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Seismic design and importance factor: Benefit/cost for overall service time versus per unit service time

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ABSTRACT

The maximum expected monetary benefit or minimum expected cost rule are often adopted to assess the optimum structural design levels under infrequent large earthquakes. In the assessment, the monetary benefit or cost functions are frequently established by considering the overall benefit or lifecycle cost at present value for a given structural design life. The selection of the structural design life is somewhat arbitrary, and in many cases one is interested in maximizing the structural service time or the benefit per unit service time. The consideration of the benefit (or cost) at present value per lifecycle or per unit service time may lead to different optimum design levels for a given planning time horizon. Moreover, it is unknown if the recommended importance factor in design codes to increase the seismic design load for classes of buildings is optimum. These two issues are investigated through numerical analyses by placing a structure at several different locations in Mexico and considering assembled detailed seismic hazard model. The implication of the results for the codified designs and for selecting the importance factor is discussed.

1. Introduction

The catastrophic losses due to seismic events for engineered systems are well-known and the losses are mostly due to severe structural and non-structural damages and business interruptions. Available resources and willingness to significantly further reduce the losses are limited. This perhaps is partly due to the fact or perception that the structures are already designed or strengthened to an optimum, efficient and/or acceptable level. If this is not the case, one should see more significant retrofitting activities and a greater increase in the seismic design load level in structural design codes, at least in affluent societies.

The investigation of the optimum seismic design level for buildings is not new and has been investigated in Rosenblueth [1,2], Liu et al. [3], Rosenblueth and Jara [4], Kanda and Ellingwood [5], Ang and De Leon [6], Rackwitz [7], Kang and Wen [8], Ellingwood [9], Esteva et al. [10,11], Liu et al. [12], Ellingwood and Wen [13] and Goda and Hong [14,15]. In these studies, the selection of the seismic design load level takes into account the safety and the economic issues that balance benefit and cost for the structural lifecycle. Most of the studies adopt the maximum expected (monetary) benefit or the minimum expected cost rule (i.e., maximum or minimum expected value (MEV) rule, where the value is associated with benefit or cost, respectively) to select the optimum design level, although the use of other decision theories has been considered in the literature [2,15–17]. Results in [15,16] indicated that the efficient or optimum seismic design level obtained based on the MEV rule represents the one that is preferred by a risk-neutral decision maker. This identified optimum design serves as the upper and lower bounds on the efficient seismic designs for risk-seeking and risk-averse decision makers, respectively. The failure probability for a reference period or the annual failure rate [6] corresponding to the optimum design can be used to aid the selection of the target reliability level for calibrating the design codes.

It is noted that in the above-mentioned studies, the total benefit or the total cost per structural design life are employed. This can be adequate if the selected design life can be justified in a logical manner. However, such a justification, if any, is not discussed in the literature, and periods of 30-, 50- and 75-year structural design life have been adopted for calibrating design codes. Further, in some cases one is interested in maximizing the benefit per unit service time or minimizing the cost spent on the structure per unit service time [18]. Therefore, rather than focusing on maximizing the expected total benefit or minimizing the expected total cost per design life or planning time horizon, one could select the optimum seismic design level by maximizing the benefit or

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minimizing the cost per unit service time. For the optimization, the use of Poissonian model for earthquake occurrence [19] is usually considered for seismic source zones that do not have very clear identified faults, while use of non-Poissonian model could be considered adequate for subduction earthquakes such as characteristic earthquakes along Mexican subduction region [20,21].

To achieve economic efficiency for a class of structures where consequences of failure are extremely severe, an increased safety level and seismic design level is necessary. Quantification of this increase has been investigated in [1,13,22], and the design codes use an importance factor to cope with the design of a class of buildings of importance. To simplify the analysis and to assess the required importance factor, the structure under seismic loading is represented as failure/safe system in [1,13]. Moreover, the investigation of the adequacy of the importance factor for Mexican building code was presented in [23] by incorporating partial damage cost. For simplicity and computing efficiency, however, simplified seismic hazard models are used in these studies, and differences between the ground motion prediction equations (GMPEs) and between inelastic seismic demands for different earthquake types are not considered.

In this study, we adopt the MEV rule to select the optimum seismic design level because it provides the optimum design level that is preferred by a risk-neutral decision maker and serves as a reference for decision makers of different risk attitudes. Both linear and nonlinear structural responses under seismic excitations are used to define the partial damage and collapse and to evaluate the expected damage cost and/or the expected annual average cost. For the analysis, a detailed seismic hazard model applicable to part of the Mexican Pacific coastal region and Mexico City is assembled and developed. The model is used to map seismic hazard and to estimate uniform hazard spectra (UHS). The model is used as the basis to investigate the differences between the optimum seismic design levels if the expected benefit (or cost) per life cycle or per unit service time is employed in the MEV rule. It is also used to investigate the optimum importance factor needed for an increased damage cost for a class of important structures. For the analyses, the same building is placed at several sites in Mexico. The effect of Poissonian and non-Poissonian earthquake occurrence modeling on the estimated optimum seismic design levels is also assessed.

