MICHe project

Rischio sismico centro storico di Firenze

Seismic risk of Florence historical center

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Summary

INTRODUCTION

Over the last 50 years, Italy has been affected by numerous earthquakes, the last one is represented by the seismic sequence in Central Italy from August 2016 to January 2017. The destruction of Amatrice, Accumuli and Arquata del Tronto with significant human losses, equal to 7% of the resident population (9% in Amatrice alone), is the most destructive event if compared to the recent earthquakes that hit L'Aquila in 2009 and Emilia Romagna in 2013, and highlights that the efforts made by the community to face the seismic hazard are still insufficient. Seismic risk prevention and mitigation represents the main defence strategies, which are urgent needs for our country.

The definition of prevention or emergency planning policies is based on the analysis of risk (or damage) scenarios, used by the Department of the Italian Civil Protection to draw up intervention plans to manage any calamities. Defined on the basis of the exposure, site hazard and vulnerability of the building heritage, risk scenarios are means for predicting damages to urban centers as well as the consequences on population. Risk scenarios provide important information regarding the size and location of the areas with major risk, the functionality of the transport networks, the state of the communication and distribution routes, the expected social and economic losses [1].

Florence is a city in central Italy worldwide recognized for its exceptional historical and architectural heritage. It is a highly urbanized and industrialized area extended in the floodplain crossed by the Arno river surrounded by hills. The area is characterized by moderate earthquakes with a local magnitude M_L of about 5. The most significant shocks that hit Florence were characterized by epicenters in Mugello (1542, 1919), Impruneta (1453, 1895) and Valdarno (1770) [2]. Historical seismology is the main source of information for the characterization of the seismic hazard of an area. It allows estimating the intensity of past events and requires a long process of analysis of historical sources (written chronicles, registers, diaries and tombstones).

Historical sources indicate the events of the 28th September 1453 and that of the 18th May 1895, as the most ruinous that ever hit Florence, both characterized by a MCS scale of VII-VIII degree (Mercalli-Cancani-Sieberg) [3]. Both iconography analysis and documentation, concerning the damage reported by the building (damage to the monuments, wall disconnections and widespread damage to non-structural elements), allowed to characterize what is called the "design earthquake", i.e. the hypothetical maximum seismic event in a given area.

It still remains to define an exhaustive picture of the seismic vulnerability of the Florentine buildings. They are composed of about 31000 units according to the ISTAT census of 2011. It is possible to distinguish three main evolutionary phases, the first one prior to 1895, the second one between 1895 and 1982 and the last one after 1982. Only 30% of the existing buildings (the historic center and the areas of expansion of the nineteenth century) have undergone the testing of the "strong earthquake" of 1895. It represents an event of intensity expected for the city according to the seismic hazard that characterizes the area. In the face of more or less invasive interventions of construction or renovation, subsequently carried out, it is not clear which would be the response of these structures to a quake similar to that already suffered. The second phase identifies the post 1895 building heritage and prior to 1982, the year of classification of Florence as a seismic area. Post-war reconstructions and the building boom of the sixties involved the construction of the 67% of the buildings in Florence, which are notoriously weak. As a matter of fact, they represent structures built in the absence of any anti-seismic regulations, suffering from structural deficiencies and degradation due to age. In light of these findings, we cannot rule out that today's Florence may be more vulnerable than the nineteenth century, in case of a new seismic event comparable to that of 1895 [4].

The retrieval and management of huge amounts of data of different nature, origin and destination is of fundamental importance, facilitated today by the use of GIS databases [5]. A system that makes possible to manage large quantities of information, infinite correlations and acquisitions of further knowledge graphed on georeferenced thematic maps.

The elaboration of a risk scenario for the city of Florence requires the definition of a Vulnerability Map of the Florentine building. It represents one of the objects of MICHe project. In particular, such a tool allows the Department of Civil Protection to establish an efficient resource planning for seismic adaptation [6].

METHODOLOGY

The need to assess the seismic vulnerability of existing buildings is required by the most recent anti-seismic codes both at national level, O.P.C.M. 3274 and following modifications and integrations [7]; D.M. 17/01/2018 [8] (NTC 2018) and European, Eurocode 8 [9]. Based on the structural typology and the required degree of precision, numerous methods of analysis are available both in the linear and non-linear fields. The advancement of scientific knowledge has made possible to develop analysis methods able to accurately simulating the dynamic behavior of structures and to provide a good approximation of the probability of failure of buildings against a seismic intensity measure (*fragility curve*). However, analysis methods of this type are very complex and require a high computational cost, therefore they are not applicable in large-scale seismic risk assessment. For this reason, simplified methods have been put in place to allow the determination of a large-scale seismic risk index.

In order to carry out a large-scale verification on entire aggregates of buildings, problems arise both as regards to the poor overall knowledge of the buildings, and with the appropriate methodology to be used. Furthermore, the choice of the tool capable of identifying, within an aggregate, the buildings most at risk during a seismic event, is of great interest. This tool must be able to provide an simple parameter, representative of the seismic vulnerability of the building, on the basis of which subsequent comparisons can be made.

Vulnerability analysis comprises at least two distinct phases:

- the census of the existing built, carried out in a more or less thorough way depending on the requiredLevel of Knowledge [8, 10];
- the evaluation of the effects that an earthquake of a given intensity can have on the construction. They can be achieved through methods of different nature, which range from the statistical processing of post-earthquake damage deduced from similar types of buildings, to analytical estimations of the capacity of buildings compared with the seismic demand.

Quantitative methods are the most common and provide the result (damage) in numerical form (probabilistic or deterministic). Instead, qualitative methods describe the vulnerability through judgments expressed in terms of "low", "medium" and "high" vulnerability. The Italian Building Code [8] requires that seismic vulnerability analyses must be based on quantitative processes.

It is also possible to frame seismic vulnerability analysis methods in direct, indirect and conventional. Direct methods determine the result in a single step, intended as a forecast of seismic damage; indirect methods involve determining a vulnerability index and subsequently establishing a relationship between damage and an intensity measure. Finally, conventional methods aim at providing only an index to which they do not associate a damage forecast such as indirect methods. They can be used only in order to compare different structures located in areas characterized by the same seismicity.

It is of greater practical interest to perform a classification linked to the various possibilities of analysis of the structure. In particular, mechanical methods, empirical methods and methods based on expert judgment can be distinguished. The mechanical methods summarize the different mechanical-analytical approaches in which a non-linear analysis of the structure is carried out. The damage is associated with the achievement of a limit state identified by the reaching of a rotation/drift limit, while the seismic action is expressed in terms of spectral accelerations, such as the Peak Ground Acceleration (PGA). This approach is the one commonly applied in the calculation of the vulnerability of individual structural organisms for which there is an adequate level of knowledge.

Empirical methods use an approach based on the statistical analysis of the damage caused by the documented earthquakes. The accuracy of the empirical methods is function of the availability of the data, sometimes insufficient especially as regards RC buildings. Unlike the mechanical methods, applicable in detail to the individual building, the empirical methods aim at a typological synthesis, evaluating the vulnerability of entire urban aggregates and based on the definition of classes characterized by typological or functional indicators (*e.g.* construction typology, year of construction, height, etc.), to which a damage probability matrix or a vulnerability curve can be associated.

There are three main empirical methods for assessing the seismic vulnerability of buildings, as widely described in Calvi *et al.* [11]:

- damage probability matrices (DPM). They express in discrete form the conditional probability of obtaining a level of damage *A*, due to a movement of earth of great intensity;
- seismic vulnerability indices. It relates the seismic action and the response of the building through a compilation of a summary sheet, which provides a final score;
- vulnerability curves. They are continuous functions that express the probability of exceeding a given state of damage, given an earthquake intensity function.

Finally, methods based on expert judgment attribute to each building a numerical evaluation that identifies its vulnerability index, expressed as a function of indicators that characterize the capacity of the building to withstand earthquakes (for example, the efficiency of the connections, material strength , morphological regularity). In a second step, each vulnerability index value is associated with a vulnerability curve or a damage probability matrix. The problem with the latter two methods is that, not relying on an analytical approach, they consider the behavior of the different types of buildings on the basis of experience and knowledge and therefore reach a qualitative result.

Among the current expeditious methodologies used for seismic risk assessment, the following deserve to be mentioned:

- The methodology developed by Petrini and Benedetti [12] is used to assess the vulnerability of masonry buildings by detecting qualitative and quantitative information. It requires the analysis of each individual building, is of the expeditious type and can be conducted by non-specialized staff. The results obtained allow to classify the building heritage present in a given territorial area according to a relative scale of vulnerability, attributing a score to each building according to its morphological and structural characteristics. A subsequent definition of the seismic hazard of each individual site allows estimating the expected damage to the buildings in the area under consideration. The vulnerability sheets examine a series of elements that influence the behavior of the building during a seismic event. They provide a score by considering also if the building complies with the Standards.
- The Italian National Group for the Earthquakes Defence (whose Italian acronym is GNDT) developed some vulnerability sheets [13, 14] based on two in-depth analysis levels. The first level sheets are used for statistical purposes to be carried out on entire urban areas, while the second ones are more detailed and then are used in the

assessment of a reduced number of buildings. The first level sheet detects just the exposure and vulnerability of buildings (masonry or reinforced concrete structures), so it is generally used to lead post-earthquake inspection. Conversely, the second level sheet, requiring an accurate retrieval of information about the seismic behavior of the building, is incompatible with emergency management times. It is therefore a procedure not completely automated as the first level procedure. As a consequence, it is not suitable for approximate calculation methods of seismic capacity .

- The methodology developed by D'Ayala and Speranza [15, 16] is valid for masonry buildings, whose purpose is to provide an simplified vulnerability assessment on a territorial scale. The procedure called FAMIVE (Failure Mechanism Identification and Vulnerability Evaluation) is based on the collection of a series of information on the building under investigation (most of which can be found through an external inspection) as well as on its construction method, in order to provide a vulnerability index.
- Formisano *et al.* proposed a method [17, 18] based on a simplified and fast approach for assessing seismic vulnerability by taking into account the interactions deriving from the structural continuity between adjacent buildings.This methodology has its foundation in the Benedetti and Petrini method, in which the GNDT vulnerability sheets are considered. The method requires fifteen parameters, the first ten taken from the Benedetti and Petrini method, while the other five are added by the new methodology.

In order to acquire in a short time a homogeneous and accurate knowledge on the risk of cultural heritage, the Italian Ministry for Cultural Heritage and Tourism has developed a program for monitoring the state of conservation of the protected architectural assets. It consists in a database containing a series of data for each artefact, structured through data sheets, relating to the knowledge of the construction, the state of conservation, the assessment of vulnerability and risk and the suggested interventions for their prevention.

The aim of the program is to acquire, in a reasonably short time, the safety level of these buildings in the seismic areas. Considering the significant number of protected assets, in case of extensive checks on a territorial scale, simplified methods should be used. In any case, it is required to quantitatively evaluate a seismic safety index, useful for highlighting critical situations and establishing priorities for future interventions.

In this regard, the "Linee guida per la valutazione e riduzione del rischio sismico del patrimonio culturale" (2010) [19] of the Italian Ministry for Cultural Heritage and Tourism represents the basic methodology to conduct seismic checks on architectural artefacts belonging to the protected cultural heritage.

The Code provides three different in-depth analysis levels for the buildings, denoted by LV1, LV2 and LV3.

The Lagomarsino and Giovinazzi method [6, 20, 21, 22] introduces a damage index (μ_D) through an empirical formula which is a function of a vulnerability index (V). The latter index is defined according to the European macro-seismic intensity EMS- 98 (I) [23] and a ductility index (Q). In particular, the vulnerability index is obtained by adding to a typological vulnerability index a modification factor due to the ascertained presence of specific factors (*i.e.* the degree of maintenance) or typological characteristics (*i.e.* the number of floors).

EXPECTED AVERAGE ANNUAL LOSS WITH "SISMABONUS"

The expected Average Annual Loss (AAL) due to seismic events was calculated based on the seismic zone in which the city falls together with the vulnerability assessment of the existing structures. After identifying the relative percentage of AAL we proceeded to estimate the costs according to the damage suffered.

Expected Average Annual Loss

The classification of the seismic risk of buildings was carried out using the simplified method reported in the "Linee guida per la classificazione del rischio sismico delle costruzioni" [24] (Sismabonus). The method is applicable only to masonry structures and allows the identification of a vulnerability class of the building to which is connected a risk class according to the seismic zone. (see also OPCM 3274 of 20/03/2003 and following modifications and integrations [7]).

The six vulnerability classes are proposed, with increasing vulnerability from V1 to V6. Eight risk classes are considered, denoted by A + *, A *, B *, C *, D *, E *, F * and G * (the asterisk indicates that the classes were obtained with the simplified method) (Table 1). The medium vulnerability classes may undergo a deviation from the nominal value in presence of high degradation, poor construction quality or peculiarities that can trigger local collapse mechanisms for particularly low values of the seismic action and increasing the global vulnerability.

The structural types to which the Guidelines refer are the same as those adopted by EMS-98 [23], see Table 2.

TABLE 1: CLASS OF RISK AND EXPECTED AVERAGE ANNUAL LOSS ACCORDING TO THE SEISMIC AREA WHERE THE BUILDING IS LOCATED (FROM [24]).

Risk Class	AAL	Zone 1	Zone 2	Zone 3	Zone 4
A+*	AAL ≤ 0.50 %				$V_1 \div V_2$
A*	0.50 < AAL ≤ 1.0 %			$V_1 \div V_2$	$V_3 \div V_4$
B*	1.0 < AAL ≤ 1.5 %	V_1	$V_1 \div V_2$	V_3	V_5
C*	1.5 < AAL ≤ 2.5 %	V_2	V_3	V_4	V_6
D*	2.5 < AAL ≤ 3.5 %	V_3	V_4	$V_5 \div V_6$	
E*	3.5 < AAL ≤ 4.5 %	V_4	V_5		
F*	4.5 < AAL ≤ 7.5 %	V_5	V_6		
G*	7.5 < AAL	V_6			

Cost estimation

The cost estimation has been carried out according to the "Libro bianco sulla ricostruzione privata fuori dai centri storici nei comuni colpiti dal sisma dell'Abruzzo del 6 Aprile 2009" [25] and in particular to chapter 5 "Analisi tecnico-economico degli edifici – Comune di L'Aquila". Within the document, the reconstruction of private building damaged or destroyed by the earthquake is divided into two main categories: light reconstruction and heavy reconstruction. Low reconstruction cost, for masonry buildings, are the following:

Average repair cost:	217.00 €/mq
Average local reinforcement cost:	68.00 €/mq
Average total cost:	**285.00 €/mq**

As regards heavy reconstruction, the repair and improvement costs are:

Average repair cost:	448.00 €/mq
Average seismic improvement cost:	320.00 €/mq
Average cost for testing and energy adjustment:	69.00 €/mq
Average total cost:	**837.00 €/mq**

To establish the repairing costs of the case study, the aforementioned damage level (low and high) have been related to the damage index together with the no damage and collapse conditions. In particular, it has been assumed that the absence of damage corresponds to μ_D = 0, low damage to μ_D = 1 and 2, high damage to μ_D = 3 and 4 and, finally, the collapse corresponds to μ_D = 5, (Fig. 1).

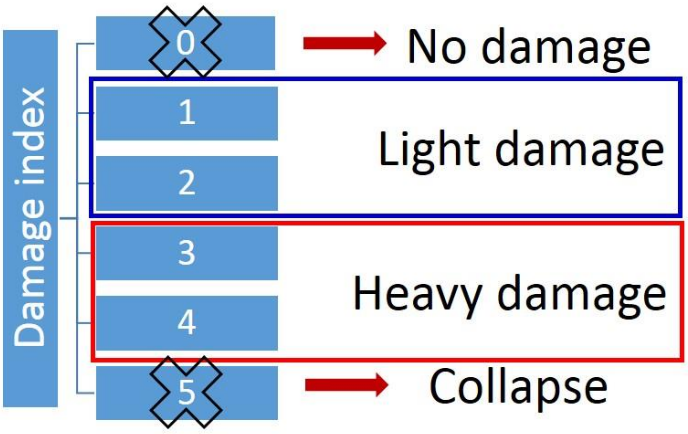


FIGURE 1: LIGHT DAMAGE AND HEAVY DAMAGE AS A FUNCTION OF μ_D.

EXPECTED AVERAGE ANNUAL LOSS WITH MACROSEISMIC METHOD

A second macroseismic methodology for the definition of the expected Average Annual Loss is reported below.

According to Lagomarsino and Giovinazzi [6], the vulnerability index V should be calculated for each building by combining the typological vulnerability index VI * (Table 1) with the modified behavior parameters $V_{m,k}$.

The typological vulnerability index is attributed according to the vertical structure [23], while the behavior modifiers proposed by Lagomarsino and Giovinazzi [6] depend on the characteristics of the building (Fig. 2).

The material typologies identified in the case study refer to simple stone (M3) and unreinforced masonry (M5); only one building belongs to massive stone.

TABLE 2: TYPOLOGIES, VULNERABILITY CLASS AND VULNERABILITY INDEX (FROM [6]).

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							0.62	0.81	0.873	0.98	1.02
	M2	Adobe (earth bricks)							0.62	0.687	0.84	0.98	1.02
	M3	Simple stone							0.46	0.65	0.74	0.83	1.02
	M4	Massive stone							0.30	0.49	0.616	0.793	0.86
	M5	Unreinforced M (old bricks)							0.46	0.65	0.74	0.83	1.02
	M6	Unreinforced M with r.c. floors							0.30	0.49	0.616	0.79	0.86
	M7	Reinforced or confined masonry							0.14	0.33	0.451	0.633	0.70
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D.)							0.3	0.49	0.644	0.80	1.02
	RC2	Frame in r.c. (moderate E.R.D.)							0.14	0.33	0.484	0.64	0.86
	RC3	Frame in r.c. (high E.R.D.)							-0.02	0.17	0.324	0.48	0.70
	RC4	Shear walls (without E.R.D.)							0.3	0.367	0.544	0.67	0.86
	RC5	Shear walls (moderate E.R.D.)							0.14	0.21	0.384	0.51	0.70
	RC6	Shear walls (high E.R.D.)							-0.02	0.047	0.224	0.35	0.54
Steel	S	Steel structures							-0.02	0.17	0.324	0.48	0.70
Tiber	W	Timber structures							0.14	0.207	0.447	0.64	0.86

SITUATION: MOST PROBABLE POSSIBLE UNLIKELY
SITUATION: MOST PROBABLE

Behaviour modifier	Masonry	
		V_{mk}
State of preservation	Good Bad	-0.04 +0.04
Number of floors	Low (1or 2) Medium (3,4 or 5) High (6 or more)	-0.04 0 +0.04
Structural system	Wall thickness Wall distance Wall connections	-0.04÷+0.04
Plan Irregularity	Geometry Mass distribution	+0.04
Vertical Irregularity	Geometry Mass distribution	+0.04
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
Aggregate Building: elevation	Staggered floors Buildings with different height	+0.04 -0.04÷+0.04
Foundation	Different level foundations	+0.04

FIGURE 2: SCORES FOR THE BEHAVIOUR MODIFIERS OF MASONRY BUILDINGS (FROM [6]).

The damage index μ_D (eq. 1) depends on three factors: i) macroseismic intensity I; ii) vulnerability index V (eq. 2); iii) ductility index Q (here assumed equal to 2.3).

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+6.25\cdot V-13.1}{Q}\right)\right] \qquad 0 < \mu_D < 5 \tag{1}$$

$$V = V_I^* + \Delta V_m \tag{2}$$

$$\Delta V_m = \sum V_{m,k} \tag{3}$$

where ΔV_m is a factor that takes into account the contribution of all the building characteristics (height, elevation and planimetric irregularities, state of maintenance, etc.) that influence its seismic behavior beyond the construction typology, expressed by $V_{m,k}$ (Fig . 2).

