

## Handbook of Earthquake Engineering

Edited by Agnes Nolan





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### **Handbook of Earthquake Engineering**

#### **Preface**

Every book is initially just a concept; it takes months of research and hard work to give it the final shape in which the readers receive it. In its early stages, this book also went through rigorous reviewing. The notable contributions made by experts from across the globe were first molded into patterned chapters and then arranged in a sensibly sequential manner to bring out the best results.

This multi-contributor descriptive book provides in-depth knowledge regarding the field of earthquake engineering. With increasing seismic activities and major earthquakes, the need for intense research and better understanding of the nature of seismisms and their effects on structures is rapidly increasing. In the wake of frequent disasters, earthquake engineering research has been expanding as significant data has become available from a large array of seismic instruments, large scale experiments and numerical simulations. This book opens with results from some of the contemporary seismic research works including 3D wave propagation in different soil media, seismic loss assessment, probabilistic hazard analysis, geotechnical problems including soil-structure interaction. It also focuses on the seismic behavior of structures including historical and monumental structures, bridge embankments and different types of bridges and bearings.

It has been my immense pleasure to be a part of this project and to contribute my years of learning in such a meaningful form. I would like to take this opportunity to thank all the people who have been associated with the completion of this book at any step.

Editor

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Section 1

# Seismic Risk, Hazard, Wave Simulation and Geotechnical Aspects

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## Seismic Risk of Structures and the Economic Issues of Earthquakes

Afshin Kalantari

Additional information is available at the end of the chapter

#### 1. Introduction

As one of the most devastating natural events, earthquakes impose economic challenges on communities and governments. The number of human and economic assets at risk is growing as megacities and urban areas develop all over the world. This increasing risk has been plotted in the damage and loss reports after the great earthquakes.

The 1975 Tangshan (China) earthquake killed about 200,000 people. The 1994 Northridge, (USA) earthquake left 57 dead and about 8,700 injured. The country experienced around \$42 billion in losses due to it. The 1995 earthquake in Kobe (Japan) caused about 6,000 fatalities and over \$120 Billion in economic loss. The August 1996 Izmit (Turkey) earthquake killed 20,000 people and caused \$12 billion in economic loss. The 1999 Chi-chi (Taiwan) earthquake caused an estimated \$8 billion in loss. The 2006 Gujarat (India) earthquake saw around 18,000 fatalities and 330,000 demolished buildings [1]. The Sichuan (China) earthquake, on May 12th 2008 left 88,000 people dead or missing and nearly 400,000 injured. That earthquake damaged or destroyed millions of homes, leaving five million homeless. It also caused extensive damage to basic infrastructure, including schools, hospitals, roads and water systems. The event cost around \$29 billion in direct loss alone [2]. The devastating earthquake of March 2011 with its resulting tsunami along the east coast of Japan is known to be the world's most costly earthquake. The World Bank estimated the cost at \$235 billion while government estimates reported the number at \$305 billion. The event left 8,700 dead and more than 13,000 missing [3].

As has been shown, earthquake events have not only inflicted human and physical damage, they have also been able to cause considerable economic conflict in vulnerable cities and regions. The importance of the economic issues and the consequences of earthquakes attracted the attention of engineers and provided new research and working opportunities

for engineers, who up until then had been concerned only with risk reduction options through engineering strategies [4].

Seismic loss estimation is an expertise provided by earthquake engineering and the manner in which it can be employed in the processes of assessing seismic loss and managing the financial and economical risk associated with earthquakes through more beneficial retrofit methods will be discussed. The methodology provides a useful tool for comparing different engineering alternatives from a seismic-risk-point of view based on a Performance Based Earthquake Engineering (PBEE) framework [5]. Next, an outline of the regional economic models employed for the assessment of earthquakes' impact on economies will be briefly introduced.

#### 1.1. The economic consequences of earthquakes

The economic consequences of earthquakes may occur both before and after the seismic event itself [6]. However, the focus of this chapter will be on those which occur after earthquakes. The consequences and effects of earthquakes may be classified in terms of their primary or direct effects and their secondary or indirect effects. The indirect effects are sometimes referred to by economists as higher-order effects. The primary (direct) effects of an earthquake appear immediately after it as social and physical damage. The secondary (indirect) effects take into account the system-wide impact of flow losses through interindustry relationships and economic sectors. For example, where damage occurs to a bridge then its inability to serve to passing vehicles is considered a primary or direct loss, while if the flow of the row material to a manufacturing plant in another area is interrupted due to the inability of passing traffic to cross the bridge, the loss due to the business's interruption in this plant is called secondary or indirect loss. A higher-order effect is another term as an alternative to indirect or secondary effects which has been proposed by economists [7]. These potential effects of earthquakes may be categorized as: "social or human", "physical" and "economic" effects. This is summarized in Table 1 [8].

