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Probabilistic seismic risk forecasting of aging bridge networks

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ABSTRACT

Bridges are the most vulnerable elements in transport systems, and they may undergo structural problems due to environmental conditions and natural disasters. Governmental agencies and owning companies must therefore plan maintenance and retrofit interventions rationally, to avoid potential severe network disruptions. With reference to seismic risk, several studies on the risk assessment of bridge networks, and on aging as one of the main factors affecting the seismic vulnerability of existing bridges, have recently also been reported. In these contributions, the seismic fragility of bridges is considered as a time-dependent parameter, whereas seismic hazard and financial exposure are described according to classic stationary assumptions. The present study proposes an innovative, comprehensive and fully time-dependent probabilistic seismic risk framework, to evaluate the expected average annual loss for stocks of deteriorating bridge structures. This framework is illustrated in a case study of 500 bridges and the results are critically discussed.

1. Introduction

Transport systems play a key role in performing economic and strategic activities and, immediately after a catastrophic event, they allow rescue operations to be initiated. However, such systems, which serve large geographic areas, may be vulnerable to a variety of hazardous natural events, such as earthquakes, hurricanes, floods and tsunamis. Network vulnerability is generally a function of individual network component vulnerabilities: in transport systems, bridges are the most vulnerable components and may also have structural problems, due to environmental conditions and aging. Bridges are usually subject to fluctuations in humidity and temperature, and are also significantly exposed to chloride ions in coastal areas and CO_2 in highly anthropic environments and, over time, these aggressive agents may cause extensive deterioration of structural bridge members. Aging causes a reduction in structural capacity and thus to vulnerability which, in some cases, may lead to structural failure if a hazardous event – such as an earthquake – occurs [1,2]. The estimation of structural and seismic capacity reduction induced by deterioration for existing structures is therefore a matter of recent interest, due to the increasing number of aging bridges and the need to define rational strategies for allocating limited financial resources for retrofit interventions. Recent studies investigating the seismic behavior of deteriorating bridges have been published by several authors [3–10], showing the close link between seismic vulnerability and the time dimension.

However, for proper characterization of the seismic risk of a structural system, vulnerability must be associated with the particular seismic hazard of the site and a consequence function expressing structural damage in terms of a chosen variable must be chosen. In this regard, structural engineers play a key role in understanding and communicating the risk of seismic hazards and their uncertainty to owners, bankers and insurers (i.e., the economic and financial aspects). In 2003, the Pacific Earthquake Engineering Research (*PEER*) Center formulated a Performance-Based Earthquake Engineering (*PBEE*) probability framework [11], based on the calculation of a triple integral equation, in which randomness and uncertainty are combined according to the total probability theorem. Seismic hazard assessment, structural response analysis, quantification of damage, and estimate of damage consequences in terms of a chosen decision variable are the main subtasks required in the framework. The decision variable may represent a direct consequence of seismic damage, such as reconstruction costs (usually expressed in terms of loss ratio, i.e., the cost to repair a structure hit by a quake divided by the total replacement cost) or as an indirect consequence, commonly expressed by specific traffic indicators [12] (e.g., drivers' total delay) in the case of analysis of transport networks. An improvement to the *PEER* formula was subsequently developed [13,14] to

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summarize a range of seismic scenarios, return rates, and expected damage in a single parameter called Expected Annual Loss (*EAL*), derived by integrating scenario losses over the entire range of occurrence probabilities.

In the *PBEE* probability framework, the mean annual frequency of a decision variable is calculated with the classical Poissonian assumption of time-independent temporal occurrence of earthquakes. This assumption significantly affects results, particularly for estimating seismic losses of bridge networks, since the time dimension is one of the main input variables to be taken into account, e.g., defining the seismic fragility of bridges. Alipour and Shafei [15] recently presented an interesting study, a first attempt to consider time dependency in seismic risk assessment, the time dimension being taken into account in the fragility sub-task. However, advances may also be made by introducing the time dimension for estimating seismic hazard and damage-consequence functions. Seismic hazard and exposure are in fact also characterized by time dependency, mainly due to the kinematics of faults, on one hand, and to the trends of market prices and inflation, on the other. A seismogenic source model of individual or composite fault sources characterized by kinematic and temporal parameters can in fact be used instead of the classic one, based on seismogenic zones defined by historical earthquake catalogs [16]. Consequence functions may also be viewed as time-dependent, taking into account inflation, which involves a variability over time of reconstruction costs and requires inflation forecast models [17,18], particularly in the case of seismic risk assessment in the medium and long term.

