Effect of active filtering on flow around a partially submerged freshwater mussel

H. Wu

IIHR-Hydroscience and Engineering, University of Iowa, Iowa City, Iowa, United States of America

J. Zeng

South Florida Water Management District, West Palm Beach, Florida, United States of America

G. Constantinescu

IIHR-Hydroscience and Engineering, Department of Civil and Environmental Engineering, University of Iowa, Iowa City, Iowa, United States of America

ABSTRACT: Freshwater mussels are bivalve mollusks that inhabit the substrates of rivers. Fully three-dimensional large eddy simulations are used to investigate flow, turbulence and the capacity of the flow to dislocate an isolated, partially-buried, isolated freshwater mussel placed in a fully-developed incoming turbulent open channel flow. The mussel is aligned with the flow direction, which corresponds to normal conditions in rivers containing mussel beds. Its submergence depth is about 60% of the mussel height. The paper focuses on quantifying the effect of the active filtering flow through the incurring and excurring siphons. Simulation results are discussed for two limiting cases with no active filtering and with a filtering flow discharge that is close to the maximum value recorded for the investigated freshwater mussel species. It is shown that the active filtering increases the turbulent kinetic energy in the wake and slightly decreases the mean streamwise drag acting on the mussel shell. The paper also discusses the main types of large-scale coherent structures generated by partially-burrowed mussels aligned with the flow, how they are affected by the filtered flow and the effects of these eddies on the bed shear stress, sediment entrainment/deposition phenomena and nutrient transport.

1 INTRODUCTION

Freshwater mussel populations in rivers have been declining over the past several decades due to numerous factors, including destruction of habitats and pollution (Strayer, 1999). In order to grow and be stabilized, freshwater mussels require substrates of sandy or gravelly material. Moreover, a minimum amount of flow is required for the mussels to survive given their food needs, mainly particulate organic material. Given that freshwater mussels play an important role in water quality and act as 'ecological engineers', preserving and restoring habitat of native freshwater mussel population is a main task for water resources management and stream restoration efforts in most rivers around the world. Mussels are filter feeders that live at the water-sediment interface. They affect the nitrogen cycle through consumption of phytoplankton and zooplankton. Mussels filter some pollutants/waste present in the water column, can reduce nitrogen levels and acquire nutrients by siphoning water from the surrounding flow.

Given that the hydrodynamic conditions in the stream directly affect habitat suitability (e.g., availability of nutrients, entrainment of nutrients) and the stability of freshwater mussels, a detailed characterization of the flow and turbulence at the mussel scale is of interest. Moreover, bed shear stress has been found to be an important indicator for habitat suitability for mussels (e.g., see Hardison and Layzer, 2001).

To better understand the relationship between hydrodynamics and mussel habitat, one has to consider how mussel size, degree of submergence, orientation and active filtering influence flow and transport around the mussel shell and the capacity of the mussel to remain anchored to the substrate. In this paper, we focus on flow past one isolated, partially-buried mussel at normal flow conditions (mussel burial depth is about 60% of the total mussel height). The main axis of the mussel is parallel to the mean direction of the incoming flow (zero angle of attack), which is the usual position along which mussels orient themselves to minimize drag. The main goal is to investigate the effect of active flow filtering through the incurring and excurring siphons on flow, turbulence and the capacity of the flow to dislocate the mussel.

2 NUMERICAL MODEL AND SIMULATION SET UP

The numerical model is the same as the one used by Constantinescu et al. (2013) to study flow past a cluster of three freshwater mussels that were placed perpendicular to the flow (90 degrees angle of attack) to increase the wake to mussel interactions. The paper of Constantinescu et al. (2013) also include detailed validation of the numerical model with particle image velocimetry data for the case of a cluster of three mussels placed perpendicular to the incoming flow. The Reynolds number of the present simulation and the mesh density in nondimensional wall units in the critical regions (horseshoe vortex region, separated shear layers) is as fine as, or finer than, the simulations reported by Constantinescu et al. (2013).