Successively, for each Limit State (LS), a damage value (μ_D) between 0 and 5 was associated. Additional parameters, defined in Cosenza et al. [26] and in Sismabonus [24], were added to the attributions of these ranges.

By considering the seismic hazard of Florence, the proposed methodology was

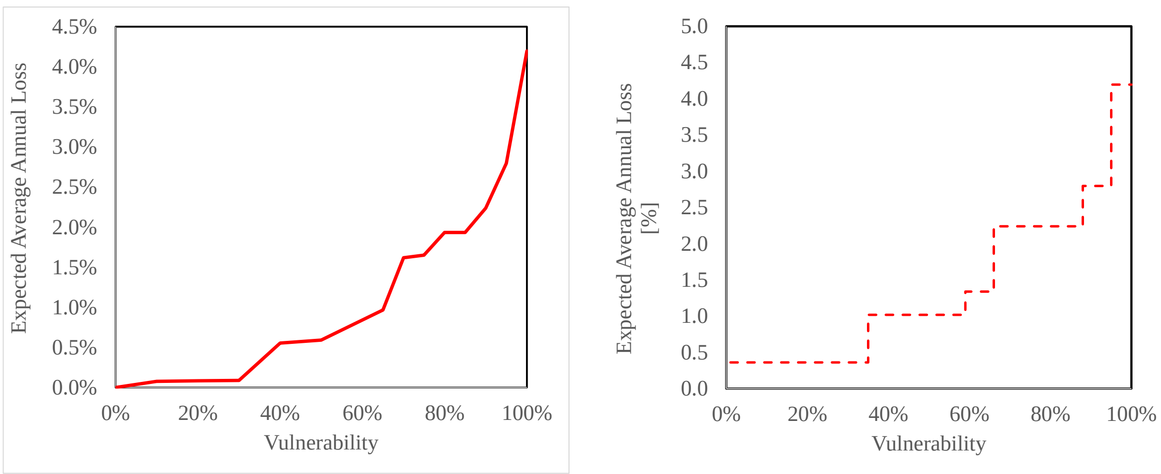
calibrated in order to obtain the maximum expected Average Annual Loss in correspondence of the E* Risk Class of the Sismabonus.

Table 3 shows, for each LS, the RP of the seismic action, the level of damage in terms of Class together with the corresponding ranges of the values μ_D, the cost of reconstruction (RC) associated with the LS and, finally, an assessment of the number of months required to recover the original condition.

TABLE 3: LIMIT STATE, RETURN PERIOD, DAMAGE INDEX, RECONSTRUCTION COST AND RECOVER.

LS	RP [years]	μ_D		RC [%]	Recover [Months]
		Class	Range		
ID	10	0	0.0 – 0.05	0	0
O	30	1	0.05 – 0.2	7	2
DL	50	2	0.2 – 1.0	15	8
LS	475	3	1.0 – 2.2	50	50
C	975	4	2.2 – 3.2	80	132
R	2475	5	3.2 – 5.0	100	168

Fig. 3 shows the AAL against the vulnerability index considering the seismic hazard of Florence. In particular, in Fig. 3(a), the behavior of the AAL as a function of the vulnerability index is shown directly, while Fig. 3(b) reports the the variation of therisk classes foreseen in the SISMABONUS with the vulnerability index.



(a) (b)

FIGURE 3: EXPECTED AVERAGE ANNUAL LOSS AGAINST VULNERABILITY INDEX.

AAL can be estimated through the actual cost of rebuilding as well as by referring to similar experiences, such as starting from the costs of the interventions observed during the reconstruction following the earthquake of L'Aquila. Another approach could be based on the market value of the properties derived from Official Bulletins or the Revenue Agency. The latter hypothesis was assumed by the DICEA Research Unit, which led to an average cost of 4100.00 €/mq.

MITIGATION

To account for the reduction of seismic risk due to the implementation of mitigation strategies, some modifiers of seismic behavior considered in the risk assessment procedure have been recalibrated (Fig. 2).

Three general levels of intervention have been taken into account, which also reflect the spirit of the current regulations.

- Local intervention: intervention involving limited portions of the building. Specifically, it was hypothesized to improve locally the state of conservation and the roofing system and with the insertion of anti-seismic devices such as chains and / or tie rods (behavior modifiers $V_{m,k}$ Fig. 2).
- Seismic improvement: intervention that tends to significantly vary the stiffness, strength and/or ductility of individual structural elements or parts and/or introduce new structural elements, so that the structural behavior, local or global, is significantly modified. In doing so, the vulnerability and consequently the damage index significantly decreases. In this case it has been hypothesized that all the possible modifiers of the behavior $V_{m,K}$ of Fig. 2 are improved.
- Adjustment: interventions that entail the achievement of performance levels that totally eliminate vulnerability and therefore damage. Therefore, these are significant interventions that substantially modify the building and for this reason not foreseen in the case of historic monumental buildings.

For each building the new vulnerability and damage index were recalculated and then defined back the new expected Average Annual Loss with the procedure previously described or directly using the graph in Fig. 3.

It is possible to evaluate the effect of mitigation by calculating the difference between the pre and post intervention economic values. To assess its effectiveness, this value must be compared with the costs incurred for the implementation of these interventions.

The estimate of the costs of the interventions can be deduced from a market analysis of the processes to be implemented to carry out the interventions. In this case, the costs for both local intervention and seismic improvement have been deduced from the “Libro bianco sulla ricostruzione privata fuori dai centri storici nei comuni colpiti dal sisma dell’Abruzzo del 6 Aprile 2009” [25]. In particular, 68.00 €/mq is the average cost of local reinforcement and 320.00 €/mq that of seismic improvement.

TOURISTS LOSS

The loss of tourists for museums or monumental heritage located in the system is also estimated.

Also for the mitigated condition, the average annual visitors lost as well as the recovery times to the pre-event conditions, have been computed.

Starting from the vulnerability of the buildings, churches, museums, libraries etc., the relative damage was defined according to the macroseismic intensity I.

The vulnerability of the churches was calculated following the provisions of LV1 assessment, of the “Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale” [19] (model churches), while for the structures the vulnerability was conducted applying the macroseismic method [6], considering the buildings ordinary or referring to evaluations conducted by other scientific studies.

Once the damage has been defined, through Table 3 it is possible to quantify the time for recovery and then evaluating the days / months of closure of the building necessary to return to the pre-earthquake conditions.

The closure period associated to each level of damage and the RP of the seismic action have been defined for each building and using the data relating to average daily visitors (information provided by UNIFI-DICEA). To quantify the economic loss reference was made to the cost of the Firenzecard, the official museum pass of the city of Florence, the cost of which is € 85.00 with a validity of 72 hours from the time of activation. At this point it is possible to determine the recovery curves in which for each RP of the seismic action it is possible to estimate the time required to restore system's functionality.

FIRENZE

Before entering into the study of vulnerability, damage, assessment and mitigation of seismic risk, it is interesting to know how some historic information about the development and urban configuration of the area under study. Information have been also provided for the subsoil, seismicity and scientific experiences on the city center.

HISTORICAL BACKGROUND

Firenze was founded in 59 BC at the behest of Cesare, when, with the agricultural Lex Julia, they wanted to entrust plots of land to be cultivated to those who had fought in the wars of Roma. The first settlement "Castrum" built according to tradition, through a process of identifying the place deemed most appropriate was divided into an orthogonal mesh with the decumani parallel to the street pedemontana. The decumano maximus can be identified in the axis given by the current Spada street and Palazzuolo street while the cardo maximus in the current Ginori, San Gallo and Faentina streets (Fig. 4).

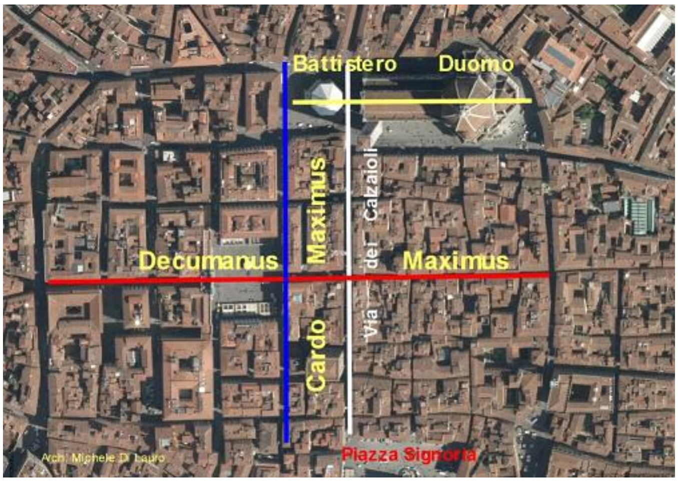


FIGURE 4: CITY OF FIRENZE MAP WITH INDICATION OF THE CARDO AND DECUMANO.

The center of the Castrum, considered a sacred place, corresponds to the current Repubblica square. The colony included a total of nine cardi and seven decumani who divided the city into about 50 insulae, within which there were residential domus. The Castrum was surrounded by brick walls whose sides were defended by circular towers with a diameter of 5 to 7 meters. At the center of the sides, there were 4 doors, as well as some minor passages near the corners of the walls, for entering the city.

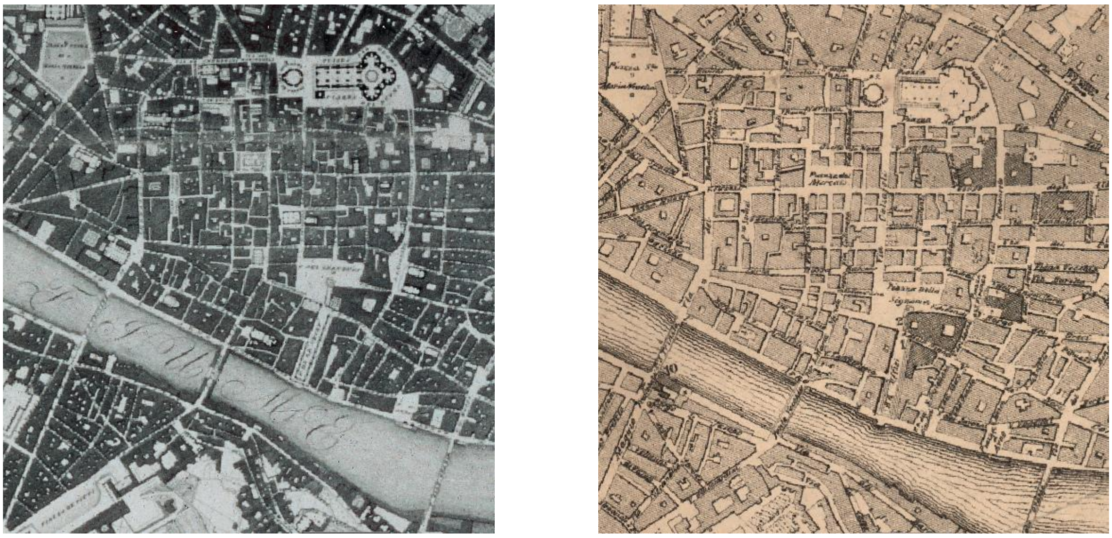
The Castrum just described remained more or less unchanged for about four centuries. There were four access doors (from the "medieval" names) now no longer visible: to the west the San Pancrazio door or Brancazio; to the east the San Piero door which was located at the intersection of del Proconsolo street and del Corso street; to the north the Aquilonia door or also Porta Contra Aquilonem; to the south, the Por Santa Maria, which leads to one of the oldest streets in the city, dating back to Roman times as an extension of the cardo outside the first city walls [27].

(a) (b)

FIGURE 5: CITY OF FIRENZE MAP. 1594-1624 (a) – 1731 (b).

(a) (b)

FIGURE 6: CITY OF FIRENZE MAP. 1783 (a) – 1837 (b).



(a) (b)

FIGURE 7: CITY OF FIRENZE MAP. 1843 (a) – 1865-1870 (b).

CITY WALLS

Six are the walls that have succeded in the city since its foundation (Fig. 8). The first coincides with the Castrum, for an area of about 20 hectares. The course of the Mugnone river, due to the construction of the walls, takes the form of a moat around the city and led to flow into the Arno near Santa Trinità door [28].

In 539, Firenze was occupied by the Byzantines and between 541 and 544 a second city walls "Byzantine circle" was built, smaller in size than the Castrum, following a typically high-medieval mode.

In the mid of IX century the "Carolingia circle" was built which goes south to the Arno, but leaves the Baptistery and the San Salvatore church (later Santa Reparata) outside it.

The "ancient circle", epithet with which Dante (Paradiso, XV, 97) refers to the Matildina circle was built in 1078 at the behest of the Toscana Countess Matilde di Canossa. The layout followed that of the first circle, with the exception of an appendix in the Uffizi area. With this intervention, the Mugnone is deviated again giving it a slight bevel, near the Canto dei Carnesecchi, to allow a greater flow of water up to the Arno.

The first municipal circle, fifth, built in 1172, was made necessary by the expansion of the villages outside the walls, along the most important communication routes exiting the city gates. Its dimensions were five times compared to the first, but inside there were many not build areas. The Mugnone is diverted from San Marco to the south along the current San Gallo street where there was a mill. In the Oltrarno area there were no real walls, but the border was delimited by the houses of the villages that had arisen here.

In 1284, the second municipal circle was erected, sixth circle, to incorporate once again the villages born outside the walls, around the convents and churches built along the lines of greater development as well as to cope with the strong urbanization within the previous walls. War events repeatedly interrupted construction until 1333 when the walls were finished. The course of the Mugnone river undergoes changes again to adapt to the new structure of the city, arriving up outside the walls along the current Spartaco Lavagnini street [28].

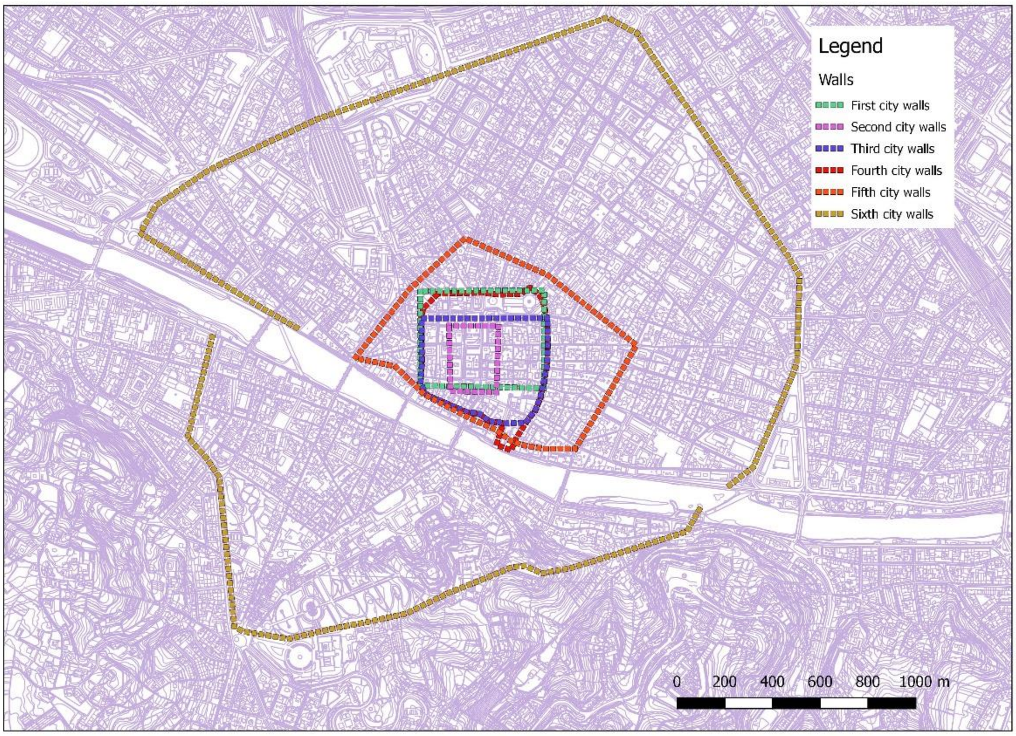


FIGURE 8: CITY OF FIRENZE MAP WITH INDICATION THE SIX CITY WALLS.

SUBSOIL

Over the last few years, the municipality of Firenze has deemed it necessary to have a more detailed and accurate knowledge of the seismic hazard of the area. In collaboration with DST (Department of Earth Sciences-UNIFI), the "Calculated Amplification Factor Card" (Fig. 9) was developed, as a variant of the Structural Plan of 2010. It has led to a high level of knowledge of the structure geological subsoil, a starting point today essential for territorial planning, urban planning and Civil Protection. For the various lithostratigraphic filling levels of the Florence-Pistoia basin, seismic anchoring speeds of the various lithological levels were defined on experimental down-hole tests and on this basis the FA (amplification factor) and the soil oscillation period (Fig. 10) for the approximately 2000 surveys available in the Florentine area. From these punctual data, with statistical interpolation techniques, the ground response for the entire urban area was extrapolated [4, 5].

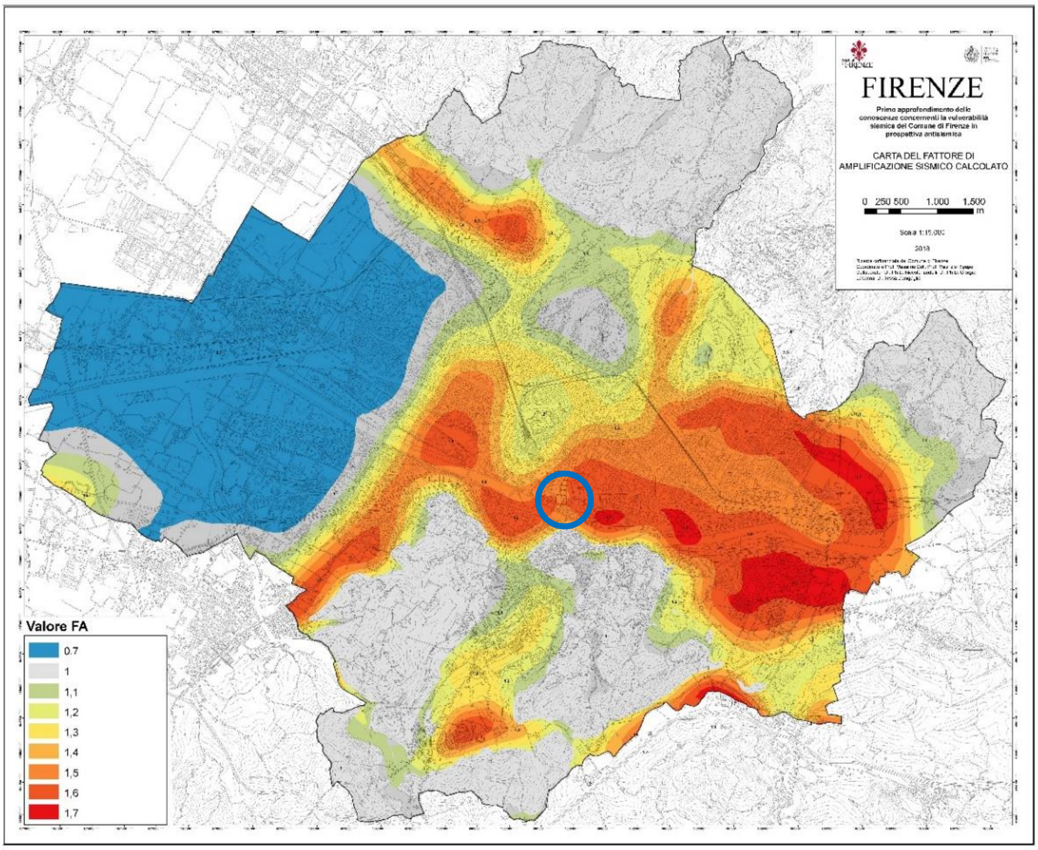


FIGURE 9: AMPLIFICATION FACTOR MAP.

