Seismic risk analysis of public hospitals in Tuscany Region - Italy

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SUMMARY:
It has been investigated the seismic risk of the buildings of public hospitals in Tuscany Region (about 5.128.000m^3) under the management of fourteen sanitary companies.
The seismic risk factor has been determined by seismic vulnerability of each construction, the seismic hazard depending from the location and the soil category, and the exposure factor due to the specific destination of each building.
From the vulnerability factor, it has been possible to deduce an estimation of the peak ground acceleration capacity, while the location and soil category furnish the peak ground acceleration requested. The seismic risk factor has been then corrected to take into account the exposure factor of the several buildings.
A proper classification, in terms of consistently groups, has been prepared to help the public administration to address the investment of public resources to consolidate the hospitals from seismic event.

Keywords: Seismic risk, Public hospitals, Tuscany Region.

1. INTRODUCTION

The high seismic hazard of the Italian territory implies the necessity of knowing the risk for the existing constructions, particularly for the public buildings. The estimation of seismic vulnerability has been the subject of study since the early 70s and can be defined according to empirical, analytical/mechanical and hybrid methods (Calvi et al., 2006). The first ones are necessary in case of seismic vulnerability assessments of a large number of buildings, for which a detailed investigation activity of each construction would be prohibitively expensive. Analytical/mechanical methods are instead characterized by a direct physical meaning and allow the study of the seismic vulnerability by analysis of the mechanical behavior of the structures by models having different levels of complexity. Finally, hybrid methods consist of a combination of the two methods described above.
The main empirical methods in the literature, that form the basis of recent studies of vulnerability, are the Damage Probability index Method (DPM), proposed by Whitman et al. (1973), and the Vulnerability Index Method (VIM) (Benedetti and Petrini, 1984; GNDT, 1993). The former provides the use of the probabilistic matrices of damage for the prediction of buildings damage caused by different seismic events; the concept at the base of the method requires that a given structural type has the same chance of damage for a given earthquake intensity. Many studies have been made to develop the method in Europe using first the MSK macroseismic scale, after the MCS and finally the EMS-98 (Braga et al., 1982; Di Pasquale et al., 2005; Giovinazzi & Lagomarsino, 2001 and 2004). Instead VIM was calibrated on the survey of a large sample of different buildings damaged by earthquakes and has been used extensively in Italy in recent decades. This method consists in filling in a surveying form with 11 parameters, using the scores given by the surveyor and by the weight coefficients assigned to each parameter, leading to a vulnerability index I_v, usually normalized, where a lower index value corresponds to a structure with high capacity under seismic action. The correlation between the vulnerability estimated by the surveying form, the level of damage (expressed as percentage of loss of economic value discounted) and the seismic intensity, measured in terms of Peak

Ground Acceleration (PGA), were obtained from studies carried out on the effects of past earthquakes (Guagenti and Petrini, 1989).
Many studies have been made on the basis of what now be described, by making changes and improvements to these methods: Giovinazzi and Lagomarsino (2001) propose a correction of the vulnerability estimate through the use of behavior modifiers; Dolce and Martinelli (2005) made changes drawing up a document about the inventory and vulnerability of strategic public buildings in south-central Italy; Grant et al. (2006) proposed a method based on different levels of vulnerability assessment by analysis with increasing detail. Crowley et al. (2008) developed a method in which the estimates of the first period of vibration were considered, and therefore the estimate of seismic demand was in terms of spectral acceleration instead of PGA.
As for the exposure, many approaches, distinguishable mainly into two categories, are proposed in the literature: methods that assess the number of people at risk in the structure (Coburn et al., 1992), using models of different complexity, and methods that consider the economic losses resulting from damage to the structure, expressed as percentages of the cost of reconstruction.
In the present work the evaluation of the seismic risk of hospitals located in Tuscany, and the drafting of a list of priorities for intervention, by assigning a priority index to each building, are carried out. The determination of the priorities for intervention is indeed necessary for a proper asset management and the optimization of resources. The sanitary building heritage studied is represented by total volumes of large scale, thus for the risk assessment was essential to choose the method to be adopted. If the chosen method was very approximately, the risk would be to obtain not reliable estimates of vulnerability; vice versa, if the method had presented a high level of detail, such as global seismic analysis, it would be extremely costly to its application. The size of the buildings volume studied then imposed the adoption of fast methods, which allowed the investigation necessary to define the priorities of adjustment intervention.
After identifying the situations with highest seismic risk, it was possible to perform advanced analysis aimed at the choice of structural intervention to be taken in order to optimize resources and results reachable in terms of seismic risk reduction.

