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Earthquakes and Multi-Hazards Around the Pacific Rim, Vol. II: Introduction

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The seismic belt along the Pacific Rim is the greatest earthquake zone in the world, generating more than 80% of the world's largest earthquakes (https://earthquake.usgs.gov/learn/topics/megaqk_facts_fantasy.php). It is also susceptible to tsunamis and volcanic eruptions, which are capable of generating serious multi-hazards. Since the beginning of the 21st century, many countries along the Pacific Rim have suffered from tremendous multi-hazards, especially earthquakes and tsunamis. For example, the 2004 Sumatra *M* 9.1 earthquake in Indonesia and the 2011 Tohoku-oki *M* 9.0 earthquake in Japan triggered mega-tsunamis and caused significant damages and human casualties. An improved understanding of the underlying physical processes and potential interactions of these multi-hazards, and better simulation and forecasting of their occurrences are needed for better hazard mitigation and disaster prevention.

APEC Cooperation for Earthquake Simulation (ACES) (http://www.aces.org.au/), endorsed by the Asia-Pacific Economic Cooperation (APEC) in 1997, has been focusing on understanding, forecasting, and mitigating the effects of earthquakes and other natural disasters for about 20 years. It links the complementary strengths of the earthquake research programs of individual APEC member economies via collaborations toward the development of earthquake simulation models and creates the research infrastructure to enable large-scale simulations and to assimilate data into the models. Since 1997, twelve workshops, including nine international workshops and three working group meetings on earthquake simulations (http://www.aces.org.au/), have been held by ACES: (1) Inaugural ACES Workshop, Brisbane and Noosa, Queensland, Australia, January 31–February 5, 1999; (2) 2nd ACES Workshop, Tokyo and Hakone, Japan, October 15–20, 2000; (3) 2nd ACES Working Group Meeting, Maui Supercomputer Center, USA, July 29–August 3, 2001; (4) 3rd ACES Workshop, Maui, Hawaii, USA, May 5–10, 2002; (5) 3rd ACES Working Group Meeting, Melbourne and Brisbane, Australia, June 2–6, 2003; (6) 4th ACES Workshop and iSERVO colloquium, Beijing, China, July 9–14, 2004; (7) 5th ACES International Workshop, Hawaii, USA, April 4–6, 2006; (8) 6th ACES International Workshop, Cairns, Australia, May 11–16, 2008; (9) 7th ACES International Workshop, Hokkaido, Japan, October 3–8, 2010; (10) ACES Workshop on Advances in Simulation of Multihazards, Maui, Hawaii, USA, May 1–5, 2011; (11) 8th ACES International Workshop on Advances in Simulation of Multihazards, Maui, Hawaii, USA, October 23–26, 2012; (12) 9th ACES International Workshop on Advances in Simulation of Multihazards, Chengdu, China, August 10–16, 2015. As a result of ACES, much progress has been achieved on Lattice Solid particle simulation Model (LSM), Australian Computational Earth Systems Simulation (ACcESS), Earth Simulator of Japan, Geotechnical Finite Element Analysis (GeoFEM), Geophysical Finite Element Simulation Tool (GeoFEST), Earthquake Simulator (QuakeSIM), Solid Earth Virtual Research Observatory Institute (SERVO), International Solid Earth Virtual Research

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Observatory Institute (iSERVO), Load–Unload Response Ratio (LURR), Pattern Informatics (PI), critical sensitivity, earthquake critical point hypothesis, the Virtual California model (VC), Relative Operating Characteristic (ROC), Multiscale Finite-Element Model (MFEM), the Uniform California Earthquake Rupture Forecast (UCERF), etc. Multi-hazards have become a theme of ACES, and the ACES Workshop on Advances in Simulation of Multihazards was held in Maui, Hawaii, May 1–5, 2011, soon after the M 9.0 Tohoku-oki earthquake and tsunami.

