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TWO-PHASE FLOW SIMULATION OF SCOUR AROUND A CYLINDRICAL PILE

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Abstract

In this contribution the application of a two-phase flow Eulerian solver, sedFoam, to the scour phenomenon under steady current is presented. First, pure hydrodynamic simulations, without sediment, are validated using Roulund *et al.* (2005) experimental and numerical data for the flow around a vertical cylinder over a smooth bed. Second, preliminary two-phase flow simulation results are presented and compared with the live-bed trail reported in Roulund *et al.* (2005) experiment. The numerical results are in qualitative agreement with the experiments for the development of the upstream scour mark.

Key words: two-phase flow, scour, 3D numerical modeling, sedFoam.

1. Introduction

The presence of a structure in a river or in the marine environment may significantly affect the flow in its vicinity such as, the contraction of the flow; the formation of a horseshoe vortex in front of the structure; the formation of vortex flow pattern (usually with vortex shedding) behind the structure; the generation of turbulence. In the case of an erodible bed, all these effects may induce an increase of the sediment transport around the structure and the formation of a scour hole. As scour may induce failure of the structure, that can have disastrous human and financial consequences, it is a very important problem in civil engineering. Briaud *et al.* (1999) have established that from 1970 to 2000, scour around bridge pier was responsible of 60% of the bridges failure in the United States. The associated cost to these scour failure is estimated at US$ 50M per year (Lagasse *et al.*, 1995). Coastal areas are also impacted, repairing coastal structure failure due to scouring has been estimated at US$2-10 million per failure (Hugues, 1993). Furthermore, the cost of a wind turbine foundation is more than 30% of its total cost in environments where waves and currents are energetic (Sumer, 2007).

A complete review of the cutting-edge scour modeling can be found in Sumer (2007). After decades of extensive research, the state of the art model predictions are not sufficient. If classical model approaches allow a partial answer to the scour problem, several limitations remains. Indeed, these classical models are based on empirical bedload formulas (Meyer-Peter & Müller, 1948; Engelund & Fredsøe, 1976) that has been obtained under steady and uniform flow conditions where the turbulence is generated by a fully-developed boundary layer. In the case of scour around an obstacle, the horseshoe vortex usually modify the turbulence so that the classical formulas are used out of their validity range, especially for deep scour hole. In the past decade, significant research efforts have been devoted to modeling sediment

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transport using multiphase approaches. Recently, an open-source multi-dimensional Reynolds-averaged two-phase eulerian sediment transport model, sedFoam, is developed by the authors and it has been adopted by many researchers to study momentary bed failure (Cheng *et al.*, 2017) and granular rheology in sheet flow (Chauchat *et al.* (in prep)) for example. The two-phase flow approach does not require to use the empirical sediment transport rate and erosion-deposition laws and no additional equation has to be solved for the bed evolution (Exner equation). In other words, conventional bedload and suspended load assumptions are not needed. The physical grounds on which this new generation of sediment transport model are based on should help to improve scour morphological evolution predictions, especially for complex geometries and/or flow forcings (waves and tides).

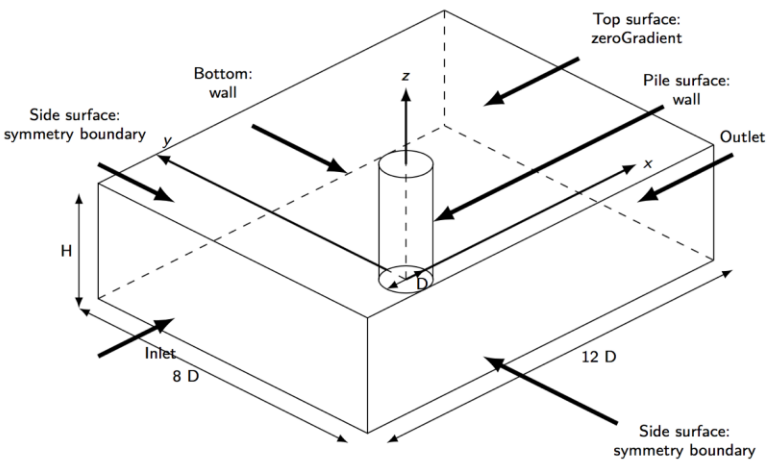
In this study, we further apply this model to the scour problem. Our primary goal is to demonstrate the applicability of the two-phase flow Eulerian approach for scour simulations. This paper will first focus on the hydrodynamic model validation, using Roulund *et al.* (2005) experimental and numerical data for flow around a vertical cylinder over a smooth bed. Second, the two-phase flow simulation of scour around a cylinder will be presented including comparison with Roulund *et al.* (2005) livebed case.

