Seismic safety of the Calabria hospitals and road networks

Alessandra Fiore, Ivo Vanzi, Camillo Nuti, Rita Greco, Davide Lavorato, Cristoforo Demartino, Bruno Briseghella

***Abstract*—** This paper shows a model to assess the seismic safety of a regional network system consisting of hospitals connected by roads. The main aim is the evaluation of the system safety. A specific indicator, namely the time taken to be cured for persons injured by the earthquake, is introduced to evaluate the system efficiency. The model takes into account the real road network.

The proposed methodology can be so summarized: i) given a seismic event, for each hospital of the system the number of available beds is calculated; ii) it is assumed that casualties leave from each municipality to reach the nearest not full hospital, up to its actual capacity; iii) the average time taken by each casualty to reach the nearest hospital is evaluated.

The above analysis allows to clearly identify which hospitals or roads should be strengthened in order to better face seismic emergencies and more precisely in order to avoid people to face unacceptable traveling times for reaching the nearest not full hospital.

The efficacy of the proposed methodology is shown with reference to the highly seismic Italian region of Calabria, where Castrovillari, Reggio Calabria and Locri result to be the most vulnerable urban centres.

***Keywords* -** seismic reliability, fragility, lifelines, hospitals, road network, random variables.

I. Introduction

Hospitals represent crucial facilities within post-earthquake emergency scenarios. These essentials facilities should ensure not only emergency care for the victims of a disaster, but also the usual healthcare services.

Retrofitting of existing hospitals is of global importance [1, 2]. Nevertheless, construction codes on this issue are mostly inadequate.

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The only exception is represented by the California law [3], that introduces specific seismic safety standards for hospitals to guarantee functionality also in emergency situations.

Past earthquake events have shown that damage in road networks and hospitals may deeply affect the emergency response [4, 5]. In fact the interruption of functionality of a single hospital may influence the services demanded to the remaining ones, due to transportation to the nearby hospitals. Similarly, after a strong earthquake, some roads may be partially or fully closed and so travellers could be forced to seek alternative ways to reach emergency facilities [6, 7].

Seismic risk assessment is the result of the combination of three main components: *i*) the hazard of the examined area, expressed in terms of seismic scenarios, either corresponding to historical earthquakes or numerically derived; *ii*) the seismic fragility of the involved structures, i.e. the probability to exceed a selected damage state for a given level of ground shaking [8]; *iii*) the exposure, referring to the expected consequences, given the hazard and the fragility.

The study herein presented focuses on the above aspects at a regional scale, that is on the ability of an hospital system and a road network to withstand to a natural disaster. Within the different indexes that could be adopted to evaluate the regional system response [9], in the proposed approach the "time taken to be cured" for persons injured by the earthquake is introduced as indicator. In particular the procedure can be so summarized: *i*) given a seismic event, the state of each hospital in terms of number of available beds is evaluated; *ii*) casualties, calculated as a population percentage, are sent from each municipality to the nearest not full hospital, up to its actual capacity (more precisely a 30% increase of the service capacity is considered, in order to account for the temporary beds usually setup under an emergency event); *iii*) the average time taken by each casualty to reach the nearest hospital is calculated. The real existing road network is taken into account. The goal of the proposed analysis is to identify the most critical hospitals, i.e. those ones mainly impacting the system behavior in emergency conditions. With respect to previous studies [10, 11], new features, like explicit consideration of the real network system, are introduced. The seismic risk assessment of existing hospitals at regional scale, can furnish useful information about the facilities and roads to be strengthened in order to improve the emergency response [12, 13].

II. DEFINITION OF THE PERFORMANCE INDEX

After a strong earthquake, the mortality rate of casualties depends on the speed and efficiency of the recovery activities. The efficacy of emergency operations in providing patient care, strictly connected to the distance from the nearest functioning hospital and to the average transportation speed, is affected by both: *i*) the collapse and/or congestion of hospitals, leading to an increase of the distance to cover in order to receive care; *ii*) the interruption and/or congestion of the transportation network, involving a reduction of transportation speed.

In the present work both damage to the hospitals and to the road network are modeled. A refined network simulation, including detailed travel demand and flow estimation for consecutive recovery phases, is implemented. Attention is focused on “rapidity”, one of the properties characterizing resilience, defined as the ability to respond to and mitigate disruption in a timely manner. In this perspective, the index “time taken by each casualty” before finding a not full hospital, to be defined in a probabilistic sense, seemed apt to fulfill the scopes. Figure 1 shows the road network considered within the study.

