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Computational modeling of flow and morphodynamics through rigid-emergent vegetation

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ABSTRACT

The flow and bed morphodynamics through rigid, emergent cylinders which are regarded as vegetation are computed using a three-dimensional numerical model by employing a large-eddy simulation approach with a ghost-cell immersed-boundary method. The scour and transport processes are solved using sophisticated sediment transport and morphodynamic models in a physics-based manner. In an infinitely long patch, the vegetation density significantly influences the flow and morphodynamic behavior. Under a low vegetation density, the scour and deposition are similar to those of an isolated cylinder, while there are significant variations at a higher vegetation density. The cylinder-interval variation has a negligible impact on the maximum scour depth, which is similar to that in an isolated cylinder case. In the high-vegetation-density case, a decrease in cylinders in a selected domain decreases the physical realism of the morphodynamic process. The scour and transport processes in a partly vegetated small patch show a significant difference, compared to the long patch. In this case, local and global scours are observed around the small patch and the maximum scour always occurs around the front cylinders (i.e., leading edge). The scour depth increases with a decrease in the cylinder interval, and the computed scour depths and trends agree well with the measured data in the literature.

1. Introduction

The vegetation in streams and rivers alters their flow velocities and turbulence structures [1]. Thus, it can affect the sediment transport and bed morphology [2]. Furthermore, vegetation can change the spatial patterns of erosion and deposition, and the landform dynamics, for example, from braided to single channels [3]. Recently, several river restoration projects have been conducted to increase the water quality and improve aquatic habitats [4,5]. Planting vegetation in rivers is one of the techniques for restoration projects. An understanding of the influences of vegetation on the flow, sediment transport, and bed morphology is one of the principal challenges for successfully restoring degraded rivers [4,6].

The effect of vegetation typically depends on the flow characteristics, vegetation flexibility, and density [7-9]. In addition, the velocity and turbulence intensity profiles vary with the vegetation density and submergence ratio, which generate coherent flow structures at adjacent vegetation [1,10]. Locally, horseshoe vortices are generated in front of and around vegetation, which can cause an increase in the turbulence stresses [8], and large-scale wake vortices induced by flow separation are produced downstream of vegetation [11].

Several numerical studies have been conducted on time-averaged flow properties. A majority of the numerical models have used the unsteady Reynolds-averaged Navier–Stokes (URANS) model. To deal with vegetation drag, additional source terms are involved in momentum and turbulence transport equations with coarser grids [12,13]. This approach is a practical method and provides reasonable results for the time-averaged velocity and turbulence quantity within vegetation [12,13]. However, such an approach cannot provide local flow properties around vegetation stems. Thus, because of their inherent problems, URANS models have rarely been applied to predict the local flow and turbulence through individual vegetation elements resolved using computational grids, which are similar to those for a flow field around cylinders [1,14]. Recently, large-eddy simulation (LES) has been used to examine flow and turbulence structures because of the development of computer resources [14]. Several studies have used LES for flows thorough vegetation, where the vegetation stems have been resolved using computational grids with the assumption that the vegetation is rigid [1,14,15]. LES results for open

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channel flows through emergent or submerged vegetation offer accurate predictions of the flow velocity and Reynolds stresses, and reproduce three-dimensional coherent structures around individual elements of vegetation [1,14].

Even though there has been considerable interest in flow and turbulence structures around vegetation, relatively few studies have investigated suspended or bedload transport through vegetation. In particular, the scour and deposition created by local bedload transport have rarely been considered in previous studies. Previous studies have mainly examined suspended sediment with changes in the flow turbulence within or around vegetation [3,6,13,16]. The deposition of suspended sediment has been observed within vegetation and between an open channel and a vegetation zone [2,6]. On the other hand, a decrease in suspended sediment has been discovered around the leading edges of vegetation patches [2,17]. This is induced by an increase in the turbulence kinetic energy and a local high flow caused by the constricted flow around vegetation stems [17]. Local scour has also been found around the leading edge of a vegetation patch due to enhanced local erosion, which is caused by an increase in turbulence like horseshoe vortices and stem wakes [2,17]. Such scour can threaten the future survival of vegetation because vegetation can be uprooted during the high flow stage. The local scour around a single rigid plant is identical to that around a bridge pier, and scouring near rigid vegetation patches (e.g., trees, shrubs or reeds) is similar to that around a pile group.

