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Review

iBem3D, a three-dimensional iterative boundary element method using angular dislocations for modeling geologic structures

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ABSTRACT

Most analytical solutions to engineering or geological problems are limited to simple geometries. For example, analytical solutions have been found to solve for stresses around a circular hole in a plate. To solve more complex problems, mathematicians and engineers have developed powerful computer-aided numerical methods, which can be categorized into two main types: differential methods and integral methods. The finite element method (FEM) is a differential method that was developed in the 1950s and is one of the most commonly used numerical methods today. Since its development, other differential methods, including the boundary element method (BEM), have been developed to solve different types of problems. The purpose of this paper is to describe iBem3D, formally called Poly3D, a C++ and modular 3D boundary element computer program based on the theory of angular dislocations for modeling three-dimensional (3D) discontinuities in an elastic, heterogeneous, isotropic whole- or half-space. After 20 years and more than 150 scientific publications, we present in detail the formulation behind this method, its enhancements over the years as well as some important applications in several domains of the geosciences. The main advantage of using this formulation, for describing geological objects such as faults, resides in the possibility of modeling complex geometries without gaps and overlaps between adjacent triangular dislocation elements, which is a significant shortcoming for models using rectangular dislocation elements. Reliability, speed, simplicity, and accuracy are enhanced in the latest version of the computer code. Industrial applications include subseismic fault modeling, fractured reservoir modeling, interpretation and validation of fault connectivity and reservoir compartmentalization, depleted area and fault reactivation, and pressurized wellbore stability. Academic applications include earthquake and volcano monitoring, hazard mitigation, and slope stability modeling.

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1. Introduction

The rapid increase in the number of geologic, seismologic, and geodetic datasets with abundant and very precise spatial information on fault geometry and slip distributions promotes the development of more complex geometric and kinematic models of modern earthquake ruptures and paleoseismic events. These datasets indicate that faults commonly are composed of multiple discrete segments, each with a curved surface and curved tipline. Construction of model fault segments using multiple rectangular dislocations (Okada, 1985) introduces nonphysical gaps and overlaps with associated stress concentrations and irregularities in slip distributions that may differ significantly from those in nature (Maerten et al., 2005). Discretization of fault segments into a set of triangular dislocations enables one to approximate the curviplanar surfaces and curved tiplines to a precision that is consistent with the data (Jeyakumaran et al., 1992; Thomas, 1993; Maerten et al., 2005; Meade, 2007; Maerten et al., 2010; Maerten, 2010a, 2010b).

The C computer code that was originally developed at Stanford University by Andrew Thomas (1993) in 1993 was called Poly3D. The idea of using the angular dislocation formalism to construct complex planar dislocations with constant displacement discontinuity was first used by Jeyakumaran et al. (1992). Since then, because of the rapid evolution of computer power and the constant demand for more complex and larger models, a new code has emerged, following the work of Jeyakumaran et al. (1992) for triangular elements. For the new code, iBem3D, the C++ object-oriented language was chosen, and an iterative solver now replaces the older direct solver (Gauss elimination). C++ allows modularity of the code (Maerten and Maerten, 2008; Maerten et al., 2010; Maerten, 2010a) while the iterative solver permits running larger models in a shorter time (Maerten et al., 2010). The strain field, given by the derivatives of the equations for the displacement field provided by Comninou and Dundurs (1975), was entirely rederived by hand for optimization considerations, whereas these derivatives in Poly3D were symbolically derived using a dedicated software. The call to the core equations now runs four times faster. Comparisons of Poly3D and iBem3D are summarized in Fig. 1, where the technological differences are highlighted.

In this paper, we summarize the theory behind iBem3D, along with verifications (Section 2), and present the latest improvements such as the implementation of material heterogeneity, static friction, optimizations, parallelization, linear-slip inversion, and paleostress recovery (Section 3). Finally, academic, research, and industrial applications are discussed in Section 4.

2. Theory behind iBem3D

The theory of dislocations in elastic materials has been used widely over the past half century to evaluate the displacement, strain, and stress fields around faults in Earth's lithosphere. Steketee (1958b, 1958a) has discussed this theory and potential applications to geophysical problems in two papers. He reviewed Volterra's formulation for the dislocation problem and presented a method for the construction of Green's functions for the semi-infinite space containing a surface of displacement discontinuity (the dislocation). Green's functions can be integrated to calculate the displacement field around the planar surface of discontinuity. These displacement fields satisfy the Navier equations, which are the governing equations for linear elastic theory. Spatial derivatives of the displacement components provide the strain components, and incorporation of Hooke's law for a homogeneous and isotropic elastic material gives the stress components. Thus, Steketee's work illustrates how the mathematical tools of dislocation theory enables one to compute the displacement, strain, and stress fields around idealized faults in an elastic half-space, but it does not make explicit comparisons to geophysical data.

Chinnery (1963) has used some results of Steketee to derive the particular solution for a vertical rectangular strike-slip fault of arbitrary dimensions and depth. He computed and illustrated the displacement and stress fields, and compared the surface displacements fields to those measured geodetically near active faults (Chinnery, 1961, 1963). The theoretical exposition of Steketee and the correlations to observations made by Chinnery had profound effects on the geophysical research community as they set the stage for the use of dislocation theory as one of the principal tools for the mechanical analysis of faulting. This usage has continued from the early 1960s to the present day with many notable successes. Integration of Volterra's dislocation over rectangular surfaces in the half-space has been used in these studies (Maruyama, 1964; Press, 1965; Savage and Hastie, 1966, 1969; Mansinha and Smylie, 1971;