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The GeoClaw software for depth-averaged flows with adaptive refinement

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ABSTRACT

Many geophysical flow or wave propagation problems can be modeled with two-dimensional depth-averaged equations, of which the shallow water equations are the simplest example. We describe the GeoClaw software that has been designed to solve problems of this nature, consisting of open source Fortran programs together with Python tools for the user interface and flow visualization. This software uses high-resolution shock-capturing finite volume methods on logically rectangular grids, including latitude–longitude grids on the sphere. Dry states are handled automatically to model inundation. The code incorporates adaptive mesh refinement to allow the efficient solution of large-scale geophysical problems. Examples are given illustrating its use for modeling tsunamis and dam-break flooding problems. Documentation and download information is available at www.clawpack.org/geoclaw.

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1. Introduction

Many geophysical flow or wave propagation problems take place over very large spatial domains, for which detailed three-dimensional modeling of the fluid dynamics is not an efficient option. Fortunately, two-dimensional depth-averaged equations such as the shallow water equations often provide models that are sufficiently accurate for many applications. Even with two-dimensional models, however, it is often necessary to use adaptive mesh refinement (AMR) techniques in order to concentrate grid cells in regions of interest, and to follow such regions as the flow evolves. This is often the only efficient way to obtain results that have sufficient spatial resolution where needed without undue refinement elsewhere, such as regions the flow or wave has not yet reached or points distant from the study area.

We will briefly describe and illustrate the use of GeoClaw, an open source research code that uses high-resolution finite volume methods together with adaptive mesh refinement to tackle geophysical flow problems. In particular, this code has recently been used together with the shallow water equations to model tsunamis and dam-break floods. In Section 7 we give a brief illustration of each. For other geophysical flow problems it may be necessary to replace the shallow water equations by a different set of depth-averaged equations. For example, in modeling landslides, debris flows, or lahars, it is necessary to incorporate terms modeling internal stress or pore pressure (e.g. [13,41]). The software is written in a manner that allows such extensions.

GeoClaw is based on the Clawpack software and is incorporated as a part of the general Clawpack distribution [30]. Clawpack (Conservation Laws Package) is an open source software package that has been under development since 1994 and is widely used for both teaching and research purposes. It is designed to solve hyperbolic systems of partial differential equations (PDEs) in one, two, and three space dimensions. This class of PDEs generally models wave propagation or fluid transport, and a wide variety of physical problems give rise to mathematical models of hyperbolic form, including for example compressible gas dynamics, linear and nonlinear acoustics, and elastic wave propagation. The theory of nonlinear hyperbolic systems and a variety of applications are described in [27], which also describes in detail the high-resolution finite volume methods implemented in Clawpack. Nearly all of the examples given in this text are available as working examples via the Clawpack website.

Clawpack is written in a formulation that allows the user to specify the system of equations being solved by providing a "Riemann solver" as described in Section 3. The software incorporates a general form of AMR as reviewed briefly in Section 4, in a manner that is easy to apply to many hyperbolic problems. However, there are several difficulties that arise when solving depth-averaged equations over realistic topography or bathymetry that required some substantial modifications to the general

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approach taken in Clawpack. The GeoClaw variant of the code provides an implementation specific to such problems.

In particular, this code addresses the following issues:

- The flow takes place over topography or bathymetry that may be specified via multiple data sets covering overlapping regions at different resolutions. (Henceforth we will generally use the term topography to refer also to bathymetry.)
- Some problems can be tackled on purely Cartesian grids, but many applications require using longitude–latitude grids on the earth's surface.
- The flow is of bounded extent; the depth goes to zero at the margins and the "wet–dry interface" is a moving boundary that must be captured as part of the flow. This is handled by allowing the fluid depth to be zero in some grid cells ("dry cells"). Cells can change dynamically between wet and dry to model evolving flows or inundation, and AMR can be used to provide sufficient resolution of the shoreline or margin.
- There often exist nontrivial steady states (such as an ocean at rest) that should be maintained exactly. Often the desired flow or wave propagation is a small perturbation of this steady state, as in tsunamis. For finite volume methods that conserve mass by using the depth as a primary variable, this requires the use of a "well-balanced" numerical method as discussed in Section 3.

These issues and the algorithms in GeoClaw are discussed in more detail elsewhere [17,18,21,32,33] and here we give only a brief summary of some key aspects of the numerical algorithms (in Section 3) and the AMR procedure (in Section 4).

The computational core of GeoClaw is written in Fortran, but a user interface written in Python is provided to simplify the setup of a single run, or of a series of runs as is often required for parameter studies, sensitivity studies, or probabilistic assessments of hazards. Python and Matlab plotting tools are also provided for viewing the results in various forms, either on the dynamically changing set of adaptive grids or on a set of fixed grids, or in other forms such as gauge plots of depth vs. time at fixed spatial locations. Some of these software tools are described briefly in Section 6, and more details can be found in the on-line documentation [31].

