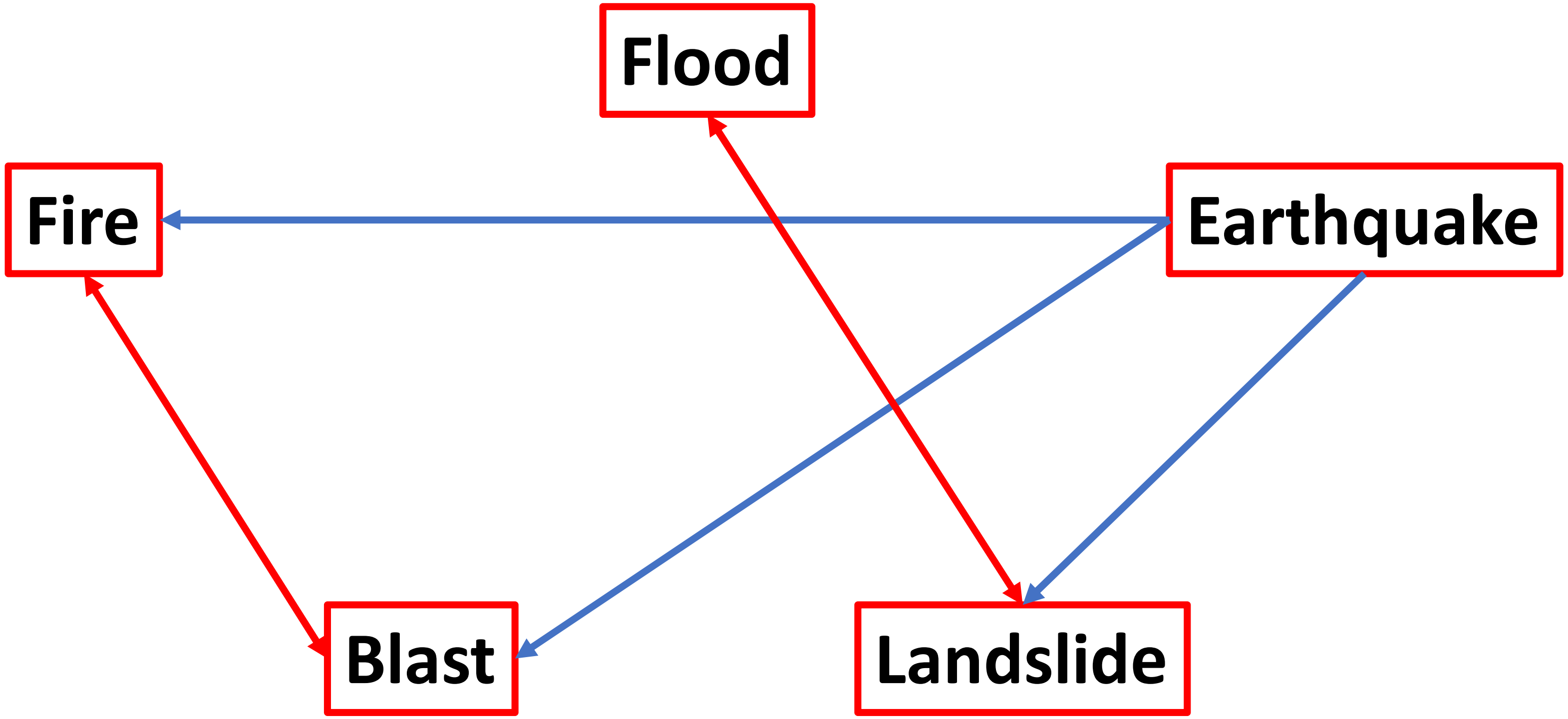
Injured: 17

Other data:

- Gas explosion in the kitchen of the 18th floor
- 22-storey tower block collapsed

The collapse highlighted the importance of avoiding progressive collapse in structural design

CORRELATION BETWEEN THE HAZARDS



A quantitative definition of these correlations is far away to be accomplished!

PEER APPROACH

Progress and Challenges in Seismic Performance Assessment

PEER research on seismic performance assessment is approaching the end of its second year. Much has been accomplished, but the end of the road still looks far away. In this brief article we describe the foundation on which performance assessment can be based, and the major challenges to the PEER research community on the way to expected success.

Proposed Probabilistic Foundation

The following scheme is presented as an effective foundation for the development of performance-based guidelines. It suggests a generic structure for coordinating, combining, and assessing the many considerations implicit in performance-based seismic assessment and design.

The suggested foundation in its generalized form assumes that the basis for assessing the adequacy of the structure or its design will be a vector of certain key ***Decision Variables***, $\underline{DV}$, such as the annual earthquake loss and/or the exceedance of one or more limit states (e.g., collapse). These can only be predicted probabilistically. Therefore the specific objectives of engineering assessment analyses are in effect quantities such as $\lambda_{\$}(x)$, the mean annual frequency[1] (MAF) of the loss exceeding x dollars, or such as $\lambda_{I_{coll}}$, the MAF of collapse, or more formally the mean annual frequency that the collapse indicator variable[2], I_{coll}, exceeds 0.

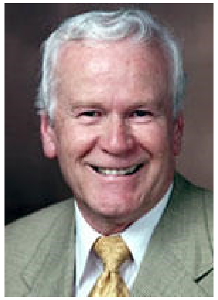
Then, the practical and natural analysis strategy involves the expansion and/or "disaggregation" of the MAF, $\lambda(\underline{DV})$, in terms of structural ***Damage Measures***, $\underline{DM}$, and ground motion ***Intensity Measures***, $\underline{IM}$, which can be written symbolically as

$$\lambda(\underline{DV}) = \iint G(\underline{DV} \mid \underline{DM})\, dG(\underline{DM} \mid \underline{IM})\, d\lambda(\underline{IM}) \qquad (1)$$

Here $G(\underline{DV} \mid \underline{DM})$ is the probability that the (vector of) decision variable(s) exceed specified values given (i.e., conditional on knowing) that the engineering Damage Measures (e.g., the maximum interstory drift, and/or the vector of cumulative hysteretic energies in all elements) are equal to particular values. Further, $G(\underline{DM} \mid \underline{IM})$ is the probability that the Damage Measure(s) exceed these values given that the Intensity Measure(s) (such as spectral acceleration at the fundamental mode frequency, and/or spectral shape parameters and/or duration) equal particular values. Finally $\lambda(\underline{IM})$ is the MAF of the Intensity Measure(s).

The first version of the "PEER scheme" appeared online in 2000 on the section "PEER News" of the PEER web site

Carl Allin Cornell (1938-2007)



Helmut Krawinkler (1940-2012)

DEFINITION OF THE DECISION VARIABLES

The first step to face the risk assessment of various alternative solutions for design of a new construction or for interventions on an existing structure is represented by the definition of a proper decision variable(s), which should be easily understandable by the stakeholders or politicians.

In **engineering** one/some of the following DVs are commonly adopted :

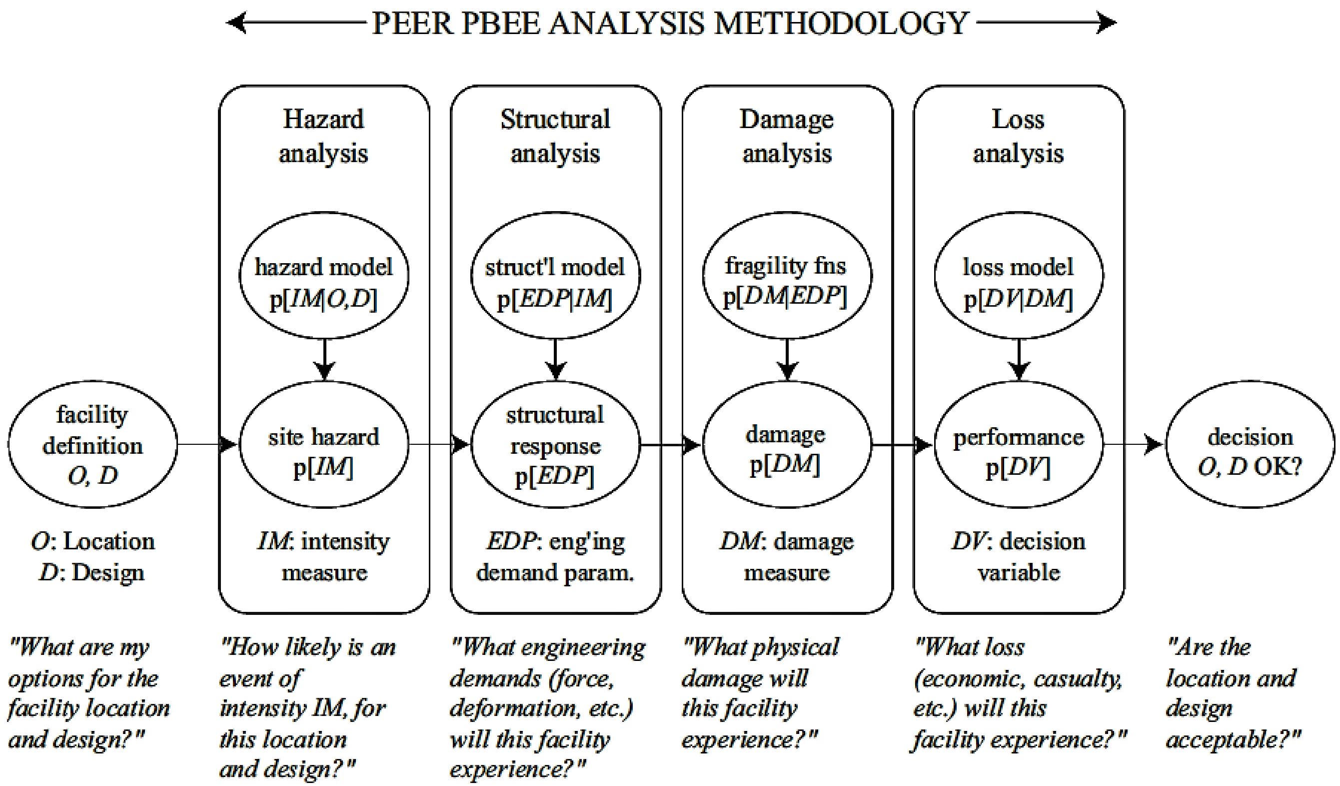
- €/year spent to repair the structure
- **downtime/year in which a facility or a monument is shut down to be repaired**
- deaths/year

PEER APPROACH AS PERFORMANCE-BASED EARTHQUAKE ENGINEERING ANALYSIS METHODOLOGY(*)

A methodology to compare:

- **Designs** (*e.g.,* structural schemes)
- **Existing buildings** (single or portfolios)
- **Retrofitting solutions**
- **Locations**
- **Etc.**

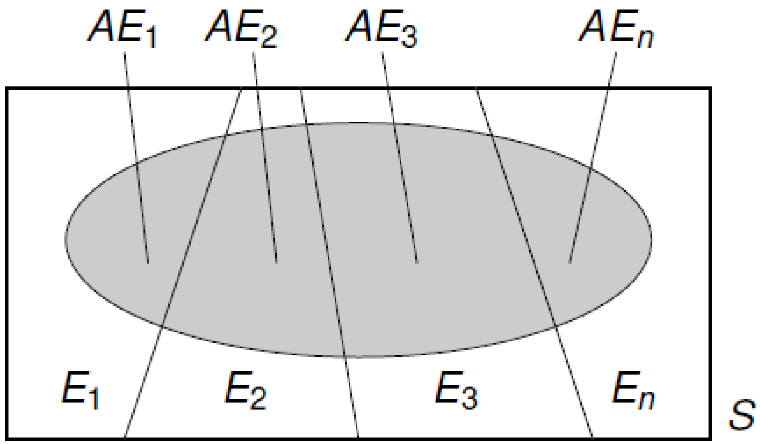
in an easily understandable manner to stakeholders and politicians



(*) Lee T.H, Mosalam K.M., Probabilistic seismic evaluation of reinforced concrete structural components and systems. *PEER Report 2006/04*, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, August, 2006.

PEER APPROACH FROM TOTAL PROBABILITY THEOREM

Let us consider the event of a certain decision variable *A* (*e.g.*, "annual economic loss higher than x euro") and the sample space *S* (the set of all possible events). One can write:



$$A = AS$$

Let us consider *n* events E_i related to a certain engineering demand parameter ("displacement at the building top")

$$E_1 : s_1 \leq s \leq s_1 + \Delta s$$
$$E_2 : s_2 \leq s \leq s_2 + \Delta s$$
$$\dots$$
$$E_n : s_n \leq s \leq s_n + \Delta s$$

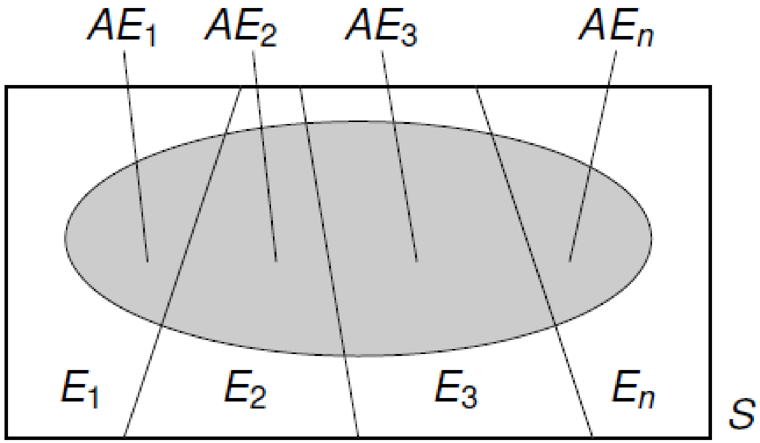
Since that they are **mutually exclusive** and **collectively exhaustive**, the sample space *S* is simply the sum of all the events:

$$S = E_1 \cup E_2 \dots \cup E_n$$

PEER APPROACH FROM TOTAL PROBABILITY THEOREM

By manipulating the previous equations one can write: $A = AS = A(E_1 \cup E_2 \ldots \cup E_n)$

By using a property of the sets: $A = A(E_1 \cup E_2 \ldots \cup E_n) = AE_1 \cup AE_2 \ldots \cup AE_n$



It can be assigned the probabilities to the previous sets and then:

$$P(A) = P(AE_1) + P(AE_2) + \ldots + P(AE_n)$$

Thanks to the conditional probability definition, we can write:

$$P(A) = P(A|E_1)P(E_1) + P(A|E_2)P(E_2) + \ldots + P(A|E_n)P(E_n)$$

For continuous events: $P(A) = \int P(A|E)p(E)dE$



PEER APPROACH

Cornell & Krawinkler(*) from PEER (Pacific Earthquake Engineering Research) center proposed:

$$\lambda(\mathbf{DV}) = \int\int G(\mathbf{DV}|\mathbf{DM})|dG(\mathbf{DM}|\mathbf{IM})|\,|d\lambda(\mathbf{IM})|$$

Few years later, Krawinkler(**):

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

The PEER formulation can be applied in the present form for **mono-hazard risk assessments**, its application to multi-hazard problems require an extension and additional information difficult to find

(*) Cornell C.A., Krawinkler H. Progress and challenges in seismic performance assessment. PEER center news; 2000. <http://peer.berkeley.edu/news/ 2000spring/index.html>.