The LES code uses a collocated finite-volume scheme to solve the filtered Navier-Stokes equations with the dynamic Smagorinsky model (Constantinescu et al., 2013). In the predictor-corrector formulation the Cartesian velocity components defined at the center of the cell and the face-normal velocities defined at the center of the face are essentially treated as independent variables. The fractional step algorithm is second order accurate in both space and time. All the operators in the code including the convective terms are discretized using central schemes. Time discretization is achieved using a Crank-Nicholson scheme for the convective and viscous operators in the momentum (predictor step) equations. After discretization in time, the governing equations are solved using the Successive over-relaxation (SOR) method.

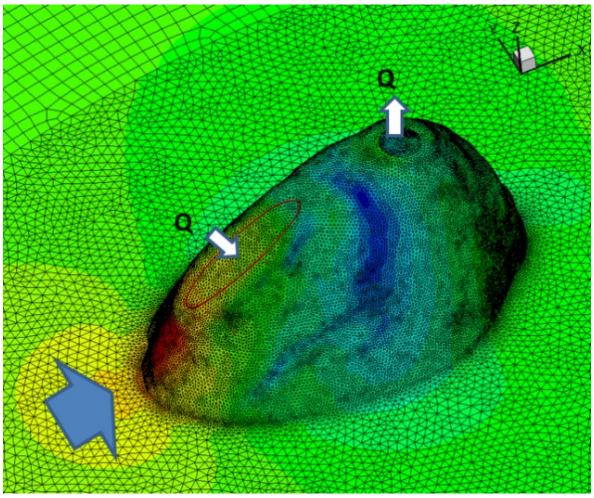

Figure 1. View of the mesh on the surface of the partially-buried mussel and on the bottom of the channel surface surrounding the mussel. Also shown is the pressure distribution on the mussel shells for the case with a strong active filtering flow. Red color denotes region of high pressure, while blue color denotes regions of low pressure.

The mussel shell geometry was that used in an experimental lab study of flow over a mussel bed conducted at the University of Buffalo. The STL file was postprocessed in AUTOCAD and read into the grid generator software were the lower part was eliminated to generate a mesh in a channel domain containing a surface-mounted, partially-burrowed mussel. A short pipe was introduced at the location of the excurrent siphon whose section was also close to circular. The channel depth was D = 0.17 m. The height of the exposed part of the mussel was 0.025 m. The lengths of the mussel's base measured along the major and minor axes were 0.045 m and 0.06 m, respectively. The mussel shell was not exactly symmetrical with respect to the vertical plane containing the major axis of the mussel. The channel Reynolds number was 50,000 corresponding to a mean velocity, U = 0.3 m/s. In the simulation with an active filtering flow, the discharge through the incurrent and excurrent siphons was $2*10^{-12}$ m^3/s, which corresponds to a velocity inside the excurrent siphon of about 0.05 m/s. In the simulation with no excurrent flow, the two openings were replaced by no-slip walls.

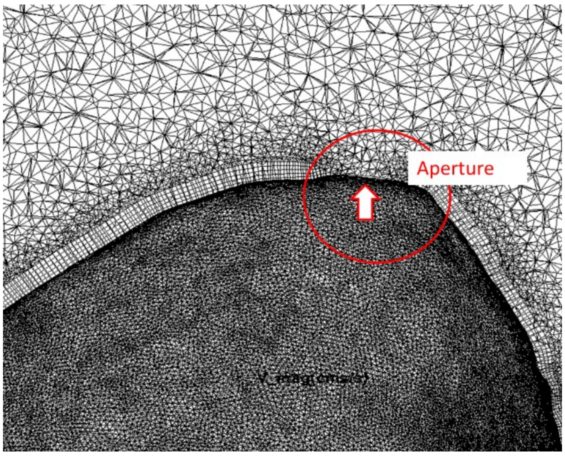

Figure 2. Mesh in a vertical plane cutting along the main axis of the mussel showing the procedure used to resolve the attached boundary layers on the mussel shell and the flow close to the excurrent siphon aperture.

The mesh contains around 2.5 million cells with about 60% of the points situated in the block containing the mussel. Hexahedral elements were used outside this block. The surface mesh for the mussel shell contains close to 300,000 elements (Fig. 1). The first grid point off the mussel and channel bed surfaces was placed at about 2 wall units in the wall normal direction, as our simulations resolve the near-wall flow (Fig. 2). The attached boundary layers on the mussel shells were resolved with at least 5 grid points (Fig. 2).

