

Functional analysis of the urban road network in seismic emergencies. A GIS application on Catania city

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Abstract

Road infrastructures, as it is easily known because of the dramatic seismic experiences that have recently happened in California (Loma Prieta, 1989; Northridge, 1994) and in Japan (Kobe, 1995), assume a central role in the management of the emergency both in the phases that follow the disaster, in order to guarantee a timely reaching of the affected areas with first aid means, and in the “long period” for an optimal planning of repair and rebuild operations. Only after these disasters, a consolidated knowledge about the problem has been acquired; indeed, a large number of studies on the evaluation of seismic risk have been started also taking into account the fundamental role of the road network, mainly according to the problems of direct and indirect seismic exposure. Nevertheless, the majority of these studies have developed on large rural areas, often neglecting the similar problems concerning the management of the emergency inside affected urban centres. In this paper these problems have been faced in order to provide an operative methodology to analyse and verify the reliability of urban road networks (Lifelines), so as to guarantee safe routes for timely access to the aid coming from outside. The proposed methodology finds as a natural applicative completion the most advanced GIS software functionalities, which represent not only a powerful instrument for filing and positioning the various data to be handled, but also advanced analysis and querying systems to support decisions (DDS). The entire procedure has been applied to a district of Catania city, obtaining important results which validate the proposed methodology.

1 Introduction

As is well-known, in the case of seismic events, road infrastructures assume a central role in the management of the emergency both in the phases that immediately follow the disaster, in order to guarantee timely access to the affected areas with first aid supplies, and in the “long period” for an optimal planning of repair and rebuild operations (AIPCR G2, 1996). The dramatic seismic experiences that have recently happened in California (Loma Prieta, 1989; Northridge, 1994) and in Japan (Kobe, 1995), proved that the induced damages (due, for example, to fire) caused by the delay in the relief operations through the inadequacy of the road network could be compared, regarding the cost, with the damages directly caused by the seism (Cooper and Vandepol, 1991). Resident population, indeed, is subjected to an indirect seismic exposure, or rather to damages originating from poor functioning of the road network and from the consequent delay in relief operations.

On the other hand, it is also important to take into account the direct exposure of the road users in addition to the “classic” one of the resident population. In effect, on road infrastructures are concentrated, for some time in a day, a large number of people exposed to risk, in the case of an earthquake, as well as the people inside the buildings. On this issue, it is necessary to keep in mind the earthquake in Loma Prieta, when the collapse of a few viaducts on the crowded Cypress Street caused the greatest part of the fatalities.

The consciousness of the importance of having a functional road network in emergency conditions, however, is quite recent both for the scientific community and for the state administrators as well as for public opinion. Only after these seismic experiences, has there started a large number of studies with the aim of providing suitable methodology for the evaluation of seismic risk concerning not only buildings but also the road network or at least part of it. So essential are these connections that have to be considered as “Lifelines”.

The most commonly used approach in these works is on a “little scale”, that is to say it consists in the examination of a large territory, considering the different urban centres exclusively such as origin or destination points to be reached by help using the “Lifeline” network (Cafiso *et al.*, 1999, 2001). According to this approach, it is disposed that every city is correctly linked to the extra-urban area from which aid is supposed to arrive, but it is usually neglected due to the broad complexity and extent of the urban area.

In this paper these problems have been faced by proposing a model for the evaluation of the functionality of the different branches of the urban road network in seismic emergency conditions. As a matter of fact, this study, articulated on different consequential phases in which proper analysis parameters have been defined and calculated, conduces both to the individuation of the safest routes to reach from outside of the strategic areas (equipped for the accumulation areas, or the shelter) inside the town and to the evaluation of the seismic risk on these routes. To confer to the proposed analysis methodology also a concrete experimental verification, the entire procedure has been applied

to a broad urban district of Catania city (Fig. 1), obtaining important results useful to support the redaction of an emergency communal plan.

2 Urban road networks in seismic emergency conditions

The issues that need to be faced, therefore, consist in the definition of the seismic risk on the routes of the urban viability that connect the external zone with the equipped areas inside the town, for accumulation or shelter. In this way it is possible to verify if the aforesaid routes, designated from now on as “Lifelines”, give not only an adequate functionality under ordinary conditions (mobility, access, penetration, etc.) but even can supply, in the post event phase, a minimal level of efficiency for the management of the critical moments of the emergency. With such an aim it is necessary that Lifelines satisfy opportune functional and structural requirements in order to grant first of all an adequate potentiality of access for the rescuers and, secondly, to decide on suitable routes for the management of the evacuation.

It must be emphasized that, in the case of a seismic event, the network of urban Lifelines must not be used for the private vehicular movements of the population, which, in a correct management of the emergency, must be excluded. The affected population, in fact, would have to reach, the nearest shelter or accumulation areas, on foot, to avoid overloading of the network (presumably already suffering from a reduced efficiency) and allowing its maximum exploitation by rescuers.

