The seismic risk of the lifeline in small communes: the cross-correlation effects

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Abstract

A significant part of the consequences of a severe earthquake in an urban area is related to the failure of the lifeline system. A systematic assessment of seismic risk, vulnerability, and criticality of lifelines in small communities (considering them both separately and from a systemic point of view) is performed. The risk is characterized by using functions related to the components of different lifelines. The approach allows the optimization of the use of economic limited resources in intervention to reduce risk. Given a set of remedial measures more expensive than the limited budget, the subset maximizing the risk reduction at the appropriate cost is selected. The developed methodology allows one to analyse the lifeline system characterized by the information related to vulnerability and to their functional model separately and as a whole. The definition of different reference earthquakes is also allowed. The information related to the vulnerability of the elements and to the seism is defined by means of probabilistic models. The present paper is organized as follows. After a brief introduction to the seismic risk associated to a system of lifelines, a synthetic description of the whole methodology adopted is given. In the second part of the paper the methodology developed to assess the risk due to cross-correlations effects between lifelines is described in detail. The problem is assessed from both structural and functional points of view. Results of the application of the whole methodology to test sites are also reported. This work is one of the outcomes of the activities promoted and directed by the Istituto Nazionale di Geofisica e Vulcanologia of Rome within the Programma Operativo di Ricerca per la Sismologia e l’Ingegneria Sismica (PRO.S.I.S.), aimed at assessing methods and instrumentations for the reduction of the seismic risk in Italy.

Keywords: lifeline, seismic risk, cross-correlation, probabilistic approach.
1 Introduction

A significant part of the consequences of a severe seism in an urban location is related to the failures and/or the unavailability of the lifeline system. Even if there is a wide amount of national and international seismic engineering studies, the work developed with the grant of Istituto Nazionale di Geofisica e Vulcanologia has got the aim to chase some innovations in:

- a whole probabilistic approach to the seismic risk related to a lifeline system;
- an assessment and a quantification of the cross-correlation issue from both a structural and a functional perspective;
- an assessment and a quantification of the consequences of the loss of functionality of the lifelines with respect to “sensible” targets (i.e. hospitals);
- a definition of the vulnerability and criticality for the single lifeline as well as for the complete system;
- a definition of the best allocation of some finite economical resources for the mitigation of the seismic risk.

In the present paper, after a brief introduction to the lifeline seismic problem and to the methodological approach, the problem of the cross-correlation is addressed from a structural and functional point of view.

2 Lifeline earthquake engineering

2.1 Generalities

The lifeline network is an extremely complex system usually composed by several sub-systems interconnected from a structural and/or functional point of view localised on a wide area [1]. The system of distribution of water and gas or the communication and transportation systems in a large urban or extra-urban areas can be considered as examples of a lifeline network. The assessment of the response of a complex system to a seism is a very complex activity. Nevertheless the importance of having a good predictive tools has been demonstrated by the effects of the recent seisms that affected urban areas such as Loma Prieta (1989), Northridge (1994) and Kobe (1995).

A good example of the complexity of the lifeline system can be derived from the list of the contributors considered during the evaluation of the impact of the seism in the area of Northridge [2]. Ten different lifelines were considered.

The potential effects of the complete loss or even partial damages of lifelines have been clearly demonstrated by recent seismic events. Although service providers (i.e. a power-station) could be safe from a structural and a functional point of view, service can be interrupted both directly and indirectly, by the unavailability of some auxiliary service provided by a cross-correlated lifeline.

Lifelines are typically geographically wide spread and complex from a functional point of view due to redundancy. On the basis of these two factors, a break in a specific point does not directly imply a loss of the service in the whole system [3]. This fact implies that a study of the lifeline has to take into account both these factors.
A general concept, adapted to the lifeline from the study of buildings, is that lifelines during the seism can be damaged but there is only a rather limited risk that fatalities derive from that failure. Nevertheless, indirect consequences can be severe. Examples of this phenomenon are represented by lack of water to promptly limit fires or by the unavailability of the communication infrastructures needed to support emergency and rescue activities in the affected areas [3].

2.2 Infrastructure risk analysis model

One of the most important instruments in the analysis of the infrastructural risk is defined as “Infrastructure Risk Analysis Model” (IRAM). This approach is based on the definition and modelling of the risk in order to define the critical resources. The finite budget could then be allocated in order to maximise the safety of the system [4].

