Numerical Modelling of the Effect of Lateral Nonuniformity due to Horizontal Flow Contraction on Flow Dynamics over a Steep Slope

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This research is motivated by recent findings indicating the presence of a three-dimensional flow phenomenon near hydraulic structures, characterized by jet-like flow and lateral nonuniformity (Broekema et al., 2018, 2019). This phenomenon has been observed to potentially enhance scour near the Eastern Scheldt Storm Surge Barrier, the Netherlands (Broekema et al., 2018). Broekema et al. (2019) further demonstrated experimentally that flow separation over steep slopes may be suppressed due to lateral non-uniformity in the upstream flow field, thereby enhancing scour potential.

To gain a better understanding of this flow phenomenon, this study employs numerical simulations using the RANS turbulence model. The simulation cases are based on an open channel experiment conducted by Broekema et al. (2019) that inspired this research. The cases vary the steepness of the bed slope (resembling the scour hole) and the distance between the obstruction and the upstream edge of the slope (resembling bed protection), which controls the magnitude of the lateral velocity gradient. The simulations were conducted using OpenFOAM with the PIMPLE algorithm, suitable for unsteady flows, coupled with the k-ω SST turbulence closure model.

The key findings of this research revealed a significant relationship between the distance of the obstruction to the slope and flow separation. Placing the obstruction further upstream allowed for the development of a mixing layer over a greater distance, resulting in reduced lateral velocity gradient and a horizontally uniform flow, ultimately leading to flow separation. Conversely, placing the obstruction closer to the slope led to vertical flow attachment due to a larger lateral non-uniformity. From a practical standpoint, this observation holds implications for the design of hydraulic structures, as bed protections around such structures should be sufficiently long to allow for adequate mixing, reducing velocity differences and turbulence intensities to induce vertical flow separation and minimize the risks of flow attachment, such as enhanced scour and erosion.

Furthermore, the study established a notable correlation between the pressure field and flow separation. In all instances of vertical flow separation, an adverse pressure gradient was consistently observed upstream and downstream of the slope. This adverse pressure gradient occurred as the flow depth increased, leading to flow deceleration. Conversely, in situations of flow attachment, a decrease in pressure prior to the slope indicated flow acceleration as the flow converged horizontally. Consequently, the deceleration of the flow from the increased flow depth at the slope was reduced, resulting in a diminished adverse pressure gradient and the boundary layer staying attached to the bed.

While the model showed good agreement with the measurement data upstream of the slope in all cases, discrepancies were observed around the slope, where high turbulence intensities were measured. The model consistently underpredicted this turbulence and the turbulent kinetic energy in all cases, highlighting limitations of the RANS modeling approach. The assumption of turbulence isotropy in RANS does not adequately reflect the actual behavior of turbulence in shallow shear flows, which exhibit anisotropic turbulence motion responsible for the transverse exchange of mass and momentum. Additionally, the RANS model simulates all turbulence length scales simultaneously, lacking the resolution necessary to capture the energy transfer between larger and smaller eddies, thereby hindering the interaction between turbulence structures and bottom turbulence and also the turbulence associated with the mixing layer (vortex shedding). In light of these findings, this research suggests employing higher-resolution models such as Detached Eddy Simulation (DES) and Large Eddy Simulation (LES), along with free-surface modelling, to improve accuracy.

In conclusion, this study sheds light on the intricate flow behavior and turbulence characteristics in the vicinity of hydraulic structures with steep slopes. The findings underscore the importance of understanding lateral velocity gradients, mixing, and turbulence in controlling flow separation and attachment. The practical implications for designing hydraulic structures call for further exploration of higher-resolution modeling approaches, as they may offer valuable insights into improving hydraulic design and mitigating scour risks.

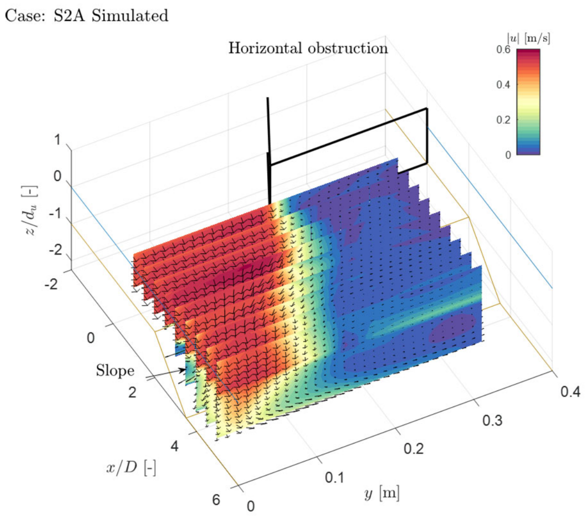

Figure 1: Horizontal convergence and flow attachment. The color bar represents the magnitude of mean velocity. Obtained from the simulation.

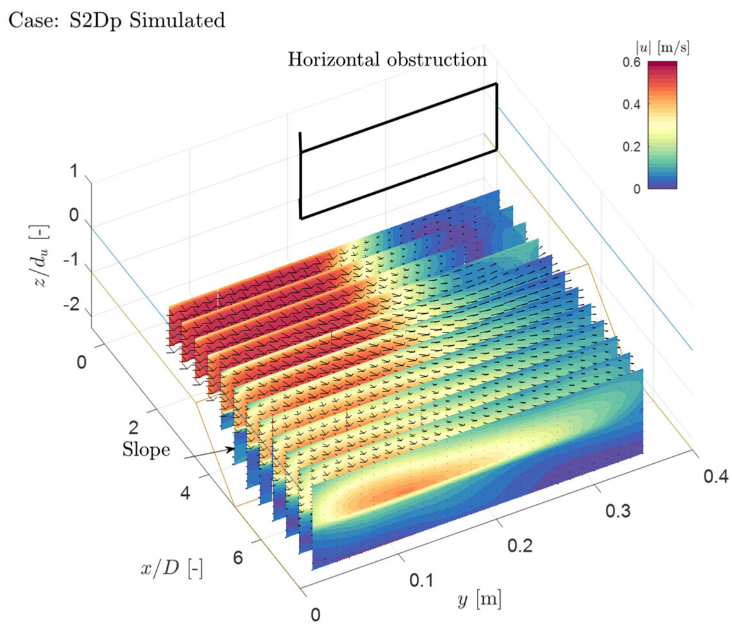

Figure 2: Horizontal divergence and flow separation. The color bar represents the magnitude of the mean velocity. Obtained from the simulation.

Broekema, Y. B., Labeur, R. J., & Uijttewaal, W. S. J. (2018). Observations and Analysis of the Horizontal Structure of a Tidal Jet at Deep Scour Holes. Journal of Geophysical Research: Earth Surface, 123(12), 3162–3189. https://doi.org/10.1029/2018JF004754

Broekema, Y. B., Labeur, R. J., & Uijttewaal, W. S. J. (2019). Suppression of vertical flow separation over steep slopes in open channels by horizontal flow contraction. Journal of Fluid Mechanics, 885, 8. https://doi.org/10.1017/JFM.2019.972