SEISMIC RELIABILITY OF THE ABRUZZO HOSPITAL SYSTEM AND UPGRADING STRATEGIES

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SUMMARY

A model for the regional hospitals system behavior in case of a seismic event is developed. The aim is the evaluation of the vulnerability of the system as well as the selection of the best intervention strategy for the retrofitting of the hospitals so as to minimize the cost benefit ratio and to evaluate the effect of different post-earthquake emergency measures like the use of camp hospitals. The efficiency of the system is measured in terms of mean distance to be cured for persons injured by the earthquake. In a previous work by the authors [Nuti and Vanzi, 1998c] a common fragility law had been assumed for all the hospitals in Abruzzo because of lack of information. This information is now available, since the vulnerabilities of the Italian hospitals have been computed and presented [Nuti et al., 1998a] in a simplified though rather accurate way. The new results thus obtained are shown and compared with the previous ones. They allow to clearly indicate the most convenient interventions

INTRODUCTION

Hospitals are central in minimizing inconveniences to population, in case of seismic events; nonetheless their seismic safety is generally low. In fact, hospitals are complex systems, containing a large quantity of seismically fragile machinery, often more fragile than the structures containing them. The retrofitting of existing hospitals is a crucial problem. Structural types are varied, comprising masonry and r.c. buildings, designed according to the norms of the construction period; these, as the present ones also, with the possible exception of the recent Californian code for new hospitals, are inadequate for this type of structures. At regional level, one can observe that the lack of functioning of a single hospital influences the services demanded to the remaining ones, because of transportation to the nearby hospitals. The analysis of the problems related to existing hospitals considered as a regional system, can usefully complement information concerning retrofitting of existing ones. One can employ various indexes to measure the regional system response. Namely, one can look both at direct damages on hospitals and at the worsening of the service quality offered by the system; in this work, attention is focused on both aspects.

As for the system behavior, the index distance covered by each casualty to be cured is an informative parameter. The distance per casualty is computed, given a seismic event, by evaluating the state of each hospital in terms of number of available beds and the number of casualties in each municipality. Casualties are further sent to the nearest hospital up to its actual capacity; and the average distance covered by each casualty is hence evaluated.

The procedure allows to spot the most critical hospitals, i.e. those ones whose functioning has the largest influence on the system behavior. The effectiveness of the various levels and strategies of intervention is hence evaluated and it is possible to identify the most convenient one.

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PERFORMANCE INDEXES FOR THE REGIONAL HOSPITALS SYSTEM

The mortality rate of casualties, in case of seismic event, is substantially reduced if they receive care in short time. Time depends both on the distance to reach hospitals and on the average transportation speed. Unfortunately, after a strong earthquake both these quantities tend towards undesired values, the former increasing and the latter decreasing, because of:

damage and/or congestion of hospitals

damage and/or congestion of the transportation network

The former causes a strong increase in the distance to cover because casualties exceeding the current hospitals' s capacity have to be moved somewhere else; the latter causes decrease in the transportation speed and increase in the distance to cover to reach hospitals e.g. because of interrupted transportation links. In the present work only damage to the hospitals is modeled, though the importance of damage to the transportation network is acknowledged; it will be considered in a successive development stage of the present model. The system's performance is described via the distance, as the crow flies, covered by each casualty. This parameter, in fact, under the assumption of uniform distribution of the transportation links, acceptable in a developed region at a large scale, is proportional to the time elapsed before a casualty is cured. In normal conditions, the CDF of distances among Abruzzo inhabitants and the nearest hospitals, weighted on the population, has been computed with the statistical data [Colozza & De Marco 1988, ISTAT 1991] and indicates a mean value of 5 km. The increase in this value due to earthquakes will synthetically define the system's performance.

MODEL OF THE HOSPITAL SYSTEM UNDER SEISMIC EVENT

The regional system: location of the population and hospitals

Abruzzo has a population of about 1'300'000, with low density; the major centers, L'Aquila and Pescara, count about 100'000 inhabitants and the remaining population is rather uniformly distributed on the territory (see figure 1; circumference radios are proportional to inhabitants of each municipality and the largest circumference represents 120'000 inhabitants). The hospital location follows population distribution rather closely (see figure 2, the largest circumference represents 1'369 beds available). The twenty-five hospitals of the region and their capacities are listed in table 1.