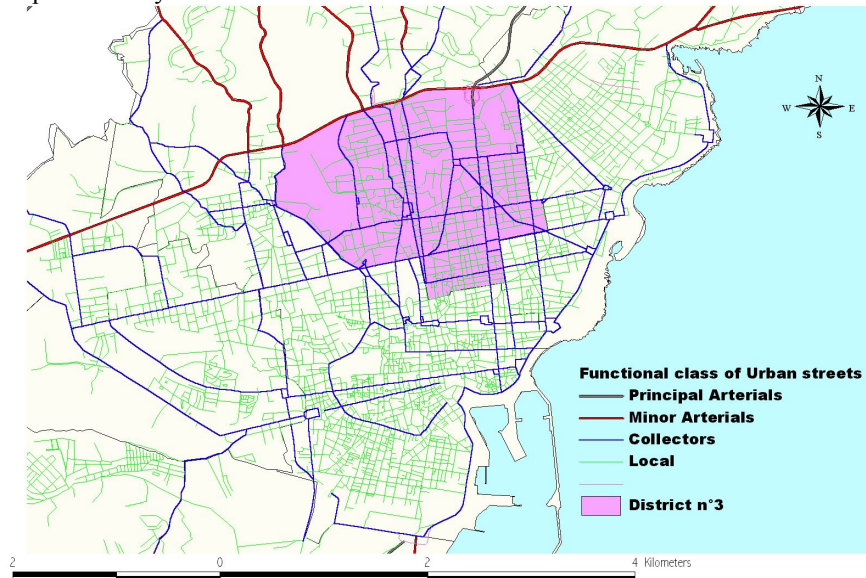


Figure 1. Area of interest

In the following sections we give a detailed description of the various phases of work, which can be led back fundamentally to the evaluation of the apposite indices of vulnerability and expected damage for roads and an analysis of the exposure of the population.

Because of the extreme complexity of the urban environment and the considerable size and heterogeneity of the data to be managed, it has been thought particularly useful, if not quite indispensable, to use the Geographic Informative System (GIS) knowing that it is not only a powerful instrument for the filing of the georeferenced data, but also of an evolved system for the analysis (D'Andrea *et al.*, 1996, 1997).

3 Evaluation of geometrical vulnerability index I_{vg} for roads

The evaluation of seismic risk R is usually defined as the aggregation (a) of the indicators of Hazard (H), Exposure (E) and Vulnerability (V) of the sections of Lifelines.

$$R = E \times H \times V \quad (a)$$

or with an analogous expression (b):

$$R = E \times D \quad (b)$$

with $D = H \times V$ damage of the element due to the earthquake. This evaluation can be the basis of the planning of interventions of anti-seismic retrofitting and definition of priority in relation to the available resources.

The term *seismic exposure* defines *the extension, the quantity, the quality of the different anthropic elements that make up the territorial context (population, buildings, system of infrastructures...) whose conditions and/or whose operation could be altered, modified in any way or damaged in a seismic event.*

Seismic hazard is defined as *the probability of occurrence of a seismic event of a specific intensity, in a definite area and in a definite period of time.*

Seismic vulnerability is *the propensity of an element, simple or complex, to suffer damage, collapse or modification during a seismic event.* As we know, seismic vulnerability is an intrinsic characteristic of each construction, that is independent from any kind of external factor. In the studies of seismic risk conducted on the rural road network the vulnerability is defined with respect to the traditional structural components of highway engineering: bridges; embankments; trenches; retaining wall and tunnels (I.G. Buckle & S.H. Kim, 1995; A.C. Zülfikar & Ö. Yüzügüllü, 1995; Cafiso *et al.*, 1999, 2001, 2003).

In an urban environment the problem must be faced in a different way, because, above all on the smaller practicability (collector and local streets) the previous structural elements are practically absent while the main crisis element of the functionality of the street derives by the collapse of the nearby buildings. The evaluation of the geometric vulnerability index (I_{vg}) is carried out on all the branches of the network, meaning by branch a road stretch of homogenous characteristics between two adjacent intersections and therefore lacking inner intersections. The definition of the road network graph on which the study had to

be executed, has been realized on the basis of a complete analysis of the urban practicability of the city of Catania. In particular, in functions of the length of the effectuated movements (long, medium or small distances), of the served urban scenery (city, district, buildings), of the typology of the movements (transit, approach, crossing) and of the geometric characteristics of the road sections to each branch of the city road network it has been attributed by one of these functional classes: Urban freeways (A), Urban arterials (D), Collectors streets (E), Local streets (F) [D.L. 05/11/2001].

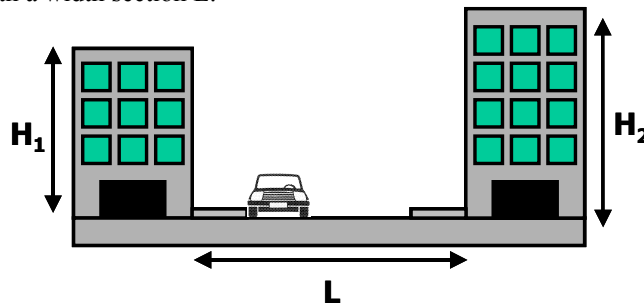
Considering the purposes of the research it has been thought useful to consider only the branches pertaining to the functional classes of urban arterials and of collector streets because they constitute the essential aspirations of the mobility of the means of aid coming from urban freeways and the rural network. Related to the branches of the local network, in this phase of the research, only the necessary ones have been considered for the final reaching of the destination nodes individuated in the equipped areas of accumulation and shelter already defined in the Communal Plan of Civil Protection of Catania.

