3-D Seismic Wave Propagation on a Global and Regional Scale: Earthquakes, Fault Zones, Volcanoes

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Abstract

For computational seismology the present years are extremely exciting. The reason is, that with the current supercomputer technology, the frequency band in which seismic waves are observed following regional or global earthquakes, can be simulated numerically for realistic 3D earth models for the first time. Depending on the spatial scales under consideration (whole planet, a sedimentary basin at risk from local earthquakes, a volcano with high risk for future eruptions) this will lead to considerable improvement (1) in the understanding of the structural properties (e.g. the Earth's mantle, the inside of a sedimentary basin or a volcano) and (2) in forecasting strong ground motion for realistic earthquake scenarios. The latter point may have considerable long-term societal benefits, as we now understand that the short-term prediction of large earthquakes may never be possible. During the first phase of this project some of the highest-resolution simulations ever done were carried out with important implications for future directions in computational seismology. The most important scientific results can be summarized as: (1) 3D Simulations of several earthquakes in the Cologne Basin in Germany demonstrate that the main characteristics of ground motion (e.g. peak motion amplitude, shaking duration) are successfully predicted through numerical simulations; (2) The low seismic velocities inside active faults (e.g. San Andreas Fault, California) may act as an amplifier for ground motion. This has implications for buildings in the vicinity of faults; (3) Large scale simulations of strong earthquakes in subduction zones show that the local 3D structure at depth strongly influences the waves propagating to the surface. Ignoring this may lead to severe misinterpretations. (4) Including topography to understand wave propagation inside volcanoes is crucial. Our simulations demonstrate the scattering effects due to topography. If we want to understand the state of a volcanic system prior to eruptions from seismic waves these effects have to be taken into account.

1 Introduction

The accurate simulation of seismic wave propagation through realistic 3-D Earth models plays a fundamental role in several areas of geophysics: (1) in global seismology knowledge of the structure of the Earth's deep interior is crucial to understand the dynamic behaviour of our planet such as mantle convection, slab subduction or hot spot activity. Accurate synthetic 3-D seismograms which can be compared with globally recorded data require a numerical approach. The structural resolution of today's tomographic models can only be improved by exploiting the 3-D wave effects of the geodynamically important regions inside the Earth. (2) As deterministic short-term earthquake fore-casting seems out of sight, the accurate prediction of likely ground motion following earthquakes in seismically active regions is a major goal which will allow measures (e.g. applying strict building codes) to be taken before major events. 3-D modelling will allow local (e.g. amplifying) effects such as low-velocity zones or topography to be studied. These so-called site effects are being investigated for several areas at risk (e.g. Cologne Basin, Germany; Los Angeles Basin, USA; Beijing Basin, China). (3) Active volcanic areas show characteristic complex ground motion which is usually recorded on local networks monitoring the activity and risk of eruption. The origin of the seismically recorded signals are poorly understood. One of the reasons is the structural complexity of volcanic areas with strong 3-D heterogeneities, topography and sources in the summit region.

The first phase of this project was dedicated to (1) Parallelization and implementation of algorithms for numerical wave propagation on the Hitachi SR8000-F1; (2) Verification of the codes and analysis of their efficiency; and (3) first applications to realistic problems.

2 Numerical simulation of seismic wave propagation

The algorithms implemented to date constitute numerical solutions to the (visco-)elastic wave equations in Cartesian and spherical coordinates. The time-dependent partial differential equations are solved numerically using high-order finite-difference methods (e.g. Igel et al., 1995, 2002). This implies that - no matter the particular problem or coordinate system - the space-dependent fields are defined on a 3-D grid and the time extrapolation is carried out using a Taylor expansion or a Runge-Kutta method. The space derivatives are calculated by explicit high-order finite-difference schemes which do not necessitate the use of matrix inversion techniques. This approach leads to naturally parallel problems where communication is only needed at the boundaries of the decomposed domains, when calculating space derivatives.

