Vulnerability assessment and seismic risk reduction strategies of hospitals in Basilicata region (Italy)

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SUMMARY
Lessons learnt from past earthquakes point out the need to execute effective actions to mitigate seismic risk of public buildings. In Italy, after the 2002 Molise earthquake, pressing rules to assess strategic and important buildings in order to define priorities for seismic intervention were issued. As a result, thousands of buildings were evaluated and, specifically in Basilicata region, data on 69 hospital buildings is currently available. Firstly, priorities have been defined on the basis of seismic capacity, local hazard and number of people possibly present (exposure). Further, a simple relationship between needed risk reduction and required intervention costs has been set-up considering various strengthening strategies. Based on such relationships, some seismic risk curves describing the reduction overtime of the global risk for the entire building set have been determined. In the paper some suggestions to define solutions and priorities for seismic intervention in hospital buildings are reported.

Keywords: Seismic Risk, Vulnerability Assessment, Hospitals, Mitigation Strategies, Intervention Priority.

1. INTRODUCTION

Worldwide there is a large amount of public buildings, originally designed without seismic criteria, that are currently located in places subsequently classified as seismic zones. In Italy, the National Department of Civil Protection (DPC) estimates that there are about 75'000 public buildings designed without seismic criteria, and nearly 35'000 of them are placed in areas having either medium or high seismic hazard (Dolce et al., 2007). Large part of these buildings is made up of hospitals and schools, that is structures.
In Italy, past earthquakes already showed poor performance of public buildings under seismic events. For example, during the M6.9 1980 Campania-Basilicata earthquake, the health-care system was severely damaged, particularly with the complete collapse of the Sant'Angelo dei Lombardi Hospital (7-storeys RC building) and the heavy damage of the Curteri Hospital at San Severino. Despite these tragic events recorded during the 1980 earthquake and, before that, during the 1976 Friuli earthquake, little attention was paid by Italian Government to evaluate and mitigate seismic risk of hospitals, schools and, generally, public buildings until the 2002 Molise earthquake. During this earthquake a primary school building collapsed causing 27 children and their teacher lost their life (Augenti et al., 2004), dramatically emphasizing once again the high vulnerability of existing public structures.
After 2002 Molise earthquake the Italian Government got an exhaustive mitigation policy underway issuing the Ordinance of the President of the Ministers' Council (OPCM) n. 3274. Specifically, a prominent national plan started in order to define actions to assess and mitigate the seismic risk of all public buildings and infrastructures designed without earthquake resistant criteria. Among buildings whose integrity during earthquakes is of vital importance for civil protection or that are significant in view of the consequences associated with their collapse, particular attention was devoted to hospitals and schools, respectively.
Lessons learnt from past earthquakes clearly indicate that preventive efforts are largely paid off in subsequent emergencies. Further, they are more effective if planned and implemented through a

continuous process, based on an appropriate analysis of hazard and vulnerability levels at hand (Lupoi et al., 2008). The performance of the Californian health-care system during the 1994 Northridge earthquake is a prominent example. In fact, performance of the hospital network showed the effectiveness of the investment plan implemented by the State of California in 1973 (Hospital Facilities Seismic Safety Act, HFSSA) to improve the seismic safety of hospitals. This plan was mainly driven by the heavy damage suffered during the 1971 San Fernando earthquake when about 85% of fatalities (50 people) were caused by the collapse of hospital buildings (Meade & Kulick, 2007).

Based on these considerations and referring to OPCM 3274 provisions, Regional governments in Italy started activities to assess and mitigate the seismic risk of their public building stock.

Specifically, the government of Basilicata Region set up the "1st Program for the assessment of strategic and important public buildings in Basilicata Region" to be performed in the period 2004-2007, involving all the hospitals and larger schools designed without seismic criteria. More than 200 buildings were evaluated, 69 of them being hospital buildings. Assessment of these buildings provided a list of intervention priorities on the basis of their seismic risk level that, in turn, showed the huge amount of funds required to carry out interventions on all the involved buildings. Then, priorities need to be supported by an appropriate intervention strategy to optimize use of available resources.

