COMPUTATIONAL GEODYNAMICS FOR SEISMIC HAZARD ANALYSIS AND EARTHQUAKE PREDICTION

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Contents

Summary

Recent advances in understanding Earth dynamics and in development of computational tools permit accurate numerical modeling and forecasting that are transforming the Earth sciences. These advances have a strong impact on studies of lithosphere dynamics, tectonic stress localization and changes, comprehensive seismic hazard assessment, and show significant potential to be applied to serve the sustainable development of society.

The vulnerability of human civilization to disasters caused by large earthquakes is growing due to the clustering of populations and proliferation of high-risk objects. The disasters have become a threat to a civilization's well-being: today a single earthquake may take up to several hundred thousand lives and cause significant material damage. The problem of earthquake prediction is a "grand challenge", although it may be solvable.

The ability to successfully predict large earthquakes would provide society with a change of reducing damage and loss of life due to ground motion, landslides, fire,

tsunamis and other associated hazards, and would assist in disaster preparedness protecting a society's population, economy, and environment. This chapter will introduce the reader to computational geodynamics and discuss its application to seismic hazard analysis. After a brief introduction into the subject, essential topics for comprehensive hazards assessment will be discussed. Special emphasis is placed on tectonic stress modeling, earthquake simulation, and seismic hazards assessment. The importance of quantitative seismic risk assessment and earthquake prediction studies are then discussed, and some final remarks are made in the conclusion.

1. Introduction to Computational Geodynamics

Geodynamics deals with the dynamical, physical and chemical processes in the Earth's interior. Phenomena subject includes fundamental geological processes such as plate tectonics, mantle convection and their interaction. According to plate tectonic theory (e.g., Turcotte and Schubert, 2002), the plates are continually created and consumed. At oceanic ridges adjacent plates diverge in a process, which is known as seafloor spreading. As the lithosphere moves away from oceanic ridges, it cools, densifies, and thickens.

Once the lithosphere becomes sufficiently dense compared to the underlying mantle rocks, it bends, founders, and begins sinking into the hot mantle due to gravitational instability. Because the lithosphere behaves elastically at short time scales (seconds to years), it can transmit stresses. The downward buoyancy forces (generated due to the excess density of the rocks of the descending lithosphere) promote the sinking of the lithosphere, but elastic, viscous and frictional forces resist the descent.

The combination of these forces produces shear stresses high enough to cause earthquakes. Other processes contributing to stress generation in the descending lithosphere and its release in earthquakes can be plastic instability at high temperature, faulting due to metamorphic phase transitions, and dehydration-induced embrittlement. Oceanic trenches are the sites of the world largest earthquakes. The earthquakes at oceanic trench zones can occur along the descending lithosphere to the depths of about 660 km depending on the thermal state in the mantle.

Modern geodynamics was born in the late 1960's with the general acceptance of the plate tectonics paradigm. At the beginning, simple analytical models were developed to explain plate tectonics and its associated geological structures (see, e.g., Turcotte and Schubert, 2002, for the analytical models). These models were highly successful explaining many of the first order features of behavior of the Earth. The necessity to go beyond these basic models in order to make them more realistic and to understand better the Earth shifted the emphasis to numerical simulations.

The development of computers heralded a new era in the approach to the solution of geodynamical problems. Programming languages, operating systems, management of large quantities of data, correctness of numerical codes and many other considerations relevant to the efficient and accurate solution of the problems became subjects of the new discipline of computer science, on which scientific computing now depends heavily. Nonetheless, mathematics continues to play a major role in scientific computing: it provides information about the suitability of a model and the theoretical foundation for the numerical methods. The numerical models of geodynamical problems have grown increasingly complex and capable over time with improvements in computational power and numerical algorithms. This has resulted in the development of a new branch of geoscience called *computational geodynamics*.

Characteristic of this new intellectual landscape is the need for strong interaction across traditional disciplinary boundaries: geodynamics, mathematics, and computer science. Mathematics provides the means to establish the credibility of numerical methods and algorithms, such as error analysis, exact solutions, uniqueness and stability analysis.

Computer science provides the tools, ranging from networking and visualization tools to algorithms matching modern computer architectures. The power of computational geodynamics is so huge that it can deal not only with the quantitative assessment of forces and processes in the Earth's interior, but also to contribute to the understanding and assessment of geohazards (e.g., seismic hazards) and assist in earthquake prediction.

