博士論文　（要約）

High-fidelity crustal deformation computations and an optimization method of the crustal structure model aimed at enhancing earthquake damage estimation

(地震被害推定高度化を目的とした高詳細地殻変動解析手法と地殻構造最適化手法の開発)

縣　亮一郎

A physics-based simulation method of crustal deformation both during an earthquake and in a long term (within a few years) is an essential tool for earthquake damage estimation, such as tsunami estimation, earthquake fault monitoring via inverse analyses, and so on. Analytical solutions of elastic or viscoelastic deformation in a simplified model of crustal structure have been typically used for the crustal deformation computation. However, some studies suggested that the effects of 3D heterogeneity and detailed geometry of crustal structure are not negligible in crustal deformation computation, when analyzing data from subduction zone earthquakes obtained due to recent progress in observational techniques.

If we seek to apply crustal deformation computation to earthquake damage estimation considering 3D heterogeneity and detailed geometry of crustal structure, it is important to ensure accountability on the estimation results via maintaining transparency of the modeling process. This is because earthquake damage estimation has a large impact on society. Therefore, to maintain transparency in the process, it is desirable to construct a computation model which is of higher fidelity to the observation data of the crustal structure accepted in the community. Since detailed elevation data of crustal structure, which are in 1-km resolution at the most detailed part, are available in and around the Japanese Islands, we should construct a computation model by using these data (hereafter called *high-fidelity model*). The finite element (FE) method is suitable for this purpose, because it enables accurate handling of geometric shapes. A high-fidelity FE model constructed in the same resolution as that of the available data results in degrees-of-freedom (DOF) of 10^8-10^{10} order, which requires a large computation cost for both the mesh construction and the FE analyses. Development of computation methods to overcome these costs is required.

On the other hand, a high-fidelity model based on the available crustal structure data cannot consistently explain the observation data of crustal deformation at this moment.It is desirable to continuously update the model by deriving model parameters from newly obtained observation data, and thus to increase transparency of the modeling process further. Using long-term crustal deformation data, we can update values of viscosity used in long-term crustal deformation computations. Determination of viscosity values is not trivial, and past studies used values that are different from each other. To update the values, we need to carry out nonlinear optimization of viscosity. In the optimization, fault slips must be estimated simultaneously because long-term crustal deformation also strongly depends on the amount of fault slip. Assuming to use a high-fidelity model for the forward problems, an optimization method that requires less computation cost is necessary.

This thesis is aimed at: (1) introduction of an elastic crustal deformation computation method using a high-fidelity FE model to tsunami height estimation, (2) introduction of a viscoelastic crustal deformation computation method using a high-fidelity FE model to long-term deformation estimation of the Japanese Islands, and (3) development of a method to update the high-fidelity model by applying the adjoint method to estimating viscous parameters in the crustal structure.

In the first part of the thesis, an elastic deformation computation method using a high-fidelity FE model is introduced to earthquake crustal deformation computation. This method assumes use of capacity computing in a smaller computation environment such as a PC cluster. As an example of earthquake damage estimation, tsunami height and inundation estimation due to a given earthquake scenario is conducted. The case in which the proposed method produces a significantly different result from that obtained with a simplified crust model indicated that simplification of crust model affects tsunami estimation results largely in some cases.

In the second part of the thesis, a viscoelastic deformation computation method using a high-fidelity FE model is introduced to long-term crustal deformation computation. Since such an approach requires computation of a larger scale, the proposed method aims at a fast and scalable computation assuming use of a supercomputer. After numerical verifications are carried out, the method for viscoelastic deformation is applied to long-term crustal deformation computation in an area including the whole Japanese Islands. It is also shown that such a high-fidelity crustal deformation computation is completed in a realistic time by using the proposed method in the K computer.

In the third part of the thesis, an optimization method of the viscosity values in a high-fidelity model using long-term crustal deformation data is developed. The target problem is formulated as simultaneous nonlinear optimization of viscosity and fault slip. The combination of the gradient-based optimization method and the adjoint method, which is an efficient computation method of gradients of the objective function, is used to perform the target optimization with relatively fewer forward problems. The proposed method is applied to a numerical experiment which imitates the 2011 Tohoku-Oki earthquake, where the advantage of the method is examined by comparing the obtained results with those obtained with a simplified crust model.

The obtained results demonstrate the advantage of the proposed method of high-fidelity crustal deformation computation in terms of both the computation results and the computation costs. The proposed method enables to introduce heterogeneous crustal structure and geometry to crustal deformation computation used in earthquake damage estimation, while maintaining transparency of the modeling process to ensure accountability for earthquake damage estimation results. In future work, the proposed method to update the models is expected to be applied to analyses of actual observation data. It is also expected to be applied to studies of other kinds of earthquake damage estimation, e.g. earthquake cycle simulation, an important tool in the next generation which examines possible earthquake scenarios.