(**) Krawinkler H., A general approach to seismic performance assessment. In International Conference on Advances and New Challenges in Earthquake Engineering Research, First annual meeting of ANCER, Hong Kong, China, 2002

PEER APPROACH

The PEER expression is obtained by applying three times the total probability theorem:

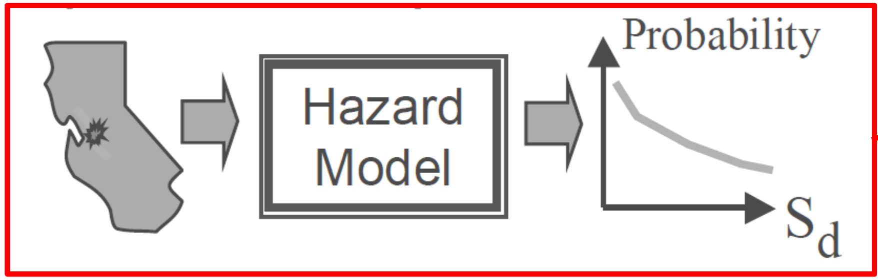
$$\lambda(\mathbf{DV}) = \int\int\int G(\mathbf{DV}|\mathbf{DM})|dG(\mathbf{DM}|\mathbf{EDP})||dG(\mathbf{EDP}|\mathbf{IM})||d\lambda(\mathbf{IM})|$$

- $\lambda(\mathbf{DV})$ is the mean annual frequency (MAF) of the decision variable (inverse of the return period)
- $G(\mathbf{DV}|\mathbf{DM})$ is the probability of exceedance of a certain decision variable given a specific damage in the structure (term provided by the **seismic engineering researchers, economists** and **practitioners**)
- $G(\mathbf{DM}|\mathbf{EDP})$ is the probability of exceedance of a certain damage variable given a specific engineering demand parameters (term provided by the **seismic engineering researchers** and **practitioners**)
- $G(\mathbf{EDP}|\mathbf{IM})$ is the probability of exceedance of a certain engineering demand parameters given a specific intensity measure (term provided by the **seismic engineering researchers**)
- $\lambda(\mathbf{IM})$ is the mean annual frequency (MAF) of the intensity measure at the site of the structure (term provided by **seismologists**)

HAZARD ANALYSIS

This analysis is conducted to describe the earthquake hazard in a probabilistic manner

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



Input:
- nearby faults
- their magnitude-recurrence rates
- fault mechanism
- source-site distance
- site conditions

Output:
- hazard curve
- selection of a number of ground motion time histories compatible with the hazard curve

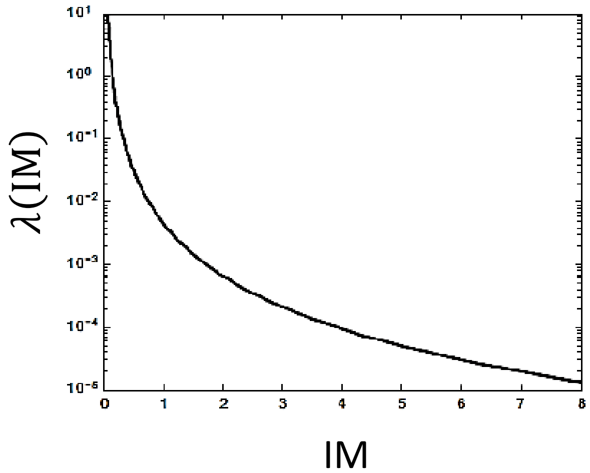
(*) Cornell C.A., Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, Vol. 58, No. 5, pp. 1583-1606, October, 1968.

HAZARD ANALYSIS

The *hazard curve* represents the variation of a selected *intensity measure* (ground motion parameter), denoted by IM, against the mean annual frequency of exceedance.

Assuming that the occurrence of an earthquake follows a *Poisson model*, the probability of exceedance of an intensity parameter in "t" years corresponding to a given mean annual frequency of exceedance is calculated through:

$$P(IM) = 1 - e^{\lambda(IM)t}$$



Intensity measures (IMs) adopted in earthquake engineering are:

- Peak ground acceleration PGA
- Peak ground velocity PGV
- Spectral acceleration at the period of the first mode $S_a(T_1)$
- Structure-specific intensity measures[(*)]

[(*)] Luco N., Cornell C.A., Structure-specific scalar intensity measures for near-source and ordinary earthquake ground motions. *Earthquake Spectra* **23** (2), pp. 357-392, May, 2007.

STRUCTURAL ANALYSIS

This analysis is conducted to determine the response of a structure to several levels of earthquake in a probabilistic manner.

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

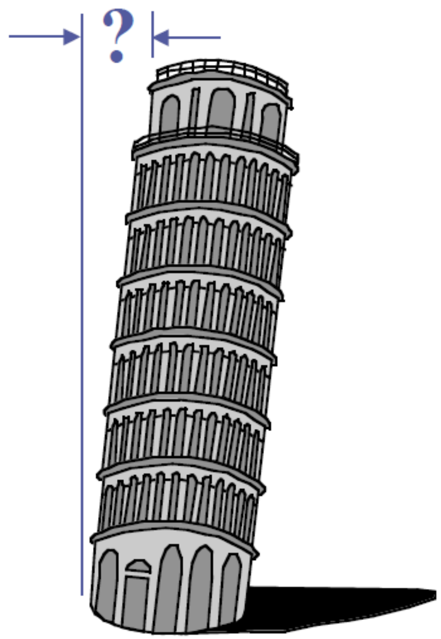
Input:
- ground motion records
- computational model of the structure
- uncertainties of the input parameters of the computational model

Output:
- vulnerability surface
- vulnerability curve

STRUCTURAL ANALYSIS

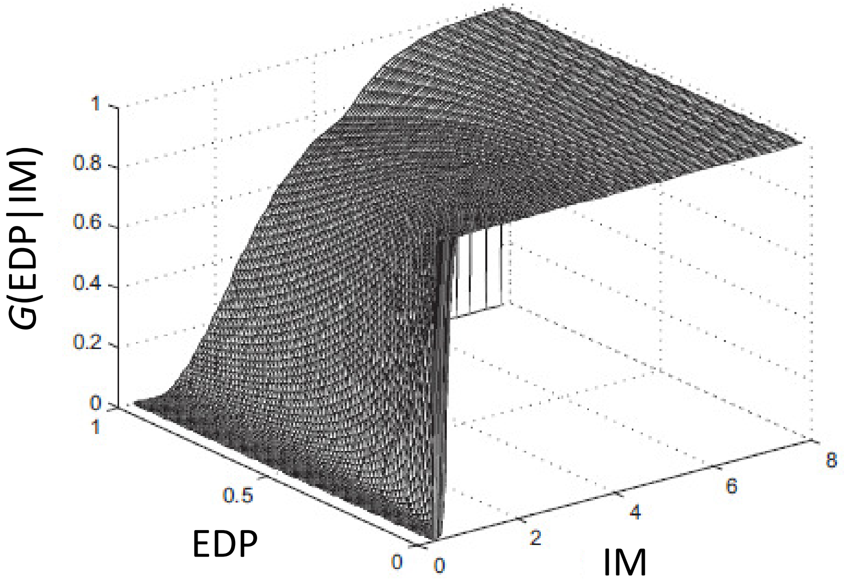
Engineering demand parameters (EDPs) adopted in earthquake engineering depends on the specific structure as well as problem:

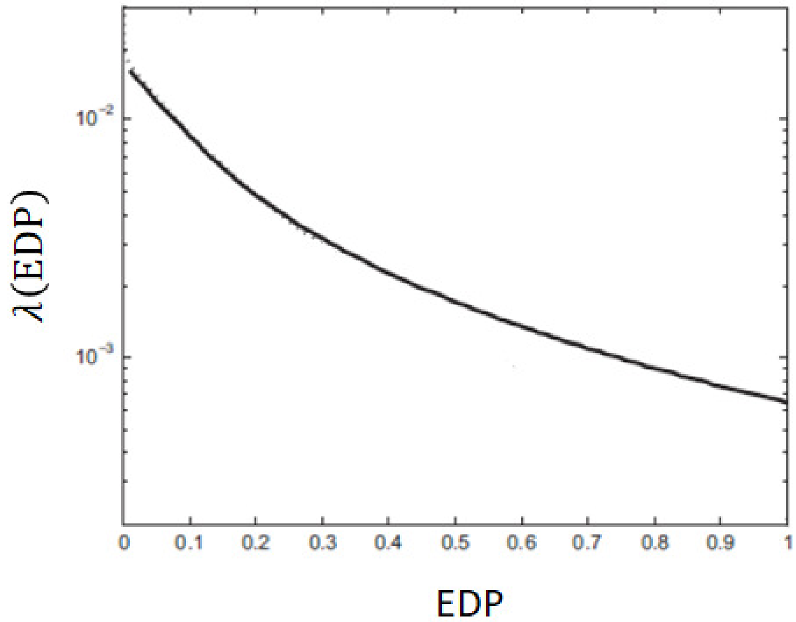
- displacement to the top of the structure (*e.g.*, frame structures, towers)
- interstory drift (*e.g.*, frame structures)
- rotation of joints (*e.g.*, racks)
- forces (*e.g.*, non-ductile frame structures)
- floor accelerations (*e.g.*, art objects)



STRUCTURAL ANALYSIS

This analysis allows obtaining the *vulnerability surface* as well as the *vulnerability curve* corresponding to a certain EDP





The vulnerability curve can be obtained by a first convolution of the hazard curve and the vulnerability surface

$$\lambda(\mathbf{EDP}) = \int G(\mathbf{EDP}|\mathbf{IM})|d\lambda(\mathbf{IM})|$$

DAMAGE ANALYSIS

This analysis is conducted to determine the damage of a structure for different structural responses in a probabilistic manner

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

Input:
- data on the correlation between the structural response (EDP) and the various typologies of damage

Output:
- damage surface
- damage curve

DAMAGE ANALYSIS

- All the main components need to be separated into performance group
- Each group is affected by the same EDP
- A fragility curve is assigned to each group

Performance group	Components	EDP
PG1	Structural system. (lateral load resisting system)	Δ_1
PG2		Δ_2
PG3		Δ_3
PG4	Exterior enclosure (glass)	Δ_1
PG5		Δ_2
PG6		Δ_3
PG7	Drift sensitive non-structural elements (doors)	Δ_1
PG8		Δ_2
PG9		Δ_3
PG10	Acceleration sensitive non-structural elements (ceiling tiles)	a_2
PG11		a_3
PG12		a_R
PG13	Office content (computers)	a_g
PG14		a_2
PG15		a_3
PG16	Equipment on roof	a_R

Table 6.8 Performance groups

Components		>= DS2	>= DS3	>= DS4
Structural system	Median	1.5	2.5	3.5
	C.o.v.	0.25	0.30	0.30
Exterior enclosure	Median	2.8	3.1	-
	C.o.v.	0.097	0.12	-
Drift sensitive non-structural elements	Median	0.39	0.85	-
	C.o.v.	0.17	0.23	-
Acceleration sensitive non-structural elements	Median	1.0	1.5	2.0
	C.o.v.	0.15	0.2	0.2
Office content	Median	0.3	0.7	3.5
	C.o.v.	0.20	0.22	0.25
Equipment on roof	Median	1.0	2.0	-
	C.o.v.	0.15	0.2	-

Table 6.9 Definition of fragility curves

DAMAGE ANALYSIS

This analysis allows obtaining the *damage surface* as well as the *damage curve* corresponding to a certain DM

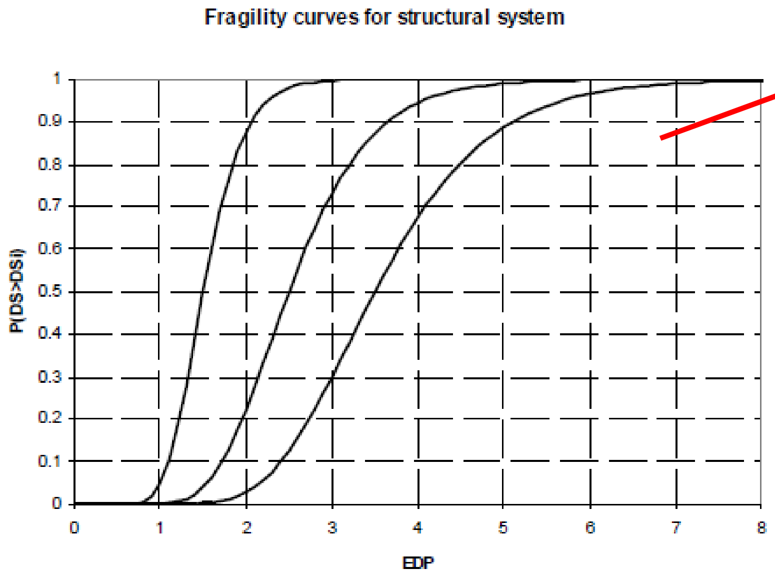
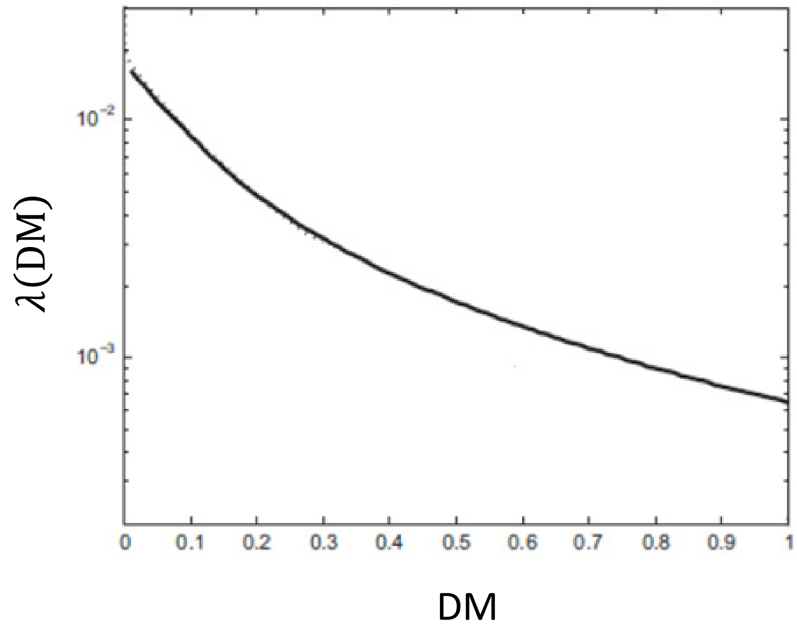


Figure 6.3 Fragility curves for structural system

It is commonly expressed in a discrete manner according to the various typologies of structural damage



The damage curve can be obtained by the vulnerability curve and the damage surface

$$\lambda(\mathbf{DM}) = \int G(\mathbf{DM}|\mathbf{EDP})|d\lambda(\mathbf{EDP})|$$

LOSS ANALYSIS

This analysis is conducted to determine the losses corresponding to different levels of structural damage in a probabilistic manner

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

Input:

- data on the correlation between the various typologies of structural damage (DM) and the losses

Output:

