Development of large-scale particle simulations for fluid and granular dynamics

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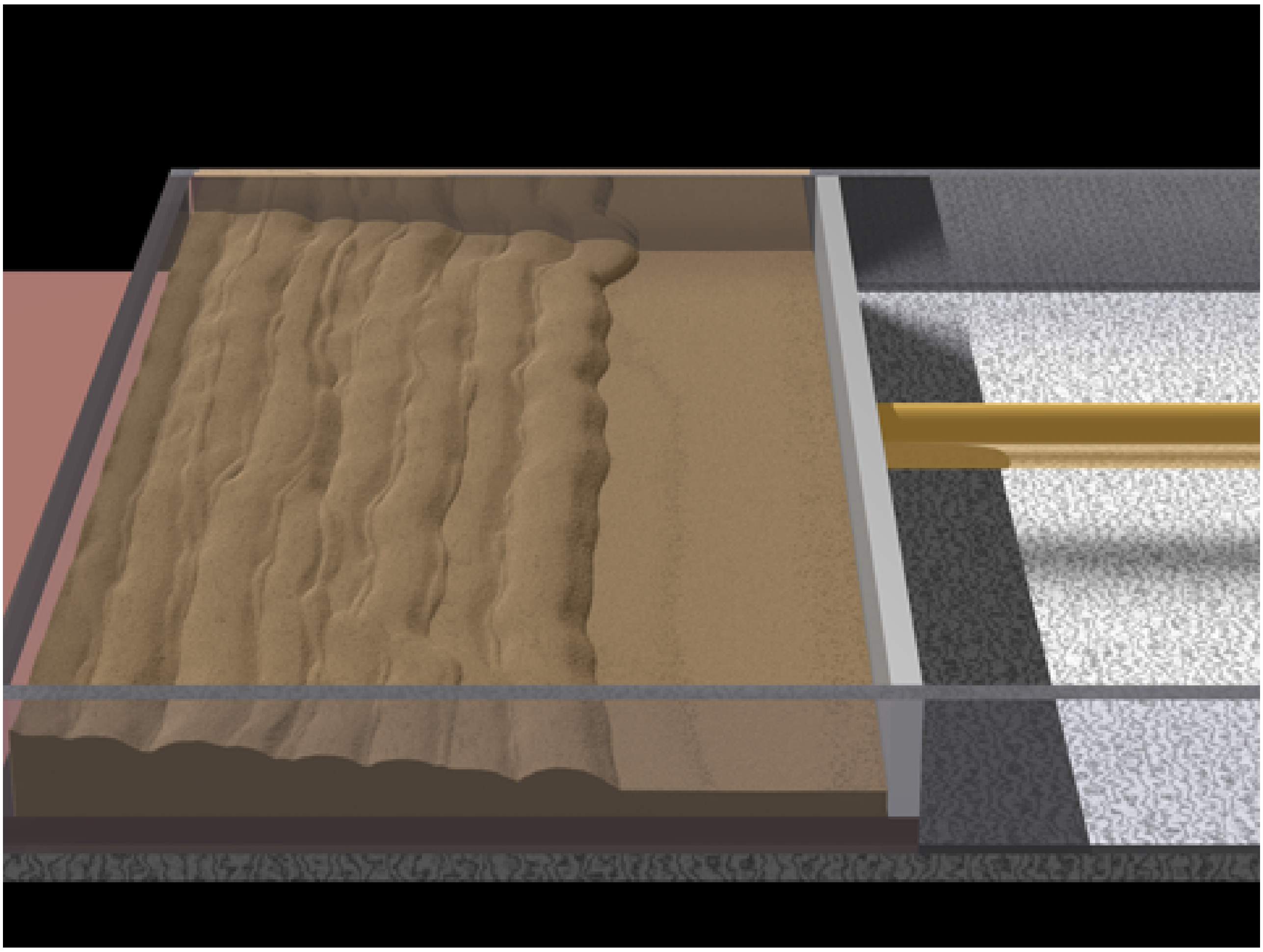
Large-scale parallel computing is important for numerically reproducing actual measurement results and dynamics of phenomena in various science and engineering areas, such as civil engineering, bioengineering, and earth sciences. The computational performance of parallelized software tools plays a critical role in such simulation studies, as these improve the computational accuracy relative to the simulation resolution within a limited computation time. Recent massively parallel computer systems based on shared- and distributed-memory architectures employ various types of arithmetic processors. Current processor designs are known to exhibit totally different computational performance depending on the numerical algorithms and implementation methods employed. Currently, parallel computing generally uses either a multi-core CPU, graphics processing unit (GPU), or many integrated core (MIC) processor. Multi-core CPUs have traditionally been used in high-performance computing, whereas GPUs were originally designed for computer graphics with many arithmetic cores. The common progress of current processor designs is the increase in the number of cores using vector operations such as single-instruction–multiple-data (SIMD). In such a situation, the shared-memory parallelization plays a basic but critical role in dealing with the increasing number of arithmetic cores in an efficient manner.
Particle simulation method (PSM) has a benefit of being mesh-free, allowing the computation of large-scale deformations and fractures of a continuum body without expensive remeshing tasks. As a PSM, smoothed particle hydrodynamics (SPH) is often used for tsunami disaster simulations because of its robustness in free-surface fluid dynamics. The discrete element method (DEM) is one popular PSM for granular dynamics in which geometrical size and shape attributes are provided for each particle. Therefore, the DEM is attractive to simulate granular materials such as sand, pebbles, and other grains.
An efficient parallel implementation of SPH and DEM methods is however known to be difficult especially for the distributed-memory architecture. Particle methods inherently have workload imbalance problem for parallelization with the fixed domain in space, because particles move around and change workloads during the simulation run. Therefore, dynamic load balance is key technique to perform the large scale SPH or DEM simulation. In this presentation, we introduce the several techniques of parallel implementation utilizing dynamic load balancing algorithms toward the high resolution simulation over large domain using the massively parallel super computer system. We will also introduce the applications of large-scale particle simulations such as Tsunami disaster simulation in consideration of structures–soil–fluid interactions and sandbox simulation for thrust dynamics of an accretion prism that require a high performance computing resources.