2. **Numerical model and setup**

The two-phase flow model is based on the solution of momentum and mass conservation equations for each phase, water and sediment (Hsu et al., 2004). The numerical implementation is based on the open-source finite volume CFD library OpenFOAM, and is named sedFoam. The version 1.0 has been developed by Cheng & Hsu (2014), and is available at CSDMS website[8]. The details on the model formulation and the numerical implementation can be found in Cheng *et al.* (2017). The present contribution is based on sedFoam2.0, a version which is under development and will be released soon (Chauchat *et al.*, in prep.).

The experimental data from Roulund *et al.* (2005) are used to validate the two-phase flow model. Two configurations are used, a Clear-Water case (CW), without sediment, and a Live-Bed case (LB) with sediment transport everywhere in the flume. As a strong adverse pressure gradient is taking place in front of the pile, Roulund *et al.* (2005) recommends the use of a k-ω SST model (Menter, 1993) to solve the Reynolds-Averaged Navier-Stokes (RANS) equations.

For the CW configuration, the sediment concentration is set to zero. The numerical domain is a 3D box with a stream-wise length Lx=12D, a span-wise length Ly=8D and a height H=0.54m with a vertical pile of diameter D=53.6cm (see figure 1). In order to account for the bed roughness, a roughness height of $k_S=0.268\times10^{-2}$ m is set at the bottom and a ω-wall function is used (Roulund *et al.*, 2005). For the CW case, a structured mesh containing 1 761 280 cells with 64 vertical levels is used. The mesh is refined around the cylinder and at the bottom. The boundary conditions (figure 1) are the identical to the ones described in Roulund *et al.* (2005), except at the inlet, where 1D profiles obtained from a 1D vertical simulation are imposed. The boundary condition for the cylinder is also set according to a ω-wall function with $k_S=5.36\times10^{-5}$ m corresponding to a smooth boundary layer.



[8] https://csdms.colorado.edu/wiki/Model:TwoPhaseEulerSedFoam

Figure 1. 3D geometry and boundary conditions.

In the LB case Lx and Ly are kept constant while the pile diameter is D=0.1m and the water depth is H=3D. The sediment bed height h_S is equal to 1D. The initial condition and the inlet boundary conditions are also set using a 1D vertical simulation. The structured mesh is composed of 3 750 144 elements with 64 vertical levels in the water column and 50 vertical levels in the sediment layer. The other boundary conditions are identical to the CW case, except for the outlet where a wall is set between z=0 and z=1D to prevent sediment erosion at the outlet.

3. **Results**

3.1. ***Hydrodynamics validation***

As explained above, a 1D vertical profile is required for the inlet boundary conditions. The same vertical mesh (64 elements), with geometric common ratio r=1.075 is used. A roughness height ks = 0.268 × 10^{-2}m is used in the ω-wall function at the bottom.

Figure 2 shows the comparison between the classical OpenFOAM single phase solver, pimpleFoam, the present two-phase flow solver sedFoam and Roulund *et al.* (2005) experimental results. From left to right logarithmic and linear velocity profiles, Turbulent Kinetic Energy (TKE) and specific dissipation rate ω are shown using two different turbulence models: k-ω and k-ω SST. Using the same bottom boundary condition for ω, both turbulence models are able to reproduce Roulund et al. (2005) experimental results. The other important result is the very good agreement between pimpleFoam and sedFoam, showing that the numerical implementation of sedFoam is consistent with classical OpenFoam solvers in the limit of zero concentration.