2. METHOD INVESTIGATION ADOPTED FOR THE HOSPITAL BUILDING HERITAGE

The building heritage belonging to the various sanitary companies in Tuscany (Figure 2.1) consists in a total volume of 5128000m^3 and is represented by 80 complexes divided into 533 structural units. The distribution of the volume percentage and those of the structural types by the number of structural units investigated are shown in Figure 2.2. The time range in which the age of the buildings are placed is quite large, as shown in the graphs of volumetric distributions of Figure 2.3. This implies that surveys were to be made with the aim of identifying characteristics of the design, construction and materials, to determine the seismic vulnerability through conventional methods. These methods are based on detailed global analysis, which, if held on existing buildings without proper documentation, involves performing a series of tests and experiments requiring the interruption of activities in the building itself. Given that the buildings under consideration are strategic, such interruption would have been so problematic that the execution of a sample screening was adopted, considering also that the objective of this research had the goal to rank the priorities of intervention and not to conduct a global seismic assessment. The methods of such screening were as follows:

- comparison with similar experiences and campaigns for investigations and harmonization of evaluation criteria with previous works done by the Regional Coordination for Seismic Prevention of Tuscany Region;
- survey and preliminary diagnosis of each building (collection of available project documentation, geographical location in relation to the seismic hazard in the area, site inspections, photographic surveys, interviews with technical staff);
- determination of geometric, typological, functional and constructional characteristics of buildings and graphic representation in a report form, with the simultaneous assessment of the quality and status of the general maintenance.

Figure 2.1. Areas of responsibility of the various sanitary companies.

