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Considerations about the optimal period range to evaluate the weight coefficient of coupled resilience index

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ABSTRACT

Resilience index can be used to plan mitigation actions of lifelines against various types of hazards as well as describing the reconstruction phase. In the paper, *community resilience* is defined as weighted sum of single infrastructure resilience indices. In particular, the paper addresses the problem of the optimal selection of the weight coefficients which are assigned to different lifelines for the evaluation of the resilience index in a region affected by natural disasters such as earthquakes. The proposed method is based on the analysis of the lifelines' restoration curves using cross-correlation functions; however, when the data series is including coupled events, the coupling effect generates distortion in the evaluation of the cross correlation coefficient $S_{i,j}$. This is the case for example when there are strong aftershocks during the lifeline restoration phase right after the main shock. The method is applied to the restoration curves recorded after March 11th 2011 Tohoku Earthquake. A criterion is proposed for the evaluation respectively of the interdependency index, weight coefficients and regional resilience index with long restoration curves data series.

1. Introduction

After the latest earthquakes which have struck urban communities, awareness has increased that these catastrophic events and their damage cannot be avoided. However planning the reconstruction phase is possible and governmental agencies and emergencies authorities are starting collaborating more to reduce the subsequent losses following the event. In this phase, resilience is necessary to plan mitigation actions of lifelines against various types of hazards as well as describing the reconstruction phase. The interest for a quantitative evaluation of the community resilience index under earthquake loads stems from the demand of assuring adequate safety in urban communities.

Communities are complex systems and predicting their response after earthquakes is very difficult, because of the several infrastructures and parameters which are involved in the model. Transportation systems, pipelines, communication and power transmission systems are examples of lifelines which can be considered part of the community. One option to simplify the problem is to consider the community as a "sum" of infrastructures which are interdependent each other. Under this assumption, the resilience of each infrastructure can be evaluated separately and the global community resilience can be considered as a weight average of the different resilience indices. In this case, the weight coefficient evaluation becomes essential to include the interdependencies in the global index. Following this assumption, in this paper is addressed the problem of the selection of the optimal period range which should be taken in account to evaluate the weight coefficients of the resilience index in a region affected by natural disasters. Different methods are proposed to estimate the weight coefficients which should be selected based on the characteristics of the restoration curves. In particular, when the restoration curves are uncoupled, the same weight coefficients can be used, while if they have coupled characteristics, the weight coefficients can be evaluated using the data of the time series between the main shock and the first aftershock. Finally the method is applied to the restoration curves recorded after March 11th 2011 Tohoku Earthquake [1].

2. State of art

Several authors have given valuable contributions to this research area. Most of the literature of the last decade mainly concentrates on using the taxonomy of lifeline interdependencies which is given in the fundamental work by Rinaldi et al. [2]. Before Rinaldi's work, Selçuk and Yücemen [3] simplified the lifeline as an

