Finite element solver for large-scale three-dimensional soil liquefaction analysis

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Soil liquefaction induced by earthquake has caused damages such as ground settlement, lateral flow, tilting of buildings, uplift of manholes and destruction of infrastructures. To examine mechanism of soil liquefaction and mitigate damages it causes, a variety of methods have been developed. Several constitutive law for liquefiable soil were proposed and numerical simulations using them were performed. However, most of the analysis used two-dimensional model because of the huge computational cost of three-dimensional (3D) analysis.

Along with the accumulation of spatial data and development of computer architecture and computational techniques in recent years, expectations have risen for large-scale 3D seismic soil liquefaction analysis. Fast and scalable finite-element based solvers have been developed for large-scale 3D seismic response analysis not considering soil liquefaction. Based on one of them, we developed a finite element solver for large-scale 3D seismic soil liquefaction analysis in previous study.

Even though our previous study enabled large-scale 3D seismic soil liquefaction analysis, there are several inefficiencies in the previous solver. It used the method for seismic response analysis not considering soil liquefaction. It did not consider the differences between the seismic response analysis without soil liquefaction and soil liquefaction analysis. In soil liquefaction analysis, liquefiable layers and non-liquefiable layers are under different constitutive laws, and have different convergence characteristics in solving the governing equation. Not considering these differences causes load imbalance in parallelization and lowers the performance. Also, the method was not suitable for our target supercomputer architecture when used in soil liquefaction analysis.

We developed a revised solver for large-scale 3D seismic soil liquefaction analysis to overcome these problems. The solver uses hybrid parallelization with MPI and OpenMP. We revised the domain partitioning scheme to improve load balancing among MPI processes. The element reordering was used to improve load balancing among OpenMP threads. In addition to the revision of load balancing method, we developed an algorithm to solve the governing equation which is accelerated by considering the characteristics of soil liquefaction. These methods were developed so that our target supercomputer architecture, many-core wide SIMD architectures was efficiently utilized. The developed method achieved 5.1-fold speedup over the previous solver.

As an application analysis, we performed soil liquefaction analysis using large scale highly detailed 3D model that mimics actual ground structure near an estuary. The model has 21,616,202 elements and 89,146,716 degrees of freedom. A 29,500-time-step analysis was carried out on Oakforest-PACS, an Intel Xeon Phi (Knights Landing: a manycore CPU with wide SIMD)-based supercomputer system. The computation time was 16 hours and 12 minutes.