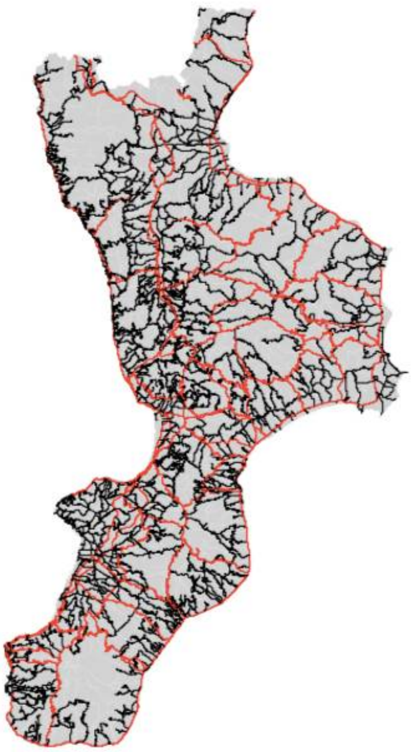

Fig. 1 The road network of Calabria.

III. MODELING OF THE ROAD - HOSPITAL NETWORK

A. *The regional network*

Calabria has a population of about 2'000'000, with low density; the major centers, Cosenza and Reggio Calabria, count about 600'000 inhabitants and the remaining population is rather uniformly distributed on the territory (see Table 1). Figure 2 shows population density (red dots), the road network (dark grey lines) and the hospitals position (blue symbols). The hospital location follows population distribution rather closely. The main hospitals (those with more than 100 beds) are listed in Table 2.

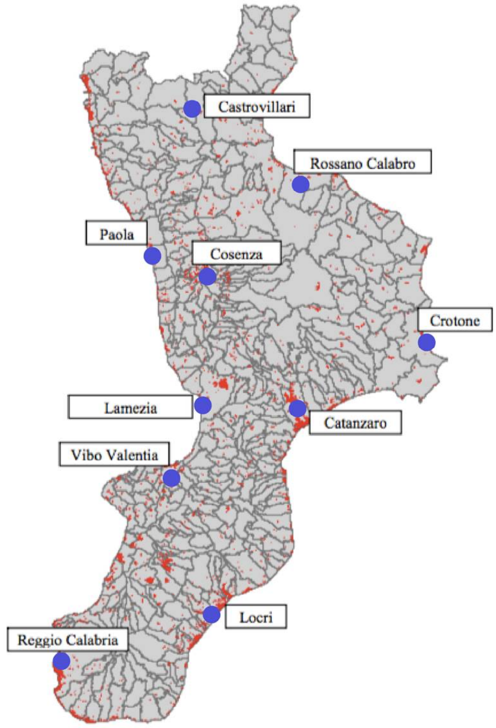

Fig. 2 Population density (red dots), road network (dark grey lines) and hospitals position (blue symbols).

Cosenza	733.142
Crotone	172.735
Vibo Valentia	169.967
Catanzaro	368.856
Reggio Calabria	562.692
TOTAL	2.007.392

Table 1 Population in Calabria.

Number	Name of hospital	Municipality	Beds
1	Ospedale Civile Ferrari	Castrovillari	106
2	Ospedale Civile Giannettasio	Rossano	113
3	P.O. S. Francesco	Paola	107
4	A.O. Annunziata	Cosenza	728
5	O.C. San Giovanni Di Dio	Crotone	422
6	A.O. Pugliese	Catanzaro	625
7	Ospedale Civile	Lamezia Golfo	252
8	P. O. G.Jazzolino	Vibo Valentia	234
9	Ospedale Civile	Locri	285
10	A.O. Bianchi-Melacrino	Reggio Di Calabria	572

Table 2 Hospitals with more than 100 beds in Calabria.

B. Fragility of hospitals

The mean number of casualties as a percentage of the population $\bar{C}(I)$, that is the post-earthquake mean number of injured patients, depends on various factors, such as: *i*) the building types and quantity, with particular reference to the building fragility and the coefficient of occupation; *ii*) the time at which the earthquake strikes; *iii*) the vicinity of available health care facilities; *iv*) the population age. For a discussion, one can consider reference [10]. In the proposed study it is expressed as function of the seismic intensity, by adopting the following relationship derived on the basis of the first aspect (*i*):

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

where I_{min}=7 MMI. Earthquake intensity is expressed in terms of Modified Mercalli Intensity (MMI) scale [14]. Equation (1) is represented as a solid line in Fig. 3. Information on population, already summarized in Table 1, are acquired by ISTAT database [15].