1.1. Mathematical Approach to Geodynamic Problems

Many geodynamic problems can be described by mathematical models, i.e. by a set of partial differential equations and boundary and/or initial conditions defined in a specific domain. Models in computational geodynamics predict quantitatively what will happen when the crust, lithosphere, and the mantle deform, often with the inclusion of complications due to factors such as simultaneous heat transport, phase changes in the Earth's interior, complex rheology, melting and melt migration, chemical reactions, solid body motion, etc.

Mathematical models of geodynamic processes can be solved analytically or numerically. Analytical solutions are those that a researcher can obtain by solving mathematical models using a pencil, a piece of paper, and thought. Simple mathematical models allow analytical solutions, which have been (and still are) of great importance because of their power: the solutions are precise and can be presented by exact formulas.

However, the usefulness of exactly solvable models is limited as many mathematical models of geodynamics are too complicated to be solved analytically. Numerical solutions are those that researchers can obtain by solving models using numerical methods and computers. Numerical models allow the solution of complex problems of geodynamic processes, although the solutions are not exact. In some geodynamic applications an analytical solution to part of the complex problem can be implemented into the numerical model to make the model much more effective.

1.2. Computational Approach to Geodynamic Problems

Only a few of the ordinary and partial differential equations describing geodynamical models can be solved exactly, and hence the equations are transformed into discrete equations to be solved numerically. The widespread access to high-performance computers has resulted in an over-reliance on numerical answers in spite of other possibilities, and has created a corresponding false sense of security with respect to serious numerical problems or errors. Nevertheless, it is now possible without too much trouble to find solutions to most equations that are routinely encountered.

According to Ismail-Zadeh and Tackley (2010), the rationale of the numerical modeling can be described as follows (see Figure 1). The initial stage of numerical modeling is to describe geodynamically complex reality by a simplification of the reality; namely, to introduce the model concept of the geodynamic problem, forces acting on the system (crust/lithosphere/mantle), physical parameters to be used in the modeling, etc. A physical model is then developed to which the physical laws can be applied. The next step in the numerical modeling is to describe the physical model by means of mathematical equations.

The comparison with observations allows the model to be tested (validated). If a mathematical model is found to be inadequate - the assumed process is not the correct one, or some significant factors have been missed - it must be refined. The mathematical model should be properly determined, at least after the numerical values of some still unknown parameters have been determined (that is, the model is tuned). Once the mathematical model is developed, proper numerical tools and methods have to be chosen, and relevant numerical codes (software) should be developed (or otherwise obtained).

The mathematical model should be transformed into the computational model containing discrete equations to be solved by using computers. An important element of numerical modeling is verification of the model, namely, the assessment of the accuracy of the solution to the computational model by comparison with known solutions (analytical or numerical). Once the computational model is verified, the numerical model can be used to simulate reality, and the numerical results can be tested against observations. If there is a good agreement between the numerical results and observed (field or experimental) data, the model results can be considered as valid model predictions.

An essential component of computational geodynamics is a *numerical method*. Although many of the key ideas for numerical solution methods were established several centuries ago, they were of little use before computers appeared. Interest in numerical methods increased dramatically with the development of the computer power. Numerical methods provide possibilities to obtain accurate solutions to geodynamic problems. However, the numerical results are always approximate.

There are reasons for differences between computed results and observations. Errors arise from each part of the process used to produce numerical solution: the physical model is too simplified compared to geodynamic reality; the equations (mathematical model) may contain approximations or idealizations; approximations are made in the discretization process; in solving the discrete equations, iterative methods are used and insufficient iterations are taken. Additionally, uncertainty in physical parameters can lead to differences between computed results and observations.