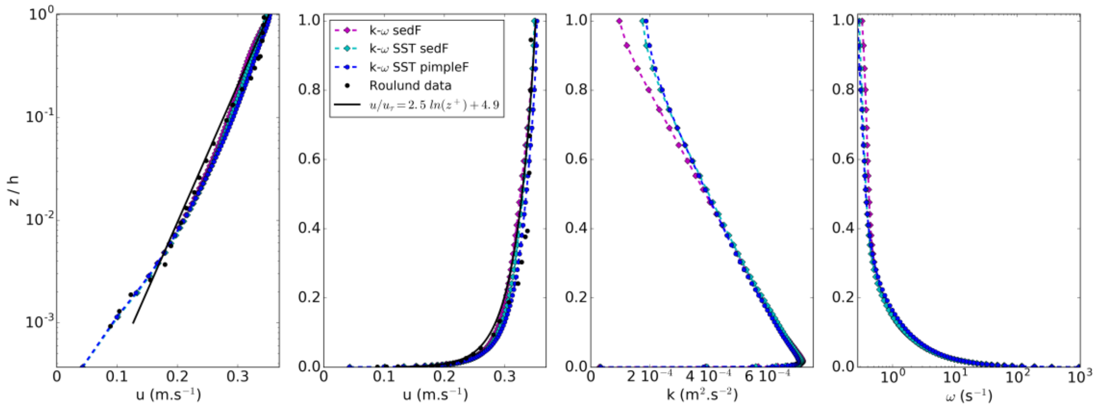


Figure 2. Comparison between pimpleFoam, sedFoam and Roulund *et al.* (2005) experimental data for velocity profiles in log and linear scales, TKE and specific dissipation rate ω using the k-ω and the k-ω SST turbulence models.

Figures 3 and 4 show a comparison of CW hydrodynamic simulations with Roulund *et al.* (2005) experimental and numerical results for longitudinal profiles of stream-wise (fig. 3) and wall-normal (fig. 4) velocities in the plane of symmetry at different elevations from the bed. The results have been averaged over 10 vortex shedding periods corresponding to approximatively 50 seconds of dynamic. Overall, the flow upstream the pile is in good agreement with Roulund *et al.* (2005) experimental data. The horseshoe vortex is very well captured by the k-ω SST model whereas it is underestimated by the k-ω model (see fig. 3). Downstream the pile, both turbulence models are able to capture the anti-clockwise circulation observed in the experimental results which was not reproduced by Roulund *et al.* (2005) steady numerical simulations (see fig 4.). This observation confirms the importance of unsteady flow simulations for this type of flow configuration (Stahlmann, 2013; Baykal *et al.*, 2015). Based on our numerical simulation results, the k-ω turbulence model underestimates the horseshoe vortex extension while the k-ω SST model underestimates the recirculation cell size at the downstream side of the pile. Despite these discrepancies, the hydrodynamic results are satisfactory enough to give confidence in the two-phase flow solver and the model will be used in the next section to simulate the LB case with sediments.

