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SEDFOAM, A OPENFOAM SOLVER FOR SEDIMENT TRANSPORT

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Sediment transport is the main process that drives the morphological evolution of fluvial and coastal environments. Consequently, the ability to predict sediment transport is a major societal issue for the management of natural systems in order to limit and prevent the impacts related to extreme events exacerbated by climate change and human activities such as construction of hard structures (dams, harbors, dikes, *etc.*), land reclamation, and dredging.

During the past two decades, an increasing amount of research efforts are devoted to develop two-phase flow models for sediment transport. In this two-phase flow approach, dynamical equations are solved for both the fluid phase (water) and the particle phase (sediment), with the latter being seen as a continuous phase dispersed in the fluid.

The purpose of the present contribution is to follow up on [1] work by adding new capabilities to the open-source model sedFoam. In particular, the mixing length turbulence model and dense granular flow rheology used by [2] and [3] for sheet flows have been implemented. In addition, we implemented and tested the $k - \omega$ turbulence model for two-phase flow sediment transport modeling purposes. Our final goal is to provide a comprehensive numerical framework that solves the two-phase flow equations in three dimensions with the capability to select different combinations of turbulent model and granular stress model for sediment transport applications. By disseminating the numerical model in the open-source framework, in the long run, we expect new capabilities will be added to the model by the scientific community. We strongly believe that developing such an open-source community model is the only effective way to make significant progress.

1 Mathematical and numerical formulations

The mathematical formulation of the Eulerian two-phase flow model is obtained by averaging local and instantaneous mass and momentum conservation equations over fluid and dispersed particles. Different averaging operators can be used, ensemble averaging [4] or spatial averaging [5], and provided that the mathematical derivation is done properly the different approaches should lead to the same conservation equations [6, 7]. The resulting governing equations can be considered as the counterpart of the clear fluid Navier-Stokes equations for single phase flow. In order to apply these equations to turbulent flow, in which turbulent motions are generated by flow shear much larger than the grain scale, additional turbulence averaging or filtering is required. In the present model, turbulence-averaged Eulerian two-phase flow equations are derived by following a similar procedure presented in [8, 9].

The momentum equations for fluid and particle phases can be written as:

$$\frac{\partial \rho^a \alpha u_i^a}{\partial t} + \frac{\partial \rho^a \alpha u_i^a u_j^a}{\partial x_j} = -\alpha \frac{\partial p}{\partial x_i} + \alpha f_i - \frac{\partial \tilde{p}^a}{\partial x_i} + \frac{\partial \tau_{ij}^a}{\partial x_j} + \alpha \rho^a g_i + \alpha \beta K (u_i^b - u_i^a) - S_{US} \beta K \nu_t^b \frac{\partial \alpha}{\partial x_i}, \quad (1)$$

$$\frac{\partial \rho^b \beta u_i^b}{\partial t} + \frac{\partial \rho^b \beta u_i^b u_j^b}{\partial x_j} = -\beta \frac{\partial p}{\partial x_i} + \beta f_i + \frac{\partial \tau_{ij}^b}{\partial x_j} + \beta \rho^b g_i - \alpha \beta K (u_i^b - u_i^a) + S_{US} \beta K \nu_t^b \frac{\partial \alpha}{\partial x_i}, \quad (2)$$

where ρ^a, ρ^b are particle and fluid density, respectively, g_i is the gravitational acceleration and p is the fluid pressure. f_i is the external force that drives the flow. The fluid stress τ_{ij}^b includes fluid grain-scale (viscous) stress and fluid Reynolds stresses and \tilde{p}^a, τ_{ij}^a are particle normal stress and shear stress. The last two terms on the right-hand-side (RHS) of equations 1 and 2 correspond to the momentum coupling between the fluid phase and particle phase through drag force, where K is the drag parameter. In particular the second to the last term represents averaged drag force due to mean relative velocity between fluid and particle phases, while the last term represents the fluid turbulent suspension term, also called drift velocity by [10]. This term is due to the correlation of sediment concentration and fluid velocity fluctuations and the gradient transport assumption is adopted here for its closure. Hence, ν_t^b is the turbulent viscosity to be calculated using a turbulence closure, and $S_{US} = 1/\sigma_c$ is inverse of the the Schmidt number. This term is equivalent to the turbulent suspension flux of the Rouse profile in the two-phase flow formalism (see [3]).

