COMPUTATIONAL GEODYNAMICS FOR SEISMIC HAZARD ANALYSIS AND EARTHQUAKE PREDICTION

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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.
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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