Structural Safety 42 (2013) 63–74

Contents lists available at SciVerse ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Seismic risk analysis with reliability methods, part II: Analysis

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ARTICLE INFO

Article history:
Available online 28 February 2013

Keywords:
Reliability methods
Probabilistic models
Seismic risk
Software

ABSTRACT

Reliability methods are employed in this paper to analyze the seismic risk to the Vancouver metropolitan region in Canada. The use of reliability methods contrasts with several contemporary approaches for risk analysis. In this paper, two analysis approaches are presented and implemented in a new computer program. One utilizes the first-order and second-order reliability methods together with a hazard combination technique. The other is a sampling-based method that repeatedly generates damage scenarios in the time period of interest. Both strategies employ the same collection of probabilistic models for seismic risk analysis. While the models are presented in the companion paper, this paper presents the analysis options and a comprehensive application that comprises 559 random variables and 3227 model objects. The primary result is the loss curve, which exposes seismic loss probabilities and serves as a basis for risk mitigation decisions. It is found that the probability of loss in excess of $100 billion in the next 50 years is 5.6%. By-products of the analysis provide further insight; the most vulnerable municipalities and the most influential hazard sources are identified.

1. Introduction

Two objectives are pursued in this paper. One is to put forward a new risk analysis methodology that is based on reliability methods. The other is to provide seismic loss probabilities and additional insight for the Vancouver metropolitan region in Canada. The use of reliability methods to assess seismic risk is emphasized. This approach is suggested here as an alternative to other risk analysis strategies; one existing approach employs the total probability theorem and conditional probability models [1]; another is based on modified Mercalli intensity and damage probability matrices [2]. The intentions in this study is to leverage the power of classical reliability methods, make them available through a new computer program called Rt [3], and put forward a library of models.

The first part of this two-part paper describes the development of models for use with reliability methods. A collection of models for seismic hazard, response, damage, and loss is proposed and implemented in Rt. The software architecture of Rt is specifically designed to accommodate reliability and optimization with many interacting probabilistic models. Another important purpose of Rt is to make reliability methods accessible to a broad engineering audience. In the past, reliability methods, such as FORM and SORM, have primarily been employed by reliability experts in special applications and code calibration. Risk analysis, in contrast, is often conducted with other analysis techniques. The ATC-13 approach [2], proposed by the Applied Technology Council, was the first comprehensive framework for regional evaluation of damage due to earthquakes. ATC employed expert opinion to develop estimates of seismic damage and loss for different values of the modified Mercalli intensity. Rojahn et al. [4] presented an overview of the methodology, including a list of building categories and results. Two decades after the introduction of ATC-13, a handful of strong earthquakes prompted the development of a new loss estimation methodology by the U.S. Federal Emergency Management Agency and the U.S. National Institute of Building Sciences (FEMA–NIBS) [5]. The methodology was implemented in the computer program HAZUS®. Unlike ATC-13, the FEMA–NIBS approach employs the capacity spectrum method [6], which introduces mechanical considerations into the assessment of damage. The result of these approaches is an expected loss value. Alternatives to ATC-13 and FEMA–NIBS are explored in this paper, with predictive probabilistic models to generate the probability distribution of loss.

Recently, the use of conditional probabilities and total probability integration has become popular in seismic loss assessment. One example is the framing equation of the Pacific Earthquake Engineering Research Center [1]. Wen and Ellingwood [7] also proposed a framework based on total probability integration for fragility-based loss estimation of buildings. Ellingwood et al. [8] assessed seismic fragilities for typical building types in the central United States. The work presented in the present paper can be regarded as a reliability-based alternative to total probability

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http://dx.doi.org/10.1016/j.strusafe.2013.01.004

Fig. 1. Vancouver metropolitan region. The map of Canada is from Geological Survey of Canada Open File 5539 [27] and shows the significant earthquakes in or near Canada, 1663–2006.

integration over conditional probabilities. The models presented in the companion paper simulate a physical phenomenon and produce measurable responses, with uncertainty described by random variables.

Another set of studies on regional infrastructure focused on spatial distribution of the building performance over a region, and spatial correlation of the ensuing damage and loss. Wesson and Perkins [9] introduced a method to calculate the spatial correlation of earthquake ground motions and losses. Bielak et al. [10] provided an overview of the methods developed for large-scale regional simulation of seismic performance in a project on Seismic Performance of Urban Regions. Lee and Kiremidjian [11] presented a framework for treating the correlation in network risk analysis. Goda and Hong [12] investigated the effect of spatial correlation of seismic demand on the aggregate seismic loss of spatially distributed structures in a region. In contrast, the present study introduces correlation in part by modeling the underlying phenomena, *i.e.*, the location and magnitude of the earthquake that causes the ground shaking.

