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Best Practices in Physics-Based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations

Introduction

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Abstract—Inspired by the first workshop on Best Practices in Physics-Based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations (BestPSHANI) conducted by the International Atomic Energy Agency (IAEA) on 18–20 November, 2015 in Vienna (http://www-pub.iaea.org/iaeameetings/50896/BestPSHANI), this PAGEOPH topical volume collects several extended articles from this workshop as well as several new contributions. A total of 17 papers have been selected on topics ranging from the seismological aspects of earthquake cycle simulations for source-scaling evaluation, seismic source characterization, source inversion and ground motion modeling (based on finite fault rupture using dynamic, kinematic, stochastic and empirical Green's functions approaches) to the engineering application of simulated ground motion for the analysis of seismic response of structures. These contributions include applications to real earthquakes and description of current practice to assess seismic hazard in terms of nuclear safety in low seismicity areas, as well as proposals for physics-based hazard assessment for critical structures near large earthquakes. Collectively, the papers of this volume highlight the usefulness of physics-based models to evaluate and understand the physical causes of observed and empirical data, as well as to predict ground motion beyond the range of recorded data. Relevant importance is given on the validation and verification of the models by comparing synthetic results with observed data and empirical models.

Key words: Physics-based fault rupture models, dynamic rupture, kinematic rupture, source-scaling, earthquake cycle, broadband ground motion, fault-zone plasticity, near-source ground motion, stochastic modeling, empirical Green's functions, source inversion, seismic hazard assessments, probabilistic and deterministic approaches, uncertainties quantification.

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1. Introduction

Physics-based fault rupture models for ground motion simulation have been developed rapidly during the last decades and have been highlighted that this approach has the potential to provide meaningful predictions in areas that go beyond the range of recorded data, especially near the source, where observed data are sparse and ground motion is dominated by the source. The use of these models is especially relevant for reliable seismic hazard assessment of critical infrastructures, such as nuclear installations. It is so, the International Atomic Energy Agency (IAEA) published the Safety Standards Series No. SSG-9 (IAEA 2010), in which it recommends the use of fault rupture modeling for ground motion evaluation and describes the overall process for conducting this type of modeling. After the Fukushima Daiichi Nuclear Power Plants Accident caused by the 2011 (Mw 9) Tohoku earthquake, the IAEA (2015a) prepared a report on this accident and recommended that further implementation of the state-of-the-art knowledge for improving seismic hazard assessment is still necessary. Since the scheme for physics-based fault rupture modeling introduced into the SSG-9 (IAEA 2010) was quite limited, the IAEA (2015b) published a new Safety Report Series No. 85, "*Ground Motion Simulation Based on Fault Rupture Modelling for Seismic Hazard Assessment in Site Evaluation for Nuclear Installations*" *(SR-85)*. With this SR-85 publication, the practical application of the physics-based schemes for seismic hazard assessment of nuclear installations has been introduced to the nuclear industry, regulatory bodies and relevant institutions from the nuclear community.

The SR-85 is based on kinematic fault rupture approach, then a further effort has been carried out by the IAEA to extend the fault rupture approach to full physics-based models, the so-called spontaneous dynamic rupture simulation. Unlike kinematic models, dynamic models consider the physical process involved in the fault ruptre, incorporating the physics of wave propagation and state of the stress and friction on the fault rupture (e.g., Day 1982). Though dynamic rupture models are not well known in engineering practice, there is an effort to introduce these models in the engineering community for ground motion simulations (e.g., Dalguer et al. 2008; Olsen et al. 2009; Shi and Day 2013; Baumann and Dalguer 2014; Andrews and Ma 2016). To disseminate the practices of those physics-based models (kinematic and dynamic) for the seismic hazard assessment in site evaluation of nuclear installations, the IAEA held the first workshop on Best Practices in Physics-Based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations (BestPSHANI) on 18–20 November, 2015 in Vienna (http://www-pub.iaea.org/iaeameetings/50896/BestPSHANI). About 100 participants from 30 member states participated in the workshop. In this workshop, several key issues were identified and the participants concluded to encourage the international nuclear safety community to catch up with the state-of-the-art practices, to assess procedures for verification and validation of numerical models, to discuss crosscutting issues with empirical schemes such as ground motion prediction equations (GMPEs), to assess the implications (from nuclear safety point of view) on the use of synthetic ground motion for engineering structures evaluation and to challenge the use of these models toward seismic risk analyses of nuclear installations. The topics presented in the workshop encompassed a wide range of important subjects, from fault rupture modeling to the structural response. The full proceeding of the workshop has been published by IAEA (2017).

Motivated by the mentioned workshop, this PAGEOPH topical volume collects several extended articles from this workshop as well as several new contributions. Seventeen papers have been selected on topics ranging from the seismological aspects of earthquake cycle simulations for source-scaling evaluation, seismic source characterization, source inversion and physics-based ground motion modeling to the engineering application of simulated ground motion for the analysis of seismic response of structures. These papers tackled problems of real earthquakes and evaluate the capability of the models to reproduce observed data and empirical findings. At the end of this volume, there are papers that provide description of current practice to assess seismic hazard in terms of nuclear safety in low seismicity areas, as well as proposals for physics-based hazard assessment for critical structures near large earthquakes. The papers make significant effort on the validation and verification of the models by comparing synthetic results with observed data and empirical models. Here the 17 papers are briefly described. The papers are organized in four sections. The first two sections present papers that use full physics-based that incorporate the frictional sliding properties on the fault and wave propagation, the so-called quasi-dynamic and full-dynamic rupture models. The third section presents papers that incorporate the physics of wave propagation in kinematic models, as well as stochastic and empirical Green's functions. The last section presents practical application in engineering practice and seismic hazard evaluation.