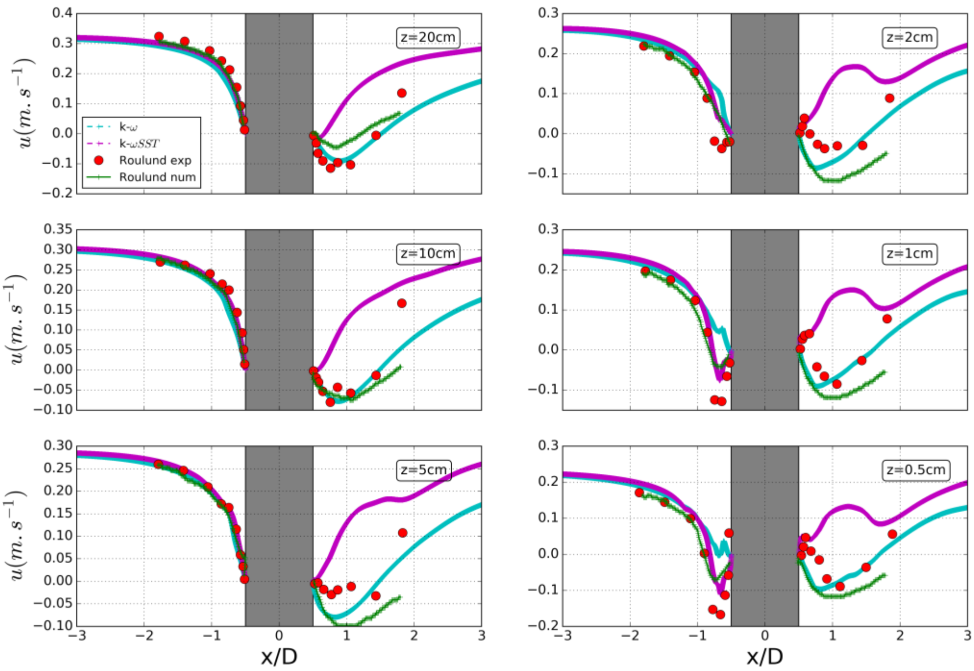


Figure 3. Horizontal (u) velocities in the plane of symmetry at different distances from the bed.

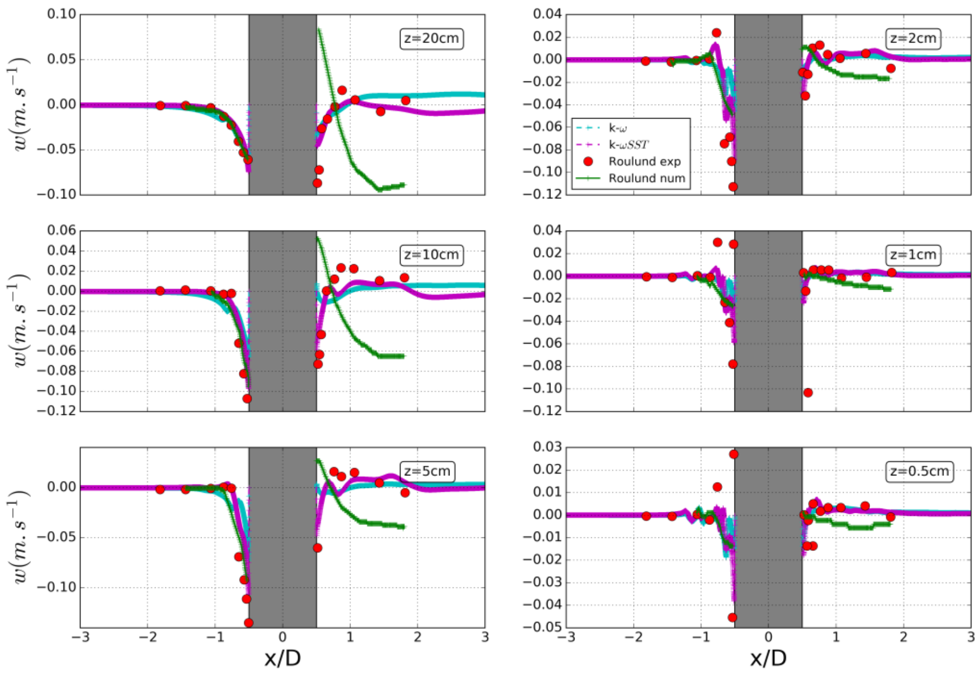


Figure 4. Vertical (w) velocities in the plane of symmetry at different distances from the bed.

3.2. *Scour simulations*

The same procedure as for the CW case is used for the LB case, 1D vertical simulations are performed to set-up the initial and inlet boundary conditions for the 3D case. The 1D vertical LB case has the same set-up as the 3D case, the water column is discretized using 64 vertical levels with the same geometric common ratio as for the CW case. In the sediment bed 50 vertical levels with r = 1.086 is used. The initial concentration profile is imposed using an hyperbolic tangent profile. The mean grain size diameter is d_{50} =0.26 mm.

Figure 5 shows the vertical profiles of velocity in linear and logarithmic scales, sediment concentration α and TKE using the k-ω turbulence model. The flow is driven by a pressure gradient computed from the estimated bed friction velocity from the experimental results (Roulund *et al.*, 2005). The differences observed between Roulund *et al.* (2005) experimental profiles (blue dots) and the numerical simulations can be explained by the presence of ripples at the bed that are not represented in 1D vertical simulations. The concentration profile exhibits a very sharp interface that requires a fine resolution to capture the vertical gradients (here 1.5×10^{-4} m).