Hospitals fragility is measured through a damage indicator, ranging between 0 (no damage) and 1 (total collapse), calculated as the ratio between the number of available beds before and after the earthquake. In particular, five damage curves, namely levels 0 to 4 in Fig. 4, are implemented in the analysis. Each of them reflects the actual retrofitting level of the considered hospital at the earthquake time. The level 3 and 4 curves, obtained from the previous ones with half a MMI degree translation, are associated to the higher upgrading levels. A significant improvement of an hospital damage level can be generally achieved by retrofitting non-structural utility systems; a further half or one MMI degree translation of the damage curve can derive by structural recovery interventions, such as the ones dealing with the introduction of base isolation devices or tuned mass dampers. At the beginning of the simulation for each hospital an occupancy level equal to 70% of its service capacity is considered.

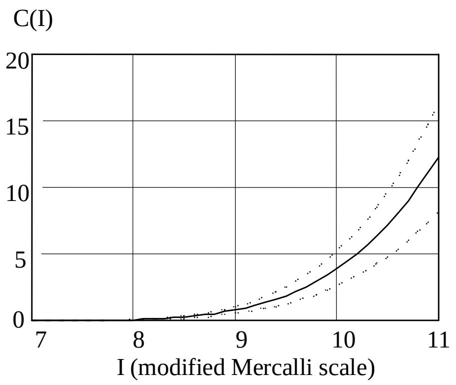

Fig. 3 Casualties as a percentage of population.

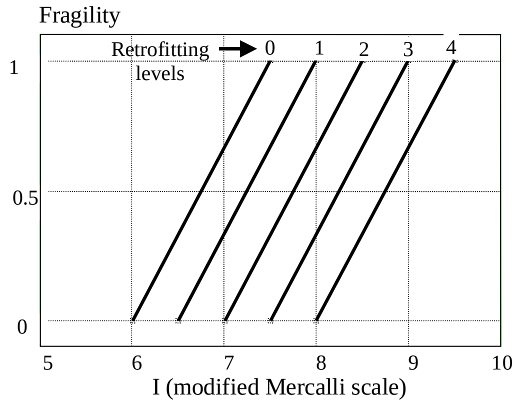

Fig. 4 Assumed damage curves.

Finally, both the ratio of casualties $\bar{C}(I)$ and the damage to hospitals are introduced in the analysis as lognormal random variables (r.v.), with the mean value modeled in terms of earthquake intensity as above defined and the c.o.v. equal to 15%.

C. Earthquake generation

Earthquakes are generated by adopting the classical Cornell model, with diffused seismicity [16, 17, 18]. Within the southern Italy seismogenic areas, provided by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) [19, 20], the ones reported in Fig. 5, involving the Calabria region, are taken into account.

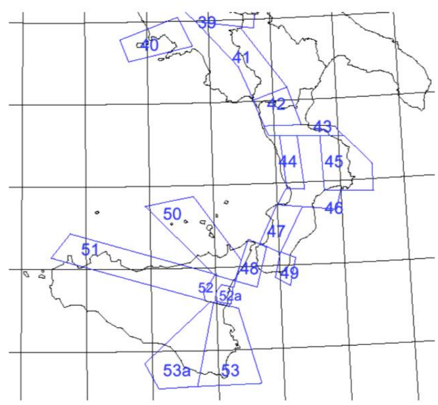

Fig. 5 Seismogenic areas.

The proposed study deals with scenarios analyses. The considered scenarios are shown in Fig. 6 and Table 3.

For each scenario, the earthquake epicenter is localized in the barycenter of the associated seismogenic area.

Earthquake intensity away from the epicenter is decreased with a simplified circular attenuation law, having general value:

$$\Delta I_s(R) = a + b \cdot (R + R_o) + c \cdot \log(R + R_o) + \varepsilon \tag{2}$$

with parameters: $R_0 = 3$ Km; $a = -0.5$; b=4.43; c=0.056; $\varepsilon =$N $(0; \sigma_{\varepsilon} = 1.037)$.

The parameters have been calibrated using registration of events in southern Italy, as in [11]. In the following, the results concerning the most interesting scenarios will be illustrated, that is the highest impact ones from a social standpoint, involving the major number of cities.

Number	MM intensity	Seismogenic area	ID
1	8	43 (Rossano)	08_43
2	11	43 (Rossano)	11_43
3	8	46 (Lamezia)	08_46
4	11	46 (Lamezia)	11_46
5	8	48 (Reggio)	08_48
6	11	48 (Reggio)	11_48
7	8	49 (Locri)	08_49
8	11	49 (Locri)	11_49

Table 3 Parameters of the scenario analyses.

