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THE GRID SCALE PROBLEM IN NUMERICAL MODELING OF FLOW AROUND LARGE WOODY DEBRIS IN RIVERS

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Abstract: Large woody debris (LWD) is a significant contributor to aquatic habitat diversity. The spatial structure of flow near LWD contributes to viability of aquatic habitat. Studying the turbulent flow around LWD may provide a better understanding of how LWD influences our environment and ecosystem. Traditional turbulence models, including Large Eddy Simulation (LES) and Reynolds-Averaged Navier Stokes (RANS), are impractical for use in modeling long stretches of a river. LES requires impractical fine-grid resolution around LWD, while more practical coarse-grid RANS model lead to grid-dependency of the drag effects for subgrid-scale structure. In this paper, the grid scale problem is studied using the steady two-dimensional flow around a circular cylinder to demonstrate subgrid-scale heterogeneity.

INTRODUCTION

Large woody debris (LWD) refers to woody material such as fallen tree trunks or root balls that become lodged in stream channels. Traditionally, LWD removal has been undertaken with little regard for the direct or indirect effects on aquatic fauna (Gippel 1995). Recently, several reviews of the literature have demonstrated that LWD provides physical habitat for fauna, and play a major role in stream channel geomorphological processes (Gippel 1995). Furthermore, LWD enhances hydraulic diversity, which in turn enhances fish species diversity by providing habitat, through a range of flow conditions (Gippel 1995; Sullivan et al. 1987): dead-water zones provide areas for resting and for refuge during floods (Gippel 1995); low-velocity zones adjacent to higher-velocity flows or eddies are the best feeding sites for fish, because such zone provide a concentrated source of food (Gippel 1995; Sullivan et al. 1987).

Water management agencies are interested in including the effects of LWD in aquatic habitat assessments used for water resource allocations. Our present models for representing turbulent flow over complex boundaries (LES, RANS) are not effective for modeling large river reaches with LWD. As a practical matter, model grid resolution to allow LES around LWD cannot be reasonably applied for engineering hydraulics as it would take a supercomputer to model the flow around just a single piece of debris. The practical coarse-grid RANS models presently in use are unsatisfactory as they lead to grid-dependency of the drag effects for subgrid-scale structure. As an example, consider a river laden with large woody debris (LWD) as shown at low flow conditions in Figure 1. Resolving the flow field around each piece of debris would require an impractical model with a grid scale on the order of centimeters. At more practical grid scales of O (1 m) – O (10 m), grid cells may have zero, one, or several pieces of LWD. As the model grid is coarsened or refined, the number of LWD pieces in an individual grid cell will be altered. Thus, any generally-applicable

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subgrid-scale model must be able to *a priori* adjust for the relationship between the size of the flow field around the structure and the size of the grid cell. In effect, the LWD introduces a subgrid-scale heterogeneity in the flow field.

Fig.1. Sulphur River (Texas) large woody debris at low-flow conditions
(Photo courtesy of Texas Water Development Board)

In this paper, we use the steady two-dimensional flow around a circular cylinder as a simple basis to demonstrate the existence the grid dependence of subgrid scale heterogeneity.

DISCUSSION

Data Source. A commercial Computational Fluid Dynamic code, Fluent, is used to model the two-dimensional fine-scale steady flow field around a circular cylinder of diameter 'D'. The computational domain (Figure 2) extends from –15D at the inflow to 25D at the outflow, and from –9D to 9D in the cross-flow direction. The Reynolds number is 3900 (based on cylinder diameter and free-stream velocity). This flow condition was selected as a starting point due to readily available experimental data (Ma et al, 2000).

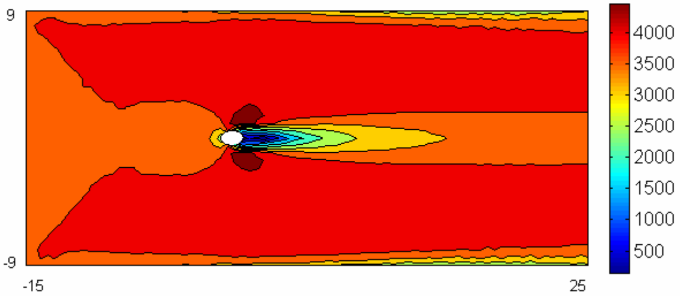

Fig. 2. Local Reynolds number contours around
a circular cylinder (white circle) in the computational domain

Normalized velocity is represented by the local Reynolds number as shown in Figure 2. The flow field illustrated in Figure 2 can be considered the subgrid-scale velocity field for a single grid cell of a coarse-grid model over a much larger domain. Typical LWD diameters are of order 10 cm, so the computational domain corresponds to a model grid scale of 1.8 x 4 m, and the selected Reynolds number corresponds to a velocity of approximately 4 cm/s (i.e. a relatively low velocity with respect to typical river conditions). Thus, this can be considered a single model cell with subgrid-scale inhomogeneity in the bottom boundary structure that affects both subgrid and resolved scales of motion.

