

SEISMIC RISK OF THE ITALIAN HOSPITALS

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1 INTRODUCTION AND SCOPE

When an earthquake strikes, hospitals are strategic infrastructures but are, at the same time, highly fragile and complicate: their correct functioning depends in fact on the proper functioning of many installations. Their design, both structural and non structural, has been nonetheless traditionally carried out as for conventional buildings; and recent earthquakes have clearly indicated that hospitals are easily put out of service even for medium intensity seismic events /1/.

On the other hand it has been shown that it is generally possible to render these structures capable of remaining in function even after severe seismic shaking. The only country having a specific code for seismic design of new hospitals is California /2/. For existing ones the problem is still unsolved. In California a recent regulation imposes to upgrade existing hospitals to the same level of seismic resistance by the year 2030. In Italy the problem is now well clear, and in fact public institutions undertake the study of retrofitting existing hospitals /3/ in order to remain functional after intense earthquakes.

Methods to model the seismic fragility of hospitals in detail are described in /4/ to /7/. However, due to the large number of existing hospitals, it is important to establish a straightforward method to individuate the ones at risk. This is the object of the present study. In /8/ it has been shown that about half of existing Italian hospitals in seismic areas have not been designed for any seismic action.

All buildings have an intrinsic seismic resistance and the problem of non structural elements and installations is so important and critical for functionality that a specific work on such kind of structures is needed to account for the system-like behavior even for very secure structures from the structural view-point. In the following a method set up to evaluate the risk associated to hospitals is presented, making reference to the Italian case for which the necessary data are available.

Two performance levels, *immediate occupancy* and *structural stability*, as defined in /9/, required to a hospital after an earthquake, are considered. The evaluation of the seismic fragility of each hospital is presented first. This is essentially based on classical bayesian analysis, based on data of damages collected in a previous work by one of the authors /1/. The fragilities obtained, which are relative to specific classes of buildings, are considered applicable to all the Italian hospitals belonging to that class. Comparison of fragilities with seismic hazard for intensities corresponding to selected return periods, allows the computation of the risk of exceeding the performance level for each hospital.

Results, at this preliminary stage, confirm the feasibility of the study, though further analyses and procedure refinement are needed to reduce the uncertainty of the final results.

2 COMPUTATIONAL PROCEDURE FOR THE PROBABILITY OF COLLAPSE OF HOSPITALS

2.1 Fragility of buildings's components

Each hospital can be represented by a logical scheme composed by the essential functions, generally located in different buildings, arranged in a series system; each function is itself represented by a series system of structural and nonstructural components. We consider two different performance levels required to a hospital after an earthquake: immediate occupancy, i.o., and structural stability, s.s., as defined in /9/. For each performance level considered, the methods of system reliability allow computation of the fragility curve of each hospital once the vulnerabilities of each component are known.

The fragility curves of each component, object of this section, are evaluated by applying the bayesian updating method to damage data recorded in past earthquakes. The assumed distribution function for each componental fragility is lognormal, defined by the two parameters mean and coefficient of variation. Through the Bayes's method, the mean of the distribution is updated using the data /1/ collected on the hospitals stricken by the 1980's Irpinia and the 1976's Friuli earthquakes.

The damage data are organised as follows: for each building, the structural (S_i) and nonstructural (NS_i) components listed in table 2.1 have been examined.

Table 2.1. Description of structural (S_i) and nonstructural (NS_i) components.

Structural components		Nonstructural components	
S1	vertical structure (load bearing)	NS1	elevators
S2	horizontal structure	NS2	electrical system
S3	roof	NS3	water system
S4	stairs	NS4	feedings
S5	interior partitions (non-load bearing)	NS5	fire extinguishing
S6	exterior partitions (non-load bearing)	NS6	telecommunications
S7	foundations	NS7	medical gases

Damage was surveyed in /1/ in an eight levels scale, from $d=0$ (*no damage*) to $d=7$ (*collapse*) for structural components; for non-structural elements, a three levels scale was used ($0=full$, $1=partial$, $2=interrupted$). Each component (S_i and NS_i) is assumed to insure the performance levels *Immediate occupancy* and *Structural stability* if its damage d , corresponding to the definitions given in /1/, satisfies the inequalities of table 2.2.

Table 2.2. Definition of performance levels and associated damage levels.

Performance levels	Damage level for S_i	Damage level for NS_i
Immediate occupancy	$d \leq 2$	$d \leq 1$
Structural stability	$d \leq 6$	-

The inequalities in the upper table, arise from the comparison between the definitions of the performance levels of ATC, /9/, and those used within the survey /1/.

The results of the Bayes updating process, in terms of posterior means of the fragility curves, are shown in tables 2.3 to 2.5. These have been computed by assigning subjectively the

prior mean and the coefficient of variation (on the basis of data in the literature) of the fragility curve and then updating the mean value with the experimental data /1/. Six classes of buildings have been considered. They have been outlined on the basis of three structural typologies, i.e. masonry, reinforced concrete (r.c.) and mixed ones (built partly as r.c. and partly as masonry), and two heights, three floors or less and more than three floors.

