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Radu Vacareanu
Constantin Ionescu *Editors*

Seismic Hazard and Risk Assessment

Updated Overview with Emphasis on Romania

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Updated Overview with Emphasis on Romania

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Preface

The Sixth National Conference on Earthquake Engineering and the Second National Conference on Earthquake Engineering and Seismology—6CNIS & 2CNISS—took place during June 14–17, 2017, in Bucharest, Romania, at the Technical University of Civil Engineering. The opening ceremony of the 6CNIS & 2CNISS was hosted by the Romanian Academy. The event was jointly organized by Technical University of Civil Engineering of Bucharest (*UTCB*), National Institute for Earth Physics (*INCDFP*), National Institute for Research and Development in Construction, Urban Planning and Sustainable Spatial Development (*URBAN-INCERC*) and General Inspectorate for Emergency Situations (*IGSU*), with the support of Romanian Academy Institute of Geography (*IGAR*), State Inspectorate for Construction (*ISC*), Romanian Association of Civil Engineers (*AICR*), and Romanian Association for Earthquake Engineering (*ARIS*). The peak audience to the conference amounted at 200 participants.

The 6CNIS & 2CNISS offered a stimulating and challenging environment to scientists, engineers, contractors, urban planners, and policy officials for the exchange of ideas, knowledge, lessons, and experience. The main topics of the 6CNIS & 2CNISS, mirrored in the conference sessions, were:

- Seismicity and hazard analysis;
- Geotechnical earthquake engineering;
- Seismic design and evaluation of buildings and structures;
- Innovative solutions for seismic protection of building structures;
- Seismic risk assessment and management of emergency situations.

During the three-day conference, a workshop devoted to the recently completed national project "RO-RISK—Disaster risk assessment at national", as well as three roundtables were organized. The latter addressed the issues of resilience-based assessment of structures, revision of Romanian seismic evaluation code, and quick post-earthquake evaluation of buildings.

The papers accepted by the International Advisory Committee and Scientific Committee were published by CONSPRESS (UTCB publishing house) in the Conference Proceedings. The authors of the accepted papers presented their contribution in the conference. The detailed program of the symposium is presented in Annex 1. The Conference Proceedings includes 14 keynote and invited papers, 15 papers in Seismology and Engineering Seismology, and 40 papers in Earthquake Engineering.

Renowned international scholars from the International Advisory Committee provided 11 keynote lectures in the plenary sessions. Moreover, ten invited lectures were delivered to the participants, in parallel sessions, by prominent international and national researchers. In addition, 53 contributions were presented in parallel sessions.

The most valuable papers selected by the members of International Advisory and Scientific Committees are published in this contributed volume, given the permission of CONSPRESS Publishing House. The papers selected from the Conference Proceedings were further extended by the authors and rereviewed before the final submission to Springer. The book benefits from the input of renowned researchers and professionals from Germany, Japan, Netherlands, Portugal, Romania, Turkey, and United Kingdom.

The book puts forward an updated overview of seismic hazard and risk assessment activities, with an emphasis on recent developments in Romania, a very challenging case study because of its peculiar intermediate-depth seismicity and evolutive code-compliant building stock. The content of the book focuses on seismicity of Romania, geotechnical earthquake engineering, structural analysis and seismic design regulations, innovative solutions for seismic protection of building structures, seismic risk evaluation, resilience-based assessment of structures, and management of emergency situations.

The book provides:

- Contributions of top researchers from seven countries;
- An integrated view on seismic hazard, risk, and resilience, with a perspective from civil protection, as well;
- Reliable and updated information on seismic hazard and risk of Romania based on the outcome of several recent research project: BIGSEES (BrIdging the Gap between Seismology and Earthquake Engineering: From the Seismicity of Romania towards a refined implementation of Seismic Action EN 1998-1 in earthquake resistant design of buildings), COBPEE (Community Based Performance Earthquake Engineering), and RO-RISK (Disaster risk assessment at national level);
- Comprehensive information on a scientifically challenging seismic source (Vrancea intermediate-depth) and a building stock designed according to compulsory seismic codes since 1963, constantly upgraded, and spanning all the progresses and paradigm shifts in engineering seismology and earthquake engineering.

This contributed volume aims at addressing some major challenges faced by Romanian researchers, educators, building officials, and decision-makers in disaster risk management and industry:

- The seismic evaluation and retrofitting of a large building stock; the national program for seismic retrofitting of residential buildings is very hard to implement because of social and institutional issues; meanwhile, the national programs for seismic retrofitting of public buildings, albeit its important achievements, need more focus and visibility;
- The highest seismic risk in Romania concentrated, by far, mostly in Bucharest; the expected social and economic impacts of destructive earthquakes are very high but mitigation is possible through a comprehensive and dedicated approach;
- The seismic design of buildings and structures for very large displacement demands in Romanian plain, and especially in Bucharest area;
- The rather weak public awareness; on average, there are two major earthquakes per century in Romania; thus, the education of population and the increase of public awareness are daunting tasks;
- The dormant shallow crustal seismic sources that, besides Vrancea intermediate-depth seismic source, endanger the territory of Romania;
- The quest for seismic resilience—a paradigm shift absolutely needed in Romania;
- The insurance premiums, versatile tools for enabling performance based design and boosting seismic rehabilitation, are not used so far up to their potential; moreover, the involvement of reinsurance companies and industry is rather scarce, so far.

The international cooperation is a major opportunity to address these challenges. Meanwhile, an approach similar to National Earthquake Hazards Reduction Program (NEHRP)—A research and implementation partnership—is definitely needed for focusing the activities aiming at seismic risk reduction in Romania.

The general readership of this book consists of researchers, engineers, decision-makers, and professionals working in the fields of seismic hazard and risk, seismic design, evaluation and rehabilitation of buildings and structures, building officials, insurers and reinsurers, and decision-makers for emergency situations, preparedness and recovery activities.

Acknowledgements

The Sixth National Conference on Earthquake Engineering and the Second National Conference on Earthquake Engineering and Seismology—6CNIS & 2CNISS—greatly benefited from the comprehensive and professional support of the International Advisory, Scientific and Technical Committees. The full list of the members is given in Annex 2.

The editors wish to extend their gratitude to the members of the International Advisory, Scientific and Organizing Committees, to the reviewers, and to all the contributing authors for their full involvement and cooperation in developing this book. The generosity of the 6CNIS & 2CNISS sponsors and the kind permission of CONSPRESS Publishing House of Technical University of Civil Engineering of Bucharest are gratefully acknowledged.