1.1. Section I: Quasi-dynamic Rupture Modeling

That section collects papers of finite-fault rupture models that use physics-based quasi-dynamic approach that incorporate the frictional sliding on the fault for earthquake cycle simulations to evaluate the mechanical origin of empirical source-scaling models.

Luo et al. (2017) develop earthquake cycle simulations using frictional sliding models to investigate the mechanical origin of empirical source-scaling relationships (seismic moment vs rupture area) used in Japan. They focus on the transition between the well-recognized small (self-similar) and very large (W-model) earthquake regimes. The main conclusion is that the transition regimes are controlled by surface rupture effects.

1.2. Section II: Full-Dynamic Rupture Modeling

That section collects papers of finite-fault rupture models that incorporate the physics of wave propagation and frictional sliding for ground motion prediction.

Tanircan et al. (2017) develop dynamic rupture simulation of the 1999 Mw 7.1 Düzce, Turkey earthquake. The initial stress parameterization is obtained based on a kinematic source inversion model. The final dynamic model results from trial-and-error approach, so that ground motion generated by the dynamic rupture model is consistent with the observed ones. The paper evaluates the heterogeneity of the supershear rupture exhibited by this earthquake.

Tsuda et al. (2017) develop dynamic rupture simulation of the 2011 Mw 9.0 Tohoku, Japan earthquake. They propose a dynamic model that follows the principle of the so-called characterized kinematic asperity source model, widely used in Japan.

Roten et al. (2017) develop dynamic rupture models to explore the effects of fault-zone nonlinearity on peak ground velocities (PGVs) for surface-rupturing strike–slip earthquakes in a medium governed by Drucker–Prager plasticity. They found that plastic yielding can significantly reduce near-fault PGVs depending on stress drop and the strength of the rock. The main results show that nonlinear effects may be relevant even at long periods, in particular in earthquakes with high stress drop and in the presence of a low-velocity fault damage zone.

1.3. Section III: Kinematic Rupture Modeling

That section collects papers of finite-fault rupture models that incorporate the physics of wave propagation, stochastic and empirical Green's functions for ground motion prediction.

Song and Dalguer (2017) propose kinematic linear source inversion methods with multiple windows to capture source complexities that include supershear rupture speed and slip reactivation generated by dynamic rupture simulations. The study focuses on the possibility of resolving complex rupture processes by inverting seismic waveform data.

Mai et al. (2017) develop advanced new pseudo-dynamic kinematic source models in a planar fault that incorporate the effects of fault roughness for near-source ground motion simulations.

Crempien and Archuleta (2017) explore different parameters that affect the variability of ground motion such as the spatial correlations of kinematic rupture parameters on a finite fault and the corner frequency of the moment-rate spectra.

Gallovič (2016) emphasizes the azimuthal dependence of the between-event ground motion variability using an advanced kinematic broadband source model. The source is composed of randomly distributed overlapping sub-sources with fractal number-size distribution. From earthquake physics point of view, the model includes positive correlation between slip and rise time as found in dynamic source simulation.

Del Gaudio et al. (2017) evaluate near-source ground motion variability of real earthquakes from simulated broadband ground motion based on kinematic source models and empirical Green's functions (EGF).

Poiata and Miyake (2017) simulate broadband ground motions for the moderate October 27, 2004 (M_w 5.8) and damaging March 4, 1977 (M_w 7.4) Vrancea (Romania) earthquakes using the empirical Green's function method.

Poiata et al. (2017) analyze the seismological aspects of the near-fault ground motion pulses from the 2009 L'Aquila, Italy (M_w 6.3) earthquake using broadband ground motion models.

Pitarka et al. (2017) analyze the performance of the Irikura's recipe (Irikura and Miyake 2011) that is widely used in Japan for ground motion simulation.

Si et al. (2017) evaluate attenuation of ground motion using wave propagation models.

Lee and Song (2016) propose stochastic earthquake rupture modeling to quantify the variability of the earthquake rupture process for future events and to produce a number of rupture scenario models to capture the variability in simulation-based ground motion predictions.

1.4. Section IV: Seismic Hazard and Engineering Application

That section collects papers oriented to practice in engineering problems and seismic hazard evaluation.

Karimzadeh et al. (2017) evaluate the suitability of simulated ground motions for the analysis of the seismic response of structures in engineering practice. For this purpose, 1999 Duzce earthquake was simulated using stochastic finite-fault methodology.

Berge-Thierry et al. (2017) provide a description of the current practices in France to assess seismic hazard in terms of nuclear safety. This article discusses in particular seismic source characterization, strong ground motion prediction, and maximal magnitude constraints, according to the practice of the French Atomic Energy Commission.

Hutchings et al. (2017) propose a methodology to use physics-based hazard assessment for critical structures near large earthquakes. The developed methodology for physics-based ground motion prediction incorporates the effects of realistic earthquake rupture along specific faults and the actual geology between the source and site.

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