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RESILIENCE FINDINGS

Holistic Modelling of Loss and Recovery for the Resilience Assessment to Seismic Sequences

Iunio Iervolino[1], Massimiliano Giorgio[2]

[1] Dipartimento di Strutture per l'ingegneria e l'Architettura, Università degli Studi di Napoli Federico II, [2] Dipartimento di Ingegneria Industriale, Università degli Studi di Napoli Federico II

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Findings

Earthquakes typically occur in time-space clusters. Classical probabilistic seismic risk analysis, only consider the prominent magnitude earthquakes within each cluster. This implicitly corresponds to neglect that, for exposed infrastructure, the clustering behavior of seismic events may, on one hand, cause damage accumulation and prolonged business interruption and, on the other hand, may delay or disrupt the repair and recovery processes. In the paper, a Markov-chain-based model, able to describe both loss and recovery during aftershock sequences is presented. It preserves most of the benefits of the classical approach and can be extended to enable modelling of peculiar resilience features such as delay in recovery initiation.

1. Questions

Earthquake clusters are made of the mainshock and its contouring events, foreshocks and aftershocks, respectively. Stochastic modelling of seismic clusters' occurrence, and related shaking at a site of interest, can consist in a hierarchical approach in which mainshocks' occurrence follows a homogeneous Poisson process, whereas the other seismic events in each cluster follow a conditional process (Iervolino, Giorgio, and Polidoro 2014). For example, aftershock occurrence can be modelled as a non-homogeneous Poisson process, the intensity of which depends on some mainshock features (Yeo and Cornell 2009). In the context of seismic risk analysis this can be referred to as hazard modelling.

Any system of interest exposed to seismic risk is virtually vulnerable to each event of a cluster, and seismic loss can accumulate in multiple partially damaging events. This is especially true in the most hazardous part of the cluster, which is around the mainshock, because of the short interarrival time between earthquakes. This issue can be treated as a form of stochastic degradation process, and Markov processes (i.e., Markov chains) have been shown being suitable to describe it (Iervolino, Giorgio, and Chioccarelli 2016, 2020). This approach to model seismic vulnerability makes use of the system's state-dependent fragility functions.

Repair is one of the possible strategies to recover from seismic loss. Recovery modelling is necessary for the *resilience* assessment (Bruneau et al. 2003). Research shows that the starting of the repair process can be delayed by factors such as the availability of resources and administrative issues (Costa, Haukaas,

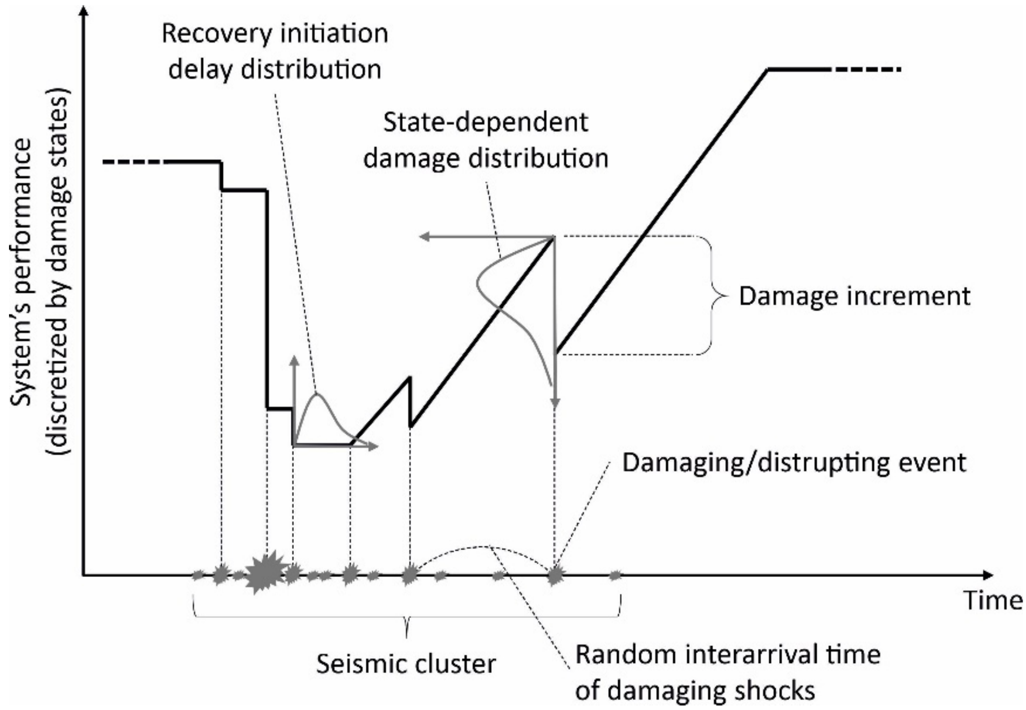

Figure 1. Sketch of the phenomenon which is the target of the question.

and Chang 2020). As mentioned above, also the time-space concentration of seismic events can temporarily delay or disrupt the recovery (Iervolino and Giorgio 2015).