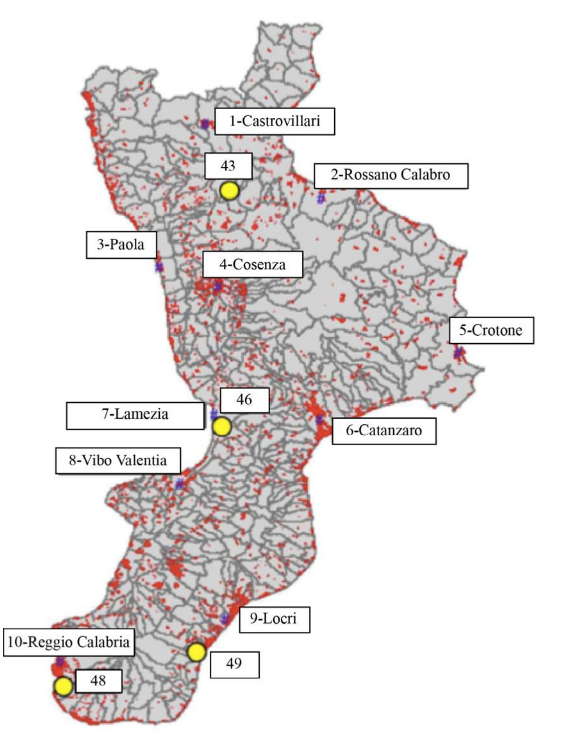

Fig. 6 Position of the epicenters in the scenario analyses.

D. Road network model

The road network modeled within this study, extrapolated by the Calabria region database, is shown in Figure 7a. It is classified into four types: *i*) highways, *ii*) state roads, *iii*) province roads, *iv*) municipality roads. In normal situations (i.e. no earthquake), or if the earthquake local intensity is below 6.5 MMI, the average traveling speed is taken respectively equal to 75, 60, 45, 30 km/h. These values are rather low since, in the Calabria region, mountain and dismal roads are highly spreading.

When the local earthquake intensity exceeds 9 MMI, the road stretch is assumed fully damaged (referring to damage at the infrastructure), and the traveling speed is set equal to zero. Vehicles must then travel through an alternative route. For MMI values between 6.5 and 9, the simplified hypothesis of linear traveling-speed variation is assumed (Fig. 7b).

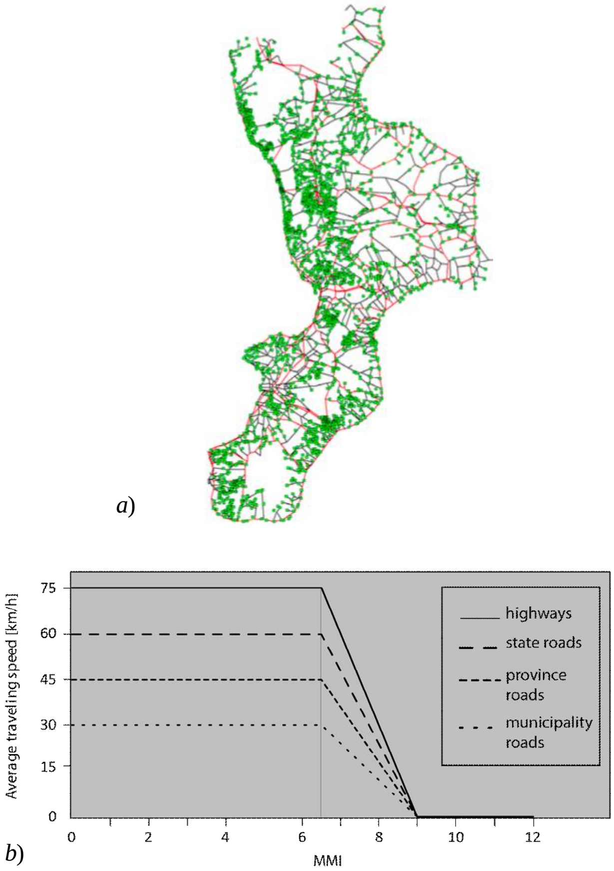

Fig. 7 Considered road network.

E. Numerical simulation procedure

The statistical properties of the performance index time taken by each casualty have been computed by the numerical simulation procedure (Montecarlo scheme) summarized in the flow-chart reported in Fig. 8.

The listed steps are relative to Montecarlo full probabilistic analyses [21], performed by a specific algorithm elaborated in Matlab. For the scenario analyses depicted in Fig. 6 and Table 3, whose results are the object of this paper, at step 1 both earthquake position and intensity are known [22, 23]. The main hospitals existing in the Calabria region have been included in the simulations (10 hospitals, listed in Table 2).

