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A novel method based on maximum likelihood estimation for the construction of seismic fragility curves using numerical simulations

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ABSTRACT

Seismic fragility curves presenting some probability of failure or of a damage state exceedance versus seismic intensity can be established by engineering judgment, empirical or numerical approaches. This paper focuses on the latter issue. In recent studies, three popular methods based on numerical simulations, comprising scaled seismic intensity, maximum likelihood estimation and probabilistic seismic demand/capacity models, have been studied and compared. The results obtained show that the maximum likelihood estimation (MLE) method is in general better than other ones. However, previous publications also indicated the dependence of the MLE method on the ground excitation input. The objective of this paper is thus to propose a novel method improving the existing MLE one. Improvements are based on probabilistic ground motion information, which is taken into account in the proposed procedure. The validity of this new approach is verified by analytical tests and numerical examples.

1. Introduction

A seismic fragility curve expresses the probability of failure or damage of a structure or a mechanical system due to earthquakes as a function of a ground motion index; for instance, peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration at a period of interest (PS_a), and so on. It is one of three ingredients, comprising seismic hazard, fragility curves and dominant accident sequences, which lead to core damage in a plant in the context of a probabilistic risk assessment (PRA) in nuclear engineering application [1,2]. Fragility curves are also applied to different structural types in the civil engineering field, e.g., buildings [3,4], bridges [5–11], special structures: chimneys [12], piping systems [13], tunnels [14], highway and railway embankments and cuts [15], etc. They are useful for the design of a new structure, and for an existing one they are helpful for seismic retrofitting decisions, disaster response planning, and quick loss estimation [5,6].

Depending on the source of data, fragility curves can be obtained either by (i) engineering judgment, (ii) an empirical approach or (iii) numerical simulation. This paper focuses on the construction of seismic fragility curves using numerical simulations in which three components are necessary: (i) methods to generate ground motion histories of a site, (ii) methods

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to simulate dynamic (in general non-linear) responses and verify damages states, and (iii) methods to derive fragility curves from obtained data. This study is situated in the third component, where there are three popular methods: (i) scaled seismic intensity (SSI), (ii) maximum likelihood estimation (MLE), and (iii) probabilistic seismic demand model/probabilistic seismic capacity model (PSDM/PSCM).

In a recent comparative publication, Mandal et al. [16,17] showed that the MLE method provides the most accurate [16] and very good [17] fragility estimations when comparing the MLE method with the "conventional" method and the PSDM/PSCM method (called "regression method" by the authors) via a test case concerning the primary containment dome of a typical Indian Pressurized Heavy Water Reactor (PHWR). Twenty-four ground motions records were used and fragility curves were verified with the discrete results of failure probability obtained by the Incremental Dynamic Analysis (IDA).

Lallement et al. [18] studied three methods for the construction of fragility curves: the method of moments (MM), a method minimizing the weighted sum of squared error (SSE) that is similar to the SSI method, and the MLE method in infill frame buildings. Based on the damage survey data of the January 12, 2010 earthquake in Haiti, and the data of simulation in an eight-story infill frame building using the IDA technique, the authors concluded that the MLE method is preferable to both the MM and SSE methods. A twenty-two far-field ground motion set was used for simulation data, and derived fragility curves were compared with analytical IDA results.

It should be noted that, in most of the previous works, a limited number of ground motion records of similar seismological origins were scaled to discrete values of seismic intensity, and they were then used for the IDA and the construction of fragility curves. However, Grigoriou [19] reported a difference of probabilistic distribution between the original ground motion index and its scaled version. The scaling technique for ground motions is not recommended.

Without the scaling technique, Dang [20] and Le et al. [21] used the Boore's model [22] to generate ground motions, and compared SSI, MLE and PSDM/PSCM methods on linear/non-linear oscillators and non-linear frame structures. The accuracy of the obtained fragility curves was checked with the results of the Monte-Carlo Simulation (MCS) method. The authors arrived to the same conclusion: the MLE method is the best in most of the considered cases. However, the MLE method suffers a shortcoming relative to ground motion time histories selected for simulations. Zentner [23] and Gehl et al. [24] indicated that fragility estimates are best when the ground acceleration histories are close to the median capacity level, so there is a good chance of obtaining failure as well as non-failure cases. If no failure case is observed, the MLE method might not converge. This fact highlighted that the construction procedure of a fragility curve depends on the choice of ground acceleration histories, although the fragility curve is considered as intrinsic to the structure. For a given site, the chosen acceleration histories must be consistent and their ground motion index (PGA for instance) must follow the probability distribution relative to the site. Therefore, the observed data (failure or non-failure) that were used for constructing fragility curves also depend on the probability distribution of the ground motion index. In the existing MLE method, this dependence is however not explicit.

The aim of this paper is thus to propose a novel method by improving the existing MLE method. The basic idea is to incorporate in the maximum likelihood estimation stage both response information and also excitation information via the probability distribution of the ground motion index, which is absent in the MLE method. The proposed method is thus called "Excitation and Response-based Maximum Likelihood Estimation" (ERMLE) method. The development of the ERMLE method in section 2 is preceded by a background about fragility curve definitions and a summary of the MLE method in the form of a step-by-step procedure. Theoretical formulations of the ERMLE method are then deployed via a step-by-step procedure for practical applications. Two comparison criteria are also proposed in order to verify the efficiency of the proposed method. Analytical tests and numerical examples are used in section 3 to validate the ERMLE method. Finally, conclusions are given in section 4.

2. Seismic fragility curves

2.1. Definitions

Let A be a chosen ground motion index, also called an "intensity measure" (IM). A can be PGA, PGV, PS$_a$ and so on. The fragility curve $F_r(a)$ is the conditioned probability of failure or of exceeding a damage state given that $A = a$:

$$F_r(a) = P[X \geq x_0 | A = a] \tag{1}$$

where the failure or the specific damage state is characterized when the structural response X exceeds a critical limit x_0. Taking into account random properties of response and critical limits due to uncertainty in loadings, material properties, dimensions and so on, the failure or the specific damage state can be considered in a more general way as the excess by seismic demand D of the seismic capacity C. The definition of the fragility curve thus becomes

$$F_r(a) = P[D \geq C | A = a] \tag{2}$$

Once the fragility curve $F_r(a)$ is available, using the distribution of the ground motion index A of a site, it is possible to calculate the probability of failure or damage state of the site by using the integral

$$p_{\mathrm{f}} = \int_{-\infty}^{+\infty} F_r(a) p_A(a)\,\mathrm{d}a = \int_{0}^{+\infty} F_r(a) p_A(a)\,\mathrm{d}a \tag{3}$$