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Flow around submerged structures subjected to shallow submergence over plane bed

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ABSTRACT

The results of an experimental investigation on the flow field around submerged structures on horizontal plane beds, measured by an acoustic Doppler velocimeter (ADV), are presented. Experiments were conducted for various conditions of submergence, having submergence factors ranging from 1.0 to 2.0 and average flow velocity ranging from 0.25 to 0.51 m/s. The Froude number and the Reynolds number of the approaching flow for different runs are in the range of 0.18–0.42 and 50 000–76 500, respectively. The vertical distributions of time-averaged three dimensional velocity components and turbulence intensity components at different radial distances from the submerged structures are plotted. Deceleration and acceleration of the approaching flow around the submerged body are evident from the vertical distributions of the horizontal velocity component, whereas the lifting and diving nature of the flow are indicated by the vertical velocity component distributions. The vertical distributions of the horizontal velocity component indicate reduction of 30% of the non-dimensional time-averaged horizontal velocity component magnitude for the cylinder of diameter 11.5 cm in comparison to the cylinder of diameter 10 cm. Also, there is an increase of 10–25% in the horizontal velocity component at different radial sections. The flow is three dimensional in the downstream of the submerged structure. The velocity and the turbulent intensity components are also well predicted by FLUENT. The flow characteristics in the wake and the induced bed shear stress are also analyzed with FLUENT.

The profiles of non-dimensional shear velocity deviate from the log law in the wake and the far downstream directions. The scour prone regions may be identified from the profiles of the induced bed shear stress around the submerged structure.

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1. Introduction

Hydraulics of submerged structures has been a topic of continued interest to the researchers and the design engineers from different branches of science and engineering for the safe, effective and economical design of the foundation of these structures. Numerous such submerged hydraulic structures in various fields of engineering (fish habitat structures, support for the submerged pipelines, sand mounds and tidal banks in shallow coastal water, submerged logs, submerged vanes, flow around buildings completely submerged in air, etc.) are encountered. The topic of hydraulics around partially and fully

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submerged structures (pier, abutment, downstream of an apron, etc.) placed in steady and unsteady flows and waves has been extensively investigated in the past. Schofield and Logan (1990) examined the hydraulics of surface mounted cubes. They found the existence of the vortices in the wakes of the cube, which travels downstream and then reattaches with the bed further in the downstream direction. Martinuzzi and Tropea (1993) studied the hydraulics of prismatic obstacle placed in a channel flow. They observed four horse shoe vortices upstream of the obstacle. The re-circulation region for a three dimensional body was found to be much shorter than for the two dimensional body. Flow field and the wake patterns around conical islands subjected to shallow submergence were studied by Lloyd and Stansby (1997). They observed well-organized pattern of vortex shedding in the wake of the submerged islands. The vortex shedding was less vigorous as the relative submergence was increased. They also compared the experimental results with the shallow water numerical 2D and 3D models. The mode of generation of the wakes was found to be different for the experiments. Marelius and Sinha (1998) conducted experiments to study the characteristics of flow past submerged vane at a high angle of attack. They carried out experimental runs to determine the optimum angle of attack for the generation of the strongest secondary circulation.

