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Representation of a velocity model with implicitly embedded interface information

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A B S T R A C T

Accurately representing a velocity model for complex media still faces many challenges. The key issue involves the description of discontinuity surface with complicated shapes, such as pinch-out layers, salt domes with overhangs, and faulted interfaces. In this paper, a novel method for representing complex models is proposed. Each velocity discontinuity is described as an iso-value surface of a signed distance function, similar to an implicitly embedded interface. The implicit representation can construct the surfaces with non-manifold characteristics or multi-valued properties, e.g., fractured interfaces or mushroom models. For the velocity field within blocks, an approach involving the multiple copies of the computational mesh is used to bind a mesh to a block. This approach can faithfully describe the velocity distribution close to the block boundary without increasing the complexity of the computational mesh. A new data structure, termed stratigraphic binary tree, is also proposed to define the topological relationships between model elements (interfaces and blocks) and to efficiently manage the model data. A number of examples for different applications are given to evaluate the feasibility of the proposed representation scheme. The velocity model represented by the proposed method can serve as a good candidate for general ray-based forward and inverse applications.

1. Introduction

The velocity of seismic wave propagation in the medium of underground formations can provide valuable information regarding the subsurface structure and lithology. Therefore, acquiring accurate velocity models becomes one of the central issues of geophysics. In geophysical forward and inverse applications, the parametric form of the velocity model lays an important foundation, and can significantly affect either the process or the results. Many parameterizations of velocity models have been proposed for different applications. These parameterizations can be roughly divided into two groups: velocity models without and with a particular description of velocity discontinuities.

The striking feature of the first group is that velocity changes slowly and smoothly without sharp variations. The widely adopted strategy is to parameterize the velocity model in cells (or grids), including regular and irregular parameterizations. The most attractive characteristics of regular parameterizations are their simple concept and easy formulation. Cells with constant velocity or grid nodes with some interpolation functions are broadly employed forms. Facilitations to forward and inverse solvers have made regular parameters very popular. However, a uniform grid size of regular parameterizations greatly constrains the ability of the model to recover the length scale of velocity anomalies. Although the expression of velocity heterogeneity can be maximized by reducing the grid size (the extreme case being that the size selected is the minimum velocity structure wavelength), the resulting model size is usually computationally prohibitive. The largest advantage of irregular parameters is that they can offer mesh size with variable scale, and thus overcome the inherent disadvantages of the regular ones. Irregular parameters are usually applied to fit the irregularity of data distributions, such as irregular observation geometry or uneven ray coverage, to maximize the amount of information extracted from data. In spite of the strong ability to describe different scales of velocity information, the implementation of irregular parameters would result in many problems, such as computational inefficiency and complicated computational algorithms for building, storing and searching.

Models in the second group are usually used to describe relatively complicated velocity distributions with drastic changes of values. A typical form is the layer model, which usually depicts the

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model region by several horizontally stratified layers. Forward and inverse applications based on such models are not rare (Zelt and Smith, 1992; Guiziou et al., 1996; Rawlinson et al., 2001). However, the ability of layer models to describe more complicated structures is not enough; instead, blocky models can perform well. A blocky model describes an earth volume as an aggregate of irregularly shaped sub-volumes bounded by surface patches. The velocity distribution within a region is assumed to be varying slowly and smoothly, whereas sharp velocity discontinuities are explicitly modeled as interfaces. Gjøystdal et al. (1985) first introduced a solid modeling technique to generate such a model. The term solid modeling refers to the fact that the internal geometrical properties of the model can be modeled as a combination of solids or volumes in 3D space. However, the algorithm defines complex regions using counter-intuitive set theoretical operations on the volumes limited by simpler surfaces. Pereyra (1996) further developed the method by using smooth surface macro-patches to represent interfaces and smooth functions to describe properties within the sub-region. The greatest advantage of Pereyra's method is that the surfaces are continuous everywhere in the curvature, whereas the main drawback is the nonlinear descriptions of surfaces, which may result in difficulties in some applications, such as ray gaps in ray tracing. Xu et al. (2006, 2010) also extended the work and used triangulated surfaces to represent interfaces. The use of triangulated interfaces can facilitate calculations in many occasions, e.g., the calculation in obtaining the intersection point between a ray and an interface. However, the represented interfaces by their method are discontinuous. Although the smoothness of the surface can be improved by applying some smoothing filters for the normal vectors, the represented surface is still an approximation and has errors.

Each type of model parameterization has its merits and disadvantages. An ideal velocity model can describe the velocity anomaly faithfully, and is easily applicable to general applications. The aim of the present study is to propose a novel model parameterization to describe very complex velocity models. Volumetric properties and velocity interfaces are described by different approaches. The new parameterization can properly handle complexities such as faulted interfaces, pinch-out layers or salt domes with overhangs. It belongs to the second group but still exploits the advantages of regular or irregular parameters. It can facilitate many operations. For example, it can efficiently determine the intersection point between a ray and an interface, and sufficiently describe the velocity information in the proximity of interfaces. Therefore, it can be a good candidate for general ray-based forward and inverse applications.