Referring to the results of the 1st assessment program in Basilicata, the paper deal with strengthening strategies for seismic risk mitigation of the regional hospital buildings. To this end, in evaluating seismic performances of hospitals, physical, human and organizational factors should be taken into account, treating the regional hospital network as a complex social system. However, defining priorities and intervention strategies for the hospital network as a whole strictly depends on the seismic capacity of the individual buildings. Then, in order to obtain effective directions on the possible seismic risk mitigation strategies, vulnerability of the hospital network of the Basilicata region has been studied starting from the evaluation of its individual buildings.

Finally, some criteria to define priorities for seismic intervention have been developed, addressing the problem on the basis of two different approaches:

1. carrying out intervention following a priority list based on the seismic risk of single buildings, i.e. starting from the one with the highest risk;
2. implementing strategies dealing with each hospital complex as a whole.

Results provided in the paper can be used to develop intervention strategies, defining priorities and timescales of the strengthening program on hospital buildings, as already proposed for school buildings in Italy (Grant et al., 2006).

2. HOSPITAL BUILDINGS IN BASILICATA REGION

In the framework of the "1st Program for the assessment of strategic and important public buildings in Basilicata Region" professional engineers were involved in assessing 69 hospital buildings located in the Basilicata territory and designed without seismic criteria. They are grouped in 12 hospital complexes, as displayed in Fig. 1.

The main features of these hospital complexes are reported in Table 1. Buildings have generally Reinforced Concrete (RC) structure (65 out of 69 buildings) and they are about 40 years old. San Carlo Hospital - made up of 22 buildings all with RC structure, 18 of them without earthquake resistant design - is the most important complex in the regional health system. In fact, nearly 45% of beds globally available in the studied hospital buildings is located in the complex of San Carlo located in Potenza, the capital town of the Basilicata region.

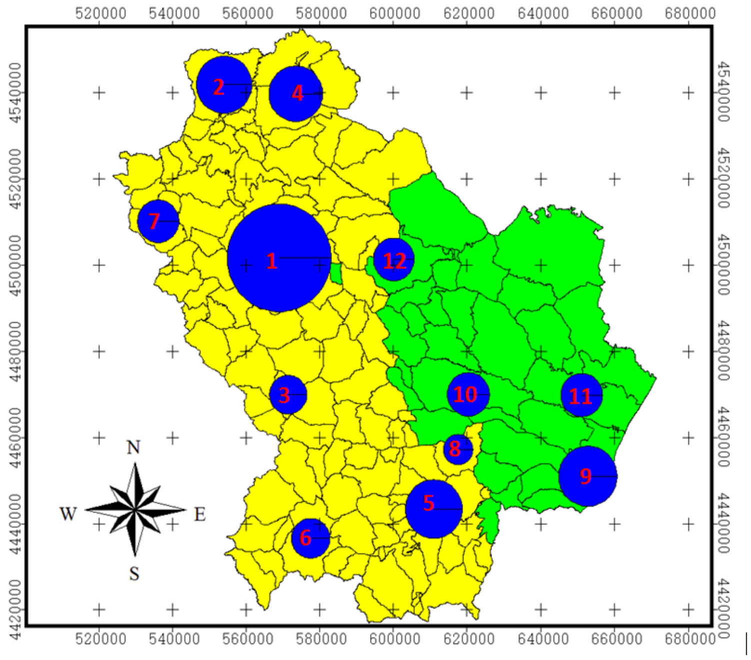

Figure 1. Map of Basilicata region displaying the hospital complexes under study in Potenza (yellow area) and Matera (green area) provinces. Dimension of blue circles is proportional to the global usable area of buildings in each complex (identification code refers to Table 1 where additional information are reported)

Table 1. Main typological characteristics of the buildings without earthquake resistant design located in each hospital complex

ID	Province	Complex	N. buildings		Use Area (m^2)	Design Period	N. Beds
			RC	Masonry		min-max	
1	Potenza	Potenza	18	0	85’200	67 - 81	931
2		Melfi	13	0	17’400	62 - 82	151
3		Villa d’Agri	2	0	4’200	91 - 92	148
4		Venosa	5	0	15’800	68 - 78	109
5		Chiaromonte	2	2	18’600	50 - 83	96
6		Lauria	2	0	4’700	70 - 76	44
7		Muro L.	3	0	6’400	60 - 78	45
8		S. Arcangelo	1	0	1’000	77 - 78	0
9	Matera	Policoro	11	0	20’100	64 - 91	165
10		Tinchi	3	0	6’600	59 - 61	97
11		Stigliano	4	1	6’900	60 - 70	103
12		Tricarico	1	1	6’000	60 - 70	96
Total on the region			**65**	**4**	**192900**	**50 - 92**	**1985**