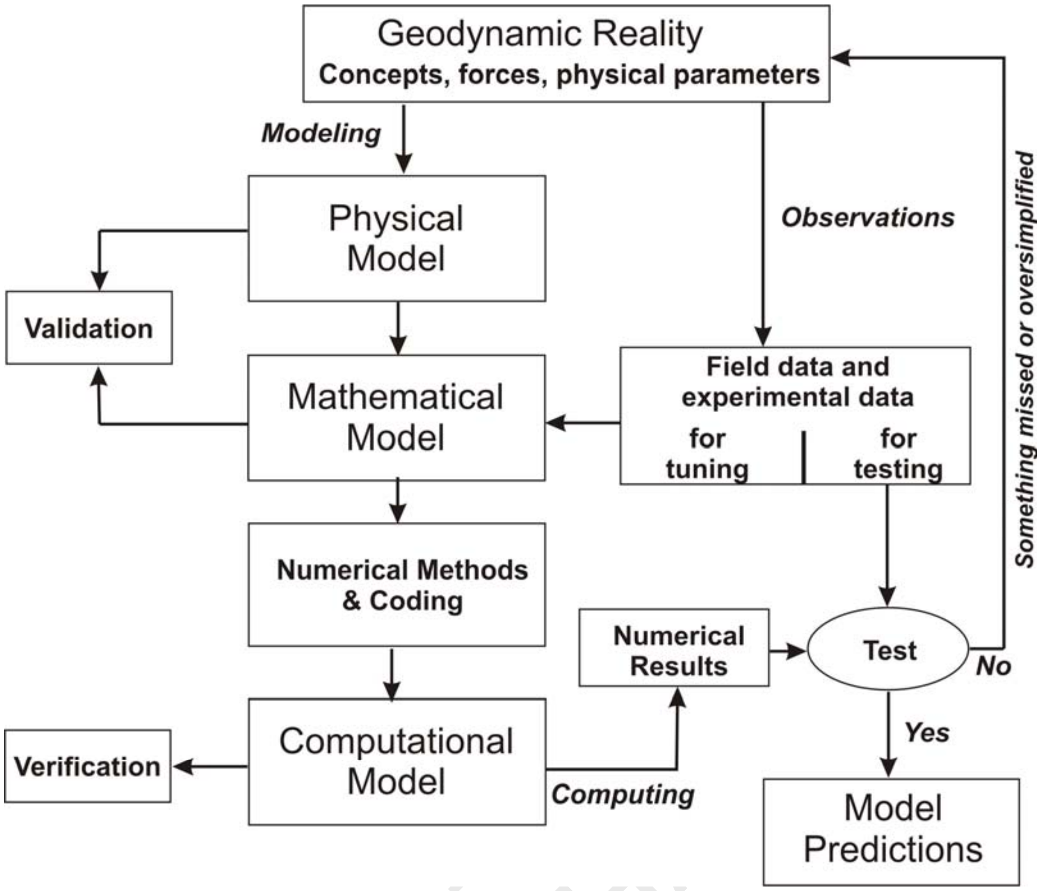

Figure 1. Schematic representation of the essential parts of numerical modeling (after Ismail-Zadeh and Tackley, 2010).

Numerical simulations in geodynamics enable one to analyze and to predict the dynamics of the Earth's interior. The basic elements of the numerical modeling are as follows: a mathematical model describing geodynamic processes; a discretization method to convert the mathematical equations into discrete equations to be solved numerically; numerical method(s) to solve the discretized equations; computer code(s) (i.e. software) to be developed or to be used, if already developed, which solve numerically the discrete equations; computer hardware, which performs the calculations; results of numerical modeling to be visualized, analyzed and interpreted by geoscientist(s).

2. Introduction to Seismic Hazards and Risk Analysis

Seismic hazard can be defined as a potentially damaging earthquake, which may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. Seismic hazard is typically interrelated with past seismicity and geological and geophysical parameters (e.g. peak ground acceleration, seismic intensity, seismic wave propagation and attenuation, site effect). *Seismic risk* is a measure that combines the likelihoods and the consequences, over a given time, of a set of earthquake scenarios.

Natural hazard and risk analysis should be considered from a holistic point of view (from the whole to details). According to Ismail-Zadeh (2010), a holistic comprehensive quantitative assessment of seismic hazard should be based on multidisciplinary research in (i) geodynamics and geodesy (to identify zones of tectonic stress and strain localization), (ii) present and historical seismicity (to localize areas prone to strong events), (iii) nonlinear dynamics of the lithosphere (to analyze statistical properties of the earthquake sequences, their clustering and critical transitions), (iv) soil property (to analyze liquefaction and seismic shaking), and (v) standard hazards assessment (to determine peak ground acceleration, response spectra amplitude, and seismic intensity). This approach to seismic hazard should be accompanied by a holistic approach to earthquake prediction (e.g., Keilis-Borok and Soloviev, 2003) and by a holistic approach to seismic risk, when a convolution of hazard, vulnerability and exposure (as functions of space and time) should be viewed also from socio-psychological (e.g., resilience of community to extreme seismic events) and legislation (e.g., role of law in risk reduction) points of view (Beer and Ismail-Zadeh, 2003).

