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A new ghost-node method for linking different models and initial investigations of heterogeneity and nonmatching grids

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Abstract

A flexible, robust method for linking parent (regional-scale) and child (local-scale) grids of locally refined models that use different numerical methods is developed based on a new, iterative ghost-node method. Tests are presented for two-dimensional and three-dimensional pumped systems that are homogeneous or that have simple heterogeneity. The parent and child grids are simulated using the block-centered finite-difference MODFLOW and control-volume finite-element FEHM models, respectively. The models are solved iteratively through head-dependent (child model) and specified-flow (parent model) boundary conditions. Boundary conditions for models with nonmatching grids or zones of different hydraulic conductivity are derived and tested against heads and flows from analytical or globally-refined models. Results indicate that for homogeneous two- and three-dimensional models with matched grids (integer number of child cells per parent cell), the new method is nearly as accurate as the coupling of two MODFLOW models using the shared-node method and, surprisingly, errors are slightly lower for nonmatching grids (noninteger number of child cells per parent cell). For heterogeneous three-dimensional systems, this paper compares two methods for each of the two sets of boundary conditions: external heads at head-dependent boundary conditions for the child model are calculated using bilinear interpolation or a Darcy-weighted interpolation; specified-flow boundary conditions for the parent model are calculated using model-grid or hydrogeologic-unit hydraulic conductivities. Results suggest that significantly more accurate heads and flows are produced when both Darcy-weighted interpolation and hydrogeologic-unit hydraulic conductivities are used, while the other methods produce larger errors at the boundary between the regional and local models. The tests suggest that, if posed correctly, the ghost-node method performs well. Additional testing is needed for highly heterogeneous systems.

Keywords: Local grid refinement; Groundwater models; Finite-difference; Finite-element; Interpolation; MODFLOW; FEHM

1. Introduction

For groundwater investigations where contaminant transport or rapidly changing hydraulic gradients are of concern, local grid refinement is needed to achieve defensible boundary conditions and adequate solution accuracy (e.g., BSC [3] and Faunt et al. [7]). The ability to use different models to simulate the different grid resolutions can allow the modeling effort to take advantage of: (1) existing models that were constructed using different codes, (2) features of different codes important for the different resolutions and simulated processes, and (3) the expertise of diverse groups of modelers. Issues that arise from linking existing models include the effects of refined grids that do not match the adjoining coarser grid and the effects of

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abrupt changes in hydraulic parameters across grids in three-dimensional (3D) simulations.

The issues addressed in this work are of concern at many sites. For example, in the assessment of the Yucca Mountain repository for high-level nuclear waste in the United States, the US Department of Energy funded the US Geological Survey to model the large-scale Death Valley Regional Flow System using the block-centered finite-difference model MODFLOW, including its Hydrogeologic-Unit Flow (HUF) Package for managing complex hydrogeology [1,7,9,10]. The US Department of Energy also requested that Los Alamos National Laboratory implement a site-scale flow and transport model using the control-volume finite-element model, FEHM [24,25]. A characteristic of these models important to local grid refinement is that it is common that the parent (regional-scale) and child (local-scale) grids do not match (Fig. 1). It is easy to coordinate the boundaries of control volumes so that the boundaries between the parent and child models coincide, but coordinating nodal locations so that all control volumes of the child model border only one control volume of the parent model might be difficult due to different model layering and horizontal grid resolution.

This work presents a ghost-node method to couple groundwater flow models using different codes (numerical techniques) to achieve local grid refinement. The method is modified from the iterative shared-node method of Mehl and Hill [13–15], which is an extension of the work of Székely [20,21] and shares aspects of other approaches, such as those presented by von Rosenberg [22], Quandalle and Besset [17,18], Forsythe and Sammon [8], Wasserman [23], Mu and Rice [16], Edwards [6], Schaars et al. [19], and Arbogast et al. [2]. Mehl and Hill [13–15] link parent and child models having quadrilateral grids constructed with MODFLOW. Mehl and Hill [13–15] explain that common methods like one-way refinement (noniterative) are prone to considerable error, that the errors generally are neither quantifiable nor readily detected, and that their more rigorous iterative method achieves acceptable levels of accuracy. Mehl and Hill [13] demonstrate that iterative refinement produces a reasonable compromise between decreased errors compared to one-way refinement, and short CPU time compared to variably-refined grids. The shared-node method is flexible and any part of an existing model can be refined with minimal alteration to the rest of the model. The technique developed here has similarities to domain decomposition methods using collaborating PDE solvers while adding the complexity of grid refinement.

The shared-node approach requires nodes in the grids to overlap, which means the method cannot be used to link the nonmatching grids examined in this work. The ghost-node method developed here is designed to accommodate rectangular grids that have nonmatching nodes. The ghost nodes, shown as open blue circles in Fig. 1, are within the parent model along a trace that passes through nodes at the centers of parent cells that lie along model interfaces. The placement of the ghost nodes along the trace depends entirely on the child grid, thereby facilitating use of nonmatching grids.

The systems of concern are commonly characterized by substantial heterogeneity in the hydraulic-conductivity distribution. In previous work, heterogeneity in linked models has been examined in one-dimensional (1D) and two-dimensional (2D) systems with smoothly varying hydraulic conductivity fields [22,17,18,8,6], or 2D systems with abrupt variations [13]. Investigating the accuracy of heterogeneous models is difficult because the flow is often too complex to solve analytically. However, insight can be gained by close examination of carefully designed test cases. Here, we investigate one typical type of heterogeneity – the existence of a confining bed between thick layers of higher hydraulic conductivity.

In addition to the development of the new, iterative ghost-node method of local grid refinement, the work presented here is unique in that (1) the numerical methods used by the coupled models differ, (2) model grids with nonmatching nodes and cell boundaries are considered, and (3) different ways of representing heterogeneity across the refinement interface are considered for a three-dimensional model. This paper describes the new ghost-node

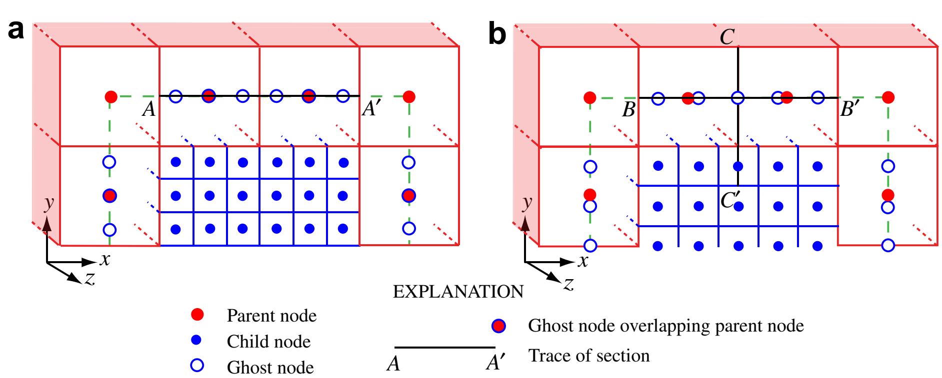

Fig. 1. (a) Matching and (b) nonmatching alignment between parent cells in red and child cells in blue for a 2D grid. Parent nodes are filled red circles; child nodes are filled blue circles. Ghost nodes (open blue circles) are on a dashed green line that passes through centers of parent cells bordering model interfaces and are also directly across from child nodes. Sections are shown in Figs. 4–6.