- loss surface
- loss curve

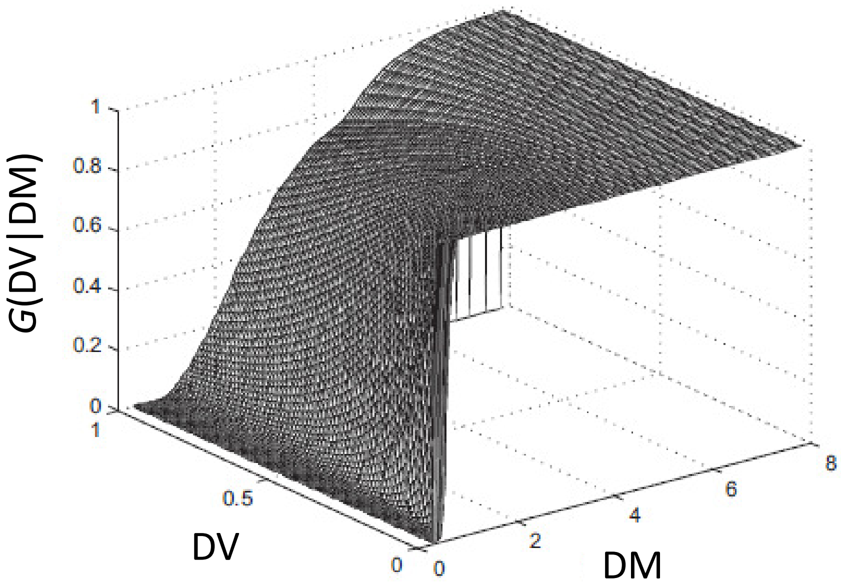
LOSS ANALYSIS

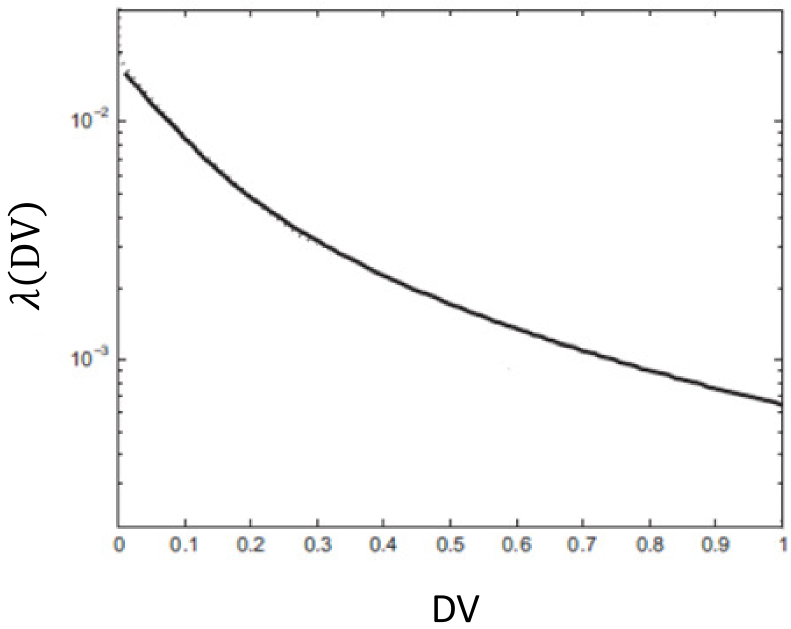
Decision variables (DVs) adopted in earthquake engineering is usually proposed by the stakeholders or owners together with the technical experts. A list of meaningful parameters for the stakeholders is here attempted:

- €/year spent to repair the structure
- downtime/year in which an industry or a monument is closed to be repaired
- deaths/year

LOSS ANALYSIS

This analysis allows obtaining the *loss surface* as well as the *loss curve* corresponding to a certain DV





The loss curve can be obtained by the damage curve and the loss surface

$$\lambda(\mathbf{DV}) = \int G(\mathbf{DV}|\mathbf{DM})|d\lambda(\mathbf{DM})|$$

PEER APPROACH IS A MODULATE APPROACH

The scheme "de-convolves" the evalutation of the probabilistic behaviour of a decision variable (DV) by introducing three intermediate variables:

- A structural damage measure DM $\lambda(\mathbf{DM}) = \int G(\mathbf{DM}|\mathbf{EDP})|d\lambda(\mathbf{EDP})|$
- An engineering demand parameter EDP $\lambda(\mathbf{EDP}) = \int G(\mathbf{EDP}|\mathbf{IM})|d\lambda(\mathbf{IM})|$
- An intensity measure IM $\lambda(\mathbf{IM})$

to which can be associated the corresponding curves.

Once the various terms are defined, one can obtain the loss curve useful for the stakeholders

$$\lambda(\mathbf{DV}) = \int G(\mathbf{DV}|\mathbf{DM})|d\lambda(\mathbf{DM})|$$



APPLICATION OF THE PEER APPROACH FOR A MULTIHAZARD ANALYSIS

To apply the PEER approach for the risk assessment of the other hazards, we need to define:

- the proper decision variables (DVs), damage measures (DMs), engineering demand parameters (EDPs) and intensity measures (IMs)
- to estimate the various probabilities of exceedance present in the scheme

In a multihazard risk assessment, the right choice of the decision variable can allow to compare and to prioritize the interventions in the different fields (flood, earthquake, blast, fire, landslide risks, etc.)

Leaving aside the problem of defining the probabilistic terms, one of the main concerns regards the definition of the correlation among the various hazards.

Intensity Measures (IMs) for various hazards

Fire	Flood	Earthquake	Blast	Landslide
• Intensity	• Water level in the river	• PGA • $S_a(T_1)$	• Intensity	• Sliding • Settlement

Engineering Demand Parameters (EDPs) for various hazards

Fire
- Rate of spread

Flood
- Water level in the invested system
- Water velocity in the invested system near the river

Earthquake
- Interstory drift
- Floor acceleration
- Horizontal displacement top level

Blast
- Degree of expulsion

Landslide
- Forces/Stresses in the structure
- Interstory drift
- Floor acceleration
- Horizontal displacement top level

Damage Measures (DMs) for various hazards

Fire

- # of damaged structural elements
- # of damaged contents

Flood

- # of damaged contents

Earthquake

- # of damaged structural elements
- # of damaged contents

Blast

- # of damaged structural elements
- # of damaged contents

Landslide

- # of damaged structural elements
- # of damaged contents

Decision Variables (DVs) for various hazards

Fire	Flood	Earthquake	Blast	Landslide
• €/year • Days/year of closure (downtime) • Casualties/year • Injured/year	• €/year • Days/year of closure (downtime) • Casualties/year • Injured/year	• €/year • Days/year of closure (downtime) • Casualties/year • Injured/year	• €/year • Days/year of closure (downtime) • Casualties/year • Injured/year	• €/year • Days/year of closure (downtime) • Casualties/year • Injured/year

RISK ASSESSMENT APPROACH

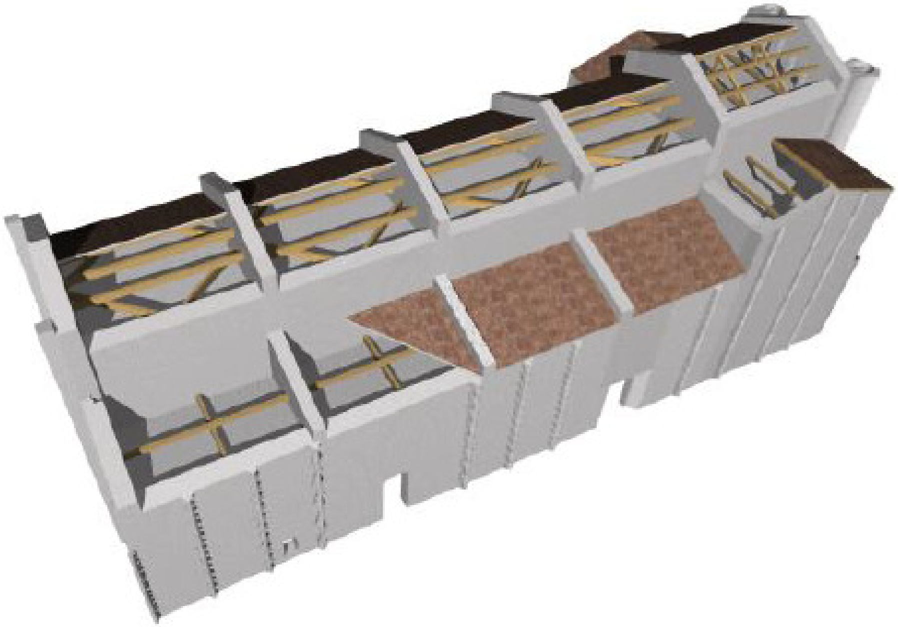
The details to be considered depend on the **extension of the system**. As a matter of fact, the approaches can be classified into:

- **Macroscale** risk assessment procedures (entire city, bridge network, etc.), in which statistics on similar case studies are used to define the various probabilistic terms
- **Microscale** risk assessment procedures (single building, bridge, facilities, etc.), where detailed analysis are developed and specific experimental *in situ* tests/measurements are used for a proper definition of the models

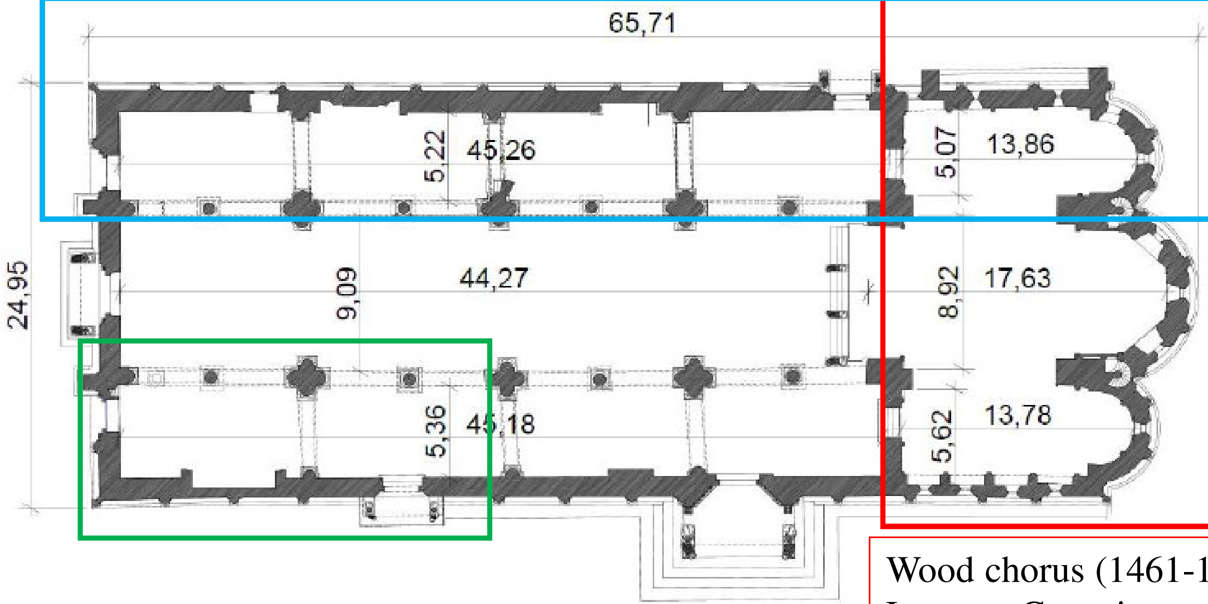
MULTISCALE APPROACH FOR THE RISK ASSESSMENT OF CULTURAL HERITAGE

MULTISCALE APPROACH: Modena cathedral

Several wood elements at risk due to fire hazard



Precious content



Wood sculpture of San Gemignano

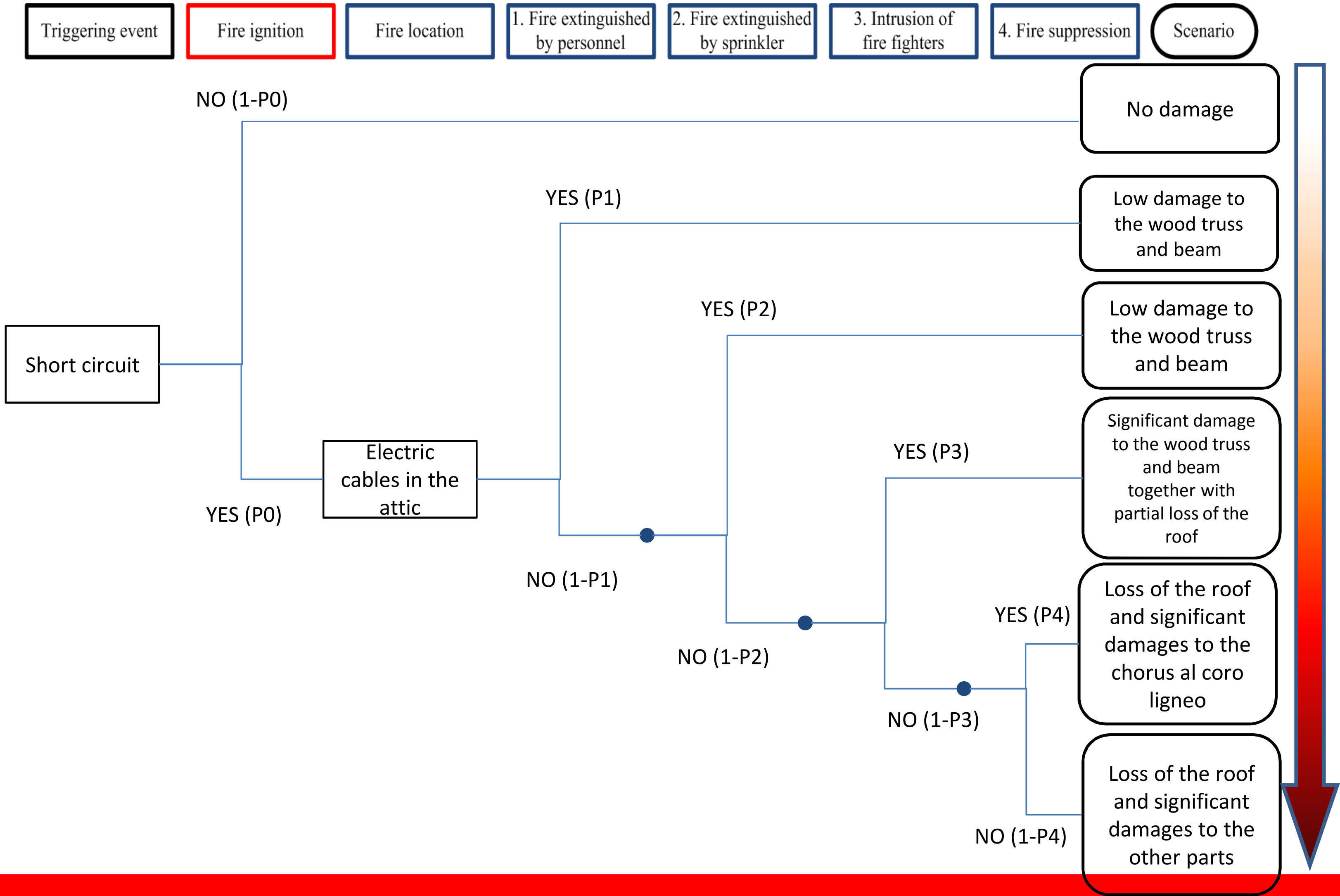
Pala di San Sebastiano (1500) build by Dosso Dossi.

Wood chorus (1461-1465) built by Cristoforo and Lorenzo Canozi.