Analysis and Discussion. For LES method, the subgrid-scale velocity is presumed to arise from, and be satisfactorily modeled by, the energy-containing eddies that resolved on the grid. Nevertheless, for a coarse-grid model like the example we showed in Figure 2, eddies generated form the cylinder cannot be resolved at the 1-cell coarse grid because the cylinder is a subgrid-scale obstruction. Furthermore, the effects of those eddies cannot be predicted from the resolved flow. Thus, LES cannot resolve the effects of subgrid-scale obstruction physical feature.

RANS methods (such as used on the fine scale to generate Figure 2) assume that the subgrid scale is a homogeneous turbulence field characterized by the Reynolds stresses, which are defined using the unsteady fluctuations from the grid-scale (local) mean velocity. At coarser grid resolutions (i.e. treating Figure 2 as a single grid cell), there is clearly subgrid scale inhomogeneity in the local mean velocity that would contribute to the nonlinear terms in the Navier-Stokes equations. Extending the RANS approach (e.g. Speziale, 1996), we can consider the subgrid scale as a local difference between the grid-scale mean velocity and the local velocity such that

$$u = U + u' \qquad (1)$$

where u is the local velocity, U is the grid-scale mean velocity and u' is the subgrid-scale contribution. By applying different grids to our model results of Figure 2, we can compute the grid-scale mean velocity and subgrid-scale velocity that would be associated with a "perfect" subgrid scale model (i.e. a model the reproduced U exactly at the grid scale). Figure 3 shows the best possible representation of the velocity field around the circular cylinder for two different grid scales. The grid-scale mean velocities with finer and coarser grids differ in both magnitude and direction. Thus, a perfectly designed subgrid model must account for the relationship between the subgrid scales of heterogeneity and the size of the grid.

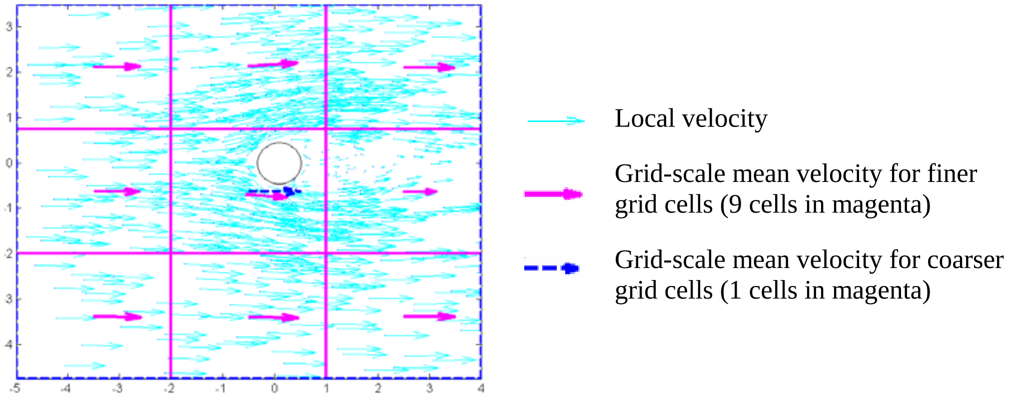

Fig. 3. Local and grid-scale mean velocity fields near a circular cylinder with finer and coarser grid cell.

The grid dependency of grid-scale mean velocity leads to grid dependency for the subgrid scale velocity. In Figure 4, u_1' is the subgrid scale velocity calculated from grid-scale mean velocity of the coarser grid cell in Figure 3; u_2' is the subgrid-scale velocity calculated from grid scale mean velocity of the finer grid cell in Figure 3. As shown in Figure 4, these two different subgrid-scale velocities are very different in both magnitude and direction.

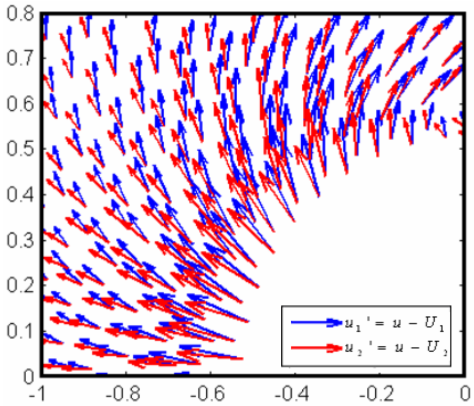

Fig.4. Grid dependency of subgrid-scale velocity

Thus, if an eddy viscosity is used to model the subgrid-scale effects, it follows that the eddy viscosity must *a priori* be a function of the grid scale. In effect, the eddy viscosity must be a calibration parameter that includes the relationship between the grid scale and subgrid-scale physical inhomogeneity. This interdependency of model and physics is exactly what modelers try to avoid: ideally, the subgrid-grid scale model should be definable from the physical processes alone, so that measurements in the laboratory or field can be used to set the model parameters. We believe the inability of present RANS models to explicitly account for the relationship between the grid scale and subgrid-scale inhomogeneity is a principle contributor to the calibration problems for models of the natural environment.

CONCLUSION AND SUMMARY

Understanding and modeling the flow around LWD is necessary to better quantify the aquatic habitat in rivers and streams. It is unrealistic to use fine-grid resolution around LWD in engineering practice and the existing practical coarse-grid models do not account for the scale relationship between LWD and the grid. This paper illustrated the problems associated with coarse grid RANS models and the grid-scale dependency of subgrid scale features. All of this indicates that a new approach is needed to account for the subgrid-scale inhomogeneity in physical features.

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