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COMMUNITY RESILIENCE ASSESSMENT INTEGRATING NETWORK INTERDEPENDENCIES

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ABSTRACT

The concept of Disaster Resilience has received considerable attention in recent years and it is increasingly used as an approach for measuring response of communities to natural disasters. Recently a framework named PEOPLES has been developed by MCEER to measure performance of communities to natural disasters. The method includes seven dimensions that include both technical and socio-economic aspects. All resilience dimensions and their respective indices to measure community performances are obviously interdependent. As first step, the physical dimension has been implemented in software and indices have been proposed to measure performance of buildings and lifelines. This paper tries to focus on developing methodologies to consider interdependencies between buildings (e.g. hospitals, strategic buildings, etc) and lifelines (road networks, etc.). An approach considering network interdependencies have been developed which is based on the time series analysis of the restoration curves of the different infrastructures. The case study of 2011 Tohoku Earthquake has been presented to illustrate the implementations issue.

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Community Resilience Assessment Integrating Network Interdependencies

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ABSTRACT

The concept of Disaster Resilience has received considerable attention in recent years and it is increasingly used as an approach for measuring response of communities to natural disasters. Recently a framework named PEOPLES has been developed by MCEER to measure performance of communities to natural disasters. The method includes seven dimensions that include both technical and socio-economic aspects. All resilience dimensions and their respective indices to measure community performances are obviously interdependent. As first step, the physical dimension has been implemented in software and indices have been proposed to measure performance of buildings and lifelines. This paper tries to focus on developing methodologies to consider interdependencies between buildings (e.g. hospitals, strategic buildings, etc) and lifelines (road networks, etc.). An approach considering network interdependencies have been developed which is based on the time series analysis of the restoration curves of the different infrastructures. The case study of 2011 Tohoku Earthquake has been presented to illustrate the implementations issue.

Introduction

In recent years, the scientific community has become increasingly interested in lifelines interdependencies and resilience evaluation [1, 2] and recent literature includes several papers addressing the evaluation of interdependency indices for infrastructures [3]. These works published in the last decade are all using the taxonomy of lifeline interdependencies which is given in the fundamental work by Rinaldi et al. [4]. Paton and Johnston [5] have provided numerical quantification of the dependencies among different infrastructures, by using an empirical approach in which the degree of dependency among different infrastructures is function of the strength of the dependency (high, medium, low dependence). Kongar and Rossetto [6] 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. [7] have used contingency analysis (power flow), reliability analysis of power systems and cascade

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diagrams for investigating interdependencies. Dueñas-Osorio and Kwasinski [8] 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. [9] 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 [8], 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.

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 to evaluate the resilience index in a region affected by natural disasters. Different methods are proposed to evaluate the weight coefficients which should be selected based on the characteristics of the restoration curves. Finally the method is applied to the restoration curves recorded after March 11th 2011 Tohoku Earthquake [10].

Lifeline resilience index

According to the literature, resilience index for each lifeline is given by the following equation [11] [12] [13]:

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

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 March 11th 2011 Tohoku Earthquake have a length of 47 days, starting from the main shock [10]. In first approximation the resilience values of each lifeline are evaluated using the control time of T_{LC}=47 days. The restoration curves of March 11th 2011 Tohoku Earthquake cover a period range of 47 days, therefore they are affected from the main shock, but also from two other strong aftershocks on April 7th and April 11th.

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 (or further strong shocks) occurs during the recovery process due to a previous extreme event (Figure 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 (Figure 1b).

