Preface

This dissertation aims to evaluate the seismic reliability of multi-span reinforced concrete (RC) bridges seismically isolated with friction pendulum system (FPS) devices, considering spatial variability of earthquake ground motion (SVEGM). The goal is to understand how it affects the response of these structures and to provide design abacuses for the FP bearings following the performance-based-earthquake engineering (PBEE) methodology.

Chapter 1 intends to provide an overlook of the most important aspects regarding seismic risk evaluation with specific attention on the concept of structural reliability, within the context of Performance-Based Earthquake Engineering (PBEE). At first, the methodology approach, following the PBEE, as framed by the Pacific Earthquake Engineering Research (PEER) Center, is examined. Next, the concept of seismic risk is explained both in qualitative and quantitative terms, emphasizing the key components involved: seismic hazard, seismic vulnerability, and exposure. A specific focus is given to the assessment of seismic vulnerability for a specific asset at risk, such as bridge structures. In this context, the derivation of analytical fragility functions, which are used to describe seismic vulnerability, is presented next.

Finally, the chapter delves into the concept of structural reliability, exposing the main source of uncertainties involved in the reliability assessment. It also discusses different approaches (reliability methods), that may be employed for evaluating structural reliability. Additionally, these approaches may require the use of simulation techniques such as the Monte Carlo technique or the more efficient Latin Hypercube sampling method. Both of these techniques are discussed in this chapter within the framework of reliability assessment.

Chapter 2 begins with an overview of the typical damage patterns caused to bridges from past earthquakes, with a particular emphasis on those damages observed to bridge configurations more susceptible to the spatial variability of ground motion. Following this, it provides a brief description of the primary bridge structural components. Finally, the chapter illustrates the basic principles of seismic isolation as applied to bridge structures, highlighting the effectiveness of this technique in mitigating or preventing structural damage caused by earthquakes.

Chapter 3 presents an overview of the elastic seismic isolation theory. It begins with an introduction of the basic principles of seismically isolated systems, originally developed by Prof. J. Kelly in 1996 for building structures. It follows a detailed description of friction pendulum bearings, specifically emphasizing their dynamic behavior and the friction-related properties that characterize these devices. Furthermore, the chapter explores the key factors influencing the friction coefficient, including apparent pressure, sliding velocity, temperature variations, and the loading history.

Finally, a proposed numerical model is presented for multi-span continuous deck bridges that are seismically isolated using friction pendulum devices.

Chapter 4 explores the fundamental concepts of spatial variability of earthquake ground motion (SVEGM). It starts with a historical overview of the key studies and findings in the scientific literature regarding the topic. It is nowadays well established that SVEGM primarily arises from factors such as the loss of coherence, the so-called wave-passage effect, and the site-response effect. Given the complexity of the phenomenon, a deterministic analysis approach is impractical, requiring the use of probabilistic methods instead. Before delving into the adopted simulation techniques, a brief description of the equation of motions valid for a multi-degree-of-freedom (MDOF) system, subjected to different input ground motions, is provided. Following this, it discusses the main aspects of the spectral representation method used to simulate spatially variable earthquake ground motion. Within this method, particular attention is given to the specifically selected power spectral density (PSD), coherency function, and modulating function. Additionally, this study adopts a generation procedure that accounts for spectrum compatibility with the specific site of interest. Thus, this procedure is described along with its implementation to the case study, which refers to a friction pendulum seismically isolated multi-span reinforced concrete bridge located near the site of L'Aquila, in Italy.

Finally, the chapter presents a validation of the adopted procedure, which particularly compares the simulated coherency functions with the target ones initially integrated into the adopted procedure.

Chapter 5 describes the testbed bridge adopted in the analysis: an existing simply supported reinforced concrete (RC) bridge located in central Italy, near the site of L'Aquila.

Due to the lack of design seismic details, primarily in the pier component, the bridge will be retrofitted with a seismic isolation system using friction-type devices (i.e., FP system).

The chapter includes an in-depth focus on the numerical model of each bridge component implemented in Opensees, the open-source software for structural and geotechnical problems. The model uses a three-dimensional spine line approach with elastic beam-column elements for the deck and fiber-section, force-based beam-column elements for the piers. Additionally, the FP devices are modeled through the built-in element of Opensees, while the soil-structure interaction at the abutments is implemented through a zero-length element with specific stiffnesses assigned along the longitudinal and transverse bridge directions.

Furthermore, details are provided regarding the parametric analysis carried out, which encompasses a wide range of bridge properties (i.e., the total number of spans and the isolation period), different seismic intensity levels along with two incidence angle conditions. Additionally, the friction coefficient at large velocities and the uncertainties related to the seismic input (both for the SVEGM condition and the uniform one) are treated as random variables relevant to the problem.

Finally, the chapter illustrates the procedure for implementing multiple-support excitation in Opensees.

Chapter 6 focuses on the seismic reliability assessment of two configurations of isolated bridges equipped with friction pendulum devices. It examines both 5-span and 7-span bridge configurations across three different isolation periods, analyzing their seismic response under both uniform input conditions and spatially variable earthquake ground motion (SVEGM). The friction coefficient is treated as a random variable in the analysis. Additionally, the friction coefficient is treated as a random variable. To ensure convergence between the target response spectrum for the reference site of L'Aquila and the ensemble-averaged spectra derived from simulations, 30 ground motions are artificially generated for each bridge support station. Two different incidence angle conditions (30° and 60° relative to the bridge longitudinal axis) are also considered. The reliability assessment begins with Incremental Dynamic Analysis (IDA), involving a total of 3600 3D simulations for each of the 9 Intensity Measure Levels (IMLs) considered in IDA. Engineering demand parameters (EDPs), chosen to evaluate the response statistics related to both bridge piers and bridge isolation system, are presented next. Subsequent steps in the seismic reliability estimation include the derivation of fragility curves for the bridge piers and friction pendulum devices, assuming different damage levels and limit state thresholds.

Finally, considering the seismic hazard curves at different isolation periods related to the reference site of L'Aquila (Italy), the seismic reliability of both bridge piers and friction pendulum devices is evaluated in the time frame of interest through the convolution integral between seismic fragility and seismic hazard.

Additionally, SRBD (Seismic Reliability-Based Design), abacuses are derived and proposed with a twofold objective:

a) to define the radius in plan of the FP bearings, accounting for both uniform excitation and spatial variability of earthquake ground motion (SVEGM), as a function of the bridge configuration, isolation period and expected reliability level.
b) To establish specific design safety factors for the seismic design of FP isolators adopted to retrofit conventional highway bridges, implicitly considering the adverse effects of SVEGM.