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Methodology for real-time prediction of structural seismic risk based on sensor measurements

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ABSTRACT

Current earthquake early warning systems utilize p-wave data to predict the extent of an earthquake threat and issue warnings at a regional scale. In the assessment of seismic risk, we propose a methodology to go beyond ground motion prediction to consider the response of the structure itself. It is a localized real-time approach where we utilize the first 3 s of data from sensors mounted on a structure to infer the characteristics of the upcoming earthquake. These parameters are used to simulate ground acceleration histories and the structural response estimated under each input motion. A structure-specific warning can then be issued based on the predicted maximum structural response. The method enables probabilistic inference on the structural risk to the earthquake event. In this paper, we describe the proposed methodology and apply it to an example earthquake. We assess the accuracy of the method, compute its computational efficiency, and investigate its robustness to uncertainty in system parameters. Finally, we apply the method to several recorded earthquakes to demonstrate its generalizability. The approach does not require extensive knowledge of regional earthquakes or site characteristics. Such data, however, if available, can be easily incorporated to improve the efficiency and accuracy of the method.
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1. Introduction

Earthquakes are among the most significant natural hazards we face, causing an average of $12 billion in economic damages and nearly 13,000 deaths annually across the globe [1]. The risk from any natural hazard depends on the occurrence and extent of the hazard, vulnerability of the infrastructure, and consequential effects on the population. With aging infrastructure, growing populations in earthquake-prone areas, and an increasing number of earthquakes including due to human activities such as fracking and saltwater disposal, global seismic risk is increasing. Effective earthquake early warning systems would enable protective measures to be taken and vulnerable populations to seek safety before the full extent of a seismic event occurs.

The complexity in the nucleation and growth of an earthquake, however, makes it difficult to accurately predict seismic events. Recently, several early warning systems have been developed, which use real-time seismology to issue an earthquake warning, e.g. Earthquake Early Warning (EEW) program run nationwide in Japan by Japan Meteorological Agency (JMA), ShakeAlert early warning system operated in California through California Integrated Seismic Network (CISN), and Seismic Alert System (SAS) running in Mexico City. These systems rely on the real-time recording and processing of earthquake data. Such models predict the extent of a regional earthquake threat based on the content of the seismic wave within the initial few seconds of a recorded event. We propose an early warning system that goes beyond ground motion prediction to consider the response of the structure itself. The objective is to create a methodology that provides an earthquake early warning based on the anticipated structural response, which is predicted from information from sparsely instrumented buildings rather than relying on extensive seismological data. The proposed localized and structure-specific approach uses collected data to run simulations and create a suite of synthetic accelerograms. These accelerograms are then used to estimate structural responses, with warnings based on predicted maximum responses.

Specifically, the methodology first takes the data from an accelerometer placed on the structure and separates the ground motion and structural response in real time. The initial 3 s of p-wave data is used to estimate the characteristics of the earthquake, including moment magnitude, Arias intensity, and hypocentral distance from the structure. A number of ground motions are then simulated based on these parameters. From these, we find the structural response for each simulated ground motion and infer the maximum structural response due to the upcoming earthquake. The future structural response is predicted as the average

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of the responses to the set of predictive simulated ground motions. The proposed method does not require extensive knowledge of the regional seismic history, local ground characteristics, or information from additional seismograph stations. It is a minimalist approach, which can, however, be made more accurate if conditioned on additional known seismological information at the site under consideration.

The rest of the paper is organized as follows: Section 2 provides background on previous work on seismic risk and earthquake early warning systems. Section 3 describes the proposed methodology, including separation of the ground motion and structural response, early prediction of earthquake parameters, and simulation of ground motions. The results of the methodology are presented in Section 4, with the distribution of predicted maximum responses and root mean square errors of the predictions presented for an example earthquake. Computational efficiency of the methodology is investigated, as well as robustness of the method to uncertainty in assumed system parameters. Finally, the methodology is applied to several earthquakes to investigate the generalizability of the methodology across earthquake events.

2. Background

Most of the previous work on structural seismic risk has focused on assessing risk to a building or region before or after an event has occurred. Pre-event analyses include recent work in response estimation and building portfolio reliability assessment to compute seismic loss probabilities [2–3]. Other work includes quantifying uncertainty in seismic risk assessment [4] and risk assessment for particular structures, such as reinforced-concrete frames [5–6], seismically isolated structures [7], and bridges [8]. Post-event analyses focus on damage mapping [9] and assessment [10] after the earthquake has occurred. In contrast to these studies, the methodology proposed here is for real-time prediction of seismic risk given the occurring ground motion. This is related to previous work in earthquake early warning with a focus on structural response in particular.