Chapel of Bellincini-affreschi (1400)

Large number of occupants

Museum adjacent to the cathedral → Risk of spread of the fire

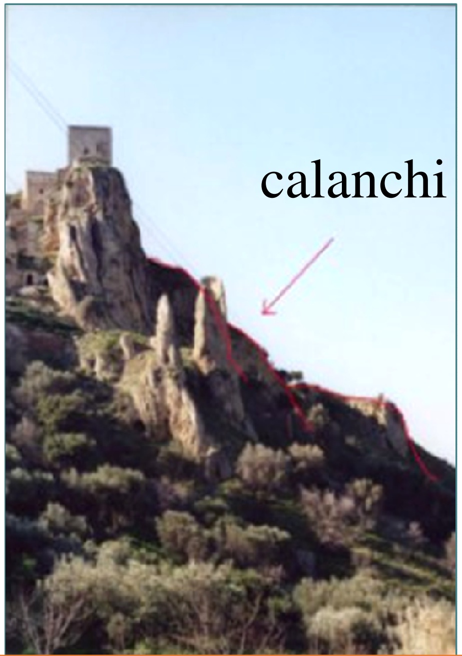

Triggering event
Fire ignition
Fire location
1. Fire extinguished by personnel
2. Fire extinguished by sprinkler
3. Intrusion of fire fighters
4. Fire suppression
Scenario
Short circuit
NO (1-P0)
YES (P0)
Electric cables in the attic
YES (P1)
NO (1-P1)
YES (P2)
NO (1-P2)
YES (P3)
NO (1-P3)
YES (P4)
NO (1-P4)
No damage
Low damage to the wood truss and beam
Low damage to the wood truss and beam
Significant damage to the wood truss and beam together with partial loss of the roof
Loss of the roof and significant damages to the chorus al coro ligneo
Loss of the roof and significant damages to the other parts

MULTISCALE APPROACH: CRACO

VIII – X secolo a.C.

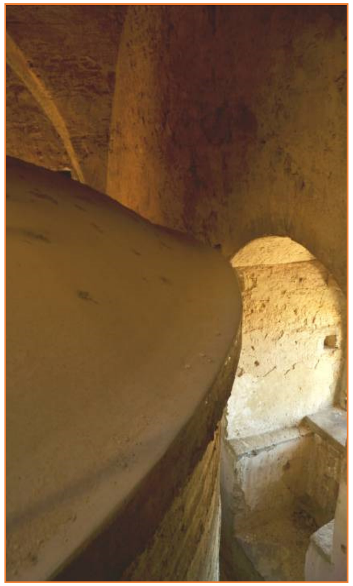
390 m a.s.l.

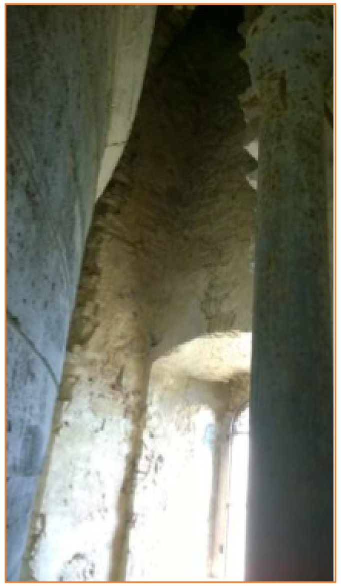
Landslide from 1959 to 1972
Evacuation in 1962 and 1991



MULTISCALE APPROACH: NORMANNA TOWER

Vault





Tank

Modal analysis of the complete model

MODE PARTICIPATION FOR TRANSLATIONAL EXCITATION

Mode	Frequency (Hz)	Modal Mass (Eng)	Modal Stiff (Eng)	PF-X (%)	PF-Y (%)	PF-Z (%)
1	2.6435E+00	8.9887E+05	2.4798E+08	0.001	71.557	0.000
2	3.1350E+00	5.9616E+05	2.3132E+08	49.177	0.002	0.000
3	5.0349E+00	9.8685E+05	9.8764E+08	0.001	0.155	0.000
4	7.1541E+00	6.5488E+05	1.3232E+09	0.004	12.011	0.000
5	1.0165E+01	1.8344E+06	7.4831E+09	0.052	0.154	0.000
6	1.0585E+01	3.7858E+05	1.6746E+09	11.626	0.002	0.000
7	1.0851E+01	1.2449E+05	5.7865E+08	5.999	0.962	0.000
8	1.0854E+01	1.2447E+05	5.7884E+08	0.963	5.999	0.000
9	1.1782E+01	3.3993E+05	1.8629E+09	2.023	0.003	0.000
10	1.2961E+01	1.3162E+05	8.7286E+08	0.000	1.653	0.000
11	1.4176E+01	1.0133E+06	8.0388E+09	0.048	0.055	0.000
12	1.7204E+01	1.4295E+05	1.6704E+09	0.249	0.409	0.000
13	1.7979E+01	3.2259E+05	4.1167E+09	0.157	0.081	0.000
14	1.8196E+01	3.0459E+05	3.9812E+09	0.007	0.017	0.000
15	1.9089E+01	2.1236E+05	3.0551E+09	0.135	0.075	0.000
16	2.0319E+01	2.1817E+05	3.5562E+09	0.895	0.247	0.000
17	2.1008E+01	1.5760E+05	2.7461E+09	1.642	0.020	0.000
18	2.1210E+01	2.0623E+05	3.6626E+09	0.003	0.005	0.000
19	2.3134E+01	9.4985E+03	2.0069E+08	0.222	0.152	0.000
20	2.3270E+01	8.9804E+04	1.9198E+09	0.000	0.000	0.000
21	2.3305E+01	1.1318E+05	2.4269E+09	0.000	0.000	0.000
22	2.3597E+01	9.0642E+03	1.9925E+08	0.022	0.115	0.000
23	2.3752E+01	1.4403E+04	3.2078E+08	0.067	0.004	0.000
24	2.4791E+01	2.1942E+04	5.3240E+08	0.000	0.653	0.000
25	2.5104E+01	4.5612E+03	1.1348E+08	0.082	0.050	0.000
TOTAL TRANSLATIONAL MASS PARTICIPATION FACTORS				73.374	94.381	0.000

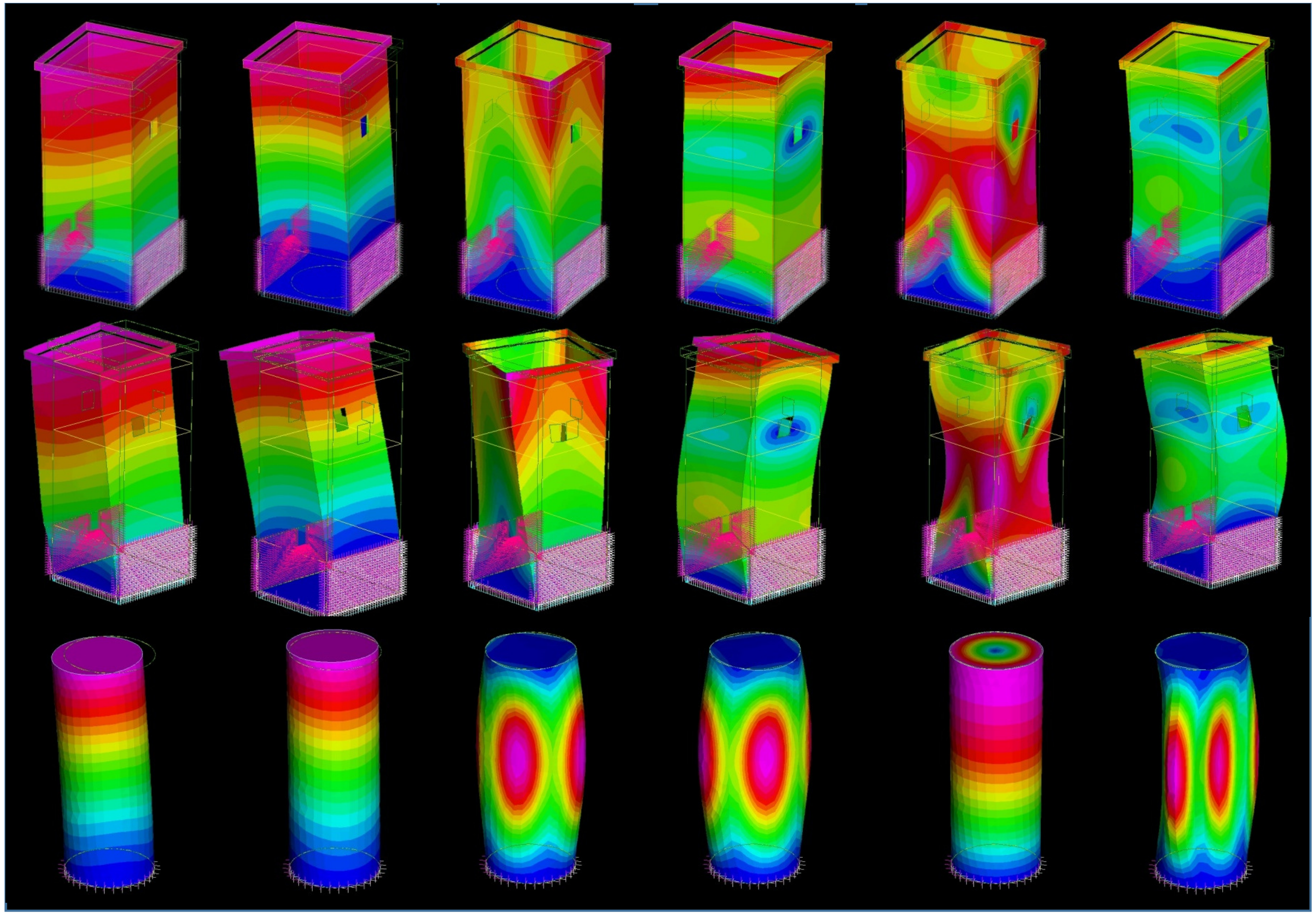
	Frequency [Hz]	Period [s]
I mode	2,643	0,38
II mode	3,135	0,31
III mode	5,034	0,19
IV mode	7,154	0,14
V mode	10,016	0,10
VI mode	10,058	0,09

Modal analysis

Complete model

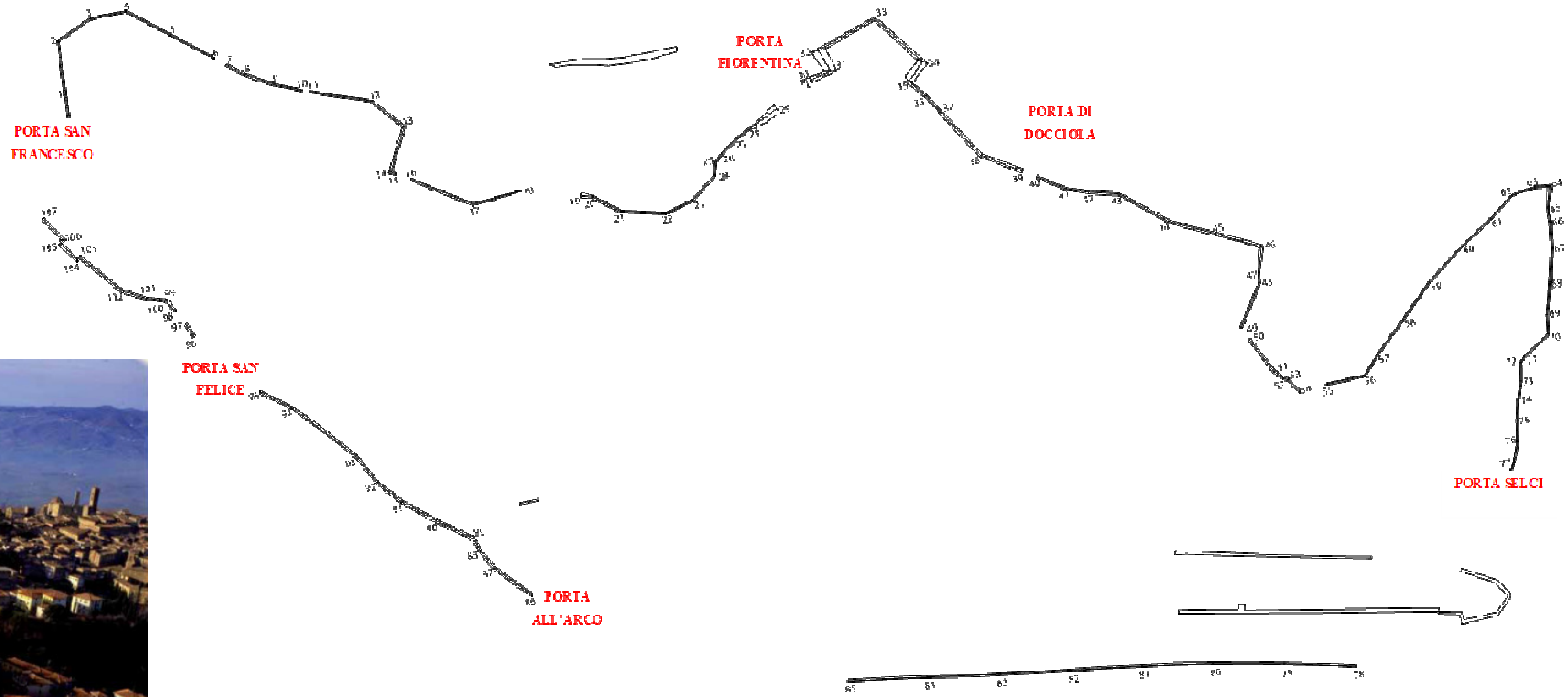
Model with only masonry

Model of the tank



1° Mode 2° Mode 3° Mode 4° Mode 5° Mode 6° Mode

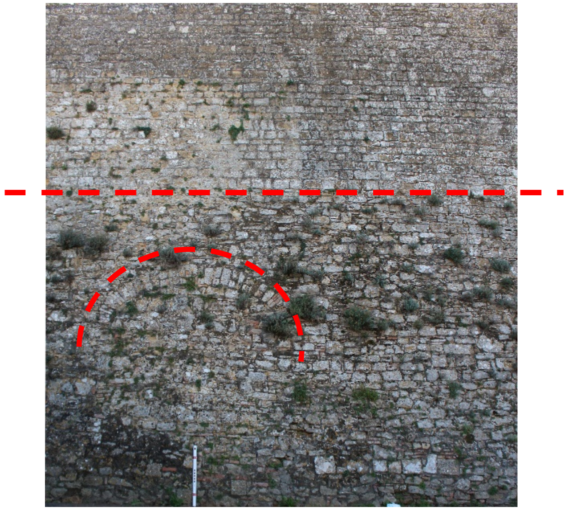
MULTISCALE APPROACH: VOLTERRA URBAN WALLS



Buildings, infrastructures and plants

Masonry texture, different periods of construction

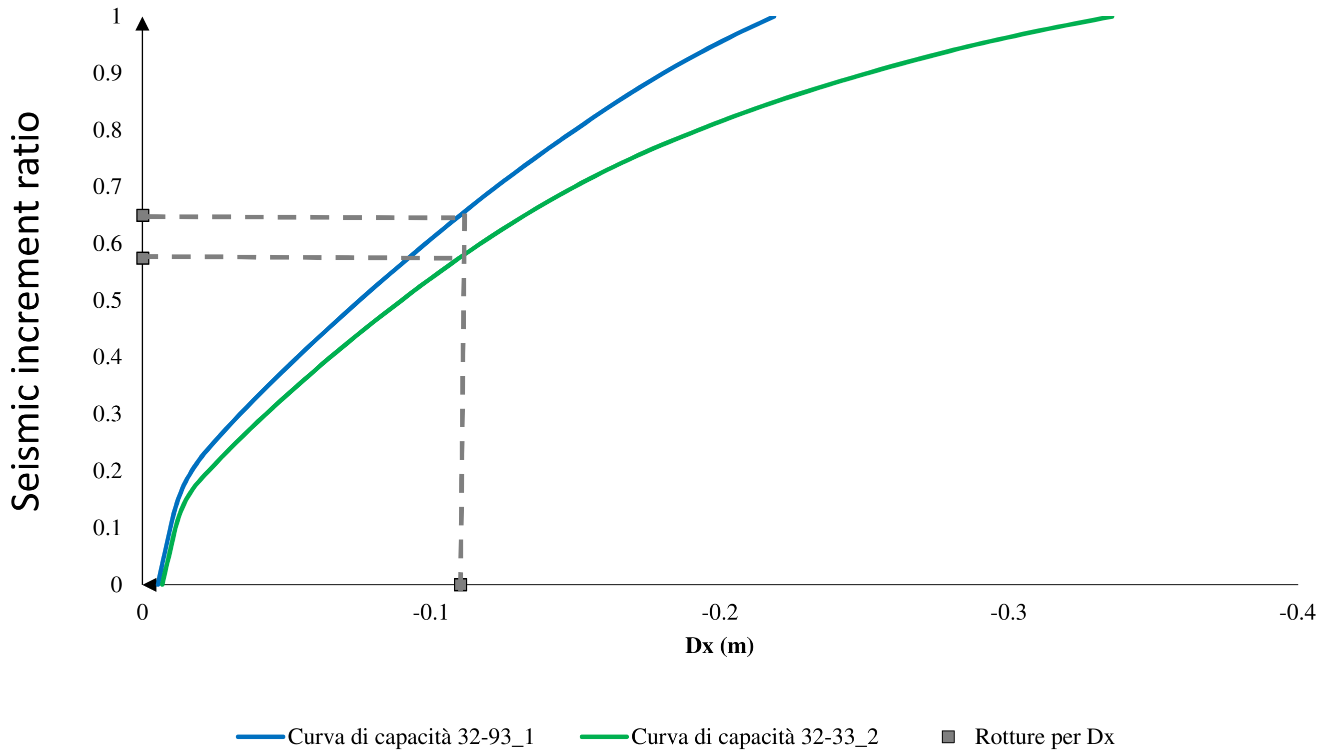
Structural deterioration and weak points observed during the survey