Tables 2.3 and 2.4 show the posterior means of the structural components for the two limit states considered.

Table 2.3. Posterior means of structural components fragility curves – Immediate occupancy.

Classes	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇
r.c. ≤3	7.95	12.07	12.07	8.83	5.91	5.94	11.37
r.c. >3	7.82	11.64	11.64	8.39	7.55	7.55	10.48
Masonry ≤3	7.56	7.28	7.18	7.28	9.36	9.36	9.36
Masonry >3	8.22	5.61	7.28	7.28	7.28	7.28	6.00
Mixed ≤3	7.97	10.60	7.97	10.60	9.32	7.63	10.60
Mixed >3	10.20	10.20	8.32	10.20	8.78	7.51	10.20

Table 2.4. Posterior means of structural components fragility curves – Structural stability.

Classes	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇
r.c. ≤3	12.07	12.07	12.07	11.76	12.07	11.76	11.37
r.c. >3	12.00	11.64	11.64	11.15	11.64	11.64	10.48
Masonry ≤3	10.50	10.11	10.20	10.11	9.36	9.36	11.37
Masonry >3	11.37	11.37	11.37	10.11	10.11	10.11	9.94
Mixed ≤3	10.95	10.60	10.95	10.60	10.19	10.60	10.60
Mixed >3	10.20	10.20	10.20	10.20	8.78	10.08	10.20

The coefficients of variation of the fragility curves, not shown in the tables, vary between 0.1 and 0.2, which are reasonable values.

The results in table 2.4 show that, as a general rule, components of r.c. buildings are stronger than those of mixed and masonry structures and that structures with a low number of stories are stronger than the taller ones. Both these results are well expected and do not deserve further comments. Less expected are the results from table 2.3. These, relative to the immediate occupancy performance level, show a less regular pattern: generally speaking, components of r.c. buildings are stronger than the remaining ones, with a few notable exceptions relative to the components *stairs* and *interior and exterior partitions*. For the *stairs*, the least fragile behaviour is observed in the mixed type of structure and this might be due to a structural difference between the component and the remaining part of the structure. As for the *partitions*, the worst behavior is observed in the r.c. structures, whose partitions are usually built with weak bricks as compared to (relatively) stronger partitions in the mixed and masonry types of structures.

Comparison of the results in tables 2.3 and 2.4 with those obtained by other authors, has been possible only for what concerns the structural components. In fact, fragility curves from literature are referred only to the structural stability performance level; the moments of the fragility curves of structural components, here obtained, are in good agreement with those obtained

from the DPM (damping probability matrix) worked out on the basis of 30,000 conventional buildings damaged during the Irpinia earthquake /10/. In the comparison, attention has to be paid to the different intensity scale adopted in the damage surveys: the MSK for the conventional buildings in Irpinia and the MCS for the hospitals in Irpinia and in Friuli. A correlation between the mentioned scales has been made according to the results given in /11/. Large differences can be observed just for high intensities; in particular for MCS=7 the corresponding MSK value is around 6.5, and for MCS=10 the corresponding MSK is not much higher than 8. Table 2.5 shows the moments of the nonstructural components referred to the functionality of the entire hospital and therefore they are not subdivided in building classes.

Table 2.5. Posterior means of non-structural component fragility curves – Immediate occupancy.

NS ₁	NS ₂	NS ₃	NS ₄	NS ₅	NS ₆	NS ₇
7.79	5.44	6.35	6.19	10.91	6.95	9.10

The value of the coefficient of variation for these cases varies between 0.15 and 0.20 and has been estimated by literature data.

It must be observed that all values in tables 2.3 to 2.5 are relative to buildings designed without any seismic provisions, n.s.d. (no seismic design). We tried to compute the statistics on the fragilities of components also for buildings designed with seismic provisions but, due to the small sample size for this case, we did not achieve stable results. For this reason, these preliminary results are not shown here.

2.2 Fragility of buildings

All buildings are classified into six classes on the basis of three structural typologies, i.e. masonry, reinforced concrete and mixed ones, and two heights, three floors or less and more than three floors. Steel buildings are not considered because they represent a negligible amount of the total volume. In fact /8/ the total volume of existing Italian hospitals is subdivided in the structural typologies as follows:

- 27.4 % masonry
- 28.9 % reinforced concrete
- 43.2 % mixed (masonry and r.c.)
- 0.5 % steel

In order to evaluate the fragility of building classes, each building is represented by a series system of appropriate structural S_i and nonstructural NS_i components. The logical schemes adopted for the two performance levels considered, i.o. and s.s., are shown in figure 2.1.