Before complex 3D models were run on the Hitachi Sr8000 all algorithms were verified by comparing the numerical solutions to analytical solutions for simple (layered) model geometries. Thereby the parameter space for stable and accurate numerical solutions for the given problems could be identified. The final programming model uses (1) the automatic parallelization for the (intra-node) shared-memory part and (2) the MPI model across the nodes. This seems to be the optimal approach for explicit FD algorithms.

In the following we review the results from the first production runs of these algorithms.

3 Scientific and technical results

3.1 Volcano topography in 3-D seismic wave propagation

How does the (usually strong) topography affect the seismic wavefield observed on volcanoes? How can we model the topographic effects and the scattering effects inside the medium? Two methods which allow the modelling of wave propagation in the presence of free surface topography were implemented and tested for a realistic topography (digital elevation map of the Merapi volcano, Indonesia). The first method is based on stretching a regular Cartesian grid in a way that the surface follows the topography. An important technical result is that while this approach is applicable to moderate topography it becomes unstable for strong topography (Ripperger, 2001), a situation frequently encountered around volcanoes.

An alternative method uses a modified free surface boundary condition which is applied to a blocky representation of the real topography. While this approach needs a large number of grid points per wavelength, it leads to a stable algorithm and was our method of choice for the first 3D simulation of wave propagation through a real volcano model (Ripperger, 2001; Ripperger et al., 2002).

Figure 1 shows the principles of the latter technique applied to the topography of the high-risk volcano Merapi in Indonesia. On this volcano a seismic network permanently records the ground motion. This project aims at modelling these data using 3D simulation techniques. We intend to use this code to investigate (1) the seismic signature of pyroclastic flows; (2) seismic sources inside magma chambers and volcanic dykes; (3) scattering vs. topographic effects as observed on Merapi. In Figure 2 a snapshot of wave propagation a few seconds after a source emitted seismic energy near the summit of the volcano is shown. Such seismic sources may be indicative of magma movements inside the volcano.

3.2 Simulation of earthquake scenarios

As reliable deterministic earthquake prediction is not in sight, the simulation of realistic earthquake scenarios is one of the most important tools to assess the seismic hazard of active regions. The ground motion observed at the surface after large earthquakes predominantly depends on (1) the source depth;

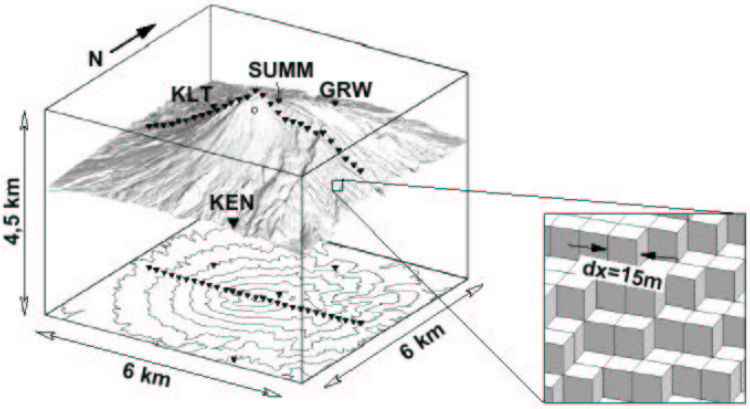

Fig. 1. Topography of volcano Merapi, Indonesia. The free surface boundary condition is implemented on the (blocky) surface of the regular finite-difference grid. Other options for the irregular free surface are being investigated.