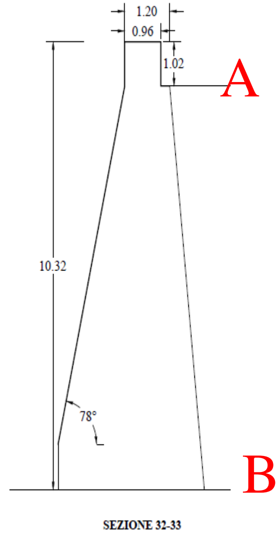


Earthquake analysis

Cross section 32-33: Comparison between capacity curves







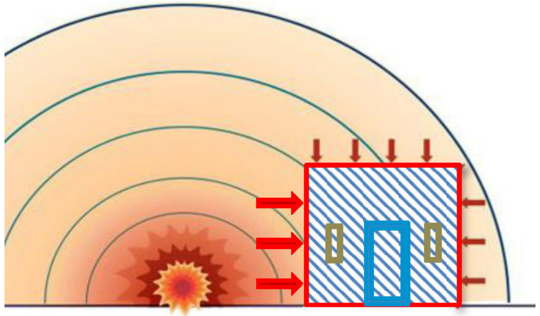
SIMPLIFIED IMPLEMENTATION FOR THE HISTORIC CITY CENTER OF FLORENCE

MULTIHAZARDS FOR CULTURAL HERITAGE

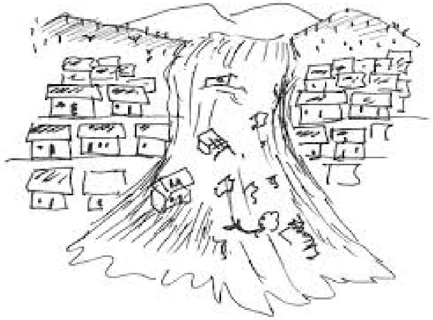
Earthquake risk

Flood risk

Fire risk

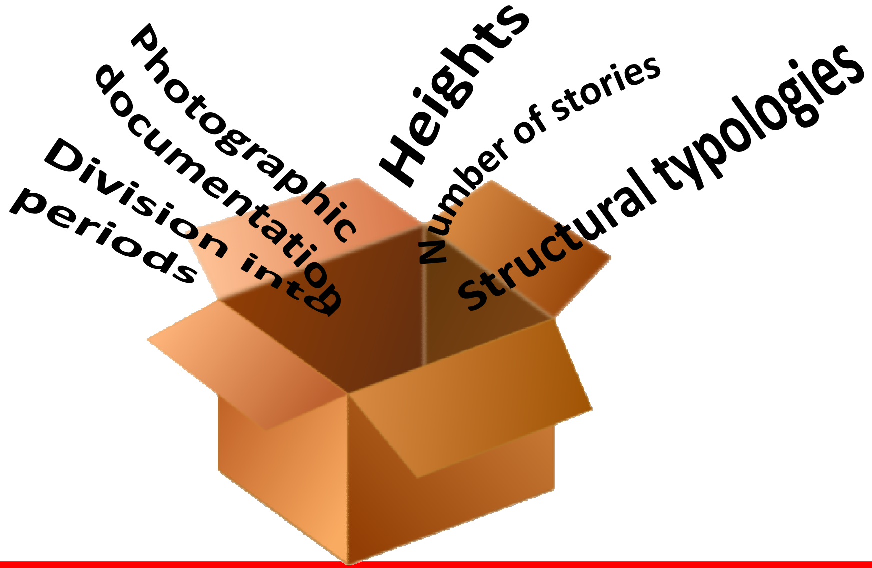


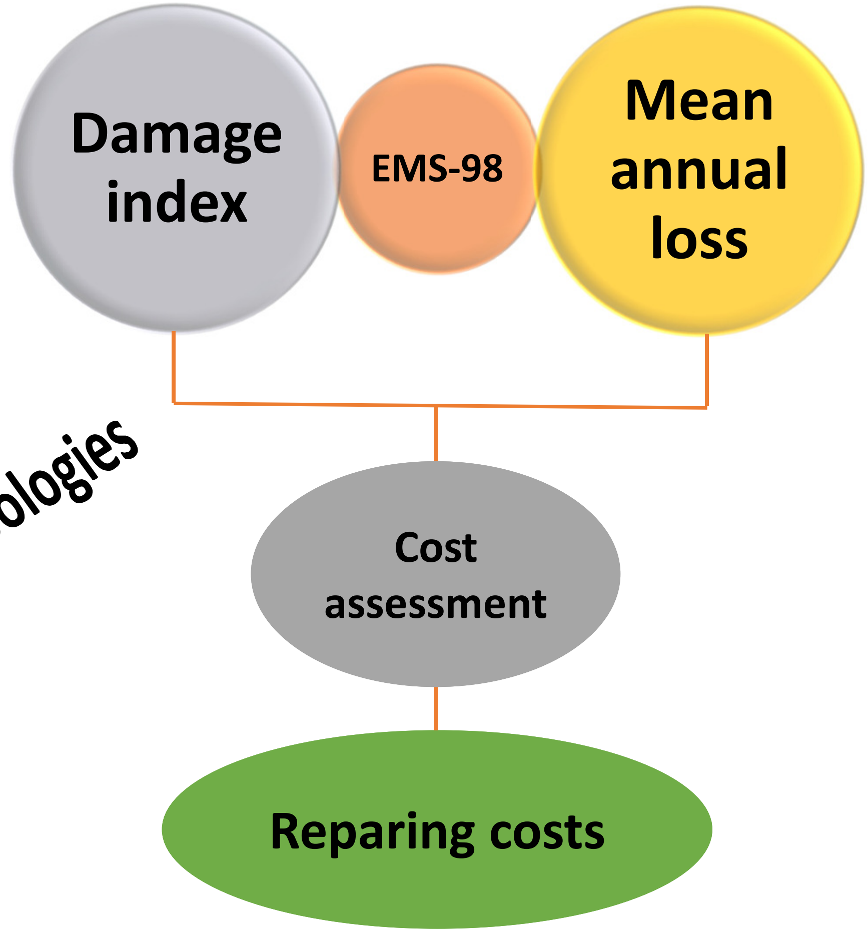
Blast risk



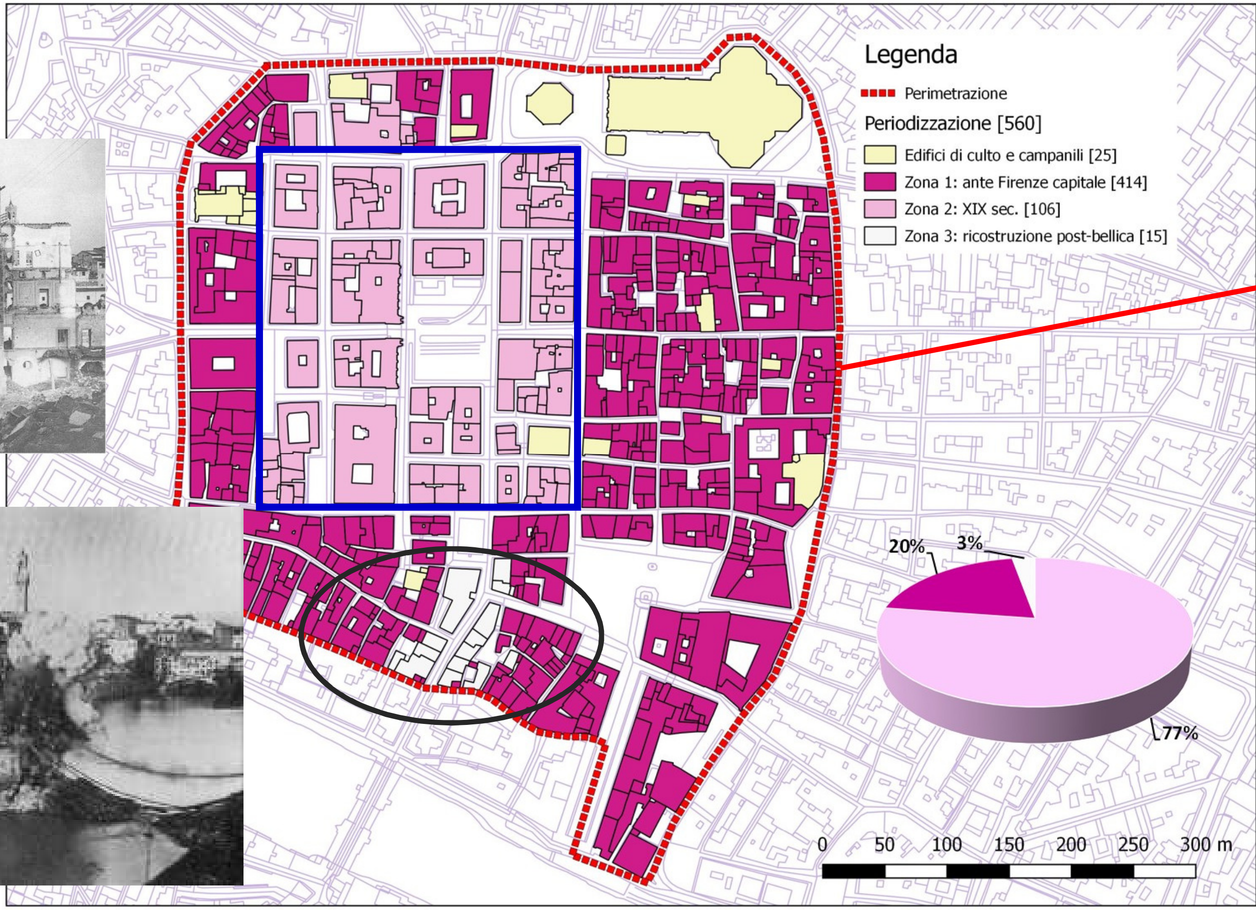
Landslide risk

Historic city center of Florence



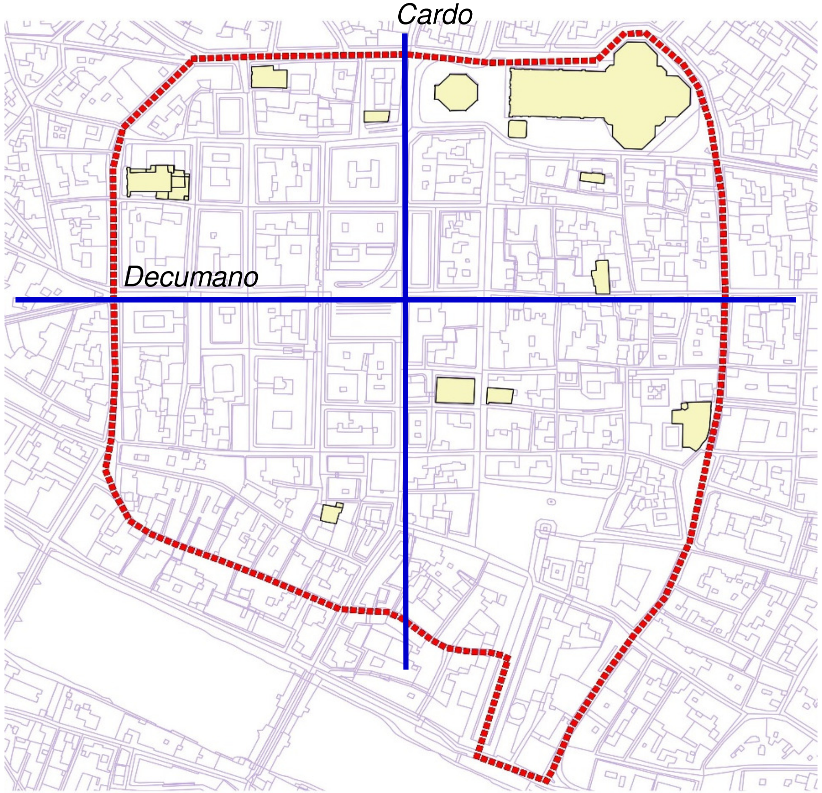


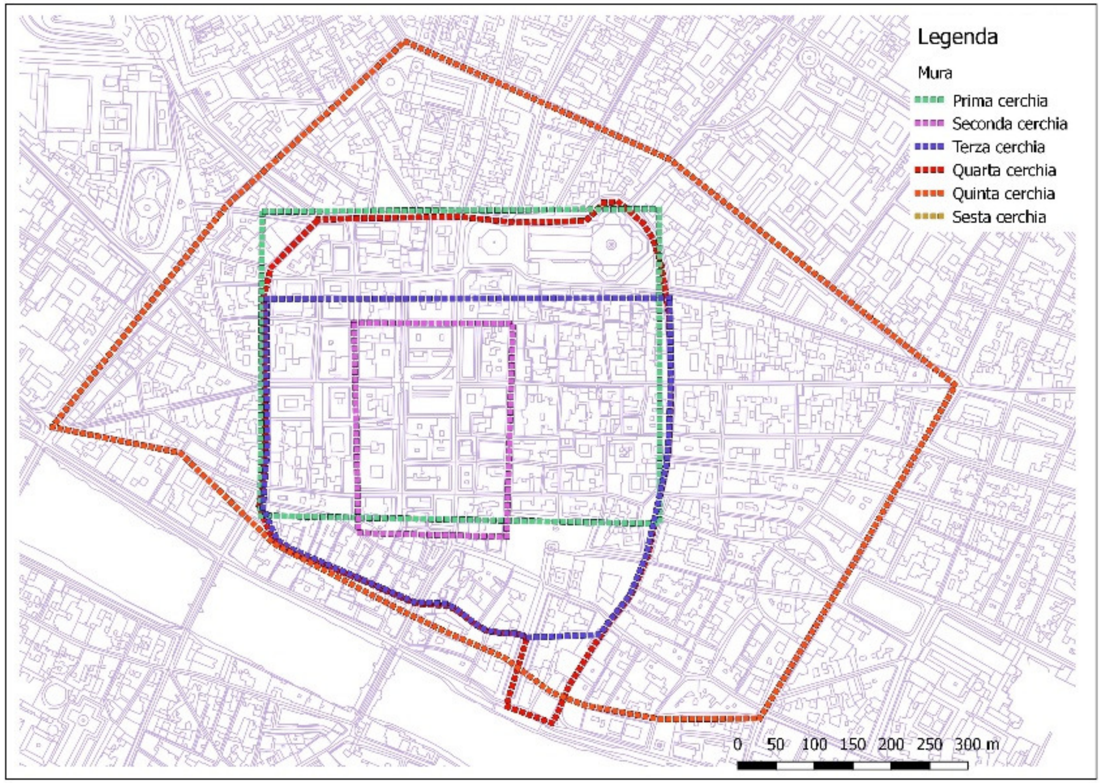
CONSTRUCTION PERIODS



Fourth town walls called "Matildina walls"