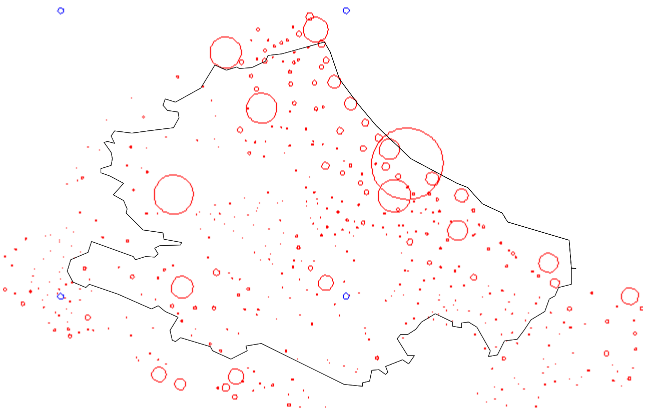

Figure 1: Distribution of the population

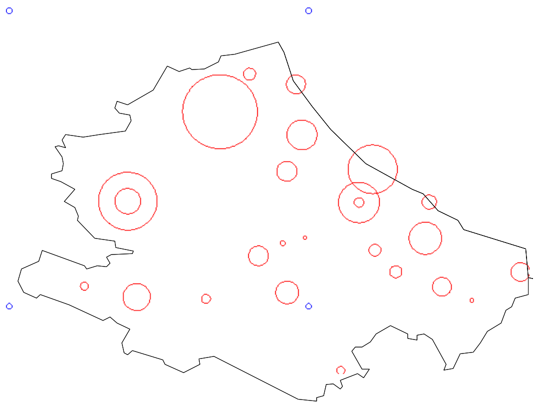

Figure 2: Distribution of hospitals

Table 1. Hospitals in Abruzzo

N.	Capacity	Municipality	Hospital	N.	Capacity	Municipality	Hospital
1	552	Atri	S.Liberatore	14	224	Casoli	Casoli
2	501	Avezzano	Ss Filippo	15	221	Sant'omero	Val Vibrata
3	165	Pescina	Rinaldi	16	262	Ortona	Berna
4	150	Tagliacozzo	Umberto I	17	370	Penne	S.Massimo
5	150	C. Di Sangro	Civile	18	901	Pescara	Dello Spirito
6	750	Chieti	Annunziata	19	365	Popoli	Ss.Trinita'
7	178	Chieti (scalo)	San Camillo	20	95	Tocco Da C.	Filomusi
8	220	Guardiagrele	Maria Ss	21	64	San Valentino	Presidio
9	350	Giulianova	Maria Sma.	22	420	Sulmona	Dell'Annunziata
10	1073	L'Aquila	San Salv.	23	1369	Teramo	Riuniti
11	470	L'Aquila	S. Maria C.	24	347	Vasto	Presidio
12	597	Lanciano	Lanciano	25	72	Gissi	Presidio
13	345	Atessa	Atessa				

Model for the casualties, fragility of hospitals and earthquake

The relationship between earthquake intensity and mean number of casualties as a percentage of the population, $\bar{C}(I)$, has been presented and discussed in [Nuti and Vanzi, 1998c] and reads:

$$\bar{C}(I) = (I - I_{min})^4 \cdot 0.00048 \tag{1}$$

where Imin=7 MM. (1) is plotted as a solid line in figure 3. Building types and years of construction for hospitals are extremely variable; while in [Nuti and Vanzi, 1998b,c] a common fragility function for all the hospitals was used since those studies had a methodological nature and no better information was available at the moment, this strong assumption has been removed herein. In fact, in [Nuti et al., 1998a] a simple, though pretty accurate, procedure was presented in order to assess Italian hospitals' safety; these data are now used. For each hospital in Abruzzo the fragilities computed with the immediate occupancy limit state have allowed the computation of a damage indicator as follows:

the damage indicator (DI) varies between 0 (no damage) and 1 (collapse) and expresses the ratio between the number of available beds before and after the earthquake

the DI is linear with respect to the earthquake intensity

DI=0 for probability of failure Pf (read from the fragility curve) lower than 0.2 and DI=1 for Pf>0.6

Hence the two intensity values IMM_o and IMM_1 for each hospital define the DI, as shown in fig. 4.