The term 'total impact' accordingly refers to the summation of direct (first-order effects) and indirect losses (higher-order effects). Various economic frameworks have been introduced to assess the higher-order effects of an earthquake.

With a three-sector hypothesis of an economy, it may be demonstrated in terms of a breakdown as three sectors: the primary sector as raw materials, the secondary sector as manufacturing and the tertiary sector as services. The interaction of these sectors after suffering seismic loss and the relative effects on each other requires study through proper economic models.

#### 2. The estimation of seismic loss of structures in the PBEE framework

The PBEE process can be expressed in terms of a four-step analysis, including [9-10]:

Hazard analysis, which results in Intensity Measures (IMs) for the facility under study,

- Structural analysis, which gives the Engineering Demand Parameters (EDPs) required for damage analysis,
- Damage analysis, which compares the EDPs with the Damage Measure in order to decide for the failure of the facility, and;
- Loss Analysis, which evaluates the occurrence of Decision Variables (DVs) due to failures.

	Social or human effects	Physical effects	Economic effects
Primary effects (Direct or first-order)	Fatalities Injuries Loss of income or employment opportunities Homelessness	Ground deformation and loss of ground quality Collapse and structural damage to buildings and infrastructure Non-structural damage to buildings and infrastructure (e.g., component damage)	Disruption of business due to damage to industrial plants and equipment Loss of productive work force, through fatalities, injuries and relief efforts Disruption of communications networks Cost of response and relief
Secondary effects (indirect or higher- order)	Disease or permanent disability Psychological impact of injury, Bereavement, shock Loss of social cohesion due to disruption of community Political unrest when government response is perceived as inadequate	seismic capacity of damaged structure which are not repaired Progressive deterioration of damaged buildings and infrastructure which are not	Losses borne by the insurance industry, weakening the insurance market and increasing the premiums Losses of markets and trade opportunities,

Table 1. Effects from Earthquakes [8]

Considering the results of each step as a conditional event following the previous step and all of the parameters as independent random parameters, the process can be expressed in terms of a triple integral, as shown below, which is an application of the total probability theorem [11]:

$$v(DV) = \iiint G[DV|DM]|dG[DM|EDP]|dG[EDP|IM\}|d\lambda[IM]$$
 (1)

The performance of a structural system or lifeline is described by comparing demand and capacity parameters. In earthquake engineering, the excitation, demand and capacity parameters are random variables. Therefore, probabilistic techniques are required in order to estimate the response of the system and provide information about the availability or failure of the facility after loading. The concept is included in the reliability design approach, which is usually employed for this purpose.

### 2.1. Probabilistic seismic demand analysis through a reliability-based design approach

The reliability of a structural system or lifeline may be referred to as the ability of the system or its components to perform their required functions under stated conditions for a specified period of time. Because of uncertainties in loading and capacity, the subject usually includes probabilistic methods and is often made through indices such as a safety index or the probability of the failure of the structure or lifeline.

#### 2.1.1. Reliability index and failure

To evaluate the seismic performance of the structures, performance functions are defined. Let us assume that  $z=g(x_1, x_2, ..., x_n)$  is taken as a performance function. As such, failure or damage occurs when z<0. The probability of failure,  $p_f$ , is expressed as follows:

$$P = P[z < 0] \tag{2}$$

Simply assume that z=EDP-C where EDP stands for Engineering Demand Parameter and C is the seismic capacity of the structure.

Damage or failure in a structural system or lifeline occurs when the Engineering Demand Parameter exceeds the capacity provided. For example, in a bridge structural damage may refer to the unseating of the deck, the development of a plastic hinge at the bottom of piers or damage due to the pounding of the decks to the abutments, etc.

Given that *EDP* and *C* are random parameters having the expected or mean values of  $\mu$ EDP and  $\mu$ C and standard deviation of  $\sigma$ EDP and  $\sigma$ C, the "safety index" or "reliability index",  $\beta$ , is defined as:

$$\beta = \frac{\mu_c - \mu_{EDP}}{\sqrt{\sigma_c^2 + \sigma_{EDP}^2}} \tag{3}$$

It has been observed that the random variables such as "EDP" or "C" follow normal or lognormal distribution. Accordingly, the performance function, z, also will follow the same distribution. Accordingly, probability of failure (or damage occurrence) may be expressed as a function of safety index, as follows:

$$P = \phi (-\beta) = 1 - \phi (\beta) \tag{4}$$

where  $\phi()$  is a log-normal distribution function.