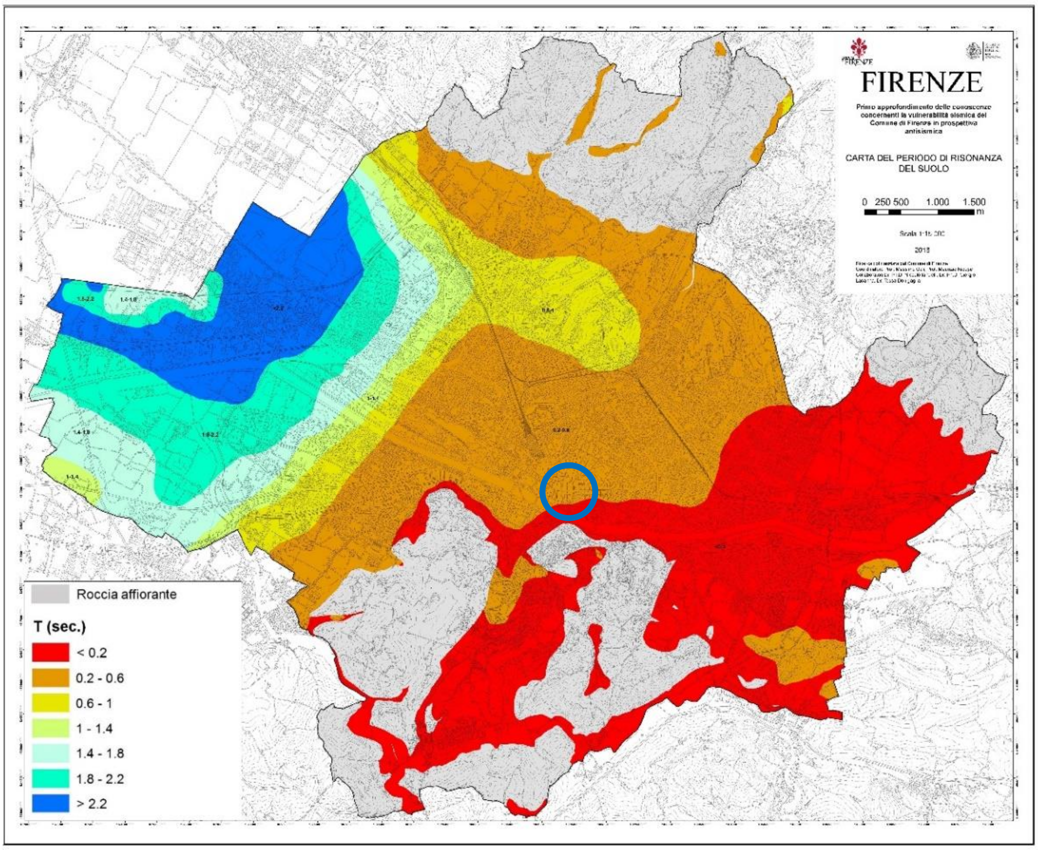


FIGURE 10: FUNDAMENTAL PERIOD OF SOIL MAP.

HISTORICAL SEISMICITY

Since the XXI century, more than 140 (Fig. 11) seismic events have occurred in the Florentine territory with an intensity greater than V on the Mercalli-Cancani-Sieberg (MCS) scale [2]. The most important events occurred in Mugello with resentments in the Florentine area up to I_{max} VII-VIII degree of the MCS scale. Numerous small earthquakes have also been recorded in the Firenze-Pistoia flood plain. The available focal solutions highlight in the Apennine area around Florence a seismic activity linked to mainly extensional mechanisms and in part of a passing type. From the study of historical seismic activity, Firenze city is also the epicenter of important earthquakes, with an estimated magnitude always lower than 5 ML.

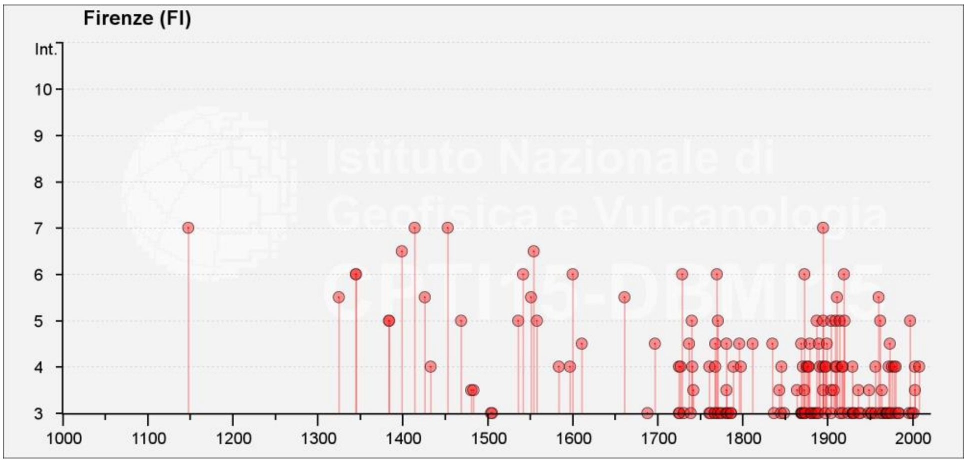


FIGURE 11: DISTRIBUTION AND INTENSITY OF HISTORICAL EARTHQUAKES IN FIRENZE AND NEIGHBOUR AREAS. (from DBM115).

With Resolution GRT no. 421 of 26/05/2014, Firenze falls in zone 3 in the regional seismic classification, but since it contains one of the most important artistic and cultural heritage not only in Italy, but in the world, the risk linked to possible destructive effects due to the earthquake becomes elevated.

There are two main earthquakes that have hit Firenze over the centuries. The earthquake of September 28, 1453, grade 7 on the MCS scale. The buildings were not collapse, but some damage occurred to the monuments, especially in Santa Reparata (today the Cathedral) where some stones from the vaults collapsed and in San Marco Convent where the walls and vaults of the library were damaged.

From the maps showing the damage suffered by the Firenze city during the earthquake of 1895 and 1919 [29] it is clear that the areas of greatest damage were concentrated in the Cure, San Jacopino, San Salvi, San Frediano and San Niccolò zones. In particular, as regards to the area inside the walls, the most damaged areas were found to be Libertà square, Santa Croce and San Gallo zones.

In particular, the earthquake of 18th May 1895 is remembered as the “Firenze great earthquake”. The damage was very extensive, but overall not very serious; in fact there were no major destructions, but most of the monuments, churches and historic buildings were damaged. Small collapses affected Palazzo Pitti and the Galleria degli Uffizi, significant damages occurred in Medici Riccardi palace, Strozzi palace, in the vaults of the arcades of SS. Annunziata square and Cavour square (today Libertà square). The Della Robbia majolica collection of at the Bargello National Museum was seriously damaged. There was serious damage to the San Marco museum, in the church and convent of the same name already affected by the earthquake of 1453, with falls of cornices and damages to the vaults and arches, especially in the refectory and in the library. The Cathedral was also affected by the breaking of a chain in the central nave.

The Vannucci et al. map [29] reports the distribution of the damage effects caused by the earthquake: the darker colors (from orange to purple) indicate the most serious effects, yellow the minor ones (Fig. 12). Overall the effects in Firenze were equal to grade 7 on the MCS scale occurred in Galluzzo.

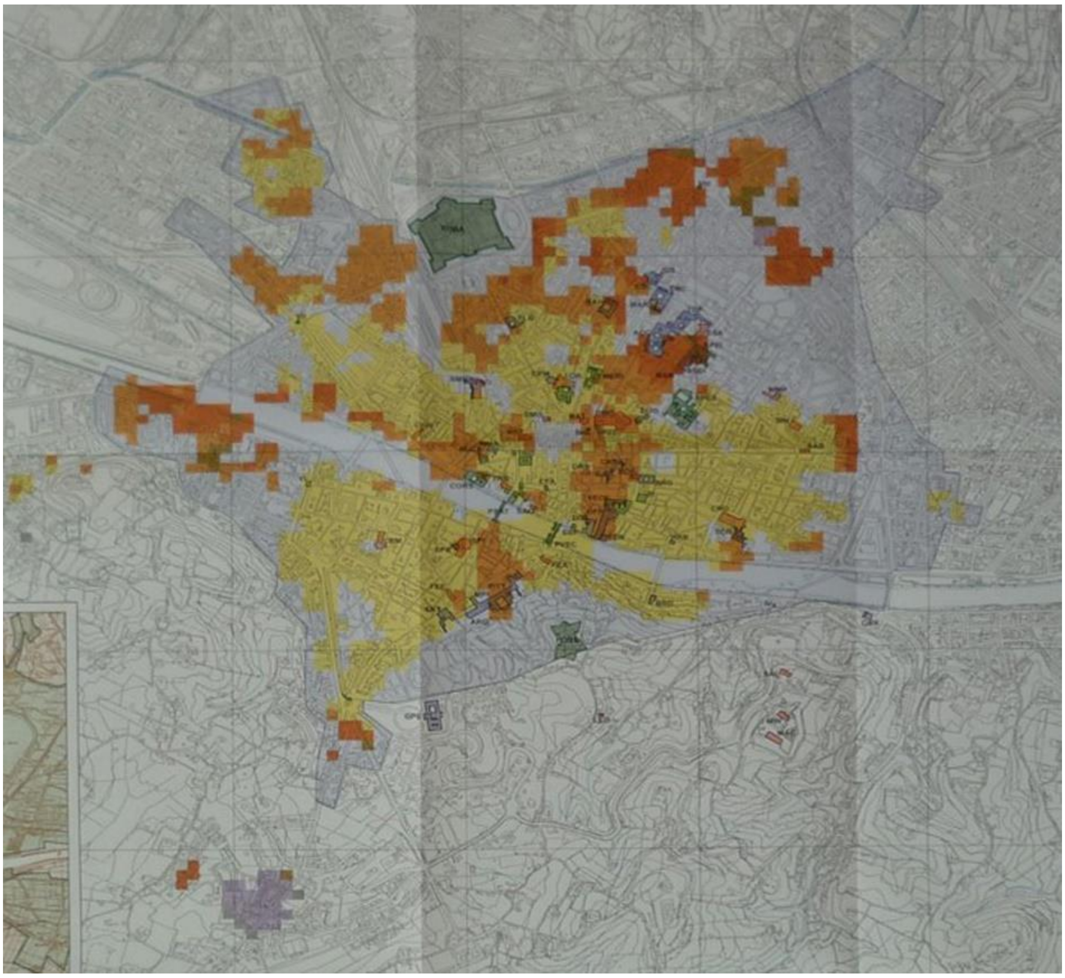


FIGURE 12: VANNUCCI ET AL. MAP RELATING TO EARTHQUAKE OF FIRENZE IN THE 1985.

CASE STUDY

The results obtained through the procedures described in the previous section are reported below, referring to a limited area of the historic center of the Firenze city "Fourth wall circle".

In particular, the first part concerned the cataloging, in GIS environment, of all the necessary information and data concerning each building. These data were used to apply the proposed procedures.

DATA INPUT, GENERAL DESCRIPTION

The aim of the research is to provide a structure in which to insert all the information through a territorial information system. Specifically, QGis [30] has been adopted which allows data from different sources to be merged into a single territorial analysis project.

The area under study falls within the fourth wall circle, called "ancient circle". The buildings of worship and the bell towers, for a total of 25 artifacts, included within this area are highlighted in yellow (Fig. 13).

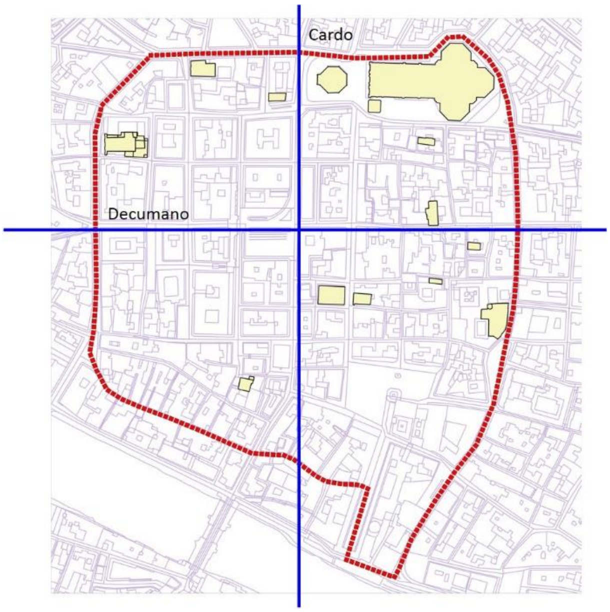


FIGURE 13: PERIMETER OF THE CASE STUDY.

This area was divided into three zones referring to three significant periods from the point of view of the development of the urban fabric (Fig 14):

Zone 1: buildings prior to the period of Firenze Capital (74%).

Zone 2: buildings falling within the area rebuilt following the demolition of the Ghetto (19%).

Zone 3: buildings in R.C. rebuilt after the bombing of August 1944 (3%).

The buildings of worship and the bell towers represent 4% of the built.

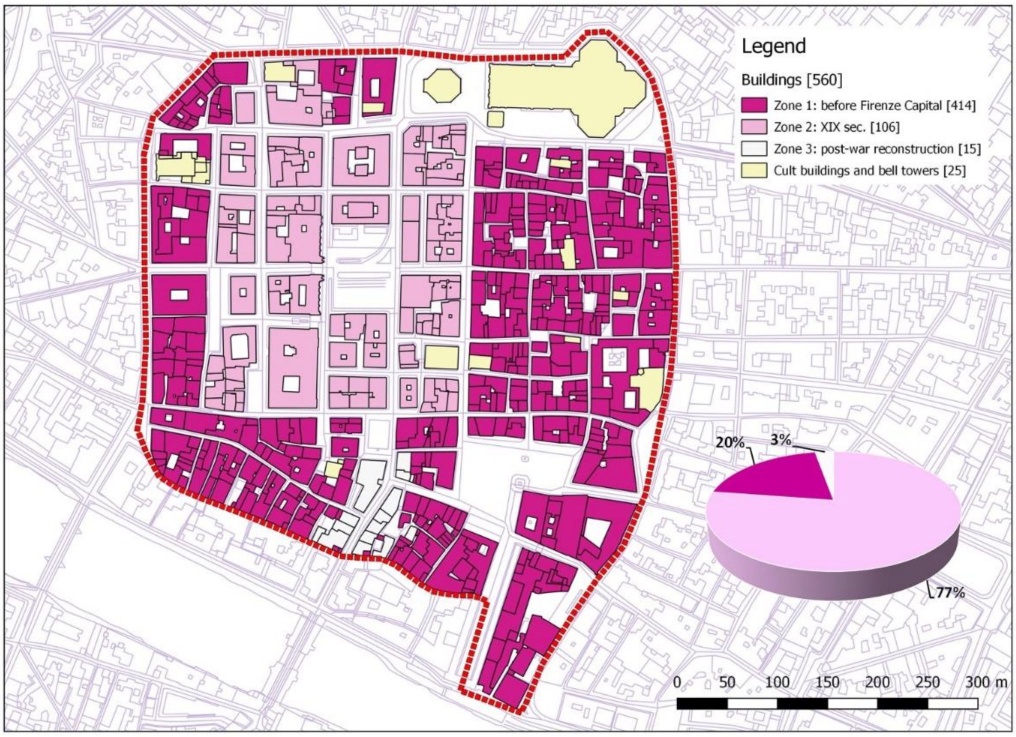


FIGURE 14: PERIODIZATION MAP.

(a) (b)

FIGURE 15: BOMBING SANTA TRINITA BRIDGE (a) – BOMBING PONTE VECCHIO AREA (b).

Each building has been identified and cataloged (INPUT) through a series of attributes:

• building identification
• block to which the building belongs
• cadastral sheet number
• cadastral parcel number
• number of floors
• building height
• building height in eaves
• total building height
• construction typology
• age of realization
• amplification factor
• fundamental period of the soil

A total of 560 buildings were detected. The aforementioned data, some of which received by the Regional Technical Card (CTR) database of the Municipality and by ISTAT data, have been processed by producing the related thematic maps and statistical analyzes. Fig. 16 shows the 3D view of the analyzed area.

(a)

(b)

FIGURE 16: 3D VIEW OF THE INVESTIGATED AREA.

By identifying the buildings by the number of floors, as indicated in [6], the division took place according to the following criterion:

1) Buildings with 1 and 2 floors
2) Buildings with 3, 4 and 5 floors
3) Buildings over 6 floors

From the deduced data it is evident that 76% of buildings fall within the range between 3 and 5 floors, 8% of buildings have a maximum of 2 floors while 16% exceed 6 floors, for a total of 535 buildings, having excluded the cult buildings and the bell towers (Fig. 17).

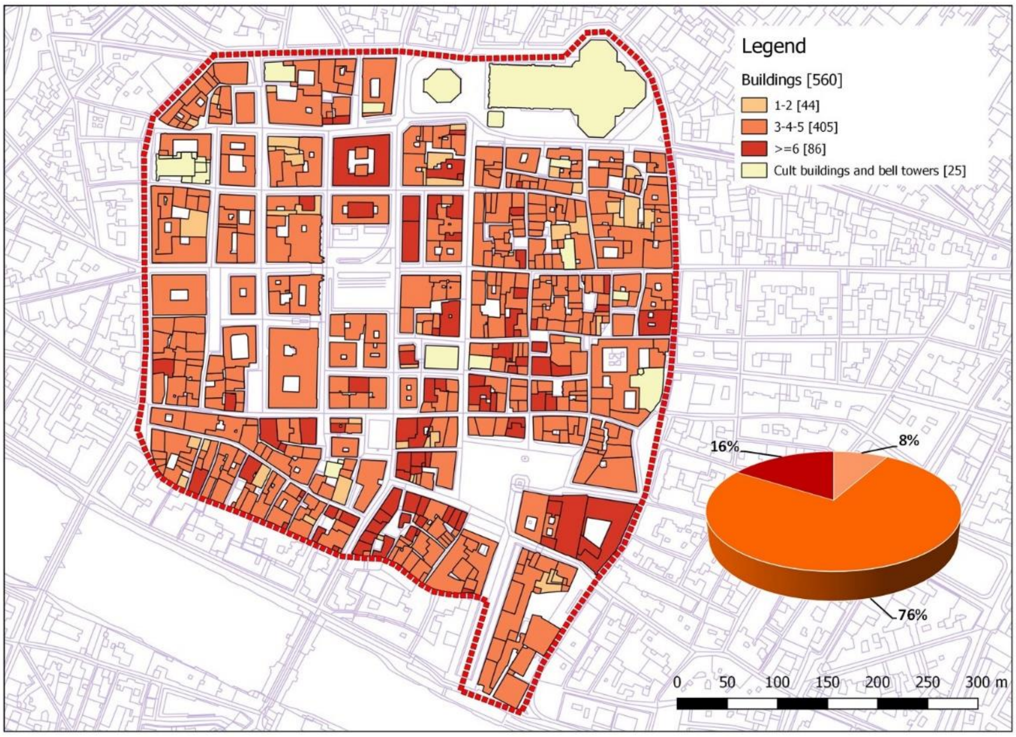


FIGURE 17: SUBDIVISION OF THE BUILDINGS BY NUMBER OF FLOORS MAP.

The classification of buildings by construction type shows that the area is mainly characterized by masonry buildings (97%), except for those near Ponte Vecchio which, as previously mentioned, are in reinforced concrete (3%) as destroyed and rebuilt after the German bombing (Fig. 18).

