論文内容の要旨

論文題目: Development of a finite-difference scheme using optimally accurate operators for computation of synthetic seismograms in heterogeneous media and its applicability to geophysical exploration

(不均質媒体における地震波形計算のための最適演算子を用いた差分スキームの開発および物理探査への応用可能性)

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High performance finite difference (FD) schemes for computation of synthetic seismograms are developed and tested following mathematical analysis and evaluations of their cost-effectiveness (as quantified by the computation time required to obtain a given level of accuracy). On the basis of these tests we find that optimally accurate $O(2,2)$ (second order in space and time) FD schemes are preferable for practical computations. We then present calculations for a standard 2-D test model.

A general criterion for optimally accurate numerical operators was derived by Geller & Takeuchi (1995) and, based on this criterion, an $O(2,2)$ optimally accurate FD scheme (second order in both time and space) was derived by Geller & Takeuchi (1998) for 1-D cases and by Takeuchi & Geller (2000) for 2-D and 3-D cases. Following a similar procedure, we derive two new optimally accurate schemes for the 1-D case: an $O(2,4)$ optimally accurate FD scheme (second order in time and fourth order in space) and an optimally accurate scheme using the spectral element method (SEM). We then compare the various optimally accurate schemes for 1-D heterogeneous and homogeneous models. All are broadly similar in cost-performance ratios for solution errors of around 1%, which is the accuracy range commonly required for practical applications. However, due to ease of programming, the $O(2,2)$ optimally accurate FD method seems preferable in practice. However, if extremely high accuracy (solution errors of, say, less than 0.01%) were required, then SEM approaches might be preferable, but the difficulty of grid generation for complex structures is a significant problem. We show that all of the optimally accurate schemes are superior to all of the conventional schemes (schemes which do not satisfy the criterion for optimally accurate operators). We also show that staggered grid (SG) schemes, which are widely used, can be transformed to conventional FD schemes which use displacement as the only dependent variable and that such schemes have no advantage in computational accuracy and efficiency over other conventional FD schemes. A major advantage of the FD schemes considered here (both optimally accurate and conventional schemes) is that they can stably handle external free surface boundaries, as they are based on the weak form of the equation of motion.

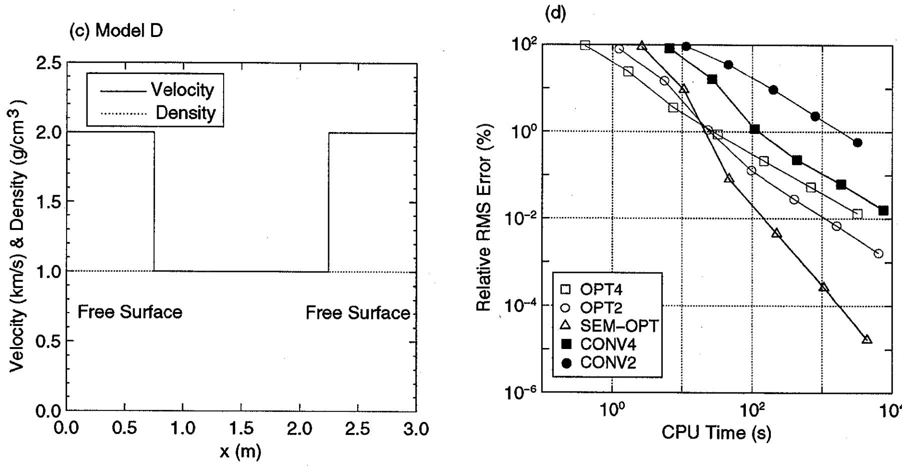

Figure 1: Discontinuous two-layered model with free surface boundary conditions (left) and relative r.m.s. error versus CPU Time (right). Compared schemes are: OPT2 and OPT4 ($O(2,2)$ and $O(2,4)$ optimally accurate scheme), SEM-OPT (optimally accurate SEM) and CONV2 and CONV4 (conventional second and fourth order scheme). Each line color is displayed by Courant number that each scheme shows the best performance with it. Relations between the color and Courant number are red: 0.1, blue: 0.3 and magenta: 0.8.