2. METHODOLOGY

In order to define a road map to mitigate the seismic risk of the health care network in Basilicata (intervention priority and optimal distribution of available funds), the following activities have been carried out:

1. analysis of current seismic risk levels of the hospital buildings processing the results provided for each building by professional technicians after extensive vulnerability assessment programs;
2. cost estimation of different seismic strengthening actions considering different tolerable risk levels before- and post-intervention;
3. construction of time-risk curves on the basis of different funds’ availability (they show the overtime reduction of risk for the whole building sample under examination considering various strengthening solutions and funds’ availability);
4. comparison of results achieved implementing different strengthening strategies to point out the

most effective one in terms of progressive and final risk reduction;
5. definition of criteria for the intervention timescale (priority lists).

2.1. Analysis of current seismic risk levels

Current seismic risk levels have been analyzed starting from the values of Peak Ground Acceleration able to determine either severe damage to structural members (PGA_{SLV}), or damage to non structural elements (PGA_{SLD}) representative of building seismic capacity. Seismic risk levels have been computed as the ratio of building capacity values to demand values required for new buildings in current seismic codes (i.e. expected values of PGA at the site where each building is located). The expected demand has been determined considering a reference period equal to 100 years and an exceedance probability equal to 10% and 63% for SLV and SLD, respectively. To this end, the national hazard maps proposed by the National Institute of Geophysics and Vulcanology (OPCM 3519, 2006) and currently considered in the Italian Building Code (NTC, 2008) have been used.
Fig. 2 shows the hazard maps for whole Italy given in terms of expected mean values of PGA for the return period of 950 years, that is 10% exceedance probability in 100 years (SLV limit state). On the basis of this approach the seismic risk indexes for Life Safety (SLV) and Damage Limitation (SLD) limit states have been calculated as follows:

Life Safety (SLV) $\alpha_{SLV} = \dfrac{PGA_{SLV}}{PGA_{950y}}$ Damage Control (SLD) $\alpha_{SLD} = \dfrac{PGA_{SLD}}{PGA_{101y}}$

α_{SLV} is the seismic risk index related to the structural safety, while α_{SLD} is related to the capability of avoiding unacceptable damage on non structural elements (occupancy). Values equal or near to 1.0 are representative of cases in which risk can be considered acceptable according to seismic code requirements for new buildings, while progressively lower values are related to cases having excessive seismic risk levels.

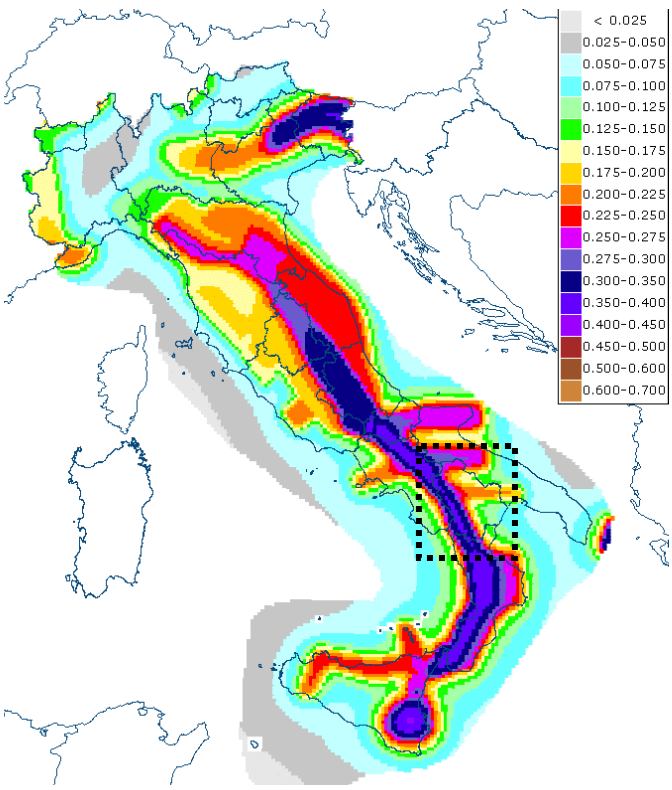

Figure 2. Seismic hazard map (in terms of PGA) of Italy for the return period of 975 years (the box with dashed lines marks off the Basilicata region)

2.2 Cost estimation of strengthening interventions

In order to evaluate the effects of specific investments on seismic risk reduction, some relationships between α_{SLV} values and intervention cost required on a building have been defined. Four models between current α_{SLV} values and estimated costs have been proposed considering different building age and tolerable risk levels before- and post-intervention. Particularly, the developed cost models, named N1, N2, N3 and N4, are function of a set of parameters depending on the chosen mitigation objective (target) and on the application framework.