One of the most relevant aspect of the IRAM methodology consists in the analytical approach used to quantify the risk. It is based on the decomposition of the problem in functions, components, structure and vulnerability. Vulnerable components can be identified as the targets of the methodology. Potential dangers are identified using an operational scenario. The decomposition ends with the selection of the critical aspects related to the system, the operative scenario and the production of an event tree. The methodology allows to define the risk in terms of overall losses conditioned to each identified scenario.

The IRAM methodology is composed by four basic tasks:

- identification of the risk;
- modelling of the risk;
- quantification of the effects of the risk;
- management of the risk related to the structure.

The key aspect of the proposed methodology consists in defining a systematic risk analysis process using a robust and flexible method. Analysing the lifeline as a system, allows to apply every consolidated techniques of risk analysis developed in other fields (e.g. the methodology adopted to analyse the aqueduct of a town [5]).

2.3 GIS applications for the evaluation of lifeline system

One of the most effective techniques used for the representation of the lifeline and for their analysis is the use of the Geographic Information System (GIS). It allows to georeference the various networks and their spatial and functional interconnections [6]. The use of the GIS allows:

- to represent the information related to the lifelines;
- to represent the information related to the site;
- to perform spatial analysis using the two type of information;
- to perform analysis of correlation to the whole set of data using typical GIS techniques;
- to represent the results of the analysis in a spatial way.
The spatial representation of the characteristics of the lifeline allows to highlight situations of high risk related to both the lifeline itself (inherent) and to the site crossed. A typical application is the representation of the damage of a pipeline [7]. An overall approach to the use of the GIS technique for the zonisation and the analysis of the effect of a seism on the lifeline and utilities has been detailed described in the paper of O’Rourke and Jeon [8].

3 The methodological approach

3.1 General approach

The methodology described in the present paper can be divided in the following five different steps:

1. site hazard analysis;
2. vulnerability analysis of the element of the lifeline;
3. analysis of the criticality and risk exposure of the element of the lifeline;
4. evaluation of the total risk for the system as the sum of the risk of the element and of the different level of damages;
5. optimization model for the selection of the remedial measure given a limited budget.

The seismic risk can be defined as the possibility of losses in terms of property, human being or functionality caused by a seism. The quantification of the seismic risk can be defined in a deterministic way with the following relation [1]:

\[ R = p_T \cdot V \cdot C \cdot E \]  

The terms used to calculate the seismic risk (R) are the following. \( p_T \) is the probability of occurrence of a seism at a given place or in a given area related to a given return period. The vulnerability (V) is the probability of exceeding a given threshold of damage. The rate of consequence (C) is the fraction of property, service or human being that is affected by the damage. The exposure (E) can be defined as the dislocation, consistency quality and quantity of the activities located on the territory that can be affected directly or indirectly by the seism (settlements, buildings, economic and productive activities, population, etc.)

The methodology presented in the present paper is based on a probabilistic approach where the eqn. (1) becomes for a defined class of damages \( i \):

\[ R_i = p_T \cdot P[D = ds_i \mid S_T] \cdot \rho_i \mid ds_i \cdot E \]  

where:

- \( R_i \): risk (expressed in an adequate unit of measurement congruent with E) associated to a defined class of damage \( i \);
- \( P[D = ds_i \mid S_T] \): probability of a certain level of damage \( ds_i \) given a seism \( S_T \) with a return period \( T \);
- \( \rho_i \mid ds_i \): rate of damage expressed as percentage of the total exposure and conditioned to a defined level of damage \( ds_i \);
- \( E \): exposition defined as the quantification of the goods exposed to the seism.
The total risk related to an element is obtained as the sum of the risk associated to each level of damage.

### 3.2 Site hazard analysis

The site is characterized by the seismic parameters of the place where the lifeline element is located. The methodology is based on the representation of the seism using PGA, PGV and PGD with the same return period $T$ (the default value is assumed equal to 475 years). If no other input value is provided by the user (i.e. after a seismic microzonation of the surroundings), the system uses default values for the whole communities. These values are provided on the basis of national data-set and general calculations. Moreover, the methodology allows to acquire alternative typology of seismic data (i.e. I, M, Sa, etc.) that are transformed into the necessary input for the software.