It is possible to consider as origin-nodes either the service centres (hospitals, barracks...) in the urban areas that have to be activated immediately after the earthquake, or the principal nodes of the urban minor arterial or collector network directly connected to the urban freeway viability (A), or rural network, that supply the connection to the external territory from where the greatest help, in the following hours and days, will arrive.

The geometric vulnerability index (I_{vg}) is defined on the basis of the free width of the road and on the sum of the heights of two facing the branch buildings:

$$I_{vg} = \min[L - (H_1 + H_2)] \quad (1)$$

where H_1 and H_2 represent the maximum height of the buildings facing the branch with a width section L .



The I_{vg} index is, from a dimensional point of view, a length, but it represents for each branch an indicator of the residual space that is useful for the means of access in the simplified (and pessimistic) hypothesis of a model of damage of the buildings consisting in a total “upsetting” of the buildings themselves onto the road section. In this sense, we propose a scheme for the classification of the I_{vg} indices, assuming 5 m as the minimal residual width that doesn’t influence the transit of the means of aid and 2.5 m as the minimal gate in order to physically concur with the transit.

Table 1. Evaluation of the classes for geometric vulnerability index Ivg

Ivg values	$Ivg > 5$	$2.5 < Ivg \leq 5$	$Ivg \leq 2.5$
Vulnerability	No vulnerability	Low	High

Using the relation (1) the Ivg index is calculated and assigned to the different branches of the network on the basis of the data for the width (L) and the height of the buildings facing the branch itself (H1, H2) filed in the GIS (Figs.2/3/4).

The results obtained in the studied area (Fig. 4) show a concerned high geometric vulnerability of the road section due to an inadequate and not with anti-seismic finalities urban system: most parts of the roads, indeed, are characterized by modest widths but above all they are placed among buildings of relevant heights.

Because the basic cartography of the GIS is derived from a scaled 1:2000 aerophotogrammetry, on the basis of which the polygonal theme for buildings and the linear one for the road network have been defined, using the “buffer” function of the GIS, it is possible to carry out a “quick” evaluation of the value classes for Ivg. Analysing the intersections between the buildings buffer (carried out using the height parameter) and the road axis buffer (carried out using the values of 5 m and 2.5 m) it is possible to individuate the branches characterized by the different classes of Ivg (Fig. 5).