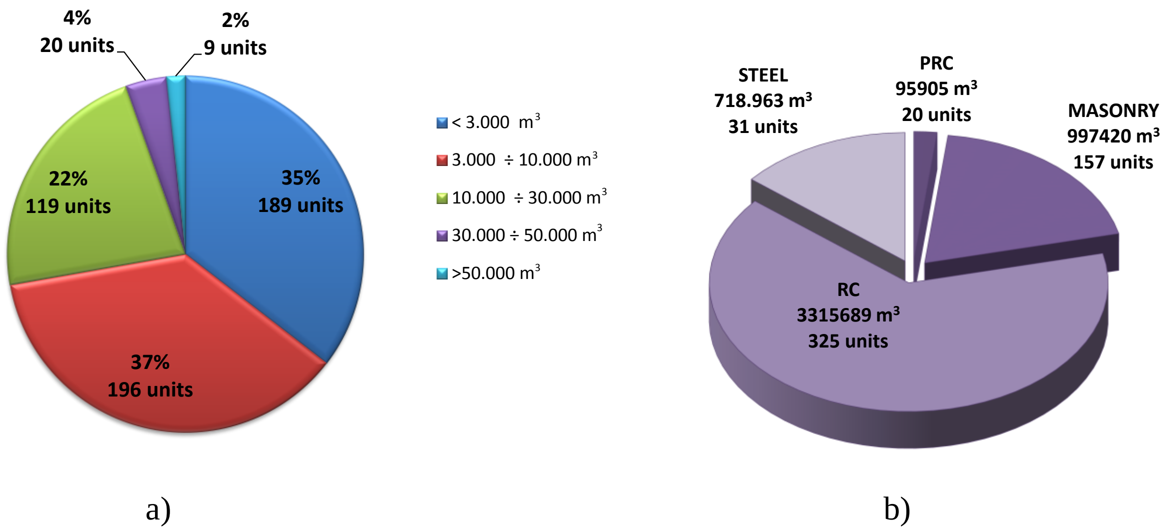
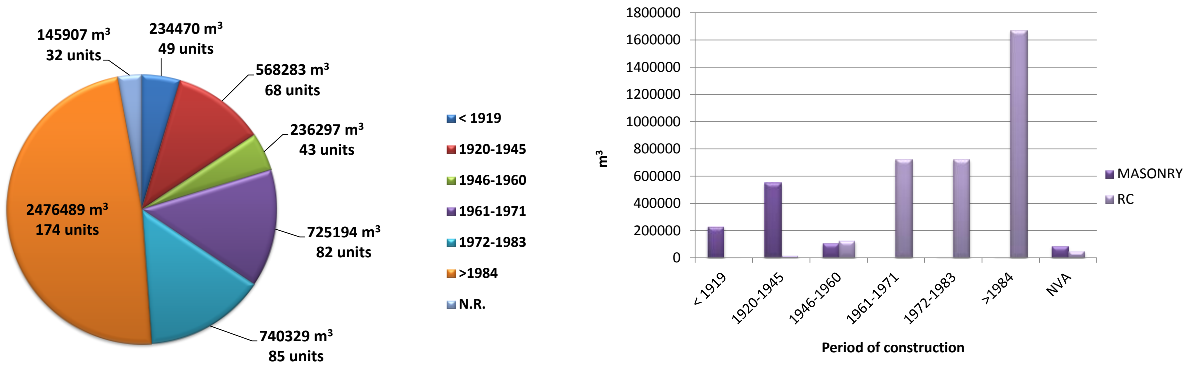


Figure 2.2. a) Distribution of the volume percentage and number of structural units surveyed. b) Distribution of structural types by number of units and total volume.



a) b)

Figure 2.3. a) Distribution of the construction period of the structural units investigated in terms of number and volume of buildings. b) Volumetric distribution of masonry and reinforced concrete (RC) structural units by period of construction.

3. SEISMIC VULNERABILITY EVALUATION

The evaluation of the seismic vulnerability and, therefore, the calculation of the vulnerability index I_v of each structural unit was performed by a procedure based on the compilation of 2nd Level GNDT form (GNDT, 1993) both for masonry constructions that for those in RC. For buildings in Precast Reinforced Concrete (PRC) and those in steel were used the same forms but with proper precautions relating to specific material. The vulnerability index is defined with respect to 11 parameters that are relevant to characterize the seismic behavior of a building: type and organization of the seismic resistant system, quality of the resistant system, conventional resistance, building location and type of foundation, storey, configuration in plan, configuration in elevation, maximum distance between the masonry walls (connections and critical elements for RC buildings), coverage (elements with low ductility for RC buildings), non-structural elements, state of maintenance.

For masonry buildings, each parameter is assigned a class that can assume 4 values. Each class corresponds to a score and a weight on the importance of the parameter. Moreover, given the uncertain nature of some information obtained, the value of the vulnerability is associated with an assessment of the reliability of the information, determined as the average of the reliability of individual parameters. The total score for the calculation of the index of vulnerability is obtained from the weighted sum of the scores of the individual parameters, as in the following expression:

$$I_V = \sum_{i=1}^{11} V_i \cdot P_i \qquad (3.1)$$

where V_i represent the score and P_i the weight of the *i-th* parameter. The vulnerability index thus determined, then normalized, is a conventional measure of relative vulnerability in a scale where zero identifies a building constructed according to current regulations.