In the models N1, N2 and N3, the target is full retrofit, corresponding to the achievement of α_{SLV} post-intervention values (α_{SLV-pi}) equal to 1. Model N4 considers the possibility to set seismic action values for existing construction as low as 70% of those required for new design (upgrading), therefore the selected target is obtaining α_{SLV-pi}=0.7 for all buildings. Model N1 is applied to the buildings having α_{SLV} before intervention (α_{SLV-bi}) less than 1, while model N2 considers a lower tolerable threshold of seismic strength for buildings older than 1972, i.e. assuming that they have to be strengthened when $\alpha_{SLV-bi} < 0.8$. It is worth noting that in 1972 a new structural code came into force in Italy determining remarkable changes to design and construction activities of RC structures (Masi, 2003). In N3 model the above mentioned limitation is extended to more recent buildings, designed after 1972, assuming the tolerable threshold $\alpha_{SLV-bi} < 0.8$ for all buildings. In model N4, given that the target value assumed for post-intervention seismic resistance is $\alpha_{SLV-pi} = 0.7$, a cost of intervention equal to 60% of that needed for full retrofit has been considered. Finally, in all models it is foreseen that buildings with a very low seismic strength, represented by values α_{SLV-bi} <0.2, should be demolished and rebuilt. The summary of all provided models is reported in Table 2.

Table 2. Summary of provided cost models

Cost Model	Model Criteria of Strategic
N1	Full retrofit of all buildings achieving α_{SLV}=1
N2	Full retrofit achieving α_{SLV}=1 of all post-1972 building and pre-1972 buildings with α_{SLV}<0.8
N3	Full retrofit achieving α_{SLV}=1 of all buildings with α_{SLV}<0.8
N4	Upgrading of buildings having 0.2<α_{SLV}<0.7 achieving α_{SLV}=0.7

Fig. 3 shows the four proposed cost models. It has to be noted that two different relationships between α_{SLV} and required cost are considered, according with the building age (before or after 1972). The models provide the required cost of intervention C_i (as a sum of structural and consequent non-structural works closely related to structural works), divided by the reconstruction cost C_{max}.

To define the cost model it has been assumed that there are α_{SLV} thresholds below which strengthening has to be considered unacceptable due to reservations on long-term outcome of the intervention and to costs required that would be too close to those required for reconstruction. Therefore, it was considered that for all buildings with α_{SLV} <0.2 it was more appropriate to provide total demolition and reconstruction ($C_i/C_{max} = 1$).

Furthermore, looking at the curves of proposed cost models reported in Fig. 3, it can be noted that when the value of α_{SLV} is very low, i.e. close to 0.2, any strengthening intervention involves a large number of structural elements. In this case also the required non-structural interventions will be very costly, although different amount for buildings built before and after 1972 can be expected. Therefore, when α_{SLV} exceeds the threshold value of 0.2, for the buildings after 1972 an abrupt decrease of the ratio C_i/C_{max} has been assumed because of the likely reduced diffusion of non structural interventions due to better quality of materials (red line), while the curve for buildings pre-1972 has no discontinuity, decreasing linearly with the increase of α_{SLV}.