Similar to Constantinescu et al. (2013), the inflow velocity fields containing resolved velocity fluctuations were obtained from a precursor LES simulation of fully-developed, turbulent flow in a straight periodic channel. A convective boundary condition was used at the outflow section. It allows the coherent structures to exit the domain in a time accurate way, without producing un-physical oscillations. The free surface was treated as a slip (zero shear stress) surface. This is an acceptable approximation given the low value of the channel Froude number (<0.2). The lateral boundaries were treated as symmetry boundaries. The width of the computational domain was about 12 mussel widths. The time step was 0.001D/U.

3 RESULTS

Figure 3 uses the Q criterion to visualize the large-scale coherent structures in an instantaneous flow field in the simulation conducted with active filtering flow. One can see that a horseshoe vortex system containing a main vortex and at least one secondary vortex is present around the upstream base of the mussel. The pattern is qualitatively similar to the one observed in the corre-sponding simulation with no filtering and also around the mussel directly exposed to the flow in the cluster simulation reported by Constantinescu et al. (2013) for mussels oriented perpendicular to the flow. Of course, in the latter case the horseshoe vortex is more coherent. One can also see the formation of horseshoe-like vortex tubes parallel to the separation line of the boundary layer forming on the upstream side of the mussel surface. These vortex tubes break into two parts as they are advected downstream in the wake of the mussel. This is more clearly seen in the case with active filtering where smaller close-to-vertically-oriented vortex tubes are observed on the two sides of the mussel in Fig. 3. The vortices maintain their original shape for a longer distance in the case with no filtering (not shown). Similar to what is usually observed for flow past surface mounted bluff bodies, large-scale eddies are shed in the wake of the partially-buried mussel. These eddies play an important role in sediment entrainment on the sides of the mussel and in nutrient transport behind the mussel.

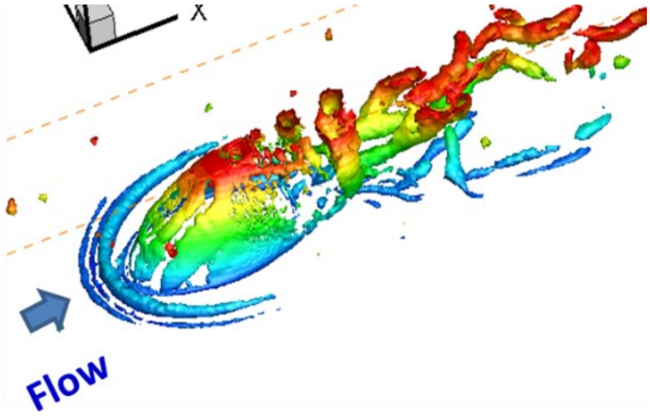

Figure 3. Flow structures in the instantaneous flow for the simulation with a strong active filtering flow.

The mean pressure distribution on the mussel shell (Fig. 2) shows that the maximum pressure is observed at the front side of the mussel where the flow decelerates as it is pushed on the two sides of the mussel. The minimum pressure is recorded beyond the separation line for the shear layer forming behind the mussel. A reduction of about 6% of the total streamwise drag force acting on the mussel is observed in the case with active filtering flow filtering compared to the case with no filtering flow. This confirms that mussels use the flow through their siphons to reduce drag and increase their capacity to oppose dislocation by the approaching flow.