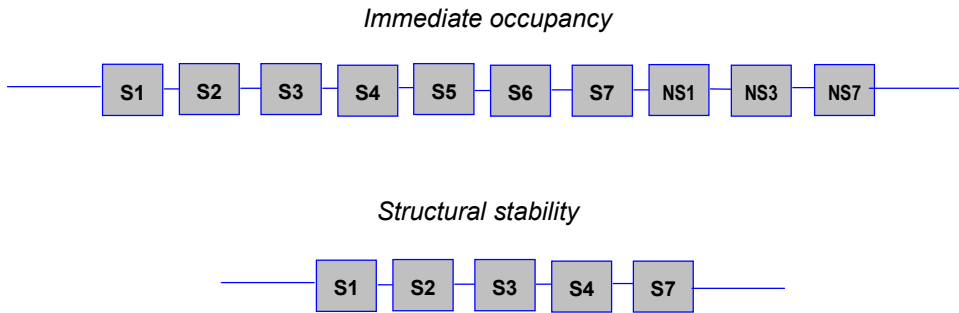


Figure 2.1: Logical schemes for buildings.

For what concerns the i.o. performance level, only NS₁ (elevators), NS₃ (water system) and NS₇ (medical gases) have been included in the model. It was assumed that in emergency conditions all hospitals were functional with independent power generation; therefore NS₂ (electrical system) has been neglected; besides NS₅ (fire extinguishing), NS₆ (telecommunications) and NS₄ (feedings) have been judged non essential for the immediate occupancy after a seismic event. For what concerns the s.s. performance level, failure of nonstructural components together with partitions (S₅ and S₆) were obviously disregarded.

Fragility curves for the six building classes defined above, are shown in the figures 2.2 and 2.3. In the figures, Pf indicates the probability of failure and MCS indicates the earthquake intensity expressed in the Mercalli - Cancani - Sieberg scale. In the computations of buildings fragility, the assumption of perfect correlation ($\rho=1$) among the components of the logical schemes of fig. 2.1, has been retained since observation of damages from past earthquakes has highlighted high (about 0.8) correlation among collapses of different components.

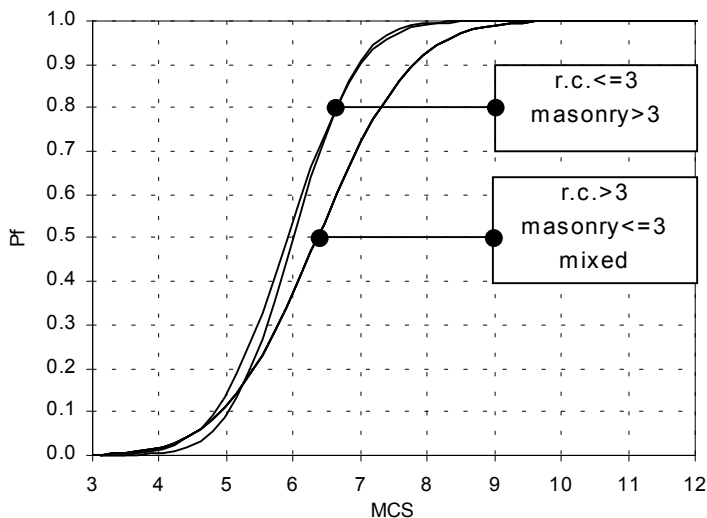


Figure 2.2. Fragility curves for immediate occupancy.

In figure 2.2 the fragility curves for all types of buildings are plotted; it must be observed that, from a practical point of view, just two curves describe the behaviour of all building types:

the fragilities of masonry buildings with more than three floors and r.c. buildings with no more than three floors agree with the curve of lower resistance; the remaining four typologies are in good agreement with the curve of major resistance. Differently from the i.o. performance level, in which the high vulnerability of the nonstructural components predominates, the fragility curves relative to structural stability for the different structural typologies cannot be grouped.