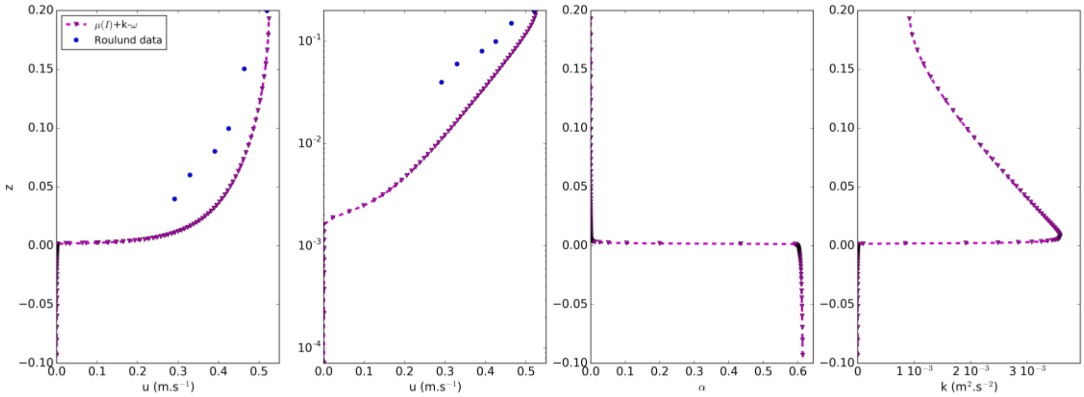


Figure 5. Velocity profiles in linear and log scales, sediment concentration α and TKE using the kω turbulence models for a two-phase flow simulation including sediment.

Figure 6 shows the vertical elevation of the isosurface of sediment concentration α = 0.57, a proxy for the quasi static bed elevation, after 50s of dynamic. The present results can be compared with the one described in figure 33 from Roulund *et al.* (2005). Qualitatively, the two-phase flow model is able to reproduce the following two topographic bed features described in Roulund *et al.* (2005):

- The upstream scour mark induced by the horseshoe vortex is predicted. The scour depth seems less pronounced than in Roulund *et al.* (2005) numerical predictions but the semi-circular shape is correctly predicted.
- The formation of a sediment accumulation downstream the pile induced by the deposition of the eroded sand from the scour mark.

Figure 7 shows a comparison of the time evolution of the upstream scour depth between the two-phase flow simulation and Roulund *et al.* (2005) numerical (blue curve) and experimental results (red dots) in which the experimental results from Roulund *et al.* (2005) are taken as the reference. The two-phase flow model is able to reproduce almost quantitatively the increase of the upstream scour depth with time, but the maximum scour depth values are slightly underpredicted compared with Roulund *et al.* (2005) experimental results. This could be due to the k-ω turbulence model that has been shown to significantly under-predict the horseshoe vortex in the CW case (see figure 4) which is known to be the main cause for the upstream scour process (Baykal *et al.*, 2015). Figure 7 also shows an abrupt decrease in scour depth between t=26s and t=29s, the dimensionless scour depth change from 0.24 to 0.11. After this event the dimensionless scour depth increases gradually up to 0.22 at t=54s, where a second abrupt decrease is taking place. These events occur when the upstream slope angle of the scour hole, bottom panel in figure 7, exceeds the angle of repose (blue dashed line). This indicates that an avalanching process is taking place. In the present case, the value of the static friction coefficient (μ_s=0.4) used in the dense granular flow rheology (Chauchat *et al.*, in prep.) corresponding to an angle of repose is of 21.8°. This value is noticeably lower that the observed value in Roulund *et al.* (2005) experiments in which the observed angle is around 30°. A sensitivity analysis on the rheological parameters will be performed in a near future.