Special Issues have been published after each ACES workshop, with themes related to the themes of the workshop (Donnellan et al. 2004, 2015; Fukuyama et al. 2013; Matsu'ura et al. 2002; Mora et al. 2000; Yin et al. 2006). This special issue is the second volume of papers published following the 9th ACES Workshop on Advances in Simulation of Multihazards, Chengdu, China, August 10–16, 2015 (http://www.csi.ac.cn/ACES2015/Home/index.html). The first volume (Zhang et al. 2017) contained 16 scientific papers related to the presentations at the workshop, as well as additional related topics. This volume continues in the same vein, with 14 papers related to problems in multi-hazards in addition to this Introduction.

This topical issue is divided into five sections. Papers on viscoelastic deformation are presented first, followed by papers on earthquake source models, and then papers related to earthquake prediction. The fourth section contains papers related to seismic hazard assessment, and the fifth section consists of a single paper on tsunami simulation.

In the first section, Shi et al. investigate the style of subduction mode such as stagnation or penetration of the slab around the 660 km discontinuity, based on 2D thermo-mechanical modeling. They find that penetration of the slab tends to occur for young slabs, while for older slabs stagnation is preferred. Fukahata and Matsu'ura investigate the behavior of a layered elastic–viscoelastic medium compared with a simple viscoelastic medium. Although the overall decay rate of the system is controlled by the intrinsic relaxation time constant of the asthenosphere (viscoelastic part of the system), they find that the apparent decay time constant at each observation point is significantly different from place to place and generally much longer than the intrinsic relaxation time constant of the asthenosphere. Noda et al. investigate transient deformation following the 2011 Tohoku-oki earthquake, consisting of slowly decaying landward movements above the main rupture area and rapidly decaying trench-ward movements in its southern extension. They are able to explain these postseismic deformation patterns in terms of the combined effect of afterslip on a high-angle downdip extension of the main rupture and viscoelastic stress relaxation in the asthenosphere.

In the second section, Li et al. perform a joint inversion of GPS and teleseismic data for the 2016 M_w 6.6 Aketao earthquake in eastern Pamir. The mainshock ruptured the right-lateral strike-slip Muji fault with a significant normal-slip component. The inversion results reveal two slip patches and unilateral rupture propagation to the SE for 60 km. The first slip patch occurred at a shallow depth of 0–8 km close to the mainshock hypocenter and was associated with surface breaks. The second slip patch occurred at a greater depth of $\sim$ 12 and $\sim$ 40 km to the SE. They also calculate static Coulomb stress changes for the surrounding regions based on their preferred slip model. As expected, the unzipped segments of the Muji fault and the northern segment of the Kungai fault are promoted closer to failure. Wen evaluates the source characteristics of the 2013 M_L 6.4 Ruisui and 2014 M_L 5.9 Fanglin earthquakes, in Longitudinal Valley, between the Central and Coastal Mountain Ranges in eastern Taiwan. Using strong motion simulations based on the empirical Green's function method, she showed that the dimensions of the strong motion generation area (SMGA) were smaller than the empirical estimation of inland crustal earthquakes, indicating a high stress drop for this area. This has important implications for accurate assessment of seismic hazard in this region. Zhang et al. systematically examine spatial distributions and decay patterns of strong ground motions during the 2008 M_w 7.9 Wenchuan earthquake. The mainshock ruptured on high-angle listric reverse fault zones along the boundaries between Eastern Tibetan Plateau and Sichuan Basin in Western China. They find that the peak ground accelerations (PGAs) within 30–40 km of the rupture zone are larger than those on both sides by a factor of two. In addition, the PGAs decay faster in the footwall than in the hanging wall. This effect is more prominent on the vertical than the horizontal components. They also compare the PGA distributions of the Wenchuan earthquake to other events that occurred on low-angle thrust faults such as the 1999 M_w 7.6 Chi-Chi, Taiwan earthquake. They suggest that the observed PGA patterns are likely controlled by the high-angle reverse faulting of the Wenchuan mainshock. The observed fault zone amplifications and hanging wall effects could be relevant to the distributions of seismically triggered landslides and seismic hazard mitigation and building design and constructions in these regions. Fukuyama et al. perform rock–rock friction experiments on metagabbro and diorite at subsonic slip rates ($\sim 10^{-3}$ m/s) and find that friction does not reach steady state but fluctuates within a certain range. They also find that the amplitudes of compressional waves transmitted across the slipping interfaces decrease when sliding friction becomes high and increase when friction is low. Such amplitude variation can be interpreted based on the scattering theory; small amplitudes in the transmitted waves correspond to the creation of large-scale ($\sim$ 50 μm) voids and large amplitudes correspond to the small-scale ($\sim$ 0.5 μm) voids. Thus, large- scale voids could be generated during the high friction state and low friction state was achieved by grain size reduction caused by a comminution process.

