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

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Introduction and Objective

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: Earthquake sequences span a wide spectrum in space and time consisting of

- (Before earthquakes) Tectonic deformation of plate, slowly stressing faults for ~ 1000 years over the length >100 km.
- (During an earthquake) Nucleation from <~1km and growing to ~100 km in ~ minutes. Affected by fractally irregular geometry.
- (After earthquake) Viscous relaxation, after-slip and stress redistribution for ~10 year over ~100 km.

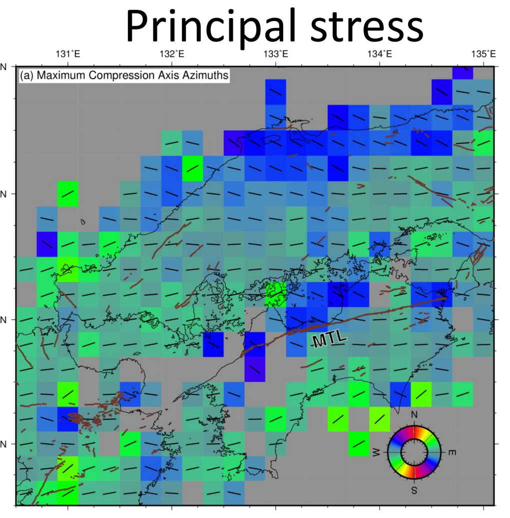
Spatial distribution of active faults in the Japanese Islands and recurrence of earthquakes

More than 100 major faults are identified in the entire area.

- MTL: One of the largest in-land active faults of ~440 km length and ~1000 years intervals of earthquake recurrence. Targeted in the current model.
- Subsurface model of faults: 3-D non-planar geometry of up to ~100 m spatial resolution over the area of 440 km x 30 km.

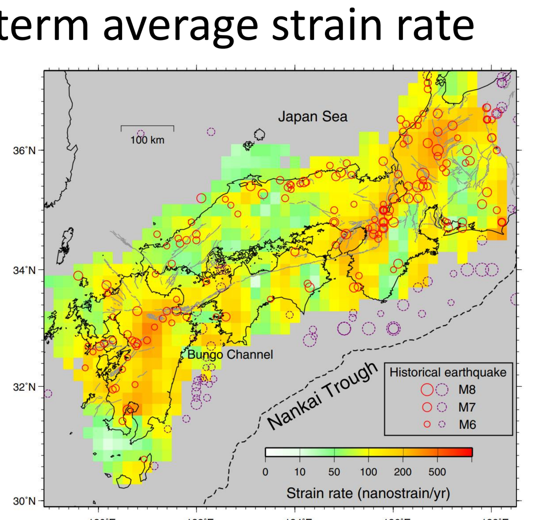
Model Inputs: Observational constraints of long-term elastic deformation to drive the system

Distributions of Principal stress



Estimated using slip directions of micro-earthquakes. (Uchide, 2022)

long-term average strain rate



Derived from permanent GNSS (GPS) network observation. Nishimura (2022)

Simulation Method for earthquake sequences [1]

+ Boundary element method (BEM)

- Adaptivity in complicated boundary geometry with triangular meshes.
- High accuracy of stress singularity analysis necessary to fracture mechanics.
- Simultaneous equations governing the system
  - Elastic stress $\Delta\tau$ response to slip Δu on fault elements

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

K : Integration kernel (dense mat.)

  - Boundary condition involving "Rate ($\Delta\dot{u}$)- and State (Θ)- dependent" friction and driving force $\dot{\tau}_i^{drv}$

