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Curvilinear grid finite difference method simulation of seismic wave propagation for depth-dependent velocity structure

MAEDA, Takuto[1*]

[1]ERI, The University Tokyo

I propose curvilinear grid method on large-scale finite difference method (FDM) simulation of seismic wave propagation in depth-dependent structure. The FDM usually uses uniform-sized grid having spatial scale smaller than 6-10 of wavelength. Although it is quite straightforward method and is therefore suitable to large-scale parallel simulation, it is not economical to use homogeneous grid size under depth-dependent structure in regional scale because of wide dynamic range of wavelength. Low-velocity sediment requires fine scale grid, but such smaller grid size also requires very small time-stepping in deeper part to satisfy the stability condition of FDM. To deal with this problem, discontinuous-grid method (Aoi and Fujiwara, 1999; Lee et al., 2008) has been proposed. However, possible numerical instability at a discontinuous surface in the former method (Kristec and Moczo, 2010).

The curvilinear coordinate method can use any non-linear, non-orthogonal coordinate. The uniform-size numerical grid is used along the curved coordinate in the computation domain. On the other hand, we still uses the Cartesian coordinate for expressing physical quantities such as velocity vector and stress tensor. This method has been used to incorporate rough ground surface (e.g., Hestholm, 1999). However the recent study on staggered-grid FDM (e.g., Nakamura et al., 2012) suggest that the rough surface can be expressed by the fine-scale homogeneous grid. So, I use a coordinate whose grid-width gradually and smoothly increases with depth to make ratio between grid-size and wavelength nearly constant. My coordinate transform equation depends on vertical depth only, so that to make the computational loads in coordinate transformation and additional memory requirements relatively small. The rotated-grid staggered grid (RSG) scheme (Saenger et al., 2000) has been adopted to make central finite differentiation possible in all directions under the curvilinear coordinate.

As a test, we implemented this curvilinear coordinate FDM in 2D SH and P-SV systems, with using the Butterworth-shape grid-size increase function. This coordinate has a characteristic depth. Grid size linearly increases with depth at deeper than the characteristic depth. On the contrary, this curvilinear coordinate converges to the Cartesian at the shallow limit. This feature is preferable since one can connect the homogeneous Cartesian grid in the shallower portion to the curvilinear grid system without any boundary conditions. In the numerical experiments, I found that the method is effective and stable even for the coordinate system having large grid-size ratio of up to 10. Extension to the 3D model is quite straightforward, and it makes possible to perform broadband large-scale wave propagation simulations including slow sediment in medium-sized computers.

Keywords: seismic wave propagation, numerical simulation, finite difference method, curvilinear coordinate