Instead, for RC buildings, the evaluation is made with only three classes for the first 10 parameters and 4 classes for the parameter 11 (state of maintenance). There are no weights of parameters and the vulnerability index is evaluated as the sum of the scores of individual parameters of the of 2nd Level form, as in the following expression:

$$I_V = \sum_{i=1}^{11} V_i \qquad (3.2)$$

where V_i represent the score of the *i-th* parameter.
Given the differences between the assessment of the two type of structures, the conversion of the indexes of RC buildings in vulnerability indexes comparable to those determined for the masonry buildings was made in order to have comparable values. The decision to adopt the scores and weights for the calculation of the vulnerability indexes proposed by the Marche Region is motivated by the presence of a conversion formula is as follows:

$$\begin{aligned} &if \quad I_V > -6.5 \quad \Rightarrow \quad V_m = -10.07\, I_V + 2.5175 \\ &if \quad I_V < -6.5 \quad \Rightarrow \quad V_m = -1.731\, I_V + 56.72 \end{aligned} \tag{3.3}$$

In this way, the percentage scale of reference for the masonry buildings varies from 0 to 100, while for RC buildings varies from 0 to 75. The vulnerability and the reliability information of each hospital complex were determined as the weighted average on the volume of each structural unit constituting the complex itself. Figure 3.1. shows the indexes of vulnerability parameterized by volume, number of buildings and structural type: it is important to note that about 75% of the buildings presents a vulnerability index less than 50%. The distribution of the values obtained in function of the period of construction are shown in Figure 3.2.
It's necessary to emphasize that, given the level of detail that has characterized the investigation, the results should not be interpreted as absolute or deterministic assessments, but as guidance on considerations for later investigations aimed at addressing a higher level of detail. This work has allowed a number of viewpoints on the need to dedicate more attention to some of the buildings in relation to others, ranking the structural units respect to the seismic vulnerability. The evaluations are fundamentally based on the estimation carried out during the inspections, on the project documentation examined, when present, on the construction elements highlighted during the surveys and in particular on the identification of any crack patterns or degradation phenomena, where relevant to the seismic behavior of the buildings. Furthermore, it should be noted that the nature and the quality of the structural materials of buildings examined are still unknown, of not secondary importance, the interpretation of which must be entrusted to the execution of experimental tests.