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

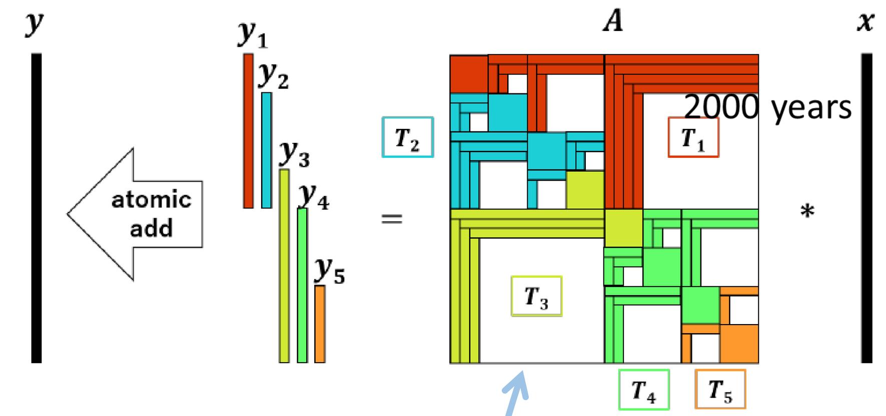
- Runge-Kutta time marching scheme with adaptative time stepper.
  Δt = ~100 yrs. (between earthquake rupture evens)
  ~0.1 sec (during an earthquake).

Lattice Hierarchical matrix vector product (HiMV) [2]

+ H-matrices reducing the numerical complexity

Dense MV: $\mathcal{O}(N^2)$ → HiMV: $\mathcal{O}(N\mathrm{Log}N)$

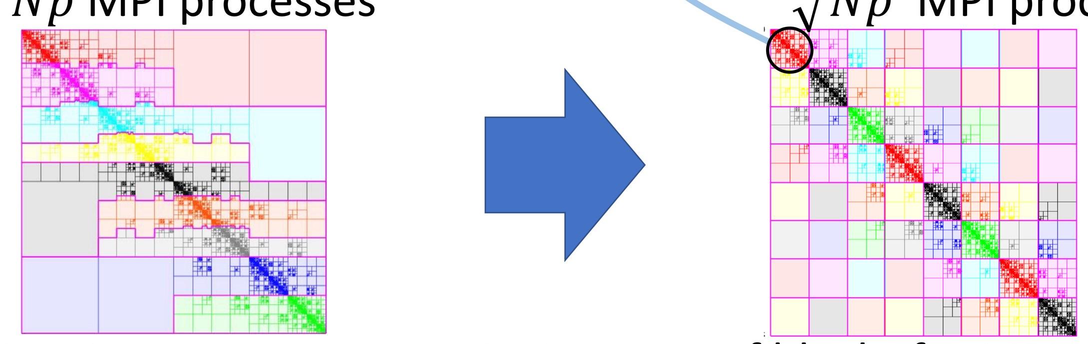
A : Low-rank approximated dense matrix (Kernel K)



+ Latice H-matrices reducing MPI communication costs

Normal H-matrices: $\mathcal{O}(N\,Np)$ All_reduce among Np MPI processes

Lattice H-matrices: $\mathcal{O}(N)$ Reduce and Broadcast among $\sqrt{Np}$ MPI processes



MPI assignment optimizing compression

Assignment of blocks for MPI on lattice structure reducing # of Proc. Np overhead.

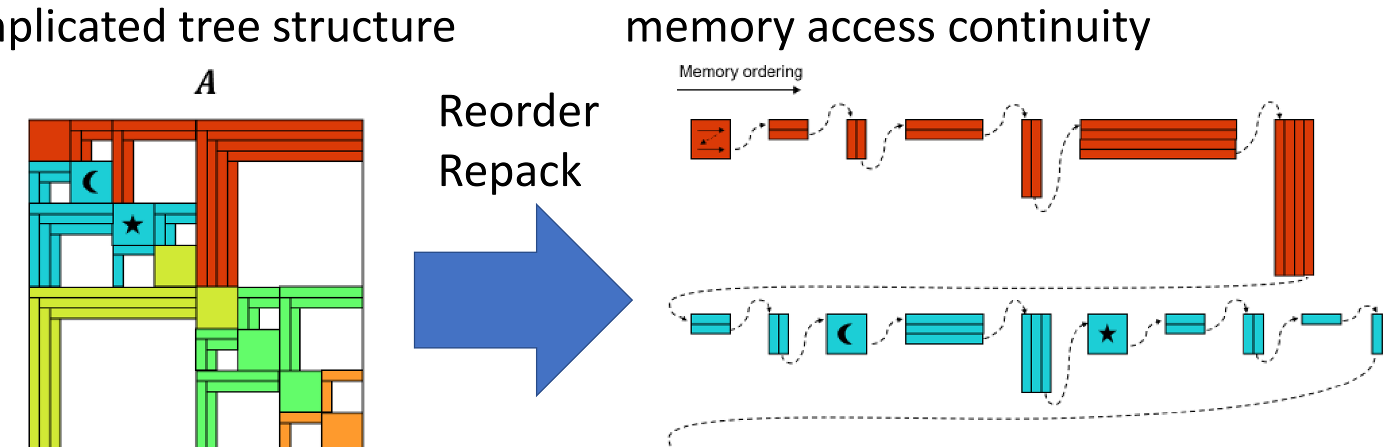
OpenMP Optimization Method of HiMV [3]