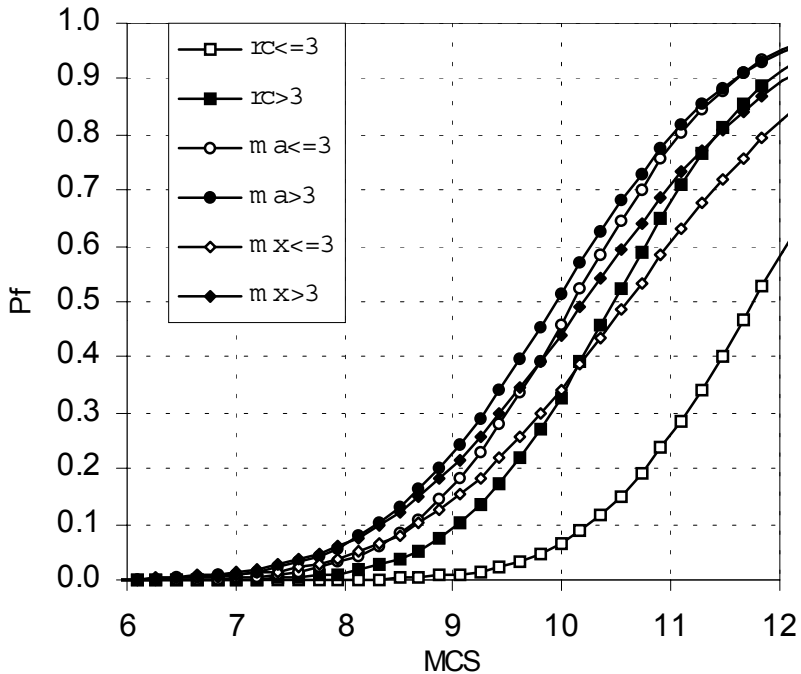


Figure 2.3. Fragility curves for structural stability.

In figure 2.3 it can be observed that r.c. buildings with no more than three floors are the most resistant. All the remaining classes are contained in the range limited from masonry buildings with more than three floors (the less resistant) and from r.c. buildings with more than three floors.

It is of interest to observe that the r.c. buildings are the most resistant with respect to the structural stability and the least resistant with respect to the immediate occupancy limit states. This is essentially due to the presence, in the assumed models, of nonstructural components and of the interior and the exterior partitions, whose resistance is very low.

2.3 Fragility of hospitals

The logical scheme adopted for hospitals shortly consists in the essential functions arranged in a series system. In this study, where the aim is to analyze hospitals on the entire national territory, the simplified scheme of figure 2.4 was adopted. A more detailed analysis can be found in /4/.

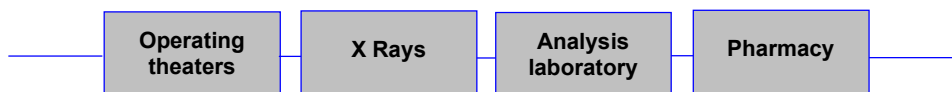


Figure 2.4. Logical scheme for the hospital.

In the simplified model, the essential functions to maintain the full service of the hospital after an earthquake are: the operating theaters, the X Rays systems, the analysis laboratory and the pharmacy.

The selection of the essential functions has been made according to other specific documents /13/. In particular, the operating theaters as well as the beds for intensive therapy are considered the most significant services, followed by the X rays and the analysis laboratory; the pharmacy is often integrated by medicine deposits at each level of the building, nevertheless this is not always true and therefore this was included in the logical scheme.

Whilst the number and types of buildings in each hospital was known from the Health Ministry data bank /14/, the location of the essential functions in the hospital's buildings was an unavailable piece of information at this stage. In order to overcome this lack of information, the least and most fragile arrangements were studied, the least fragile one (P_{min}) being all the functions contained in the least fragile building and the most fragile one (P_{max}) being the functions contained in the four most fragile buildings. The results shown in the sequel are relative to the assumption of perfect correlation among buildings' failures, which has again been verified from the experimental data /1/.

2.4 Probability of failures of hospital

For each hospitals' location, the intensity corresponding to a return period of 50, 100, 200, 300, 400, 500, 750 and 1,000 years have been computed with the Cornell's method /15/, using the Italian historical earthquakes's catalogue. The goal of the study was to check the two performance levels i.o. and s.s. against the earthquake intensities so as to identify the hospitals which do not satisfy predefined dual performance objectives; in /9/, for reference, hospitals are required to satisfy the i.o. performance level under the design earthquake (500 years return period) and the s.s. performance level under the maximum earthquake (1,000 years return period). Existing hospitals in Italy are already known to fail these tight requirements but a screening on a national scale had not been tried yet.

3 RESULTS OF THE ANALYSES

Results are given in terms of the mean probability P_{avg} , arithmetic mean between P_{min} and P_{max} defined above, of exceeding of i.o. and s.s. limit states. At present, the public hospitals on the Italian territory are 1007; for 947 (i.e. about 94%) of these, data are available and only these ones are included in the study. The territorial seismic risk evaluation of hospitals, is referred to local intensities corresponding to return periods T_{rit} spanning from 50 to 1,000 years.

A synthetic view on the situation for all the Italian hospitals for both the performance levels i.o. and s.s., is shown in figures 3.1 to 3.3.

In figure 3.1, for each return period, the number of hospitals whose probability of failure (either P_{avg} or P_{min} or P_{max}) is higher than 0.5, for the i.o. limit state, and 0.05, for the s.s. limit state, is shown.