Keywords: DEM, SPH, Parallel computing, Tsunami, Sandbox, Accretion prism



Development of tsunami Green’s function database based on linear dispersive-wave theory and its application to real-time tsunami forecasting

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Real-time tsunami forecasting based on source inversion of offshore tsunami data is effective for update of tsunami early warnings. We developed tsunami forecasting method based on inversion of offshore tsunami data for initial sea-surface height distribution, named tFISH (Tsushima et al., 2009). The purpose in this study is improvement of tsunami-waveform Green’s function database (DB) that is one of key elements of tFISH algorithm. In tFISH algorithm, tsunami forecasting calculation is based on linear superposition of Green functions. Therefore, error in the functions directly affects tsunami-forecasting error. The present DB is prepared by using tsunami simulations based on linear long wave (LLW) theory. Generally, tsunamis have lone-wave length, and thus this approximation is valid. When a tsunami source is abundant in short-wave length component, however, the resultant tsunami waveforms become dispersive even at the near-field observing point (Saito et al., 2009). In such situation, use of LLW Green function degrades source-estimation accuracy (Saito et al., 2010). To overcome this problem, we have to prepare Green’s function DB based on linear dispersive-wave (DSP) theory, instead of LLW. However, the cost of the DSP calculation is much higher than that of LLW simulation. In addition, we have to conduct DSP simulations for more than 3000 cases to construct DB, and thus total computation cost is extremely huge. To overcome this difficulty, we implemented functions to accomplish these huge calculations in realistic calculation time by using K computer and then constructed DSP DB for Nankai-trough region (Tsushima et al., 2015, JpGU). In this presentation, we introduce construction of DSP DB for Kuril-Japan trench region and results of numerical simulations to show effectiveness of DSP Green functions in real-time tsunami forecasting.