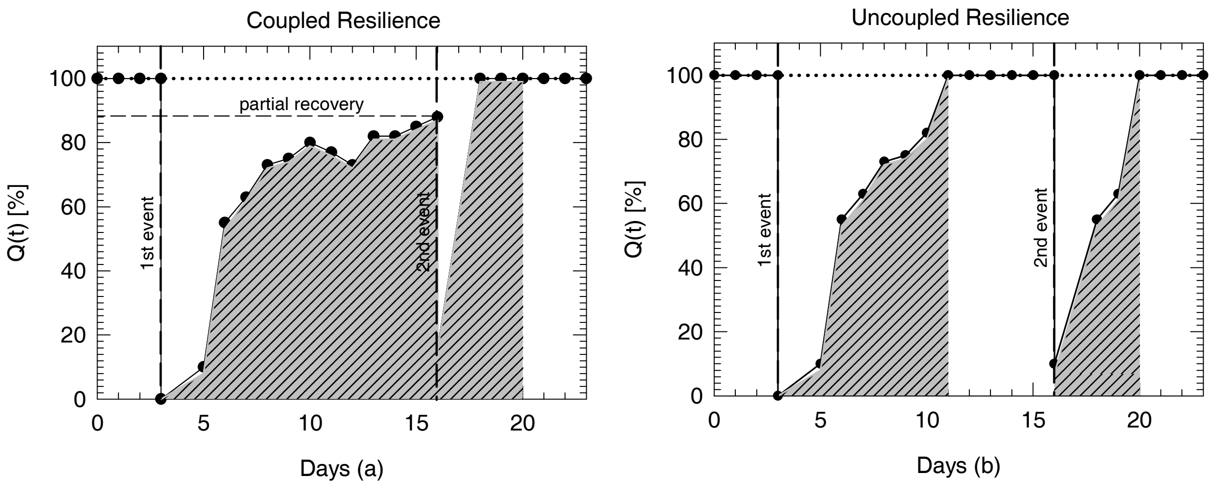

Figure 1 Coupled and uncoupled resilience.

Restoration curves of Physical infrastructures after the 2011 Tohoku earthquake

On the basis of the previous definition, the restoration curves of March 11th 2011 Tohoku Earthquake [10] have been subdivided in two categories: the coupled restoration curves (Figure 2a) and the uncoupled restoration curves (Figure 2b).

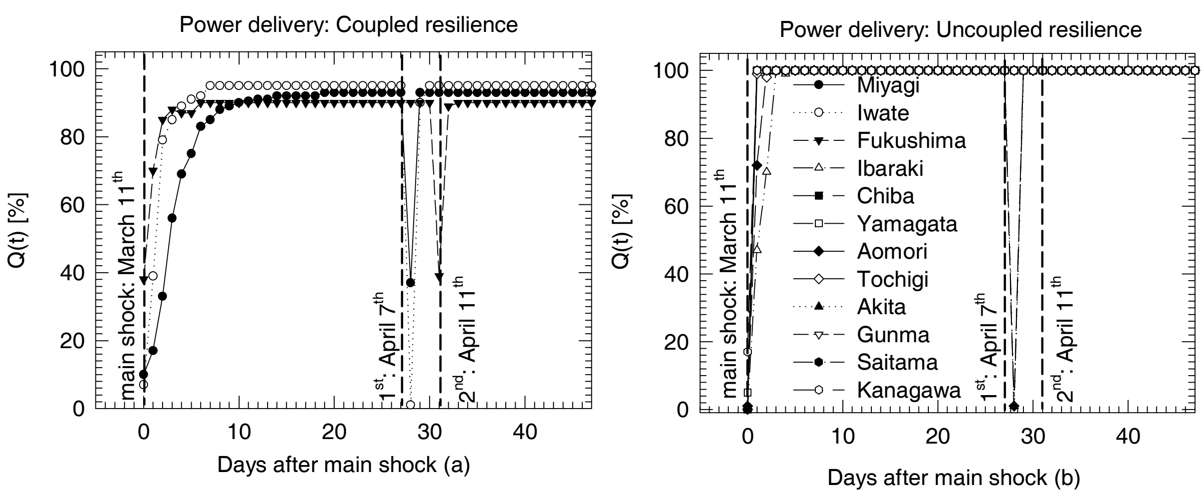

Figure 2 Restoration curves of March 11th 2011 Tohoku Earthquake divided into (a) coupled resilience curves and (b) uncoupled resilience curves