The valuable constructive comments and suggestions of the reviewers consistently enhanced the quality of the manuscripts. The editors deeply acknowledge the dutiful and careful checking of all the manuscripts performed, before the final submission to Springer, by our colleagues from Technical University of Civil Engineering of Bucharest (UTCB), Veronica Colibă and Ionuţ Crăciun.

A final word of gratitude is conveyed to Johanna Schwarz, Dörthe Mennecke-Bühler, Claudia Mannsperger, Ashok Arumairaj, Sooryadeepth Jayakrishnan and all the editorial staff from Springer International Publishing AG for their professional coordination and support in preparing this contributed volume.

Bucharest, Romania
March 2018

Radu Vacareanu
Constantin Ionescu

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Part I
Seismicity Analysis

Earthquake Hazard Modelling and Forecasting for Disaster Risk Reduction

Alik Ismail-Zadeh

Abstract Understanding of lithosphere dynamics, tectonic stress localization, earthquake occurrences, and seismic hazards has significantly advanced during the last decades. Meanwhile despite the major advancements in geophysical sciences, yet we do not see a decline in earthquake disaster impacts and losses. Although earthquake disasters are mainly associated with significant vulnerability of society, comprehensive seismic hazards assessments and earthquake forecasting could contribute to preventive measures aimed to reduce impacts of earthquakes. Modelling of lithosphere dynamics and earthquake simulations coupled with a seismic hazard analysis can provide a better assessment of potential ground shaking due to earthquakes. This chapter discusses a quantitative approach for simulation of earthquakes due to lithosphere dynamics that allows for studying the influence of fault network properties and regional movements on seismic patterns. Results of earthquake simulations in several seismic-prone regions, such as the Vrancea region in the southeaster Carpathians, the Caucasian region, and the Tibet-Himalayan, are overviewed. A use of modelled seismicity in a probabilistic seismic hazard analysis is then discussed.

Keywords Lithospheric dynamics · Faults · Earthquake simulation
Earthquake disasters

1 Introduction

Challenges posed by disasters due to earthquakes or related natural hazards can result in negative impacts for the sustainable development. Since the beginning of the 21st century the impacts of earthquake-related disasters have risen rapidly,

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e.g., the 2004 Sumatra-Andaman earthquake and induced tsunamis, the 2005 Kashmir earthquake, the 2008 Wenchuan earthquake and induced landslides, the 2011 Tohoku earthquake and induced tsunamis and flooding, and the 2015 Nepal earthquake and landslides. The disasters affect developed and developing countries and almost all sectors of economy at local, national, and regional levels. The vulnerability of our civilization to seismic events is still growing in part because of the increase in the number of high-risk objects and clustering of populations and infrastructure in the areas prone to earthquakes. Today an earthquake may affect several hundred thousand lives and cause significant damage up to hundred billion dollars. A large earthquake may trigger an ecological catastrophe, if it occurs in close vicinity to a nuclear power plant; the 2011 Tohoku earthquake and subsequent tsunamis damaged the cooling system of the Fukushima Dai-ichi nuclear power plant and resulted in nuclear radiation leaks (Ismail-Zadeh 2014).

Earthquake disasters continue to grow in number and impact, although the number of strong earthquakes a year is not growing with time (strictly speaking, the logarithm of the cumulative number of earthquakes shows a linear dependence on the earthquake magnitudes; Gutenberg and Richter 1944). Reducing disaster risk using scientific knowledge is a foundation for sustainable development (Cutter et al. 2015). Our knowledge on seismic hazard and other geohazards and their interaction with human systems is lacking in some important areas and is being challenged by the unforeseen or unknown repercussions of a rapidly changing and increasingly interdependent world. In such a tightly coupled world a disaster not only affects the immediate area where it occurs, but also may have cascading impacts that can affect other nations near and far.

Understanding of disasters associated with earthquakes (and/or other geohazards) comes from recent advances in basic sciences, engineering, and applied research including advances in: (1) geophysics, Earth's lithosphere dynamics, and understanding of hazardous event occurrences, all gained from Earth observations, analysis, and modelling; (2) comprehensive hazard assessments combining knowledge on seismology, geology, geodesy, geodynamics, electro-magnetism, hydrology, and soil properties with modelling tools and forecasting; (3) engineering related to development of earthquake resistant constructions; and (4) analysis of physical and social vulnerabilities and exposed values as well as studies of resilience of the society that help to prepare, respond and adapt to possible disruptions due to disasters. The understanding may become full, if it is based on co-designed and co-productive transdisciplinary work of all stakeholders involved in disaster risk reduction, including natural, social and behavioural scientists, engineers, insurance industry, media, emergency management and legislation authorities, and policymakers (Ismail-Zadeh et al. 2017a).

2 Lithospheric Dynamics, Tectonic Stresses and Earthquakes

According to plate tectonic theory (e.g. Turcotte and Schubert 2014), lithospheric plates are continually created and consumed. At ocean ridges, adjacent plates diverge and move away from the ridges cooling, densifying, and thickening. Once the lithosphere becomes sufficiently dense compared to the underlying mantle rocks, it bends, founders, and subducts into the mantle due to gravitational instability. The downward buoyancy forces, which are generated due to the excess density of the rocks of the subducting lithosphere, promote the lithosphere descent, but elastic, viscous and frictional forces resist it. The combination of these forces produces shear stresses high enough to cause earthquakes. Earthquakes occur as a sudden release of stresses. At ocean trench zones, they occur along the subducting lithosphere to the depths of about 660 km depending on the thermal state in the mantle. When an earthquake occurs, part of the released energy generates elastic waves propagating through the Earth. These waves generate sudden ground motions and shaking, which may result in building damage or collapse, landslides, tsunami wave generation, etc.

Ocean trenches are the sites of the world greatest earthquakes, which produce significant ruptures every century or rarely in the same ocean trench. According to Lay and Kanamori (2011), great earthquake occurrences can be understood from plate-boundary frictional characteristics. A slip may generate an earthquake at some patches of a fault surface, whereas the slip may occur without an earthquake. Conditionally stable patches normally slip continuously, but can slip seismically, when loaded abruptly during the failure of neighbouring seismic patches. "A failure of one seismic patch may produce a large earthquake. But when two or more patches fail in a cascade that also prompts conditionally stable regions between them to slip seismically, the result is a much larger earthquake than one would otherwise expect from just the seismic patches alone" (Lay and Kanamori 2011).