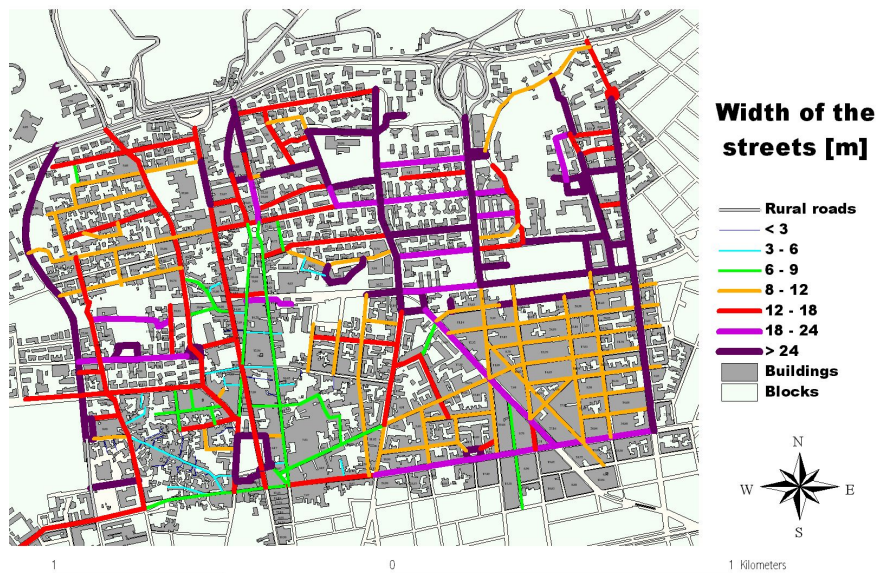


Figure 2. Thematic map of the width of the urban streets

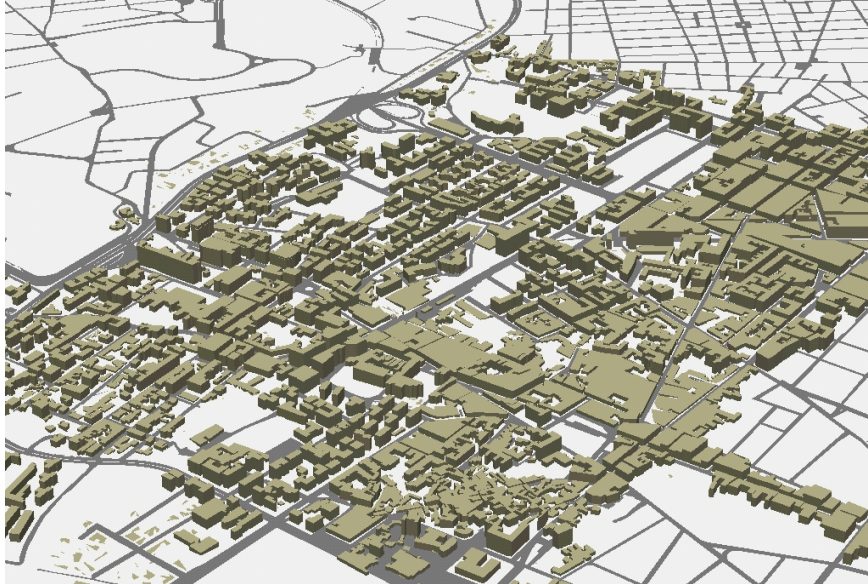


Figure 3. 3-D representation of the height of the buildings

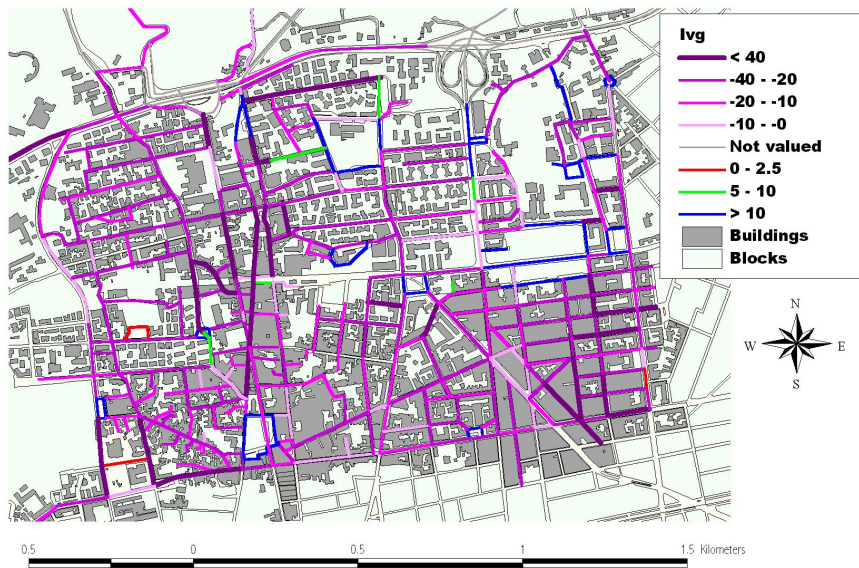


Figure 4. Thematic map about the geometric vulnerability index (Ivg)

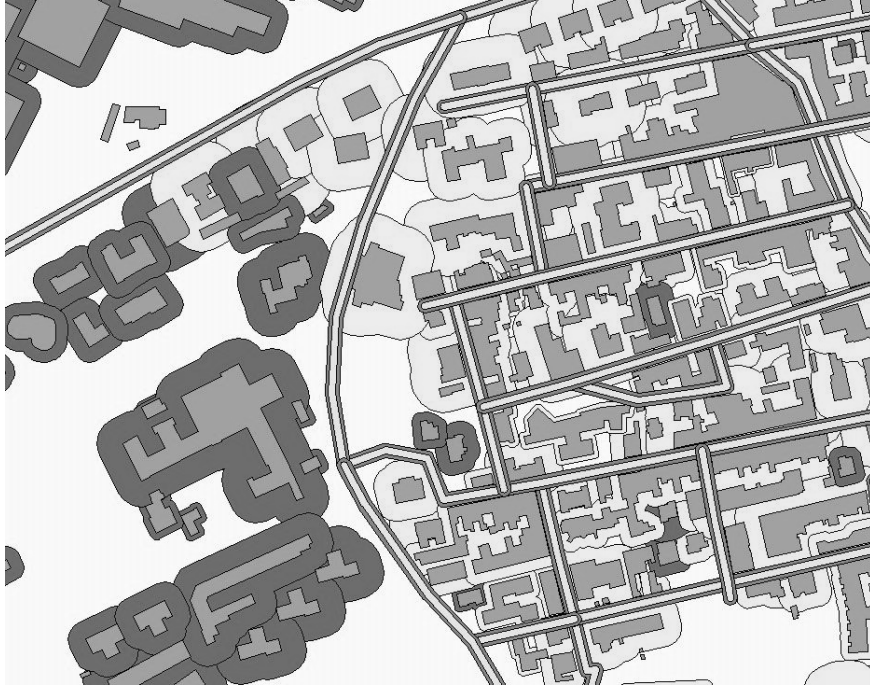


Figure 5. Thematic overlay between building buffers and road axis buffers (2.5 m axis buffer = light grey; 5 m axis buffer = grey; intersecting building buffer = very light grey; non-intersecting building buffer = dark grey)