In general, coherent flow structures and complex turbulence occur around piers and within scour holes [18,19]. Because it is almost impossible to obtain analytical solutions for the bridge-scour depth, extensive investigations using laboratory experiments have been carried out to understand the parameters related to the local scour depth and obtain prediction equations for the scour depth [20]. The scour around piers, which can typically be seen in rivers, is caused by horseshoe vortices in front of the pier, wake vortices, and enhanced flow due to flow separation, which are three-dimensional flow structures. For a better understanding of unsteady coherent vortices, which are the primary mechanism of scouring, as well as scour processes, three-dimensional numerical models have been developed since the early 1990s [21-25]. Numerical studies have mainly used URANS models with a two-equation turbulence model (e.g., k–ε or k–ω model). The scour process for a bed has been calculated using the sediment continuity equation with empirical bedload models. Previous numerical investigations simulated the local scour around an isolated cylinder embedded on non-cohesive sediment materials [21-23]. Overall, the URANS model combined with a morphodynamic model has been shown to capture the general patterns of local scour around obstructions, but it has failed to predict local scouring at the base of an upstream cylinder where turbulent horseshoe vortices dominate [21,23,25,26]. In addition, URANS models have underestimated not only the evolution of scour but also the equilibrium scour depth. This is due to the fact that URANS model with a two-equation turbulence model are too diffusive to resolve the fluctuation components of a turbulent horseshoe vortex system [23,25].

In order to overcome the inherent limitation of the URANS model, LES or detached-eddy simulation (DES) has been employed to accurately resolve the dynamics of horseshoe vortices [18,24,27]. As mentioned above, LES or DES accurately simulates the unsteadiness flow field around a cylinder [11,14,19,27]. Escauriaza and Sotiropoulos [18] developed DES combined with a bedload transport model to consider the effects of the instantaneous flow field in the bedload layer. Their model was applied to calculate the bedform dynamics around a cylinder presented by Dargahi [28]. The results showed that the model captures the ripple dynamics evolving from the interactions between the vortical structures and sand bed. Kim et al. [24] explored the flow and scour processes around cylinders using LES coupled with sediment transport and morphodynamic models, and their results dramatically improved the local scour at the junction of the cylinder, along with the equilibrium scour depth and shape. They extended their simulations to two cylinder cases with side-by-side and tandem arrangements and showed that the model reproduces the scour and transport processes around cylinders with physically realistic phenomena. Niño and Garcia [29] proposed a Lagrangian model for the saltation of sand and the model was applied to experiments of Niño and Garcia [30]. The results showed that the mean value and standard deviation of saltation height, length and particle velocity were in good agreement with experimental measurements.

The locally enhanced scour and deposition induced by the coherent turbulence within and around vegetation have a considerable effect on the future survival of plants. Thus, these need to be considered in planting plans and restoration projects in rivers and floodplains. A majority of studies have depended on laboratory experiments [5,8]. However, detailed flow and morphodynamic measurements with vegetation are very difficult. Thus, it is hard to describe the temporal and spatial variability of the bed elevation around and through vegetation. Therefore, numerical simulations are the best tool. However, there have been no studies using three-dimensional numerical modeling of the bed morphodynamics around and through vegetation. An approach using LES or DES combined with sediment transport and morphodynamic models is the most appropriate method to understand the physical mechanisms and scour and transport processes around and through vegetation.

In this paper, we describe a study of the flow, scour, and transport processes through regular arrays of circular cylinders, which are regarded as idealized rigid-emergent vegetation (e.g., trees, shrubs or reeds), using a large-eddy simulation coupled with sediment transport and morphodynamic models. Individual cylinders are explicitly resolved through computational grids using a ghost-cell immersed boundary method. First, to validate the LES for the flow through a regular array of cylinders, the time-averaged streamwise velocities are compared with laboratory data. The bed morphodynamics through the vegetation are computed to investigate the temporal and spatial variability in the bed elevation and the evolution of the local and maximum scour depth. The effect of the vegetation density on the flow, scour, and transport processes is examined, and a sensitivity study of the computational domain with periodic boundary conditions is also conducted to explore the relative importance of the numerical error in relation to the temporal and spatial variability in the morphodynamic behavior. To investigate the differences in the bed morphodynamic behaviors and local scour depths between infinitely long vegetation patches with fully developed flows and small patches (i.e., partial vegetation patches in open channels), numerical simulations of small-patch cases are carried out. The discrepancy between infinitely long and partial vegetation patches in terms of the bed morphodynamics and local scour is examined and discussed.

2. Governing equations

The computational model proposed by Nabi et al. [31-33] is employed to solve the present problem of hydrodynamic, sediment transport and morphodynamics. Hence, it includes three models which are solved in a coupled way. The hydrodynamic model was based on the assumption that the flow is incompressible and isothermal. The sediment is assumed to be in the form of spherically shaped rigid particles of uniform size. The collision of sediment particles with the bed and the cylinder is accounted for whereas collisions among particles are neglected. The vegetation is assumed to be in the form of rigid-emerged cylinders. In the next sections, we explain these models in more details.

2.1. Hydrodynamic model

The equations governing the instantaneous, resolved flow field for the three-dimensional incompressible fluid flow are the spatially