For each seismogenic area, simulations are repeated until the c.o.v. $\hat{\delta}_m$ of the mean value of the performance index "time taken by each casualty", defined as follows,

$$\hat{\delta}_m = \frac{1}{\sqrt{N}} \cdot \frac{\hat{\sigma}}{\hat{\mu}}; \qquad \hat{\mu} = m = \frac{\sum_{i=1}^{N} x_i}{N}; \qquad (3)$$

$$\hat{\sigma} = s = \sqrt{\frac{1}{N-1} \cdot \left(\sum_{i=1}^{N} x_i^2 - N \cdot m^2 \right)}$$

reaches the value 10%. This limitation allows to obtain acceptable computational times. In fact on average the above value is achieved after 2000 simulations, with consequent computational times equal to about 1-2 hours.

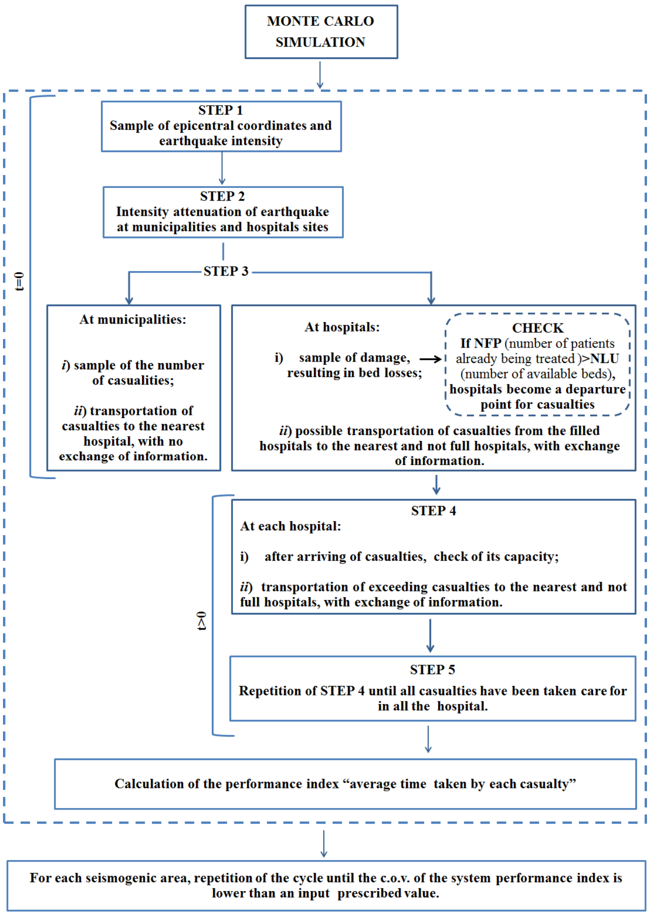

Fig. 8 Flow-chart of Monte Carlo simulation.

IV. ANALYSIS RESULTS

Results are here shown for the time taken by each casualty index in a two-fold fashion: (*i*) iso-value maps; (*ii*) cumulative distribution functions (CDF).

Firstly, in Fig. 9, the iso-chrone map of the Calabria region in the current state (i.e. no earthquake) is shown. Population on the coast, where most hospitals and roads are located, takes a short time to reach a hospital. The internal part of Calabria, less inhabited and with mountains, is in a worse situation. The results referring to the scenario analyses listed in Table 3 are instead summarized in Fig.s 10 to 18.

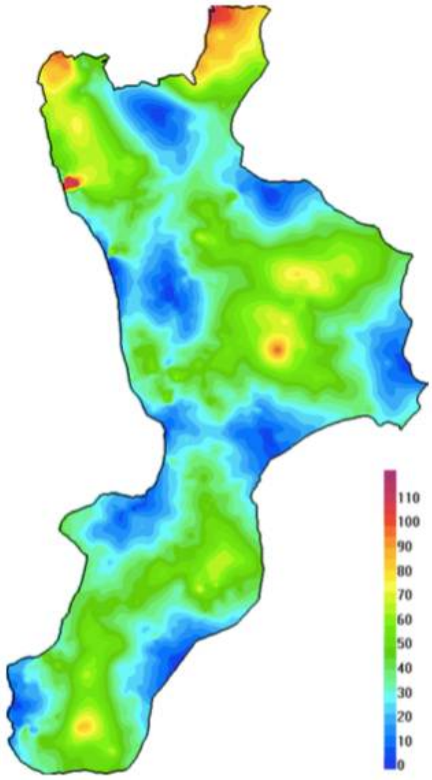

Fig. 9 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Current state.