2. Depth-averaged mathematical models

The simplest depth-averaged set of fluid equations in two lateral space dimensions are the shallow water equations

$$\begin{aligned}
&h_t + (hu)_x + (hv)_y = 0,\\
&(hu)_t + \left(hu^2 + \frac{1}{2}gh^2\right)_x + (huv)_y = -ghB_x - Du,\\
&(hv)_t + (huv)_x + \left(hv^2 + \frac{1}{2}gh^2\right)_y = -ghB_y - Dv,
\end{aligned} \tag{1}$$

where $u(x,y,t)$ and $v(x,y,t)$ are the depth-averaged velocities in the two horizontal directions, $B(x,y,t)$ is the topography or bathymetry, and $D = D(h,u,v)$ is the drag coefficient. Coriolis terms can also be added to the momentum equations. Eq. (1) have the form

$$q_t + f_1(q)_x + f_2(q)_y = \psi(q,x,y), \tag{2}$$

where $q = (h, hu, hv)$ is the vector consisting of the depth and momentum of the fluid. In the absence of bathymetry ($B \equiv$ constant, so $B_x = B_y = 0$) and drag ($D \equiv 0$), the source terms would be zero ($\psi \equiv 0$) and these equations would express the conservation of mass and horizontal momentum. We use conservative finite volume methods that in general conserve mass to machine precision (since there is no source term in the mass equation) and would also conserve momentum in the absence of source terms. This is true even when AMR is applied, with the exception of cells that intersect the coastline, as discussed further in Section 4.

Note that for an ocean at rest, in which $h(x,t) + B(x,y) \equiv 0$ (sea level) in all wet cells, the topography source terms exactly cancel the derivatives of the hydrostatic pressure $\frac{1}{2}gh^2$. Maintaining this balance numerically is critical and is discussed in Section 3. The drag term could have many forms; for the experiments reported here we use

$$D = \frac{gM^2\sqrt{(u^2+v^2)}}{h^{5/3}}, \tag{3}$$

where M is the Manning coefficient, which we take to be 0.025. (Typical values for the Manning coefficient for a given substrate are empirically based. See [10] for a description and examples of values used in various applications.)

Most tsunamis are generated by motion of the sea floor due to an earthquake or submarine landslide, setting the entire water column in motion. The wave length is generally very long compared to the depth of the ocean, and under these conditions the shallow water equations (1) are generally appropriate. This has been confirmed in comparisons done by many groups (e.g. [50,25,34,44]), although in some cases it is believed that dispersive terms may need to be included (e.g. [22,43]), particularly when modeling tsunamis generated by submarine landslides, which typically have short wavelengths (e.g. [35,48]). In Section 7 we illustrate the use of GeoClaw for tsunami modeling using the shallow water equations. Adding dispersive terms would generally require the use of implicit time stepping algorithms, which are not yet implemented in GeoClaw. Development of an implicit version of the AMR routines in Clawpack is a current project and this may be possible in the future.

For other applications it is less clear that the classical shallow water equations are sufficient. For shallow flow on steep terrain, such as following a dam break for example, vertical acceleration terms may need to be added to improve the model. However, the simple equations (1) are often still used for many practical problems and can give fairly accurate results. In Section 7.3 we display some dam-break results from [19]. Some possible extensions to other depth-averaged systems of equations are mentioned in Section 8.

3. Numerical methods

The algorithms used in GeoClaw are described in detail elsewhere; see in particular [33]. Here we only give a brief summary with pointers to other sources for further reading. GeoClaw is based on Clawpack, which provides a general implementation of "wave-propagation algorithms", a class of high-resolution finite volume methods in which each grid cell is viewed as a volume over which cell averages of the solution variables q are computed. Logically rectangular grids are used and Q_{ij}^n denotes the cell average in cell (i,j) at time t_n. In each time step the cell averages are updated by waves propagating into the grid cell from each cell edge. These are Godunov-type methods in which the waves are computed by solving a "Riemann problem" at each cell edge. The Riemann problem is an initial value problem using the shallow water equations together with piecewise constant data determined by the cell averages of the dependent variables and topography on each side of the interface. The advantage of Godunov-type methods is that they provide a robust approach to solving problems with discontinuous solutions, in particular shock waves that generally arise in the solution to nonlinear hyperbolic equations. In the shallow water equations, shocks are "hydraulic jumps" or "bores", as often arise in practical flow problems. The Riemann problem defined at each cell