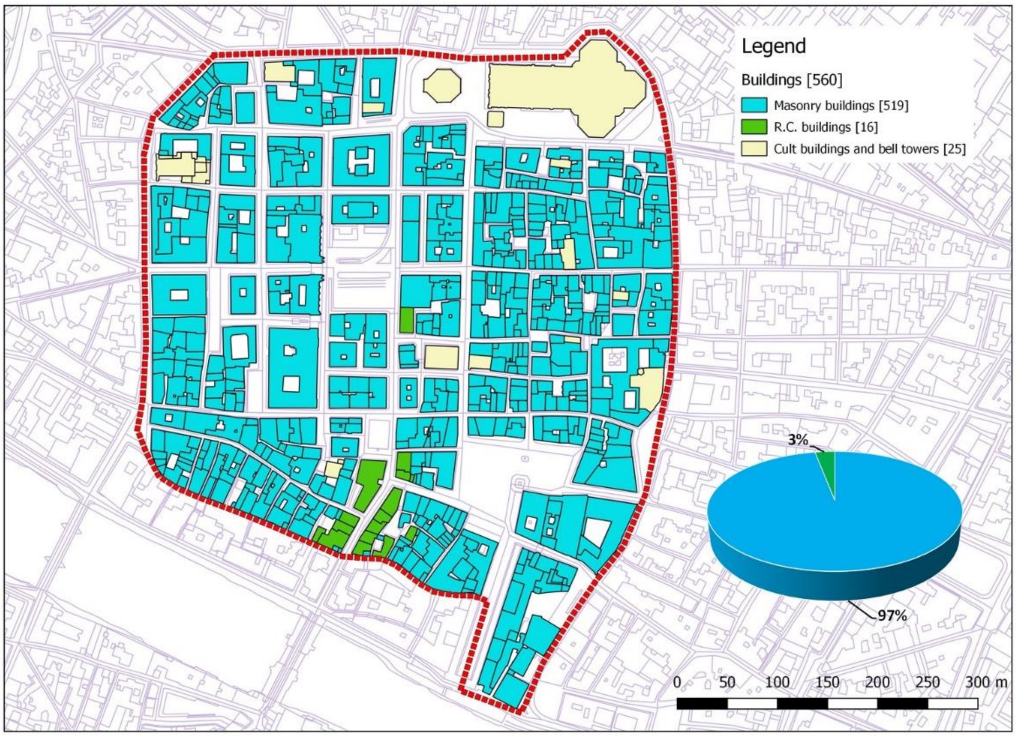


FIGURE 18: SUBDIVISION BUILDINGS BY TYPOLOGY.

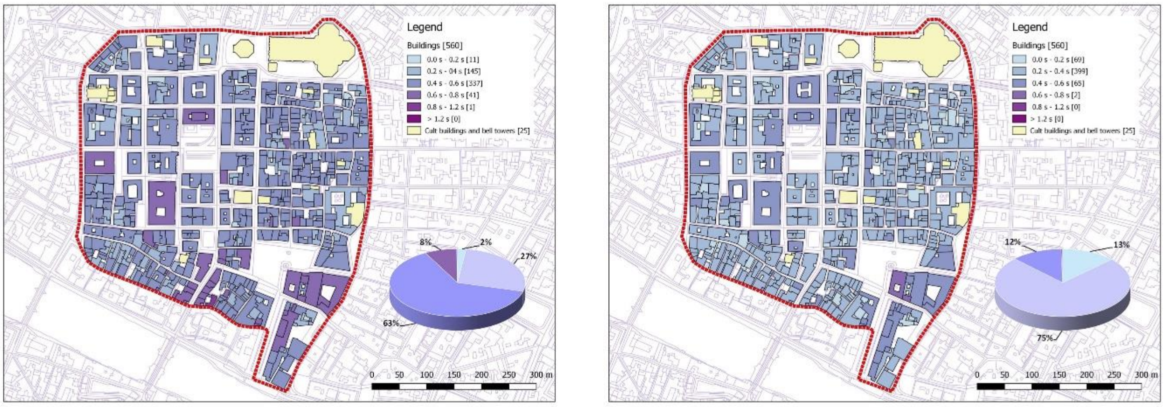
Fundamental period and resonance

Following the provisions of the Italian building code (NTC 2008) [31] and formulations developed within Sismed Project [32, 5, 4] for the Florentine buildings, the fundamental period of the buildings was calculated. The formulations adopted are shown in Table. 4.

TABLE 4: FORMULATION TO DETERMINING THE BUILDING PERIOD.

Construction typology	NTC 2008	Sismed project
Masonry	$T = 0.05 * H^{3/4}$	$T = 0.0162 * H$
R.C.	$T = 0.075 * H^{3/4}$	$T = 0.019 * H$

Even if the buildings of worship and bell towers have been excluded from the computation, the calculations relating to the fundamental period, according to the two procedures, have shown a substantial heterogeneity (Fig. 19).



(a) (b)

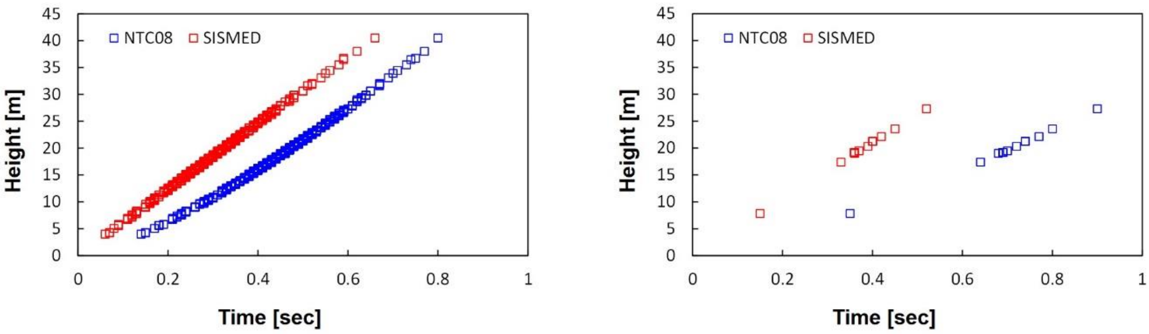
FIGURE 19: FUNDAMENTAL PERIOD OF BUILDING MAP. NTC 2008 (a) – SISMED PROJECT (b).

With the NTC 2008 formulations, about 63% of buildings were found with the fundamental period between 0.4 s and 0.6 s, about 27% with 0.2 s < T <0.4 s and 8% with a period between 0.6 s and 0.8 s. The formulations developed with the Sismed Project shows that there is a high percentage of buildings falling within the range 0.2 - 0.4 s, 75% between 12% and 13% of buildings fall respectively in the range 0.4 - 0.6 s and 0.0 - 0.2 s (Table 5).

TABLE 5: FUNDAMENTAL PERIOD OF BULDING USING THE TWO METHODS.

Range T [s]	NTC 2008 [%]	Sismed [%]
0.0-0.2	2	13
0.2-0.4	27	75
0.4-0.6	63	12
0.6-0.8	8	0
0.8-1.2	0	0
> 1.2	0	0

The graphs below (Fig. 20) show the trend of the fundamental period of the buildings in relation to the height and construction typology, specifying that none of them exceeds 40 m in height.



(a) (b)

FIGURE 20: FUNDAMENTAL PERIOD OF BUILDINGS - MASONRY (a) – R.C. (b).

From the fundamental period of the soil and that of the buildings, the resonance index map was produced (Fig. 21 and 22) evaluated as follows [33]:

$$I_R = T_e/T_s \tag{4}$$

where T_e is the period of the building and T_s is the period of the soil.

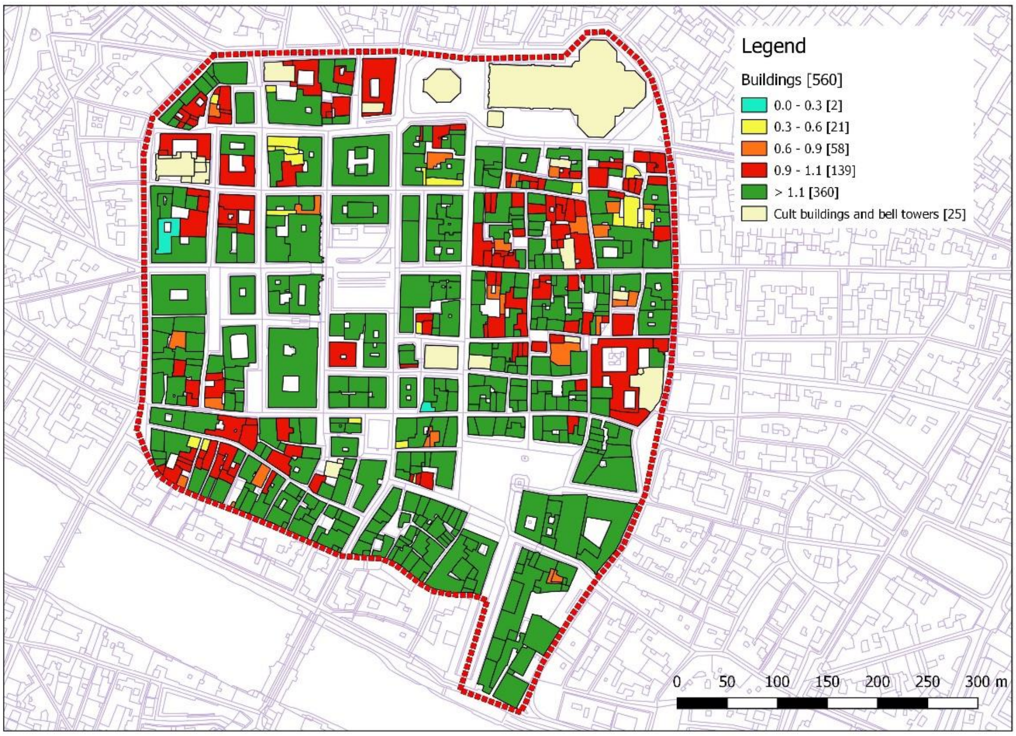


FIGURE 21: RESONANCE INDEX MAP – NTC 2008.

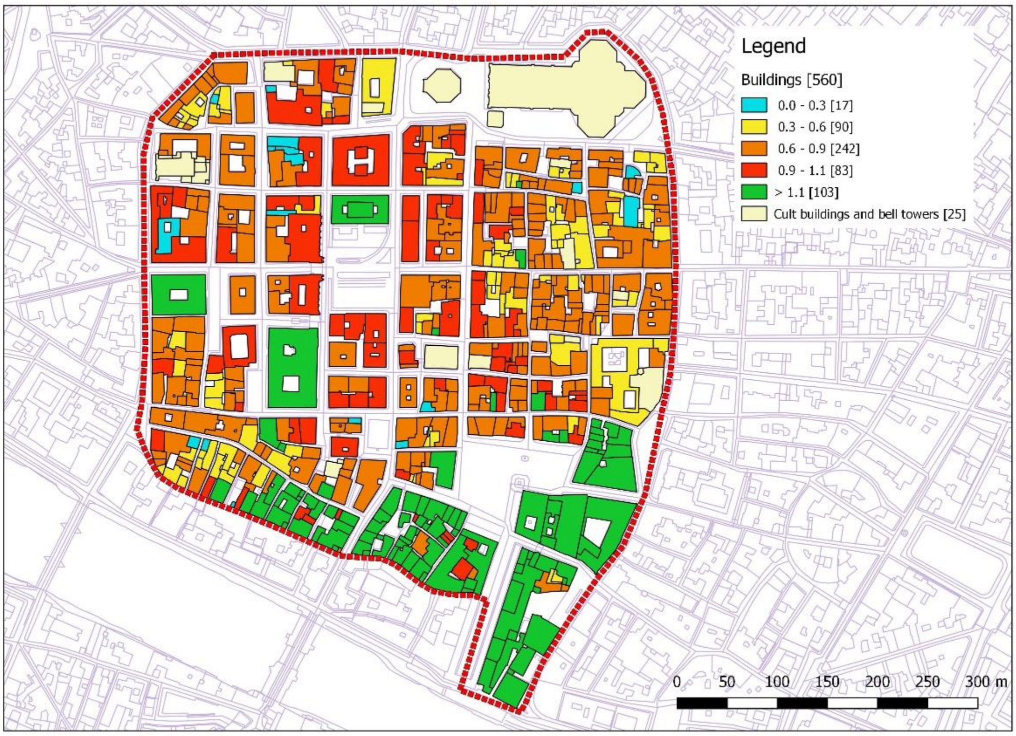


FIGURE 22: RESONANCE MAP – SISMED.

From the results obtained, ranges were selected to identify the presence or absence of resonance, whether it is calculated with the period of the building according to NTC 2008 or with the formulation proposed in Sismed. In Table. 6 the results are reported:

TABLE 6: RESONANCE INDEX.

RI	Resonance	NTC 2008 [number of buildings]	Sismed [number of buildings]
0.0-0.3	Absent	2	17
0.3-0.6	Scarce	21	90
0.6-0.9	Relevant for high intensity earthquake	58	242
0.9-1.1	Relevant for low intensity earthquake	107	83
> 1.1	Absent	347	103

HAZARD

Starting from the seismic hazard of the area under study, according to the provisions of the Italian building code [8], the PGA is obtained for each RP and, through literature formulations, it is possible to obtain the associated macroseismic intensity (I) as defined in Margottini et al. [34] (Table 7).

TABLE 7: PEACK GROUND ACCELERATION AND MACROSEISMIC INTENSITY FOR EACH RETURN PERIOD.

RP	PGA [g]	I_{EMS98}
10	0.032	4.555
30	0.047	5.324
50	0.056	5.673
72	0.064	5.940
101	0.072	6.175
140	0.080	6.385
201	0.094	6.706
475	0.131	7.369
975	0.167	7.854
2475	0.221	8.413

Many of these laws in literature can be traced back to the same formula (eq. 5) proposed by Lagomarsino and Giovinazzi [6]:

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

Where a_g is the ground acceleration in units of g, I is the macroseismic intensity measured in the conventional EMS-98 scale, c_1 is the acceleration value corresponding to a macroseismic intensity equal to 5 and c_2 is the slope of the curve of correlation.

Table. 8 shows the coefficients obtained for three different correlation laws [21].

TABLE 8: VALUES OF c_1 AND c_2 FOR THREE CORRELATION LAWS CONSIDERED (FROM [21]).

Correlation laws	c_1	c_2
Guarenti - Petrini	0.03	2.05
Margottini	0.04	1.65
Murphu O'Brien	0.03	1.75

VULNERABILITY INDEX

The structural typologies present in the analyzed buildings, from which deriving the typological vulnerability index VI*, are:

- M3: simple stone $V_I^* = 0.74$
- M4: massive stone $V_I^* = 0.616$
- M5: unreinforced masonry (old bricks) $V_I^* = 0.74$

Fig. 23 shows the mapping of the structural typology. There is a strong percentage of buildings falling in the category of simple stone (88%), 12% of that in unreinforced masonry and only 1 building is characterized by massive stone "Strozzi Palace".

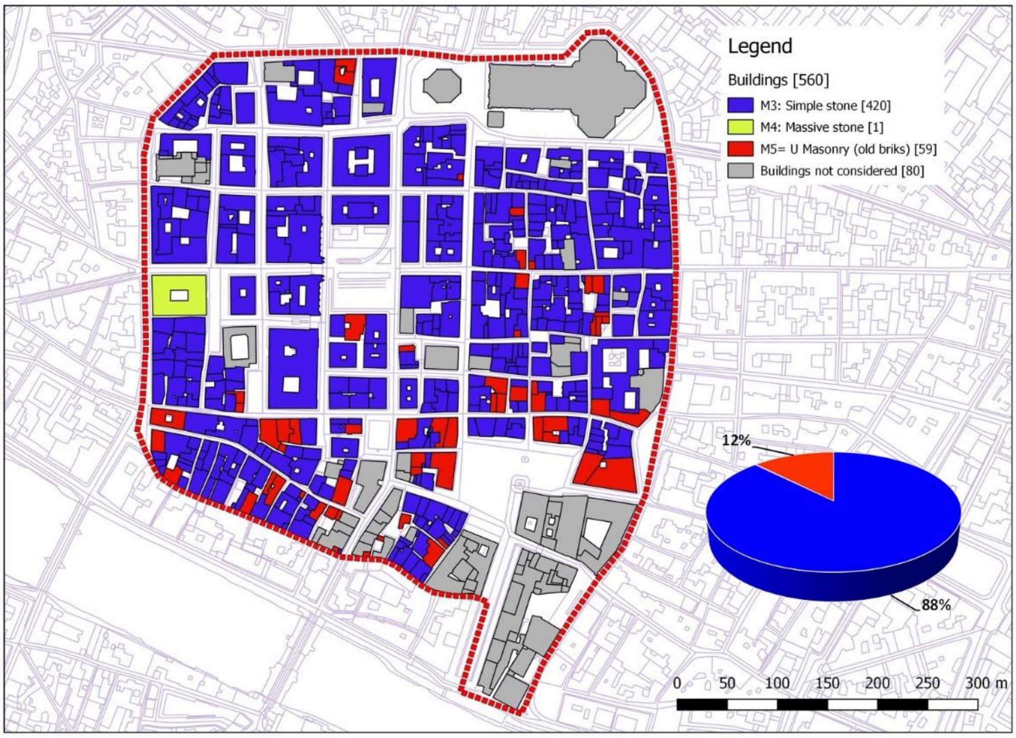


FIGURE 23: STRUCTURAL TYPOLOGIES MAP.

Fig. 24 shows the vulnerability map considering the modifying factors detected on each building (Fig. 2).

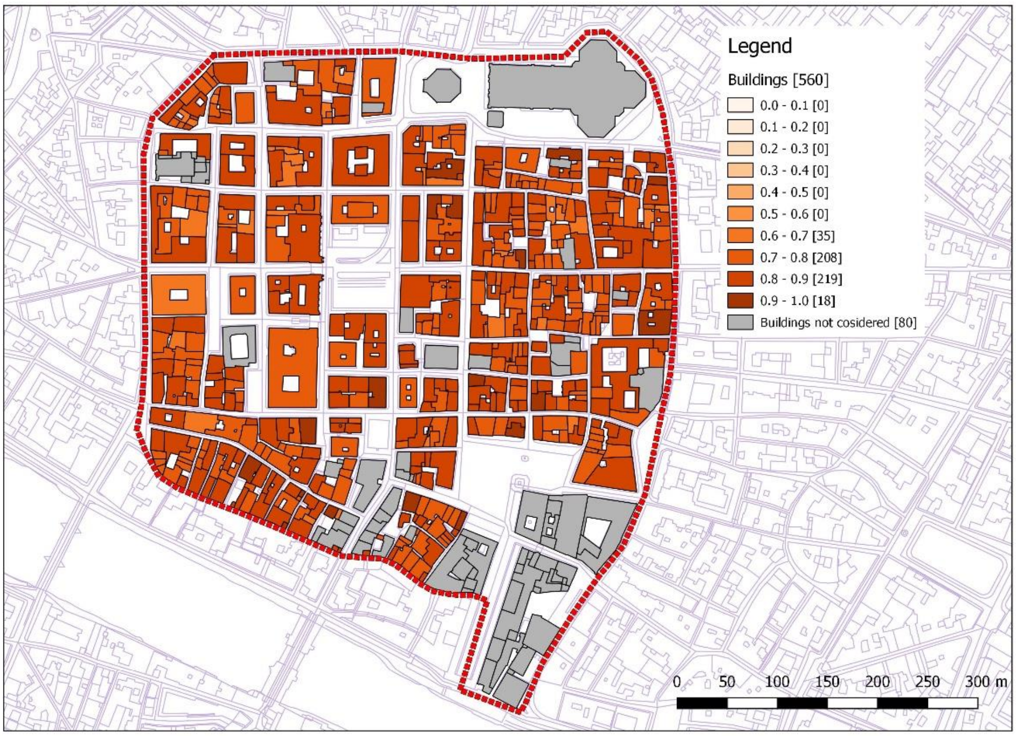
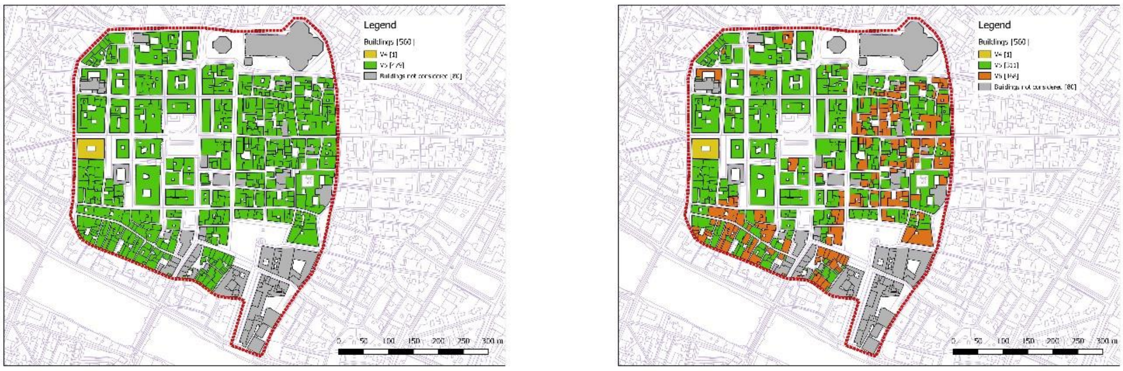


FIGURE 24: VULNERABILITY INDEX MAP – ACTUAL CONDITION.