4 Evaluation of global damage index I_{dg} for road

The propensity of roads to damage and the possibility of maintaining its functionality after a seismic event must be evaluated both on the basis of the geometrical characteristics of the street section and on the expected damage due to the earthquake for the buildings facing the street. In this work, for this purpose, two GRID themes, related to the index of the damage expected for buildings, have been elaborated. In particular, using apposite indices of damage for buildings (I_{de}) in Fig. 6 it is represented as an “*Urban centre masonry buildings’ damages detailed distribution*”, while in Fig. 7 it is represented as “*reinforced concrete buildings’ built surface (in each census tract) subjected to heavy damage or collapse*” caused by a scenario earthquake with a return period of 475 years (Faccioli *at al.*, 2000). Using the acquired data, for every branch of the analyzed network, the “index for the global damage of roads” (I_{dg}) has been defined, by the relation:

$$I_{dg} = \min[L - (I_{de1} \cdot H1 + I_{de2} \cdot H2)] \quad (2)$$

where Ide represents the “edifice damage Index” related by Table 2 to the different damage classes carried out by the GNDT (National Defence from Earthquakes Group) for the area under study (Fig. 6/7).

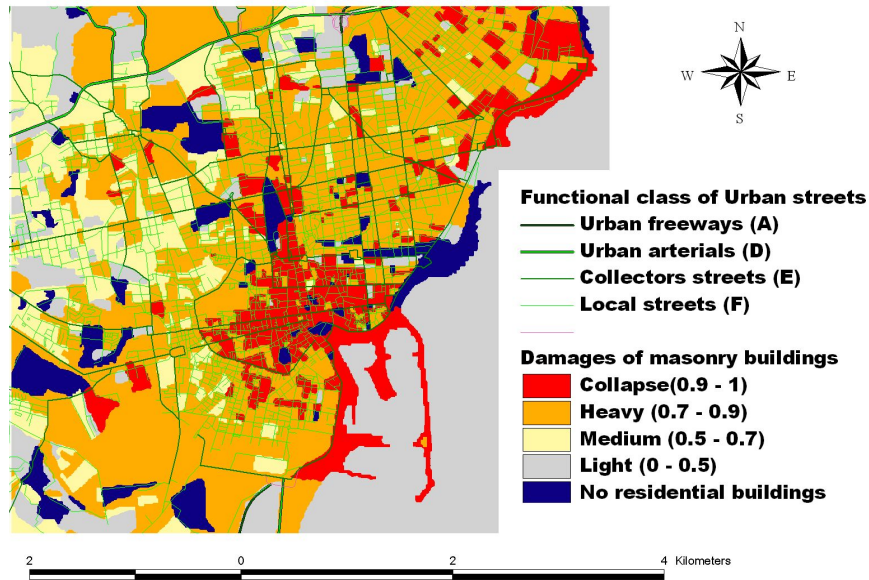


Figure 6. Masonry buildings: damage classes

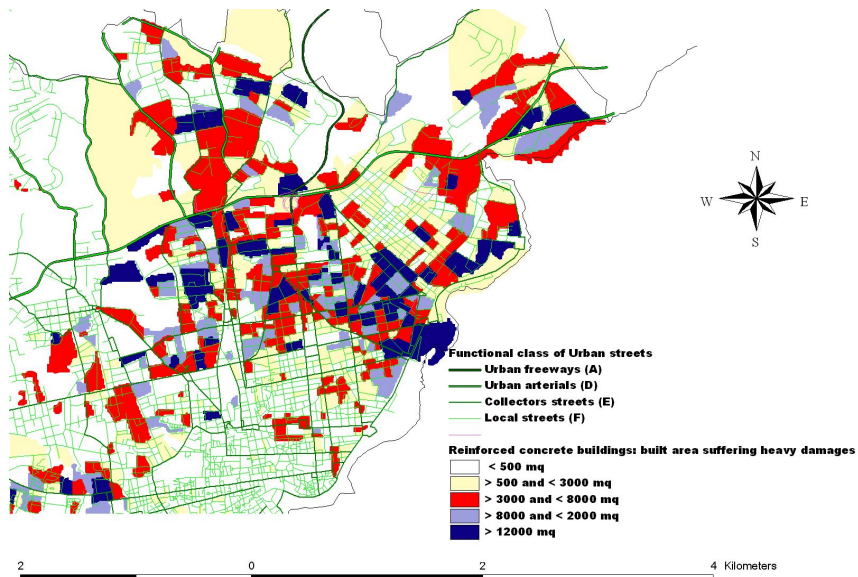


Figure 7. Reinforced concrete buildings: built-up area suffering heavy damage

Global damage index I_{dg} of road branches (Fig. 8) represents the completion of the concept of the geometrical vulnerability index I_{vg} in order to consider both the structural characteristics for seismic resistance of roadside buildings and the hazards of the site. For this reason it is possible to associate to each branch of the road one of the damage classes (Fig. 9) on the basis of the vulnerability class I_{vg} and of the value of the global damage index I_{dg} (Fig. 8) by the damage matrix of Table 3.

