Assessing Urban Road Network Seismic Vulnerability: An Integrated Approach

Gonçalo Caiado
Instituto Superior Técnico

Carlos Oliveira
Instituto Superior Técnico

Mónica Amaral Ferreira
Instituto Superior Técnico

Francisco Sá
Instituto Superior Técnico

SUMMARY:
Transportation infrastructures are considered by some authors as the most important lifeline system, largely because damage to it inhibits interventions on housing and other lifeline systems. Typically, when planning or managing urban road networks, seismic risk concerns have been tackled exclusively through a structural link-by-link approach. This conservative procedure focuses on infrastructure construction requirements but fails to capture network related issues (such as connectivity redundancy to essential facilities). In this context, the proposed paper aims at presenting an innovative methodology focusing on strengthening urban network resiliency in seismic scenarios based on three main dimensions: **i)** network connectivity; **ii)** land use, and; **iii)** specific transportation demand patterns. Furthermore, potential applications of this work include urban planning micro and macro scale solutions to be included in specific instruments (including, among others, urban planning instruments and policies; urban master plans; renewal policies; emergency plans and protection of critical mobility assets programs).

Keywords: Road, Network, Vulnerability

1. INTRODUCTION

Past experience shows that strong earthquakes cause a tremendous impact in terms of both material damages and human losses. While the majority of these losses occur during - or shortly after - the quake, it is recognized that a significant proportion of human losses also take place in the following hours or days. Those post collapse losses can happen either by lack of intervention capacity (owing to limited emergency response resources) or by the inability to reach critical locations (due to blockage situations). The latter will be the focus of our work.

Particularly, the underlying hypothesis of the current research work is that the impacts on the performance of road transport infra-structures for emergency response functions can be minimized when facing a major earthquake, namely by the introduction of measures, not only in terms of infra-structural reinforcement but also in terms of network connectivity and activities location. Therefore the focus of this research effort is on ex-ante interventions and, ultimately, it will contribute to ensure the maintenance of road network emergency response functions in case of earthquake. Potential applications of this work include urban planning micro and macro scale solutions to be included in specific instruments (including, among others, urban planning instruments and policies; urban master plans; renewal policies; emergency plans and protection of critical mobility assets programs).

This paper aims at presenting a methodology focusing on strengthening urban road network resiliency in seismic scenarios based on three main dimensions: **i)** network connectivity; **ii)** land use, and; **iii)** demand pattern.

The first proposed dimension - connectivity - introduces the network perspective or origin - destination paths redundancy (for example, it should be critical to reduce the closure probability of a link which, not having alternative routes, has the potential to isolate a street or a small city quarter). Secondly, the land-use dimension refers to critical functions accessibility in earthquake scenarios (such as hospitals, schools, fire-departments, etc.). In this sense, it should be urgent to strengthen the vulnerability of a link which, for example, allows access to a major hospital. Finally, demand patterns refer to specific patterns which are induced by a large quake (such as emergency vehicles using wrong way streets due to road closures). Therefore, it is important to analyse network performance from a critical origin-destination paths operability perspective (instead of a conventional volume/ capacity perspective) taking into account the induced specific demand patterns and network operability.

2. CONTEXT

This work was built on the basis of the existing knowledge in each of the following related domains: **i)** seismic risk management and urban planning; **ii)** risk assessment and loss estimation, and; **iii)** road network vulnerability studies and applications. A brief resume of the main findings from the literature review carried out in each of the above mentioned domains is presented in this section.

2.1. Seismic Risk Management and Urban Planning

Even though land-use techniques and other planning related measures should be included in a strategy to cope with disaster risk mitigation in urban areas, in practice, they are still neglected in many local planning processes and management procedures of cities around the world.

For example, a common argument in post disaster studies is the establishment of a high correlation between population density and both human and material losses caused by disasters. When cross analyzing the deadliest recorded earthquakes with its magnitude, McDonald (2003, pp 28 - 29) affirms that loss of life is linked to the density of population on the particular location more than the magnitude of the earthquake.

Moreover, the broad implications of controlling population densities, unavoidably invoke the wider discussion regarding urban form and structures. In what concerns mobility, the concept of the compact city has been argued as more efficient. However - and although the issue of disaster risk mitigation has not yet been included in the urban form debate - it is also obvious that a transport network in a compact city operates closer to its capacity, therefore has greater difficulty to cope with unscheduled events.