The development of earthquake early warning systems using real-time seismology dates back to Nakamura's introduction to the concept of using frequency content of p-waves for inferences on the characteristics of an earthquake [11]. The frequency content in the initial few seconds of the p-wave can be analyzed either as the period of a monochromatic wave (τ_c) or as the maximum period (τ_p^{max}). Kanamori [12] extended Nakamura's work to use in practical real-time seismology. Studies by Wu and Kanamori [13–16] show a strong correlation between τ_c and moment magnitude M_w. They developed an early warning system based on the initial 3 s of the p-wave by observing τ_c and the maximum ground displacement P_d. Through the τ_c - P_d method, P_d was found to have a good correlation with the peak ground velocity (PGV) of the approaching earthquake. Allen and Kanamori [17] and Olson and Allen [18] used τ_p^{max} to develop a similar methodology. Through the τ_p^{max} - P_d method, their work shows a strong relationship between τ_p^{max} and M_w.

Wurman, Allen, and Lombard [19]; Allen [20]; and Allen et al. [21] proposed ElarmS, which uses a network-based approach. It extends the single station approach from previous studies to a network of stations, where the data from the entire network is processed simultaneously to issue a regional warning. Cua and Heaton [22] developed virtual seismologist (VS), using a Bayesian approach to predict the most probable magnitude and location of an earthquake given observations through conditioning on historical data. An extensive data history is required for the prior distributions and conditioning. Wu, Kanamori, Allen, and Hauksson, [23]; and Shieh, Wu, and Allen [24] found relationships between the initial ground motion parameters and earthquake characteristics, with these methods subsequently used for earthquake warning applications in Böse, Hauksson, Solanki, and Kanamori [25]; Böse, Heaton, and Hauksson [26]; and Cheng, Wu, Heaton, and Beck [27].

All of the described earthquake early warning systems predict the extent of an upcoming earthquake for a region. These methods do not account for the behavior of individual structures. Assessing the seismic risk for a particular building requires a combined analysis of the ground motion and structural behavior. Therefore, we move beyond regional earthquake warnings to create a structure-specific and localized earthquake early warning system. This study investigates our proposal that from the first 3 s of structural sensor data, we can obtain predictive characteristics of the earthquake. If we then simulate a number of ground motions, then the average structural response will conform to the actual response of the structure under the approaching earthquake, enabling an early warning to be issued.

3. Methodology

3.1. Flowchart

The full methodology is shown in the flowchart given in (Fig. 1). The specific steps of the process are described in detail in the following sections.

3.2. Separation of ground motion and structural response

In this study, we assume a minimally instrumented building using low-cost accelerometers. The first step of the process is to use the data from the accelerometers placed on the structure to obtain the ground motion signal. If the accelerometer is placed on the ground at the structure, then it captures the ground motion directly, but if the same sensor is placed on any other part of the structure, then it records the sum of the ground motion and the structural response. Therefore, we need to separate these two elements from the accelerometer measurements [28]. To do this, the unscented Kalman filter (UKF) is used as in [29]. In addition, the sensor recordings contain ambient noise. As shown in [30], the error in the estimate due to ambient noise reduces significantly if the sensor is placed on the higher stories of a structure. Hence, if a structure is instrumented with a single accelerometer, as is assumed in this study, we recommend that the sensor be placed on the top story of the building for these applications. The effect of ambient noise and uncertainty in structural parameters are studied in [29–30] and the methodology is shown to perform well even under high uncertainties. Therefore, separate terms for different uncertainties are not considered in this analysis.

To separate the ground motion from the structural response, we begin with the equation of motion for a structure subjected to ground acceleration

$$\mathbf{M}\ddot{\mathbf{u}}_\mathbf{s} + \mathbf{C}\dot{\mathbf{u}}_\mathbf{s} + \mathbf{F}(\mathbf{u}_\mathbf{s}) = -\mathbf{M}1a_g \quad (1)$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{F}$ represent the mass, damping and spring force matrices, respectively. $\mathbf{u}_\mathbf{s}$ represents displacement of the structure and a_g acceleration of the ground. Defining $\mathbf{z}^\mathbf{T} := [\mathbf{u}_\mathbf{s}^\mathbf{T}\dot{u}_\mathbf{s}^\mathbf{T}]$ in first-order form, the equation of motion is

$$\dot{z} = \begin{bmatrix} 0 & \mathbf{I} \\ 0 & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}\mathbf{z} + \begin{bmatrix} 0 \\ -\mathbf{M}^{-1}\mathbf{F}(\mathbf{z}) \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix}a_g \quad (2)$$

$$\dot{z} = \mathbf{A_c}(\mathbf{z})\mathbf{z} + \mathbf{b_c}a_g \quad (3)$$

We discretize Eq. (2) as in [29] to obtain the evolution of the system from time step k to $k+1$