The Unified Community Velocity Model Software Framework

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Abstract

This paper presents the Unified Community Velocity Model (UCVM) software framework developed at the Southern California Earthquake Center. UCVM is a collection of software tools and application programming interfaces designed to provide standard access to multiple seismic velocity models used in seismology and geophysics research. Seismic velocity models are key components of current research efforts dedicated to advancing our knowledge of the Earth's crustal structure and its influence on the ground response during earthquakes, including both the regional deep geology and local effects due to the geometry, spatial distribution, and material composition of sediments in basins and valleys. UCVM provides a framework to facilitate research activities that involve the use of seismic velocity models and has particular direct applications in physics-based earthquake ground-motion simulation and seismic hazard analysis in large regions prone to earthquakes, such as Southern California. We describe the background that led to the development of the UCVM and its various software components, including advanced high-performance computer tools available within UCVM, its performance, and product deliverables. We also present examples of recent applications that use UCVM tools or output datasets.

Keywords:
seismic velocity models, earthquake simulation, high-performance computing, meshing

1. Introduction

The quantitative understanding of the physical world is an essential goal of geoscience research. We use mathematical abstractions to represent the behavior of systems in static and dynamic states; and properties such as density and elastic moduli to characterize the response of materials to absorbe or transmit forces. In seismology and geophysics, our understanding of earthquakes and their impacts, depends in part on our knowledge and representation of the geometry and properties of seismically-active faults and of the Earth's crust itself. On the one hand, we use fault and stress models to describe the geometry and conditions that facilitate the initiation and dominate the propagation of an earthquake's rupture process; and, on the other hand, we use seismic velocity and attenuation models to describe how the geologic structure of the crust, and the mechanical properties of the materials in geologic structures, basins and sedimentary deposits controls the characteristics of seismic waves and the resulting ground motion generated by earthquakes.

We are interested in how seismic velocity models are managed by and distributed to scientists, with emphasis on simulation applications. Source models and seismic velocity models are the basic inputs to physics-based earthquake simulation. Physics-based earthquake simulation uses numerical methods and models that incorporate, explicitly, the solution of wave propagation problems through crustal structures, with specific applications in the assessment of the expected levels of ground motion in a region prone to earthquakes for use in seismic hazard analysis. During the last two decades, various seismic velocity models have been made available to the geophysics and seismology research community (e.g., Brocher, 2008) (add more refs.). This gave way to the conception of community velocity models (CVMs). CVMs are seismic velocity models that have been developed, maintained, and advanced by a community of interested investigators who provide open-access to models and the information available therein (e.g., Magistrale et al., 2000) (add more refs).

CVMs have been typically distributed in the form of static datasets or computer programs that dynamically operate on those datasets to provide information about the geometry and material properties of the crust in a particular region. However, these datasets and computer programs have not always been thought carefully from a computational perspective. In addition, recent advances in earthquake simulations, powered by the increasing capability of supercomputers (e.g., add ref), have increased significantly the computational demand placed

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on CVMs as input to these simulations.

This paper presents the Unified Community Velocity Model (UCVM), a software framework designed to provide standard and computationally efficient access to seismic velocity models. UCVM was developed at the Southern California Earthquake Center (SCEC). It is a collection of software tools and application programming interfaces (APIs) that facilitate the access to the material properties stored in CVMs, with specific applications in physics-based earthquake ground-motion simulation and regional seismic hazard assessments. Here, we describe the development of the UCVM and its various software components, including features for dedicated use in high-performance parallel computers, and present examples of recent applications of UCVM tools in earthquake research.

2. Community Velocity Models

This section will present how CVMs work and the various CVMs available to the community today. It will basically explain that CVMs provide the triplets of Vs, Vp and density, and, as an example, we can expand on a description of CVM-S and CVM-H, including their variations CVM-SI and CVM-H+GTL.

3. The UCVM Software Framework

The primary functionality provided by UCVM is the ability to query a wide array of community velocity models for material properties in a standard way. Once a velocity model has been successfully integrated with UCVM, the framework can be utilized to query for the primary and shear seismic wave velocities (Vp, Vs) as well as the soil/rock density (ρ) at any geographic point within that model. The original model's local coordinate system and map projection are concealed behind a generic interface that instead allows queries by geographic latitude and longitude along with a vertical z-coordinate. The z-axis may be defined as either depth below the free surface or elevation relative to mean sea level.

To support this flexible query mechanism consistently across all models, UCVM includes a high-resolution digital elevation model (DEM). The DEM is synthesized from the USGS National Elevation Dataset (TODO: cite USGS NED) and the ETOPO1 Global Relief Model (TODO: cite ETOPO1). It currently spans the State of California along with portions of surrounding States. However, it may be modified to cover any arbitrary region of the Earth's surface, provided adequate resolution elevation datasets exist. An additional advantage to providing the built-in DEM is that UCVM is able to return the surface elevation at any query point in addition to the traditional Vp, Vs, and ρ parameters.