Evaluation of the weight coefficients of the infrastructures

In general, when evaluating the resilience of a community, the weight coefficient of each infrastructure should be taken in account. However, usually when no information are available, the same weight is assumed for each lifeline. Recently a more rational evaluation of the weight coefficients has been proposed by Cimellaro et al. [9], which is based on the analysis of the cross-correlation functions (CCF) among the restoration curves of different lifelines in a given community. First, it is necessary that the time series would be at least weakly stationary [14] to calculate the *CCF* functions of the different restoration curves. Then the time series data have been logarithmically transformed and second-differenced (Figure 3a) for minimizing the effects of non-stationary and obtain meaningful statistical analyses. The transformation stabilizes the variability, and the mean value which remains constant through the time, while the auto-covariance values decay rapidly and depend only on the time-difference $h = t_1 - t_2$ between the data series, where t_1 and t_2 are arbitrary points in time [14]. An example of the results of the transformation, about Power delivery and water supply for Iwate region is shown in Figure 3a. After the logarithmical transformation and the second-differenced of the data series, it is possible to evaluate the *CCF* functions ($\rho_{i,j}(h)$) for different combinations of the restoration curves. In Figure 3b is shown an example of *CCF* function between *Power delivery* and *water supply* for Iwate region. Then the interdependency index $S_{i,j}$, that is necessary for the calculation of weight coefficients are computed with the following equation [9]:

$$S_{i,j} = \left|A_{i,j}\right|^{\frac{1}{N}} \cdot \operatorname{sgn}\left(A_{i,j}\right) \tag{2}$$

where

$$A_{i,j} = \frac{1}{N}\sum_{k=1}^{N}\left(\begin{cases} \dfrac{\rho(h_k)}{\sqrt{|h_k|}} \times \operatorname{sgn}(h_k) & \mathit{when} \quad \rho(h_k) \geq \rho_{tr} \quad \mathit{and} \quad h_k \neq 0 \\ \rho(h_k) & \mathit{when} \quad \rho(h_k) \geq \rho_{tr} \quad \mathit{and} \quad h_k = 0 \end{cases}\right) \tag{3}$$

and where $\rho(h_k)$ corresponds to the *CCF* values which occur at lag time h_k, ρ_{tr} is the value of the positive threshold of statistical significance, *N* corresponds to the number of *CCF* values that exceed the upper bound of statistical significance.

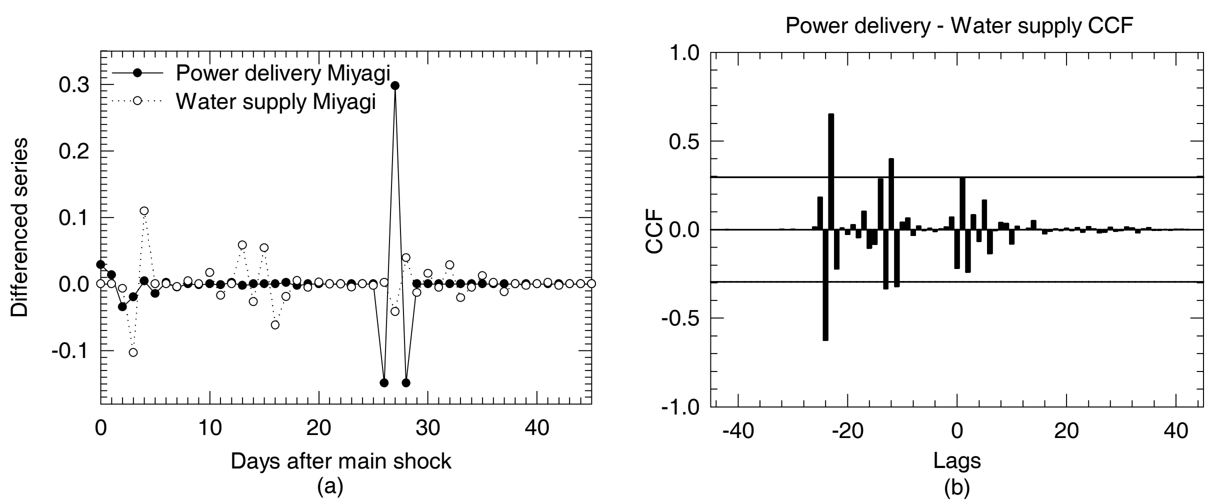

Figure 3 Miyagi region data: (a) Power delivery and Water supply restoration curves logarithmically transformed and second differenced; (b) Cross correlation function of Power delivery and Water supply.