APPLICATION OF THE EXPECTED AVERAGE ANNUAL LOSS THROUGH "SISMABONUS"

In the case study, the structural typologies identified are the same as those considered in the estimation of the vulnerability index (Fig. 23 and Table 2). Since Firenze falls in seismic zone 3 and the prevailing structural typologies are M3 and M5 (only one building falls into M4), the corresponding vulnerability class in both cases is V_5. Some of the buildings have undergone a change in the initial vulnerability due to the presence of critical issues, consequently, for some buildings the changeover from V_5 to V_6 has taken place (Fig. 25).



(a) (b)

FIGURE 25: VULNERABILITY CLASSES MAP - WITHOUT DEVIATION (a) – WITH DEVIATION (b).

By interpolating the zone of belonging (zone 3) with the vulnerability class (V_5 and V_6), the Risk Class obtained for the entire area is D* (Fig. 26) which is associated with an expected Average Annual Loss ranging from 2.5% to 3.5%.

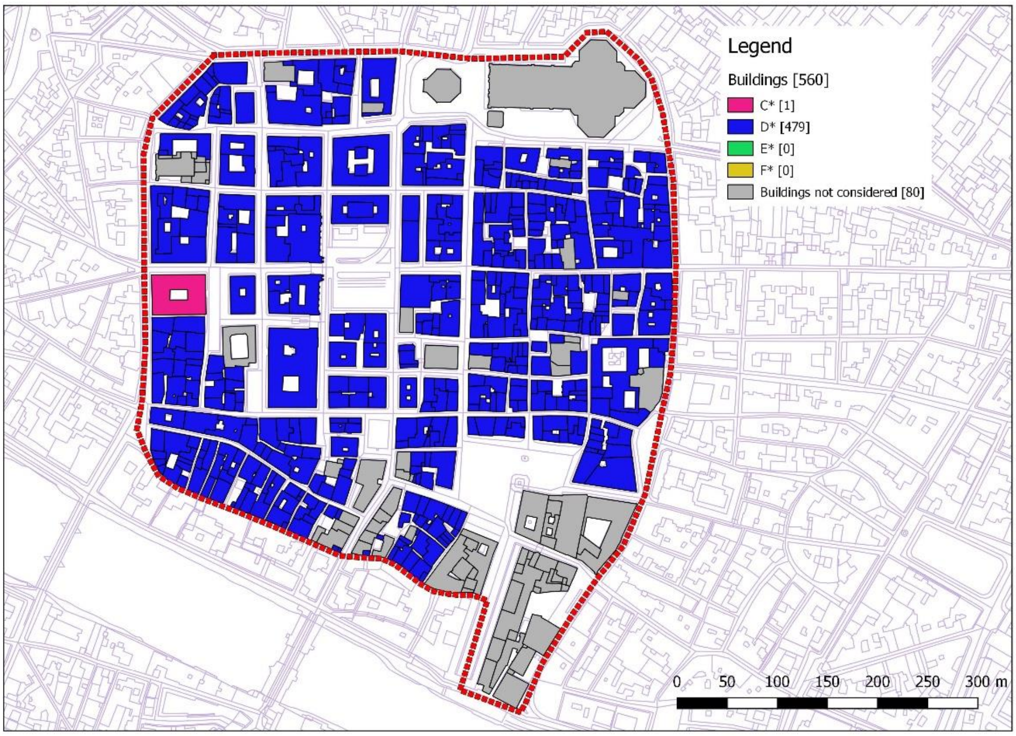


FIGURE 26: RISK CLASSES MAP - ZONE 3.

Considering the correlation of Margottini et al. [34], for a macroseismic intensity equal to 8, Firenze would belong to zone 2 and the scenario of the Risk Class would be completely different corresponding to classes E* and F*, as better illustrated in Fig. 27.

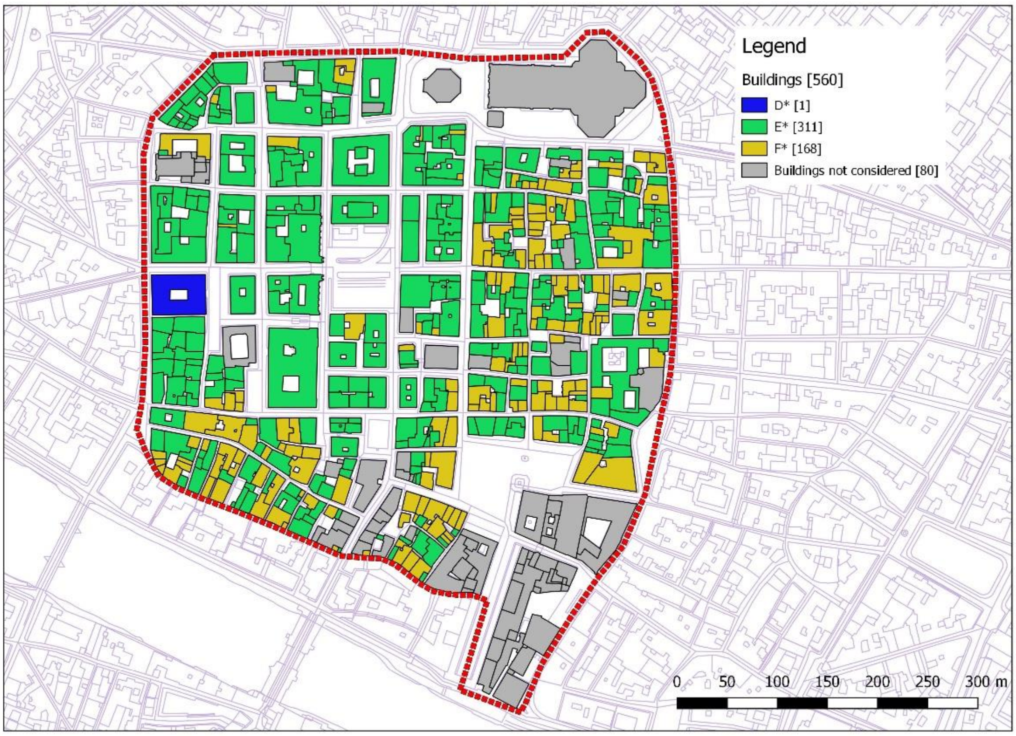
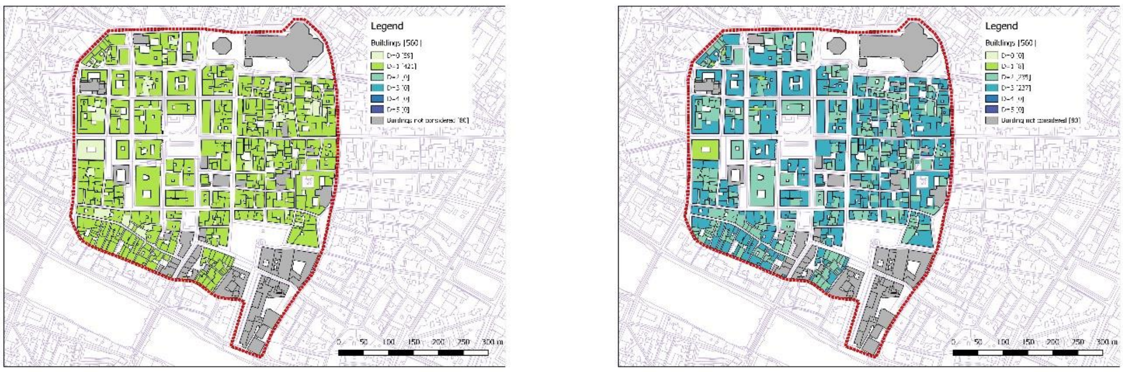


FIGURE 27: RISK CLASSES MAP - ZONE 2.

Fig. 28 shows the mapping of the damage index μ_D calculated with eq. 1, considering the macroseismic intensity I equal to 6 and 8, while Fig. 29 reports the resulting risk index.



(a) (b)

FIGURE 28: DAMAGE INDEX MAP - I=6 (a) – I=8 (b).

On the analyzed sample, 535 buildings excluding those of worship and the bell towers (25), it is evident that μ_D varies from 0 to 1 in the case of macroseismic intensity equal to 6, and between 1 and 3 for I = 8.

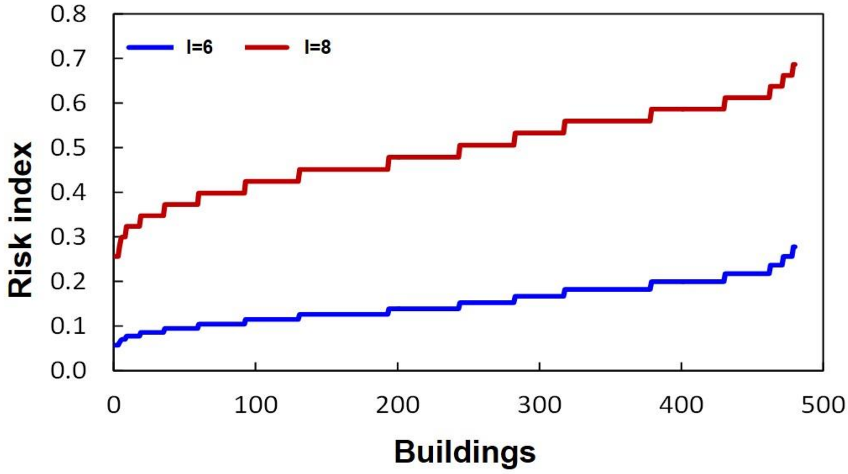


FIGURE 29: RISK INDEX.

In particular, the division of costs was divided as follows:

- μ_D = 1 – Light damage

Average repair cost only:	217.00 €/mq

- μ_D = 2 – Light damage

Average repair cost + average cost of local reinforcement	285.00 €/mq

- μ_D = 3 – Heavy damage

Average repair cost only :	44.00 €/mq

It is possible to hypothesize two possible scenarios:

1. Macroseismic intensity I=6 and zone 3 (Fig. 30)

The entire study area is affected by a risk class of D* (2.5% < AAL ≤ 3.5%) and μ_D equal to 1 (Fig. 28 (a)). Assuming AAL = 3% we have:

μ_D = 1 217.00 €/mq x 0.03 = 6.51 €/mq

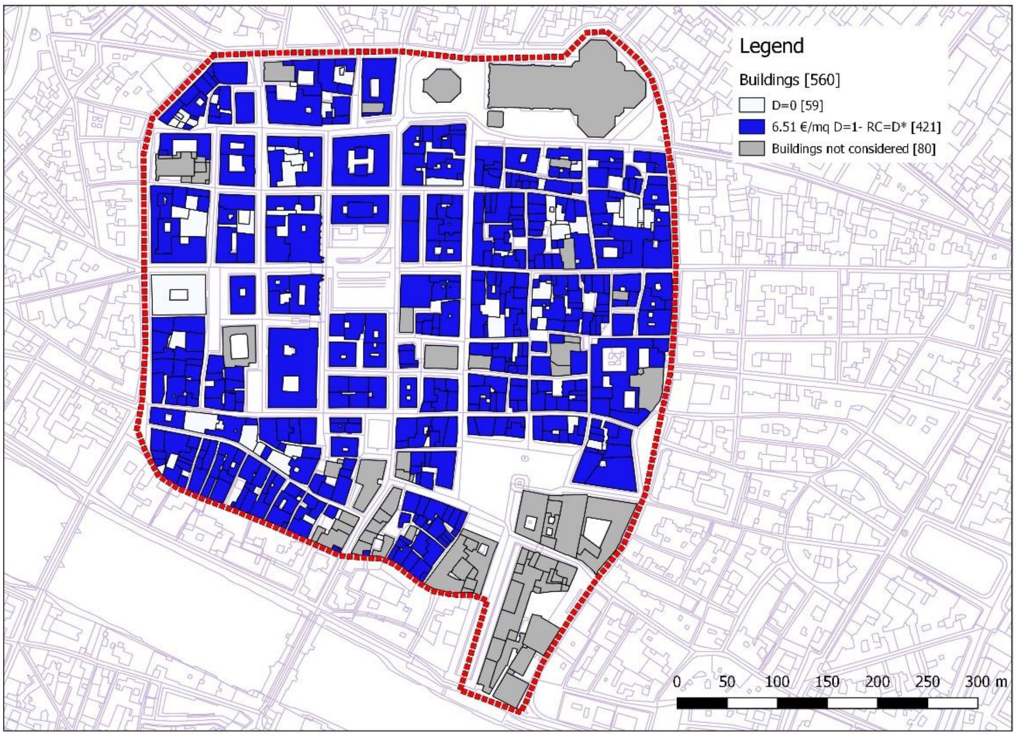


FIGURE 30: REPAIR COSTS MAP - I=6 AND ZONE 3.

2. Macroseismic intensity I=8 and zone 2 (Fig. 31)

The study area is affected by a risk class E* (3.5% < AAL ≤ 4.5%) and F* (4.5% < AAL ≤ 7.5%), with μ_D mainly equal to 2 and 3 and in very few cases equal to 1 (Fig. 28 (b)).

Assuming, for the risk class E*, AAL = 4% and for the risk class F*, AAL equal to 6%, we have:

$\mu_D = 1$ 217 €/mq X 0.040 = 8.68 €/mq

$\mu_D = 1$ 217 €/mq X 0.060 = 13.02 €/mq

$\mu_D = 2$ 285 €/mq X 0.040 = 11.40 €/mq

$\mu_D = 2$ 285 €/mq X 0.060 = 17.10 €/mq

$\mu_D = 3$ 448 €/mq X 0.040 = 17.92 €/mq

$\mu_D = 3$ 448 €/mq X 0.060 = 26.88 €/mq

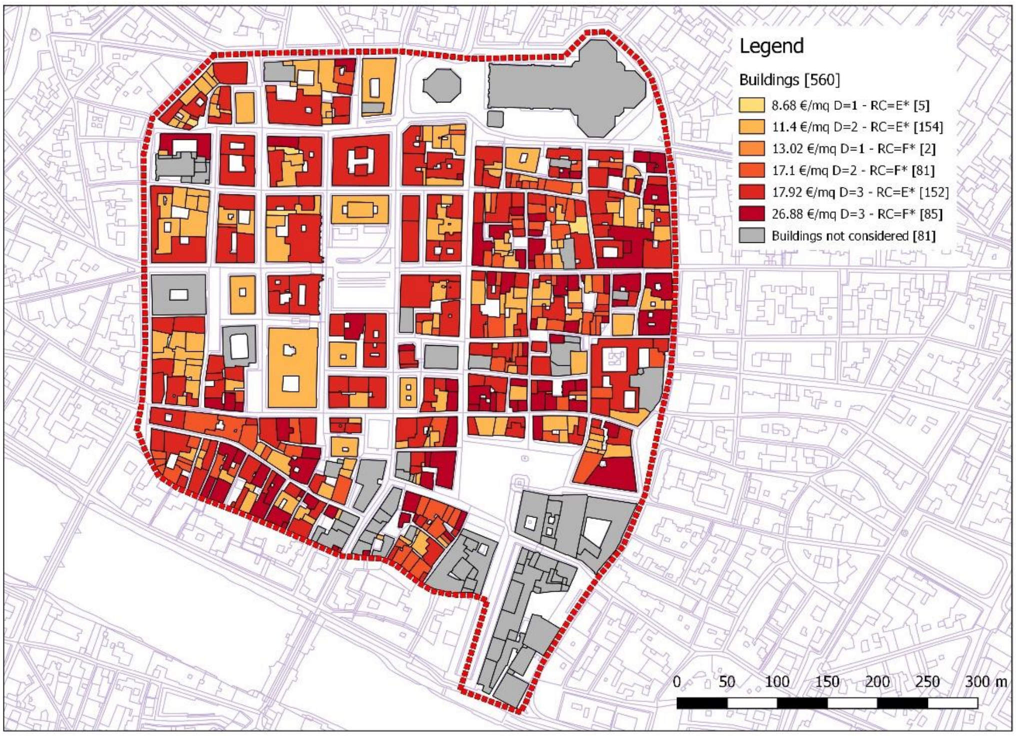


FIGURE 31: REPAIR COSTS MAP - I=8 AND ZONE 2.

APPLICATION OF THE EXPECTED AVERAGE ANNUAL LOSS WITH MACROSEISMIC METHOD

In the following, it is reported the calculation of the expected Average Annual Loss defined through the level of damage of private or ordinary building. The evaluation of the loss is obtained through the procedure described in the previous chapter and allows to estimate the economic loss associated with the damage.

The buildings subject to evaluation are included within the fourth walls, for each of them the vulnerability index was defined with the macroseismic procedure according to the typological class and modified with the corrective factors shown in Fig. 2.

Once the vulnerability index has been defined, the damage index is calculated for each RP. For brevity, the distribution of the damage index for a RP equal to 475 years is shown in Fig. 32. The scale of values is between 0 and 5 and the division into classes from D=0 to D=5 is shown in Table. 3.

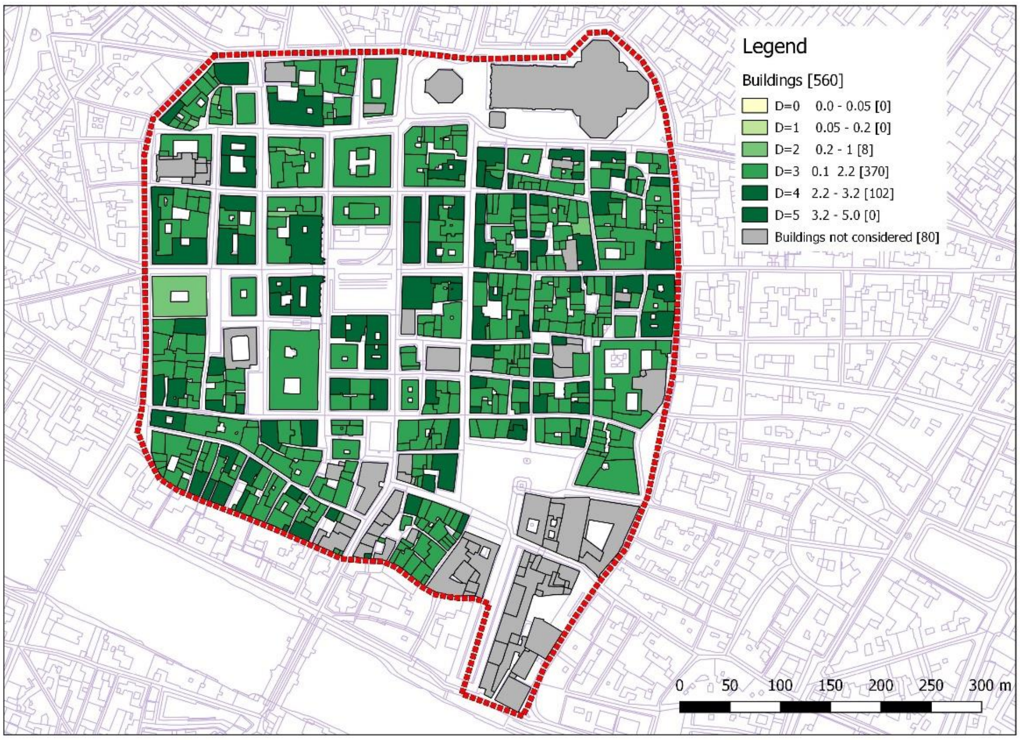


FIGURE 32: DAMAGE INDEX MAP - RP=475 YEARS – ACTUAL CONDITION.