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equivalent network with random and spatially correlated elements and they developed a comprehensive probabilistic model for the assessment of lifelines' reliability under earthquake loads. The seismic hazard of the network is described by a probability distribution function derived by past earthquakes data [4]. Later, Menoni et al. [5] developed a model to evaluate lifelines seismic vulnerability, considering physical, functional, and organizational factors deeply interconnected each other. The developed assessment tool consists of a set of parameters measuring the response capacity of lifelines exposed to earthquakes. More recently, Paton and Johnston [6] proposed a numerical quantification of the dependencies among different infrastructures, by using an empirical approach in which the degree of interdependency among different infrastructures is function of the level of dependency (high, medium, low dependence). Instead, Cimellaro et al. [7,8] defined resilience as "*a normalized function indicating capability to sustain a level of functionality or performance for a given building, bridge, lifeline, networks or community over a period of time T_{LC} (life cycle, life span etc. etc.)*". They also provided the first definition of coupled and uncoupled resilience [7]. Afterwards Mc Daniels et al. [9] developed a conceptual framework identifying the two factors that influence the resilience of infrastructure systems: *robustness* (the extent of system function that is maintained) and *rapidity* (the time required to return to full system operations and productivity). Bigger et al. [10] have collected different interdependent lifeline information associated with the 2004 hurricane season in Florida, while Delamare et al. [11] have studied the potential effect of interdependencies that may occur between the telecommunication and the electrical network and they have proposed a model that describes the behavior of these interdependent systems. Instead, Hadjsaid et al. [12] have focused towards understanding the interdependencies between the information and communication technologies and the power system to identify vulnerabilities and come up with suitable mitigation actions. More recently, Cimellaro et al. [13] have presented a comprehensive model to quantify disaster resilience of systems that is defined as the capability to sustain functionality and recover from losses generated by extreme events. The model combines loss estimation and recovery models and can be applied to critical facilities (e.g. hospitals, military buildings, etc.), as well as utility lifelines (e.g. electric power systems, transportation networks, gas distribution networks [14], water systems [15], etc.) that are crucial to the response of recovery processes, decisions [16] and policies. Schmidtlein et al. [17] have examined the spatial linkage between social vulnerability and estimated earthquake losses for different levels of magnitude. Kakderi et al. [18] have summarized the available methodologies and models for the vulnerability and risk assessment of *systems of systems*. They reported illustrations, identifications and definitions of the interaction of complex dependencies available in literature. The classification schemes of dependencies are reviewed, and the available methods for the simulation of interdependencies are summarized and classified in five categories. Furthermore, the main characteristics, advantages and limitations of each category of interdependency are also reported. Ouyang and Dueñas-Osorio [19] introduced an approach to assess and improve the time-dependent resilience of urban infrastructure systems, where resilience is defined as the ability that systems have to resist to various hazards, to absorb the initial damage from hazards, and to recover to normal operation one or multiple times during a time period *T*. Kongar and Rossetto [20] provided a literature review using a matrix approach in which are described the gaps in knowledge and based on the review outcomes, they proposed a methodological framework for the assessment of infrastructure vulnerability accounting for interdependencies. Kjølle et al. [21] have used contingency analysis (power flow), reliability analysis of power systems and cascade diagrams for investigating interdependencies, while Poljansek et al. [22] have studied the seismic vulnerability of the European gas and electricity transmission networks from a topological point of view. Network interdependency is evaluated using the strength of coupling of the interconnections, together with the seismic response. Dueñas-Osorio and Kwasinski [23] have proposed an approach based on the post-analysis of the restoration curves. The interdependency index between infrastructures is calculated with an empirical equation that depends on the maximum positive value of the cross correlation function (*CCF*) of the two data series. Finally, in Cimellaro et al. [24] is proposed a method to evaluate the degree of interdependency among infrastructures which is calculated using an empirical equation that depends on the maximum positive value of the cross correlation function (CCF) of the two data series of the two infrastructures. With respect to the model proposed by Duenas-Osorio and Kwasinski [23], the proposed equation takes into account the level of statistical significance for each CCF function, considering only the values above it. More weight has been given not only to the peak values, but also to the number of times in which the CCF function exceeds the threshold of statistical significance.

3. Lifeline's resilience index

According to literature, resilience index for lifelines is given by the following equation [8,13,25]:

$$R_i = \int_0^{T_{LC}} \frac{Q_i(t)}{T_{LC}} dt \tag{1}$$

where R_i is the value of resilience of the *i*th infrastructure, $Q_i(t)$ is the functionality of the *i*th infrastructure at time *t*, T_{LC} is the control period. The data available for the analysis are the restoration curves of March 11th 2011 Tohoku Earthquake which cover a period range of 47 days, therefore they are affected from the main shock on March 11th, but also from two other strong aftershocks on April 7th and April 11th [1]. First the resilience values of each lifeline are evaluated using the control time of T_{LC} = 47 days. Distinction is made between *coupled* and *uncoupled resilience* due to the interaction of the recovery process between narrow events. In particular, resilience is defined *coupled* when a second drop of functionality occurs during the recovery process due to a previous extreme event (Fig. 1a).

This characteristic appears when extreme events are narrow in time. Instead, resilience is defined *uncoupled* when the second drop of functionality occurs after the recovery process due to the previous event is fully recovered (Fig. 1b). In Fig. 2 are shown the restoration curves of three different types of lifelines (*Power delivery*, *Water supply*, *City Gas delivery*) for the prefectures of Miyagi, Iwate, Fukushima, Ibaraki, Aomori and Saitama. Instead, for the prefecture of Yamagata, Akita, Tochigi and Gunma are available only the data of Power delivery and Water supply, whereas for Chiba and Kanagawa prefecture are available only the restoration curves of the Power delivery and City Gas delivery.

On the basis of the definition above, the restoration curves of March 11th 2011 Tohoku Earthquake [1] have been subdivided in two categories: the *coupled restoration curves* (Fig. 2a, c, e) and the *uncoupled restoration curves* (Fig. 2b, d, f). In Fig. 2 are also shown the aftershocks that occurred during the restoration phase (represented by vertical dashed lines). The first aftershock reduced the serviceability in the prefectures located near the epicenter of the main shock and of the first aftershock, whereas the second aftershock reduced the serviceability of the lifelines in Fukushima prefecture only. It is interesting to note that the City Gas delivery was not influenced from the two aftershocks in any prefecture. Furthermore, the restoration curves of only three prefectures (Miyagi, Iwate, and Fukushima) are *coupled* for all the regional lifelines, while in the Ibaraki prefecture only *Water supply* restora-