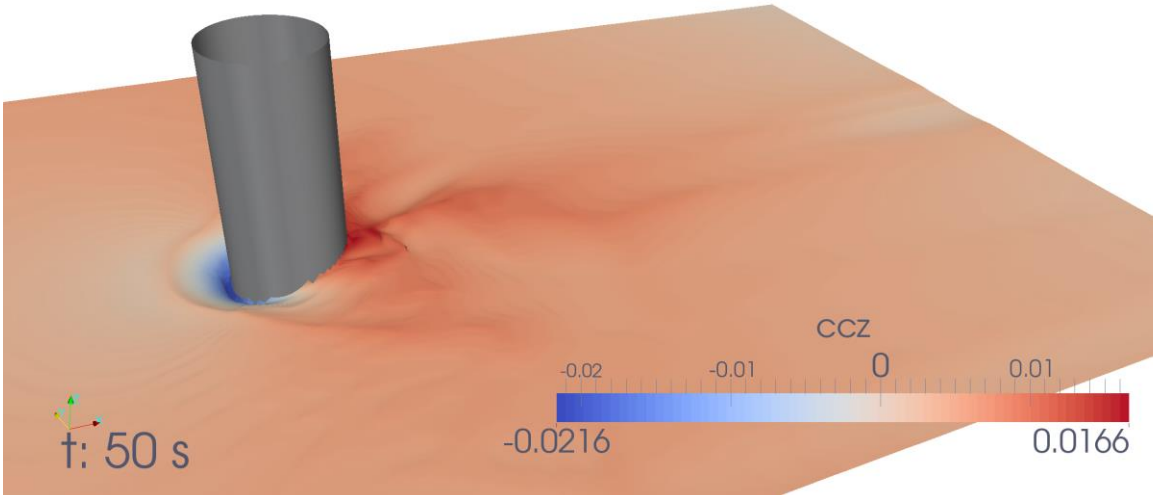


Figure 6. Bed elevation after 50s of dynamics using the k-ω turbulence model.

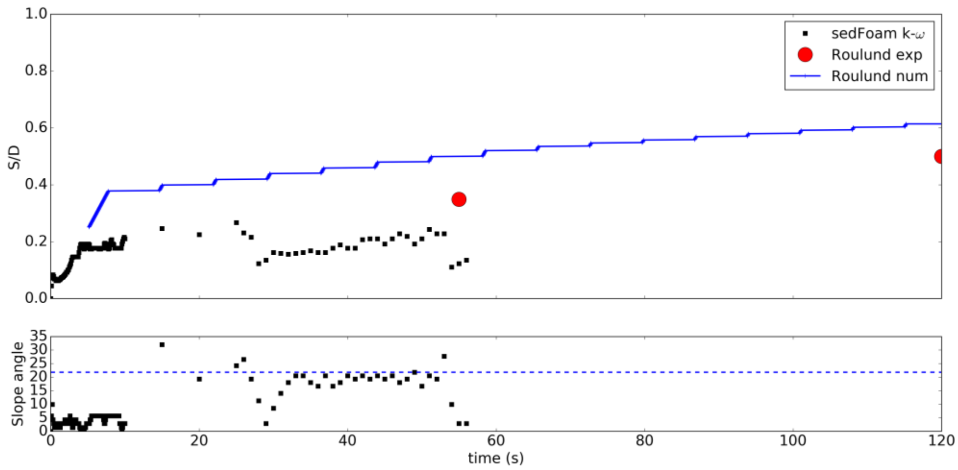
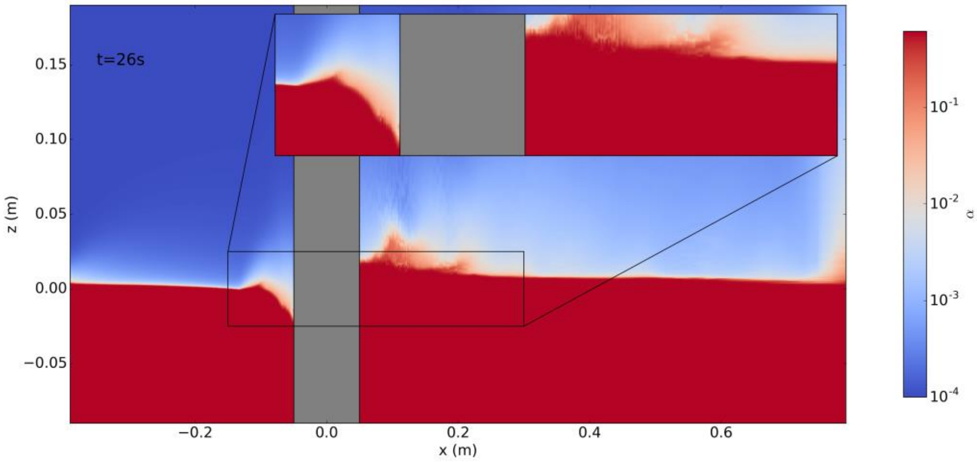
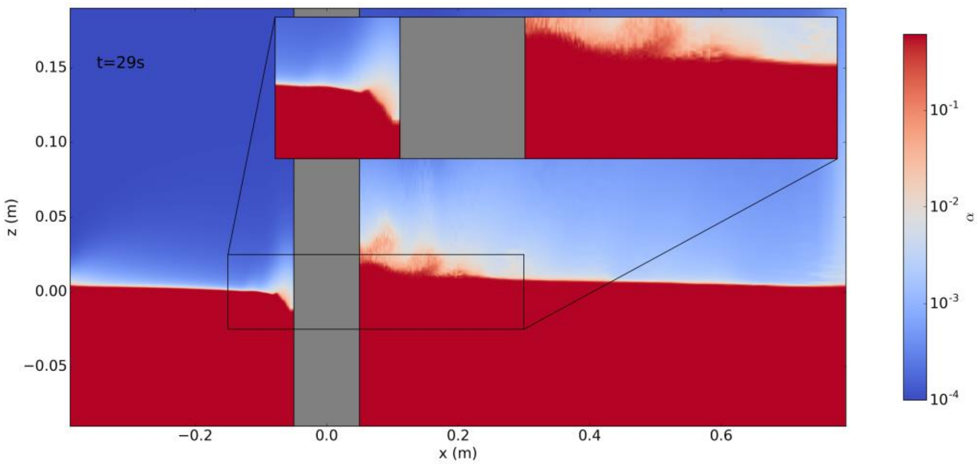