The framework further extends the standardized interface by allowing multiple velocity models to be aggregated into a single composite model. Composition is accomplished by tiling two or more velocity models in three dimensions according to a user-specified priority ordering. Under this scheme, a query point is submitted sequentially to each velocity model within the ordered list that comprises the composite. The first model to return valid velocity data for the point is considered to have fulfilled the data request and subsequent models are not queried. Thus, overlap among the individual models is acceptable and their relative priority ordering arbitrates which one satisfies any given query. Generally, no smoothing is performed at the interfaces between models (an exception is interpolation between a geotechnical layer and a crustal model as discussed later in this paper). This tiling concept is illustrated in Figure 1.

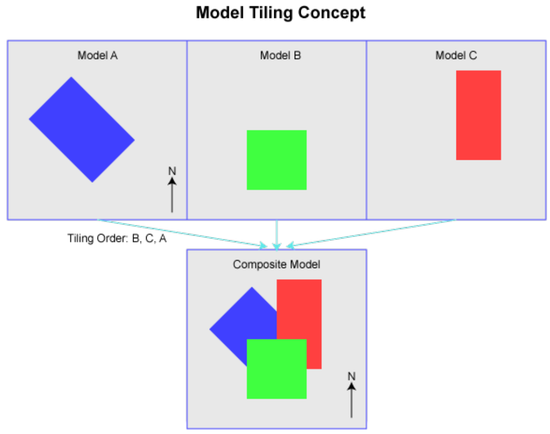

Figure 1: Tiling of velocity models (TODO: Redo/cleanup this figure).

Community velocity models vary widely in their area of coverage, depth extent, and resolution. UCVM is flexible in its support for such variability. However, in order to better accommodate high frequency ground motion simulations, it categorizes models into two general groups: crustal models, and geotechnical layers (GTLs). Crustal models provide subsurface seismic wave velocities associated with basin, crust, and mantle structures. These models may potentially extend to many tens of kilometers below the Earth's surface yet do so at coarse resolutions (TODO: cite CVM-H, CVM-S). Geotechical layers, in contrast, provide velocities for only the near-surface (typically a few hundred meters) at very high resolution (TODO: cite Ely Vs30 GTL). Ground motion simulations, in particular, rely on high-resolution near-surface velocities and therefore a GTL serves to supplement the coarser data provided by crustal models.

Whereas a set of velocity models consisting only of crustal models is aggregated by the tiling mechanism described above, a more sophisticated interpolation mechanism is employed if one or more GTLs are involved. The primary motivation for performing interpolation in this particular case is to eliminate near-surface discontinuities in the composite model which would adversely affect ground motion simulations. When a GTL is specified in the ordered list of models, the framework creates a default interpolation zone along the z-axis over which smoothing between this GTL and the underlying crustal models

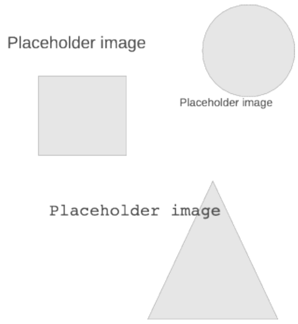

Figure 2: Interpolation of GTL and crustal model.

is performed. Query points that fall within the zone are assigned an interpolated velocity based on the GTL velocity at the top of the zone boundary and the crustal model velocity at the bottom. By default, linear interpolation is used for the smoothing but both the zone dimensions and interpolation function can be modified by the user. Figure 2 illustrates how this interpolation is performed.

A single geotechnical layer is currently supported, based on Ely's Vs30-derived algorithm (TODO: cite Ely Vs30-derived GTL). This algorithm procedurally estimates Vp, Vs, and ρ from the Vs30 velocity at the point of interest. To that end, two separate Vs30 maps are provided for use with the Ely GTL, and each covers the same geographic region as the DEM (namely, California). One map is based on the the Wills and Walls dataset (TODO: cite Wills and Wald), and the other is based on the Yong dataset (TODO: cite Yong). Alternative Vs30 maps may be integrated as new datasets become available. As with the surface elevation from the DEM, the raw Vs30 value from the Vs30 map is returned by UCVM for each query point.

3.1. Command-line Utilities

3.1.1. Querying

TODO: command-line query

3.1.2. Meshing

TODO: single core and parallel meshing/etree extraction

3.2. Application Programming Interface

TODO: how to interface programmatically with UCVM

3.2.1. Integrating New DEMs, Vs30 Maps, and Community Velocity Models

TODO: describe how to support new DEMs, Vs30 maps, and models

4. Computational Performance

It would be desirable to do some experiments in terms of performance, especially for the parallel applications utilities in UCVM. With some examples of how long the same thing would take if doing it differently. We will need to discuss this.

5. Recent Case Applications

This section will be dedicated to show case applications. Some ideas for potential subsections follow.

5.1. Visualization and Model Comparisons

5.2. Chino Hills Simulation Series

5.3. CyberShake

6. Summary and Conclusions

A couple of paragraphs with a summary of what is shown in the paper and a few key conclusions about the impact that we expect UCVM has already have and will have on earthquake research.

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