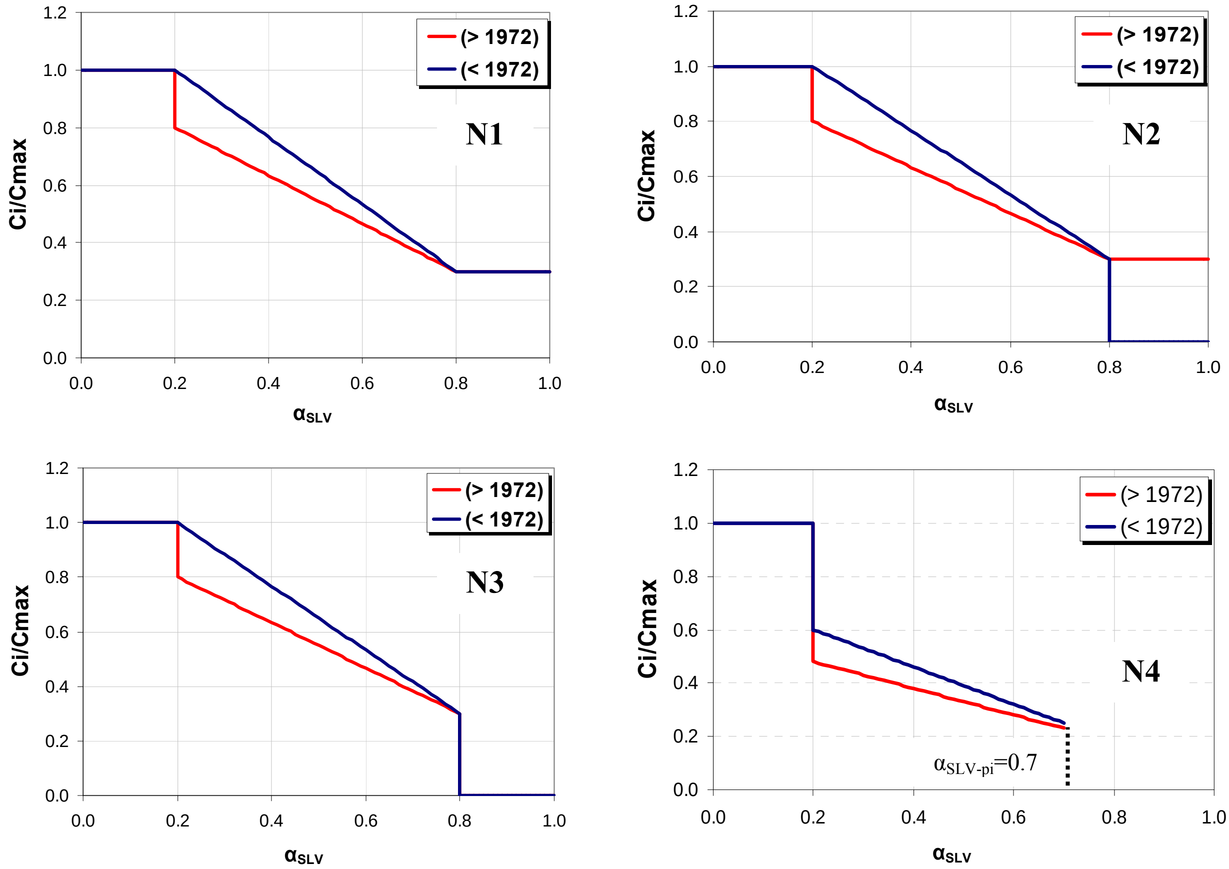

Figure 3. Proposed cost models. See Table 2 for more details

2.3. Time-risk curves

Interventions for seismic risk reduction progressively involve a certain number of buildings, thus reducing the global seismic risk at a given time *t*. In order to identify the most effective intervention strategies on the entire building sample, given the limited financial resources, time versus seismic risk relationships have been determined. They show the overtime variation of seismic risk of a set of buildings previously selected, depending essentially on kind of strengthening strategy and ratio between required and available financial resources. In order to prepare the risk curves, an index to express the seismic risk of the entire building stock has been defined. Considering only the life safety seismic index (α_{SLV}), different social (i.e. consequences on people) and economic (i.e. intervention costs) impact can be expected for different α_{SLV} values. However, in the computation of α_{SLV} only vulnerability and seismic hazard are taken into account, while exposure (in terms of number of people at risk) is not included. Lacking more accurate data, the number of people in each hospital building has been assumed proportional to the total floor area. By doing so, it is believed that also the expected number of operators and visitors is roughly taken into account better than considering the number of beds representing only the expected total number of in-patients.
Moreover, for two buildings having the same α_{SLV} but different floor areas, intervention costs are assumed to be proportional to their respective floor area. With reference to risk related to the life safety of structures, an average index $\overline{\alpha}$ has been introduced starting from the α_{SLV} value of each building. The $\overline{\alpha}$ index value for each group of buildings was calculated using the following expression (3.1):