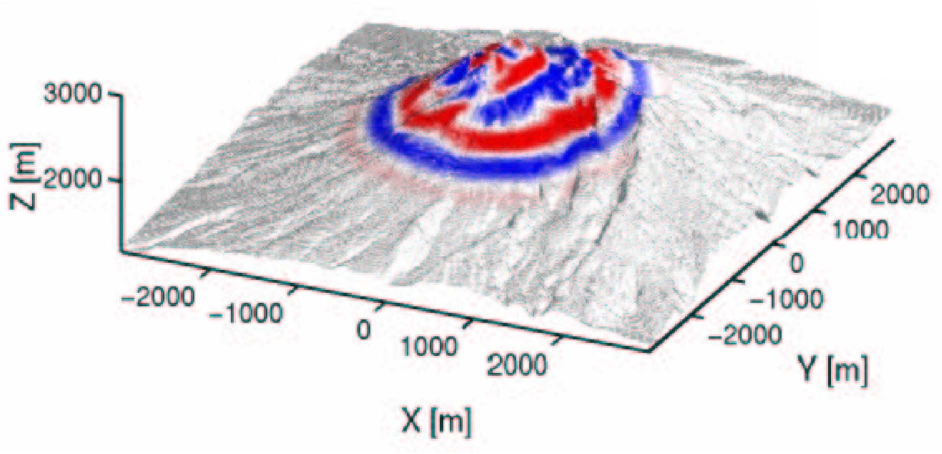

Fig. 2. Snapshot of seismic wave propagation for a source near the summit of volcano Merapi. Such events frequently occur during active periods of volcanoes and they are associated with magma movement inside the volcano.

(2) the magnitude; (3) the source mechanism (the orientation and size of the slip on the fault plane); and (4) the structure of the Earth's crust. One of the key factors in shaking hazard is the local seismic velocity structure. Low seismic velocities near the surface (e.g. sedimentary basins as in Los Angeles, Mexico City, the Cologne Basin area) may amplify the ground motion up to ten-fold and thereby increase the hazard even for moderate earthquake magnitudes or distant large earthquakes. This is an inherent 3D effect and can only be properly modelled with the use of 3D modelling techniques.

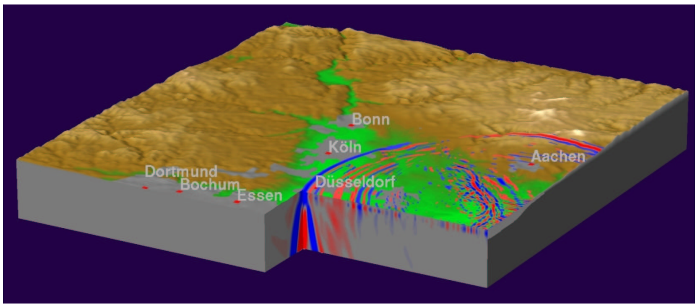

Fig. 3. Snapshot of ground motion for a 3D simulation of the M5.9 Roermond earthquake that shook the Cologne Basin in 1992 (Ewald, 2001). The complex structure of the local sedimentary basin leads to strong lateral variations in peak ground acceleration and shaking duration. These parameters are crucial for the estimation of structural stability.

In this project the first high-resolution 3D calculations for the area in Germany with the highest seismic risk - the Cologne Basin - were undertaken. It is important to note that the simulations were carried out on a 3D spatial grid with approx. 150 million grid points. This allowed us to carry out a simulation with a dominant frequency of approx. 1 Hz. The data available for the simulated M5.9 earthquake near the village of Roermond in 1992, which shook the area of the Cologne Basin are in a similar frequency range (see Figure 3).

Even though the simulations are based on a relatively simple 3D velocity model of the sedimentary structure, they show remarkably good agreement with observed data as far as the amplitudes for the ground motion is concerned. This tells us that we may be on the right way to be able to calculate the possible ground motion amplification due to 3D structure for this (and other) areas. The numerical algorithms provide us with the ground motion at the Earth's surface at all times of the simulation. These data enable us to extract crucial information on the maximum amplitudes of motion or the shaking duration and convert them into so-called shaking hazard maps (see Figure 4), a measure of (expected) damage in a region. One of the main goals of this study is to compare and calibrate simulated results with observed ground motion (or damage observations). At present our study areas are the Cologne Basin, the Beijing area and the Los Angeles Basin.