In numerical simulations of tsunami forecasting, we assumed the 1933 Sanriku earthquake (magnitude 8.4) as a target event. This earthquake is an outer-rise normal-faulting event. Since the seafloor deformation is abundant in short wavelength and water depth in the source is great, the resultant tsunami waveforms are dispersive. To produce synthetic observation, we assumed earthquake faulting model proposed by Kanamori (1971) and then calculate the tsunami propagation based on nonlinear dispersive-wave theory. Then, we estimated initial tsunami height distribution using the synthetic data at offshore stations to forecast coastal tsunami waveforms. In tFISH inversion with LLW DB, significant source artifact appeared, while the artifact disappeared by applying our DSP DB. At coastal points around which offshore tsunami stations are few, better forecasting results were obtained with DSP Green functions than with LLW ones. This indicates that use of DSP Green functions is important to improve tsunami source estimation and tsunami prediction for dispersive event. Next, we assumed one of the huge Nankai-trough earthquakes proposed by the Cabinet Office: an earthquake with huge slip off Kochi Prefecture. To simplify situation, we neglect finiteness of rupture velocity in production of synthetic observations. It is noteworthy that the resulting synthetic data are less dispersive. Then, we compared the predicted tsunami waveforms at coastal points based on DSP DB and those based on LLW DB. As a result, these show good agreement. This result indicates the possibility that DSP DB works well for both dispersive and non-dispersive events. To clarify this point, we will perform more performance tests in future.

This research used computational resources of the K computer provided by the RIKEN Advanced Institute for Computational Science through the HPCI System Research project (Project ID: hp150216).

Keywords: K computer, Real-time tsunami forecasting, Database, Linear dispersive-wave theory, Disaster mitigation

A proposal of monitoring and forecasting system for crustal activity in and around Japan using a large-scale high-fidelity finite element simulation codes

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Here we propose a system for monitoring and forecasting of crustal activity, especially great interplate earthquake generation and its preparation processes in subduction zone. Basically, we model great earthquake generation as frictional instability on the subjecting plate boundary. So, spatio-temporal variation in slip velocity on the plate interface should be monitored and forecasted. Although, we can obtain continuous dense surface deformation data on land and partly at the sea bottom, the data obtained are not fully utilized for monitoring and forecasting. It is necessary to develop a physics-based data analysis system including (1) a structural model with the 3D geometry of the plate interface and the material property such as elasticity and viscosity, (2) calculation code for crustal deformation and seismic wave propagation using (1), (3) inverse analysis or data assimilation code both for structure and fault slip using (1)&(2). To accomplish this, it is at least necessary to develop highly reliable large-scale simulation code to calculate crustal deformation and seismic wave propagation for 3D heterogeneous structure. Actually, Ichimura et al. (2014, SC14) has developed unstructured FE non-linear seismic wave simulation code, which achieved physics-based urban earthquake simulation enhanced by 10.7 BlnDOF x 30 K time-step. Ichimura et al. (2013, GJI) has developed high fidelity FEM simulation code with mesh generator to calculate crustal deformation in and around Japan with complicated surface topography and subducting plate geometry for 1km mesh. Further, for inverse analyses, Errol et al. (2012, BSSA) has developed waveform inversion code for modeling 3D crustal structure, and Agata et al. (2015, this meeting) has improved the high fidelity FEM code to apply an adjoint method for estimating fault slip and asthenosphere viscosity. Hence, we have large-scale simulation and analysis tools for monitoring. Furthermore, we are developing the methods for forecasting the slip velocity variation on the plate interface. Basic concept is given in Hori et al. (2014, Oceanography) introducing ensemble based sequential data assimilation procedure. Although the prototype described there is for elastic half space model, we will apply it for 3D heterogeneous structure with the high fidelity FE model.