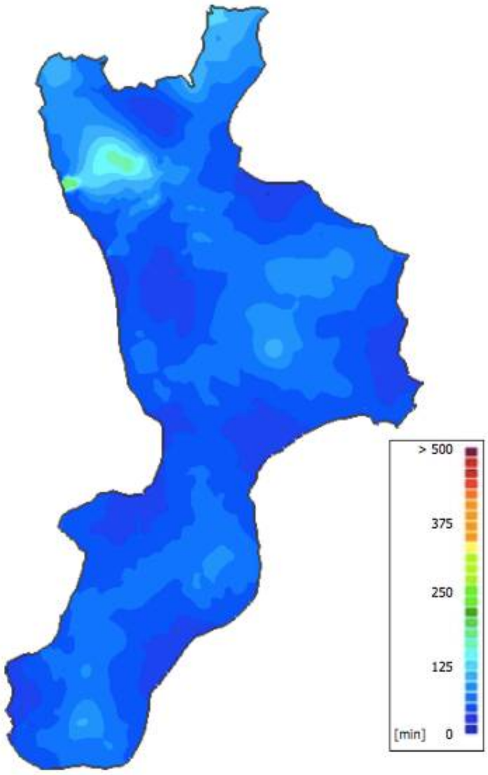

Fig. 10 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 43 (see Fig. 5). Intensity 8 MMI.

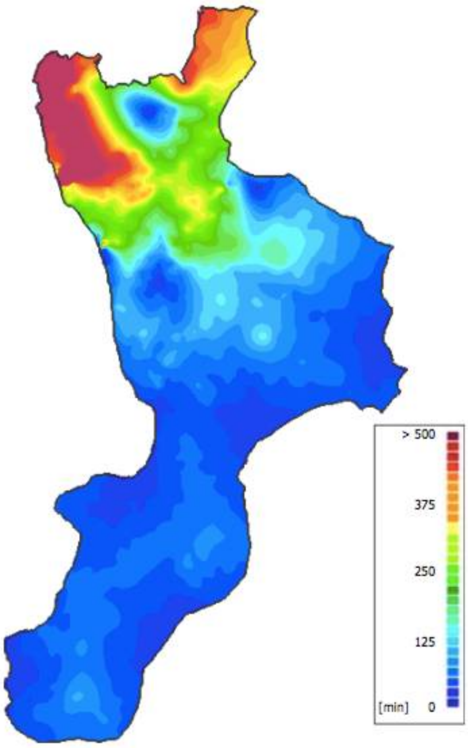

Fig. 11 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 43 (see Fig. 5). Intensity 11 MMI.

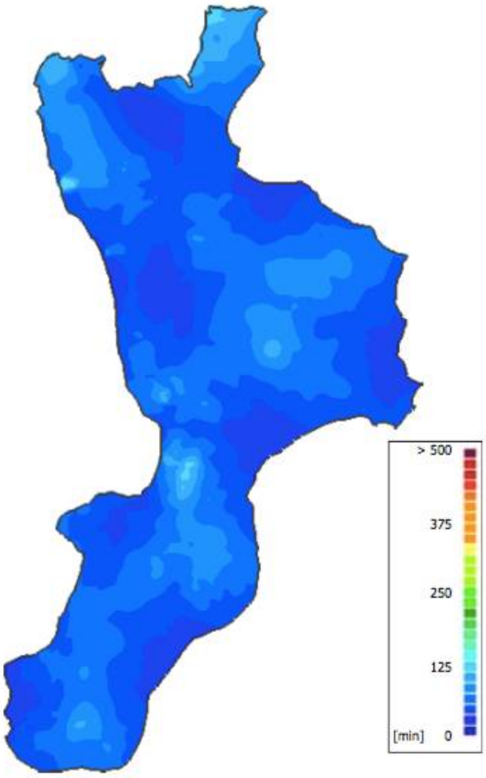

Fig. 12 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 46 (see Fig. 5). Intensity 8 MMI.

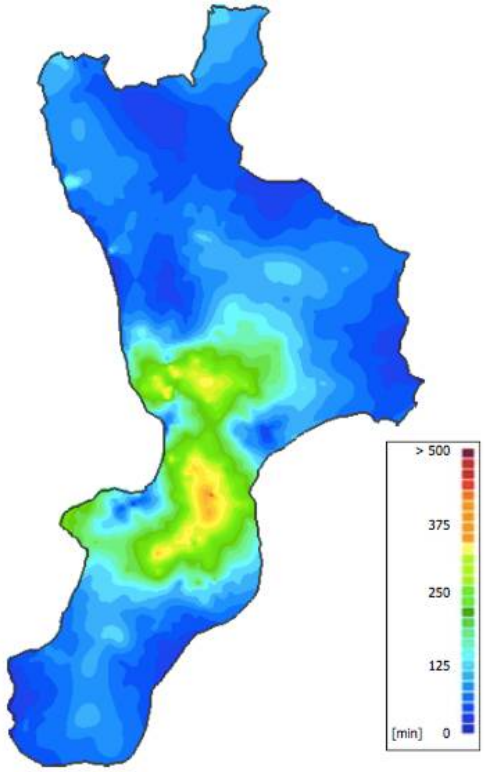

Fig. 13 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 46 (see Fig. 5). Intensity 11MMI.