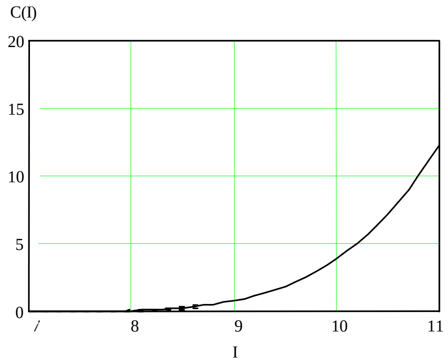

Figure 3. Casualties as a percentage of population

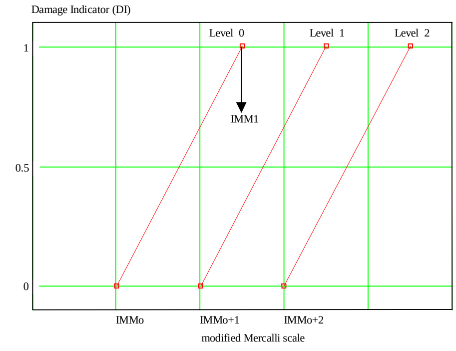

Figure 4: damage indicator as a function of the earthquake intensity

The values of IMMo and IMM1 for the Abruzzo hospitals are shown in table 2.

Table 2. Damage indicator for hospitals in Abruzzo

N.	IMMo	IMM1	N.	IMMo	IMM1	N.	IMMo	IMM1
1	6.2	7.5	10	5.3	6.5	19	6.2	7.5
2	6.2	7.5	11	6	7.5	20	6	7.5
3	6.2	7.5	12	6	7.5	21	6	7.5
4	6	7.2	13	6	7.5	22	5.3	6.5
5	5.3	6.4	14	5.2	6.4	23	6.2	7.5
6	6	7.5	15	5.2	6.4	24	6	7.5
7	6	7.5	16	6	7.5	25	6	7.5
8	5.2	6.2	17	5.2	6.4			
9	5.2	6.5	18	6.2	7.5			

In the analyses, damage to hospitals and the ratio of casualties to the population are modeled as lognormal r.v., having c.o.v. equal to 15%, while the mean values are functions the earthquakes intensities as discussed previously. Also, when upgrading, the DI of each hospital is assumed to move parallel to itself by whole IMM degrees so as to go from level 0 to level 3 (see fig. 4, levels 0, 1 and 2 are shown). As for earthquake generation, the classical Cornell model, with diffused seismicity, has been assumed. The reader is referred to [Nuti and Vanzi, 1998c] for the description of both the model and the values of the parameters of the considered seismogenic areas.

RESULTS

Introduction

Results have been computed with MonteCarlo analyses; details on the procedure are in [Nuti and Vanzi, 1998c] and are omitted for the sake of brevity. The analyses carried on in the following aim at answering some key questions:

which hospital, in a network, should be chosen to be first retrofitted

which retrofitting level is more convenient

what is the effect of a common emergency measures, installing camp - hospitals

The analyses have been conditioned to one seismic event in one of seismogenic areas and are especially suited to assess the relative effectiveness of intervention decisions and, hence, at indicating the most convenient one. Analyses consist in five investigations (1a to 1e):

(1.a) Identification of the retrofitted hospitals to which the maximum benefit is associated.

Analyses have been carried out considering the fragility of a single hospital at level 1, while maintaining the fragilities of the remaining hospitals at level 0 (see figure 4). Retrofitting of a single hospital, at level 1 , brings, in fact, about some decrease in the value of the distance which each casualty has to cover; the maximum obtainable improvement is that associated with a hospital network in which hospitals are not fragile. It has been chosen to express improvements associated with retrofitting of a single hospital normalised to the maximum possible improvement i.e.:

$$\mathrm{i1a(H,F)} = \frac{\mathrm{r(0)} - \mathrm{r(H,F)}}{\mathrm{r(0)} - \mathrm{r(\infty)}} \tag{2}$$

where r(H,F) is the mean value of the distance per casualty after retrofitting of hospital H at level F(=1), r(0) and $\mathrm{r}(\infty)$ indicate the same quantity with the hospitals respectively in the current state and in the state such that they are not fragile, ∞ level.