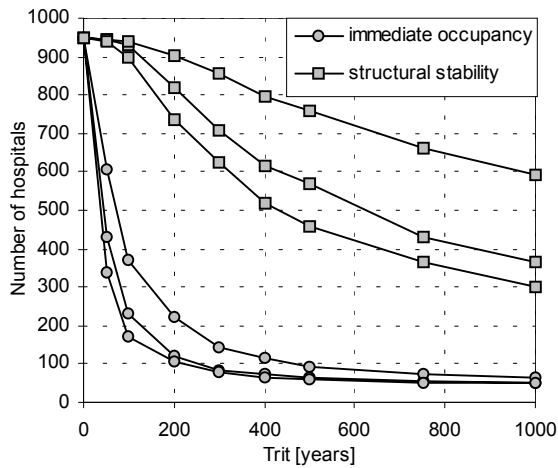


Figure 3.1. Number of hospitals with P_{min} , P_{avg} , P_{max} (respectively bottom, medium and top curves) higher than 0.5 or 0.05 (i.o. or s.s. limit states) vs. return period (Trit)

One should first notice that the situation, for the i.o. limit state, is critical: if one looks at the values of P_{avg} , about half the hospitals show values larger than 0.5 already for the action with return period of 50 years; for 200 years return period, about 850 of the 947 hospitals are in this very situation. The fragility values for the i.o. limit state depends, in fact, mainly on the installations which are very vulnerable. For the s.s. limit state, the behavior improves; for the action with 750 years return period, about half the hospitals have values of P_{avg} lower than 0.05.

These findings are confirmed by figures 3.2 and 3.3 which show the mean values and coefficient of variation of the variables P_{avg} , P_{min} and P_{max} over all the hospitals, for the two limit states.

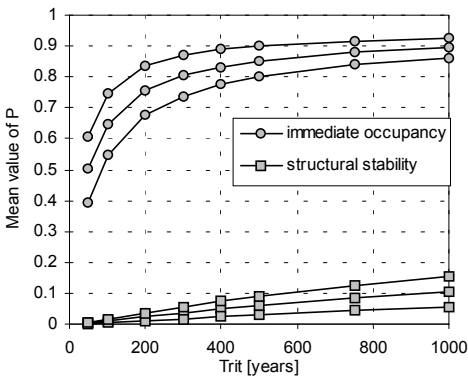


Figure 3.2. Mean value of P_{min} , P_{avg} , P_{max} (respectively bottom, medium and top curves) vs. return period (Trit)

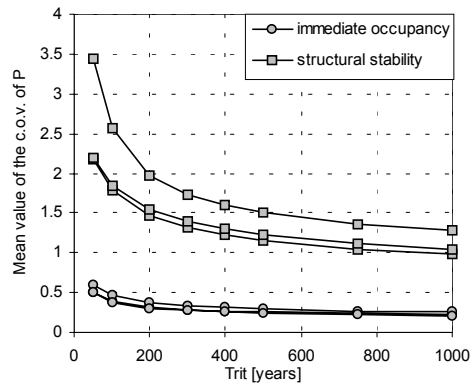


Figure 3.3. Coefficient of variation of P_{min} , P_{avg} , P_{max} (respectively bottom, medium and top curves) vs. return period (Trit)

For the i.o. limit state, the average value of P is high even for $T_{rit}=50$ years, with a low value for the c.o.v., whereas for the s.s. limit state the mean value of P_{avg} is equal to 0.1 for $T_{rit}=1,000$ years.

Next, risk maps on the Italian territory are presented (figures from 3.4 to 3.11), for selected values of the return period and of P_{avg} , for the immediate occupancy limit state. The first set of maps for i.o. (figures 3.4 to 3.7) is relative to 50 years return period and to constant intervals of P_{avg} of 0.25.

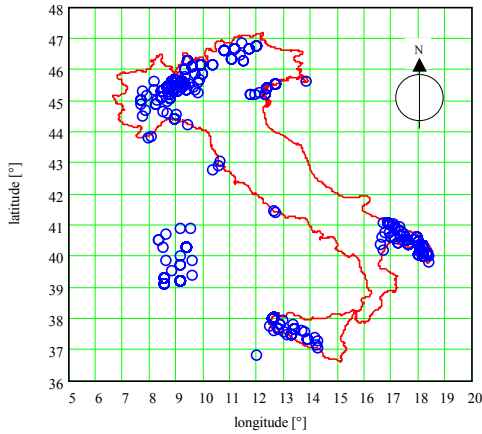


Figure 3.4: (i.o.) $T_{rit}=50$ years.
Location of hospitals with $P_{avg} \in [0;0.25[$

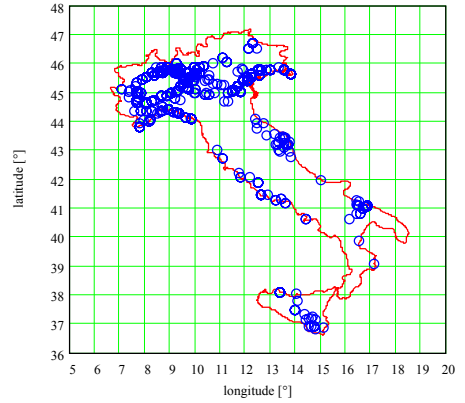


Figure 3.5: (i.o.) $T_{rit}=50$ years.
Location of hospitals with $P_{avg} \in [0.25;0.5[$