For all these reasons, this study proposes a fully time-dependent framework for seismic risk assessment of bridge networks, taking into account the influence of the time dimension in the various subtasks, as shown in Fig. 1. An overview of the theoretical background and the best ways of treating time dependency in each seismic risk subtask are comprehensively discussed. The proposed framework is then applied to a case study of 500 bridges in the main road network of the Veneto Region, North-East Italy, and results are compared with those deriving from traditional methods of time-independent seismic risk assessment.

2. Improving classical EAL methodology estimation

Calculation of financial losses due to seismic risk for a portfolio of structures can be assessed, in general terms, with the *PEER* triple integral equation [19]:

$$\lambda(dv) = \iiint G(dv|dm)dG(dm|edp)dG(edp|im)|d\lambda(im)| \tag{1}$$

where $\lambda(x)$ is the annual rate of exceedance of x; *im* is the seismic intensity measure (e.g. peak ground acceleration or spectral acceleration at structural period T_s); *edp* is an engineering demand parameter (e.g., interstorey drift, maximum top pier displacement); *dm is* a measure of damage (e.g., slight/moderate/extensive damage, collapse); dv is a decision variable (e.g., loss ratio, loss of human lives, drivers' delay); and $G(x|y) = P(x > X|y = Y)$ is the conditional complementary cumulative distribution function (*CCDF*). *EAL* can be calculated ~~by~~ integrating all the losses over the entire range of probability as follows:

$$EAL = \int_0^\infty L_r|dP(L_r)| \tag{2}$$

where dv is assumed in (2) to be a loss ratio *Lr* (defined as the ratio between cost to repair a structure and related total replacement cost) and *P*(*Lr*) represents the probability of the loss ratio exceeding a specified value *Lr*. Considering *EAL* as a measure of the seismic risk of a portfolio of structures, estimation of financial loss may be obtained substituting (1) into (2), which gives the following four-fold integral:

$$EAL = \iiint \int L_r dG(L_r|dm)dG(dm|edp)dG(edp|im)|e^{-\lambda}d\lambda(im)| \tag{3}$$

These terms allow us to estimate the expected annual losses for the structures in question, with the classical assumption of seismic risk independence of time. However, each factor considered in the calculation of *EAL* is characterized by the dependence of time. The calculation of *EAL* therefore requires a time-dependent framework which takes into account variability over time for each factor

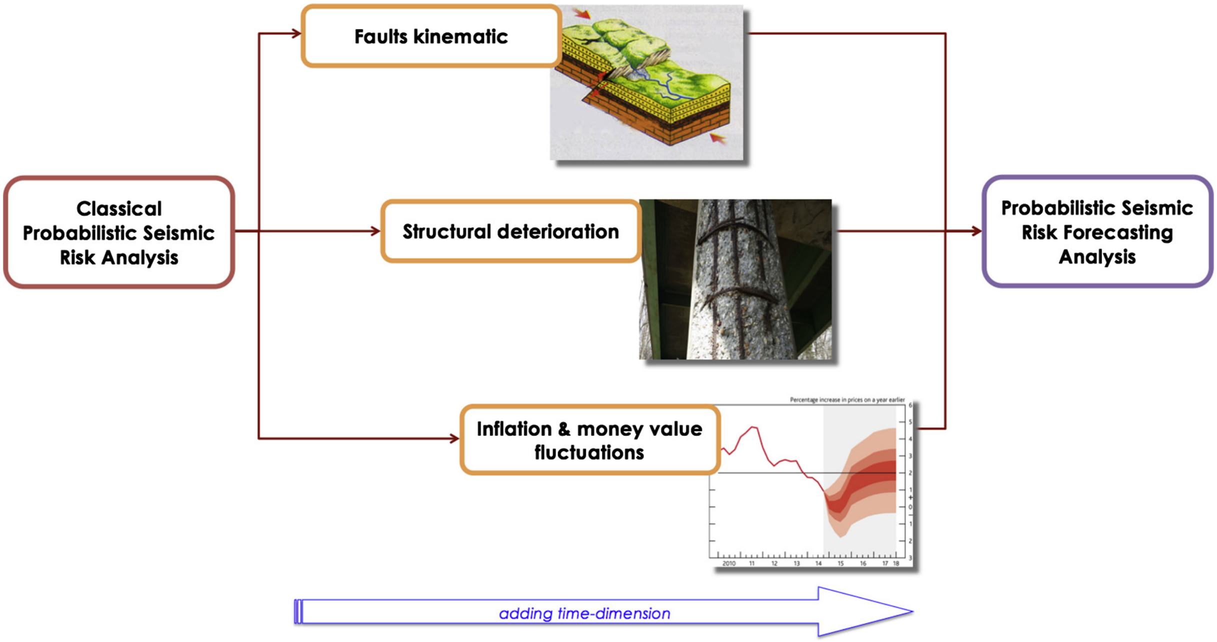

Fig. 1. Moving from classical to fully time-dependent probabilistic seismic risk analysis framework.