(1.b) As (1.a), per unit retrofitting intervention

Retrofitting of a hospital would normally be accomplished by intervening on all its facilities at the same time and hence analysis (1.a) is reasonable. However results are biased towards larger improvements for larger hospitals, whereas it would also be interesting to compare improvements for unit retrofitting cost. Under the assumption that retrofitting cost is directly proportional to the number of beds in a hospital, improvement for unit retrofitting cost may be simply computed dividing the results achieved in (1.a) by the number of beds:

$$\mathrm{i1b(H,F)} = \frac{\mathrm{r(0)} - \mathrm{r(H,F)}}{\mathrm{r(0)} - \mathrm{r(\infty)}} \cdot \frac{1}{\mathrm{nb}(H)} \tag{3}$$

where nb(H) is the number of beds in hospital H

(1.c) Identification of the most convenient level of retrofitting intervention

The choice of the retrofitting level (levels 1 to 2) should be made on the basis of a cost - benefit analysis; this allows identification of the most convenient level of retrofitting intervention. So the values of i1a(H,F) and i1b(H,F) have been computed for the first three hospitals in the ranking according to (2) and (3) and for values of F ranging from 1 to 3.

(1.d) Assessment of effectiveness of common emergency strategies

A common emergency measure after a major earthquake consists in installing a camp hospital in the epicentral area so as to be as near as possible to the casualties concentration. The effectiveness of such strategy has been assessed by comparing the mean value of the distance per casualty in the hospital network as is with those computed after installing a camp hospital at the epicentral location with number of beds ranging between 10 and 500

Analysis 1.a, b: identification of hospitals with maximum associated benefit

The average distance per casualty in normal conditions is 5 Km (see figure 1); this value increases to r(0)=20.1 Km (after an earthquake); the maximum obtainable improvement, if retrofitting was made at such a level that hospitals were not fragile, is at the value of $r(\infty)$=11.7 Km. Improvement, for each hospital and retrofitting level, has been computed according to (2) and (3) and is shown in figure 5 and figure 6.

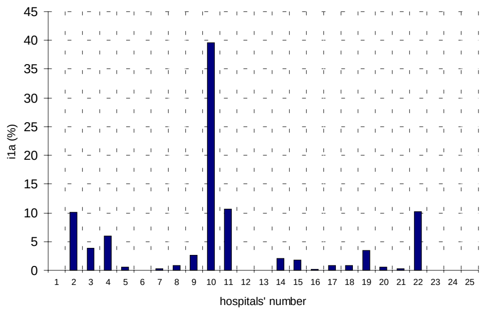

Figure 5. Improvement i1a with level 1 fragility

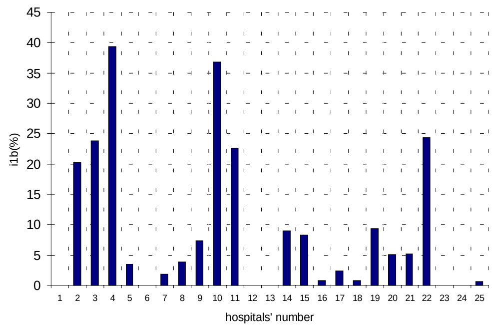

Figure 6. Improvement i1b with level 1 fragility

The three most important hospitals for i1a are numbers 10, 22 and 2 while for i1b are 4, 10 and 22. The most important feature of these results is that the ranking changes little whether absolute (i1a) or by bed unit (i1b) improvements are considered. This differs from what found in [Nuti and Vanzi, 1998c] where different retrofitting choices would be made looking at the two indexes. However these features are extremely problem dependent and cannot be generalized and stress the importance of an accurate evaluation of hospitals' fragility.

Analysis 1.c: identification of the most convenient level of retrofitting intervention

It is intuitive that the overall reliability improvement is a monotonically increasing function of the retrofitting level. The rate of increase, in terms of distance per casualty, is a decreasing function of the retrofitting level. It has been decided to conduct a comprehensive analysis with the three most important hospitals according to the results of analyses (1.a) and (1.b). The fragility of each hospital has been moved parallel to itself by a full MM degree, as shown in figure 4. The results in terms of improvement quantified via i1a or i1b are plotted in figures 7 and 8.