Once the damage index has been defined, for each building and RP, an economic value is associated, as shown in Table 3. The graph in Fig. 33 depicts the trend of the economic loss as the RP changes.

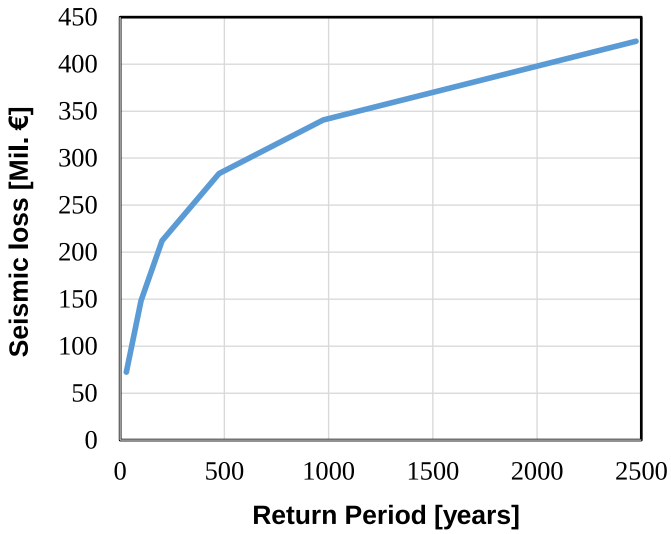
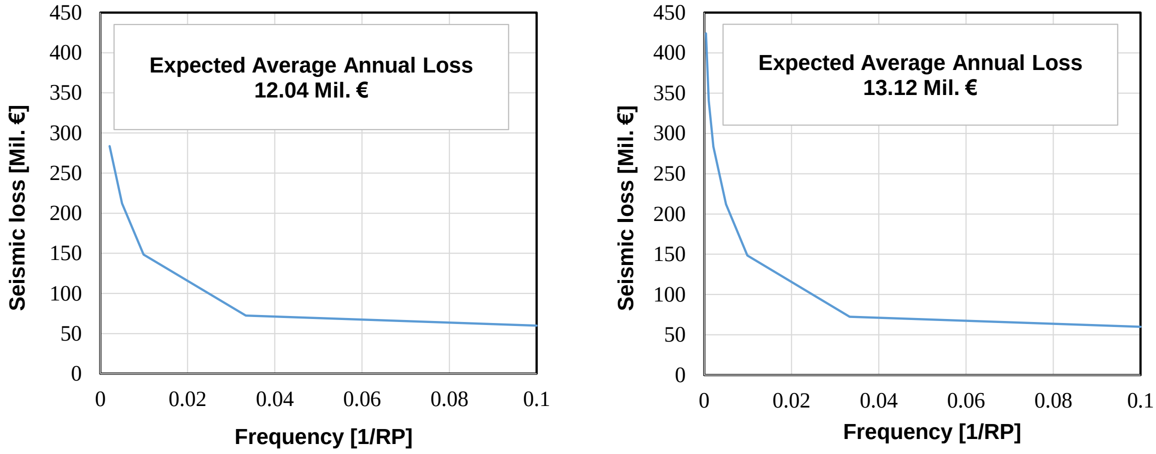


FIGURE 33: TREND OF ECONOMIC LOSS TO VARIATION OF RP – ACTUAL CONDITION.

The expected average annual loss is calculated considering two intervals of return periods. The first 10 ≤ RP ≤ 475 years and the second 10 ≤ RP ≤ 2475 years. Fig. 34 shows the trend of the loss as a function of frequency (1/RP). Fig. 34 (a) shows the first interval with a AAL of 12.04 million €/year while Fig. 34 (b) shows the second interval with a AAL of 13.12 million €/year. It should be noted that the economic value shown is equal to 488 million €. As a percentage, the expected average annual loss are 2.47% and 2.66%, respectively.



(a) (b)

FIGURE 34: ACTUAL CONDITION - EXPECTED AVERAGE ANNUAL LOSS – FIRST RANGE (a) – SECOND RANGE (b).

The following figure (Fig. 35) shows the distribution of the expected Average Annual Loss on the area under study divided by 5 value classes (between 0 and 100 €/mq/year) with a minimum value of 38 €/mq/year, a maximum of 97.5 €/mq/year and an average value of 75 €/mq/year. A fairly homogeneous distribution of the values starting from the third range of the scale (40 €/mq÷ 60 €/mq) can be seen.

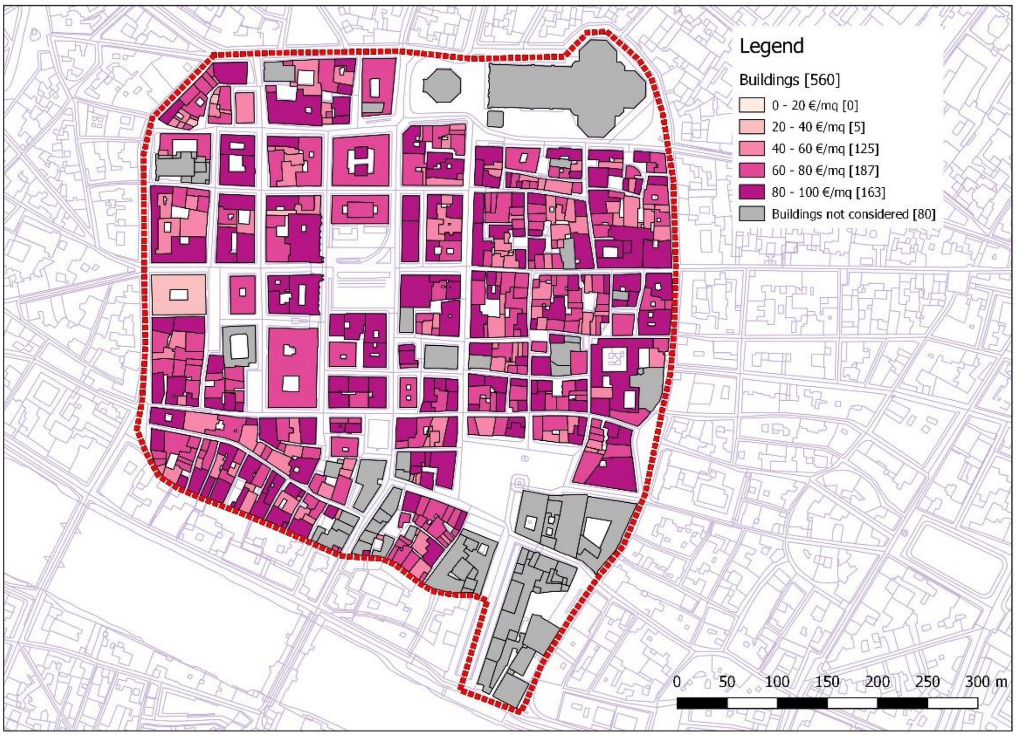
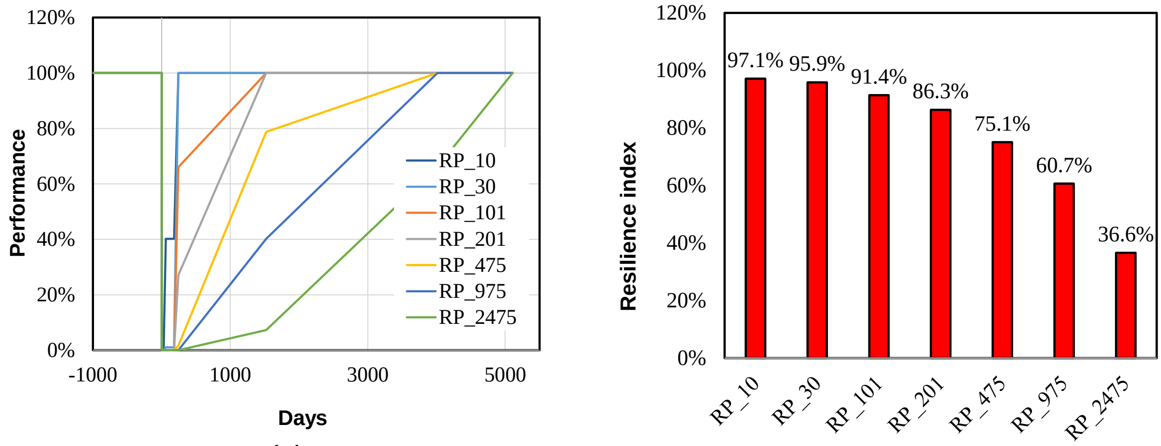


Figure 35: Expected Average Annual Loss map- Actual condition.

TIME REQUIRED FOR THE SYSTEM TO RETURN TO THE INITIAL PERFORMANCE LEVEL

From the distribution of the damage classes and for each RP, the number of buildings belonging to the single class was determined. For each RP, the percentages of buildings belonging to each individual class were obtained. From this information and the related period necessary for restoring the structure's performance (see Table. 3), the plot was obtained which expresses for each RP the time necessary for the system to return to the initial performance level (Fig. 36 (a)). In Fig. 36 (b) the efficiency of the system is shown as the ratio between the area above the segments and the total area. It can be noted that for return periods up to 200 years the system has satisfactory performance levels, while considering both the 475 and 975 years the situation presents loss values above the 20%. This evaluation is made only with reference to the structures, the infrastructures or any other related systems have not been taken into consideration.



(a) (b)

FIGURE 36: ACTUAL CONDITION - TIME REQUIRED FOR THE SYSTEM TO RETURN TO THE INITIAL PERFORMANCE LEVEL (a) – SYSTEM EFFICIENCY (b).

MITIGATION

Once the economic and efficiency loss of the system have been determined in the current situation, two preventive intervention levels have been defined. They consist in reducing the vulnerability by modifying the parameters $V_{m,k}$ (Fig. 2). A first intervention of the local type consists in modifying only three parameters: conservation status, roofing system and anti-seismic protection. A second intervention, for improvement, in which all possible modifiers are changed through building works or other. As in the previous case, the new vulnerability of the buildings was defined and the same assessments were carried out obtaining the expected Average Annual Loss values to be compared with the pre-intervention ones as well as the relative costs to implement the interventions. The estimated cost was defined in the previous section and relates to the economic evaluations of the costs observed after the L'Aquila post-earthquake.

Local intervention

As in the case of the current situation, the vulnerability index has been defined. The new distribution is shown in Fig. 37.

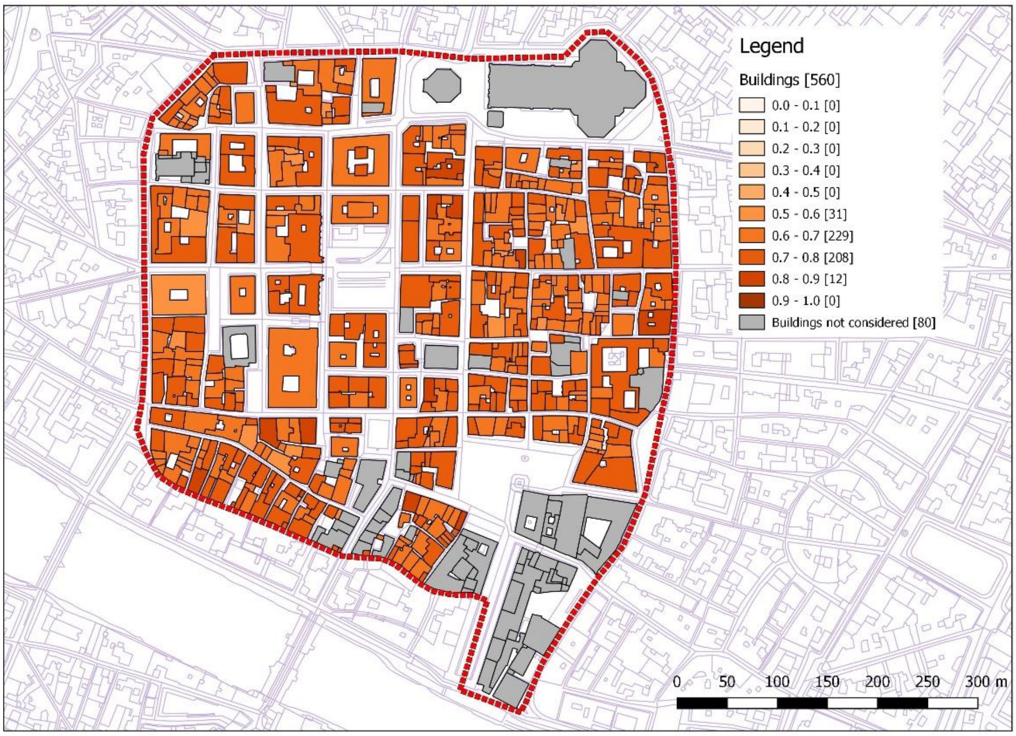


FIGURE 37: VULNERABILITY INDEX MAP – LOCAL INTERVENTION.

Once the vulnerability index was defined, the damage index was calculated for each RP. For brevity, the distribution of the damage index for a RP equal to 475 years is shown in Fig. 38. The scale of values is between 0 and 5 and the division into classes from D=0 and D=5 is shown in Table. 3.

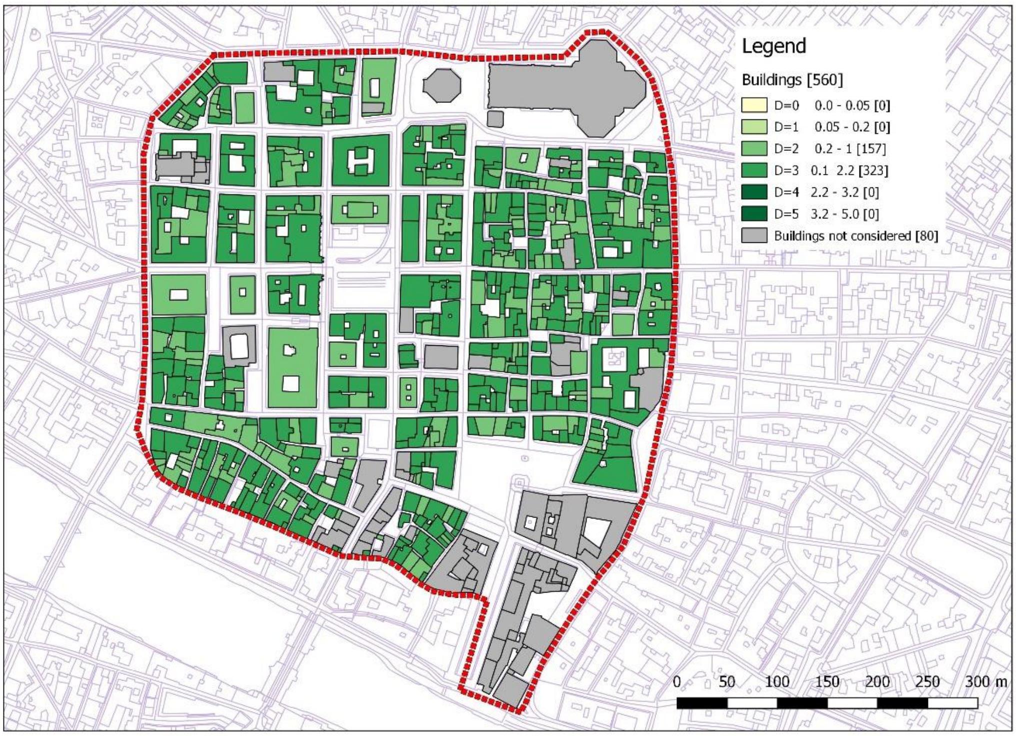


FIGURE 38: DAMAGE INDEX MAP - RP 475 YEARS– LOCAL INTERVENTION.

From the damage index obtained and for each RP, the estimation of the economic loss associated to the level of damage that the building can manifests in the new configuration has been conducted. The plot shown in Fig. 39 represents the trend of the economic loss against the RP.

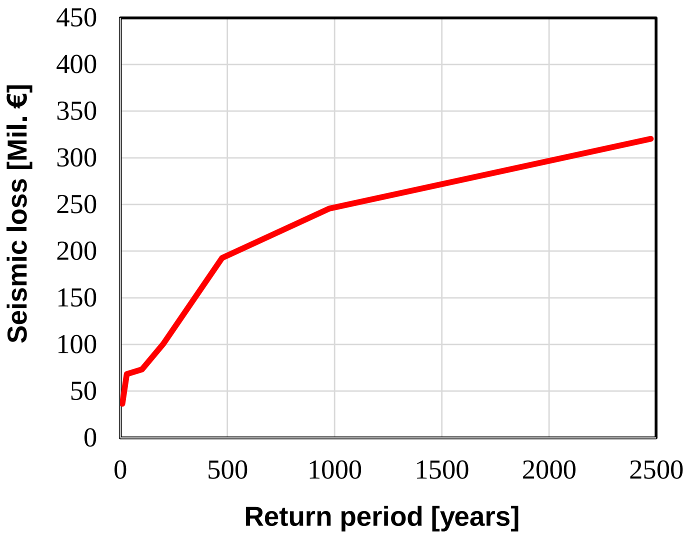


FIGURE 39: TREND OF ECONOMIC LOSS AGAINST THE RP – LOCAL INTERVENTION.

The expected Average Annual Loss is calculated considering two return period intervals. The first was 10 ≤ RP ≤ 475 years and the second 10 ≤ RP ≤. Fig. 40 shows the trend of loss as a function of frequency (1/RP) and the relative value of the AAL. For the two ranges, values of 8.40 million €/year, first case, and equal to 9.04 million €/year are obtained. As a percentage, the average annual loss are 1.72% and 1.85% respectively.

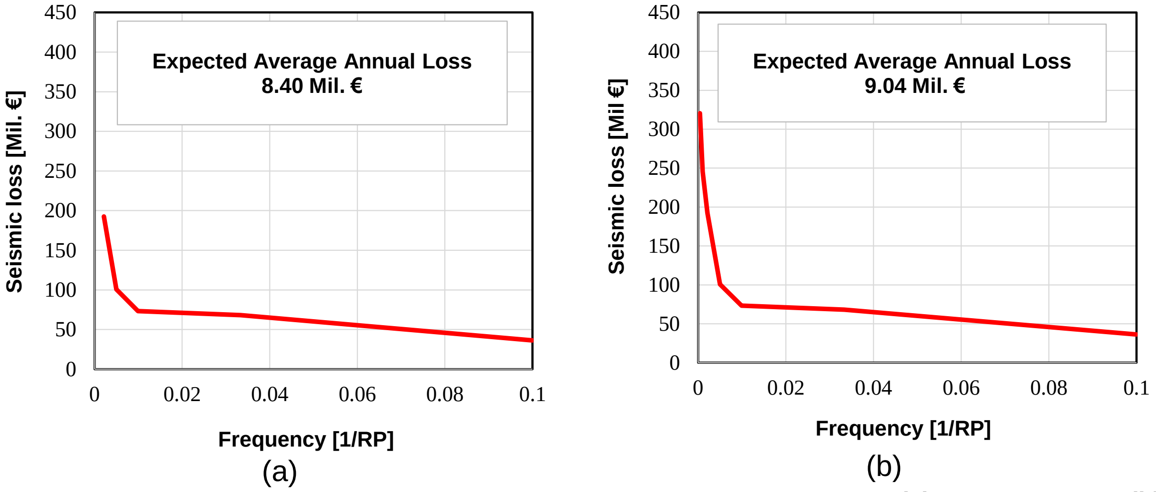


FIGURE 40: LOCAL INTERVENTION - EXPECTED AVERAGE ANNUAL LOSS – FIRST RANGE (a) – SECOND RANGE (b).