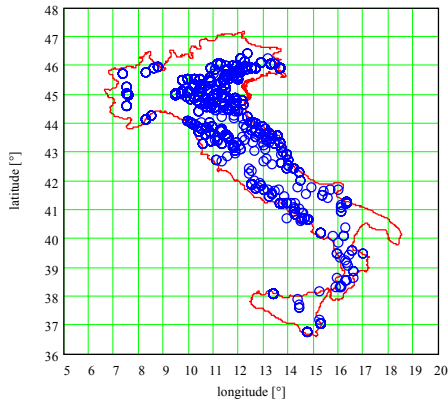


Figure 3.6: (i.o.) $T_{rit}=50$ years.
Location of hospitals with $P_{avg} \in [0.5;0.75[$

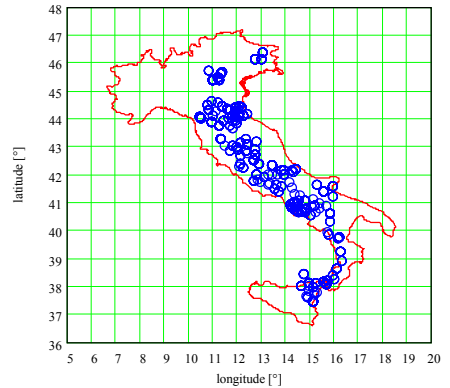


Figure 3.7: (i.o.) $T_{rit}=50$ years.
Location of hospitals with $P_{avg} \in [0.75;1]$

Examining the figures, one can see that the worst situation is located along the Appennini mountains, from SE to NW in figure 3.7, where most faults are located. This is also reflected in the Italian seismic code, in which the areas of high/medium seismicity (S=12, S=9) are distributed similarly to figure 3.7. The results in figure 3.7 depend of course, also on the fragility of hospitals. The second set of maps for i.o. (figures 3.8 to 3.11) is relative to 200 years return period.

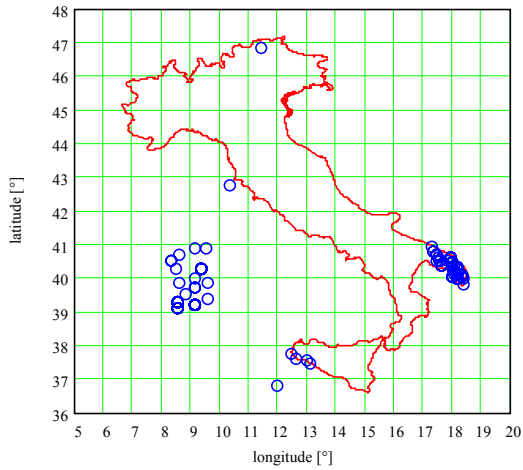


Figure 3.8: (i.o.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0;0.25[$

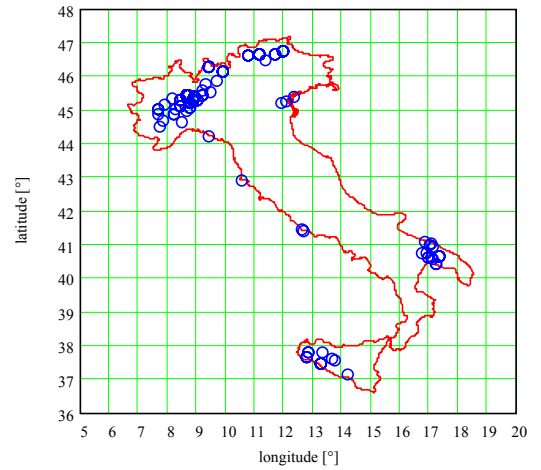


Figure 3.9: (i.o.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0.25;0.5[$

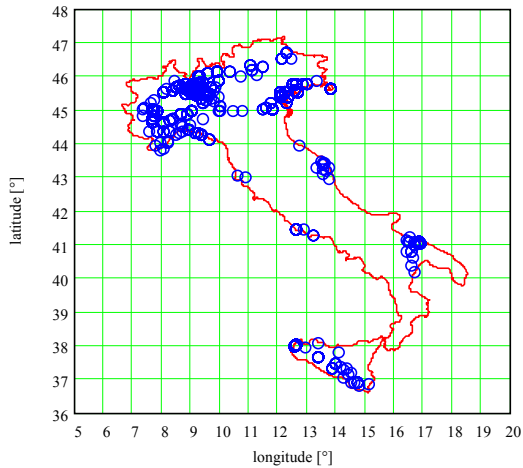


Figure 3.10: (i.o.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0.5;0.75[$