DIVISION INTO PERIODS





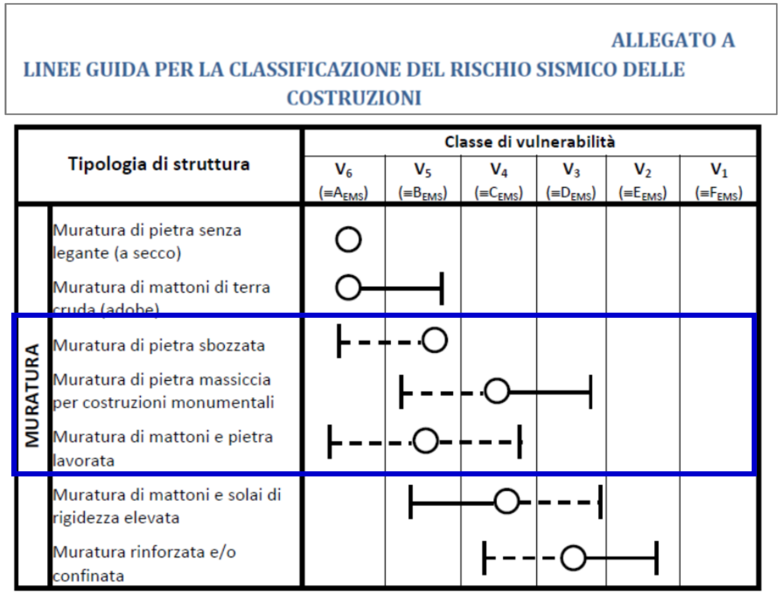
"Matildina walls" (Dante, Paradiso, XV, 97) built in 1078 by Tuscany Countess Matilde di Canossa

DAMAGE INDEX(*)

Typologies		Building type	Vulnerability Classes A	B	C	D	E	F
	M1	Rubble stone						
	M2	Adobe (earth bricks)						
	M3	Simple stone						
	M4	Massive stone						
	M5	Unreinforced M (old bricks)						
	M6	Unreinforced M with r.c. floors						
	M7	Reinforced or confined masonry						
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)						
	RC2	Frame in r.c. (moderate E.R.D.)						
	RC3	Frame in r.c. (high E.R.D.)						
	RC4	Shear walls (without E.R.D)						
	RC5	Shear walls (moderate E.R.D.)						
	RC6	Shear walls (high E.R.D.)						
Stell	S	Steel structures						
Tiber	W	Timber structures						

Situations: ■ Most probable class; ■ Possible class; ■ Unlikely class (exceptional cases)

Mean annual loss
Perdita Annua Media attesa
PAM



For both the parameters (ID and PAM) the EMS-98 structural typologies are considered

(*) Giovinazzi S., Lagomarsino S., A macroseismic method for the vulnerability assessment of buildings. *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, August 1-6, 2004.

DAMAGE INDEX

Vulnerability classes for the different building typologies: EMS98

Typologies		Building type	Vulnerability Class EMS98						Vulnerability Index				
			A	B	C	D	E	F	V_{Imin}	V_I^-	V_I^*	V_I^+	V_{Imax}
Masonry	M1	Rubble stone	More probable						0.62	0.81	0.873	0.98	1.02
Masonry	M2	Adobe (earth bricks)	More probable	Possible					0.62	0.687	0.84	0.98	1.02
Masonry	M3	Simple stone	Less probable	More probable					0.46	0.65	0.74	0.83	1.02
Masonry	M4	Massive stone		Possible	More probable	Less probable			0.30	0.49	0.616	0.793	0.86
Masonry	M5	Unreinforced M (old bricks)	Less probable	More probable	Less probable				0.46	0.65	0.74	0.83	1.02
Masonry	M6	Unreinforced M with r.c. floors		Possible	More probable	Less probable			0.30	0.49	0.616	0.79	0.86
Masonry	M7	Reinforced or confined masonry			Less probable	More probable	Possible		0.14	0.33	0.451	0.633	0.70
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D.)	Less probable	Possible	More probable				0.3	0.49	0.644	0.80	1.02
Reinforced Concrete	RC2	Frame in r.c. (moderate E.R.D.)		Less probable	Possible	More probable	Possible		0.14	0.33	0.484	0.64	0.86
Reinforced Concrete	RC3	Frame in r.c. (high E.R.D.)			Less probable	Possible	More probable		-0.02	0.17	0.324	0.48	0.70
Reinforced Concrete	RC4	Shear walls (without E.R.D.)		Less probable	More probable	Possible			0.3	0.367	0.544	0.67	0.86
Reinforced Concrete	RC5	Shear walls (moderate E.R.D.)			Less probable	More probable			0.14	0.21	0.384	0.51	0.70
Reinforced Concrete	RC6	Shear walls (high E.R.D.)				Less probable	More probable	Possible	-0.02	0.047	0.224	0.35	0.54
Steel	S	Steel structures			Less probable	Possible	More probable	Possible	-0.02	0.17	0.324	0.48	0.70
Tiber	W	Timber structures		Less probable	Possible	More probable	Possible		0.14	0.207	0.447	0.64	0.86

Condition ■ More probable ■ Possible □ Less probable

$$V_I = V_I^* + DV_m$$ ⟹ **Vulnerability index**

$$V_I^*$$ ⟹ **Typological vulnerability index**

$$DV_m = \sum V_{m,k}$$ ⟹ **Factor accounting for the seismic behavior**

Scores for the modification factors related to the masonry building behavior

Behaviour modifier	Masonry		Reinforced Concrete ERD Level	Pre/Low	Medium	Hight
		V_{mk}		V_{mk}	V_{mk}	V_{mk}
State of preservation	Good Bad	-0.04 +0.04	Good Bad	- +0.04	- +0.02	- 0
Number of floors	Low (1or 2) Medium (3,4 or 5) High (6 or more)	-0.04 0 +0.04	Low (1-3) Medium (4-7) High (8 or more)	-0.02 0 +0.08	-0.02 0 +0.06	-0.02 0 +0.04
Structural system	Wall thickness Wall distance Wall connections	-0.04÷+0.04				
Plan Irregularity	Geometry Mass distribution	+0.04	Geometry Mass distribution	+0.04 +0.02	+0.02 +0.01	0 0
Vertical Irregularity	Geometry Mass distribution	+0.04	Geometry Mass distribution	+0.04	+0.02	0
Superimposed flors		+0.04				
Roof	Weight, thrust and connections	+0.04				
Retroffiting Intervention		-0.08÷+0.08				
Aseismic Devices	Barbican, Foil arches, Buttresses	-0.04				
Aggregate Building: position	Middle Corner Header	-0.04 +0.04 +0.06	Insufficient aseismic joints	+0.04	0	0
Aggregate Building: elevation	Staggered floors Buildings with different height	+0.04 -0.04÷+0.04				
Foundation	Different level foundations	+0.04	Beams Connected beams Isoleted Footing	-0.04 0 +0.04	0 0 0	0 0 0
			Short-column Bow windows	+0.02 +0.04	+0.01 +0.02	0 0

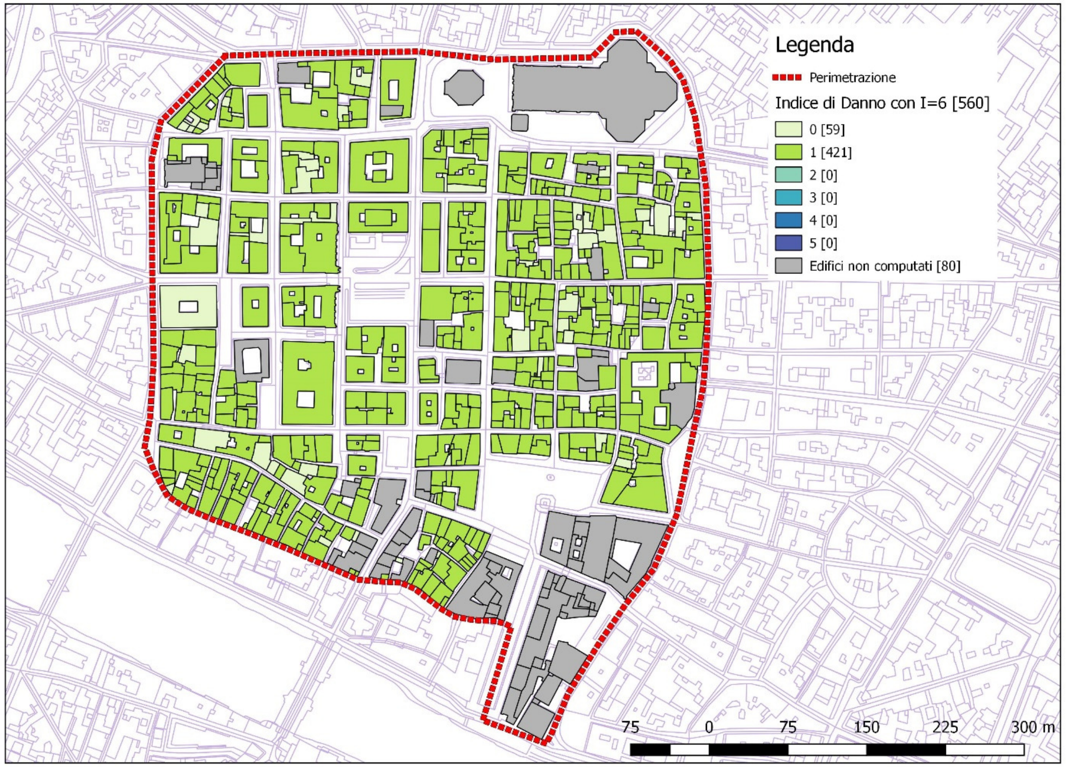
12 Parameters:

1. *Conservation status*
2. *Number of stories*
3. *Structural system*
4. *Plan irregularity*
5. *Elevation irregularity*
6. *Raising of a building*
7. *Roof*
8. *Adjustement intervention*
9. *Antiseismic devices*
10. *Planimetric configuration*
11. *Elevation configuration*
12. *Foundations*

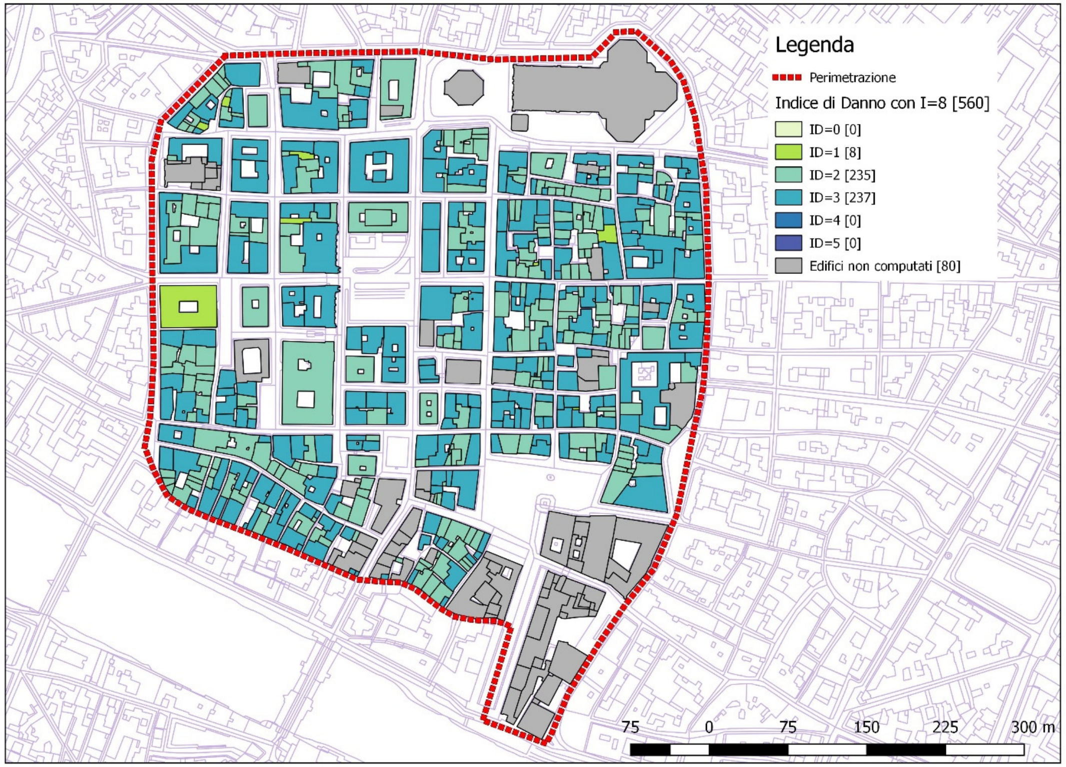
$$\mu_D = 2.5 + 3\tanh\left(\frac{I + 6.25V - 12.7}{2.3}\right) \quad \Big| \quad 0 \le \mu_D \le 5$$

Damage index

DAMAGE INDEX



Macroseismic intensity 6



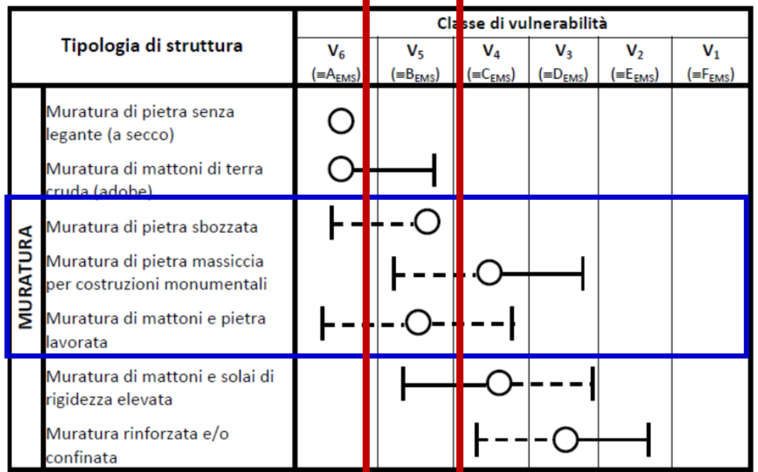
Macroseismic intensity 8

Mean annual loss

PAM

(Perdita Annuale Media attesa, in italian)