$$\overline{\alpha}(t) = \frac{\sum \alpha_i(t) \cdot S_i}{\sum S_i} \qquad (3.1)$$

where the sum is extended to all buildings of a group, $\alpha_i(t)$ is the risk index α_{SLV} of the i-th building at the time t (i.e., before or post intervention determined according to the cost model used) and S_i represents the total floor area of the i-th building. Really, being directly proportional to the seismic capacity of individual buildings, α_{SLV} and $\overline{\alpha}(t)$ are inversely proportional to risk level. Therefore, the following index can be more appropriately considered as a global risk index:

$$IR(t) = 1 - \overline{\alpha}(t) \tag{3.2}$$

3. RESULTS

Table 3 summarizes the seismic risk levels α_{SLV} of the hospital buildings under study, separately for the two administrative provinces of Basilicata region, where rather different average values of seismic hazard are foreseen. For each group the total number of examined structures and the number and percentage of them having α_{SLV} values less or higher than 1.0 are reported. The buildings having risk index less than 1.0 should be either retrofitted or upgraded according to purposely defined priority list. As can be seen, the hospital system in Basilicata region shows a high seismic protection deficit, in fact all hospital buildings located in Potenza province have $\alpha_{SLV} < 1$, while in Matera province only one building has risk level higher than 1.

Starting from the distribution of α_{SLV} for buildings of a given sample (e.g., hospitals of the province of Potenza) and assuming an annual economic funds' availability, the number of buildings that can be retrofitted or upgraded during a given time period has been estimated.

Table 3. Buildings stock assessment for the two provinces in Basilicata region (Potenza and Matera)

Province	$PGA_{975\ ys}$ (g) min-max	N. of buildings	α_{SLV}		
			<1	>1	%>1
Potenza	0.155 – 0.352	48	48	0	0
Matera	0.100 – 0.215	21	20	1	4.70

Doing this until all the buildings of the sample have been strengthened and progressively re-evaluating the global seismic risk value through eqs. (3.1) and (3.2), the related time-risk curve can be obtained. The trend of this curve depends on the adopted cost model N_i, the average reconstruction cost C_{max}, the annual funds' availability D and the average annual rate of inflation I. With regard to C_{max}, a comprehensive average value equal to 2.250 Euros/m^2 has been taken. The inflation rate has been taken equal to 1.94% for the whole duration of the intervention plan, obtained as the average Italian inflation rate over the period 2006-2010. With respect to annual funds' availability D, various values have been considered, as discussed in the following.

Fig. 4 shows the risk curves of the hospitals of Basilicata computed through a computerized procedure purposely set-up, referred to the 4 cost models assuming D = 10 MEuro. The benchmarks to analyse the results with respect to each cost model and given values of inflation rate and funds' availability, are: (i) total cost of interventions, (ii) time required to complete the strengthening program, and (iii) residual risk value, i.e. the value of IR at the end of the intervention plan.

Table 4 reports the results achieved varying the strengthening strategy (cost model) and the funds' availability per year D in the range 10-20 MEuro. Analysis of results in Table 4 shows that the total required costs are strongly dependent on the value of D: as an example, by adopting the model of full retrofit N1, the total cost decreases from 580 to 470 MEuro, that is a reduction around 20%, for D values varying from 10 to 15 MEuro per year. This is due to the inflation rate that works on a longer period with D=10 MEuro (total time required to complete the program is 59 years), while total duration decreases to 32 years for D=15 MEuro per year. It is worth noting that in case the computed intervention time is too long, say over 20-25 years, estimates can be meaningless, or they need to be revised as a consequence of progressive deterioration of building state and evolving architectural, functional and aesthetic requirements. As a rule, dealing with a low annual funds' availability leads to excessively long intervention times and total costs should be further increased.