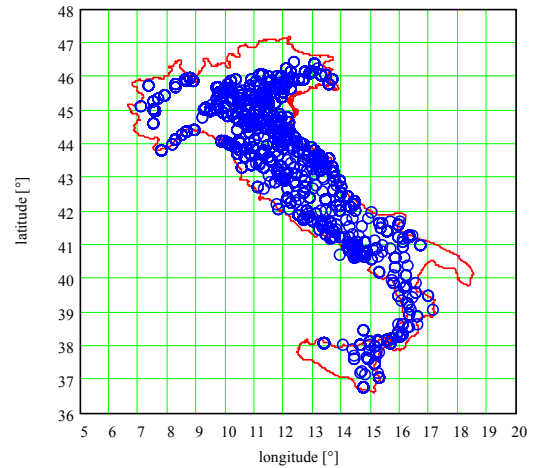


Figure 3.11: (i.o.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0.75;1]$

The most secure facilities are obviously in areas with low seismicity (the island of Sardinia at West, the western part of Sicily at SW, the south of Apulia, SE, fig. 3.8); the probability of failure is high anywhere else.

In figures 3.12 to 3.19, the location of hospitals for the structural safety limit state is shown. The first set of maps (figures 3.12 to 3.15) is relative to 200 years return period and to variable intervals of P_{avg} ; the second set of maps (figures 3.16 to 3.19) to 500 years return period.

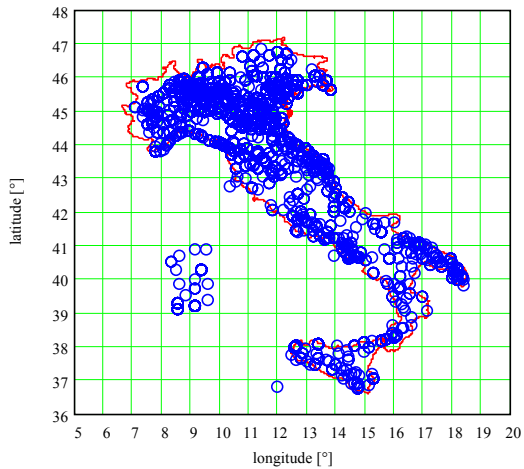


Figure 3.12: (s.s.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0;0.05[$

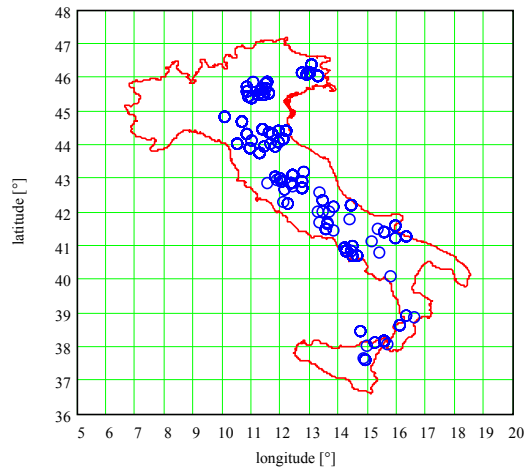


Figure 3.13: (s.s.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0.05;0.1[$

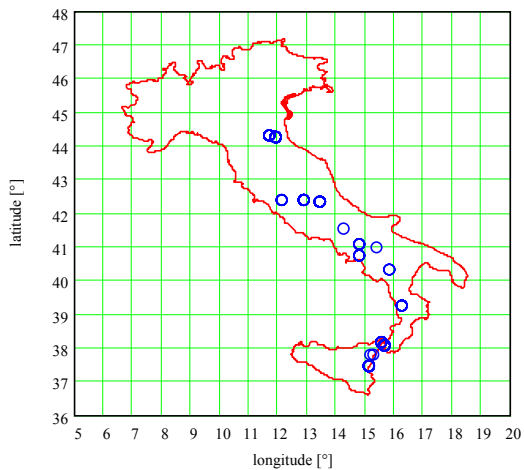


Figure 3.14: (s.s.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0.1;0.2[$

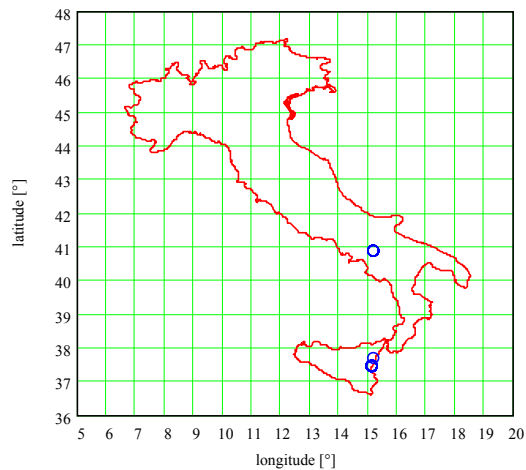


Figure 3.15: (s.s.) $T_{rit} = 200$ years.
Location of hospitals with $P_{avg} \in [0.2;1]$