Although the majority of large earthquakes occur in subduction zones, some of them happen inside of continents (so called 'intraplate earthquakes'), especially in the regions of continental collisions, rifts, and grabens. For example, the Vrancea intermediate-depth strong earthquakes occur far away from lithosphere plate boundaries in the southern Carpathians (Romania) at the depths of about 70–180 km (e.g. Ismail-Zadeh et al. 2012). These earthquakes are considered to be associated with the relic slab sinking beneath the old Carpathian continental collision zone (e.g. Ismail-Zadeh et al. 2005, 2008). Other examples are the 2001 Bhuj M7.7 earthquake, which occurred in the Kutch rift zone, India, and caused widespread damage and death toll of over 20,000 people (Gupta et al. 2001); and large earthquakes, which took place in 1811 and 1812 in the New Madrid Rift complex, USA (Braile et al. 1986). According to the global risk analysis (Dilley et al. 2005), an area of about 10 million km^2 is estimated to undergo significant shaking by earthquakes or more precisely, peak ground acceleration of at least 2 m s^{-2} are expected in the area for 50 years with probability 0.1. This area is inhabited by more than one billion people.

Tectonic stress generation and its localization due to lithosphere plate motions is an important component in studies of earthquake-prone regions (e.g. Aoudia et al. 2007; Ismail-Zadeh et al. 2005, 2010). For example, Ismail-Zadeh et al. (2005) analysed stress localization in and around a descending lithospheric slab in the Vrancea region using a three-dimensional numerical model of mantle flow induced by the slab. The numerical model, which was based on temperatures derived from seismic P-wave velocity anomalies (Martin et al. 2006) and surface heat flow (Demetrescu and Andreescu 1994), predicted the maximum shear stress localization to coincide with the hypocentres of the intermediate-depth seismicity (Fig. 1), and stress orientations to be in a good agreement with the stress regime defined from fault-plane solutions for the intermediate-depth earthquakes.

Understanding stress re-distribution after earthquakes have been improved for the last few decades. Using the Coulomb failure criterion King et al. (1994) explored how changes in Coulomb stress conditions associated with an earthquake may trigger subsequent earthquakes (aftershocks). An earthquake alters the shear and normal stress on surrounding faults, and small sudden stress changes cause large changes in seismicity rate. These or relevant studies of tectonic stress and its

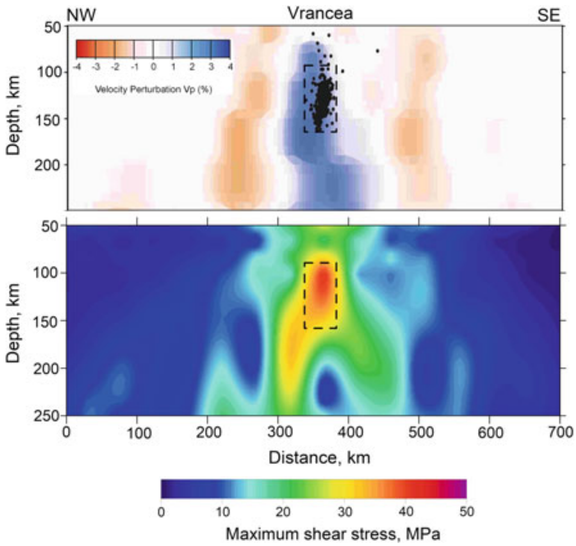

Fig. 1 Seismic velocity anomalies, earthquake hypocentres, and predicted tectonic stresses for the Vrancea region. Upper panel: *P*-wave velocity tomography image across NW-SE section through the south-eastern Carpathians (Martin et al. 2006) and the projection onto this cross section of the hypocentres of the Vrancea intermediate-depth earthquakes from 1995 to 2005. Lower panel: predicted maximum shear stress for the same cross-section. The dashed boxes delineate the area of hypocentres and maximum shear stress. After Ismail-Zadeh et al. (2005)

distribution before and after earthquakes provide important information on the localization of stresses and stress changes, which can be used in hazard assessment. Meanwhile, quantitative earthquake simulations at a fault or a system of faults can provide an insight into tectonic stress release at sites that have not been ruptured (or their ruptures in the past have not been recorded).

3 Quantitative Earthquake Simulations

Studying seismicity using the statistical and phenomenological analysis of earthquake catalogues has the disadvantage that instrumental observations cover a short time interval compared to the duration of the tectonic processes responsible for earthquakes. The patterns of earthquake occurrence identifiable in a catalogue may be apparent and yet may not be repeated in the future. Meanwhile, historical data on seismicity are usually incomplete. Numerical modelling of seismic processes, including tectonic stress localisation and its release in earthquakes, allows generating synthetic earthquake catalogues covering long time intervals and provides a basis for reliable estimates of the parameters of the earthquake occurrences (e.g. Soloviev and Ismail-Zadeh 2003).

Earth-specific quantitative earthquake simulators help to study seismicity in a system of faults (e.g. Gabrielov et al. 1990; Soloviev and Ismail-Zadeh 2003; Rundle et al. 2006). Particularly, a block-and-fault dynamics (BAFD) model by Gabrielov et al. (1990) can answer the following questions: how upper crustal (or lithospheric) blocks react to the plate motions and to a flow of the lower ductile crust (or highly viscous asthenosphere); how earthquakes cluster in the system of major regional faults; at which part of a fault system large events can occur, and what is the occurrence time of the extreme events; how the properties of the frequency-magnitude relationship change prior extreme events; and how fault zones properties influence the earthquake clustering, its magnitude and fault slip rates. The BAFD model was applied to several earthquake-prone areas. A recent review of the model and its applications can be found in Ismail-Zadeh et al. (2017b). Here we discuss briefly the application of the BAFD model to the Vrancea, Caucasus, and Tibet-Himalayan regions.

Vrancea. Large intermediate-depth earthquakes in Vrancea caused destruction in Bucharest (Romania) and shook central and eastern European cities several hundred km away from the hypocentres of the events. The earthquake-prone Vrancea region is situated at the bend of the south-eastern Carpathians. Epicentres of the intermediate-depth earthquakes are concentrated within a very small volume in the mantle extending to a depth of about 180 km. This seismicity is proposed to be associated with a relic part of the oceanic lithosphere sinking in the mantle (McKenzie 1972), and detached from or weakly linked to the continental crust (Fuchs et al. 1979). Seismic tomography imaged a high-velocity body beneath the Vrancea region (e.g. Bijward and Spakman 2000; Wortel and Spakman 2000; Martin et al. 2006; Raykova and Panza 2006), which can be interpreted as a dense lithospheric slab. A detailed review on geology, geodynamics, seismicity, and related studies in the Vrancea region can be found in Ismail-Zadeh et al. (2012).