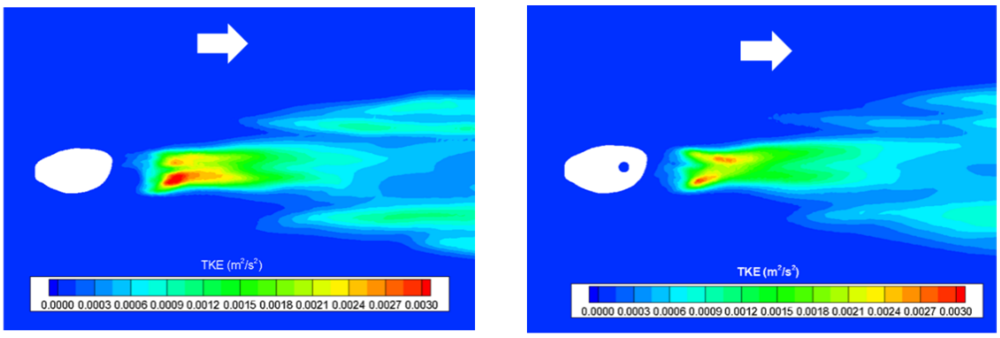

Figure 4. Turbulent kinetic energy in a plane cutting at 0.01 m from the bed in the simulation with no active filtering flow (left) and with a strong active filtering flow (right).

The turbulent kinetic energy distributions in Figure 4 do not show qualitative differences between the two cases. The stronger interactions of the vortex tubes shed from the two separated shear layers in the no filtering case, where the excurrent flow does not act to break the vortex tubes, explain the larger values of the turbulent kinetic energy inside the near-wake region in the simulation with no active filtering flow.

Figure 5 shows the distribution of the bed friction velocity, which controls erosion around the mussel. Again, the distributions in the two simulations are qualitatively and quantitatively similar. Despite the presence of strong necklace vortices, no large amplification of the bed shear stress is observed around the upstream face of the mussel. The largest bed shear stress values are induced on the outer side of the two separated shear layers where the flow accelerates as it passes the mussel and also about one mussel length downstream of the back of the mussel, where the flow advected over the mussel plunges toward the bed. The amplification in this second region of high bed shear stress is slightly larger in the case with active filtering flow. However, the development of scour in this region is not expected to affect the mussel stability.

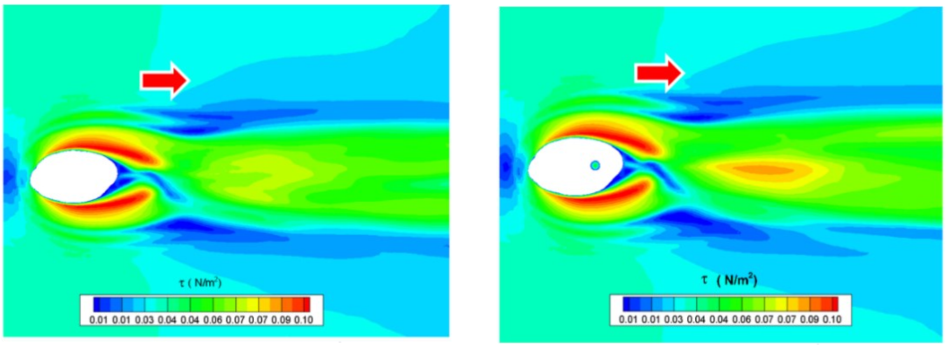

Figure 5. Mean bed shear stress in the simulation with no active filtering flow (left) and with a strong active filtering flow (right).

4 CONCLUSIONS

The LES simulations provided detailed information on flow hydrodynamics and turbulence structure past a single, partially-buried, isolated mussel aligned with the incoming flow direction. Understanding these processes and the interactions among flow, sediment, nutrients and freshwater mussels is essential to be able to understand biological aspects related to the life and behavior of these aquatic organisms and their habitat requirements (Constantinescu et al., 2013). The main types of coherent structures forming around the mussel were found to be similar to the ones observed past mussels placed perpendicularly to the flow. However, the coherence of the horseshoe vortices and of the vortex tubes shed in the separated shear layer was lower compared to the former case investigated by Constantinescu et al. (2013). The main effect of the active filtering flow was to decrease the mean streamwise drag force acting on the mussel shell, to decrease the turbulent kinetic energy in the near-wake and to amplify the mean bed friction velocity in a region situated about 2-3 mussel lengths behind the mussel, close to the streamwise axis of the mussel. Even for the ecologically relevant case when mussels are aligned with the flow, the horseshoe vortex system is expected to play an important role in scour around the mussels partially exposed to the oncoming flow. The more energetic smaller scale content of the near-wake flow in the case with active filtering is expected to increase the nutrient availability to mussels.

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