Table 2. Evaluation of damage indices for buildings (I_{de} = edifice damage Index)

Damage classes (GNDT)	1 No damage	2 (light)	3 (medium)	4 (heavy)	5 (collapse)
Coeff. I_{de}	0	0.2	0.5	0.7	1

Table 3. Evaluation of Global Damage Index classes for roads

I_{vg}	$I_{vg} > 5$	$2.5 < I_{vg} \leq 5$		$I_{vg} \leq 2.5$	
I_{dg}	Every	$I_{dg} > 7$	$I_{dg} \leq 7$	$I_{dg} > 5$	$I_{dg} \leq 5$
Damage classes	No damage 0	Low 1	Medium 2	Heavy 5	Very heavy 10



Figure 8. Thematic map about Global Damage Index (I_{dg})

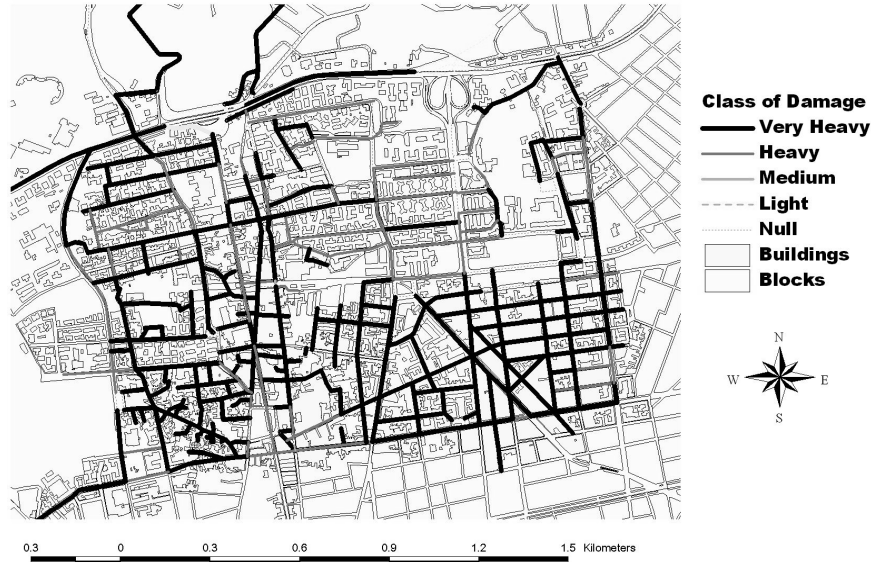


Figure 9. Thematic map about class of Global Damage Index (Idg)

5 Exposure analysis

The principal object of the exposure analysis is to quantify the number of people who can be affected by the earthquake either directly (road users injured or killed by the collapses) or indirectly (delay of help due to a malfunctioning of the road network). The two cases need different approaches, so it is necessary to examine them separately.

5.1 Direct exposure analysis

Direct exposure is determined by the users who are on the road network and who can be directly involved by the damage or the collapse of the road facing buildings or, eventually, of the structural elements of road infrastructures (bridges, tunnels, retaining walls...). To give an evaluation of the direct exposure it isn't possible to use the parameter of the resident population because it is necessary to take into account the presence of the people on the road considering the population as a dynamic entity on the studied area. Supposing an average value of people for each vehicle, it is possible to estimate the number present on the street using suitably known parameters of traffic such as, for example, the average daily traffic (ADT) or the hourly traffic flow. In Fig.10, for example, is shown a thematic map of the traffic flows on the urban road network of Catania during the traffic peak hour, from 8 to 9 a.m. Using an average traffic parameter as ADT it is possible to refer to meaningful information about an entire day.

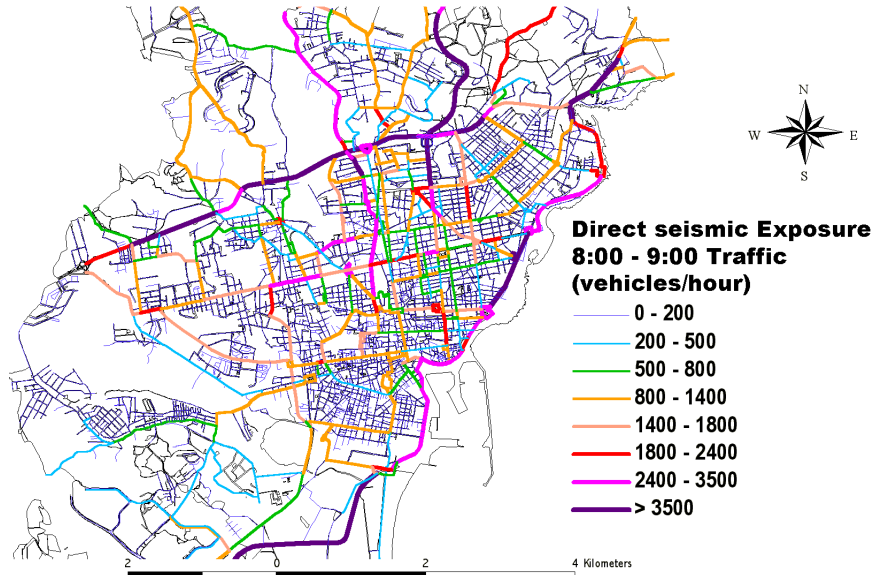


Figure 10. Direct seismic exposure: map of traffic flows (8:00 a.m. - 9:00 a.m.)