The research question is about developing a Markovian model that enables a holistic modelling of seismic damage (yet neglecting foreshocks) for a system of interest. This was first envisaged in Chioccarelli, Giorgio, and Iervolino (2021) and is conceptually formulated herein. Figure 1 sketches the phenomenon which is the subject of the modelling question.

2. Methods

Aftershock probabilistic seismic hazard analysis (APSHA; Yeo and Cornell 2009) models the occurrence of aftershock according to a non-homogeneous Poisson process; i.e., characterized by a time-variant rate. In this context, the evolution over time of the seismic damage accumulation and recovery in aftershock sequences can be described by using a non-homogeneous Markov chain, where both the damage level and the time elapsed from the mainshock are measured on discrete scales. Given the probability vector of the initial state, the model is fully defined by its transition matrix. This matrix, indicated as $[P(k, k+1)]$, contains the probabilities that in each time unit the system passes from a given damage state to another, as:

$$[P(k,k+1)] = \begin{bmatrix} p_{1,1}(k) & p_{1,2}(k) & p_{1,3}(k) & p_{1,4}(k) \\ p_{2,1}(k) & p_{2,2}(k) & p_{2,3}(k) & p_{2,3}(k) \\ p_{3,1}(k) & p_{3,2}(k) & p_{3,3}(k) & p_{3,4}(k) \\ p_{4,1}(k) & p_{4,2}(k) & p_{4,1}(k) & p_{4,4}(k) \end{bmatrix}. \quad (1)$$

The size of the transition matrix refers to the number of damage states used to define the ordinal scale of the system's quality (i.e., performance) function; in the example, four damage states (i.e., $DS_1, \ldots, DS_4$), ordered by increasing severity, are considered. The parameter k indicates the number of units of time elapsed from the mainshock. The generic element, $p_{i,j}(k)$, represents the conditional probability that the system, which is in state $D(k) = DS_i$ at time k, is in $D(k+1) = DS_j$ at time $k+1$, that is:

$$p_{i,j}(k) = P\left[D(k+1) = DS_j \mid D(k) = DS_i\right]. \tag{2}$$

The transition matrix can be formulated as:

$$\begin{aligned} [P(k, k+1)] &= v(k) \cdot [D] + [1 - v(k)] \cdot [R] \\ &= v(k) \cdot \begin{bmatrix} d_{1,1} & d_{1,2} & d_{1,3} & d_{1,4} \\ 0 & d_{2,2} & d_{2,3} & d_{2,3} \\ 0 & 0 & d_{3,3} & d_{3,4} \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &+ [1 - v(k)] \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ r_{2,1} & r_{2,2} & 0 & 0 \\ r_{3,1} & r_{3,2} & r_{3,3} & 0 \\ r_{4,1} & r_{4,2} & r_{4,3} & r_{4,4} \end{bmatrix}, \end{aligned} \tag{3}$$

where $v(k)$ is the rate of aftershock occurrence evaluated at time k (which is dependent on the magnitude of the mainshock). D is the matrix that contains the (conditional) probabilities of transitions determined by a generic aftershock (of unspecified magnitude and location), that is those of the type $DS_i \rightarrow DS_j, i \leq j$. R is the matrix that contains the (conditional) probabilities of transitions of the type $DS_i \rightarrow DS_j, i \geq j$, because of the recovery activities. The model assumes that in a unit of time only one of these two types of transitions can occur. For the model to work, it should be $v(k) << 1$, that is achieved by assuming a time scale in which units are small enough.

The probability vector of the state of the system at time m, $P(m) = [P_1(m), \ldots, P_4(m)]$, where $P_i(m) = P[D(m) = DS_l]$, $l = 1, \ldots, 4$, can be obtained as:

$$P(m) = P(0) \cdot \prod_{k=0}^{m-1} [P(k, k+1)] \tag{4}$$

The probability vector of the initial state $P(0) = [P_1(0), \ldots, P_4(0)]$, refers to the damage state of the system immediately after the mainshock.

Apparently, the model in equation (3) cannot describe the early phase of the recovery process that usually shows a delay in starting the recovery activities (i.e., Figure 1). In fact, a more general Markovian model (i.e., a Markov chain), which can also address this issue, can be formulated by using the *device of stages* (DOS) technique (e.g., Cox and Miller 1965). DOS entails modeling a non-exponential sojourn time by a proper arrangement of stages in which sojourn time is exponentially distributed, enabling to deal with non-Markovian processes via the Markovian theory.

3. Findings

Building on previous works on the topic by the authors, a holistic Markovian model for seismic damage accumulation and recovery during seismic sequences was formulated. The model works in the hypothesis of aftershock probabilistic seismic hazard analysis. Hence, it should be intended conditional to the known features of the triggering mainshock. Its main limitations are: (i) that it neglects foreshocks, and (ii) that it does not explicitly model the typical random delay in starting the recovery activities. However, both these issues can be addressed by suitable adjustments of the model. For example, issue (ii) can be readily solved by using the DOS technique.

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