Figure 7. Top panel: Time evolution of the dimensionless scour depth at the upstream edge of pile, Bottom panel: slope angle of the upstream side of the scour hole, the blue dashed line corresponds to the angle of repose of the rheology.

The avalanching phenomenon has also been reported in Roulund *et al.* (2005) experiments. Figure 8 shows 2D color-plot of concentration in log scale in the symmetry plane of the domain. At t=26s the bed slope at the upstream side of the scour hole is steeper than the one observed at t=29s, this time evolution of the bed slope is a signature of the avalanching process. At the downstream side of the pile, a strong sediment suspension dynamic is predicted by the two-phase model under the influence of the vortex-shedding. The importance of the suspended sediment transport in this scour configuration has been demonstrated by previous studies (Stahlmann, 2013; Baykal *et al.*, 2015). Qualitatively, the suspended load dynamic is captured by the two-phase flow model. Further work is needed to improve the two-phase flow model predictions.



(a)



(b)

Figure 8. Sediment concentration in the plane of symmetry at t=26s (a) and t=29s (b).

4. ***Conclusion***

In this paper, the multi-dimensional two-phase flow model sedFoam (Cheng *et al.*, 2017; Chauchat *et al.*, in prep.) has been validated on Roulund et al. (2005) datas for the flow around a vertical cylinder in clear water. As reported in Stahlmann (2013) or Baykal *et al.* (2015), most of the discrepancies reported in Roulund et al. (2005) can be overcome by using an unsteady solver. However, some questions remain on the validation of the k-ω SST at the lee-side of the cylinder.

The first application of sedFoam to the live-bed configuration qualitatively reproduce the first minute of the scour phenomenon, *i.e.* the scour upstream the pile, the avalanching process and the sediment accumulation downstream the cylinder are predicted. Quantitatively, the scour depth upstream the pile is slightly underestimated by the model. This is probably due to the k-ω turbulence model used here, which underestimates the horseshoe vortex intensity. From the clear water study it seems that the use of a k-ω SST turbulence model is required to improve the Live-Bed simulation results.

In conclusion, we would like to remind that two-phase flow simulations are extremely time consuming, so far we have been able to run the code for about 60 seconds of dynamics. The computational time for this simulation is about 6,000 CPU hours for 10 seconds of dynamics on the Ciment regional cluster[9].

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