The *vulnerability* of human civilization to natural disasters is growing due to the proliferation of high-risk objects, clustering of populations, and destabilization of large cities. Today a single earthquake may take up to several hundred thousand lives, and cause material damage up to several hundred billion EURs (see Munich Re., 2012) with a possible chain reaction expanding to a world-wide financial crisis and economic depression.

A large earthquake in (or close to) Tokyo might result in a world financial crisis, because many Japanese companies, which invested considerable funds in foreign enterprises, will withdraw these funds to rebuild or to restore the city infrastructure after the disaster. A large earthquake can trigger an ecological catastrophe (e.g. Chernobyl-type calamities or recent Fukushima incident) if it occurs in close vicinity to a nuclear power plant built in an earthquake-prone area.

Extreme seismic events (e.g., the 1755 Lisbon, the 2004 Aceh-Sumatra, and the 2011 Great East Japan earthquakes) are a manifestation of the complex behavior of the lithosphere structured as a hierarchical system of blocks of different sizes. Driven by mantle convection these lithospheric blocks are involved in relative movement, resulting in stress localization and earthquakes.

Despite the lithosphere behaving as a large non-linear system, featuring instability and deterministic chaos, some integral empirical regularities emerge, indicating a wide range of similarity, collective behavior, and the possibility for earthquake prediction (e.g., Keilis-Borok et al. 2001). These great earthquakes, when they occur, are surprising, and society is poorly prepared to deal with them.

Protecting human life and property against earthquake disasters requires an uninterrupted chain of research and civil protection tasks (Ismail-Zadeh, 2010): from (i) an understanding of the physics of earthquakes, their analysis and monitoring, through (ii) interpretation, modeling, seismic hazard assessment, and earthquake prediction, to (iii) delivery of the scientific forecasts to local authorities, public awareness, preparedness, and preventive disaster management.

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Kantorovich L., Keilis-Borok V.I., Molchan G. (1973). Seismic risk and principles of seismic zoning. In: Keilis-Borok V.I. (ed.), *Computational and Statistical Methods for Interpretation of Seismic data*. Moscow, Nauka, pp. 3-20 (in Russian). [This paper introduces a mathematical background for seismic risk assessment and presents the basic principles of seismic zoning.]

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Keilis-Borok V.I., Kossobokov V.G. (1990). Premonitory activation of earthquake flow: algorithm M8. *Physics of the Earth and Planetary Interiors*, 61, 73–83. [Many of large earthquakes occurred in different regions of the world are preceded by specific low-magnitude seismic activation, which was depicted by the algorithm M8. The algorithm presented in the paper is designed to alert the times of increased probability of large earthquakes.]

Keilis-Borok V.I., Soloviev A.A. (2003). *Nonlinear Dynamics of the Lithosphere and Earthquake Prediction*, 337 p. Heidelberg, Springer. [The book provides the reader with a holistic approach to earthquake modeling and prediction.]

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Kossobokov V. (2006). Quantitative earthquake prediction on global and regional scales. In: Ismail-Zadeh A.T. (ed.), Recent Geodynamics, Georisk and Sustainable Development in the Black Sea to Caspian Sea Region. American Institute of Physics Conference Proceedings, vol. 825, Melville, New York, pp. 32–50. [This chapter discusses earthquake prediction experiments conducted by the author on global and regional scales.]

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Naimark B.N., Ismail-Zadeh A.T., Jacoby W.R. (1998). Numerical approach to problems of gravitational instability of geostructures with advected material boundaries. *Geophysical Journal International*, 134, 473–483. [The paper presents a numerical approach for solving 2-D mantle flow problems, where the chemical composition changes abruptly across intermediate boundaries. The method combines a

Galerkin-spline technique with a method of integration over regions bounded by advected interfaces to represent discontinuous variations of material parameters.]

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Turcotte D.L., Holliday J.R., Rundle J.B. (2007). BASS, an alternative to ETAS. *Geophysical Research Letters*, 34, L12303, doi:10.1029/2007GL029696. [In this paper, the authors introduce the branching aftershock sequence (BASS) model, which utilizes Båth's law.]

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Varotsos P., Alexopoulos K., Nomicos K., Lazaridou M. (1986). Earthquake predictions and electric signals. *Nature*, 322, 120. [This is brief communication regarding the applications of the VAN method for earthquake prediction.]