The BAFD model was applied to study the dynamics of the lithosphere and intermediate-depth large earthquakes in the Vrancea region (Panza et al. 1997; Soloviev et al. 1999, 2000). Figure 2a shows the pattern of faults on the upper plane of the BAFD structure used to model the region. The catalogue of synthetic seismicity was computed for the period of 7000 years. The maximum value of the magnitude in the catalogue of model events is 7.6, close to the magnitude Mw = 7.7 earthquake occurred in Vrancea in 1940. The observed seismicity is shown in Fig. 2b, and the distribution of epicentres from the catalogue of synthetic events in Fig. 2c. A simple BAFD model, consisting of only three lithospheric blocks, was capable to reproduce the main features of the observed seismicity in space. Also, the modelling showed an irregularity in the time distribution of strong synthetic seismic events. For example, groups of large earthquakes occur periodically in the time interval from about 500 to 3000 model years, with a return period of about 300–350 years (Fig. 2d). The periodic occurrence of a single large earthquake with a return period of about 100 years is typical of the interval from 3000 to 4000 years. There is no periodicity in the occurrence of large earthquakes in the remaining parts of the catalogue of synthetic events. These results

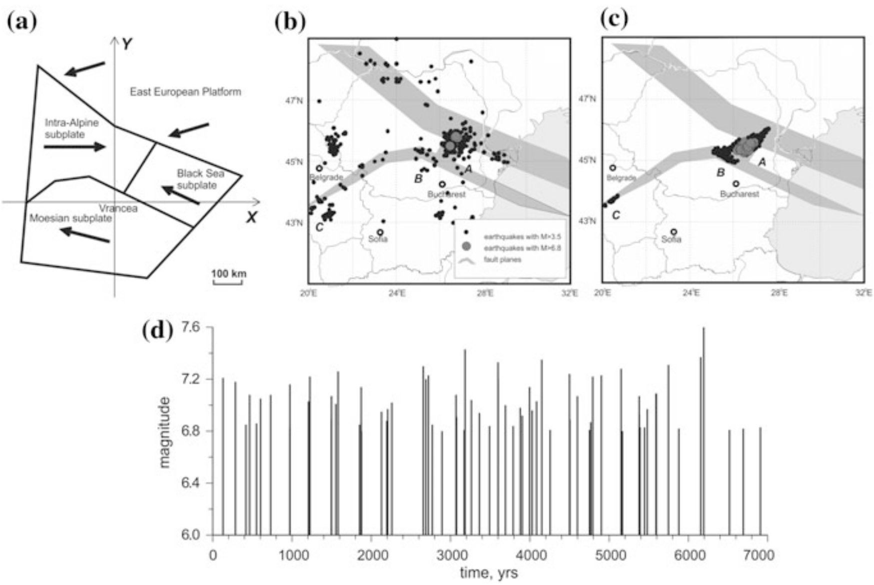

Fig. 2 BAFD model for the Vrancea region. **a** Block structure used for earthquake simulation in Vrancea. Arrows outside and inside the BAFD structure indicate the movements of the model blocks and of the sub-lithospheric mantle, respectively. Maps of observed seismicity in Vrancea in the period 1900–1995 (**b**) and modelled seismicity for 7000 years (**c**). Grey areas are the projections of fault planes on the upper plane. **d** Temporal distribution of large (M > 6.8) synthetic earthquakes for 7000 years. Modified after Soloviev and Ismail-Zadeh (2003)

demonstrate the importance of a careful estimation of the duration of seismic cycles to predict the occurrence of a future large earthquake.

Ismail-Zadeh et al. (1999) introduced a mantle flow into a BAFD model of the Vrancea region. The rate of the motion of the lithospheric blocks was determined from a model of mantle flow induced by a sinking slab beneath the Vrancea region (Ismail-Zadeh et al. 2000). It was shown that changes in modelled seismicity was controlled by small changes in the lithospheric slab's descent, e.g., slab position or dip angle (Ismail-Zadeh et al. 1999).

Caucasus. Earthquakes in Caucasia are associated with the Alpine-Himalayan seismic belt and collision between Eurasia and Arabia. The effect of this collision propagated into the Caucasus region in the early Pliocene (e.g., Philip et al. 1989). Regional deformation is quite complicated and includes lateral transport and rotation of crustal blocks along strike-slip faults (e.g., Reilinger et al. 2006). Most of deformations in Caucasus occurs within the Greater Caucasus Mountains (Jackson et al. 2002). The 1991 M7.0 Racha, Georgia, earthquake occurred in the western Greater Caucasus, and several destructive historical earthquakes occurred near the city of Shamakhi in the eastern Greater Caucasus in 1667, 1859, and 1902 (Kondorskaya et al. 1982).

The BAFD model was used to study earthquake occurrences in the Caucasian region (Ismail-Zadeh et al. 2017b; Soloviev and Gorshkov 2017). The movement of the block structure was constrained by the regional geodynamic models (Philip et al. 1989) and geodetic measurements (Reilinger et al. 2006). The BAFD experiments covered the time interval of 8000 years, which is by factor of about 80 larger than the earthquake catalogue. The synthetic earthquakes mimic the regional seismicity but with some exceptions: synthetic events occurred at some faults segments where no earthquakes have been previously recorded (instrumentally or historically). Meanwhile, the slope of the frequency-magnitude plot for synthetic events shows a good agreement with that for observed regional seismicity in the magnitude range from 4.5 to 7.

Tibet-Himalayas. Following the closure of the Mesozoic Tethys Ocean, the India-Asia collision initiated the development of the Himalayan range and the Tibetan plateau and induced widespread strain in south-eastern Asia and China. Ismail-Zadeh et al. (2007) developed a BAFD model for the region based on a model structure (Fig. 3a) made of six major blocks delineated by Replumaz and Tapponnier (2003). The crustal blocks were separated by thrust and strike-slip faults hundred km long. The movement of the blocks was specified with the rate constrained by the present rate of convergence between India and Asia (Bilham et al. 1997). Using the BAFD model, Ismail-Zadeh et al. (2007) performed a number of numerical experiments generating catalogues of synthetic earthquakes to analyse the earthquake clustering, frequency-to-magnitude relationships, earthquake focal mechanisms, and fault slip rates in the Tibet-Himalayan region. Each BAFD-generated catalogue contains crustal (down to 30 km) events occurring at the same fault planes introduced in the model and covers the time interval of 4000 years. The distribution of maximum magnitudes $M_{\max,\,\mathrm{BAFD}}$ of earthquakes from the merged three catalogues along the model faults is presented in Fig. 3b.