The restoration curves of n-infrastructures are analyzed and the results are organized in a interdependency square matrix **S** of dimension n x n in which the terms in the diagonal always have value 1, whereas the terms $S_{i,j}$ outside the diagonal can range from -1 to +1. Equation (3) is used only for the evaluation of the off diagonal terms $S_{i,j}$ of the interdependency matrix **S**. A positive value of the index show that the i^{th} infrastructure (row) leads the restoration process of the j^{th} infrastructure (column), while a negative value of the index show that the i^{th} infrastructure (row) lags behind the restoration process of the j^{th} infrastructure (column). The degree of dependency is given by the absolute value of the index. When the index is close to 1 the dependency is high, while when it is close to 0 the dependency is weak (zero value indicates independency). The weights coefficients w_i of the different infrastructures, which are necessary to assess the regional resilience, are given by

$$w_i = \frac{\sigma_i}{\sum_i \sigma_i} \tag{4}$$

where σ_i is the sum of the positive values $S_{i,j}$ of the i^{th} row of the interdependence matrix **S** that is given by

$$\sigma_i = \sum_j S_{i,j} \qquad when \quad S_{i,j} > 0 \tag{5}$$

In other words, all the positive values $S_{i,j}$ in a row of the interdependency matrix **S** are added and then normalized by the sum of all the positive terms $S_{i,j}$ of the **S** matrix. In particular, they are calculated using the positive values of the interdependency matrices corresponding to different lifelines. The physical meaning of the weights coefficients can be explained with an example by assuming that the infrastructures are independent. In this special case the S matrix is an identity matrix; therefore, the weight coefficients evaluated with Equation (4) will be all identical. Equal weight coefficients in this particular condition have physical meaning because in this case no infrastructure is leading another one, so no one can be considered more important than the other ones.

Evaluation of the Regional Resilience Index

Finally, once the weight coefficients are evaluated, community resilience [20] is evaluated using the following Equation

$$R = \sum_i \left(R_i \times w_i \right) \tag{6}$$

where R_i is calculated using Equation (1). Finally, the proposed methodology for the evaluation of the weight coefficients is applied to the 12 Japanese prefectures affected by the 2011 earthquake and for the three different types of lifelines.

Decomposition of the restoration curves in interval ranging between two consecutive shocks

As highlighted in the paper of Cimellaro and Solari (2013)[15] an anomalous behavior of the interdependency values $S_{i,j}$, which gives a negative value for the combinations Power-Water and Power-Gas was observed. Same behaviors were observed in other case too. The reasons of this anomalous behavior in the evaluation of the $S_{i,j}$ terms with the proposed procedure is probably due to the shape of data collected. Indeed the main shock generates an initial drop of functionality which is coupled with other two strong and narrow aftershocks in the same region. This generates coupling between these three narrow events which modify the shape of the restoration curves. This coupling effect generates distortion in the evaluation of the $S_{i,j}$ terms using Equation (2). The data set recorded of 47 days has been divided in three periods (A, B and C) to solve the numerical problems. The partition is shown in Figure 4 for the case of Iwate region, where each period is bounded between two consecutive aftershocks.

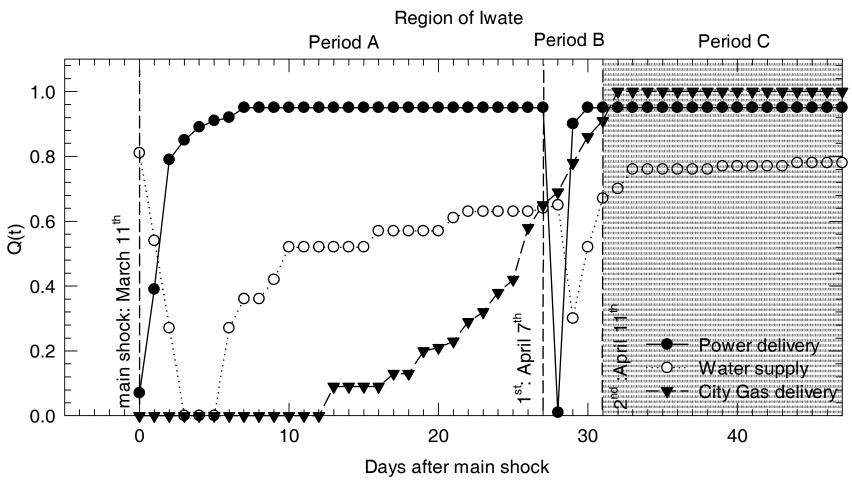

Figure 4 Restoration curves of Iwate region with subdivision into homogeneous parts between two consecutive strong shocks