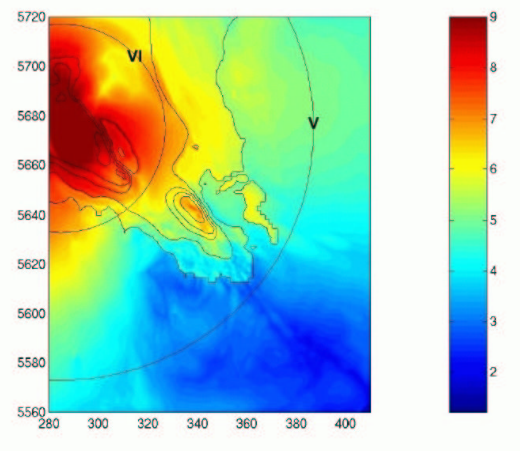

Fig. 4. Shaking intensity map calculated from 3D simulations of the M5.9 Roermond earthquake in 1992 for the same geographical area shown in the previous Figure. The colour scaling denotes the modified Mercalli scale, an indicator for expected damage in the region. The theoretical damage predictions can be compared to the observed damage during earthquakes. The most important goal of this area of research is to make the simulated results accurate enough so that local authorities can use them for planning purposes.

3.3 Seismic wave propagation on a planetary scale

To first order the structure of the Earth's interior is spherically symmetric. Yet, the 3D perturbations thereof play a fundamental role in the dynamic behaviour of our planet as lateral variations in temperature and density drive convective processes in the Earth's mantle and core. Therefore, we need to understand how such 3D structural perturbations (e.g. subduction zones, plumes, lateral variations at the core-mantle boundary) affect the seismic wavefield observed at the Earth's surface after large earthquakes.

The problem of wave propagation in spherical geometry is complicated by the occurrence of singularities in the wave equation in spherical coordinates. Therefore, standard numerical methods such as the finite difference method can not directly be applied to the simulation of whole Earth wave propagation. The options are (1) using an axi-symmetric approach, thereby reducing the problem to two dimensions (see Figure 5); (2) considering a spherical section while centering the physical domain around the equator thus avoiding problems with the singularities. For whole earth wave propagation unstructured grid methods (e.g. finite elements, spectral elements) have to be employed.

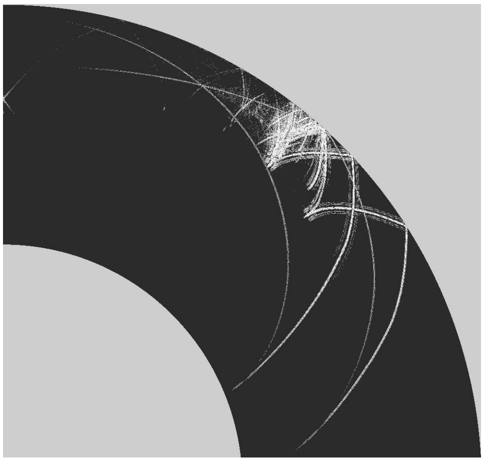

Fig. 5. Snapshot of shear wave propagation inside the Earth 10 minutes after the origin time of an earthquake at the surface. Waves travel along the surface and through the interior. The bright colours denote the energy in the wave field. This simulation was carried out with an axi-symmetric solution of the wave equation, which leads to a 2D computational domain, while allowing the calculation of a 3D wave field. The dominant period of this simulation 5s. This is the actual frequency band which is observed around the globe for shear wave propagation. The grid spacing for such simulations is below 1km (Jahnke et al., 2002).

Subduction zones contain the largest earthquakes on Earth. Knowledge of there structural details not only is important for hazard assessment but also to understand the dynamics of subduction and mantle convection. In this study a 3D algorithm in spherical coordinates was implemented and earthquakes in subduction zones simulated (Nissen-Meyer, 2001; Igel et al., 2002). We were able to simulate particular wave effects observed in nature which - in the future - can be used to further constrain the structure of subduction zones (Figure 6). Furthermore, hot spots like Hawaii, the Galapagos Islands or Iceland are characterized by large scale plumes underneath them, which are thought to consist of rising material from inside the mantle. However, it is not clear, how deep the roots of the plumes are. 3D simulation for plume models were investigated. These simulations will be important to design future large scale seismic experiments around hot spots (Strasser, 2001).

