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A multi-type multi-occurrence hazard lifecycle cost analysis framework for infrastructure management decision making

Ehsan Fereshtehnejad, Abdollah Shafieezadeh*

Department of Civil, Environmental & Geodetic Engineering, Ohio State University, Columbus, OH, USA

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ABSTRACT

Infrastructure systems, especially in hazard-prone regions, may face multiple occurrences of multiple types of hazards during their lifetime. The type and intensity of the hazards and impacts on systems can vary from one event to another. An important factor that has yet to be properly addressed in natural hazard loss estimation models is the impact of damage induced by various types of prior events on the increased vulnerability of systems against various types of potential future hazards. This paper presents a new hazard lifecycle cost analysis framework that addresses this gap and accounts for effects of incomplete repairs of damage conditions induced by prior natural hazards on the future hazard performance of systems. Considering that the space of scenarios for multi-hazard occurrences and the impacts over the lifetime of infrastructure systems is significantly large, a recursive algorithm is proposed to efficiently determine the lifecycle cost of the system. This framework is applied to a realistic bridge exposed to flood and earthquake hazards to determine the optimal retrofit plan that reduces the overall lifecycle cost of the bridge. Results show the significance of considering different damage types induced by multiple types of hazards and repair time variations for lifecycle cost analysis of infrastructure systems.

1. Introduction

Critical infrastructure systems such as highway bridges play an important role in providing essential services to communities and supporting economic growth and prosperity of societies. In some regions, these systems are exposed to multiple types of hazards with the potential of each hazard type occurring multiple times with different intensities during the service lifetime of the infrastructure. For example, in a seismic region, an arterial highway bridge built on a river with high water discharge is prone to experience multiple occurrences of earthquakes and floods. These hazards may induce different types of damage once they occur. An incurred damage, if not fully repaired before the next hazard event occurs, may aggravate the extent of induced damage during future potential hazards. Thus, damage could accumulate and degrade the condition of an infrastructure at a faster rate, if repair actions are incomplete by the time of next hazard incidents. Moreover, repair time may vary from a short period to a long time depending on many factors including the extent of damage, type of repair or retrofit strategy, the agency's response time to plan for post-hazard inspections and repairs, and socio-economic factors. This highlights the need to consider variations in repair times and account for effects of residual damage of different types from prior events in the hazard performance assessment of infrastructure systems. Each occurrence of damage in an infrastructure is accompanied by a set of potential adverse consequences including human casualties, damage to the environment, and economic losses. As a large variety of retrofit plans have been developed for various infrastructure systems, a decision-making framework capable of properly modeling hazards and the above mentioned dependencies and uncertainties is needed to identify the most cost-effective retrofit strategies that minimize adverse consequences of hazards.

In the literature of risk analysis for infrastructure systems, Lifecycle Cost (LCC) that expresses the risk of extreme events in terms of monetary loss over the service life of the system is considered as one of the most appropriate performance measures for infrastructure decision-making [1–4]. In LCC analysis frameworks, risk of an extreme event is defined as the product of the likelihood of that extreme event and the incurred damage consequences expressed in a monetary unit. LCC can also include costs of routine maintenance and inspections that are periodically performed. A number of studies have developed and applied LCC frameworks to investigate effects of a single type of hazard on an infrastructure and identify optimal strategies for managing risks to the system. Examples of such studies include Vanmarcke and Guerrero [5], Yeo and Cornell [6,7], Veneziano et al. [8], Freddi et al. [9], Junca and Sanchez-Silva [10], Yilmaz et al. [11], and Chandrasekaran and

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* Corresponding author.
E-mail address: shafieezadeh.1@osu.edu (A. Shafieezadeh).

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Banerjee [12]. In these investigations, for all possible damage states that the system may experience, the repair following each hazard occurrence was considered to be instantaneous or it was assumed that no repair action is performed after such events. In reality however, the repair time and the time of preparing for the repair actions varies depending on the damage state that the system experiences, type of rehabilitation/repair strategies, and socio-economic factors, among others. In case of long repair times in the aftermath of severe damage states, the likelihood of next hazards occurring before the system is completely repaired increases. In this case, the existing damage very likely aggravates the level of damage that the next hazard can induce, which consequently increases the vulnerability of the infrastructure system. On the other hand, if the structure sustains a less severe damage following an extreme event, there is a high probability that the repair action is complete and the system is back to the intact damage state before next hazard events affect the system. Successive hazard events can be of the same or different types. As an example for the former case, in September 2010, an earthquake with the magnitude of 7.1 caused widespread damage to structures and infrastructure systems in Christchurch, New Zealand [13]. Six months later, an aftershock with the magnitude of 6.3 shook the same region and induced further damage in already damaged structures and infrastructure systems, and caused 185 casualties [14]. In some regions, successive hazard events appear to be of different types. For instance in 2011, in the east coast of Honshu, Japan, a devastating tsunami took place due to a strong earthquake that happened just before the tsunami [15]. Both the earthquake and the tsunami caused massive destructions to the region's infrastructure [16]. Thus, it is imperative to incorporate multi-hazards and account for the dependencies among their induced damages in order to reliably evaluate the performance of infrastructure systems.