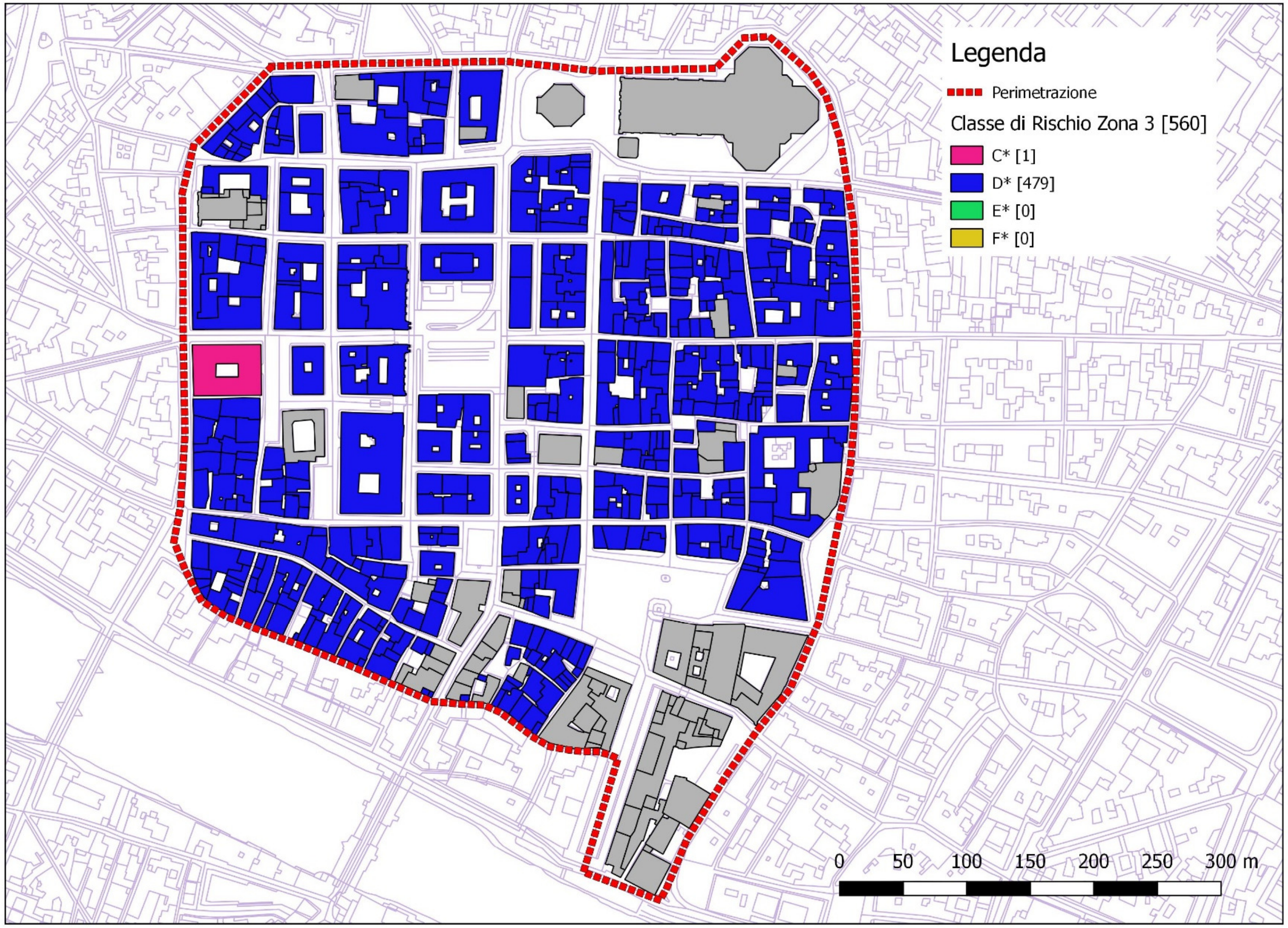
Structural typology



Some buildings present an increase of vulnerability (from V_5 to V_6) due to the presence of some vulnerability sources in their structural behaviour

Risk class

Classe di Rischio	PAM	Zona 1	Zona 2	Zona 3	Zona 4
A+*	PAM ≤ 0,50%				$V_1 \div V_2$
A*	0,50%<PAM≤1,0%			$V_1 \div V_2$	$V_3 \div V_4$
B*	1,0%<PAM≤1,5%	V_1	$V_1 \div V_2$	V_3	V_5
C*	1,5%<PAM≤2,5%	V_2	V_3	V_4	V_6
D*	2,5%<PAM≤3,5%	V_3	V_4	$V_5 \div V_6$	
E*	3,5%<PAM≤4,5%	V_4	V_5		
F*	4,5%<PAM≤7,5%	V_5	V_6		
G*	7,5%≤PAM	V_6			


Legenda
Perimetrazione
Classe di Rischio Zona 3 [560]
C* [1]
D* [479]
E* [0]
F* [0]
0 50 100 150 200 250 300 m

Case A – Low rebuilding

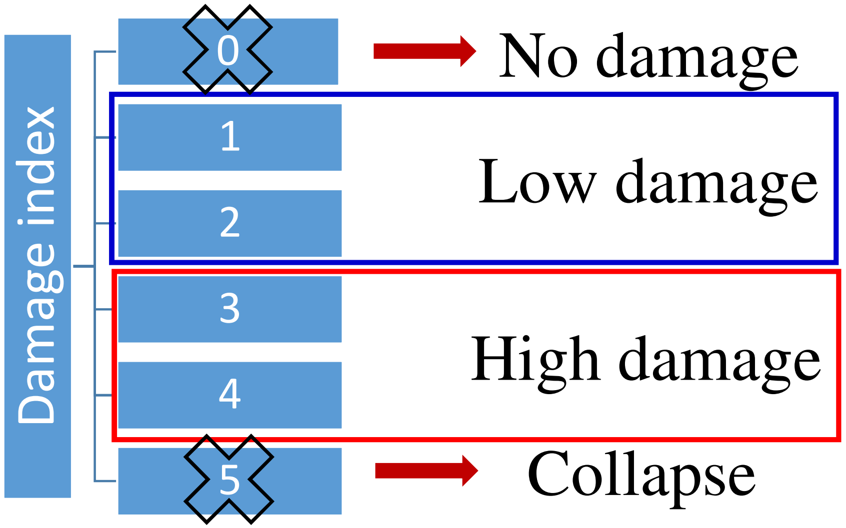
- Mean costs for repairing 217 €/m^2
- Mean costs for retrofitting 68 €/ m^2

Tot. 285 €/m^2

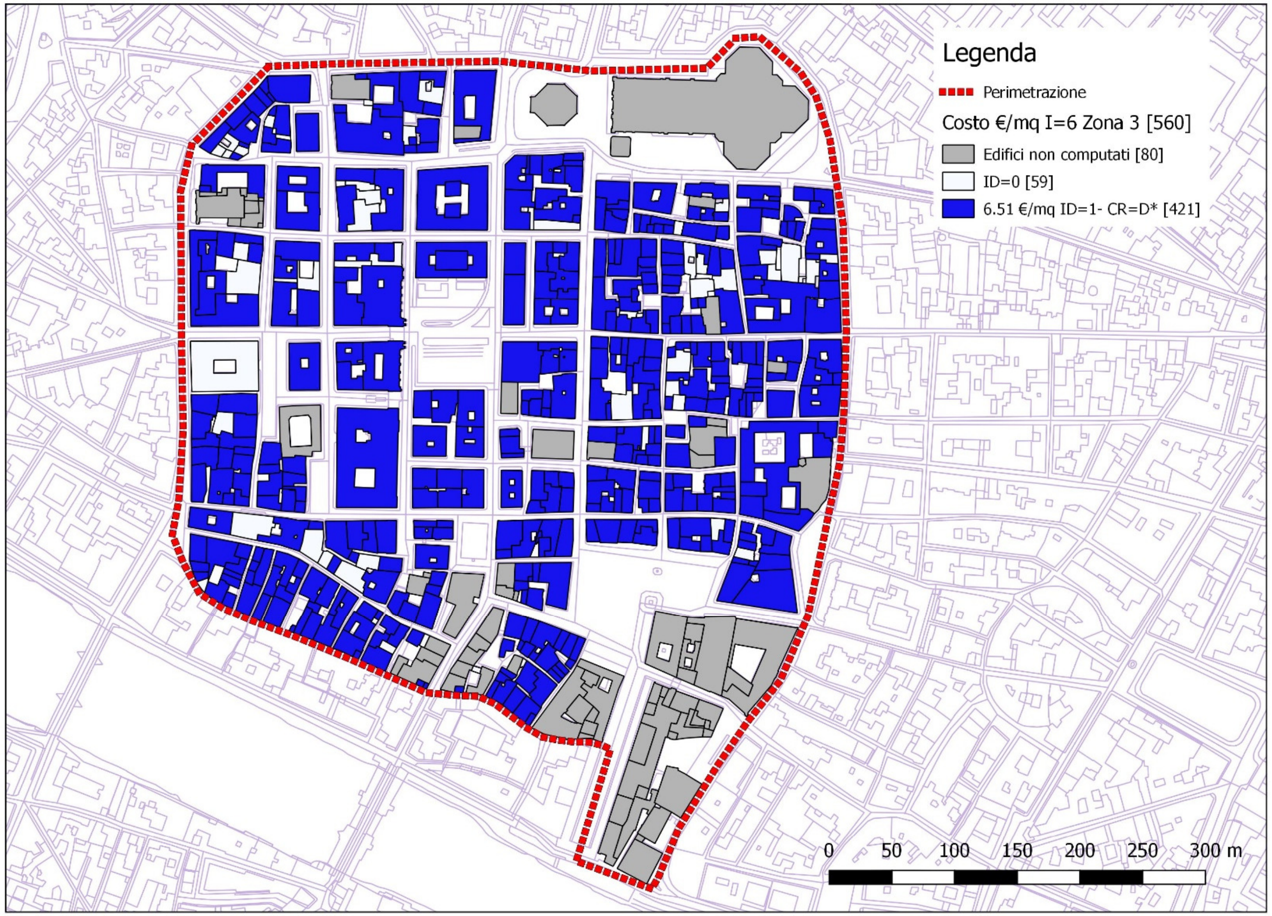
Caso B – High rebuilding

- Mean costs for repairing 448 €/ m^2
- Mean costs for seismic improvement 320 €/ m^2
- Mean cost for tests and energetic adjustment 69 €/ m^2