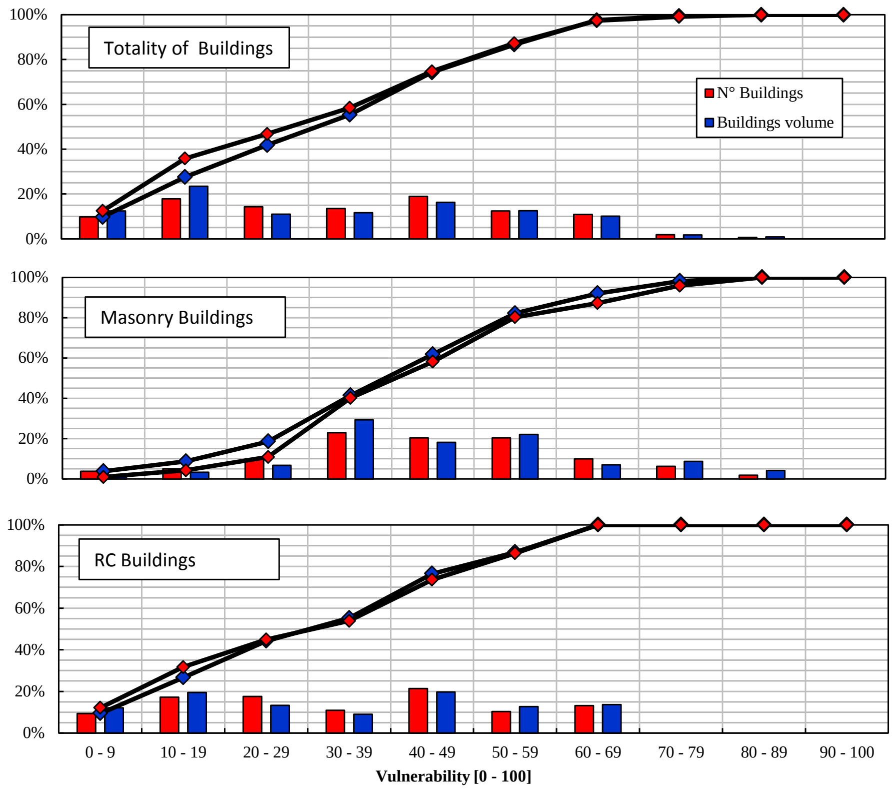


Figure 3.1. Index of vulnerability parameterized by volume, number of buildings and structural type.

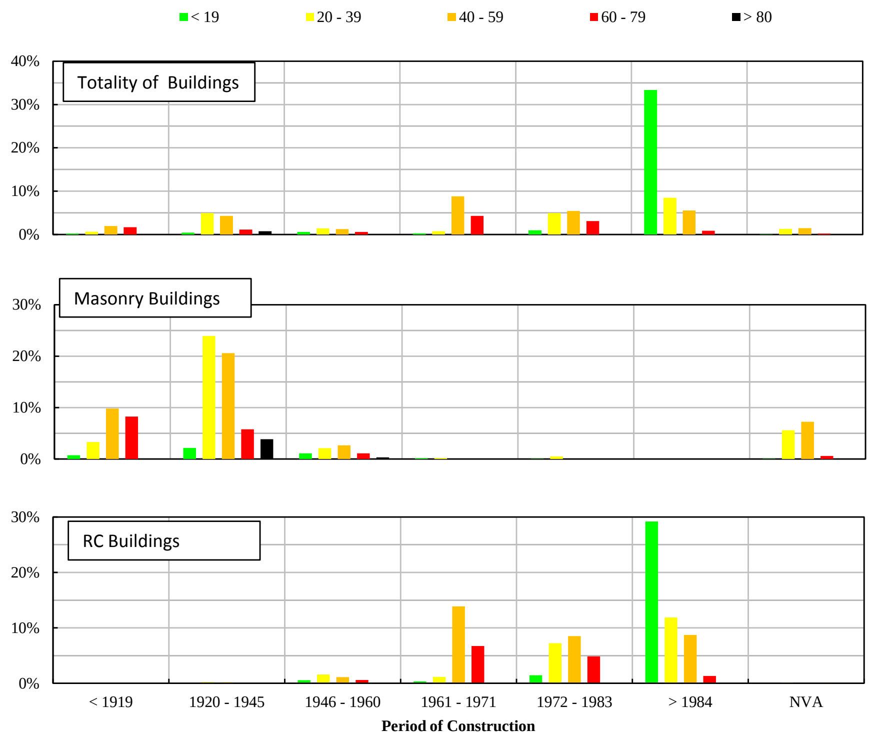


Figure 3.2. Index of vulnerability parameterized by period of construction and structural type.

4. DETERMINATION OF THE SEISMIC RISK

The seismic risk is defined in economic terms as the possible loss of the property or function of a building, or part of it, due to a seismic event. Its evaluation may be represented in quantitative terms with a relationship linking the seismic hazard, vulnerability and exposure:

$$R = f(h, V, e) = Hazard * Vulnerability * Exposure \quad (4.1)$$

where seismic hazard expresses the probability that, in a certain interval of time and in a given place, occurs a seismic event with assigned characteristics; the vulnerability assess the propensity of buildings to be damaged and, finally, the exposure is understood as the quantity and value of assets that are present in the area subject to the seismic event.