2.2. Risk Assessment and Loss Estimation

Belonging to the United States Department of Homeland Security, the Federal Emergency Management Agency (FEMA) has developed a risk assessment software program (HAZUS) for analyzing potential losses from floods, hurricane winds and earthquakes, before, or after, a disaster occurs. However, in the case of earthquakes, interdependence of components on overall system functionality is not addressed by the methodology. According to the source (FEMA 2003, pp 7-3), such considerations require a network system analysis that would be performed separately by a highway system expert.

2.3. Road Network Vulnerability Studies and Applications

Since the Hanshin-Awaji earthquake in 1995, transport network vulnerability has emerged as a new research topic (Murray 2007, pp 10 - 12) and "subsequent research was directed at degraded networks, usually urban road networks subject to traffic congestion, in which the network remained physically intact but the performance of one or more links could be so severely affected by congestion that their use by traffic is curtailed". It is important to note that being a relatively recent topic, there is still no theoretical basis on which to build nor a standard definition of vulnerability, and the meaning of this concept may depend on the context (Jenelius 2005, pp 539).

3. URBAN ROAD NETWORK VULNERABILITY ASSESSMENT

The focus of the proposed model is the measurement of potential impacts on road transport infra-structures performance in earthquake scenarios. These impacts are particularly detrimental for emergency response functions; not only because the first days following a large earthquake are critical for this type of functions, but also because available resources are usually insufficient to cope with all occurrences. According to the research carried out by (Macintyre 2006), based on an extensive effort of earthquake data collection, trapped victims generated by structural collapses from earthquakes, infrequently survive more than 4 days. In countries with limited resources to search and rescue activities, timing is especially important for allocating those resources.

In parallel, past experience shows that, during an earthquake, roads are subject to both direct and indirect damages. The nature of the predominant damages is different for distinct types of roads; for instance, regional roads seem to be more prone to direct damages, while indirect damages are a major source of inaccessibility in urban roads. According to (Argyroudis 2003, pp 5) direct damages in roads are more often caused by: **i)** ground failure due to subsidence and cracking of pavements (caused by lateral spreading or settlement of soils liquefaction); **ii)** sliding of embankments and slopes due to landslides, or; **iii)** surface fault rupture. As for indirect damages, road closures are due to: **i)** fallen obstacles such as debris from collapsed buildings or other structures such as overpasses, or; **ii)** damages caused by other lifelines (e.g.: gas or water distribution network). Within urban areas both types of indirect damages are major inaccessibility sources.

The ongoing research includes not only a theoretical framework development for assessing road network seismic vulnerability but also an application of this framework to a case study. The latter consists in a relatively small area within the Lisbon city with approximately 683 thousand square meters (occupying approximately 25% of the *São Domingos de Benfica* parish). The motivation to choose a small area has to do not only with the performance of the algorithms (in terms of computational time) but mainly with the necessity to collect detailed information concerning the system components to be analyzed.

3.1. Road Links Vulnerability Assessment

The main output of the first module will be a closure probability for each individual link (obtained from the combined vulnerability of the several urban components that, if damaged, may block those links). As a reasonable balance between reality representation and model applicability two sources of road closures are modelled: **i)** debris from collapsed buildings, and; **ii)** damages in pavements (there are no bridges or tunnels in the study area).

In what concerns buildings vulnerability, the assessment method was adapted from (Giovinazzi 2002). This methodology is based on the Damage Probability Matrix method (which is a statistical correlation between the macro seismic intensity and the apparent damage described in terms of damage grades). This is a typological model, as it considers that buildings of the same type behave in a similar way. Aspects such as construction date; buildings height; conservation state; structural complexity and type of soil allowed determining the probability of each building suffering level 4 (very heavy) or 5 (destruction) damage grades in the European Macro seismic Scale EMS-98 (which are considered critical in terms of collapsed debris and, consequently, road operability). The seismic action parameter used was the maximum reference acceleration recommended for the Lisbon area in the Portuguese Annex of Eurocode (Civil 2010; LNEC 2010)[1] and the applied conversion equation between seismic acceleration (PGA) and magnitude was the one proposed by (Gutenberg 1956). The results from the application of this method to the 682 buildings in the study area are presented in Figure 1.

[1] Which basically corresponds to an exceeding probability of 10% in 50 years or, in other words, to a return period of 475 years.