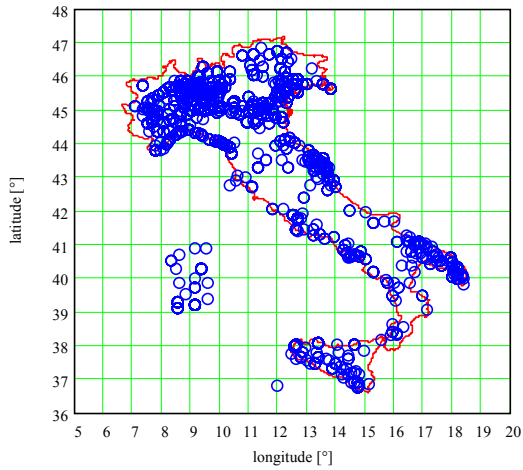


Figure 3.16: (s.s.) $T_{rit} = 500$ years.
Location of hospitals with $P_{avg} \in [0;0.05[$

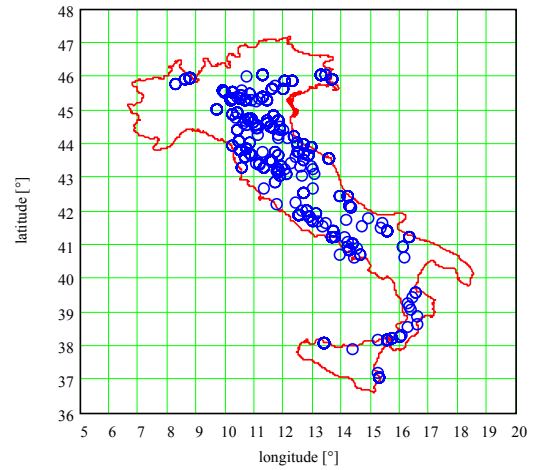


Figure 3.17: (s.s.) $T_{rit} = 500$ years.
Location of hospitals with $P_{avg} \in [0.05;0.1[$

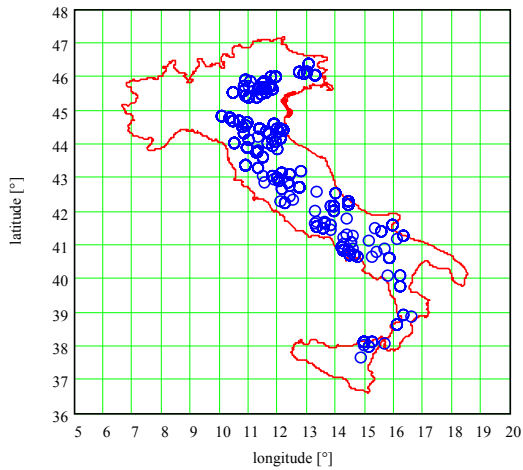


Figure 3.18: (s.s.) $T_{rit} = 500$ years.
Location of hospitals with $P_{avg} \in [0.1;0.2[$

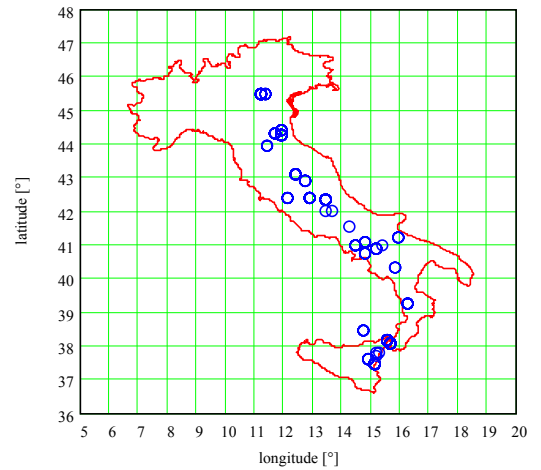


Figure 3.19: (s.s.) $T_{rit} = 500$ years.
Location of hospitals with $P_{avg} \in [0.2;1]$

Examining both sets of figures, considerations similar to those relative to the i.o. performance level can be inferred. For this limit state, however, the facilities are in a less critical situation.

4 CONCLUSIONS

A method for the evaluation of the seismic risk of the Italian hospitals has been presented. The probability of exceeding the immediate occupancy and structural stability limit states and the relative locations on the national territory are shown with reference to local intensities corresponding to return periods spanning from 50 to 1,000 years. One of the results is that about half Italian hospitals cannot remain functioning even for a return period of 50 years.

The procedure presented contains simplifying assumptions due to the lack of data on hospital but is however flexible enough to include additional data. In particular it is of interest to know the location of the essential functions in the hospital's buildings. This would allow elimination of the uncertainties on the average value of the probability of exceeding the assumed limit states; moreover, detailed information about installations would allow to refine the adopted simplified logical schemes.

5 REFERENCES

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