The procedure for seismic vulnerability assessment performed is summarized in a series of phases:

- recovery of available documentation on the construction and drafting of appropriate 0 Level forms;
- analytical evaluation of seismic vulnerability through the drafting of the 2nd Level GNDT needed to calculate a vulnerability index I_v, as described in the previous paragraph;
- determination of seismic hazard of the construction site, expressed by the expected peak ground acceleration PGA_D with a return period of 949 years (elastic spectrum related to life-safety limit state, assuming a nominal life of 50 years, an importance coefficient equal to 2, the fourth functional type and a probability of exceedance of 10% in 50 years);
- determination of exposure depending on the use and the importance of the building, to be considered as a strategic factor.

Subsequently, the priority index I_p assignable at each hospital is given by the product of the mentioned vulnerability, hazard and exposure indexes.

For the evaluation of the risk index I_R, the parameters of vulnerability and hazard were considered using the following formula proposed by Grant et al. (2006):

$$I_R = f(p,V) = \left(\frac{PGA_D}{PGA_C}\right)^k \tag{4.2}$$

that is the *k-th* power of the ratio between expected peak ground acceleration PGA_D and the structure capacity expressed in terms of peak ground acceleration PGA_C at "failure". The coefficient k assumes values in function of PGA_D as follows (Figure 4.1):

$$\begin{aligned}
&if \quad 0 < PGA_D < 0.056g \quad \Rightarrow \quad k = 3.6 \\
&if \quad 0.056g < PGA_D < 0.11g \quad \Rightarrow \quad k = -16\left(\frac{PGA_D}{g}\right) + 4.5 \\
&if \quad 0.11g < PGA_D < 0.26g \quad \Rightarrow \quad k = -2.7\left(\frac{PGA_D}{g}\right) + 3.1 \\
&if \quad PGA_D > 0.26g \quad \Rightarrow \quad k = 2.4
\end{aligned} \tag{4.3}$$

Having carried out the conversion of the vulnerability of RC buildings in the scale [0; 100] related to masonry buildings, the following expression was used for PGA_C determination:

$$PGA_C(V) = \frac{1}{\alpha_C + \beta_C V^{\gamma}} \tag{4.4}$$

where V is the vulnerability, α_C is equal to 1.5371, β_C is 0.000974 and γ is 1.8087, as proposed by Bernardini (2000) and Zonno et al. (1999). The calibration of these parameters was performed on the observation of the damage shown by a set of 350 masonry buildings during seismic events.
The graph in Figure 4.2 shows the values assumed by the expression of the seismic risk index I_R (4.2) in function of the vulnerability V and the PGA_D. Figure 4.3. shows the indexes of seismic risk parameterized by volume, number of buildings and structural type, while the distribution of the values obtained in function of the period of construction are shown in Figure 4.4. It is important to note that about 95% of the buildings present a risk index seismic less than 50%. In addition, structures of more recent construction have a lower vulnerability and a lower seismic risk.
The exposure was evaluated by adopting an index called "strategic factor" assigned by the local sanitary companies through a score ranging from 1 to 10. In function of this factor, a coefficient of exposure C was given as follow:

$$\begin{aligned}
&if \quad 1 < strategic\ \ factor < 4 \quad \Rightarrow \quad C = 0.70 \\
&if \quad 5 < strategic\ \ factor < 7 \quad \Rightarrow \quad C = 0.85 \\
&if \quad 7 < strategic\ \ factor < 10 \quad \Rightarrow \quad C = 1.00
\end{aligned} \tag{4.5}$$

The situations of greatest seismic risk were thus identified, and a ranked list of priorities for intervention was drawn by assigning to each building the mentioned index of priority I_p, obtained multiplying I_R of the expression (4.2) for the respective value of C.