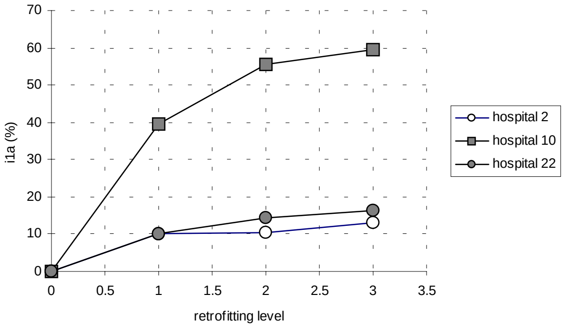

Figure 7

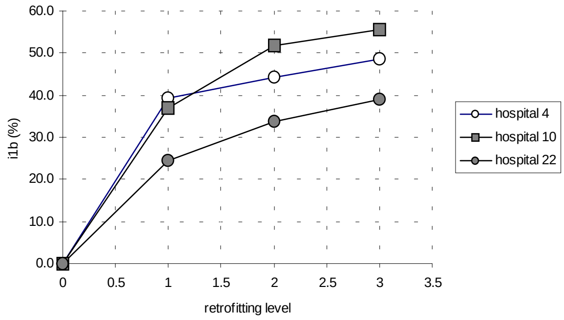

Figure 8

As a general remark, one can see that the trend is towards a constant value for high retrofitting levels and that this is reached at a lower level for less effective retrofitted hospitals. This is in agreement with what found in [Nuti and Vanzi, 1998c] with the important difference that retrofitting's improvement reaches a maximum at higher retrofitting levels than in [Nuti and Vanzi, 1998c].

Analysis 1.d: assessment of effectiveness of installing camp - hospitals

The effects of a common emergency measures after a major earthquake on system response i.e. installing a camp hospital in the epicenter is presented in figure 9.

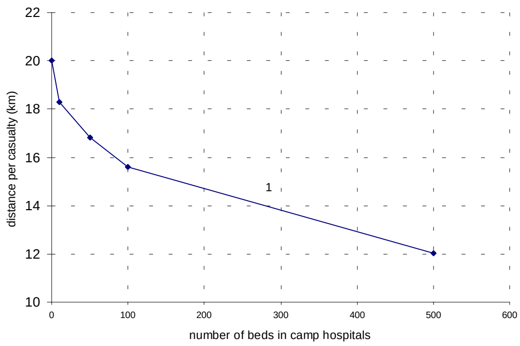

Figure 9

Here the effect is very similar to what found in [Nuti and Vanzi, 1998c]. A clear decreasing trend is observed, with interesting improvement in the overall behavior. It has to be stressed that installation of camp - hospitals is particularly interesting since, though the problem of reaching the installation may be critical, it can be set - up immediately.

CONCLUSIONS

A procedure for the evaluation of seismic safety for Hospital Regional System (HRS) is presented. The main parameter employed to measure the efficiency of the system is the mean distance (MD) to reach an unfilled hospital that injured people have to cover. In fact after a seismic event many hospital can be completely or partially out of order, while the request of medical care has a peak; one can therefore expect that the hospitals around the epicentre easily fill their reduced capacity. The method developed here is applied to a case study region, Abruzzo in Italy; various results of interest have been obtained:

which is the present level of safety;

which hospital or group of hospitals should be first retrofitted: i.e. the ones whose improvements mostly reduces MD;

which retrofitting level is more convenient

which is the effect of a emergency measures i.e. installing camp hospitals

Results show a current high vulnerability for the system, whose efficiency is obviously of dramatic importance in post-earthquake conditions. In a previous work [Nuti and Vanzi, 1998c] a certain number of simplified assumption had been considered, the most important being a single fragility function for all hospitals. Since the vulnerabilities of the Italian hospitals have been computed and presented [Nuti et al., 1998a] in a simplified though rather accurate way, this information has herein been exploited. The new results thus obtained are shown and compared with the previous ones. They allow to clearly indicate the most convenient interventions. It should be stressed that in this context, the simplified procedure to assess hospitals' fragilities [Nuti et al., 1998a] and the present one, form an integrated tool which may be useful in decision making.

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