+ Contiguous Memory Placement

Increase communication efficiency in each node

Hierarchical matrix with complicated tree structure

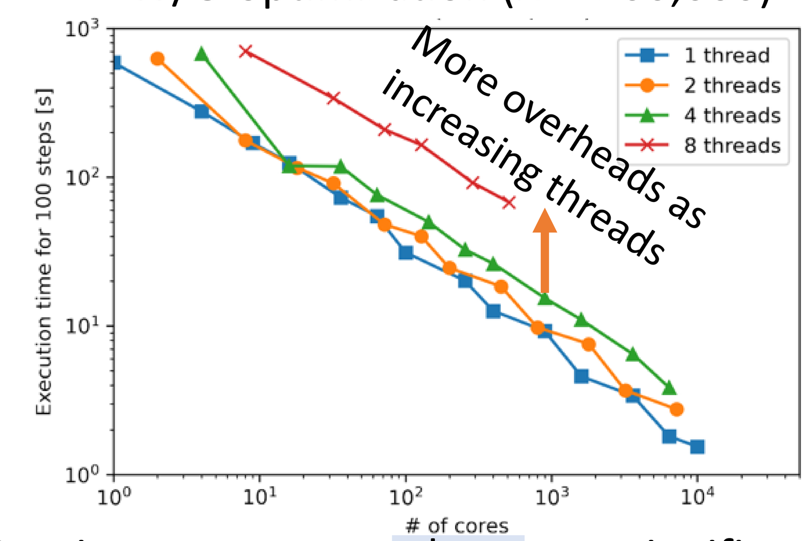
Large single 1-D array guarantees memory access continuity



Numerical Experiments on computational efficiency

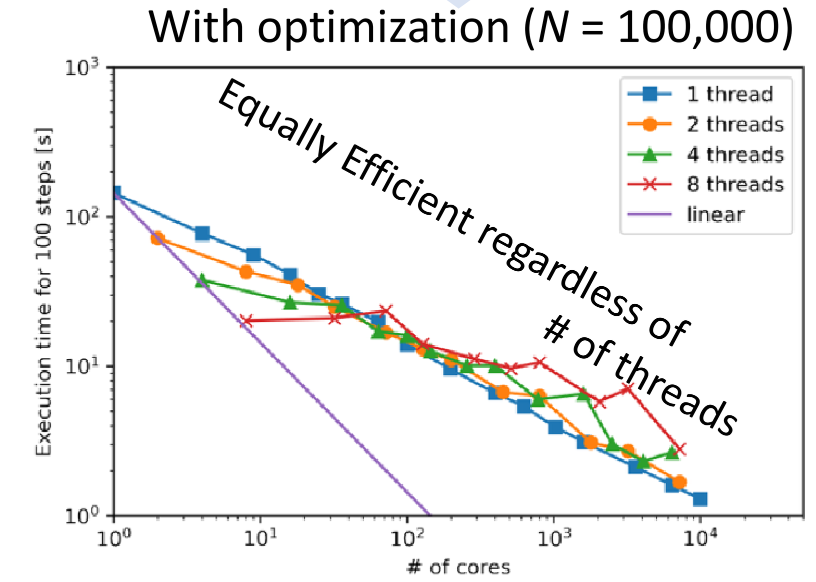
+OMP Optimization improves performance in a MPI process