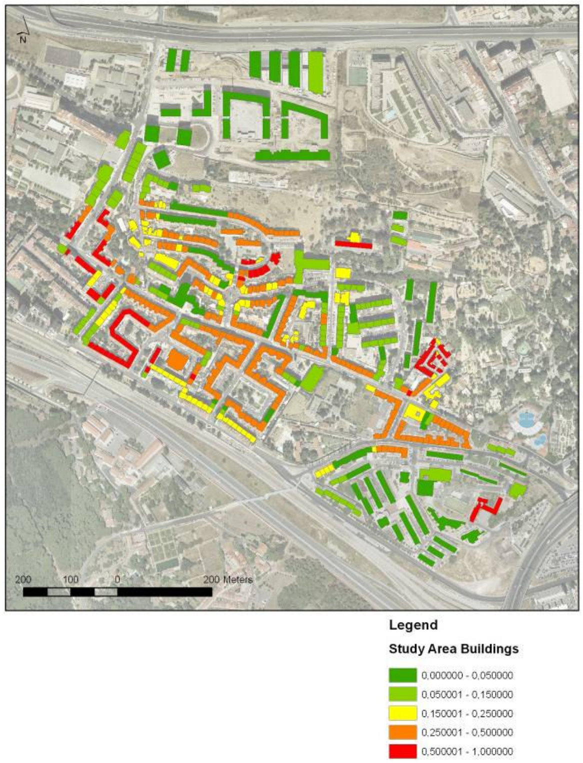

Figure 1 – Buildings probabilities of suffering EMS-98 level 4 or 5 damages

The transformation of the probabilities presented in Figure 1 into road network edges closure probabilities (due to debris from collapsed buildings) is obtained by determining the potential debris area. The method was adapted from (Argyroudis 2005) which basically consist in a correlation between the building's height (i.e. number of storeys) and the width of the induced debris based on the visual inspection (i.e. photographs) of collapsed buildings from past earthquakes.

Regarding pavement damages, the approach suggested in the HAZUS methodology was applied, which is based on fragility curves describing the probability of reaching, or exceeding, certain damage states given the level of ground failure (FEMA 2003). The application of this methodology to the study area road network resulted in a probability - for each network link - of reaching "extensive" or "complete" damage states. These states are defined by "major settlement of the ground" which, theoretically, hinders emergency vehicle traffic (or any other vehicle traffic, for that matter).

Finally, the combined probabilities of reaching critical damage states from both, buildings and road pavements, resulted in a global closure probability for each road link of the study area network. These results are presented in Figure 2.

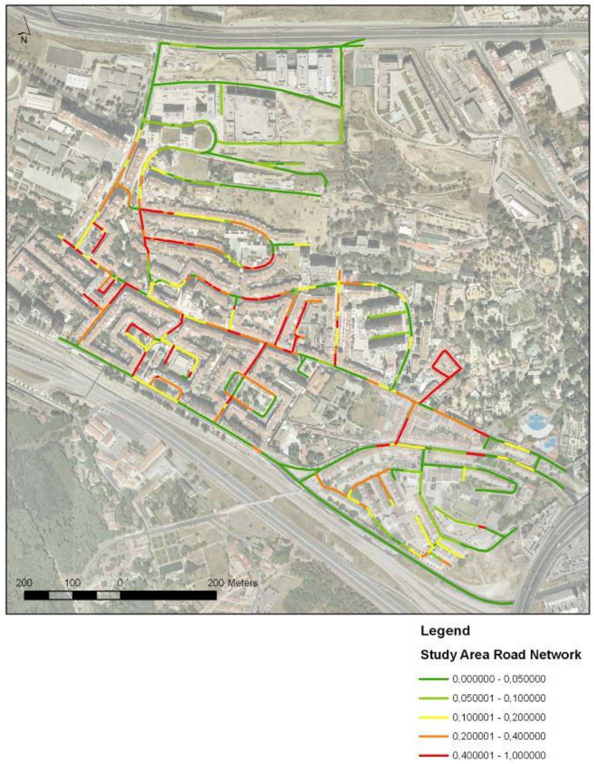

Figure 2 – Road network closure probabilities

3.2. Blockage Scenarios Risk Computation

The ultimate goal of the projected model is to diagnosis road network seismic vulnerability, particularly for emergency response functions following a large quake. Thus, the most logical application of this model is to be used as a starting point to improve such vulnerability. Ultimately, its application will contribute to minimize inaccessibility situations in earthquake scenarios. Therefore, as previously stated, the analysis of individual links is not sufficient. In fact, the term “network” implies the consideration of links connectivity. As such, individual links vulnerabilities (measured as closure probabilities) are a necessary output of this model but are not sufficient *per si* to tackle inaccessibility situations. Ultimately, if intervention strategies are developed based solely on individual links vulnerabilities, most likely the output of those strategies will not be the optimum in order to prevent or mitigate inaccessibility situations in earthquake scenarios.