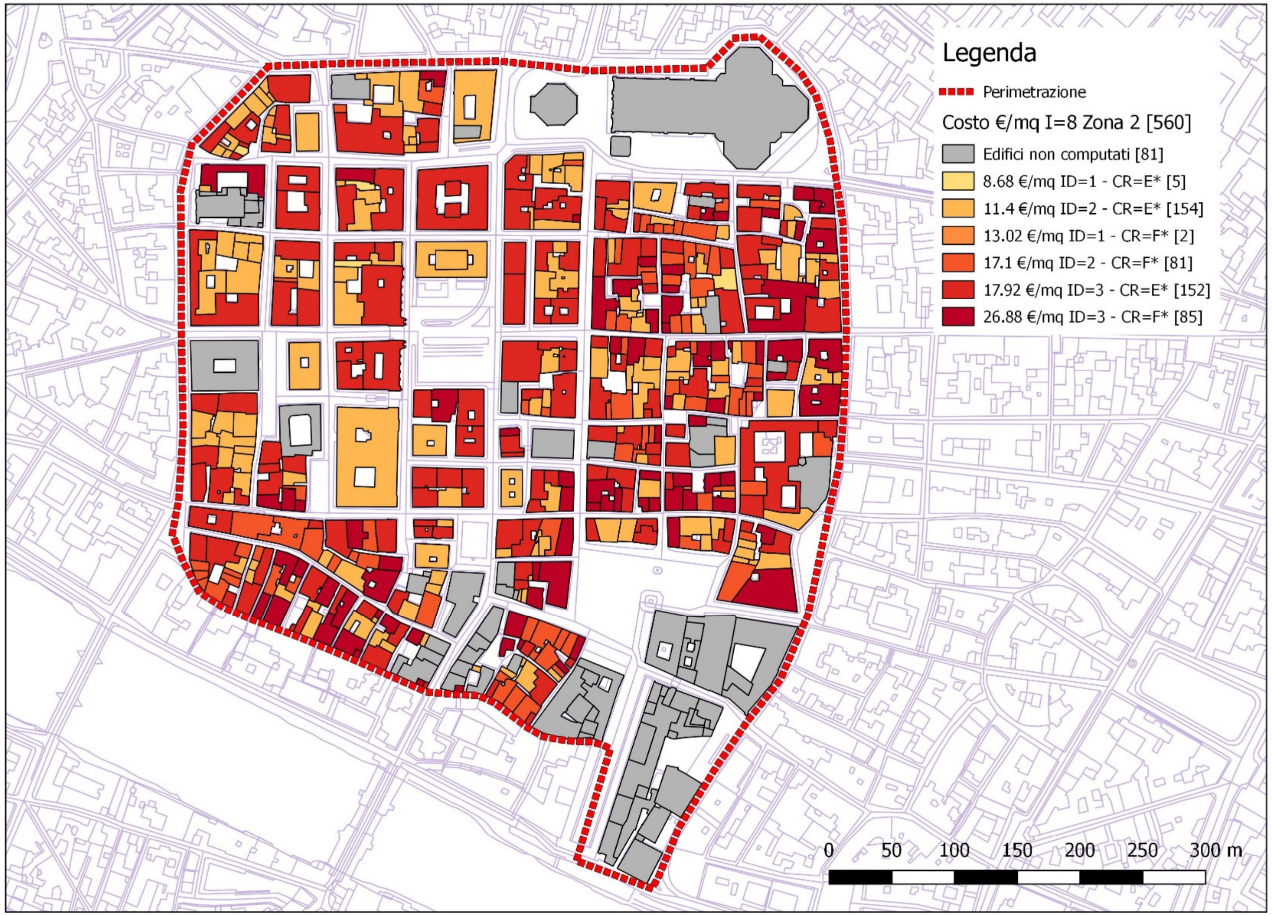
Tot. 837 €/m^2



Cost €/m^2 - I=6 e z=3



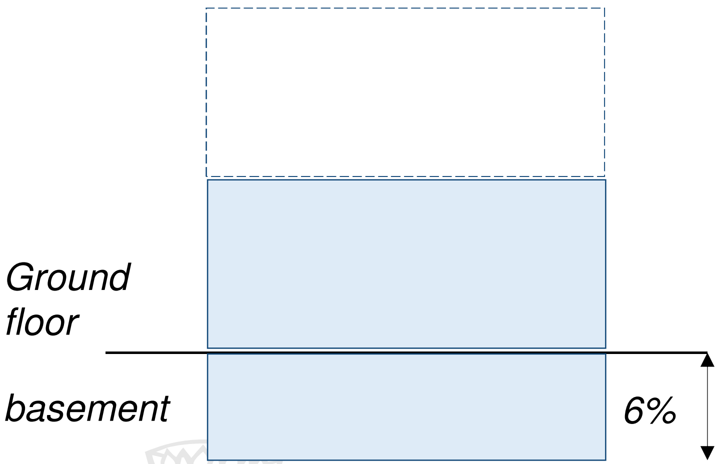
Cost €/m^2 - I=8 e z=2



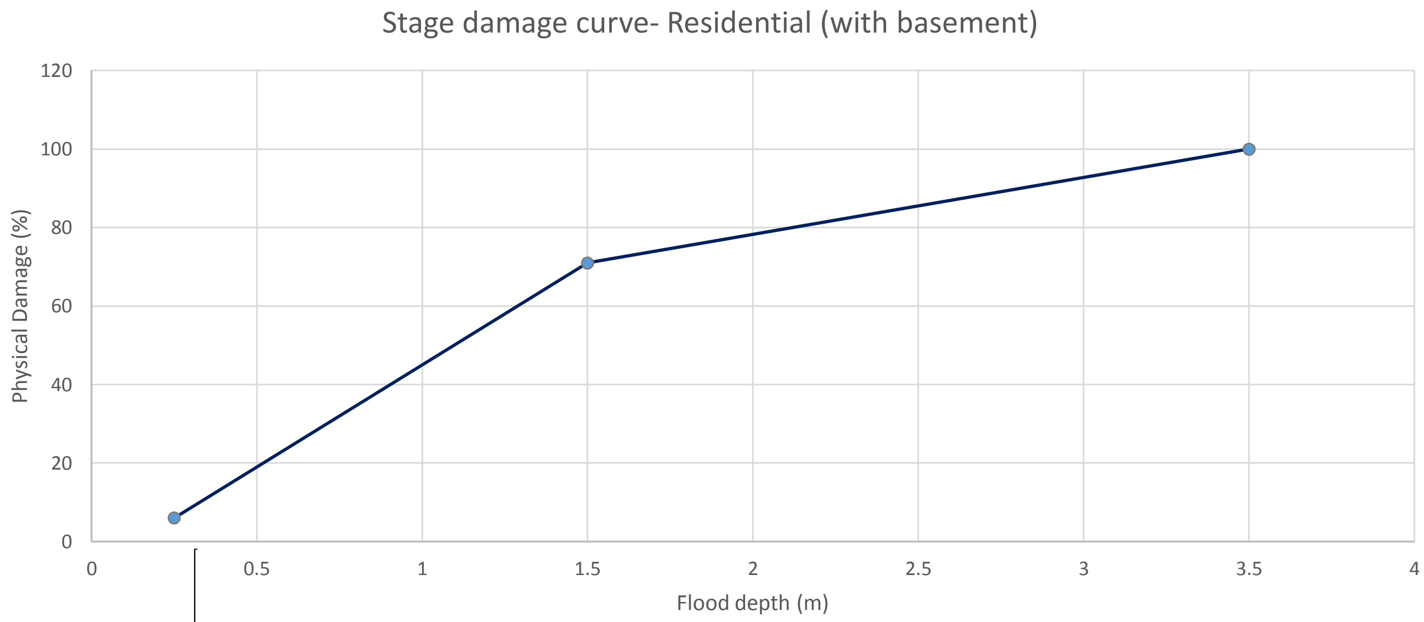
FLOOD RISK

- R=HE**V**

Vulnerability curve for a building with one underground (basement) floor



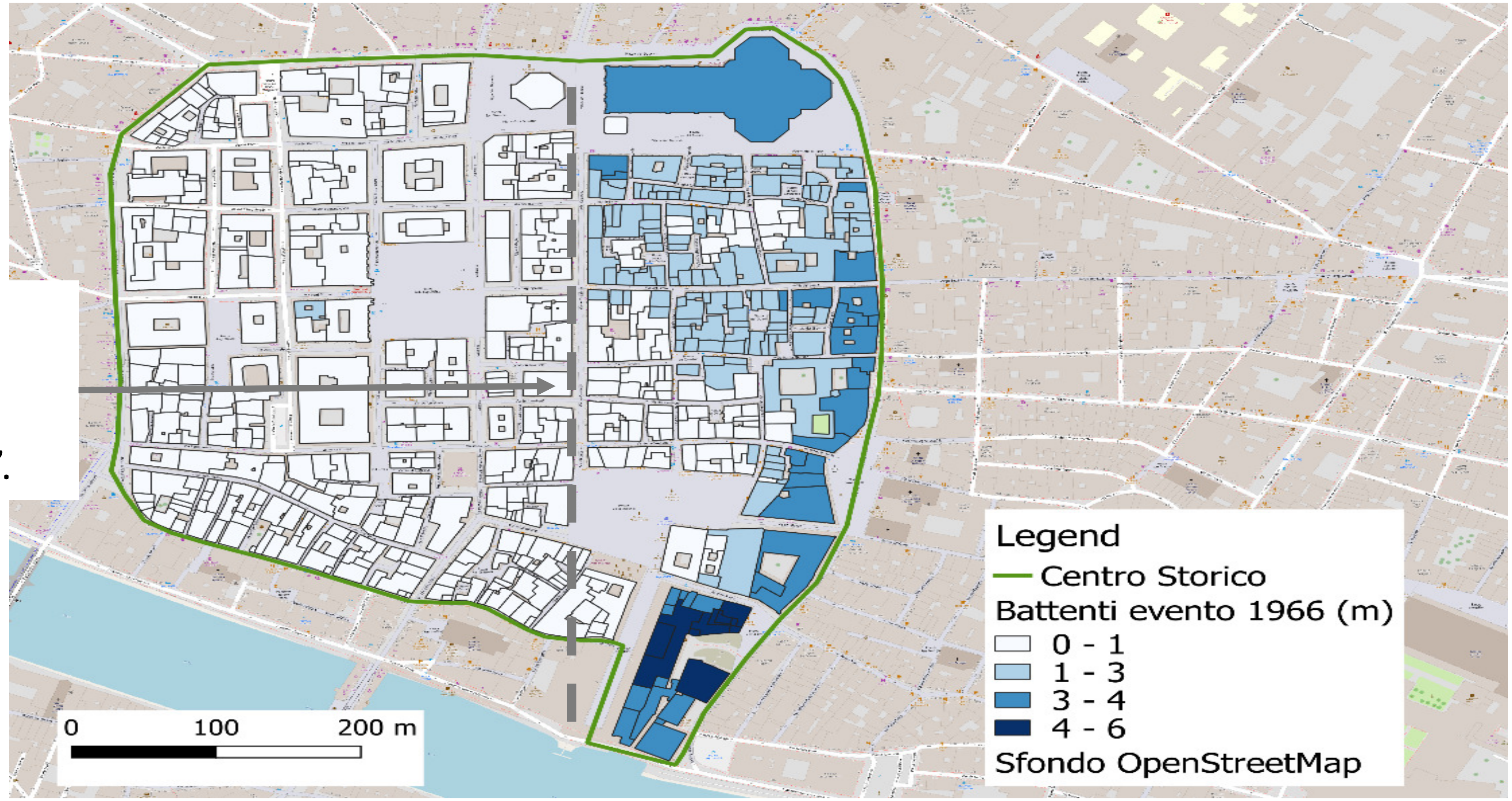
Basements are affected for low H due to possible backwater effects (Arrighi et al., 2013)



Courtesy of Arrighi & Castelli, DICEA - UNIFI

Results: water level in the area under examination for 1966-type flood

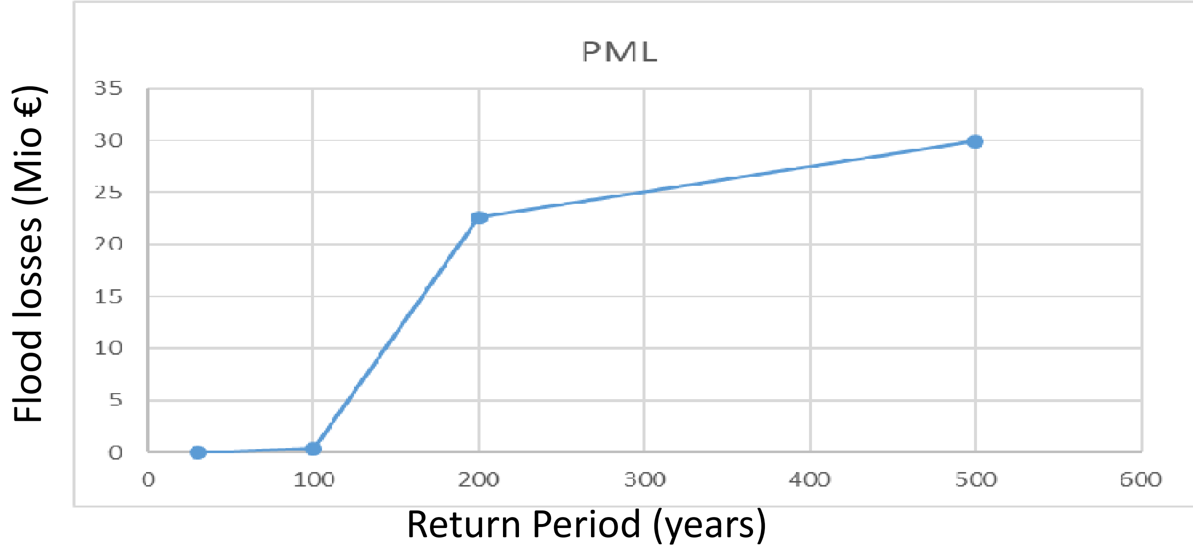
Hydraulic discontinuity between the East-side of historical center and the ancient 'castrum romanum'.

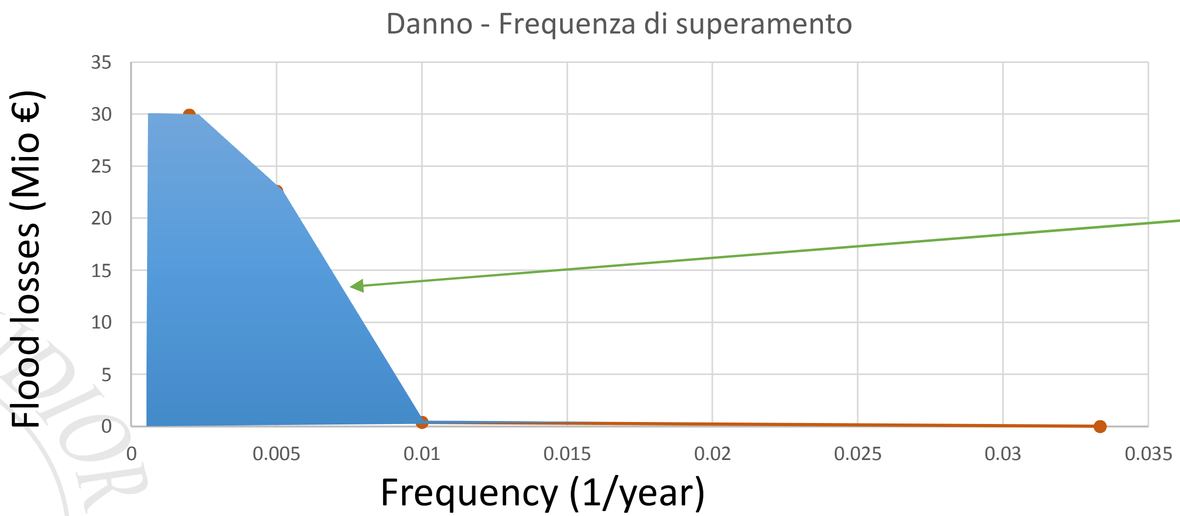


Courtesy of Arrighi & Castelli, DICEA - UNIFI

RISK EVALUATION

Courtesy of Arrighi & Castelli, DICEA - UNIFI

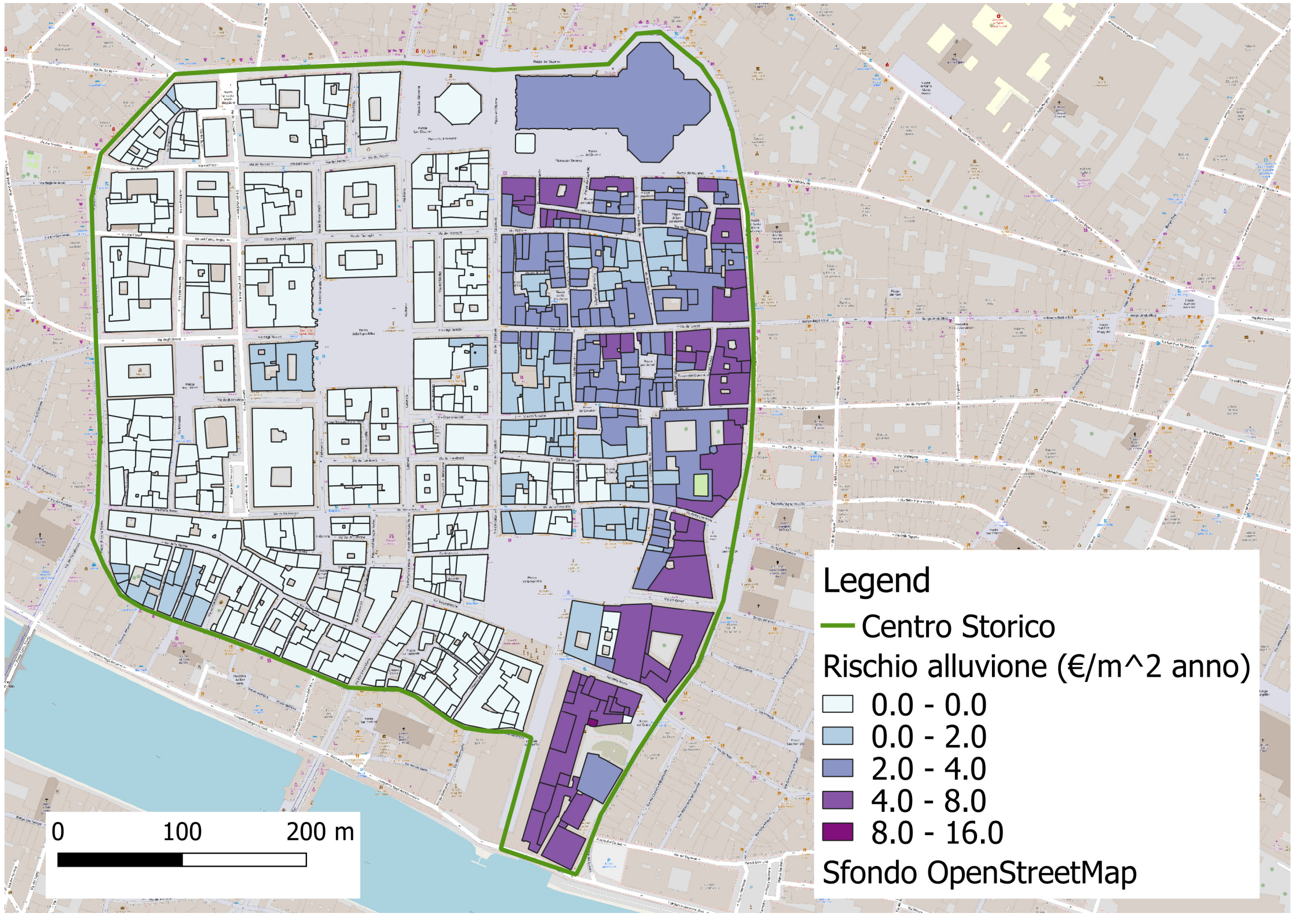




AAL- PAM
0.2 Mio€/anno*

*Excluding 'special' value of cultural heritage

FLOOD RISK – Average Annual Loss (PAM)



Courtesy of Arrighi & Castelli, DICEA - UNIFI

SEISMIC-FLOOD RISK ASSESSEMENT

- Since no correlation between the two hazards can be considered the mean annual frequency of the decision variables can be simply added
- A direct comparison between the two hazards can be done.

PRELIMINARY CONCLUSIONS OF THE MULTI-HAZARD RISK ASSESSEMENT

- The maximum costs due to the floods can be compared to those related to earthquakes (earthquake-induced damages higher than flood-induced damages ??????)
- For a non negligible number of buildings the total cost (earthquake + flood) could reach the value of **43 €/m^2** per year (?????)
- The different "weight" of the two costs could influence the choices of the politicians/managers on the allocation of future monetary sources for risk mitigation in the Florence center.



National Research Project
PRIN 2015

"MITIGATING THE IMPACTS OF NATURAL HAZARDS ON CULTURAL HERITAGE SITES, STRUCTURES AND ARTEFACTS (MICHe)"