Previous optimally accurate $O(2,2)$ schemes handled internal lithological discontinuities by treating each such boundary as a potential external free surface, and then "overlapping" the operators for the respective regions. This approach can be used for simple models, but is impractical for the complex heterogeneous models used in exploration seismology. In order to extend the optimally accurate $O(2,2)$ operators to such complex models, we developed an optimally accurate heterogeneous method, following similar approaches using conventional FD operators. A theoretical analysis supports the use of this method at internal boundaries, and computational examples demonstrate its accuracy. We also developed a method for computing synthetics in combined fluid-solid media. Finally we apply the new heterogeneous scheme to the "Marmousi model," a standard test model used in exploration seismology, and demonstrate that the new scheme is well suited for application to actual problems. The Marmousi model was originally presented as an acoustic model. We use a Poisson's ratio of 0.25 and also make calculations for an elastic Marmousi model.

All of the calculations in this thesis are for 1-D or 2-D cases, but the heterogeneous $O(2,2)$ scheme presented here can be applied to the 3-D case.

REFERENCES

Geller, R. J. & Takeuchi, N., 1995. A new method for computing highly accurate DSM synthetic seismograms, *Geophys. J. Int.* **123**, 449-470.

Geller, R. J. & Takeuchi, N., 1998. Optimally accurate time domain second-order finite difference scheme for the elastic motion: 1-D case, *Geophys. J. Int.*, **135**, 48-62.

Takeuchi, N. & Geller, R. J., 2000. Optimally accurate second-order time-domain finite difference scheme for computing synthetic seismograms in 2-D and 3-D media, *Phys. Earth planet. Int.*, **119**, 103-138.

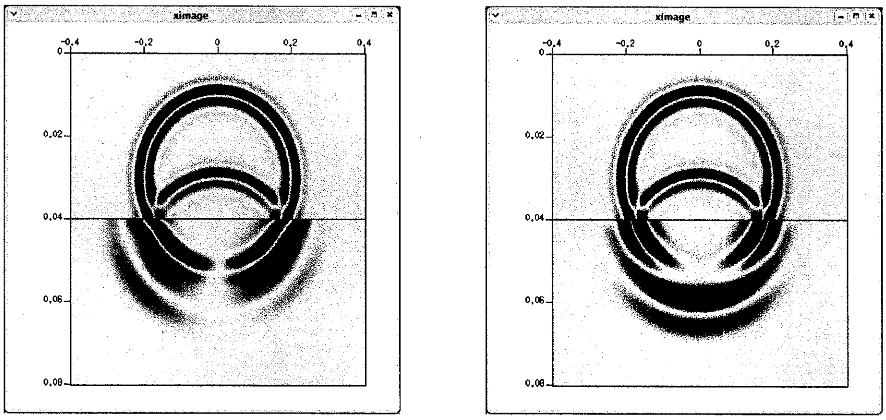

Figure 2: Snapshots of a computation in combined fluid-solid mdeia. The upper and lower layer are fluid and solid respectively. The fluid-solid interface exists in the middle of the model and a source of a point force is located in the fluid layer. Snapshots at $t = 0.1875$ (s) of the x- (left) and z- (right) components of the displacement with the pressure change. Propagation of P wave in the solid layer can be seen to be faster than in the fluid layer and S-wave can be also seen in the solid layer. In the fluid layer reflected P wave from the boundary is seen.

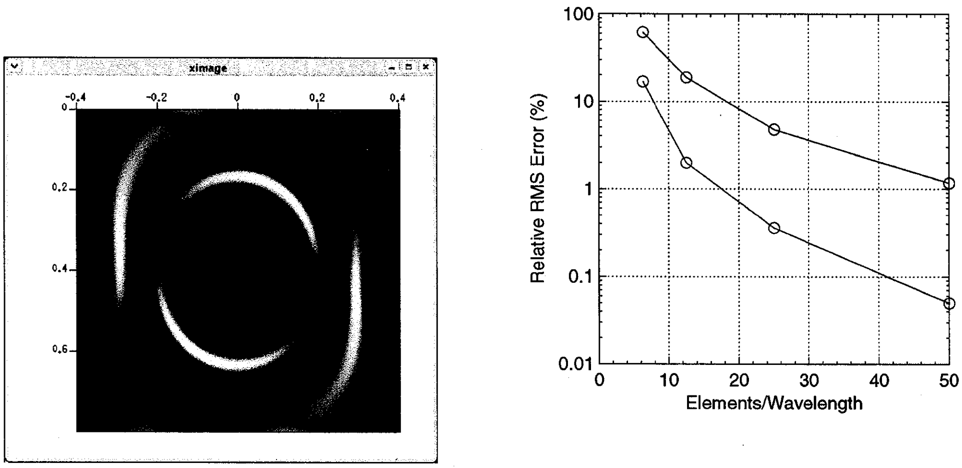

Figure 3: a 2-D numerical example for validation of the new scheme. Snapshot of x (left) displacement at 0.25 (s) computed by OPT2 and used as a numerical solution to compute relative RMS errors and relative RMS errors versus elements per wavelength of x displacement (right). The log scale used for the vertical axis and results by OPT2 and CONV2 are shown in red and green respectively.

