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Efficient parallel seismic simulations including topography and 3-D material heterogeneities on locally refined composite grids

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The finite difference method on a uniform Cartesian grid is a highly efficient and easy to implement technique for solving the elastic wave equation in seismic applications. However, the spacing in a uniform Cartesian grid is fixed throughout the computational domain, whereas the resolution requirements in realistic seismic simulations usually are higher near the surface than at depth. This can be seen from the well-known formula $h \leq L/P$ which relates the grid spacing h to the wave length L, and the required number of grid points per wavelength P for obtaining an accurate solution. The compressional and shear wave lengths in the earth generally increase with depth and are often a factor of ten larger below the Moho discontinuity (at about 30 km depth), than in sedimentary basins near the surface. A uniform grid must have a grid spacing based on the small wave lengths near the surface, which results in over-resolving the solution at depth. As a result, the number of points in a uniform grid is unnecessarily large.

In the wave propagation project (WPP) code, we address the over-resolution-at-depth issue by generalizing our previously developed single grid finite difference scheme to work on a composite grid consisting of a set of structured rectangular grids of different spacings, with hanging nodes on the grid refinement interfaces. The computational domain in a regional seismic simulation often extends to depth 40-50 km. Hence, using a refinement ratio of two, we need about three grid refinements from the bottom of the computational domain to the surface, to keep the local grid size in approximate parity with the local wave lengths.

The challenge of the composite grid approach is to find a stable and accurate method for coupling the solution across the grid refinement interface. Of particular importance is the treatment of the solution at the hanging nodes, i.e., the fine grid points which are located in between coarse grid points. WPP implements a new, energy conserving, coupling procedure for the elastic wave equation at grid refinement interfaces. When used together with our single grid finite difference scheme, it results in a method which is provably stable, without artificial dissipation, for arbitrary heterogeneous isotropic elastic materials. The new coupling procedure is based on satisfying the summation-by-parts principle across refinement interfaces. From a practical standpoint, an important advantage of the proposed method is the absence of tunable numerical parameters, which seldom are appreciated by application experts.

In WPP, the composite grid discretization is combined with a curvilinear grid approach that enables accurate modeling of free surfaces on realistic (non-planar) topography. The overall method satisfies the summation-by-parts principle and is stable under a CFL time step restriction. A feature of great practical importance is that WPP automatically generates the composite grid based on the user provided topography and the depths of the grid refinement interfaces.

The WPP code has been verified extensively, for example using the method of manufactured solutions, by solving Lamb's problem, by solving various layer over half- space problems and comparing to semi-analytic (FK) results, and by simulating scenario earthquakes where results from other seismic simulation codes are available. WPP has also been validated against seismographic recordings of moderate earthquakes.

WPP performs well on large parallel computers and has been run on up to 32,768 processors using about 26 Billion grid points (78 Billion DOF) and 41,000 time steps. WPP is an open source code that is available under the Gnu general public license.