5.2 Indirect exposure analysis

Indirect exposure analysis aims at evaluating the earthquake effects not during but after the event. It is necessary to evaluate the consequences that the population can suffer from the quake because of the delay of aid operations due to a breakdown of the road network. The object of study is always the population, but, in this case, it is necessary to consider all the resident population and their related distribution on the territory that, in the hypothesis of this paper, has been considered distributed in the planned areas of the Emergency Plan of Comune di Catania (Fig. 11). In particular, the plan defines: *Equipped areas*, arranged for the preparation of the structures and of the means of emergency; *Shelter areas*, for assistance to the population; *Accumulation areas*, “safe” places that people who don’t need any immediate assistance would have to reach, to avoid subsequent seismic aftershocks. Besides, as has been said before, all these points represent the destination nodes of the network.



Figure 11. Position of emergency areas and resident population in census tract

The number of the population that could gather in each emergency area has been calculated using a “proximity analysis” giving the resident population in the nearest area. In the application in the ArcView® environment it is used as function of the Spatial Analyst module that needs the presence of a GRID theme in which each cell is featured by the value of the present population density. Considering the apposite barycentre point of the emergency areas (Destinations), the “proximity assignation” function associates to each point a determined number of cells that for proximity are related to the same point. The group of cells referred to the same point constitutes a new polygon whose population gravitates to the correlated emergency area. To obtain the total of people who gravitate to a determined emergency area, when the polygon is known, it is sufficient to calculate its area and multiply it for the values of density in the cells.

To do an evaluation of the risk related to the Lifelines it is necessary to associate this population (Exposition, E) to the different branches of the network for whom a value of damage (D) has already been defined .

For the last phase of the indirect exposition analysis process we have used a function of the Network Analyst module for the research of optimal access routes to the emergency areas. It is possible to effect this research on the basis of different “cost functions” relative to each branch of the studied network:

- the length of the branches;
- the damage class (Idg) of the branches;
- the product between the length and the damage class (Idg) of the branches.

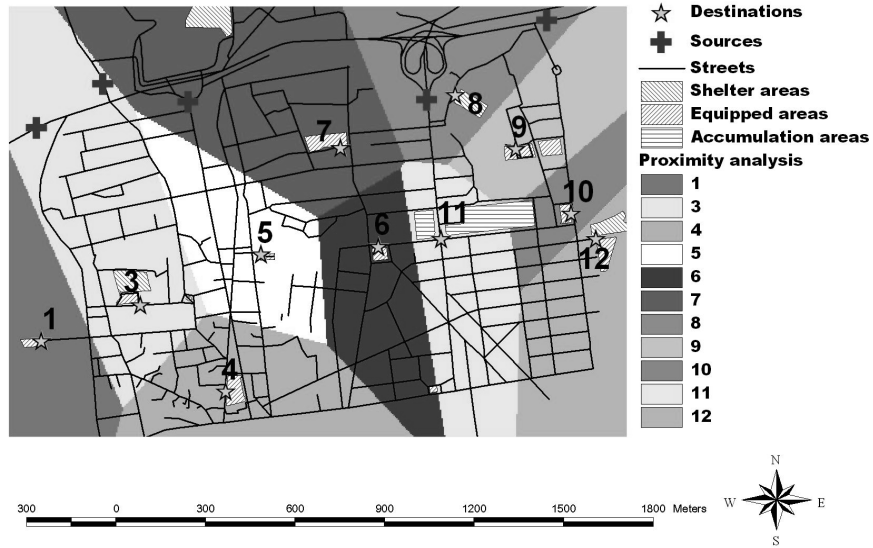


Figure 12. Results of assign proximity analysis

The network analysis, finds different routes that minimize the costs on the basis of the different cost functions. With the aim to operate the best choice between the different selected routes, three efficiency factors (Fe) of the route have been appositely defined:

$$Fe1 = \frac{L}{L \min} \quad (3)$$

$$Fe2 = \frac{Idg}{Idg \min} \quad (4)$$

$$Fe3 = \frac{(L \times Idg)}{(L \times Idg) \min} \quad (5)$$

These efficiency factors constitute a valid support for decisions because they allow a quick and effective comparison among possible alternatives. Even if the most balanced way to operate privileges is one of these three criteria, it can't avoid considering the other two. For instance, route A, on the basis of the cost functions "branches' damage class index", is supposed to suffer a global damage of 37. Route B, conversely, suffers a global damage of 39, but it is optimal on the basis of the cost functions of length. If route B is sensibly shorter than route A, probably the optimal choice would have to be addressed to route B. Therefore, an accurate analysis of the efficiency factors of the various obtained routes suggests, time by time, which has to be considered the best solution. In particular the situation proposes equivalent alternatives:

- $L(a) = 738.50$ m; $Idg(a) = 32$; $Fe1(a) = 1.289$; $Fe2(a) = 1$; $Fe3(a) = 1$;
- $L(b) = 572.70$ m; $Idg(b) = 37$; $Fe1(b) = 1$; $Fe2(b) = 1.1156$; $Fe3(b) = 1.1159$.