#### 2.1.2. Engineering demand parameters

The Engineering Demand Parameters describe the response of the structural framing and the non-structural components and contents resulting from earthquake shaking. The parameters are calculated by structural response simulations using the IMs and corresponding earthquake motions. The ground motions should capture the important characteristics of earthquake ground motion which affect the response of the structural framing and non-structural components and building contents. During the loss and risk estimation studies, the EDP with a greater correlation with damage and loss variables must be employed.

The EDPs were categorized in the ATC 58 task report as either direct or processed [9]. Direct EDPs are those calculated directly by analysis or simulation and contribute to the risk assessment through the calculation of P[EDP | IM]; examples of direct EDPs include interstory drift and beam plastic rotation. Processed EDPs - for example, a damage index - are derived from the values of direct EDPs and data on component or system capacities. Processed EDPs could be considered as either EDPs or as Damage Measures (DMs) and, as such, could contribute to risk assessment through P[DM | EDP]. Direct EDPs are usually introduced in codes and design regulations. For example, the 2000 NEHRP Recommended Provisions for Seismic Regulations for Buildings and Other Structures introduces the EDPs presented in Table 2 for the seismic design of reinforced concrete moment frames [12-13]:

#### Reinforced concrete moment frames

Axial force, bending moment and shear force in columns
Bending moment and shear force in beams
Shear force in beam-column joints
Shear force and bending moments in slabs
Bearing and lateral pressures beneath foundations
Interstory drift (and interstory drift angle)

Table 2. EDPs required for the seismic design of reinforced concrete moment frames by [12-13]

Processed EDPs are efficient parameters which could serve as a damage index during loss and risk estimation for structural systems and facilities. A Damage Index (DI), as a single-valued damage characteristic, can be considered to be a processed EDP [10]. Traditionally, DIs have been used to express performance in terms of a value between 0 (no damage) and 1 (collapse or an ultimate state). An extension of this approach is the damage spectrum, which takes on values between 0 (no damage) and 1 (collapse) as a function of a period. A detailed summary of the available DIs is available in [14].

Park and Angin [15] developed one of the most widely-known damage indices. The index is a linear combination of structural displacement and hysteretic energy, as shown in the equation:

$$DI = \frac{u_{max}}{u_c} + \beta \frac{E_h}{F_V u_c} \tag{5}$$

where  $u_{max}$  and  $u_c$  are maximum and capacity displacement of the structure, respectively, Eh is the hysteresis energy,  $F_y$  is the yielding force and  $\beta$  is a constant.

See Powell and Allahabadi, Fajfar, Mehanny and Deierlein, as well as Bozorgnia and Bertero for more information about other DIs in [16-19].

#### 2.2. Seismic fragility

The seismic fragility of a structure refers to the probability that the Engineering Demand Parameter (*EDP*) will exceed seismic capacity (*C*) upon the condition of the occurrence of a specific Intensity Measure (*IM*). In other words, seismic fragility is probability of failure, P<sub>f</sub>, on the condition of the occurrence of a specific intensity measure, as shown below:

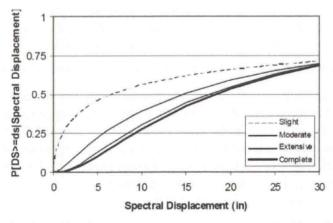
Fragility=P [EDP>C|IM] 
$$(6)$$

In a fragility curve, the horizontal axis introduces the IM and the vertical axis corresponds to the probability of failure,  $P_f$ . This curve demonstrates how the variation of intensity measure affects the probability of failure of the structure.

Statistical approach, analytical and numerical simulations, and the use of expert opinion provide methods for developing fragility curves.

#### 2.2.1. Statistical approach

With a statistical approach, a sufficient amount of real damage-intensity data after earthquakes is employed to generate the seismic fragility data. As an example, Figure 1 demonstrates the empirical fragility curves for a concrete moment resisting frame, according to the data collected after Northridge earthquake [20].



**Figure 1.** Empirical fragility curves for a concrete moment resisting frame building class according to the data collected after the Northridge Earthquake, [20].