Numerical Modeling

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Chapter

Numerical Modeling

Shigekazu Kusumoto and Yasuto Itoh

Abstract

Numerical simulation to reproduce patterns of topography or subsurface structure is a useful technique for validating hypotheses regarding their forming processes and/or tectonics as their background. Here, the author describes an outline of dislocation modeling and several methods for applying it to reproduce topography or subsurface structure. Finally, it is reported that the formation processes of the Hohi Volcanic Zone proposed from geological viewpoints are validated by dislocation modeling.

Keywords: numerical modeling, dislocation modeling, pull-apart basin, restoration, Beppu Bay, Hohi Volcanic Zone

1. Introduction

Numerical modeling or numerical simulation is a useful technique for validating hypotheses and quantitatively evaluating phenomena. Analog experiments are also helpful for validating hypotheses and have often been used to analyze surface deformation or trishear zones caused by fault motions and to model caldera formation [1–5]. However, it is sometimes difficult to conduct laboratory experiments as analog experiments, depending on the scale of the structures or phenomena, because the similarity rule for the model, including physical properties, has to be considered. Additionally, issues with the quantitative analysis of the experimental results sometimes occur.

In contrast, numerical simulations are used for the validation and quantitative evaluation of various geological and geophysical phenomena, as they enable modeling on a realistic scale. Numerical simulation methods, such as dislocation modeling, finite element modeling, boundary element modeling, finite difference modeling, and discrete element methods, have frequently been used to solve solid earth science problems [6–14].

Pull-apart basins, the main structures in our study area, are known to form at the fault terminations of right-lateral, right-stepping or left-lateral, left-stepping fault zones [15]. Because the lateral fault motion creates subsidence at the fault terminations, pull-apart basins are formed at the terminations of the fault zone or fault arrangement area, as mentioned above, where the subsidence is superimposed, and they are widely distributed worldwide. Rodgers [6] was probably the first study to discuss the formation of pull-apart basins through numerical simulations using Chinnery's dislocation solution [16]. Currently, Okada's dislocation solutions [17, 18] are often employed to understand crustal deformation.

2. Dislocation modeling

Okada's dislocation solutions are closed analytical solutions that calculate the surface and internal deformation and strain fields due to shear and tensile faulting with an arbitrary dip in an elastic isotropic half-space.

In geodesy, these solutions have been employed for estimating fault parameters, such as fault displacement on fault surfaces (dislocation planes), fault positions, and dip, by inverse analysis of surface displacements obtained by GNSS, leveling, and other geodetic observations [19, 20]. However, in tectonics, we focus on the basic deformation patterns formed by fault motions and discuss whether a combination of fault motions can form the topography or subsurface structures estimated by geophysical prospecting [21, 22].

In restoration (reproduction) modeling of topography or subsurface structures, the analysis is conducted by forward modeling, in which the fault parameters are estimated through trial and error. The geological background and geophysical validities are considered in the modeling. The validity of the model for restoring topography or subsurface structures is determined by comparing the pattern of the calculated topography or subsurface structures with the pattern of the actual structures.

There is a technique in which large Poisson's ratios are assumed if the phenomena at geological time scales are modeled in elastic media [8, 22]. This method covers the influence of the cumulative deformation of the fault motion by the elastic constant, such as assuming a soft medium imitating fluid.

To reflect the multiple motions of active faults over geological timescales in dislocation modeling, Itoh et al. [21] introduced historical fault activities into the modeling by superimposing analytical solutions in which fault parameters for each fault motion are specified on the concerned fault. They attempted to reproduce the shape pattern of the Takayama Basin in central Japan by applying this technique and showed that it is a tectonic basin caused by the accumulated right-lateral motions of two active faults. In addition, it was revealed that this technique could explain not only the topography but also changes in the declination of thermoremanent magnetization. This technique has also been applied to validate the formation processes of tectonic basins distributed in central Hokkaido [22–24], and the fault motions and their combinations have been discussed.

Because these simulations focus on the shape pattern of the topography or subsurface structures, the calculated deformation field is often normalized by the absolute value of the maximum deformation.

3. Restoration of basement structure of the Hohi Volcanic Zone

A numerical simulation to reproduce the pattern of the basement structure of the Hohi Volcanic Zone (HVZ) [25], including Beppu Bay, was performed using dislocation modeling [26]. The basement structure was estimated by gravity analyses, considering surface geological information, drilling core data, and seismic prospecting data, and was shown to have three basins distributed along the Oita-Kumamoto Tectonic Line and Median Tectonic Line (MTL) [27]. Okada's dislocation plane [17] was employed in the modeling.

Following and simplifying the tectonic history of the HVZ, which Itoh et al. [28] proposed from a geological point of view, Kusumoto et al. [26] assumed that the basement structure was formed in three stages:

1. Formation of a half-graben (Stage I, Pliocene).

2. Formation of initial pull-apart basins due to the activation of right-lateral faults (Stage II, early Quaternary).

3. Growth of the pull-apart basins due to change in the active area of the right-lateral fault (Stage III, middle to late Quaternary).

In stage I, it was assumed that the Oita-Kumamoto Tectonic Line and the Kurume-Hiji Line [29] moved as normal faults under the strong N-S extension stress field. They formed a half-graben, which is the basic structure of the HVZ. In stage II, it was assumed that the MTL and the Kurume-Hiji Line moved as right-lateral faults under the E-W compression stress field. As a result, they formed an initial pull-apart basin (Beppu Bay and Shonai Basin). In stage III, the reduction in the active area of the MTL promoted the evolution of Beppu Bay. A series of numerical simulations showed that the tectonic models of the HVZ proposed by Itoh et al. [28] are also correct from a geophysical viewpoint.

In addition, Kusumoto et al. [30] assumed a two-layer model consisting of a basement and sedimentary layer in the HVZ. They attempted to calculate the gravity anomaly pattern caused by the basement structure reproduced by Kusumoto et al. [26]. They showed that gravity anomalies due to tectonic structures are mostly explained, except for the gravity anomaly caused by volcanic structures such as the Shishimuta caldera [31].

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