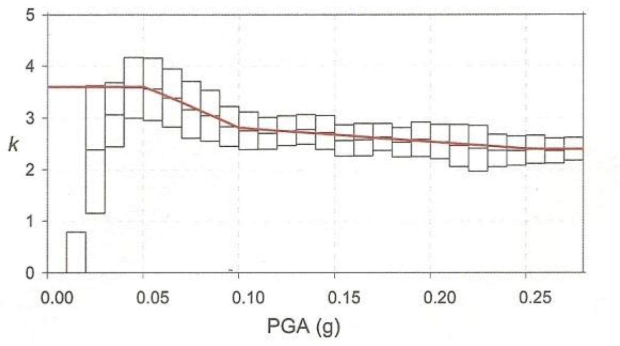


Figure 4.1. *k* factor in function of the expected peak ground acceleration PGA_D.

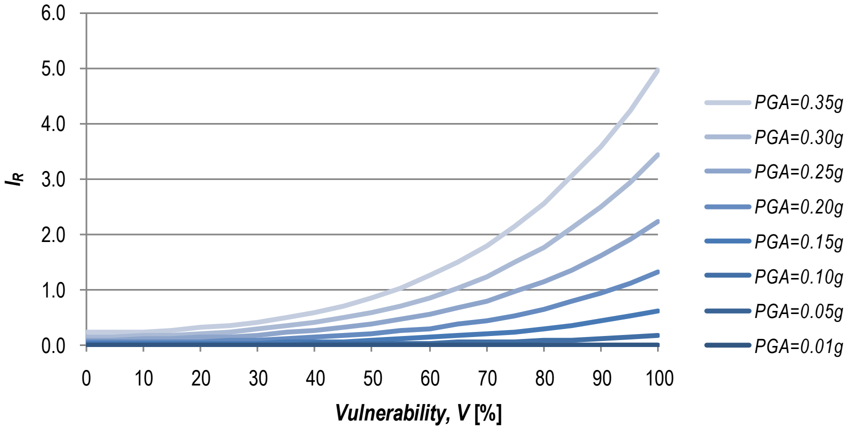


Figure 4.2. Seismic risk index I_R in function of the vulnerability V and the PGA_D.

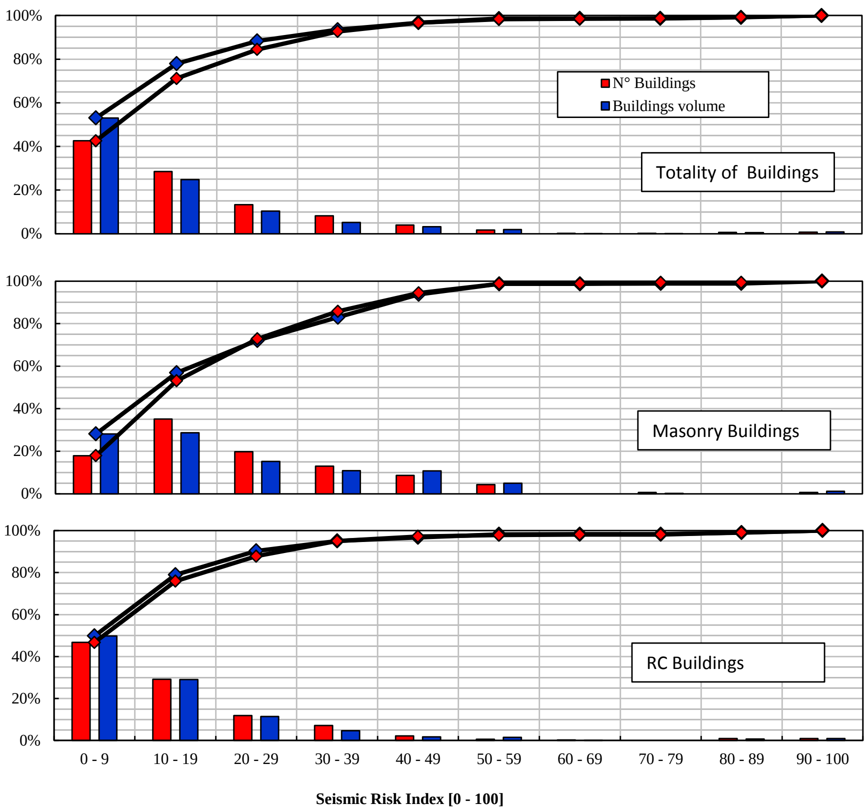


Figure 4.3. Seismic risk index parameterized by volume, number of buildings and structural type.