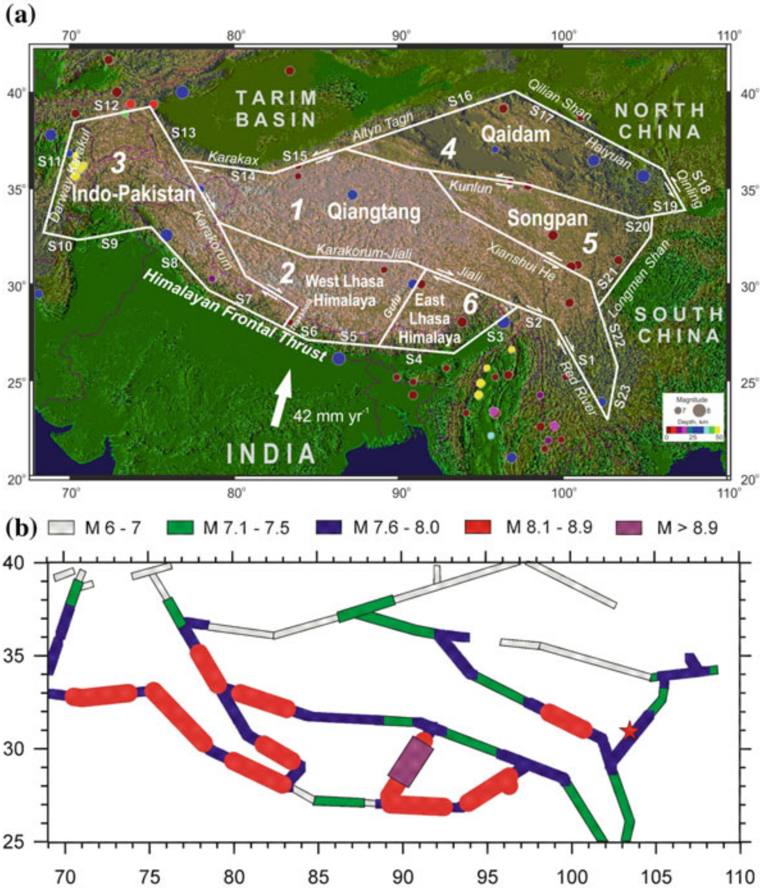

Fig. 3 BAFD model for the Tibet-Himalayan region. **a** Geometry of the block-and-fault structure and spatial distribution of observed seismicity ($M \geq 7.0$) from 1902 to 2000 (after Ismail-Zadeh et al., 2007). White bold lines (model faults) delineate the structural geological elements, and the white arrow indicates the motion of India relative to Eurasia. Earthquake epicentres are marked by coloured (depending on the depth of the hypocentres) circles. **b** Distribution of maximum magnitudes $M_{\max,BAFD}$ of the earthquakes predicted by the three chosen BAFD model experiments. Modified after Sokolov and Ismail-Zadeh (2015)

The numerical results demonstrate that large events localize only on some of the faults, and this illustrates the fact that the BAFD model describes the dynamics of a network of crustal blocks and faults rather than the dynamics of individual fault planes. As an example, a cluster of large modelled events (M7.6–8.0) along the Longmen Shan fault was identified by the BAFD model (Fig. 3b). The 2008 M = 7.9 Sichuan (Wenchuan) earthquake (red star in Fig. 3b) occurred along this fault killing about 70,000 in addition to about 400,000 injured and about 20,000 missing people. Ismail-Zadeh et al. (2007) also analysed the focal mechanisms of the synthetic earthquakes computing the angle between the slip direction (in the fault plane) and the fault line and showed a reasonably good agreement between the focal mechanisms of the synthetic and observed earthquakes. Namely, in both cases (in the model and reality) most thrust faulting events occur on the Himalayan seismic belt and normal faulting events on the Gulu rift.

4 Earthquake Hazard Analysis

Seismic hazard can be defined as potentially damaging earthquake, which "may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (UN 2017). Meanwhile seismologists and earthquake engineers define seismic hazard in terms of engineering parameters of strong ground motion, namely, peak ground velocity/acceleration or seismic intensity. Seismic hazard assessment (SHA) is then based on the information about the features of excitation of seismic waves at the source, seismic wave propagation (attenuation), and site effect in the region under consideration and combines the results of seismological, geomorphological, geological, and tectonic investigations and modelling (e.g. Ismail-Zadeh 2014).

Two principal methods are intensively used in seismic hazard assessment: probabilistic and deterministic SHA. The probabilistic analysis deals with the rates of exceeding various levels of ground motion estimated over a specified time period (Cornell 1968). The probabilistic assessment considers uncertainties in earthquake source, path, and site conditions. The uncertainties are classified as epistemic and aleatory. Epistemic uncertainties reflect the incomplete knowledge about input model parameters to the assessment and variability of interpretations of available data, whereas aleatory uncertainties consider the inevitable unpredictability of the parameters (the uncertainties are mainly quantified using the standard deviation of the scatter around the mean values). The deterministic (or earthquake scenario-based) assessment model analyses the attenuation of seismic energy with distance from a specified earthquake to determine the level of ground motion at a particular site. Ground motion calculations consider the effects of local site conditions and use the available knowledge on earthquake sources and wave propagation processes. Namely, attenuation relationships are used for a given earthquake magnitude to calculate ground shaking demand for rock sites, which is then amplified by factors based on local soil conditions. Although the occurrence frequency of the ground motion is usually not addressed in the deterministic SHA, the method is robust for an assessment of seismic hazard and remains useful in decision-making (e.g. Babayev et al. 2010).

Compared to deterministic seismic hazard maps, probabilistic maps do not present the ground shaking at site, but instead present a level of ground shaking, which can be exceeded with a certain probability within a certain period of time. The probabilistic seismic hazard maps provide a low bound of seismic hazard useful for engineering purposes. Meanwhile non-expert scientists and other stakeholders dealing with hazard assessments try sometimes to associate the colours in probabilistic maps with potential ground shaking, and become surprised, if the real ground shaking is higher than predicted by the probabilistic maps. This reveals a weakness in mapping and interpretations of probabilistic SHA results.

An alternative approach to SHA is based on computations of realistic synthetic seismograms (Panza et al. 2001) and employs the knowledge of the crust and the lithosphere, seismic sources, and regional seismicity. The synthetic seismograms quantify peak values of acceleration, velocity and other ground motion parameters relevant to earthquake engineering. Considering a wide set of scenario events, including maximum credible earthquake, as well as geological and geophysical data, this approach offers the envelope of values of earthquake ground motion parameters (Panza 2017).

In many cases, large earthquakes are not accounted in the SHA due to the lack of information about them and unknown reoccurrence time of the extremes. Our present knowledge about characteristics of seismicity is based on observed (recorded) data and available historical data (obtained from palaeo seismological and archaeological studies, written stories about intensities of large earthquakes and some other sources). The information about large events in a particular region is incomplete as they are rare. Modelling of seismic events using earthquake simulators can overcome the difficulties in SHA by combination of observations, historic data and modelled results.