In particular, in Figure 4 the vertical dotted lines correspond to the main shocks and aftershocks. The first period (A) ranges from the first main shock which occurred on March 11th until the first main aftershock which occurred on April 7th; the second period (B) ranges from April 7th to the second main aftershock which occurred on April 11th; the third period (C) ranges from April 11th until the end of the recorded data. Then the proposed procedure for the evaluation of the weight coefficients described in previous paragraph is applied separately in the three different period ranges. Extensive sensitivity analysis described in Cimellaro and Solari (2013) [15] bring to the following conclusions:

1. Every event that causes loss of functionality should be maintained separate when cross-correlation methods are used for the calculation of the interdependency indices and the weight coefficients;
2. The separation point of the restoration curves should be selected in correspondence of an evident drop of functionality of at least one lifeline within the same region.

Numerical results of the regional resilience index

In Fig. 5 are shown the values of the weight coefficients of each lifeline calculated according to the different period ranges used for the evaluation of the interdependency index $S_{i,j}$, for the Iwate prefecture. In particular, the weight coefficients calculated using period B and C have almost all the same values, because the interdependency matrices $S_{i,j}$ from which the weight coefficients depend are almost all identity matrices. The same trend is observed on the period B+C for the regions of Yamagata, Akita, Ibaraki, Tochigi, Chiba, Gunma, Saitama and Kanagawa which were slightly or no affected by the aftershocks (not shown). Relevant variations of the weight coefficients on the period range B+C has been observed instead in the regions of Miyagi, Iwate, Fukushima and Aomori which were closer to the epicenter. For comparison purpose in Fig. 6 are shown all the regional resilience indices calculated using the first period range and the entire period range on the 12 Japanese prefectures.

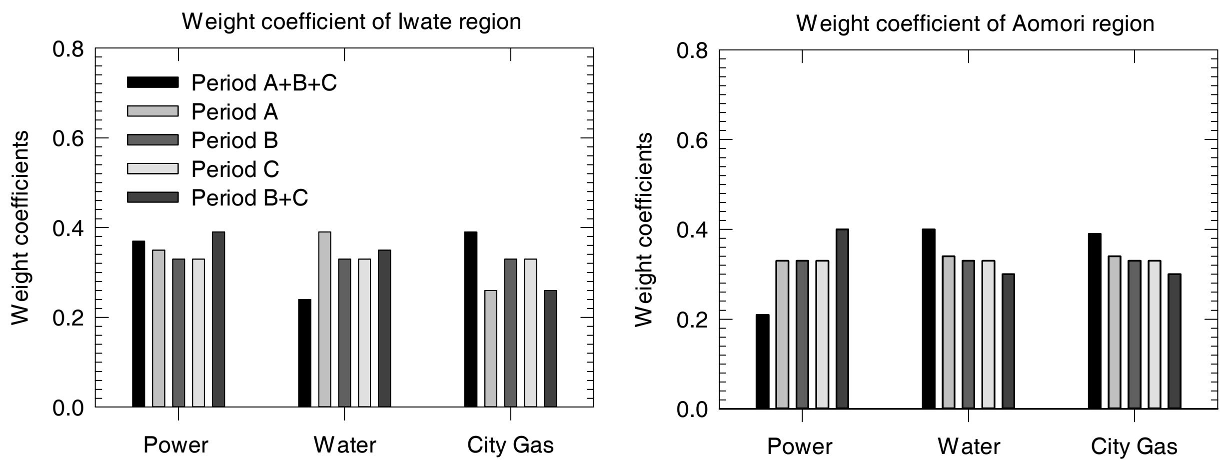

Figure 5 Comparison of weight coefficient for Iwate and Aomori regions calculated for different period ranges.

