論 文 の 内 容 の 要 旨

論文題目

Improving reliability of urban earthquake disaster simulation with many scenario computing and 3D nonlinear ground motion analysis

(多数シナリオ解析と非線形三次元地盤振動解析による都市震災シミュレーションの信頼性向上)

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To make effective and efficient earthquake disaster mitigation plans, reliable earthquake disaster estimates are needed. Such estimates should have high degrees of scientific rationality, accuracy, and resolution. To improve the reliability of current estimates based on observations of past earthquake disasters, researchers have developed physics-based earthquake disaster estimation methods that combine geospatial data and physics-based numerical analysis to analyze each phase of an earthquake disaster. These methods have the potential to generate accurate estimates, since current physics models (e.g., the wave equation) are able to accurately model wave propagation and the responses of structures. However, two problems limit the reliability of such methods. The first problem is the lack of geospatial data (e.g., data on soil and structures), compared with the actual complexity of the environment. The lack of data leads to uncertainties in the analysis models inputted into the numerical analyses. The other problem is that simplified analysis methods, which are less reliable, are used for solving some of the physics models.

This study aims to improve the reliability of physics-based urban earthquake disaster simulation by: (1) developing a method to compute a large number of earthquake disaster simulations to reflect uncertainties in the models and estimates and (2) using three-dimensional (3D) ground motion analysis to solve the physics model with higher reliability.

In the first part of this study, I developed a method for efficient computation of a large number of earthquake disaster simulations on high-performance computers. When the distribution of uncertainties in a set of analysis models is known, analysis models that exhibit the uncertainty distribution can be analyzed to estimate the distribution of results. The difficulty of such analyses is obtaining scalability on high-performance computers when analyzing many cases of simulations of large areas with large number of structures. Based on the measurements of previous implementations, I found that the data transfer between the ground motion analysis program and the structural response analysis program becomes a bottleneck. By careful management of data transfer between the analysis programs, 97.4% weak scalability was attained using 40,000 nodes of the K computer at RIKEN. This enables the computation of more than 1,000 scenario simulations of 0.25 million structures in Tokyo within an hour using 20,000 nodes of the K computer.

In the second part of this study, I replaced the one-dimensional (1D) ground motion analysis used in a previous urban earthquake disaster simulation with a highly scalable 3D ground motion analysis. Here, a finite element method with unstructured tetrahedral elements and nonlinear constitutive modeling was used to model and analyze the complex ground geometry, and the ground motion recorded at the surface was used to shake the 4,066 structures in the target area. To assure the convergence of structural response, I conducted ground motion analysis with target frequencies of 5, 10, and 15 Hz. Although the analysis with target frequency of 15 Hz leads to a large-scale problem with 1 billion degrees of freedom, it can be computed in 11 h using 8,192 nodes of the K computer. The results show that the structural response is converged at a target frequency of 15 Hz. Next, I compared the ground and structural responses with the results obtained by 1D ground motion analysis. A difference of 15% was obtained when comparing the seismic intensity index of the ground motion obtained by 1D and 3D analysis. As a demonstration of the many cases analyzed for uncertainty modeling, I generated structure models for each structure in the target area, and analyzed them to obtain the distribution of responses. By analyzing 10,000 models for each structure, I obtained convergence in the distribution of structural response.

The results obtained demonstrate that the combination of 3D ground motion analysis and structural response analysis of each structure in an urban area can be useful for completing detailed analysis considering the 3D geometry of soils and the properties of each structure. The results further show that computing a large number of cases can be useful for uncertainty modeling of structures. Such analysis could lead to more reliable earthquake disaster estimates.