2. Representation of velocity model

Blocky models are normally used to describe velocity model for complicated media, as illustrated in Fig. 1. The overall model region is divided into an aggregate of irregularly shaped block elements. Seismic velocities vary smoothly within the block elements but are discontinuous across the element boundaries. In general, describing such a complicated velocity model mainly involves the following subtasks: properly representing the discontinuity interfaces, using the interfaces to partition geospace and assigning velocity values to the nodes within the geological blocks.

2.1. Velocity discontinuity across geological interfaces

Various types of parameterizations are used to represent velocity interface structures, such as a grid of depth nodes with a specified interpolation function (Pereyra, 1996) or triangulated surfaces (Xu et al., 2006, 2010). Unlike these explicit descriptions,

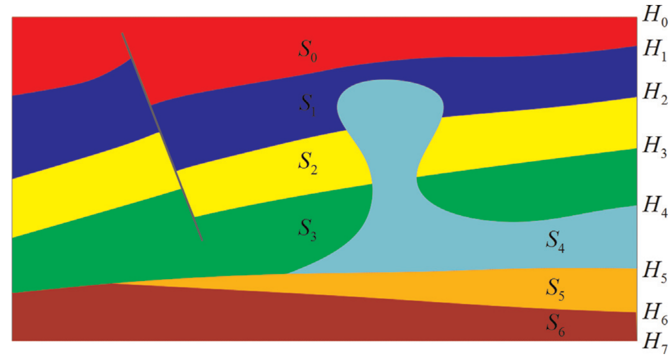

Fig. 1. Internal view of a typical blocky model, accompanied by complicated geological phenomenon, including a fault, intrusion and pinch-out. Eight interfaces H_i ($i = 0, \dots, 7$) divide the model region into seven blocks S_j ($j = 0, \dots, 6$). It should be noted that although block S_2 is faulted and intruded by S_4, the broken parts are still considered to be a single unit. The same is true for S_3.

we use an implicit method — the level set method (LSM) to describe the velocity discontinuities (Ohtake et al., 2003; Frank et al., 2007). The LSM was originally introduced to compute and analyze the subsequent motion of an interface under a velocity field (Osher and Sethian, 1988), which is widely used in the physical sciences (Sethian, 1999; Osher and Fedkiw, 2003). The basic idea behind a level set formulation is that each interface is described as the zero level set or the zero-value contour of a signed distance function. If we denote the signed distance function by $\varphi(x)$, then at some given point x_A, $\varphi(x_A)$ is the distance from x_A to the closest point on the interface, and is negative if x_A is inside the interface and positive if x_A is outside the interface (Fig. 2). This implicitly represented interface can then be evolved by the finite difference solution of a set of partial differential equations, which explicitly describe the behavior of the signed distance function over time. Generally, the LSM describes the evolution of an n-dimensional manifold in $(n+1)$-dimensional space. Thus, a curve is tracked on a 2D grid of points and a surface is tracked on a 3D grid of points. More details of the implementation of the LSM are given by Osher and Fedkiw (2003).

The strength of the LSM lies in its implicit representation of an interface. Topological changes such as breaking and merging are handled naturally. Many studies have focused on the reconstruction of closed and manifold surfaces by using this method (Osher and Fedkiw, 2003; Zhao et al., 2001). However, employing this

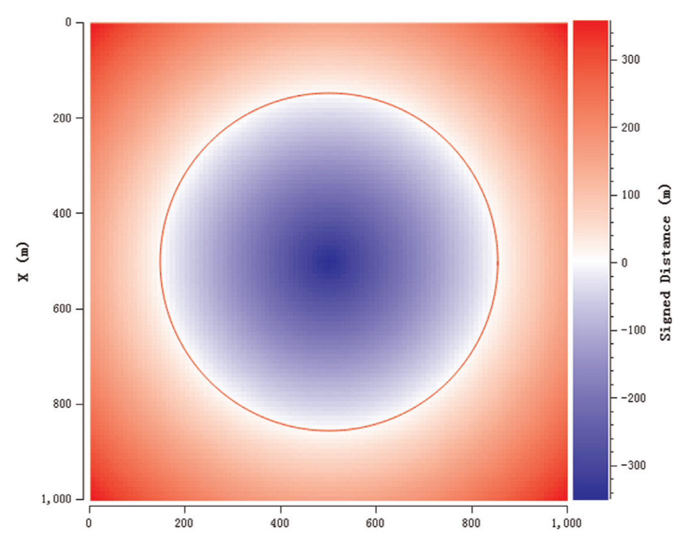

Fig. 2. Level set representation of an interface. In this example, the zero level set of the signed distance function is a circle.