Looking at the LCC performance assessment of infrastructure systems subjected to multiple types of hazards, many studies disregarded potential dependencies among damage conditions induced by various hazard types. For instance, in the frameworks proposed by Wen and Kang [17] and Deco and Frangopol [18], total LCC of an infrastructure exposed to multiple types of hazards was derived as the sum of independently-computed LCC of individual hazard events. Jalayer et al. [19] attempted to address such dependencies for multiple hazard types in a framework that requires simulating all possible scenarios for the order of hazard events of various types and intensities. According to the theorem of total probability, in order for the risk evaluation to be complete, all possible combinations of these ordered-event scenarios must be evaluated for the LCC analysis; this requirement makes the strategy significantly time-consuming considering that the required number of combinations of hazard order and intensities can be extremely large. In addition, in that framework, modeling each hazard scenario requires extensive static pushover and nonlinear dynamic analyses, thus further increasing the computational demand of the framework. There are also a number of assumptions in the framework that may not accurately represent the performance of actual systems as elaborated in [20].

In a previous study by the authors [20], a probabilistic framework was developed for the calculation of lifecycle hazard risk costs; the framework addressed some of the above issues by incorporating dependencies of the hazard performance of an infrastructure during the next extreme event to existing conditions considering the likelihood of incomplete repair of damages from prior events. However, the framework could handle only one type of hazard e.g. only earthquakes. This study extends the framework by addressing the remaining issues and releasing the assumption of one hazard type throughout the service life of the system. The new contributions offered in this paper are listed below:

- The proposed method probabilistically incorporates all possible scenarios of multiple types and multiple occurrences of hazard events.
- It models dependencies among various types of damage induced by consecutive hazards of the same or different types.
- The framework takes into account the impact of the repair time associated with each damage type and the likelihood of repair actions being completed by the time of the next hazard occurrence.
- A complete and computationally efficient risk analysis procedure is developed for the calculation of multi-hazard lifecycle risk costs. This is achieved by developing a dynamic programming procedure for computing the expected damage state probabilities at each hazard occurrence.

The proposed framework applies the total probability theorem and conditional probability chain rule to capture the above uncertainties and dependencies among multiple events. In addition to the expected lifecycle hazard-induced risk costs, initial cost of construction/retrofit, and lifetime cost of implementing maintenance actions are accounted for in the total LCC analysis framework. The proposed methodology is demonstrated for the calculation of the LCC of a realistic bridge in California. Data from various sources are gathered and, when not available, reasonable assumptions are made. The total LCC is used for the identification of optimal retrofit plans for the bridge for a wide range of decision-making time horizons. While the case study focuses on LCC assessment of a structural system, the proposed framework can be used to analyze the LCC of infrastructure networks [21].

In the rest of this paper in Section 2, the proposed framework is presented in detail. Section 3 explains the characteristics of the case study bridge and presents data required for the application of the proposed LCC analysis framework. In Section 4, a numerical analysis is performed to investigate the convergence of the framework, and LCC analysis results are provided for a set of retrofit options for various decision-making time horizons. Moreover, the various advantages offered by the proposed framework are explained in this section. Finally in Section 5, conclusion remarks are presented.

2. Lifecycle cost analysis framework

The total incurred cost, C_T, in the service lifetime of an infrastructure system typically includes the initial construction cost, C_0, total maintenance cost, C_M, and the total cost incurred on users, agencies, the economy, and environment as a result of damage induced by extreme hazards that occur in the lifetime of these systems, C_R. When LCC is evaluated for an existing building, C_0 is the cost of retrofit, and C_M and C_R are the total LCC of maintenance and hazards for the retrofitted structure, respectively. Due to uncertainties in the incurred future costs and investments, it is important to calculate the expected value of the total incurred costs. Furthermore, for the purpose of comparison and to account for the discounted values of these costs incurred in different years, Net Present Value (NPV) of the expected value of costs are considered in the LCC formulation presented as follows:

$$\overline{C}_{T,NPV} = \overline{C}_0 + \overline{C}_{M,NPV} + \overline{C}_{R,NPV} \tag{1}$$

where $\overline{C}_{T,NPV}$, $\overline{C}_{M,NPV}$, and $\overline{C}_{M,NPV}$ are the discounted NPV of the expected value of C_T, C_M, and C_R cost terms, and $\overline{C}_0$ is the expected value of C_0, respectively. If the LCC is evaluated for an existing system, $\overline{C}_0$ will be zero. In case of planning to upgrade the system, this cost is equal to the cost of such upgrade. It is often practical to perform periodical maintenance actions on infrastructures to keep them functioning in a healthy condition. On annual basis, $\overline{C}_{M,NPV}$ can be represented as follows:

$$\overline{C}_{M,NPV} = \sum_{t=1}^{T_{LC}-1} \gamma^t \times \overline{C}_{m,t} \tag{2}$$

where $\overline{C}_{M,NPV}$ is the expected maintenance cost at year t, T_{LC} is the expected service lifetime of the infrastructure, and γ is the annual discount factor equal to $\frac{1}{1+\delta}$, with δ as the discount rate.