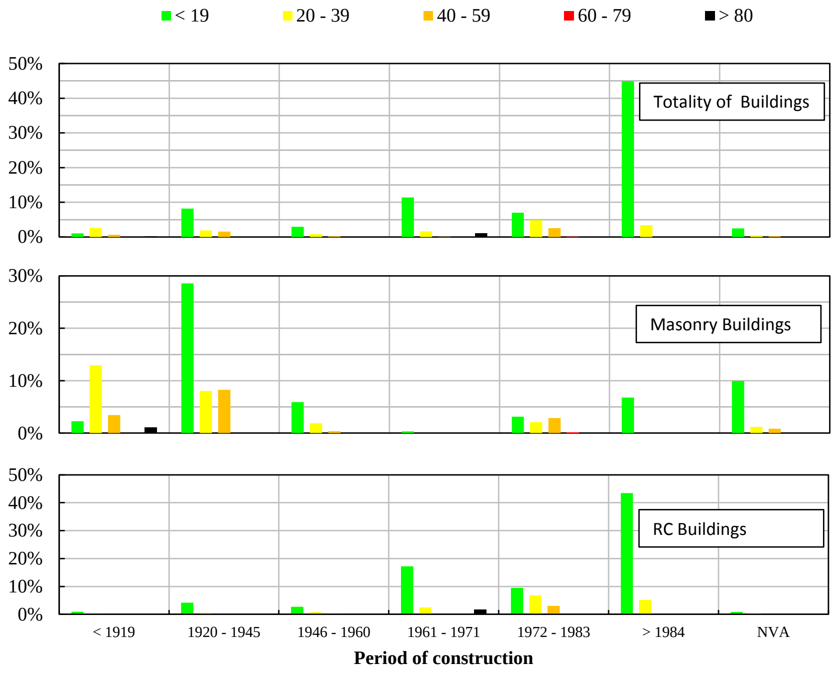


Figure 4.4. Seismic risk index parameterized by period of construction and structural type.

CONCLUSIONS

It should be pointed out that the survey of seismic vulnerability does not include the totality of the sanitary buildings, but only those with hospital use or similar, leaving the health districts, administrative offices, community services etc., except for specific requests. Moreover, the buildings being sold for the next sales or transfers or otherwise those covered by new design hypotheses were not examined. In general, the investigation of this study focused on all hospital buildings of Tuscany currently used, not designed according to modern seismic criteria, and which must be operational and available for a significant number of years. In fact, the new seismic regulations associate to the concept of seismic risk, the concept of return period of the design earthquake; unlike the previous regulations, which defined the seismic action with a predetermined value, the current regulations (Technical Standards for Constructions, Ministerial Decree 14 January 2008) relate the intensity of the design earthquake to a "time window" where the individual building is exposed, to a nominal life and to functional type that in this case is always the fourth. The indices of vulnerability obtained (value between zero and one hundred) identify, although in a synthetic way, the level of seismic criticality of the building, regardless of the soil in which it is located (seismicity more or less marked) and of the functional type relevance of the structural unit (operating rooms, stores, wards, etc.). It was therefore evaluated the index of seismic risk, which includes in itself two of the three mentioned, which is the vulnerability of the building and the hazard of the soil. It should be emphasized that a survey of this type was conducted for synthetic parameters and then, if considered on individual buildings, is far from an exhaustive evaluation of seismic reliability. Its function is only to provide an overview, derived from standard parameters, of the entire building heritage in question. Further investigations should be addressed to determine the role of non-structural elements and the equipment, such as medical machinery, instruments and pipes, in order to correctly evaluate the operation of the main parts of the hospital immediately after an earthquake.

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