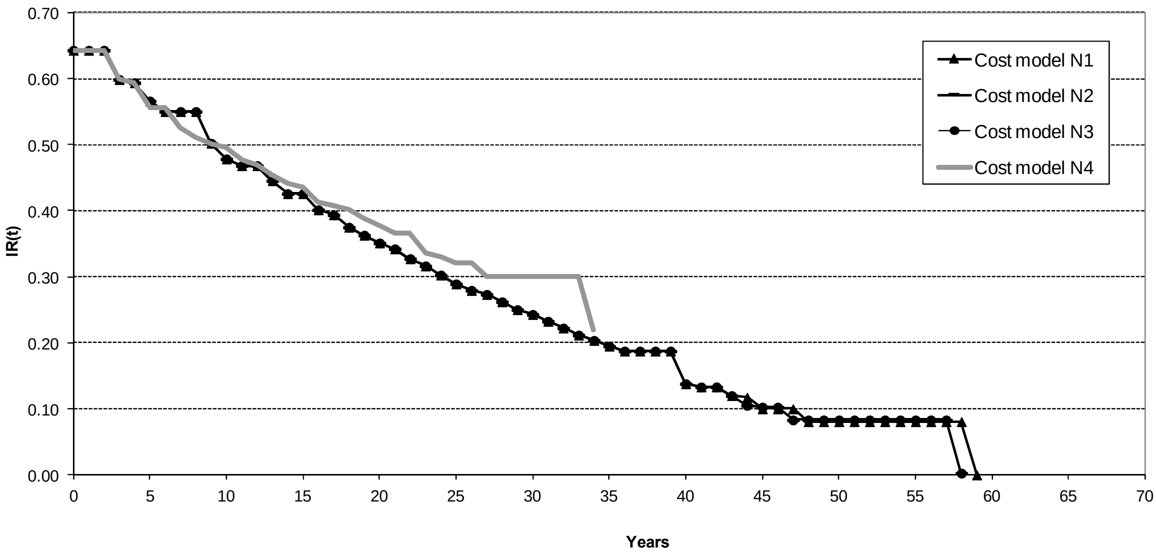

Figure 4. Examples of time-risk curves for hospital buildings in Basilicata region (D=10 MEuros)

For funds availability D equal to or higher than 10 MEuro per year, the difference among costs required adopting models N1-N3 is practically negligible. Remarkable reductions to the number of buildings to be strengthened and, consequently, to the required costs can be obtained by adopting model N4 (seismic upgrading). However, the price to be paid in this case is accepting a high residual value of the final risk level IR, particularly if compared to the initial (i.e. before the intervention program) value IR_0=0.64. In fact, residual risk has null value applying cost model N1, and is very close to null value with cost models N2 and N3. On the contrary, it becomes 0.22 with model N4, with a total risk reduction around 65% with respect to IR_0.

Table 4. Main data resulting from risk curves for building hospitals (I=1.94%, C_{max}=2250 Euro/mq)

Cost Model	D [MEuros/year]	Total intervention cost [MEuros]	Δt [years]	Residual risk
N1	10	580	59	0.00
	15	470	32	0.00
	20	435	22	0.00
N2	10	575	58	0.00
	15	465	32	0.00
	20	430	22	0.00
N3	10	575	58	0.00
	15	465	31	0.00
	20	430	22	0.00
N4	10	335	34	0.22
	15	300	21	0.22
	20	285	15	0.22

Further, the strategy of seismic upgrading (cost model N4) could be somehow disputable considering the importance of the structures under consideration. Rationale of upgrading (i.e. partial retrofitting) derives from funds' availability constraints, therefore it can allow intervening more quickly on a larger number of buildings, thus considerably reducing overall seismic risk in the first years of the program. Really, results on the building sample at hand show that applying model N4 does not appear advisable because the advantage of lower total costs globally required is frustrated by the drawback of a large value of the overall residual risk, therefore to be considered unacceptable. Moreover, even though

limited financial resources are available, models N1, N2 and N3 provide good results in terms of decreasing IR(t) values even in a relatively short time period.
A crucial aspect in preparing intervention plans is defining priorities for action, although results show that risk curves do not substantially change adopting a different order for the interventions on buildings. Further, different priority lists do not modify the amount of funds and time globally required.
On the basis of the parameters here considered (local seismic hazard, building structural capacity and total floor area of each building) two approaches can be used to define priorities. In the first approach $\bar{\alpha}$ values referring to whole hospital complexes are computed, that is grouping all the buildings located in each hospital complex. Subsequently, on the basis of the ordinal values of $\bar{\alpha}$, a priority index can be assigned to each complex. As a result, all the buildings of each complex are strengthened in the framework of a comprehensive intervention, in case starting from the building having the higher seismic risk in that complex (i.e. the lower α_{SLV} value). The second approach provides a list of priority based on the α_{SLV} value of individual buildings irrespectively to the complex which they belong to.
The first approach avoids that partial actions may be carried out on each complex considering that complex functionality can depend on the functionality of all buildings forming the complex. The second approach avoids that the strengthening actions may be concentrated on a single complex because of a single highly vulnerable building, postponing intervention on other critical complexes.
Finally, it is worth noting that when defining priorities, also the strategic role of some hospital complexes in the vulnerability and functionality of the health-care regional network should be recognized and taken into account. This derives from plans of health policy concerning the whole regional hospital system.

