High-resolution Simulation of Earthquake Recurrence Enabled by Optimization for Multi-core CPUs and Large-scale Parallelization

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We have successfully developed an efficient algorithm capable of computation of N=1 million elements and 0.1 million time-steps. Strong-scaling analyses show that the algorithm exhibits the good scalability for OpenMP / MPI of 8 threads and more than 10000 cores (~200 nodes). This capacity is necessary to simulate the nationwide fault activity for the Japanese Islands with the current HPC systems. The algorithm is applied to simulate the 15 thousand years of the earthquake recurrence history along one of the largest active faults in SW Japan, the Median Tectonic line. We demonstrate that the optimized algorithm is a powerful tool enabling us to build a physics-based method applied to long-term forecast of earthquake generation.

Keywords—Earthquake sequence simulation, H-matrices, Contiguous memory placement

I. INTRODUCTION

Earthquake fracture mechanics require the interaction between the elastic response of the medium and the temporally evolving boundary condition due to fracture and friction. The system is highly nonlinear and requires the accurate evaluation of stress singularity on the boundary surfaces, characterized by geometrical complexity and fractal. Nationwide modern observations have provided constraints for fault geometry and spatial distributions of rate/directions of driving forces. Developing a physics-based method of the long-term forecast of earthquake activity is important in earthquake sciences and engineering. We develop an efficient numerical algorithm capable of fully utilizing the observations to simulate the earthquake recurrence processes on active faults in a wide area of the Japanese Island for more than 10,000 years.

Computational challenges in modeling earthquake sequences are spatiotemporal scales spanning a wide spectrum. Before earthquakes, the tectonic deformation of elastic plates slowly stresses faults for about 1000 years over the length of more than 100 km. During an earthquake event, rupture is nucleated from the scale of less than about 1km and grows to more than100 km in a few minutes. The rupture propagation is affected by fractally irregular geometry of faults. After an earthquake, viscous relaxation, after-slip and stress redistribution take place for about ten years over 100 km. These characteristics demand us to develop efficient algorithms with optimization to the supercomputer environment.

II. SIMULATION METHOD FOR EARTHQUAKE SEQUENCES

We use the boundary element method (BEM) [1], given the advantages in the fracture mechanical analyses. BEM has adaptivity in complicated boundary geometry with triangular meshes and high accuracy of stress singularity analysis necessary to fracture mechanics. We solve the simultaneous equations governing the system given by the elastic stress, $\Delta\tau$, response to slip, Δu, on fault elements

$$\Delta\tau_i(t) = \Sigma_j^N K_{ij}\Delta u_j(t) \text{ for } i = 1, \dots, N, \quad (1)$$

where K denotes the integration kernel (dense matrix), coupled with the boundary condition involving "Rate ($\Delta\dot{u}$)- and State (Θ)- dependent" friction and driving force $\dot{\tau}_i^{drv}$ as

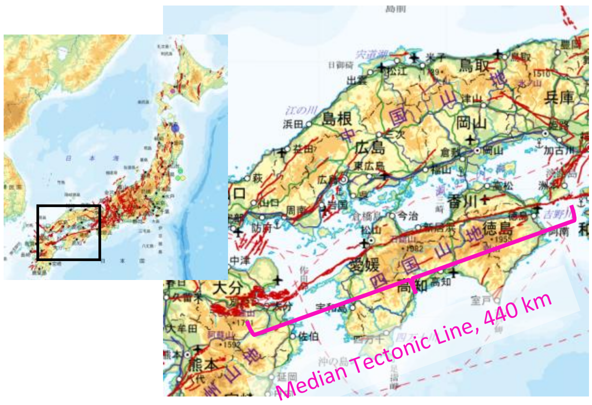

Fig. 1. Geometries and distributions of inland active faults (red lines) on the Japanese Island. Median Tectonic Line active fault is the largest one among more than 100 major faults.

