論文の内容の要旨

論文題目：Large scale simulations of 3D wave propagation induced by supershear rupture

（スーパーシア破壊に誘発される三次元波動伝播の大規模シミュレーション）

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Supershear earthquakes were long considered more as a theoretical possibility than an actual realistic risk. However, a number of observations in the last two decades, in particular the recent 2018 Palu earthquake in Indonesia, proved that although rare, some strike-slip earthquakes could exhibit a fault rupture speed exceeding the Rayleigh wave velocity, and even nearing the P-wave velocity. Compared to standard sub-Rayleigh earthquakes, the wave front consists of a Mach cone of shear shock waves, in which the shear deformation is highly localized, and which can propagate significantly longer distances away from the fault without dissipating. For this reason, supershear rupture is expected to have a significant effect on the ground motion, which could trigger very different responses from infrastructures, especially in areas close to the fault. Estimating the impact of such events can be crucial to determine the sustainability of critical infrastructures such as nuclear power plants.

However, this requires a numerical method which can both reproduce accurately the shock waveform and the dynamic rupture propagation at a large scale, both computationally expensive especially in three dimensional settings. Therefore, we develop a model based on the Particle Discretization Scheme (PDS)FEM proposed by Hori *et al.* which uses a simple and effective particle-based approach for failure and allows for a relatively light numerical treatment of crack propagation. In particular, we expand the crack representation, originally designed for mode-I failure, to the treatment of mode-II cracks with frictional contact. We also detail the implementation of the displacement-based and strain-based Hamiltonian formulation of the dynamic wave equation, which enable an accurate and efficient explicit time integration. The treatment of shear cracks and frictional forces, which are central to the supershear rupture mechanism, are thoroughly verified and validated. In addition, the developed framework was applied to the study of wing cracks, which play an active role in the rupture of brittle materials under compression, with a focus on the quantitative evaluation of the interactions between coplanar aligned cracks. The dynamic crack propagation simulations are also verified and validated, by comparing with photoelastic observations of a dynamic mode-I crack captured with a 1Mfps camera. The simulated results show a good agreement with the analytical solution for simple problems, and the experimental measures in term of crack path, rupture speed and stress distribution around the crack tip. The two Hamiltonian formulations are observed to be numerically indifferentiable although the displacement-based one proved to be significantly more computationally efficient.

Nevertheless, the real-scale simulation of a supershear earthquake scenario can involve a simulation domain spanning hundreds of kilometers, while requiring a detailed refinement (few tens of meters) for elements in the region near the fault to capture the rupture mechanism and the shock waveforms. As the computational domain can then involve hundreds of millions of elements, an efficient parallel program is necessary. Since modern cluster architectures tend to consist of computer nodes with a large number of cores, we explore improvements to the original flat MPI management by enhancing the operations in the shared memory environment. We develop MPI-MPI Hybrid communication utilities based on MPI Shared memory windows available from MPI-3 Standard, with fine-grained synchronization based on C++ atomic operations. Communications between processes are designed to mimic the organization of data in standard flat MPI so that the new method can be easily implemented in an already existing parallel code. Moreover, parallel operations are designed separately from the main program for easy maintenance. Performance tests conducted on the Reedbush-U supercomputer suggest that our method is slower than standard MPI utilities such as MPI_Barrier and MPI_Allreduce in a single computer node, but leads to a significantly better synchronization between processes, while ghost updates perform significantly better. However, our method leads to overall more stable performance in a multiple node environment than standard MPI, with lower in average execution times for all operations.

The developed numerical method is then applied to the simulation of supershear rupture. We first conduct a 2D study of ideal supershear scenarios in which the frictional contact follows a linear slip-weakening law. We demonstrate that our method can reproduce both sub-Rayleigh and supershear rupture regimes as a function of the initial stress distribution on the fault surface. In particular, rupture regimes were in agreement with the analytical estimates for self-similar cracks for different seismic ratio. Also,the transition mechanism from sub-Rayleigh to supershear rupture, known as the Burridge-Andrew mechanism, could be clearly observed, while the variation of the transition rupture length as a function of the initial stress and the slip-weakening distance was in good agreement with analytical estimates.

The methodology is then used to the large scale simulation of the 2018 Palu earthquake on the Palu-Koro fault. The fault geometry is extrapolated from satellite observations of the fault trace on the surface and the dip angles estimated from the focal mechanism. The contact between the fault surfaces is modelled by a Mohr-Coulomb friction law, leading to a realistic initial stress distribution on the fault, while the dynamic rupture is controlled by a rate and state velocity weakening friction law. The simulation successfully reproduces the early and sustained supershear rupture. Also, it indicates that the presence of an off-fault damage zone can contribute to the low rupture velocity measured during the earthquake. Unlike sub-Rayleigh earthquakes, the shock wave propagation was observed to lead to significant amplitudes of the ground motion even far from the fault. The frequencies of supershear-induced vibrations appear lower than in sub-Rayleigh earthquakes suggesting potentially higher damage on higher-rise structures, including nuclear power plants.