In this sense, the present section addresses both network connectivity and land-use related issues. Thus, the final output of the model herein presented will not be a simple vulnerability measure for each individual link but rather the identification of the potentially most critical inaccessibility situations in earthquake scenarios in terms of both, occurrence probability and consequence.

3.2.1. Inaccessibility Situations Analysis

In graph theory, a graph G consists of a finite set V (G) of objects called vertices together with a set E (G) of unordered pairs of vertices; the elements of E (G) are called edges. Additionally, a graph is called disconnected if its vertex set can be partitioned into two subsets (V1 and V2) that have no common element, in such a way that there is no edge with one endpoint in V1 and the other in V2. A disconnected graph consists of a number of disjoint subgraphs; a maximal connected subgraph is called a component (Bóna 2006, pp 6-10). Among connected graphs, some are connected so slightly that removing a single vertex or edge will disconnect them. A vertex x is called a cutpoint in G if G - x contains more components than G does; in particular if G is connected, then a cutpoint is a vertex x such that G – x is disconnected. Similarly, a bridge (or cut-edge) is an edge whose deletion increases the number of components (Wallis 2007, pp 6).

Some bridge-finding algorithms can be found in the literature (Tarjan 1974). However the complex problem to be addressed by the proposed model requires further sophistication. In fact, streets or small urban areas isolated by large earthquakes can result from the inoperability of one single edge or link, but can also result from the combined inoperability of two or more links. The unique nature of the addressed problem requires an algorithm to identify, not only "bridges" (i.e., cut-edge or cut-link) but also combinations of links which, together, isolate another links. No algorithm to find combinations of links which isolate parts of the network can be found in the literature; nor a similar problem, for that matter.

In order to identify the most critical inaccessibility situations in a given urban network one must first identify all possibly inaccessibility situations. In its turn, the identification of all possible inaccessibility situations implies the identification of all combinations of links. The complexity of this problem derives from the high number of links combinations which can be produced from a certain urban road network.

If one considers a small network where the total number of existing links (n) is 100, the number of possible "combinations" of just one closed link (k) is 100. However, when increasing the number of k closed links to two, the total number of possible combinations (including not only K=2 but also K=1) is 5.050. Similarly, when k equals 3, the number of combinations for that particular network results in 166.750 (including not only K=3 but also K=1 and K=2).

It is important to stress that the number of combinations analyzed by the model must be limited in number. In fact, each combination will correspond to a possible post earthquake scenario in terms of network operability. Moreover, most of those combinations will not isolate any link or set of links simply because every urban road network has a high degree of connectivity, resulting in a high level of path redundancy. Therefore, all combinations generated will have to be further analyzed in terms of determining which of those correspond to authentic inaccessibility situations. As already stated, no such algorithm can be found in the literature. Therefore, not only the algorithm must be developed has it will have to be extremely efficient since it will have to analyze a considerable amount of combinations (or possible post earthquake networks). Even if this algorithm only takes a fraction of a second to analyze each combination, it will easily reach unacceptable computation times has the number of combinations exponentially increase with both, network size and number of links closed in simultaneous. For example, it is estimated that the network analysis algorithm developed within this research (to identify isolated links) takes nearly 0,636 seconds[2] to process each combination in a network with 633 edges (see Figure 3). Since there are approximately 42 million possible combinations in such network[3], the expected total computational time to analyze all of them is about 309 days.

In this context, for large networks and/ or demanding requirements in terms of exhaustive analysis of inaccessibility situations involving a high number of links simultaneously closed, the processes will have to be further optimized. Particularly, a naive approach based on exhaustion or brute force techniques will have to be replaced by a more efficient method including combinations generators and network analysis algorithms. In short, the problem at hands is not an optimization one but rather an enumerative combinatory problem[4] involving graph theory.

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[2] In a desktop computer with a 3.00 GHz processor and 1.97 GB of RAM memory.
[3] If the number of links simultaneously closed is limited to a maximum of three.
[4] Enumerative combinatory is an area of combinatorics (branch of mathematics concerning the study of finite or countable discrete structures) that deals with the number of ways that certain patterns can be formed.