Fig. 41 shows the distribution of the expected Average Annual Loss on the area studied. The distribution is divided into 5 loss classes (between 0 and 100 €/mq/year) with a minimum value of 37 €/mq/year, a maximum of 74 €/mq/year and an average value of 54 €/mq/year. It can be noted that the new distribution mainly concerned to the reduction of the higher values of the economic range. In fact, a comparison between the maps of Fig 35 and Fig. 41 shows a decrease in the fourth and fifth ranges corresponding to the highest loss.

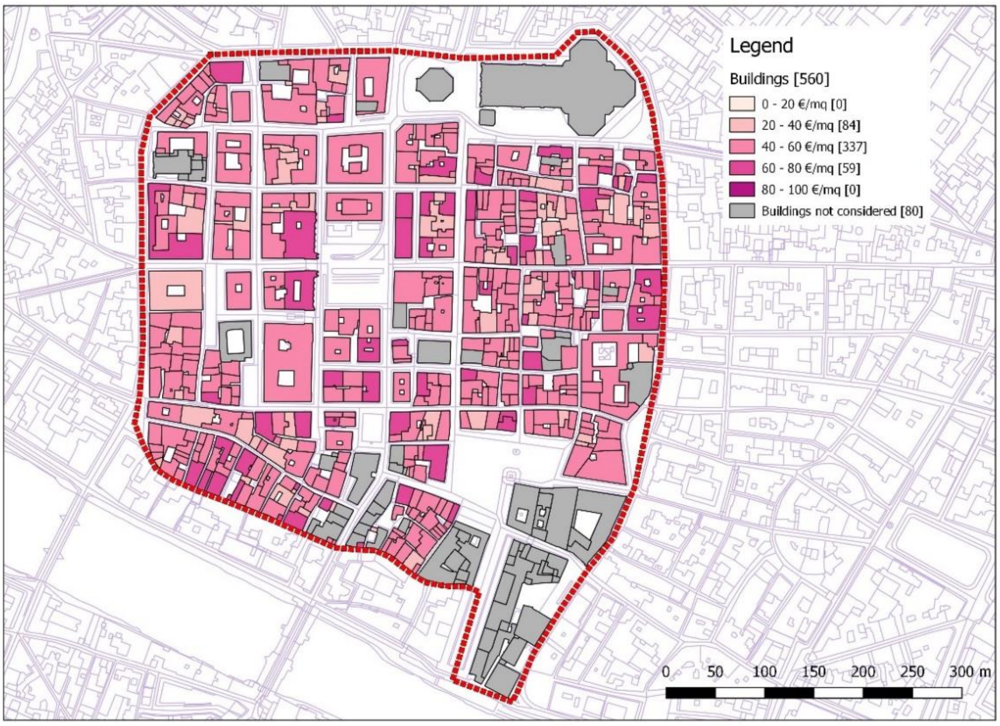
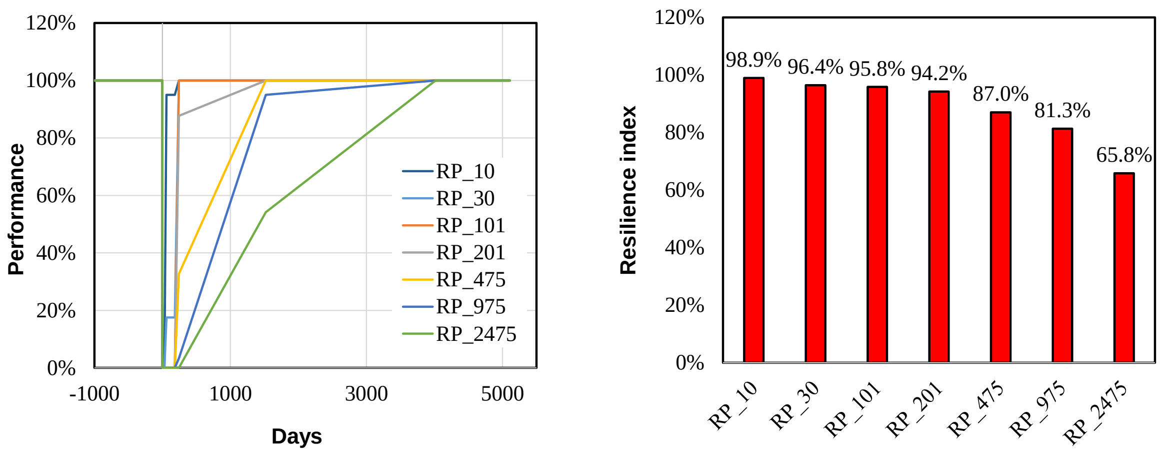


FIGURE 41: EXPECTED AVERAGE ANNUAL LOSS MAP. – LOCAL INTERVENTION.

As in the previous case, the performance of the system has been defined and in Fig. 42 (a) is shown the plot which expresses, for each RP, the time necessary for the system to return to the initial performance level. In Fig. 42 (b) the efficiency of the system is reported as the ratio between the area above the segments and the total area. It can be noted that for return periods up to 475 years, the system has satisfactory performance levels, while considering 975 and 2475 years the situation shows loss values above the 20%.



(a) (b)

FIGURE 42: LOCAL INTERVENTION - TIME REQUIRED FOR THE SYSTEM TO RETURN TO THE INITIAL PERFORMANCE LEVEL (a) – SYSTEM EFFICIENCY (b).

Improvement intervention

As in the case of the current situation, the vulnerability index was defined with the macroseismic procedure. The new distribution is shown in Fig. 43.

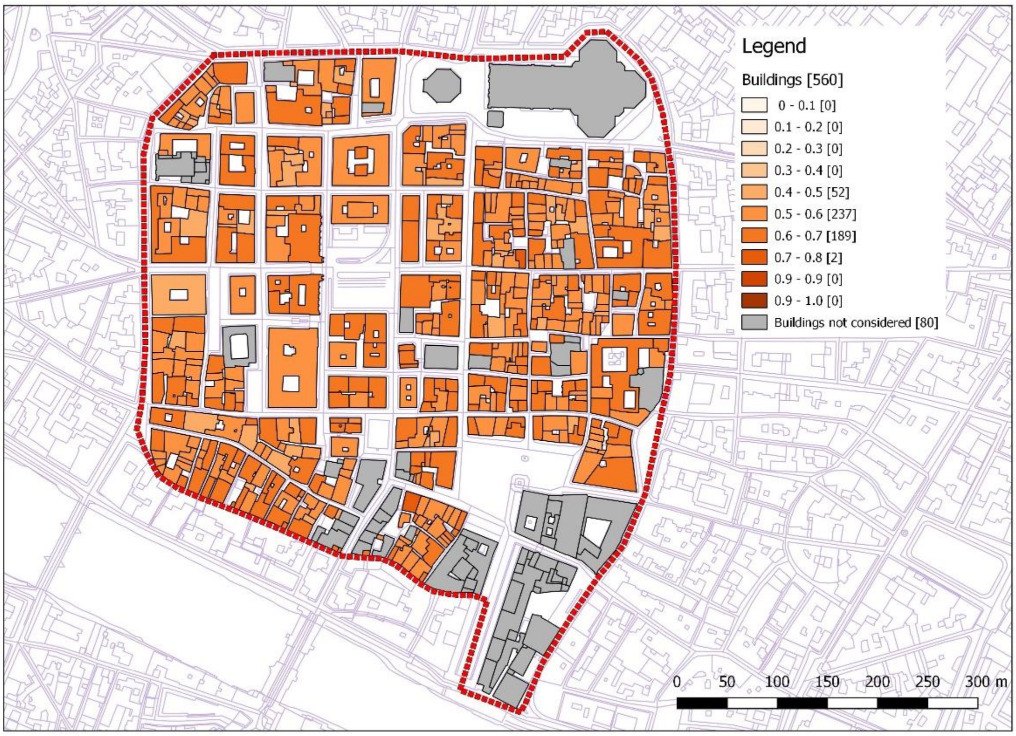


FIGURE 43: VULNERABILITY INDEX MAP – SEISMIC IMPROVEMENT.

Also in this case, once the vulnerability index has been defined, the damage index is calculated for each RP. For brevity, the distribution of the damage index for a RP equal to 475 years is shown in Fig. 44. The scale of values is between 0 and 5 and the division into classes from D=0 and D=5 is shown in Table. 3. Comparing the maps that report the results of the vulnerability and the damage index, with local intervention and with seismic improvement, in the latter case a homogeneous reduction of these indices can be noted.

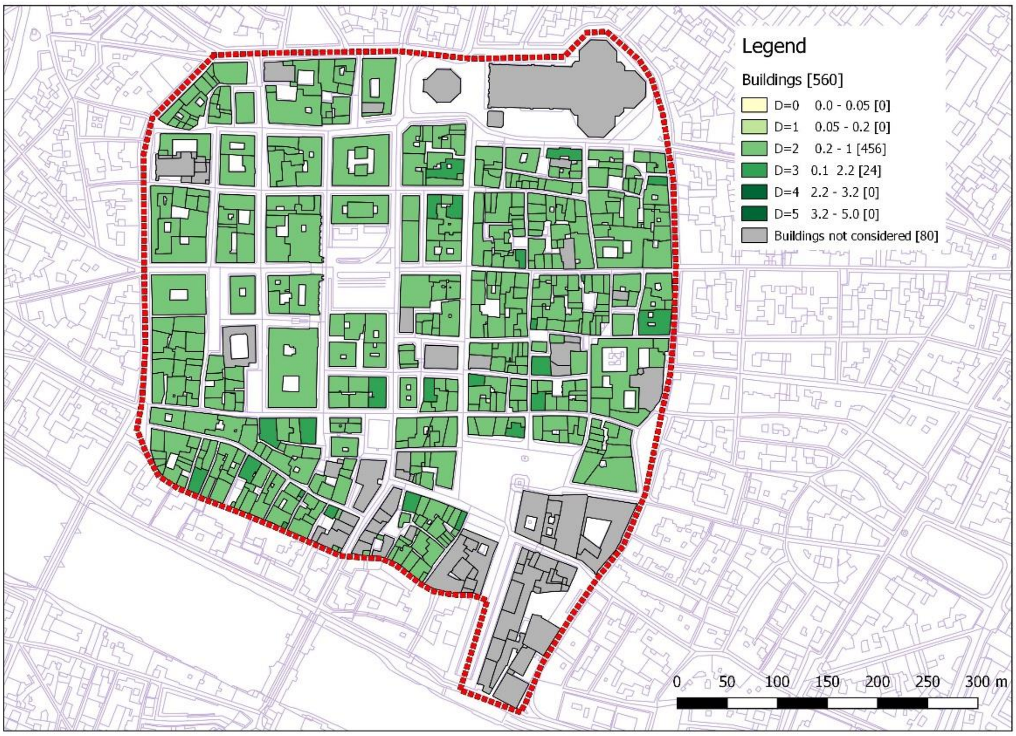


FIGURE 44: DAMAGE INDEX MAP - RP 475 YEARS- SEISMIC IMPROVEMENT.

From the damage index obtained and for each RP, the estimation of the economic loss associated with the level of damage of the new configuration is reported. The results are shown in Fig. 45 where the trend of the economic loss is shown against the RP.

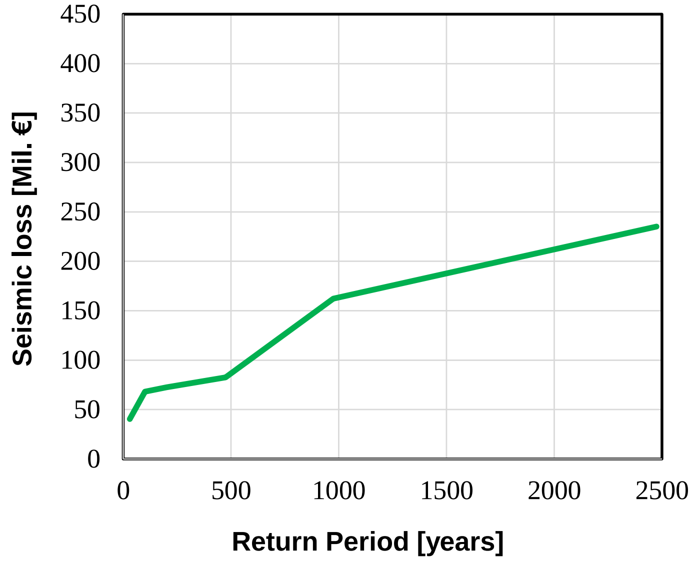


FIGURE 45: TREND OF ECONOMIC LOSS TO VARIATION OF RP – SEISMIC IMPROVEMENT.

The average annual loss is calculated considering two intervals of return periods. The first 10 ≤ RP ≤ 475 years and the second 10 ≤ RP ≤ 2475 years. Fig. 46 shows the trend of loss as a function of frequency (1/RP) and the corresponding value of the expected Average Annual Loss. For the two intervals, values of 5.82 million €/year are obtained, for the first case, while for the second 6.36 million €/year. As a percentage, the expected average annual loss are 1.19% and 1.30% respectively.

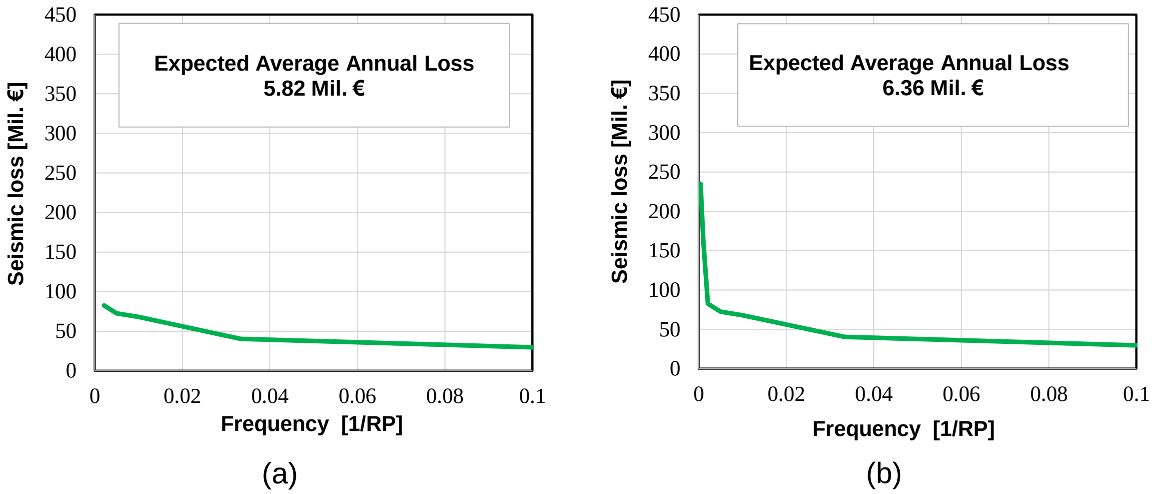


FIGURE 46: SEISMIC IMPROVEMENT - EXPECTED AVERAGE ANNUAL LOSS – FIRST RANGE (a) – SECOND RANGE (b).

Fig. 47 shows the distribution of the expected Average Annual Loss on the area under study divided by 5 loss classes (between 0 and 100 €/mq/year) with a minimum value of 20

€/mq/year, a maximum of 57 €/mq/year and an average value of 37 €/mq/year. It can be seen that the new distribution significantly reduced the loss. In fact, a comparison of the maps (Figs. 35, 41 and 47) shows a decrease in the third and fourth range.

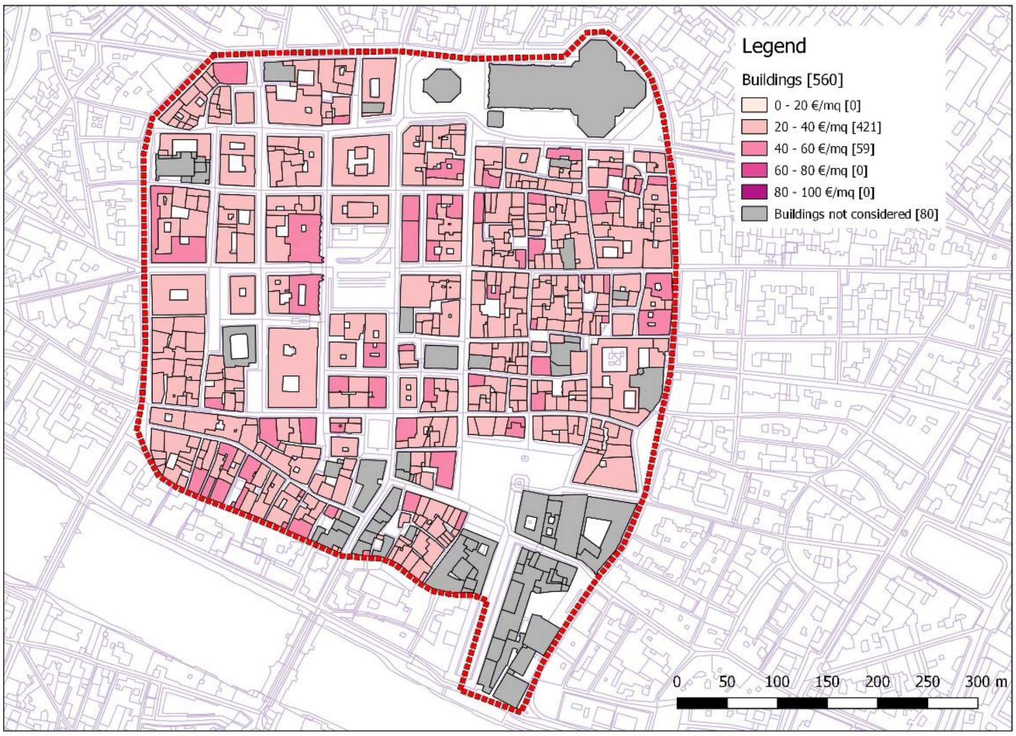


FIGURE 47: EXPECTED AVERAGE ANNUAL LOSS MAP. – SEISMIC IMPROVEMENT.

The performance of the system has been defined and in Fig. 48 (a) is shown, for each RP, the time necessary for the system to return to the initial performance level. In Fig. 48 (b), the efficiency of the system was assessed as the ratio between the area above the segments and the total area. It can be noted that, for all return periods, the system has satisfactory performance levels with loss of less than the 20%. From the comparison with the current state, it is noted that the improvement intervention, for all return periods, produces a positive effect.

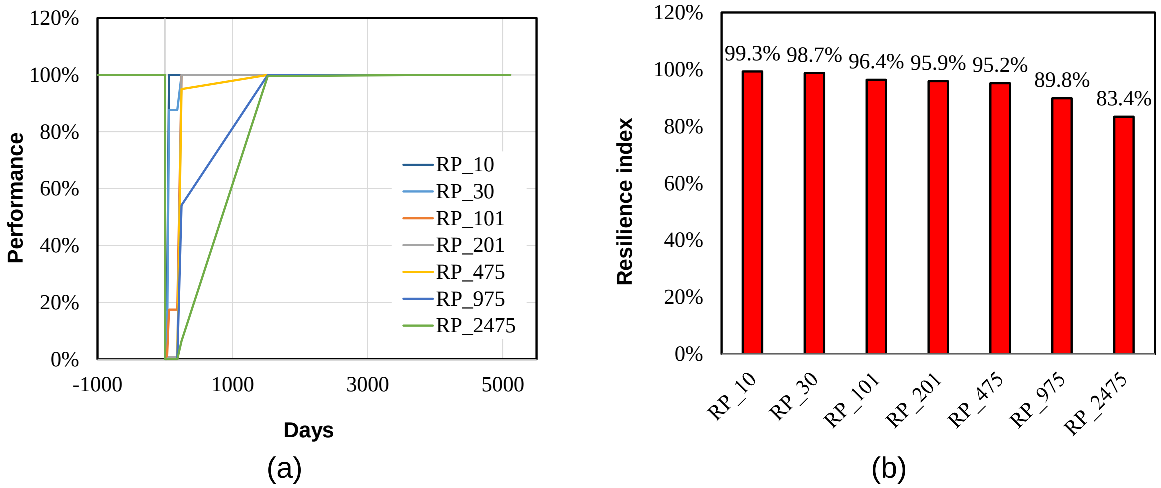


FIGURE 48: SEISMIC IMPROVEMENT - TIME REQUIRED FOR THE SYSTEM TO RETURN TO THE INITIAL PERFORMANCE LEVEL (a) – SYSTEM EFFICIENCY (b).