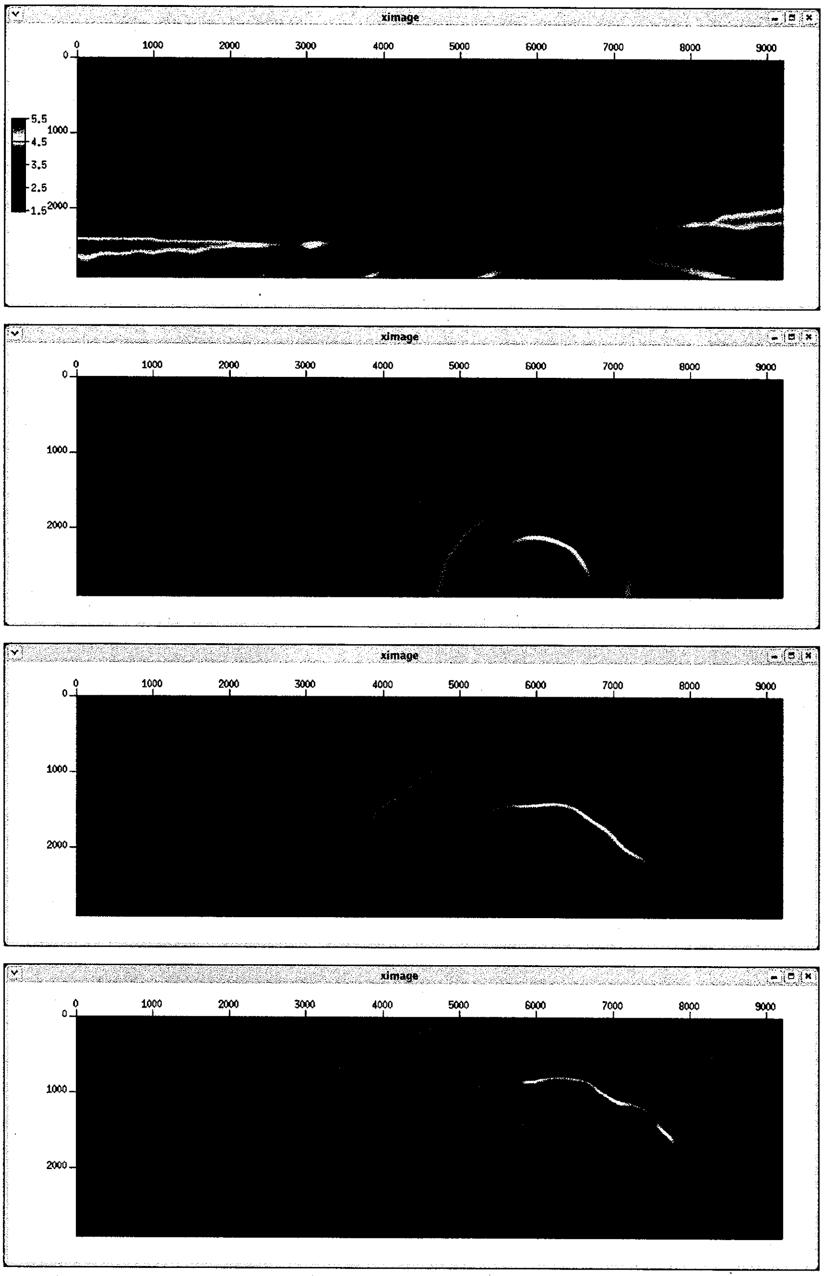

Figure 4: P velocity of Marmousi model (top) and snapshots of x displacement of P-SV problem from 0.4 to 1.6 s by 0.4 s interval (from second to bottom). A point force is located at $x = 2800$ and $z = 6000$ m. The free surface condition is used for the top boundary and an absorbing boundary is used for other external boundaries. These figures indicate aplicability of the new scheme to actual problems arise in the geophysical seismology.