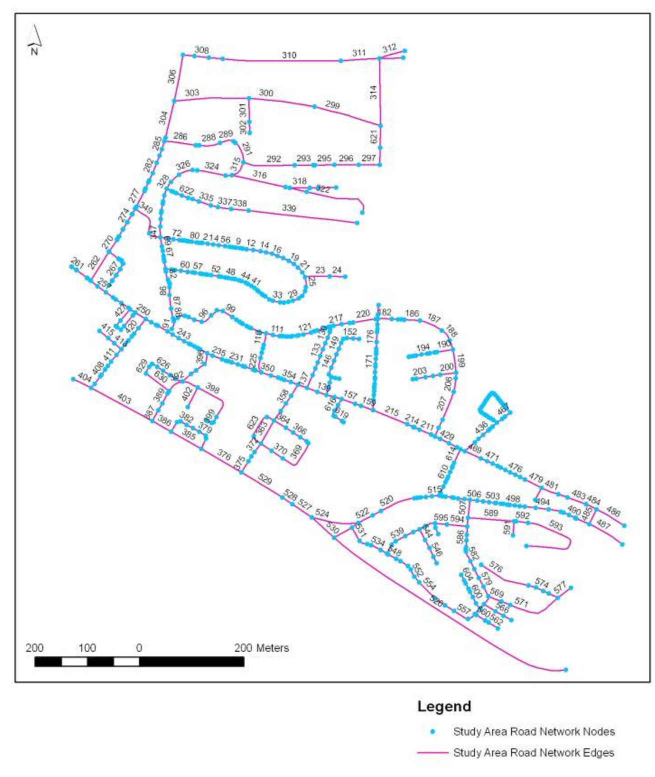

Figure 3 – Micro Scale Road Network Representation

3.2.2. Inaccessibility Impact

Before explaining the experimental method developed to cope with excessive information and improve computational times, one must first introduce the concept of consequence or impact in inaccessibility situations. As previously argued, vulnerability assessment methods should include not only structural and network connectivity concerns but also land-use issues. This requirement is based on the assumption that the network serves specific purposes and, in extreme scenarios, if certain parts of the network do not serve any purpose, than they are not relevant. For example, two links with identical structural vulnerabilities and similar path redundancies within the network may have different importance since one may serve more population and/ or critical functions than the other. These land-use concerns should also be considered when determining the vulnerability of a certain urban road network.

An inaccessibility situation is characterized by a closed link (or set of links) and by an isolated link (or set of links). These situations can be characterized not only by their occurrence probability, but also by their consequence or expected impacts in terms of inaccessibility. In its turn, the latter should reflect not only the demand for emergency assistance but also the supply of the necessary resources to provide such assistance. In fact, a certain inaccessibility situation may involve the isolation of several housing buildings to emergency vehicles but also of critical functions in case of earthquake (such as hospitals or fire departments headquarters). Interestingly, past events have shown that functional infrastructures may become useless in earthquake scenarios simply because they are inaccessible.

In this context, the quantification of inaccessibility impact should combine: **i)** an indicator reflecting the present population, and; **ii)** another indicator addressing the existence of critical functions in case of earthquakes. The former, should take into consideration the space-time population distribution while the latter should be measured according to the importance of those critical functions.

3.2.3. Optimized Inaccessibility Situations Analysis Method

The identification of critical inaccessibility situations is a combinatory problem in graph theory.

However, the unique nature of this problem requires an innovative method which allows identifying and quantifying the risk level (in terms of both occurrence probability and impact) of possible inaccessibility situations caused by large quakes. The high number of possible combinations can easily result in unendurable computation times even for relatively small networks. This section provides the necessary guidelines to set up a heuristic approach allowing for the identification and quantification of critical inaccessibility situations within convenient computational times.

The rationale behind the developed approach is based upon three interrelated principles: **i)** division of the problem into several sets of smaller problems; **ii)** combination of different analysis scales, and; **iii)** grouping and discarding large number of combinations. An outline of the heuristic approach developed to optimize the inaccessibility situations analysis is presented in Figure 4.