Sokolov and Ismail-Zadeh (2015) developed a new approach to a Monte-Carlo probabilistic SHA combining the observed regional seismicity with large magnitude synthetic events obtained by BAFD simulations. Three catalogues of synthetic events from Ismail-Zadeh et al. (2007) were chosen. The choice of these catalogues was based on the proximity of observed and simulated values of the following physical or statistical parameters: the slip rate at major faults, the orientation of crustal movements, the earthquake focal mechanism, the rate of seismic moment release, and the slope of the frequency-magnitude relations for the observed and modelled earthquakes. Also, the catalogues were chosen to minimize the difference between the annual rate of earthquake occurrence in the BAFD model and that of observed seismicity. Earthquake scenarios for hazard assessment are generated stochastically to sample the magnitude and spatial distribution of seismicity, as well as the distribution of ground motion for each seismic event.

This approach was employed for seismic hazards analysis in the Tibet-Himalayan region. Figure 4 presents a comparison of the results of the hazard assessment performed by the standard probabilistic SHA (the Global Seismic Hazard Assessment Program (GSHAP) model, Giardini et al. 1999) and the data-enhanced SHA approach accounting for large synthetic events (DESHA model, Sokolov and Ismail-Zadeh 2015). It is evident that the difference in ground shaking predicted by the two models, or, strictly speaking, the difference $\Delta_{PGA} = \log_{10}(\mathrm{PGA}_{DESHA}/\mathrm{PGA}_{GSHAP})$ between the relevant peak ground acceleration (PGA) estimates obtained by the DESHA model (PGADESHA) and by the GSHAP model (PGAGSHAP), is significant ($\mathrm{PGA}_{\mathrm{DESHA}} \geq 1.5\mathrm{PGA}_{GSHAP}$, i.e. $\Delta_{PGA} \geq 0.176$) for several areas including the area of the 2008 Wenchuan earthquake. Therefore, the DESHA model by Sokolov and

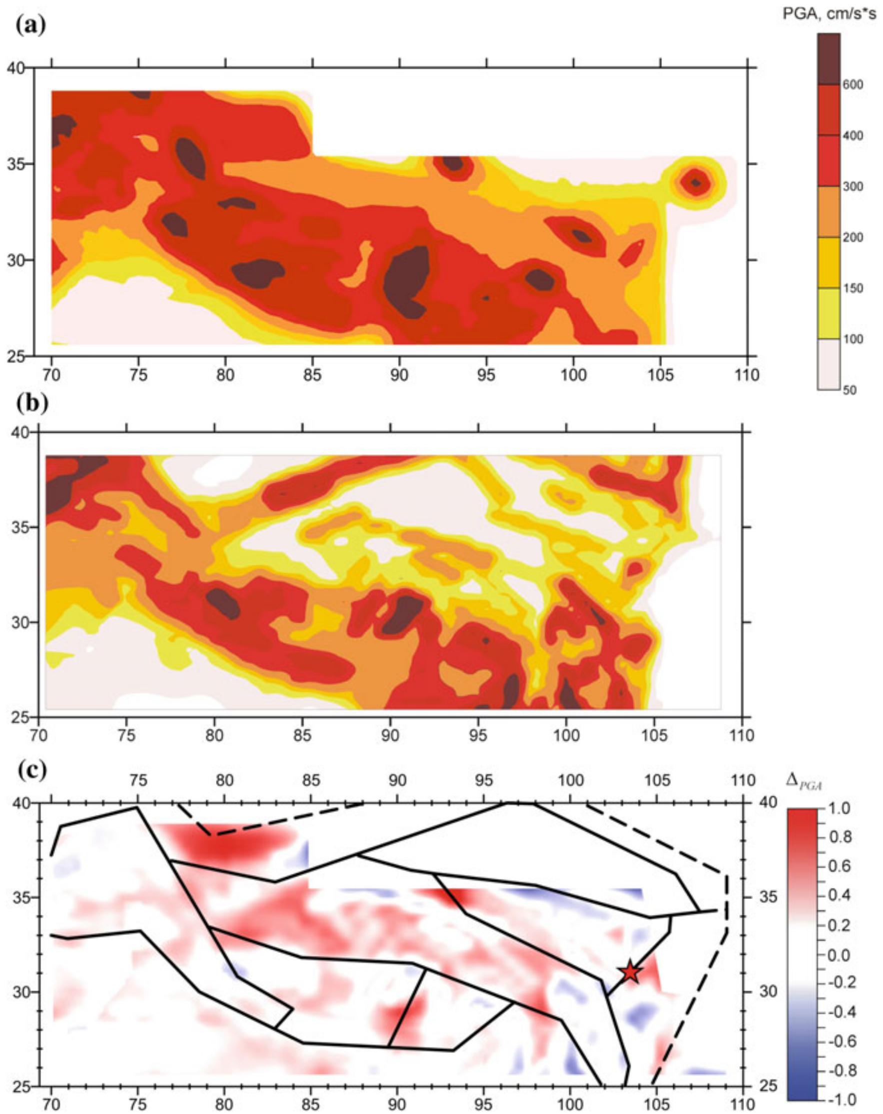

Fig. 4 Probabilistic seismic hazard maps of the Tibet-Himalayan region obtained (**a**) in this study and (**b**) from the GSHAP data (Giardini et al. 1999). The maps present peak ground accelerations, which are expected to be exceeded at least once in 50 years with probability 0.1 (with the average return period of 475 years). **c** The difference Δ_{PGA} between two ground motion assessments defined in the text. Black lines are the fault system used in the BAFD models. Due to the lack of information on earthquake source zones for the area located to the north from 35°N and to the east from 85°E, the PGA values are not calculated for this area After Sokolov and Ismail-Zadeh (2015)

Ismail-Zadeh (2015) allows for better understanding of ground shaking and could be useful for earthquake risk assessment, engineering purposes, and emergency planning.