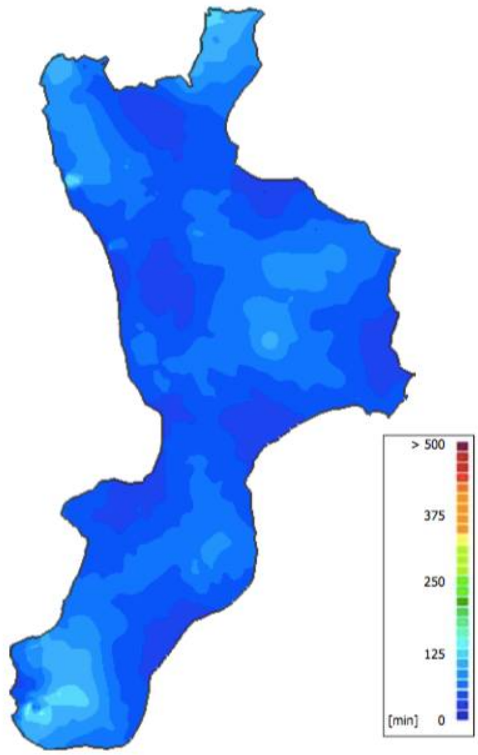

Fig. 14 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 48 (see Fig. 5). Intensity 8 MMI.

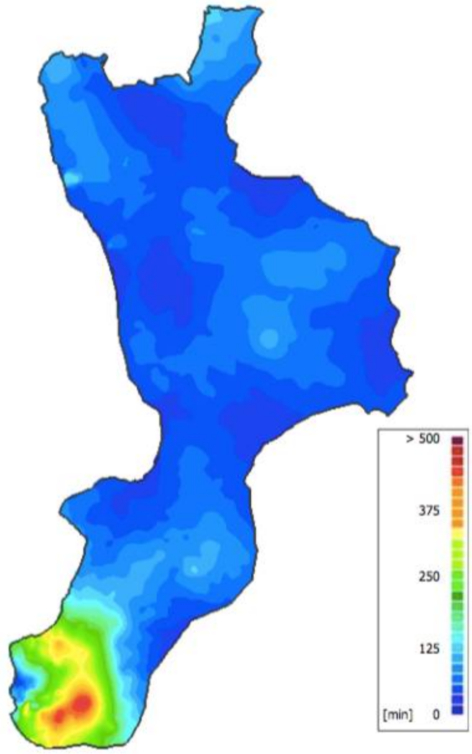

Fig. 15 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 48 (see Fig. 5). Intensity 11.

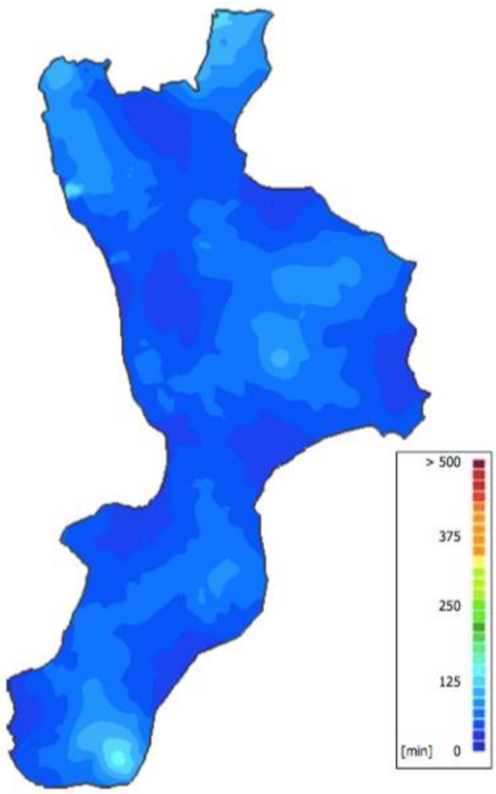

Fig. 16 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 49 (see Fig. 5). Intensity 8 MMI.