W/O optimization (N = 100,000)



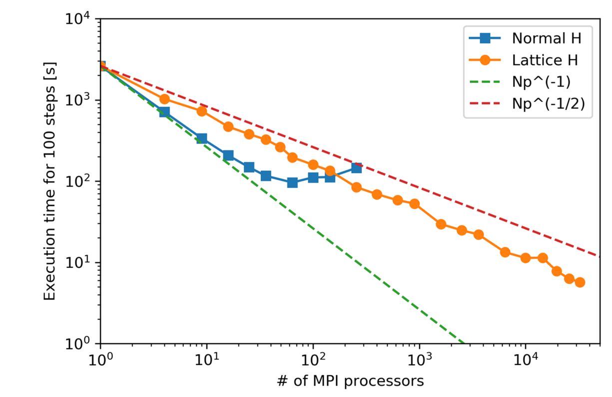
Contiguous memory placement significantly reduces memory access latency due to cache misses.

With optimization (N = 100,000)



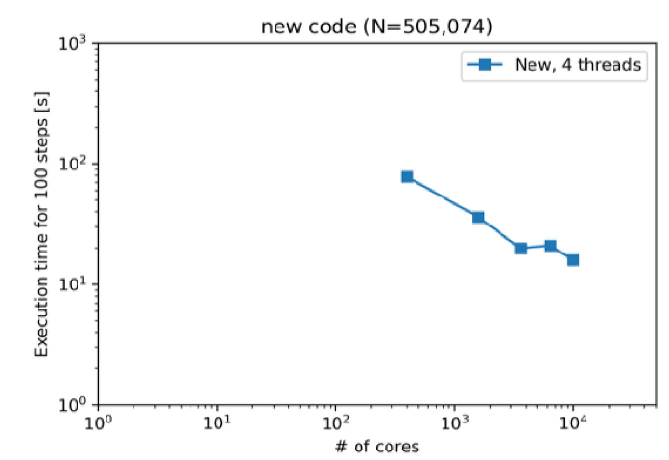
+MPI communication costs are reduced by Lattice H-matrices

Normal vs. Lattice H-matrices [1]



Wisteria-Odyssey
Processor: A64FX, 48 Core, 2.2GHz
Memory: 32 GB

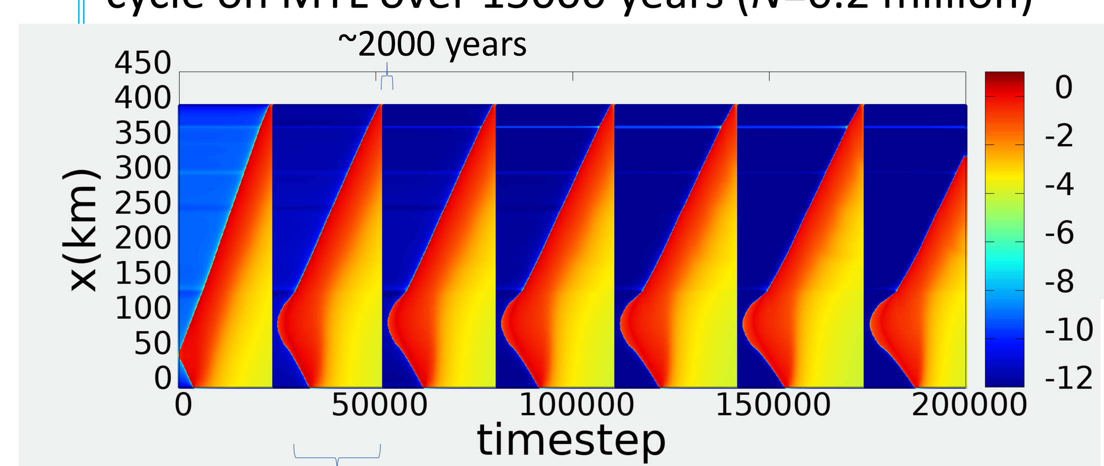
Preliminary results with optimization for N=500,000



The good scalability is held for the larger number of elements. The performance for shared-memory will enable a larger scale computation, reducing the total memory requirement.