The additional dangerousness of the site is represented by means of an amplification factor of the seismic input that represents the possible amplification related to topology, geology and local conditions of the soil, which are not included in the vulnerability of the element. The factor is calculated on the basis of the value of the parameters related to the areas that are crossed by the element.

The software, by means of the spatial location of the seismic input, is ready to include the results of information derived from activities of local microzonations.

### 3.3 Vulnerability

The inherent vulnerability of a structure represents the attitude to be damaged by a seismic action. In the following, the vulnerability is represented using fragility curves describing the probability of reaching or exceeding different states of damage given a response peak of the structure/element [9]. The curves are calculated for defined classes of damage. The software allows to modify the basic parameters of the curves in order to consider the availability of advanced technologies.

The vulnerability related to the presence of other lifelines allows to quantify, for each element, the interaction with other lifelines from both a physical and a functional point of view. This phenomenon expresses the attitude of an element to be damaged by the action of a near lifeline subjected to a seismic action and is described in details in Chapter 4.

The total vulnerability is assumed as the combination of the two previously described types, the inherent (amplified by the site vulnerability if necessary) and the correlated to the other lifelines (also considering the site vulnerability).

### 3.4 Criticality

The methodology adopted is based on three different aspects of the criticality of the element:

- the impact on the human being;
- the impact on the property in terms of loss of the interested infrastructures;
• the impact related to the loss of functionality of the lifeline, in particular focused on the users needs during the emergency.

These three aspects are used to evaluate the rate of damage $\rho_i$ that expresses the percentage of the exposition $E$ conditioned by a level of damage.

The values of $\rho$ for each type of criticality are determined for each element of the lifeline in terms of class of consequences related to the levels of damage. The class of consequences has been adopted by analogy to the international codes [10]. The class of consequences defined are applied to both structural and human being damage and connected to the rate of consequences. The consequence rate of damage related to the lack of services is defined on the basis of the same class of consequences not related to the element of the lifeline but to the final users.

3.5 Exposure

The exposure is considered separately for the following areas:

1. economic exposition (structural damage and patrimonial damage);
2. casualties (injuries and fatalities);
3. functional damage (lack of services).

The first two aspects are related to the direct exposure to a seismic risk depending on the quality and the quantity of goods and the number of the people involved to the risk. The third is the indirect (functional) exposure of an element based on the reduction of the service due to the degradation of the element. For each considered lifeline, it has been defined an index of service that represents the operability of the lifeline especially related to the emergency phase (the reconstruction phase is not considered in this paper).

With respect to each case, the exposure is quantified by means of classes of consequences that are defined using a consequences rate. The rate is function of the classes of damages associated to the element.

Appropriate factors are determined in order to evaluate the consequences in terms of money. For the human being consequences the Implied Cost of Averting a Fatality (ICAF) methodology has been adopted [11].

3.6 Optimisation of the remedial measures

In order to characterise the most effective remedial, a library of possible actions has been defined by the application field, the results in terms of risk reduction, the unitary cost of the realisation and the time needed to complete the works.

A criterion allowing to define the benefit of each remedial measure by combining the risk in terms of estate, human being (using ICAF) and possible lack of services related to the lifeline has been considered.

The user can define the budget limit and the criterion of selection of the remedial measures in order to configure the analysis at the best. The adopted methodology allows to define:

• the sub-set of remedial measures that maximise the reduction of the total risk of the system with a limited budget;
• the sub-set of the remedial measures that allows to minimise the investment necessary to reach a given level of risk mitigation.

4 The cross-correlation issue

4.1 Generalities

The structural and functional interaction between the elements of different lifelines is one of the most complex aspects to be assessed in the analysis of the seismic risk of a lifeline system. In the literature, the interrelation between specific couple of lifeline is mostly assessed. The problem of a complete assessment of the problem related to the whole lifelines system and their relationships seems not to be widely discussed. A brief resume of some of the articles appeared on this topics are reported in the following.

The dependences between the different lifeline and the electrical supply lifeline has been analysed in relationship to the Northridge seism (1994) that caused large damages to the power supply distribution network. The distribution to almost any user has been interrupted immediately after the seism [12]. The paper of Shift et al. describes the analysis of the operations carried out during the emergency phase and some new design specifications that integrate the existing ones in order to reduce the damages to the electrical system under a seism.