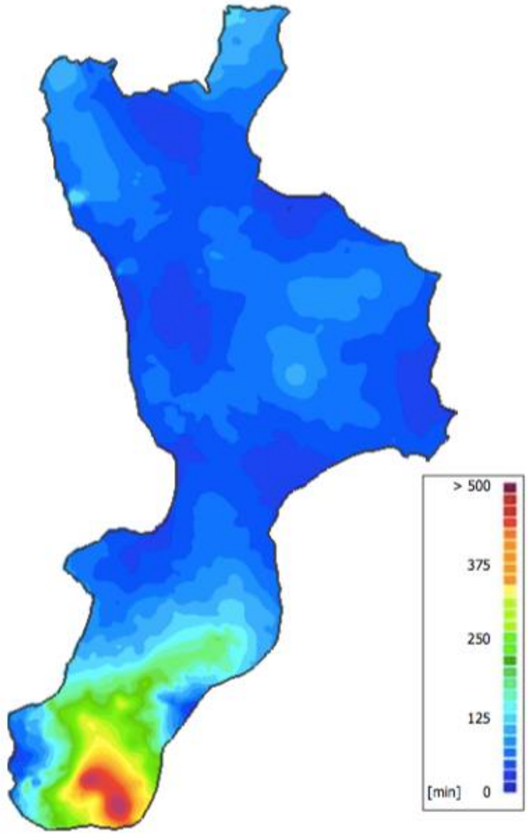

Fig. 17 Iso-chrone map for the *time taken by each casualty* index. Time is in min. Scenario analysis in seismogenic area 49 (see Fig. 5). Intensity 11 MMI.

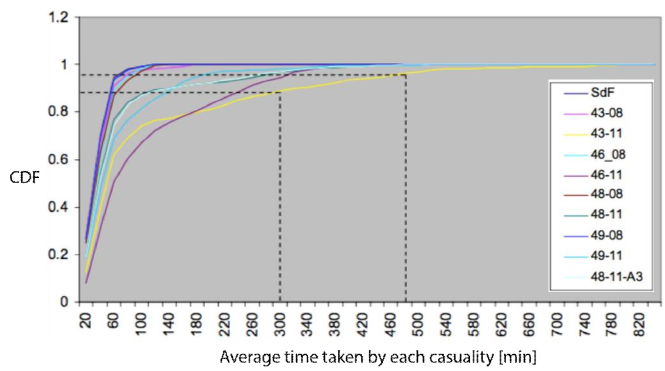

Fig. 18 CDF for the *time taken by each casualty* index. Time is in min. Scenario analyses in Fig. 5 vs current state (SDF).

It clearly emerges that there is a very strong worsening with scenario earthquakes with respect to current state. The average traveling times increase sensibly, reaching unacceptable values (more than 4 hours). The worst scenario is the one associated to seismogenic area 43 (MMI=11), in correspondence of which unacceptable traveling times involve a large area in proximity of Castrovillari urban centre. Other urban centres particularly vulnerable to seismic events in seismogenic areas 48 and 49, are Reggio Calabria and Locri. The performed analysis allows so to establish a priority order according to which road network and hospital system should be strengthened in order to increase seismic safety. At the aim to improve the regional emergency response, facilities and roads should be firstly strengthened in the Castrovillari, Reggio Calabria and Locri urban centres.

V. CONCLUSIONS

In this study a methodology for the evaluation of the seismic safety of road-hospital regional systems has been proposed. The traveling time that injured people have to cover to reach an unfilled hospital, has been employed as the main parameter to measure the efficiency of the system. The choice of the performance index represents a first novelty parameter with respect to former analyses. Moreover, differently from previous studies, attention has been focused on the Calabria Region and the real road network has been implemented in the analysis. The latter represents a major improvement, considerably increasing the analysis complexity but also allowing a more accurate simulation of post-earthquake emergency.

The main steps of the proposed methodology, carried out by Matlab numerical simulations, are: *i*) given a seismic event, the number of available beds is calculated for each hospital; *ii*) casualties leave from each municipality to the nearest not full hospital, up to its actual capacity; *iii*) the average time taken by each casualty to reach the nearest hospital is calculated.

Results show a current high vulnerability of the examined system, whose efficiency is obviously of dramatic importance in post-earthquake conditions. The performed analyses allow so to establish a priority order of hospitals and roads to be retrofitted. In particular Castrovillari, Reggio Calabria and Locri result the most vulnerable urban centres, where injured people would be significantly exposed to unacceptable traveling times to reach the nearest not full hospital. As a consequence these centres should be the first to be strengthened within the Calabria Region.

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