Characteristics of flow at the optimal angle responsible for the bed scour were also identified. Tang and Chang (1998) investigated experimentally and numerically the interaction of a solitary wave passing over a submerged structure in shallow water. They found the formation of a large vortex followed by a secondary vortex at the back of the structure. The primary vortex decays with time but the secondary vortex grows in strength. The temporal evolution of the vortex system is well matched by the numerical model results. Chou and Chao (2000) studied the branching of the horse shoe vortices upstream of the rectangular cylinders. They conducted the flow visualizations and surface pressure measurements and concluded that initially, the horse shoe vortices are wavy in nature but subsequently branch themselves into smaller regular vortices. Hydraulics of simple fish habitat structures of hemispherical shape under shallow submergence was investigated by Shamloo et al. (2001). They found different regimes of flow based on the relative submergence ratio of the submerged structure. The hydraulics of flow and the pattern of erosion around the structure were different for all the flow regimes. Wallerstein et al. (2002) conducted an experimental study on the action of surface wave forces on submerged logs. They measured the drag forces on the submerged logs and calculated the drag coefficient for different submergence and slenderness values of the log. For shallow submergence, the drag coefficient was found to depend on the proximity of the log to the free surface and the slenderness of the log. Flow around surface mounted pyramids was examined by Martinuzzi and AbuOmar (2003). They investigated the effect of different parameters (pyramid apex angle and angle of attack) for square based pyramids on the flow characteristics. They categorized the pyramids based on the periodicity of the wakes developed, into slender and broad pyramids. Except for the smaller angle of attacks, the behavior of the wakes is same for the slender and broad pyramids and it depends on the vortex shedding. Testik et al. (2005) conducted an experimental study on the flow around a horizontal cylinder under steady and oscillatory flows. Horse shoe vortices of different signs were observed from either side of the cylinder. For oscillatory flows, these vortices of different signs move to the other side with the change in the direction of flow. Manes et al. (2007) conducted an experimental study on the measurement of flow field for shallow open channel flows using particle image velocimetry (PIV). The depth of the flow was too low to give rise to a logarithmic velocity distribution but at the same time large enough so that the flow is not influenced by the roughness of the bed. The three dimensional flow characteristics around the bottom mounted short cylinder were investigated by Smith and Foster (2007). The experimental data of the vortex shedding around the cylinders were compared with the simulations using the large eddy simulation approach. They also evaluated the mean bed shear stress and concluded that the sediment transport models using the mean shear stress underpredict the sediment transport in the wake around the structure. Dey et al. (2008) investigated experimentally the scour around submerged cylindrical obstacles under steady flow. They introduced a submergence factor to determine the scour depth for submerged condition from the results of scour depth under un-submerged condition. They also presented the vector plots around the submerged structures to show the strength and dimension of the horse shoe vortex. Sadeque et al. (2008) investigated the flow around cylinders at different submergence levels. They compared the flow visualization results with the measurements of the bed shear stress. Alternate vortex shedding was found to be suppressed by the submergence of the cylinders. Oruc (2012) used screens to control the flow characteristics downstream of a circular cylinder. The screen forced the reattachment of shear layers separated from the cylinder. The turbulence characteristics and the Reynolds shear stress decreased when compared with the bare cylinder. Rostamy et al. (2012) used PIV technique to study the flow field and the wake region downstream of a circular cylinder. Flow separation from the leading edge of the cylinder resulted in the formation of recirculation zone above the free end of the cylinder. Increased levels of turbulence intensity and Reynolds shear stress were reported above the free end of the cylinder.

The use of submerged weirs for reducing the bank erosion along meandering streams was studied by Abad et al. (2008). They measured the three dimensional velocity components around the submerged weirs with ADV and also simulated the flow pattern numerically. They found a good agreement between the model and the field measurements. Huang et al. (2006) simulated two dimensional, laminar, unsteady, water flow around cylinder arrays of unequal sizes using FLUENT at Reynolds numbers below 150. They observed the incomplete vortex shedding behind the first row cylinders. Karman vortices were not formed and a near-stagnant separated flow region appeared between the aligned cylinders. Lam et al. (2008) performed two- and three-dimensional numerical simulations of cross-flow around four cylinders in an in-line square configuration using FLUENT. They observed three distinct flow patterns in two dimensional flow. They also observed the large discrepancy between 2-D simulation and flow visualization results at spacing ratio $L/D=4.0$ and $\mathrm{Re}=200$ due to the strong 3-D effect at the ends of the cylinder at low aspect ratio. Lam et al. (2012) studied the three dimensional flow around wavy rectangular cylinders with sinusoidal variations in cross section area along the span-wise direction over wide

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