WaveQLab3D: A Software Framework for Seismic Wave Propagation and Dynamic Earthquake Rupture

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Abstract

High-fidelity numerical simulations of seismic wave propagation and spontaneously propagating dynamic earthquake ruptures in realistic geological models are essential for understanding nonlinear earthquake source processes and improving seismic hazard assessment. We present *WaveQLab3D*, an open-source, high-performance computing framework that solves the three-dimensional elastic and viscoelastic wave equations on curvilinear multi-block grids using provably stable summation-by-parts (SBP) finite-difference operators. The framework supports non-planar fault interfaces, surface topography, and heterogeneous Earth structures.

We assess the accuracy of *WaveQLab3D* for high-frequency viscoelastic wave propagation beneath complex free-surface topography, and we implement a stable, scalable perfectly matched layer (PML) for attenuating media. To assess grid-refinement consistency, we simulated a point source beneath a Gaussian hill, with a non-planar fault embedded in the curvilinear mesh, at grid spacings of $h = 100$ m and 40 m. The two resolutions produce consistent arrival times and waveforms. We have also implemented frequency-dependent attenuation using a coarse-grained memory-variable approach, in which the seismic quality factor Q remains constant below a transition frequency and increases according to a power law at higher frequencies. We are verifying this implementation against a frequency–wavenumber solution for a corresponding half-space test problem.

In addition, we have developed Python tools that visualize station seismograms and fault-interface quantities, including slip, slip rate, tractions, and stress changes. These tools help us analyze how ruptures evolve on complex fault geometries.

Keywords: WaveQLab3D; seismic wave propagation; dynamic rupture; topography; grid refinement; frequency-dependent attenuation; perfectly matched layer (PML); summation-by-parts (SBP); computational seismology