Ward S.N. (1992). An application of synthetic seismicity in earthquake statistics: The Middle America Trench, *Journal of Geophysical Research,* 97, 6675–6682. [This paper demonstrates how synthetic seismicity calculations, which are based on the concept of fault segmentation and incorporate the physics of faulting through static dislocation theory, can improve earthquake recurrence statistics and hone the probabilities of hazard.]

Ward S.N. (2000). San Francisco Bay Area earthquake simulation: A step toward a standard physical earthquake model, *Bulletin of the Seismological Society of America,* 90, 370–386. [This article represents a first step in developing a standard physical earthquake model for the San Francisco Bay Area through realistic, 3000-year simulations of earthquakes on all of the area's major faults.]

Wells D.L., Coppersmith K.J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bulletin of the Seismological Society of America,* 84, 974–1002. [Source parameters for historical earthquakes worldwide are compiled to develop a series of empirical relationships among moment magnitude, surface rupture length, subsurface rupture length, down-dip rupture width, rupture area, and maximum and average displacement per event.]

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Working Group on California Earthquake Probabilities (1988). Probabilities of large earthquakes occurring in California on the San Andreas fault, U.S. Geological Survey Open-File Report 1988-398. [This report presents the assessment of the probabilities for large earthquakes resulting from slip on the major faults of the San Andreas fault system. The evaluations are based on a probability model that assumes increase of probability with elapsed time since the previous major earthquake on the fault segment.]

Working Group on California Earthquake Probabilities (2007). The Uniform California Earthquake Rupture Forecast, Ver. 2 (UCERF 2). U.S. Geological Survey Open-File Report 2007-1437. [This report describes a new earthquake rupture forecast for California developed by the 2007 Working Group on California Earthquake Probabilities (WGCEP 2007).]

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Zechar J.D., Jordan T.H. (2008). Testing alarm-based earthquake predictions. *Geophysical Journal of International*, 172, 715–724. [The paper presents a method for testing alarm-based earthquake predictions, which is based on the Molchan diagram (a plot of miss rate and fraction of space-time occupied by alarm) and is applicable to a wide class of predictions.]

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Zöller G., Hainzl S. (2007). Recurrence time distributions of large earthquakes in a stochastic model for coupled fault systems: the role of fault interaction. *Bulletin of the Seismological Society of America*, 97, 1679–1697. [This paper presents the study of the effect of fault interaction on the recurrence time distribution of large earthquakes on the same fault.]

Zöller G., Hainzl S., Holschneider M., Ben-Zion Y. (2005). Aftershocks resulting from creeping sections in a heterogeneous fault. *Geophysical Research Letters*, 32, L03308, doi:10.1029/ 2004GL021871. [This paper presents a model consisting of brittle fault segments separated by creeping zones generates realistic aftershock sequences with space-time characteristics compatible with observations.]

Biographical Sketch

Alik Ismail-Zadeh is a Senior Scientist at the Karlsruhe Institute of Technology (KIT), Germany; Chief Scientific / Research Professor at the Russian Academy of Sciences in Moscow; and Visiting Professor at the Institut de Physique du Globe in Paris, France. He graduated from the Baku State University, Azerbaijan (mathematics, 1982) and the Lomonosov Moscow State University in Russia (mathematics and physics, 1983) before being awarded the Ph.D. (1990) and the D.Sc. (1997), both in geophysics, from the Russian Academy of Sciences. He lectures at KIT and Abdus Salam International Centre for Theoretical Physics (Trieste, Italy) and worked at several universities as visiting scholar/professor, including University of California, Los Angeles (USA); University of Cambridge (UK); University of Tokyo (Japan); University of Trieste (Italy); University of Uppsala and Royal Institute of Technology (Sweden). Scientific interests of Alik Ismail-Zadeh cover studies of dynamics of the crust and upper mantle and their surface manifestations (including seismicity, seismic hazard and risk, sedimentary basins, salt tectonics) through multidisciplinary synthesis, theoretical and computational analysis. He is a principal author and coauthor of over 90 peer-reviewed papers and four books. Alik Ismail-Zadeh is Secretary-General of the International Union of Geodesy and Geophysics (IUGG), Chair of the Natural Hazards Focus Group of the American Geophysical Union (AGU), and Past-President of the IUGG GeoRisk Commission. He is a recipient of the Academia Europaea Young Scientist Award and the AGU International Award, and he was awarded several research fellowships including the Russian President, the Alexander von Humboldt Foundation, the Royal Society of London, and the Royal Swedish Academy of Sciences.