When the optimal routes have been individualized for all the O/D (Origin/Destination) links it is possible to pass onto the conclusive phase of the process of analysis of indirect exposure. We proceed by associating to each branch of a route the data of populations served by one of the links. In case a branch belongs to more than one O/D route, the summary of the various data of populations served by the various links is associated to it. Indirect seismic exposure is incapacitation because of the malfunctioning of one of the routes. In Fig. 14 a thematic paper is represented, showing the obtained values of exposure distinguished in five classes.

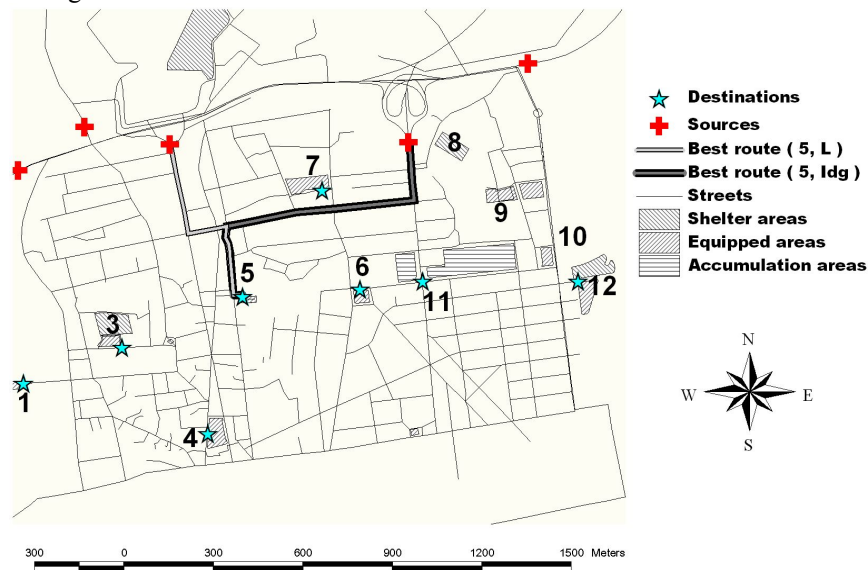


Figure 13. Best route selection by efficiency factors (L=Length; Idg)

6 Conclusions

In this paper we proposed a methodology for a functional analysis of an urban road network in seismic emergency conditions. Apposite indices to value the intrinsic vulnerability and the expected damage for each road branch have been defined, considering even the structural vulnerability of the road side buildings. Also, specific procedures to value direct and indirect exposure have been carried out. It has been noted that from the knowledge of damage and exposure it is simple to quantify the risk along the selected routes O/D. From a “dimensional” point of view it would be sufficient to operate a sort of “product” between the global damage indices of different routes and the indirect exposure (to obtain the indirect risk) or the direct exposure (to obtain the direct risk). The proposed methodology, based on the use of the most evolved functionalities of the GIS software in commerce today, has been applied to a wide urban district in the city of Catania and the first experiences have given some results that could be considered meaningful.

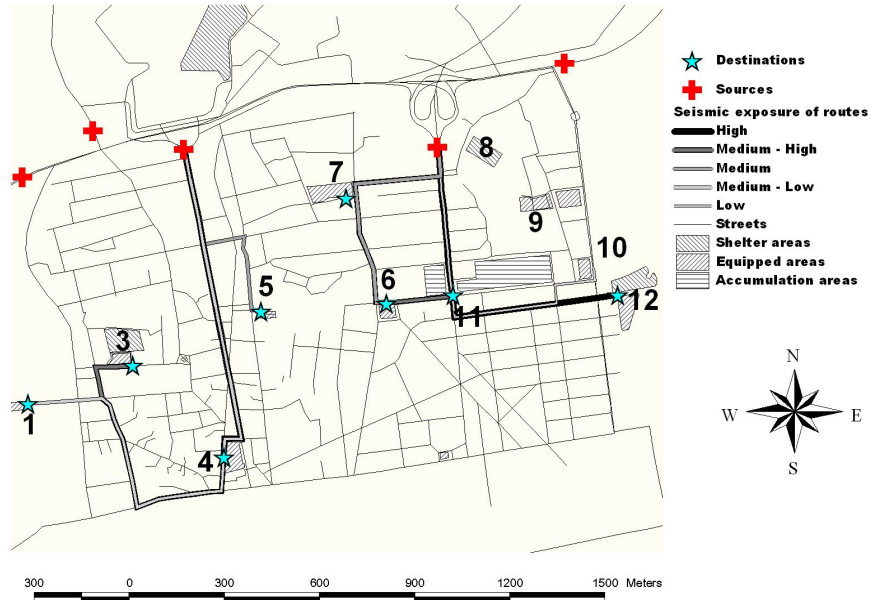


Figure 14. Indirect seismic exposure of the selected routes

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