2. Formulation of objective functions

Consider that $B(A,\ t)$ denotes the benefit at present value derived from the service and existence of an engineered structure up to the time t, where A is a set of design parameters. The construction of such a structure requires an initial capital investment $C_0(A)$. If it is damaged or collapsed due to a large earthquake at a time there would be a corresponding damage cost at the present value, that represents structural and non-structural damage cost, cost of lost life and limb and cost of demolition and removal. Consider that the structure is immediately repaired or reconstructed upon damage or collapse without modifying the design and construction rules (i.e., systematic reconstruction after failure), and that the total damage cost (including the repair and replacement cost) is denoted by $C_{DT}(A,\ t)$ for service until the end of a planning time horizon t. The optimum design dictated by the MEV rule is obtained by maximizing the following objective function $O(A,\ t)$ [1],

$$O(A,t) = B(A,t) - C_0(A) - C_{DT}(A,t). \tag{1}$$

$O(A,\ t)$ at the optimum must be positive for the structure to be viewed as of a benefit.

By ignoring the possible failure at the completion of the structure, and considering that there are n seismic source zones that affect the structure, and that the earthquakes occur randomly in time τ_{ij}, $i = 1, \cdots, N_j(t)$, $j = 1, \cdots, n$, where $N_j(t)$ denotes the total number of earthquakes originated from the j-th source zone in the time interval 0 to t, $O(A,\ t)$ shown in Eq. (1) can be written as,

$$O(A,t) = B(A,t) - C_0(A) - \sum_{j=1}^{n}\sum_{i=1}^{N_j(t)}(C_D(A|x_{ij}) + C_R(A|x_{ij}))e^{-\gamma\tau_{ij}}, \tag{2}$$

where $C_D(A|x_{ij})$ and $C_R(A|x_{ij})$ represent the damage cost and repair/reconstruction cost given that the damage state (or level) induced by the earthquake occurred at τ_{ij} is x_{ij}, and γ is a discount rate adjusted for inflation which is often set to 5%. If the annual average benefit (or cost) is of interest, the objective function presented in Eqs. (1) and (2), is replaced by $O_a(A,\ t)$, which is defined by,

$$O_a(A,t) = O(A,t)/t. \tag{3}$$

If the objective function $O(A,\ t)$ is considered, the optimum seismic design is the one that maximizes the expected value of $O(A,\ t)$, $E(O(A,\ t))$, where $E()$ denotes the expectation. If the annual average benefit (or cost) rather than the benefit (or cost) for the planning time horizon is of interest, the optimum seismic design is obtained by maximizing $E(O_a(A,t)) = E(O(A,t)/t)$. In this case, the optimum seismic design is not only a function of the set of design parameters A but also a function of the planning time horizon t. This suggests that the maximization of $E(O_a(A,t))$ for a given planning time horizon t, leads only to a suboptimum since it does not ensure that $E(O_a(A,t))$ is minimum for all possible t values. The use of $E(O(A,t))$ or $E(O_a(A,t))$ could lead to different optimum design level. In either case, one may need to treat t as a decision parameter as well to find the optimum seismic design level. Note that since the direct comparison of $E(O(A,t))$ for two different t values is not meaningful, its use is not valuable for selecting the optimum design for all possible t values. However, the use of $E(O_a(A,t))$, that emphasizes the expected benefit per unit service time, for selecting the optimum seismic design level could overcome this problem.

In general, if a limited planning time horizon is considered and the earthquake occurrence is non-Poissonian, simulation technique could be employed to evaluate $E(O(A,t))$ and $E(O_a(A,t))$ since no closed-form analytical solution is available. The analysis procedure includes the assessment of seismic hazard in terms of the UHS for a site of interest, the design of the structure for a considered seismic design level and, the evaluation of the objective function $O(A,\ t)$ or $O_a(A,\ t)$ defined in Eqs. (2) and (3) using the sampled seismic events and seismic demand for a considered planning time horizon.

3. Seismic hazard model

The evaluation of $E(O(A,t))$ and $E(O_a(A,t))$ for a construction site of interest requires the information on the probabilistic characterizations of the seismic hazard and, on the initial construction cost that is a function of the seismic design level. The characterization of the seismic hazard is based on the earthquake occurrence modeling, magnitude-recurrence relation, seismic source zones and ground motion prediction equations (GMPEs) (i.e., attenuation relations). An often employed methodology to assess the seismic hazard is the one given in [19]. A computational implementation of this method based on simulation technique that is described in [24] is adopted in the present study.

To characterize the seismic hazard for Mexico City and part of the Mexican Pacific coastal region, we adopt the seismic source zone model shown in Fig. 1 and Table 1 [25–29], where the source zones are classified into three groups, depending on the earthquake type and earthquake magnitude. The source zones for the first and second groups are located near the Mexican Pacific coastal