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Research paper

Robust and portable capacity computing method for many finite element analyses of a high-fidelity crustal structure model aimed for coseismic slip estimation

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ABSTRACT

Computation of many Green's functions (GFs) in finite element (FE) analyses of crustal deformation is an essential technique in inverse analyses of coseismic slip estimations. In particular, analysis based on a high-resolution FE model (high-fidelity model) is expected to contribute to the construction of a community standard FE model and benchmark solution. Here, we propose a naive but robust and portable capacity computing method to compute many GFs using a high-fidelity model, assuming that various types of PC clusters are used. The method is based on the master–worker model, implemented using the Message Passing Interface (MPI), to perform robust and efficient input/output operations. The method was applied to numerical experiments of coseismic slip estimation in the Tohoku region of Japan; comparison of the estimated results with those generated using lower-fidelity models revealed the benefits of using a high-fidelity FE model in coseismic slip distribution estimation. Additionally, the proposed method computes several hundred GFs more robustly and efficiently than methods without the master–worker model and MPI.

1. Introduction

Estimation of coseismic slip distribution and interplate couplings is an important topic in the field of solid earth science. Estimates are based on inverse analysis using crustal deformation analyses and data obtained through observations. Such inverse analyses usually apply analytical solutions of elastic deformation in a simple crustal structure model (Okada, 1985; Meade, 2007). However, recent progress in observational techniques has provided more information about the areas around subduction zones (e.g., crustal deformation data, Sato et al., 2011; Kaneda et al., 2009; Chadwell and Spiess, 2008, and crustal structure data, Hayes et al., 2012; Koketsu et al., 2008), which has led to use of numerical simulation methods such as the finite element (FE) method in crustal deformation analyses. Forward analysis methods using commercial or noncommercial FE software packages have been proposed (Aagaard et al., 2013; Masterlark, 2003), and some studies have applied these methods to coseismic slip estimations (Kyriakopoulos et al., 2013; Sato et al., 2011; Pulvirenti et al., 2014; Hsu et al., 2005). These studies suggested that simplification of the three-dimensional heterogeneity of crustal structure possibly has a non-negligible impact on the analysis results in some cases. The FE models used in these studies commonly have 10^6 degrees of freedom (DOFs).

The construction of FE models requires geometry data of the target crustal structure. In Japan, digital elevation (DE) data of 3D heterogeneous crustal structure are available for the region, including the source regions of megathrust earthquakes. For example, a DE dataset, which is at a 1-km resolution in some areas, is available for the focal region of the 2011 Tohoku-oki earthquake (Koketsu et al., 2008). Ichimura et al. (2013) developed a method for constructing numerical simulation models at the same 1-km resolution with slight approximation of the detailed DE data (i.e., a high-fidelity model) for a subduction zone. Such a technique is important because it could help to establish a community standard for FE analysis of crustal deformation in the near future via the construction of a community FE simulation model using the most

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updated crustal structure data. It can also contribute to providing a benchmark problem and solution in a certain target area, although a high-fidelity model may not always yield significantly better results than a lower-fidelity one. One major drawback of high-fidelity models is the heavy computational cost. For example, Ichimura et al. (2013) constructed a high-fidelity model with 10^8 DOFs. They also developed a fast computation method for such a large DOF model using a single computation node with shared memory parallelization (SMP) to run a single simulation. On the other hand, coseismic slip distribution estimation requires the computation of many (10^2–10^3) Green's functions (GFs), using the FE method to represent crustal deformation by superimposing the GFs. If the crustal structure uncertainty is studied using a Monte Carlo approach, the number of required GFs is even larger. To carry out such computations in a realistic time period, we must use a parallel computation environment, such as a PC cluster, to shorten the computation time.

Because the configurations of PC clusters are quite different from one another, it is desirable to parallelize the computation in a way that can maintain robustness and portability. For instance, it is better if the scalability of the program is independent of the network speed between the computation nodes constituting the system. Additionally, the input/output (I/O) operation should be managed carefully because its performance often depends on which type of file system is implemented. In this study, assuming several hundred GF computations using PC clusters consisting of tens of computation nodes, we propose a naive but robust and portable GF computing method. The method is based on the “capacity computing” approach, in which multiple FE analyses are executed simultaneously over the PC cluster to maintain scalability. We also adopt the “master–worker model” (Yongge, 2008) to perform efficient I/O operations and dynamic load balancing to maintain the robustness and the portability of the code. The proposed method is then applied to coseismic slip distribution estimation using synthetic crustal deformation data. The estimation results suggest that the proposed methods provide two types of advantages, based on comparisons of coseismic slip estimation results with those of FE models that do not possess high fidelity, and on the efficiency and robustness of the computation.