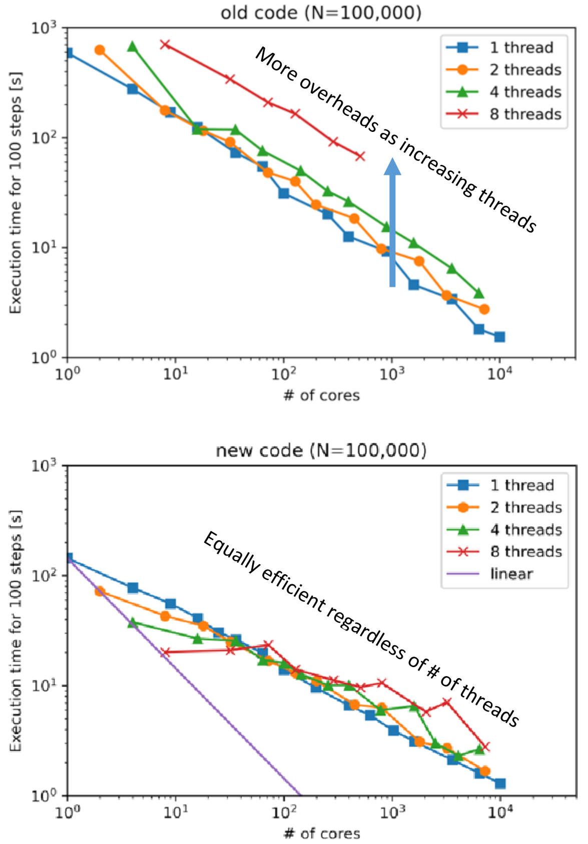

Fig. 2. Scalability of the optimized algorithm. Strong scaling evaluation of the code without optimization (top) and that with the contiguous memory placement (bottom)

$$\begin{cases} \Delta\tau_i(t) = -\{A\mathrm{Log}(\Delta\dot{u}_i(t)/V_o) + B\mathrm{Log}(\Theta_i(t)V_o/D_c)\} + \dot{\tau}_i^{drv}t. \\ \dot{\Theta}_i(t) = 1 - \Theta_i(t)V_o/D_c \end{cases} \quad (2)$$

Runge-Kutta time marching scheme with adaptative time stepper is used to handle the large variability of the timestep intervals such as Δt= ~100 years between rupture evens ~0.1 seconds during rupture events.

III. Computational Optimizations

We first adopt the Hierarchical matrices for the matrix vector product and acceleration of the MPI communication with assigning the blocks of MPI to the lattice structure [2]. H-matrices reduce the numerical complexity of the matrix vector product to $\mathcal{O}(N\mathrm{Log}N)$ from the original dense matrices of $\mathcal{O}(N^2)$. The Latice H-matrices reduces the MPI communication costs to $\mathcal{O}(N)$ from the normal H-matrices of $\mathcal{O}(N\,Np)$ with the number of MPI Np, which was associated accounted for the compressibility. To increase communication efficiency in each node, we next optimize OpenMP for the memory access processes of the Hierarchical matrix vector product, which retain the complicated tree structures [3]. The contiguous memory placement is implemented by reorder and repack the complicated Hierarchical matrix structure to large single 1-D array, guaranteeing the memory access continuity. We expect the contiguous memory placement significantly reduces memory access latency due to cache misses.

IV. Numerical Experiments on Computational Efficiency

The numerical experiments are performed to test the efficiency of the algorithms implemented in the earthquake sequence simulation. We use a supercomputer system, Wisteria-Odyssey, with the processor of A64FX, 48 cores (4 Core Memory Groups and 12 cores per CMG) and 2.2GHz and the memory of 32 GB per node. The execution time for 100 time-steps is evaluated by the strong scaling setup, varying the number of cores from 1 to 10^4 (1 to 200 nodes) as well as the number of threads from 1 to 8 to test the efficiency of both MPI and OpenMP.

As demonstrated earlier [1] [2], we confirm that the Lattice H-matrices are shown to avoid the saturation of the efficiency for a large number of MPI processes. Moreover, newly implemented OpenMP optimization successfully demonstrates the efficiency for the larger number of threads, avoiding the overheads that appeared in the original non-optimized code. An example of the number of elements (degree of freedom) N=100,000 is shown in Fig. 2. The other cases of N will be shown in the poster. Since the use of the thread parallelization is inevitable to reduce the memory requirement, the current results demonstrate the strong performance of our optimized algorithm to be applied to large-scale and long-time simulations, modeling realistic geometries and distributions of natural active faults.

V. Earthquake Cycle Simulation of Median Tectonic Line

As an example of the application, we modeled the earthquake cycle (multiple sequences of the stress buildup and earthquake generation) of the Median Tectonic Line active fault (MTL) for more than 10 thousand years. By considering the stressing rate constrained by GNSS (GPS) network observations, we generate seven earthquake events of the earthquakes over the area with an average interval of 2000 years. The long-term averaged slip rate on the fault is calculated as about 10 m / thousand years. Such results are validated by comparing with the independent geological observation and are shown to be in good agreement.

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