Current probabilistic SHA methods are based on point-wise (site by site) assessments of ground shaking. Sokolov and Ismail-Zadeh (2016) analysed some features of multiple-site (MS) probabilistic SHA, i.e. the annual rate of ground-motion level exceedance in at least one site of several sites of interest located within an area or along a linear extended object, and showed that the expected ground motion level in selected area (multiple sites) are higher than that at individual sites. To assess the difference between point-wise and the multiple-site estimations of seismic hazards, Sokolov and Ismail-Zadeh (2016) considered an area located near the epicentre of the 2008 Wenchuan earthquake or stretched along the causative fault. It was assumed that the entire area is characterized by the same design PGA value (PGAPNT) and that there are several sites (e.g. strong-motion stations or critical facilities), where the multiple-site hazard (PGAMLT) should be evaluated. Also, a low level of the ground motion correlation (e.g. the correlation distance of 5 km) was assumed and allows for a high difference (variances) between the expected ground-motion parameters even for neighbouring sites. The dependence PGAMLT/PGAPNT on the area size, the number of sites, and the return period is shown in Fig. 5. The greater is the area (and the larger is the number of considered sites), the greater is the difference between the hazard estimates for individual sites and the multiple sites. In the considered case, the level of multiple-site hazard estimated for the 2475-year return period is larger than the highest recorded level of ground motion even for the relatively small area and for a

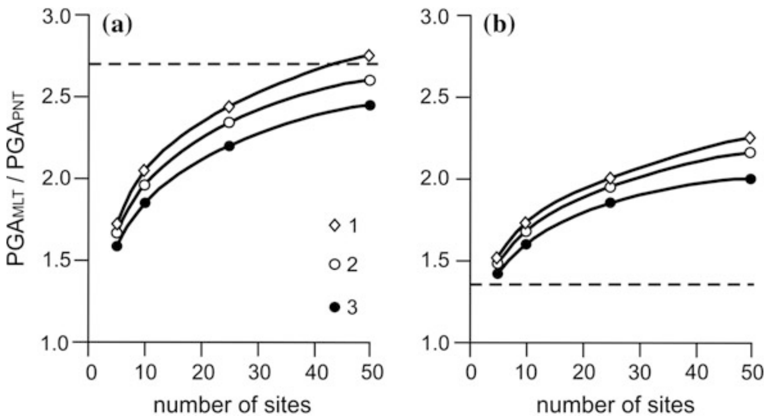

Fig. 5 Relation between the peak ground acceleration obtained from multiple-site (PGA_{MS}) and point-wise (PGA_{PW}) hazard assessments for the area of the 2008 Wenchuan earthquake for the 475-year (**a**) and 2475-year (**b**) return periods. The dashed line shows ratio between the maximum PGA recorded during the earthquake (about 810 cm s^{-2}) and the estimated design ground motion $PGA_{475} \sim 300$ cm s^{-2} (**a**) and $PGA_{2475} \sim 600$ cm s^{-2} (**b**). 1: area 600 km^2; 2: 400 km^2; 3: 100 km^2. Modified after Sokolov and Ismail-Zadeh (2015)

small number of sites. Sokolov and Ismail-Zadeh (2016) proposed a multi-level approach to probabilistic SHA considering fixed reference probability of exceedance (e.g. 10% in 50 years): (i) a standard point-wise hazard assessment to be performed in a seismic-prone region, and (ii) this analysis should be supplemented by a multiple-site hazard assessment for urban and industrial areas, or zones of an economic and social importance. This multi-level approach can provide better assessment of expected ground motion in a region of high vulnerability and/or exposed values, and hence enhance SHA.

5 Forecasting Seismic Hazard Events

The abruptness along with apparent irregularity and infrequency of large earthquake occurrences perpetuate the perception that earthquakes are random unpredictable phenomena (Ismail-Zadeh 2013). Earthquake prediction research has been widely debated, and opinions on the possibilities of prediction vary from the statement that earthquake prediction is intrinsically impossible (Geller et al. 1997) to the statement that prediction is possible, but difficult (Knopoff 1999; Keilis-Borok et al. 2001). Although many observations reveal unusual changes of geophysical fields at the approach of a large earthquake (e.g. animal behaviour, ground elevation, water level in boreholes, radon emission), most of them report a unique case history and lack a systematic description (e.g. Wyss 1991).

To predict an earthquake, one must "specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. … Moreover, scientists should also assign a confidence level to each prediction" (Allen et al. 1976). A prediction of an earthquake of certain magnitude range can be identified by (1) duration of time interval (long-term or a decadal time scale, intermediate-term or one to several years, short-term or weeks to months, and immediate or seconds to hours), and/or (2) territorial specificity based the rupture size of the incipient earthquake.

Earthquake forecasting based on monitoring of precursor(s) of earthquakes (that is, physical, chemical or biological signals, which indicate that a large earthquake can be anticipated) issues an alarm at the time of the abnormal behaviour of the precursor (the so-called time of increased probability of large event occurrence). Sometimes such forecasting is referred to as 'alarm-based earthquake prediction' (Ismail-Zadeh 2013). Several alarm-based intermediate-term earthquake prediction methods have been developed for the last decades (e.g., Keilis-Borok and Kossobokov 1990; Shebalin et al. 2006; among others). The intermediate-term earthquake prediction method (M8 algorithm; Keilis-Borok and Kossobokov 1990) aims to forecast large (magnitude 8 and greater) earthquakes by monitoring and analysis of several parameters of the seismic activity in a region. This prediction algorithm has received a fair amount of attention due to on-going real-time experimental testing unprecedented in rigor and global coverage (Ismail-Zadeh and

Kossobokov 2011). The accumulated statistical data of this experiment confirm intermediate-term predictability of large earthquakes with middle- to exact-range of location (Kossobokov 2013). Independent assessments of the M8 algorithm performance confirm that the method is non-trivial to predict large earthquakes (Zechar and Jordan 2008; Molchan and Romashkova 2011).

A short-term prediction of the devastating 1975 Haicheng (China) Ms = 7.0 earthquake by Chinese seismologists was based on monitoring anomalies in land elevation, in ground water level, and in seismicity prior to the large event and on the observations of peculiar behaviour of animals (Zhang-li et al. 1984). The success of this prediction stimulated further design of methods for diagnosis of an approaching large earthquake. Unfortunately, other prediction methods suggested at that time were not confirmed in the following years. The catastrophic 1976 Tangshan (China) Ms = 7.4 earthquake, which caused hundreds of thousands of fatalities, was not predicted.

A method of short-term earthquake prediction (the VAN method) was proposed in the 1980s; it was based on detection of characteristic changes in the geoelectric potential (so called "seismic electric signals", SES) via a telemetric network of conductive metal rods inserted in the ground (e.g. Varotsos et al. 1986). The anomaly pattern is continually refined as to the manner of identifying SES from within the abundant electric noise the VAN sensors are picking up. Despite many years of investigations and some progress for the last three decades (Lazaridou-Varotsos 2013), the short-term prediction by the VAN method is still controversial.

Another type of short-term prediction is based on calculating the probabilities of target events within future space-time domains, e.g., the short-term earthquake probability (STEP) method developed by Gerstenberger et al. (2005). The STEP method uses aftershock statistics to make hourly revisions of the probabilities of strong ground motion. The probability-based forecasts are the mean for transmitting information about probabilities of earthquakes in the region under monitoring. While the probability gains of short-term forecasts can be high, the probabilities of potential destructive earthquakes remain much smaller than 0.1 as the forecasting intervals are much shorter than the recurrence intervals of large earthquakes.