An interesting and detailed analysis has been performed by Lau and Eidinger [13] related to the interaction between the aqueduct and the electrical supply lifeline. The analysis has been carried out considering three different situations:
• the normal operation;
• the presence of a large fire;
• a seism.

An analysis of interdependency between the telecommunication net and the other lifeline systems has been developed by Wong et al. in order to evaluate the functionality of the first one during an earthquake [14].

Among the papers devoted to the generic problem of the functional interaction between existing lifelines, a particular attention in this context has been posed on the interdependency analysis accomplished by Nojima et al. that has given many ideas regarding a systematic approach to the problem [15].

4.2 Structural cross-correlation

In order to evaluate the vulnerability related to the structural cross-correlation between two elements of different lifelines for each type of lifeline element, a maximum interaction distance is defined. This distance depends on the characteristics of the lifeline and of the considered element. It defines a 3D space where the collapse of the element can cause damages to elements of other lifelines.

The methodology has been developed under the following assumption. The effect of the rapture has been considered equal in the whole volume defined by
the maximum interaction distance. This simplification is conservative and would be superseded in further implementation of the model using different attenuation curves for each lifeline.

The structural cross-correlation vulnerability is evaluated using an iterative method. For each element of each lifeline the GIS elaboration selects what is included in the buffer defined by the maximum interaction distance. For each selected element the probability of a certain $i$ level of damage of the element $j$ (3), probability of a certain $n$ level of damage of the element $k$ (4) and probability of a certain $i$ level of damage of the element $j$ given a certain level $n$ of damage of the element $k$, are estimated (5).

\[
P_j[D_j = ds_i \mid S_T]
\] (3)

\[
P_k[D_k = ds_n \mid S_T]
\] (4)

\[
P_j[D_j = ds_i \mid D_k = ds_n]
\] (5)

For the element $j$ an “or” combination between (3) and (6) is used in order to evaluate the vulnerability of the element $j$ due to structural and cross-correlation vulnerability.

\[
\sum_{n} \{P_k[D_k = ds_n \mid S_T] \times P_j[D_j = ds_i \mid D_k = ds_n]\}
\] (6)

The default values of the probability of damage are given but for a proper use of the methodology they have to be estimated for each situation by the user.

### 4.3 Functional cross-correlation

On the basis of the different possibilities depicted in Paragraph 4.1, the problem of the functional cross-correlation has been approached using a methodology that is based on the tables elaborated by Noijima et al [15] and Hopkins et al [16] implemented in a simplified and directly applicable version. The tables contain the dependences between the different lifelines and give them a ranking on the basis of the importance for the service.

A limited number of functional dependencies are defined between the considered lifelines. The functional vulnerability related to the functional interdependencies is evaluated in the same way as the structural dependencies. A library of default probability of damage is given for the different interactions. On the basis of this library of dependencies, the user has to identify the real interactions existing in the system under study.

The methodology evaluates the functional cross-correlation vulnerability of the different elements using the same iterative methodology defined for the structural cross-correlation.

### 5 Applications

The methodology and the derived software have been applied to two different small communes of different typology in order to test them. The territory of the first commune is mostly characterised by urban environment while the second...
one is characterised by a lower density of population. The application activities have highlighted that there is a reasonable correspondence between the results of the analysis and the in situ survey that is closely related to the level of details of the input data.

6 Conclusions

The described methodology represents an example of a new approach to the problem of the seismic risk connected to the lifeline. Within a robust theoretic framework the following different aspects have been assessed:

- seismic site dangerousness;
- structural and functional vulnerability of each element;
- structural and functional cross-correlation vulnerability;
- criticality in terms of the impact on the human being, on the property and related to the loss of functionality of the lifeline;
- definition of the exposure in the same terms;
- definition of remedial measures and optimisation of their implementation.

Some key issues addressed are:

- a comprehensive probabilistic approach to the seismic risk associated to a system of lifelines;
- development and quantification of the cross-correlation between the different lifelines from both a “physical” and a functional point of view;
- development and quantification of the consequences of the lack of functionality related to the “sensible” users.

The whole methodology allows to develop analytical and detailed studies on the structure of the risk related to a given territory by evaluating what the most relevant components are. This analysis is necessary in order to accurately define the set of remedial measures to be optimised.

The carried out activities have highlighted the importance of the cross-correlation aspect in evaluating the seismic risk of the lifeline system.

References