COMPARISONS

Fig. 49 shows the comparison of the expected Average Annual Loss for the three conditions considered: i) actual condition (blue curve); ii) local intervention (red curve); iii) seismic improvements (green curve). In Fig. 49 (a), the trend of EAL is reported considering 10 ≤ RP ≤ 500 years while in Fig. 49 (b) 10 ≤ RP ≤ 2475 years.

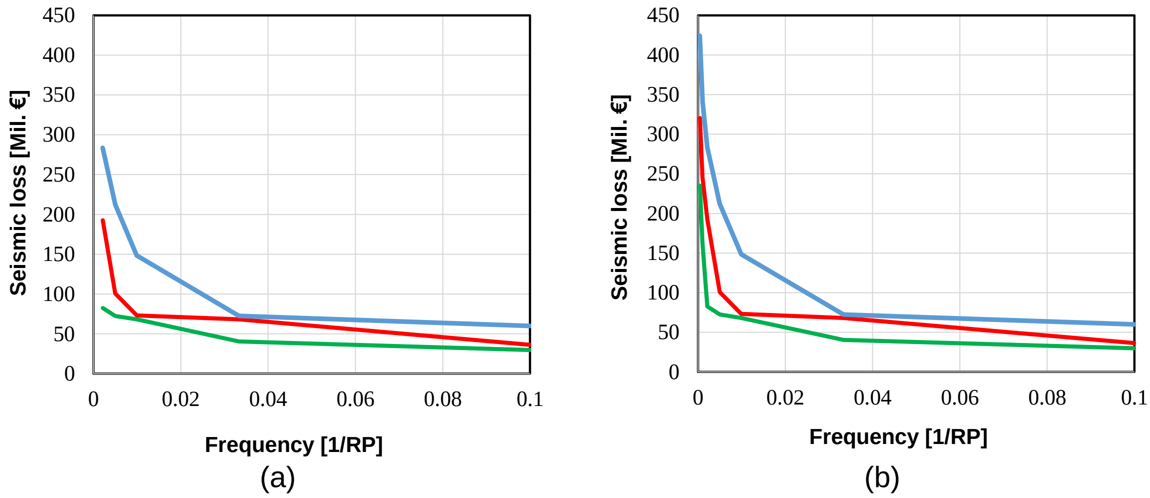


FIGURE 49: EXPECTED AVERAGE ANNUAL LOSS – FIRST RANGE (a) – SECOND RANGE (b).

The total value of the building heritage falling within the study area is 488 million €. The cost of local interventions on these properties is 8.10 million € while for improvement interventions it is equal to 38.10 million €.

For the three conditions considered, Table 9 shows the costs distributed over 10 years and those relating to 10 ≤ RP ≤ 500 years and 10 RP ≤ 2475 years. It should be noted that already with the local intervention, a significant reduction in the monetary loss is achieved. Both the local and improvement interventions already show their effectiveness with RP equal to 10 years.

TABLE 9: ANNUAL COST FOR 10 YEARS, FIRST RANGE OF EAL AND SECOND RANGE OF EAL.

Condition	Annual cost for 10 years	AAL 10 ≤ RP ≤ 500	AAL 10 ≤ RP ≤ 2475
	[Mil. €]	[Mil. €]	[Mil. €]
Actual condition	-	12.04	13.12
Local intervention	0.81	8.40	9.04
Improvement	3.81	5.82	6.36

A final assessment of the effectiveness of the interventions is shown in Fig. 50 where the performance of the three conditions are compared, for the various return periods. The resilience index is almost unchanged, for the three conditions (actual condition, local intervention and improvement), for return periods equal to 10 and 30 years. It begins to vary slightly for a RP equal to 101 years until reaching significantly different values for a RP equal to 975 and 2475 years.

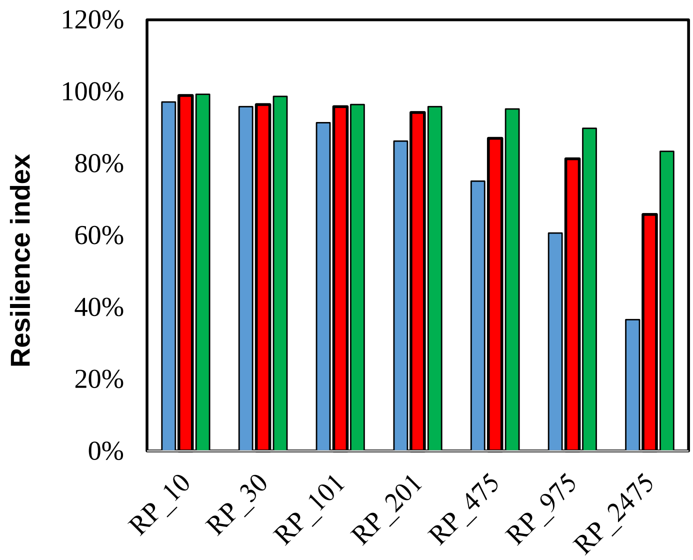


FIGURE 50: PERFORMANCE FOR THE THREE CONDITIONS.

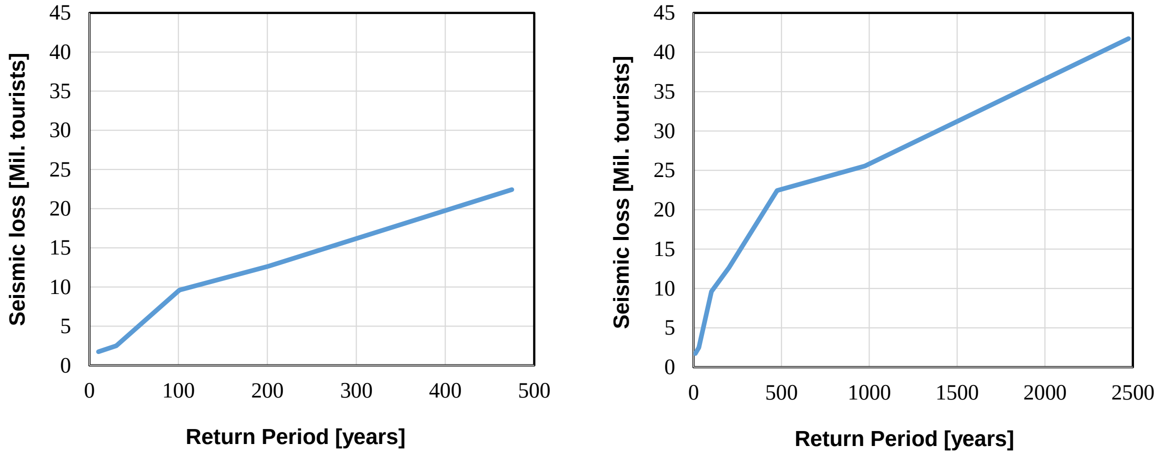
APPLICATION OF THE EXPECTED AVERAGE ANNUAL LOSS OF TURIST

Once the Average Annual Loss deriving from the damage to private or ordinary building has been defined, we move on to the determination of the loss linked to the cultural heritage. The evaluation of the loss is evaluated through the procedure described above and allows to reach an estimate of the number of lost tourists and an economic estimation of the loss.

The buildings that are included within the study area are shown in Table 10. For each of them are reported the values of the vulnerability index defined through expeditious methodologies, and the number of tourists (provided by the Research Unit UNIFI-DICEA). Once the vulnerability has been determined, the damage index is calculated, for each value of the macroseismic intensity in terms of number of days (10, 30, 101, 201, 475, 975 and 2475 years). After defining the damage index, for each RP and for all buildings, a time period is associated, expressed in terms of months, for both the closure of the building and the restoration of the damage. Fig. 51 shows the trend of the loss of tourists against the RP. In particular, Fig. 51 (a) shows the results considering a range of return periods of 10 ≤ RP ≤ 475 years, while Fig. 51 (b) shows 10 ≤ RP ≤ 2475 years.

TABLE 10: BUILDINGS AND RELATIVE NUMBER OF TOURISTS/DAY, TOURISTS/MONTH AND VULNERABILITY INDEX.

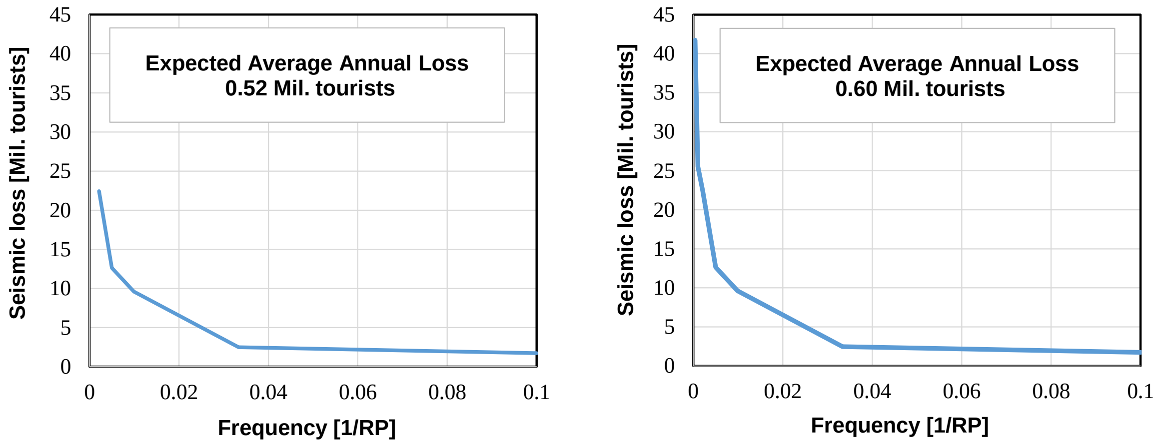
Buildings	Tourists/day	Tourists/month	Vulnerability
Duomo and Cripta Santa Reparata	3140	81912	0.544
Campanile di Giotto	2001	52189	0.544
Battistero di S. Giovanni	2230	58172	0.546
Museo del Bigallo	592	15439	0.74
Chiesa di S. Maria Maggiore	617	16093	0.557
Chiesa dei SS. Michele e Gaetano	612	15959	0.565
Museo della Misericordia di Firenze	588	15325	0.88
Capitolo Metropolitano Fiorentino	583	15209	0.88
Palazzo Strozzi	863	22500	0.656
Biblioteca gabinetto Vieusseux	583	15209	0.656
Chiesa S.Margherita in S.Maria dei Ricci	589	15364	0.562
Museo casa di Dante	256	6667	0.9
Museo di Orsanmichele	257	6699	0.616
Palazzo dell'arte della lana	585	15256	0.86
Chiesa della badia Fiorentina	607	15837	0.571
Museo di Palazzo Davanzati	667	17407	0.9
Biblioteca palagio di Parte Guelfa	584	15229	0.5
Palazzo Vecchio-quartieri monumentali	2182	56917	0.92
Galleria degli uffizi	7090	184927	0.45
Museo di Storia della Scienza	1664	43403	0.78
Duomo e Cripta Santa Reparata	3140	81912	0.544
Campanile di Giotto	2001	52189	0.544



(a) (b)

FIGURE 51: TOURISTS LOSS – FIRST RANGE (a) – SECOND RANGE (b).

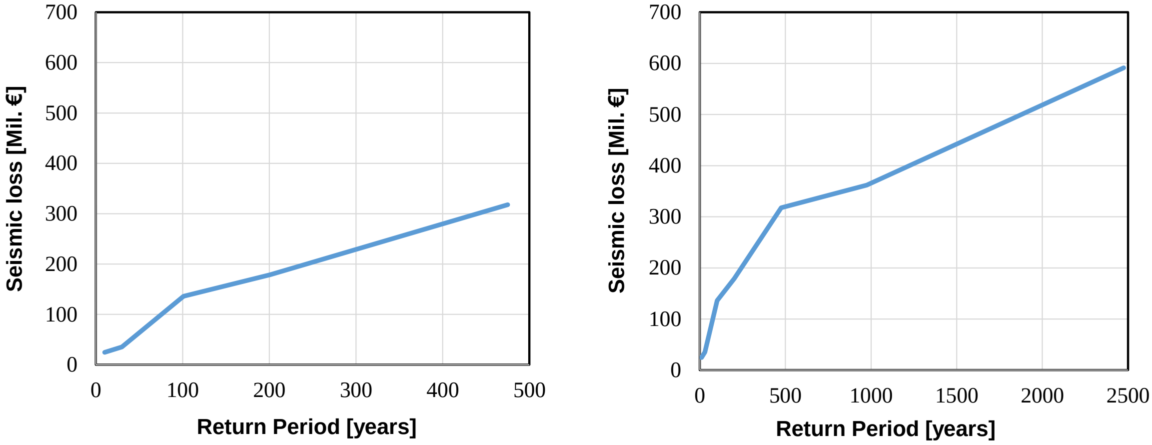
Fig. 52 shows the trend of tourist loss as a function of frequency (1/RP) and the relative value of the expected Average Annual Loss. For the two ranges, similar values are obtained. In the case of 10 ≤ RP ≤ 475 years, there are 0.52 million/year of lost visitors while for 10 ≤ RP ≤ 2475 years there are 0.6 million/year, on an annual value of 8.2 million tourists or on 115 million, if we consider the time span of 14 years, maximum recovery time in case of damage D=5.



(a) (b)

FIGURE 52: EXPECTED AVERAGE ANNUAL LOSS – FIRST RANGE (a) – SECOND RANGE (b).

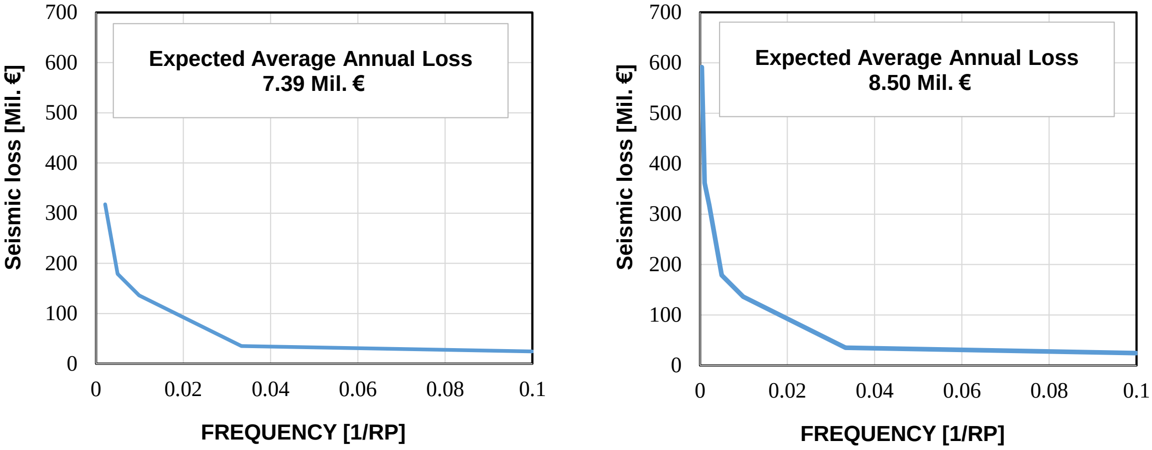
Fig. 53 shows the trend of the economic estimation of the losses associated to lost tourists, considering an economic value of € 85.00 (cost of the Firenzecard for 72 visit hours). A weight of 0.5 is considered which takes into consideration that a visitor cannot access multiple places on the same day. As for the number of lost tourists, in Fig. 53 (a) and (b) the economic loss linked to the various return periods 10 ≤ RP ≤ 475 years and 10 ≤ RP ≤ 2475 years are reported.



(a) (b)

FIGURE 53: ECONOMIC LOSS – FIRST RANGE (a) – SECOND RANGE (b).

The average annual economic loss is calculated considering two ranges of return periods. The first 10 ≤ RP ≤ 475 years and the second 10 ≤ RP ≤ 2475 years. Fig. 54 shows the trend of economic loss as a function of frequency (1/RP) and the relative value of the average annual loss. For the two intervals, values of 7.39 million €/year and 8.50 million €/year are obtained. Considering a period of 14 years, the economic loss is equal to 1630 million €.



(a) (b)

FIGURE 54: EXPECTED AVERAGE ANNUALLOSS – FIRST RANGE (a) – SECOND RANGE (b).

The performance of the cultural system present within the fourth walls is assessed below. The resilience of the system is evaluated through the ratio between the area under the curve and that corresponding to a constant performance of the 100% (Fig. 55).

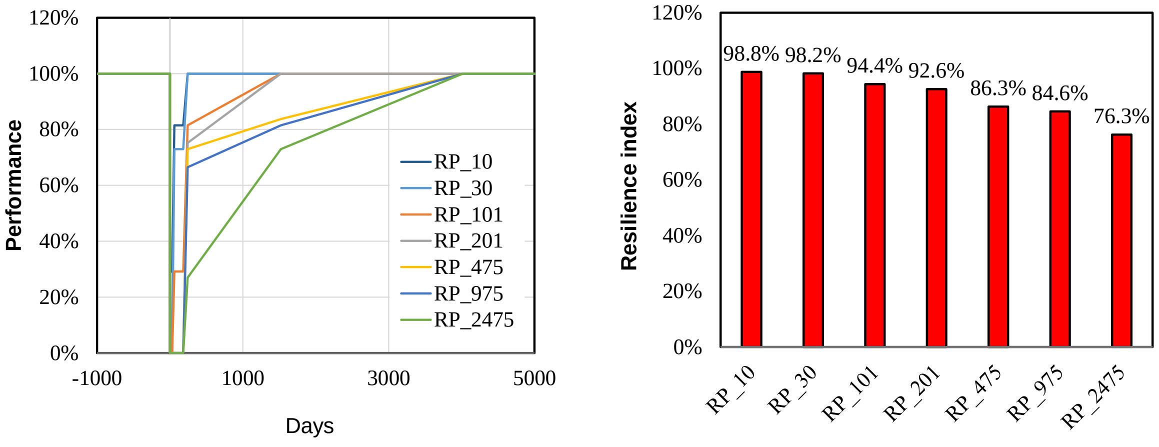


FIGURE 55: TIME REQUIRED FOR THE SYSTEM TO RETURN TO THE INITIAL PERFORMANCE LEVEL (a) – SYSTEM EFFICIENCY (b).

CONCLUSIONS

The work developed by the Research Unit UNIFI-DIDA has been aimed at developing a seismic risk scenario for the city center of Florence. In addition, some strategies of mitigations have been proposed in order to reduce the seismic risk.

Maps for structural typologies, hazards, vulnerability and damage have been built for reaching the quantification of the seismic risk. They also represent a powerful tool for future efficient planning of the monetary sources to be allocated for wished seismic improvements.

The case study analyzed belongs to the forth walls of the city, which represents the historic city center of Florence, where is also located the main part of the monumental and historic constructions.

The modification of proper methodologies for the estimation of the mean annual cost due to the earthquake hazard (SISMABONUS and macroseismic method), allowed to estimate both direct and indirect economic losses for the system together with the identification of the effects due to different strategies of mitigation.The procedure developed by UNIFI-DIDA for the seismic risk evaluation of the specific case study required the adoption of results coming from recent Italian post-earthquakes evaluations. As a matter of fact, no data were available for the damages and repairing costs in the analyzed case study. Therefore, it represents a pilot method for earthquake risk estimation on historic urban areas and for its mitigation.

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