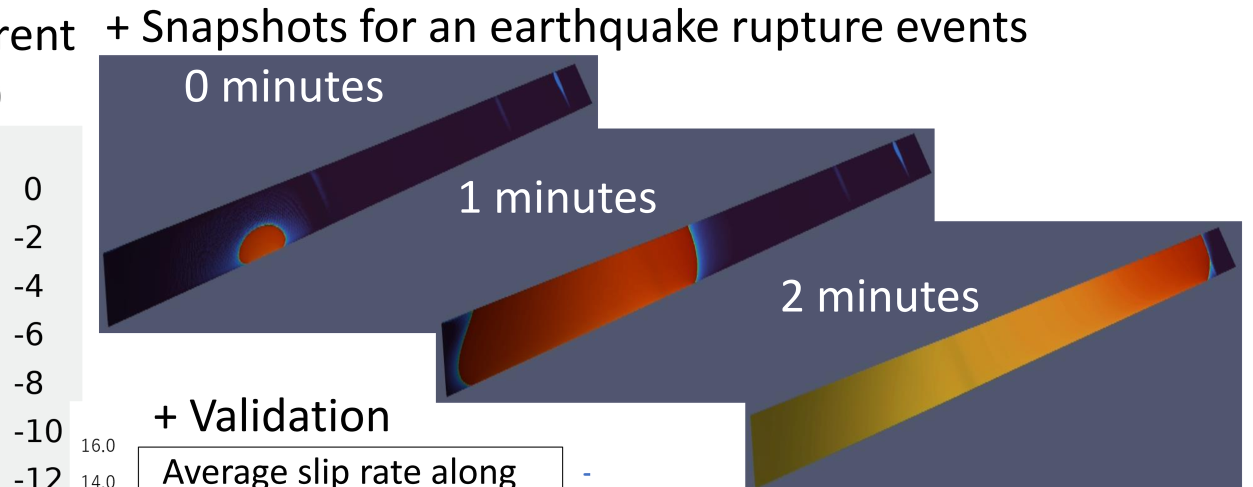
Earthquake cycle simulation of Median Tectonic Line (MTL)

An applicational example of earthquake recurrent cycle on MTL over 15000 years (N=0.2 million)

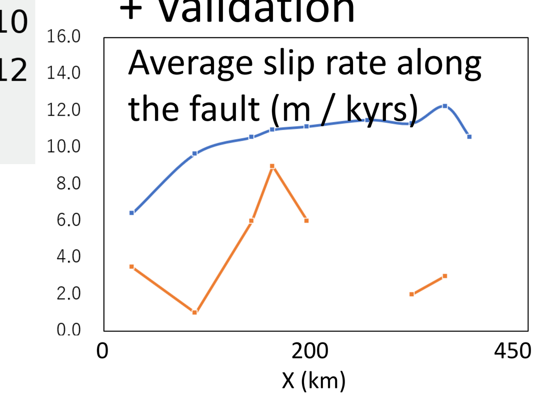


Note: time is not in scale due to variable Δt

+ Snapshots for an earthquake rupture events



+ Validation



Comparison of long-term slip rate between simulation (blue) and independent geological observation (orange) shows relatively in good agreement, given the insufficient data availability.

Conclusion

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. We will extend the modeling area to a wider area in and around the island.

References

1. Ozawa+, Large-scale earthquake sequence simulations of 3D geometrically complex faults using the boundary element method accelerated by lattice H-matrices on distributed memory computer systems, Submitted to GJI (2022)
2. Ida, Lattice H-matrices on distributed-memory systems, IPDPS (2018)
3. Hoshino+, Optimizations of H-matrix-vector Multiplication for Modern Multi-core Processors, Cluster (2022)