While most regional studies have considered a portfolio of hypothetical structures, some applications have established databases of actual buildings. In accordance with the ATC-13 [2] approach, Ventura et al. [13] developed the BC-31 classification of buildings in British Columbia, Canada, and generated a comprehensive database. The data were collected using rapid screening and visual inspection and covered a considerable part of the buildings in the cities of Vancouver, New Westminster, and Victoria in British Columbia. The first two cities are located within the Vancouver metropolitan region that is considered in this paper. Onur et al. [14] applied the ATC-13/BC-31 approach to the collected data to assess the regional seismic risk. One result was that the mean loss for the City of Vancouver due to an earthquake with a modified Mercalli intensity equal to eight is \$3.5 billion.

The Vancouver metropolitan region covers an area of 2887 km^2 and consists of 23 municipalities. For readers unfamiliar with the region, it is shown in the large map in Fig. 1. The names in the figure identify cities and townships that are addressed in this study. The small upper-right map in Fig. 1 identifies the region on a map of Canada to highlight the significant seismic hazard that the region is exposed to. This paper presents a comprehensive seismic risk analysis for the region, conducted with Rt and the models presented in the companion paper. In the following, the two analysis approaches are first presented, followed by a description of the Vancouver-specific modeling assumptions. Thereafter, the analysis results are presented and discussed.

2. FORM, SORM, and hazard combination

The essence of a reliability analysis is random variables, collected in the vector $\mathbf{x}$, and limit-state functions, $g_i(\mathbf{x})$. Both physical variables, *e.g.*, magnitude, and model variables, *e.g.*, model error, are included in $\mathbf{x}$. The primary objective of a reliability analysis with one limit-state function is to determine the probability that the limit-state function will take on negative outcomes. This probability is denoted by $p_i = P[g_i(\mathbf{x}) \le 0]$. In other words, the limit-state function identifies the event for which the probability is sought. The limit-state function

$$g_i(\mathbf{x}) = l_o - l_i(\mathbf{x}) \tag{1}$$

is central in this paper because it yields the probability that the loss, $l(\mathbf{x})$, is greater than the threshold, l_o. It is emphasized that the evaluation of $l(\mathbf{x})$ requires a host of probabilistic models of the type developed in the companion paper.

Any reliability method evaluates g and perhaps the gradient vector $\partial g/\partial \mathbf{x}$ several times, for different realizations of $\mathbf{x}$, to obtain an estimate of p_i. The first-order reliability method (FORM) is an appealing method because it requires only a handful of evaluations of g and $\partial g/\partial \mathbf{x}$ to produce a good estimate. FORM also provides valuable insight into the relative importance of each random variable. As described in [15], FORM includes a search for the "design point", which is the most likely realization of $\mathbf{x}$ associated with g_i = 0 in the space of standard normal variables. The result of the search is the reliability index β_i, which is related to the sought probability by the equation

$$p_i = \Phi(-\beta_i). \tag{2}$$

This result may be inaccurate if the limit-state function is strongly nonlinear in the space of standard normal variables. Under such circumstances, the second-order reliability method (SORM) and importance sampling are utilized to improve the FORM result; see details in, *e.g.*, [15] and [16].

The problem under consideration has several limit-state functions of the form in Eq. (1) because several sources of seismic hazard are present. Specifically, the region is subjected to shallow crustal earthquakes, deep subcrustal earthquakes, and megathrust subduction earthquakes. Because each of these sources is associated with different location and magnitude models, they are modeled as different hazards with different occurrence rates. In fact, the aforementioned sources are further subdivided in this study, and N denotes the total number of hazards. As a result, multi-hazard analysis is necessary when analyzing the seismic risk in Vancouver. Several multi-hazard analysis methods are available in the literature. One option is the load coincidence method described by Wen [17], which employs the Poisson pulse process. However, matters simplify in this study because the probability of the coincidence of two earthquakes is negligible. This implies that the Poisson point process is employed to model each hazard, each with rate of occurrence denoted by λ_i , i = 1,2,3,…,N.

Suppose a reliability analysis is carried out for each hazard, so that β_i and p_i are known for all hazards. It follows that the rate of exceeding the loss threshold l_o is $\lambda_i{\cdot}p_i$ for each hazard. The combined rate that includes all hazards is the sum of the individual rates, and the well-known Poisson distribution provides the probability of exceedance within a time period, T:

$$p = 1 - \exp\left(-T \cdot \sum_{i=1}^{N} \lambda_i \cdot p_i\right), \tag{3}$$

where p is the probability that the total loss, $l(\mathbf{x})$, exceeds the threshold, l_o, when all hazards are considered. It is noted that this analysis approach is associated with inaccuracy when the probability of more than one earthquake in T is substantial. This is because