The remainder of this paper is organized as follows. Section 2 illustrates the methodology: the inverse analysis formulation for an assumed target problem, a brief explanation of the FE mesh construction method and fast computation method developed in Ichimura et al. (2013), and the robust and portable capacity computing method. Section 3 illustrates an application example of the proposed method to coseismic slip distribution estimation in the Tohoku region, and Section 4 provides concluding remarks.

2. Methods for inverse analysis using the high-fidelity model

2.1. Inverse analysis formulation

The fault slip distribution is modeled from crustal deformation data corresponding to m observation points on the earth's surface. The fault slip distribution is represented by a linear combination of a finite number of basic functions. We introduce unit fault slips in two directions, x and y, on $n/2$ small faults, where n is an even number distributed over the fault surface for the basic functions in the formulation. Because coseismic crustal deformation is modeled as linear elastic deformation, the fault slip estimate is formulated using a linear equation, as follows:

$$\mathbf{G}\mathbf{x} = \mathbf{d}, \tag{1}$$

where $\mathbf{G}$ is an $m \times n$ matrix of GF, $\mathbf{x}$ is a $n(= n/2 \times 2)$-dimensional vector of unknown displacement for each subfault, and $\mathbf{d}$ is a m-dimensional vector of the observed displacements. $\left[g_{1i} g_{2i} \cdots g_{mi}\right]^T$ are computed simultaneously by inputting the unit fault slip as the source fault in the high-fidelity FE models. Thus, the FE analysis with a 10^8 order DOF model must be completed n times to construct $\mathbf{G}$. In our target problem in this study, n is on the order of 10^2–10^3. The inverse problem defined by Eq. (1), which is usually ill conditioned, is regularized using a smoothness constraint on $\mathbf{x}$ with a discrete Laplacian operator (Sato et al., 2011). By writing this constraint in matrix notation $\mathbf{L}\mathbf{x} = \mathbf{0}$, for the $n \times n$ matrix $\mathbf{L}$, the target equation becomes

$$\begin{pmatrix} \mathbf{G} \\ \alpha \mathbf{L} \end{pmatrix} \mathbf{x} = \begin{pmatrix} \mathbf{d} \\ \mathbf{0} \end{pmatrix}, \tag{2}$$

where α is the weight coefficient of the smoothness constraint and is determined by the L-curve method (Hansen, 1992).

We use a bicubic B-spline as the unit fault slip (Yabuki and Matsu'ura, 1992). The central point of each small fault is in a 30-km interval, following the small fault size of the coseismic slip distribution estimation of the 2011 Tohoku Earthquake in Koketsu et al. (2011). The smooth function shape of the bicubic B-spline is finely discretized by the 1-km resolution mesh in the fault surface of the high-fidelity model. These unit fault slips are inputted in directions such that the fault slips occurred along the fault surface gradients. If a small fault intersected the trench axis, dislocations are inputted only at nodes located between land and the trench axis.

2.2. Summary of the FE mesh construction method and the fast computation method

We use the FE method for our simulation because it is suitable for analyzing continua with complex geometries. Coseismic crustal deformation is typically modeled as an elastic deformation due to dislocation of the fault surface. The target equation is rewritten after considering the boundary conditions:

$$\mathbf{K}\mathbf{u} = \mathbf{f}, \tag{3}$$

where $\mathbf{K}$, $\mathbf{u}$, and $\mathbf{f}$ are the global stiffness matrix, displacement vector, and force vector, respectively. Infinite elements (Zienkiewicz et al., 1983) are generated on the side and at the bottom of the target domain to describe the infinite condition. There are a few methods by which fault dislocation can be introduced to an FE model (e.g., using the linear constraints equations through the Lagrange multipliers technique, Aagaard et al., 2013). The split-node technique (Melosh and Raefsky, 1981) is used in our simulation because it does not require modification of $\mathbf{K}$, which is suitable for our implementation.

For FE mesh construction, we use a method that enables automated and robust construction directly from DE data of crustal structure without creating a CAD model. The geometrical resolution of the FE model can be the same as that of the inputted DE data, with a slight approximation of geometry in a user-independent prescribed threshold. These features are in contrast to widely used FE software packages, which require the generation of CAD data with a user-dependent geometry approximation and trial-and-error processes. These advantages are realized by the mesh generation within each grid of a background cell in the target domain. The constructed mesh consists of linear tetrahedral elements and linear voxel elements. Linear tetrahedral elements sometimes have problems with accuracy, especially when the mesh quality is poor. Therefore, the algorithm allows slight approximation of the geometry to maintain the mesh quality. The solution computed using an FE mesh constructed by this method was verified (Ichimura et al., 2013) with a model of complex mesh