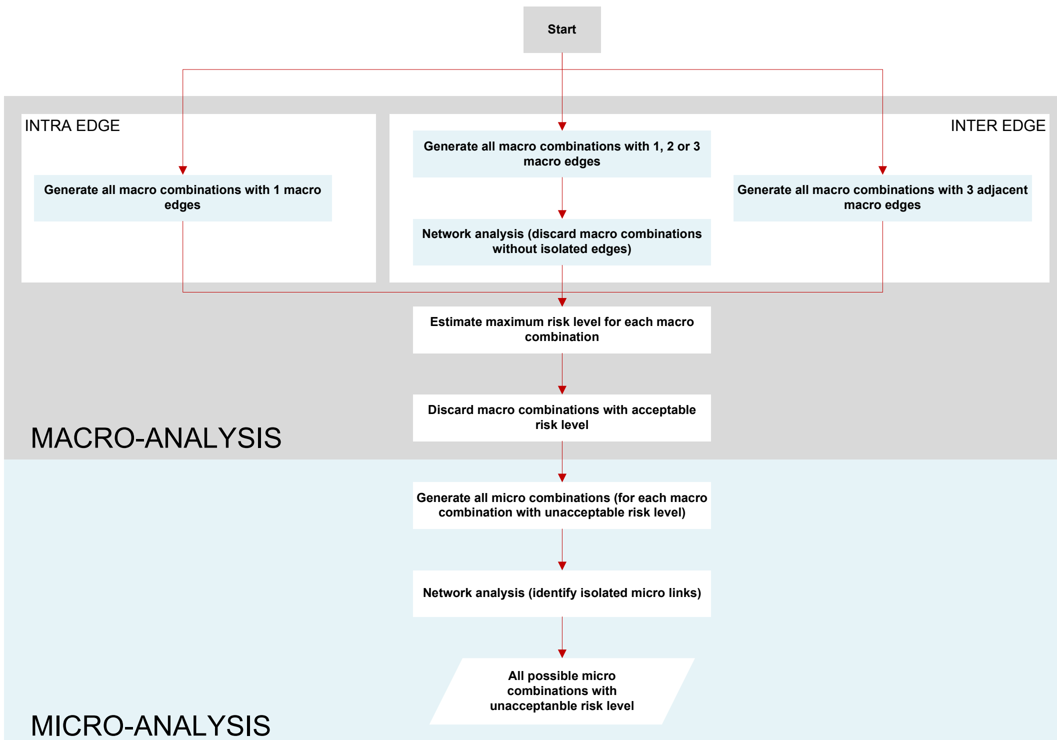

Figure 4 - Outline of the heuristic approach developed to optimize the inaccessibility situations analysis

In this sense, and in order to reduce computational times to reasonable values, the approach has two main stages: **i)** a macro scale analysis, and; **ii)** a micro scale analysis. The first stage - the macro scale analysis – will allow discarding a significant amount of combinations simply because their risk level is acceptable (or not critical). The logic associated with the macro scale analysis is similar to the one behind "*branch-and-bound*" algorithms. It is based on a systematic enumeration of all possible solutions followed by massive discarding of large subsets of ineffective solutions by applying estimated bounds. Afterwards, in the second stage - micro scale analysis - only the combinations with unacceptable risk level will be studied in detail.

The application of the above explained model to the case study area is still in progress and no definitive results are yet available. However, as previously mentioned, the output of this model will be a list of the most critical inaccessibility situations (in terms of both: occurrence probability and consequence) that may occur in earthquake scenarios. As an example of the expected results from the model, two critical inaccessibility situations are presented in Figure 5. Although, the consequence component of risk cannot be quantified at this stage, it is expected to be high in both of the presented examples. In the one on the left, the closure of one single link isolates a set of five buildings which correspond to a major hospital. In the example on the right, the simultaneous closure of three links, strategically located, isolate a large area with a total of 131 buildings (including a major public school).

Figure 5 – Examples of inaccessibility situations

4. CONCLUSIONS

Typically, when planning or managing urban road networks, seismic risk concerns have been tackled exclusively through a structural link-by-link approach. This conservative procedure focuses on infrastructure construction requirements (usually translated in specific building codes) but fails to capture network related issues (such as connectivity redundancy to essential facilities: schools, hospitals or fire departments).

This paper is part of an on-going research effort in which the underlying hypothesis is that the impacts on road transport infra-structures performance for emergency response functions can be minimized when facing a major earthquake, namely by the introduction of measures, not only in terms of infra-structural reinforcement but also in terms of network connectivity and activities location.

Furthermore, potential applications of this work comprise urban planning solutions to be included in specific instruments (including, among others, urban planning instruments and policies; urban master plans; renewal policies; emergency plans and protection of critical mobility assets programs).

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