In the third section, Liu and Yin develop a dimensional analysis technique based on the π-theorem to evaluate quantitatively the magnitude and time of the ensuing large earthquake within the anomalous areas derived from the load/unload response ratio (LURR) method of Yin (1987). Two dimensionless quantities associated with earthquake times and magnitudes are derived from five parameters. Their earthquake case study shows that the dimensional analysis technique may be a useful tool to augment the predictive power of the traditional LURR approach. Rundle et al. make use of the concept of natural time (“NT”) that was first used by Varotsos et al. (2005) and later by Holliday et al. (2006) in their studies of earthquakes. They discuss the ideas and applications arising from the use of NT to understand earthquake dynamics, in particular with the use of the idea of “nowcasting”. They apply the nowcasting idea to the practical development of methods to estimate the current state of risk for dozens of the world’s seismically exposed megacities. For example, the current nowcast ranking of the Los Angeles region is comparable to its ranking just prior to the January 17, 1994 Northridge earthquake. Luginbuhl et al. make further use of nowcasting and NT to examine the temporal clustering of large global earthquakes. They apply both nowcasting and time series analysis of interevent counts to the Global Centroid Moment Tensor (CMT) catalog from 2004 to 2016. Based on their best fitting Weibull distribution, they conclude that the interevent natural times in the CMT catalog are not random.

In the fourth section, Wilson et al. develop a method for ground motion forecasts after major earthquakes based on empirical estimates of expected spatio-temporal aftershock decay, including spatial aftershock anisotropy and ground motion prediction equations. Their method has the potential to improve ground motion forecasts for aftershock sequences after major earthquakes. Rahman et al. perform a probabilistic seismic hazard assessment for the Himalayan–Tibetan region by combining incomplete historical earthquake records for more than 1000 years and instrumental earthquake catalogs since 1906. With the catalog incompleteness in mind, they estimate several key statistical seismicity parameters such as mean seismicity rate, the Gutenberg–Richter b value and maximum expected magnitude $M_{\max.}$ Using a logic tree to account for epistemic uncertainties, they combine different seismogenic source models and ground motion prediction equations to compute seismic hazard values in this region. They obtain 2 and 10% probability of exceedance over 50 years for spectral accelerations with bedrock conditions. As expected, the resulting peak ground acceleration (PGA) maps show a significant spatio-temporal variation. The obtained maximum hazard value for regions where great earthquakes occurred in the past appears to be much higher than previous studies have obtained. They suggest that a combination of historical and instrumental earthquake catalogs provides better hazard estimation in this region. Zhang et al. use a stochastic finite-fault model to generate time histories and peak values of strong ground motion at near-fault locations for characteristic earthquakes. They determine and verify the source parameters by comparing them with simulated time histories and intensity distribution and observations from the 2014 M_w 6.0 Kangding earthquake at the Xianshuihe Fault Zone, which produces strong and relatively frequent earthquakes, and exposes millions of people to the risk of strong motion and earthquake-induced geologic hazards in Southwest China. Their results show that current design ground motion for the Xianshuihe Fault area is not adequate.

In the final section, Tanioka provides a new approach in modeling tsunami height distributions that does not require direct source information but rather takes advantage of a large number of ocean bottom pressure sensors off the coast of Japan. Several detailed test scenarios suggest that the new method provides good results for Japan and could be advantageous for tsunami early warning.

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