3.4 Fault zone wave propagation

The detailed structure of fault zones (FZs) plays an important role in problems related to fault mechanics, earthquake rupture, wave propagation and

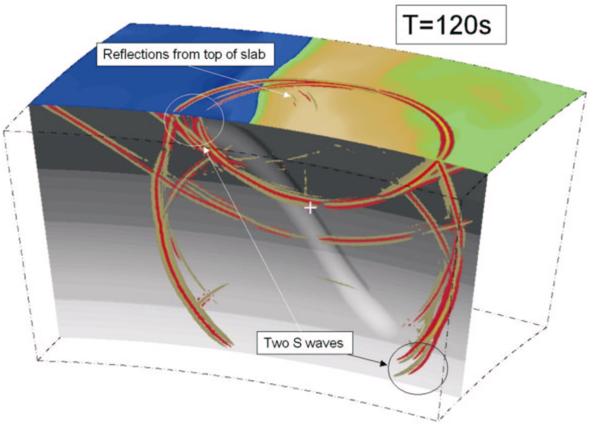

Fig. 6. Snapshot (curl of the wavefield) for a source inside a subduction zone. The calculations are calculated in spherical geometry in order to account for the Earth's spherical surface relevant to large scale wave propagation problems. The complex 3D structure of subduction zones, which host the largest earthquakes observed on Earth, leads to wave effects which need to be accounted for when investigating the rupture mechanisms of deep earthquakes.

seismic hazard. FZs are thought to consist of a O(10-100)m wide region of decreased seismic velocity but structural details such as their depth extent, lateral and vertical variations etc. are elusive. The small spatial scales involved make such structures difficult to image with ray-theoretical methods such as tomography. However, seismic energy trapped inside FZ layers can provide dispersive wave trains that carry information on the FZ structure. These waves can travel many kilometers inside the FZ before reaching the surface and are therefore strongly altered by its properties. Candidate trapped waves have been observed above several active faults. Inversion algorithms exist that can model these observations in terms of planar fault zone structures. However, at present it is not clear how reliable these estimates are, as the effects of (even small) 3-D variations on trapped waves are not well understood. The goal of this study is to distinguish 3-D structures that do and do not significantly affect FZ waves. To achieve this, we perform numerical calculations of wave propagation in various FZ geometries and analyze the waveforms, spectra and envelopes of the synthetic seismograms. The main results are that (1) moderate changes of the shape of FZ or (2) small-scale heterogeneities or (3) depth-dependent properties do not strongly affect the observed FZ waves. In contrast, strong effects are to be expected from (4) breaks in the continuity of FZ structure (e.g. offsets), which may at some point allow imaging such features at depth (Jahnke et al., 2002; Igel et al, 2002).

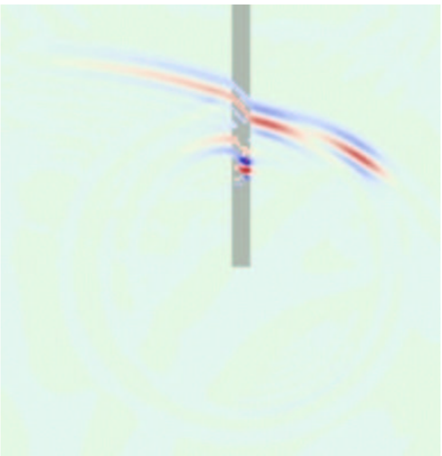

Fig. 7. Snapshot of 3D wave propagation for a source outside a shallow low-seismic velocity zone associated with an active seismic fault (e.g. San-Andreas fault, North-Anatolian fault). An important result of recent simulations is the fact that sources outside faults can generate high-amplitude trapped waves and therefore lead to elevated shaking hazard in the vicinity of faults.

Fig. 8. Arial view of the surface manifestation of the San-Andreas fault, California. It is thought that the fault contains a O(100m) wide zone with low seismic velocities down to a depth of several kilometres. This zone acts like a wave guide and leads to characteristic wave phenomena relevant to shaking hazard as well as the understanding of the rupture process.

An important discovery in the course of these 3D simulations was the fact that sources outside shallow FZs are capable of producing considerable trapped wave energy (Fohrmann et al., 2001, 2002). This means that a much larger volume of possible earthquake hypocenters may lead to amplified motion at the surface in the vicinity of faults. These numerical results are supported by observations of aftershocks of the large earthquakes in Turkey of 1999.

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