6. CONCLUSIONS

Vulnerability data on a set of 69 hospital buildings without earthquake resistant design located in Basilicata region were available as a result of the "1st Program for the assessment of strategic and important public buildings in Basilicata Region". Based on this data, a procedure to estimate time and funds needed for seismic intervention of the hospital network of the Basilicata region, has been proposed and applied. It is made up of the following steps:

1. obtaining a set of demand-capacity ratios (named α_{SLV}) mainly achieved from vulnerability assessment programs previously carried out on the building stock under examination;
2. calculating costs needed for either full retrofit or upgrading (i.e. partial retrofit) of each building entering the value of α_{SLV} in the selected cost model (N1-N4 or other specifically set-up) once the suitable value of the reconstruction cost C_{max} has been assumed;
3. assuming the annual funds' availability D on the basis of national and/or local mitigation policies;
4. defining a priority list for seismic intervention;
5. calculating the global risk index IR(t) at time t_0 before the start of the intervention program by means of eqs. (3.1) and (3.2) (first point of the time-risk curve (t_0, IR(t_0)) ;
6. identifying the buildings on which the interventions can be made during the i-th year, given the annual funds' availability and the estimated value of inflation rate, I;
7. calculating the updated value of the global risk index IR(t) at time t_i at the end of the i-th year of the program by means of eqs. (3.1) and (3.2), so that obtaining the new point of the risk curve IR(t_i);
8. repeating steps 6-7 until all buildings have been strengthened;
9. calculating duration and costs totally required as well as residual risk value, if any (i.e. value of IR(t) at the end of the program).

Analyses have been performed considering four cost models which provide different relationships between a given reduction of seismic risk on a building and the funds to be employed. The proposed cost models (N1-N4) refer to four different mitigation strategies. In fact, model N1 aims at full retrofit of all the buildings, that is aiming at a capacity-demand ratio (C/D) equal to 1, as that prescribed by seismic code for new buildings. Model N3 considers tolerable a risk slightly higher than model N1 (i.e. C/D=0.8), while model N2 is intermediate between models N1 and N3 considering C/D thresholds depending on the building age. Finally, model N4 aims at a controlled upgrading without

reaching the full retrofit of the building. All models share the choice to demolish and rebuild the structure if the demand-capacity ratio is too low (i.e. $C/D < 0.2$).
Applying the procedure at the hospitals of Basilicata region some results have been found, able to provide suggestions on the mitigation strategies to be planned: i) model N4 (controlled upgrading) does not result in an effective strategy because of the high value of residual risk; ii) a low annual fund availability leads to excessively long time for the completion of the interventions on the entire building stock and to higher costs determined by the inflation rate; iii) models N1-N3 provide practically the same results.
With respect to the last point, the result is dependent on the building set under examination, where a few buildings with demand-capacity ratio higher than 0.8 have been found. This could not happen dealing with other building sets, e.g. hospitals located in other Italian regions.
Finally, two different approaches have been proposed to prioritize interventions. The first one is based on the calculation of risk index values concerning each hospital complex made up of several buildings. As a result, the intervention program begins with the complex with the higher risk value and strengthening all its buildings is carried out. As a consequence, intervention on single buildings with higher risk but located in other complexes could be delayed. Contrarily, the second approach deals with single hospital buildings defining priorities according to the risk value of each building. Optimal decisions in defining priorities and timescales are pursued considering a mix of the two methods, taking also into account both the role of each hospital complex in the whole regional health network and the function of each building within the complex which it belongs to. To this end, beyond evaluations based on design code provisions, also scenario studies are required to compare expected number of injured people and capacity of each hospital complex for treating them in the aftermath of selected scenario earthquakes.

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