Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS035-40 Room:IC Time:May 24 18:15-18:30

Fast computational methods for large- and multi-scale earthquake cycle simulations

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Recently, we have developed several methods for reducing memories and computational times in earthquake cycle simulations based on a rate and state friction law. In this talk, we give the need and a brief summary of the methods for reduction and their characteristics.

Model sizes in earthquake cycle simulations have become large as in the case of the Nankai trough (Hori,2006). We need to simulate earthquake cycles including earthquakes with different sizes and long- and short-term slow slips, leading to a multi-scale simulation. Toward predictive simulations for future earthquakes, we need to apply data assimilation methods to estimate initial conditions of variables as well as frictional parameters with uncertainties, which requires a large number of forward and backward computations. In simulations, dividing the plate interface into N smaller cells, the multiplicative computation of N∗N slip response function matrix (SRFM) and slip deficit rate vector (SDRV) frequently appears. The memory and the computational time are O(N∗N). The large- and multi-scale predictive simulations with N amounting to a million orders as in the Nankai trough model requires huge memories and computational times. Therefore, indeed, we need the speed-up of the computations with less memory.

In this study, we compare three methods for computing the product of SRFM and SDRV; Fast Fourier Transform (FFT), Fast Multipole Method (FMM) and Hierarchical Matrices (H-matrices) method. FTT has been used in earthquake cycle simulations (e.g., Kato,2008). The memory and the computational time are O(N) and O(NlogN). FFT, however, requires cyclic boundary conditions. At subduction zones, such conditions cannot be assigned in the dip directions because of the free surface. FMM was developed for rapid evaluation of the long-ranged forces in N-body problem in astrophysics and has been widely applied to a variety of problems. In earthquake cycle simulations, however, FMM has not so far been applied except for the studies in Tullis and Beeier (2008) and ours. It enables the faster evaluation with a multipole expansion of the slip response function, which allows one to group sources and receivers that lie close together and treat them as if they are a single source or receiver. The memory size and the computational time are O(N). Hirahara et al.(2009) developed the code for the multiplication in an infinite homogeneous elastic medium based on FMM formulation of Yoshida et al.(2001) and tree-structure algorithm of Liu and Nishimura(2006). FMM does not require any cyclic boundary conditions, but the functional forms suitable for multipole expansion. However, any suitable functional forms have not been obtained for the dip slip faulting on the dipping interface in the semi-infinite homogeneous elastic medium (Ohtani et al.,2010). H-matrices, which are efficient low-rank compressed representations of dense matrices, enable rapid arithmetic operations with less memory (Hackbusch,1999). Ohtani et al.(2011) implemented H-matrices in the code of Hori (2006) and examined the performance up to N of 10∗∗6. With the proper ranges of parameters controlling the accuracy, the memory is O(N), and the computational time is O(N) in the range of N smaller than 10∗∗5 and O(N)-O(NlogN) in the larger N range. Application of H-matrices requires only the slip response function decays with the distances between source and receiver cells, but not limitations of functional forms. In fact, Ohtani et al.(2011) use slip response function in a triangular cell in the semi-infinite homogeneous elastic medium. So far, we have examined only the case of homogeneous elastic medium. H-matrices would enable us to simulate earthquake cycles in a more realistic heterogeneous medium at subduction zones, by constructing SRFM with FEM.

Keywords: Large- and multi-scale earthquake cycle simulatio, Fast computation methods, Fast Fourier Transform Method, Fast Multipole Method, H-matrices