Although earthquake prediction methods are improving along with seismological data analysis, the current quality and accuracy of earthquake forecasting is significantly low compared to those of weather forecasting (Bauer et al. 2015). Our knowledge of earthquake physics and earthquake dynamics is still limited to predict large earthquakes with a relatively high accuracy. There is no strict mathematical description of non-linear dynamics of fault systems, earthquake generation process, and earthquake rupturing. This situation is unlike meteorology, where huge observations, a set of well-known mathematical equations describing atmospheric flow, and data assimilation techniques allow weather forecast with a relatively high accuracy for time scales ranging from a few hours to a few days. Success in earthquake hazard forecasting can be achieved by enhancement in (i) studies of non-linear tectonic stress generation, its localization and release in earthquakes as well as the rupture dynamics and earthquake mechanics; (ii) more geophysical, seismological and geodetic observations and data on fault and fault network geometry and their interaction; (iii) a mathematical description of the processes leading to earthquakes and methods for earthquake analysis (e.g., a set of governing equations and relevant conditions describing a transition to an earthquake; data assimilation and ensemble forecasting in stress and earthquake research); (iv) development of earthquakes models and powerful simulators (incl. numerical methods and supercomputer power to allow interactions in fault networks, at the scale of about 50 m).

Meanwhile, even current level of earthquake prediction capacity can be useful for seismic risk assessment and disaster preparedness. How the available basic scientific knowledge and earthquake-forecasting strategies could be linked to risk reduction strategies to make cost effective mitigations? "Optimized earthquake prediction algorithms will greatly aid disaster managers and decision makers in their preparations once a prediction is made. The loss functions help to develop a greater understanding between earthquake prediction research and disaster preparedness implementation, allowing for future improvements in earthquake disaster prevention" (Davis 2012).

6 Conclusion

Although the origin of seismology could be dated back to the Eastern Han Dynasty (25–220 AD) in China and great progress is achieved in this branch of science, there still exist several challenging problems (Forsyth et al. 2009), and among them an important question: how do faults interact and slip to generate an earthquake? The fundamental difficulty in solving the challenging problems is that no earthquake (process of rupture initiation at depth) has ever been observed directly and just a few of them were subject to an in situ verification of their physical parameters. Many of the extreme seismic events of the beginning of this century are linked in a chain of subsequent events that produce a disaster (the chain of events is called also 'concatenated events'). The 2004 great Sumatra-Andaman earthquake was following the Indian Ocean tsunami, which affected the coastal regions by flooding, contaminated water resources, and influenced the tourism business in the entire region. The 2008 Wenchuan earthquake was followed by the number of big landslides with a significant damage and human/economic losses. The 2011 Great East Japan earthquake followed by extreme tsunami waves, significant inundation, technological accident in the nuclear power plant, an environmental pollution with food and health security problems in the country and abroad.

Seismic hazards have been recognized as a grant challenge long time ago, and seismological and engineering communities concentrated their efforts on solving the challenging problem with a significant progress achieved. Recent advances are associated with neo-deterministic approach (Panza et al. 2010) and data-enhanced probabilistic approach (Sokolov and Ismail-Zadeh 2015) to SHA. Particularly, tectonically-realistic earthquake simulators help to generate seismicity for a significant duration of time and to employ large synthetic seismic events for hazard assessment. New scientific methods and approaches can enhance understanding of natural extreme events and vulnerabilities assessments at all levels including the gathering of a wide range of measures for increasing the resilience of society to seismic hazards.

With time, it was recognized that there are more challenging problems requiring co-produced research on disaster risks associated with earthquakes and other natural hazards that can enable understanding of the roots of potential disasters. Some challenging problems are analysed and discussed in the accompanying chapter "Earthquake risk assessment for seismic safety and sustainability" along with major components of earthquake risk assessment (seismic hazards, vulnerability and exposure), preventive measures to mitigate earthquake disasters, and the progress in disaster risk science in the framework of sustainability.

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References

Allen CR, Edwards W, Hall WJ, Knopoff L, Raleigh CB, Savit CH, Toksoz MN, Turner RH (1976) Predicting earthquakes: a scientific and technical evaluation—with implications for society. Panel on Earthquake Prediction of the Committee on Seismology, National Research Council. U.S. National Academy of Sciences, Washington DC

Aoudia A, Ismail-Zadeh A, Romanelli F (2007) Buoyancy-driven deformation and contemporary tectonic stress in the lithosphere beneath Central Italy. Terra Nova 19(6):490–495

Babayev G, Ismail-Zadeh A, Le Mouël J-L (2010) Scenario-based earthquake hazard and risk assessment for Baku (Azerbaijan). Nat Hazard Earth Syst Sci 10:2697–2712

Bauer P, Thorpe A, Brunet G (2015) The quiet revolution of numerical weather prediction. Nature 525:47–55

Bijwaard H, Spakman W (2000) Non-linear global P-wave tomography by iterated linearized inversion. Geophys J Int 141:71–82

Bilham R, Larson K, Freymueller J, Project Idylhim members (1997) GPS measurements of present-day convergence across the Nepal Himalayas. Nature 386:61–64

Braile LW, Hinze WJ, Keller GR, Lidiak EG, Sexton JL (1986) Tectonic development of the New Madrid rift complex, Mississippi Embayment, North America. Tectonophysics 131:1–21

Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Amer 58:1583–1606

Cutter S, Ismail-Zadeh A, Alcántara-Ayala I, Altan O, Baker DN, Briceño S, Gupta H, Holloway A, Johnston D, McBean GA, Ogawa Y, Paton D, Porio E, Silbereisen RK, Takeuchi K, Valsecchi GB, Vogel C, Wu G (2015) Pool knowledge to stem losses from disasters. Nature 522:277–279

Davis CA (2012) Loss functions for temporal and spatial optimizing of earthquake prediction and disaster preparedness. Pure appl Geophys 169(11):1989–2010

Demetrescu C, Andreescu M (1994) On the thermal regime of some tectonic units in a continental collision environment in Romania. Tectonophysics 230:265–276

Dilley M, Chen RS, Deichmann W, Lerner-Lam AL, Arnold M (2005) Natural disaster hotspots: a global risk analysis. The World Bank, Washington DC

Forsyth DW, Lay T, Aster RC, Romanowicz B (2009) Grand challenges for seismology. EOS Trans AGU 90(41):361–362. https://doi.org/10.1029/2009EO410001