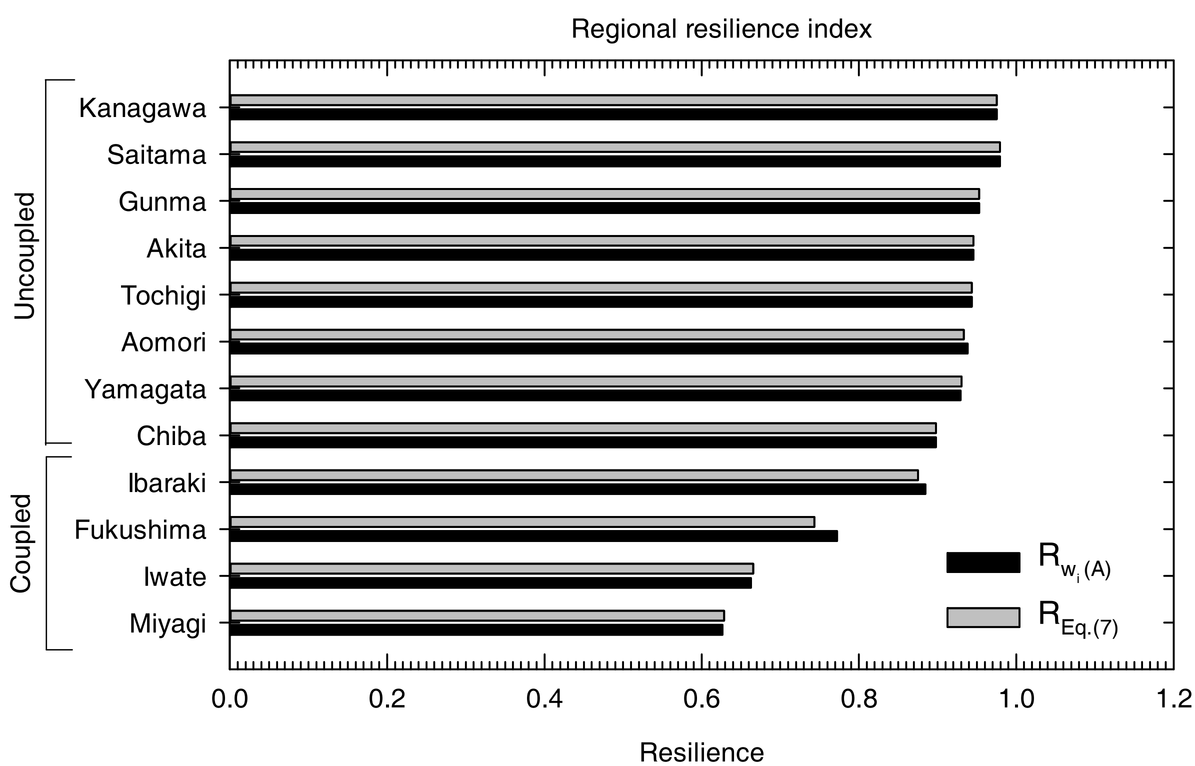

Figure 6 Regional resilience index with Tc = 47 days

The prefectures with the greater variability are closer to the epicenter of the main shock (Miyagi, Iwate, Fukushima). These three regions have also restoration curves with coupled resilience behavior (Fig. 1). Therefore, from the observation of Fig. 6 it can be concluded that in the regions that have the characteristics of uncoupled resilience, the weight coefficient distribution tends to be irrelevant for the evaluation of the regional resilience index. The weight coefficient distribution becomes important for lifelines with coupled resilience behavior. This also implies that the same weight distribution can be used as first approximation for the lifelines of a region in which the restoration curves has uncoupled resilience behavior.

Remarks and Conclusions

The paper presents a methodology for the optimal selection of the period range to evaluate the weight coefficients which are assigned to different lifelines for the evaluation of the resilience index in a community. The proposed method is based on the analysis of the lifelines' restoration curves using cross-correlation functions. To show the implementation issues, the restoration curves recorded after March 11th 2011 Tohoku Earthquake, which are characterized by the effects of strong aftershocks, subsequent to the main event, are considered. Based on the analysis of the restoration curves, it was observed that a good approximation of the weight coefficients is obtained when the period range between the main shock and the first aftershock that causes the drop of functionality in at least one lifeline and in at least one region is selected.
The main general approach consists in the evaluation of the weight coefficients and their different period ranges. The selection among different methods is based on the characteristics of the restoration curves. If the restoration curves have uncoupled resilience characteristics, the equal weight coefficients can be used or the approximated method with weight coefficients evaluated only on the period between the main shock and the first aftershock that causes the drop of functionality of at least one lifeline in the analyzed region. Instead, if the restoration curves have coupled resilience characteristics, the exact method based on the entire period range can be adopted.

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