The numerical implementation of the present Eulerian two-phase flow sediment transport model is based on the open-source finite volume CFD library called OpenFOAM. The numerical solution procedure for the proposed two-phase flow model is outlined as follow:

1. Solve for sediment concentration α (and update the volume concentration of fluid: $\beta = 1 - \alpha$);
2. Update the drag parameter K in the drag term;
3. Solve for the fluid turbulence closure, update k , ε or ω (depends on the turbulence closure), and then calculate the eddy viscosity and effective fluid total viscosity;
4. Solve for the particle phase stress (kinetic theory model or the dense granular rheology);
5. Classical PISO-loop, solving velocity-pressure coupling for N loops
6. Advance to the next time step

From our experience, three iterations ($N=3$) is usually enough for a convergence. The finite volume discretisation of the equations have not been shown here but all the details can be found in [11] and [12].

2 Model verification and benchmarking

In this section, the laminar bed-load problem, for which an analytical solution exists, is used as a benchmark to validate/verify the numerical implementation of the model.

The test case is inspired by [13] in which an analytical solution for laminar bed-load driven by a Poiseuille flow has been used to verify a three-dimensional numerical model. The solution is based on a Coulomb rheology for the solid phase and the Einstein's mixture viscosity for the fluid phase ([14]).

The numerical domain setup is based on [15] experimental configuration. The channel height is $h_0 = 0.065$ m, the particles are made of PMMA with a density $\rho^a = 1190$ kg/m³ and a diameter $d = 2 \times 10^{-3}$ m. The fluid density is $\rho^b = 1070$ kg/m³ and the kinematic viscosity is $\nu^b = 2.52 \times 10^{-4}$ m²/s. The pressure gradient is fixed to $\text{gradPMEAN}=100$ kg.m⁻².s⁻². The vertical domain is discretized into 200 uniform cells, and the time step is $\Delta t = 10^{-3}$ s. The lateral boundaries are set to cyclic while the front and back boundaries are set to empty (*i.e.* 2D problem). The velocity of both phases are set to zero at the top and bottom boundaries while the pressure is fixed to zero at the top boundary and a fixedFluxPressure condition is imposed at the bottom boundary.

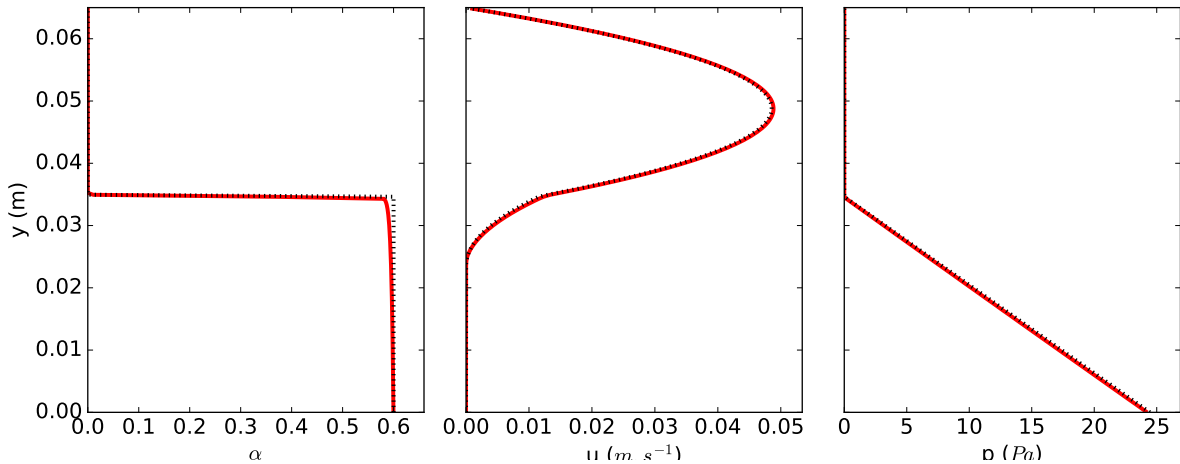


Figure 1: Comparison of the streamwise velocity profiles for the flow of a Newtonian fluid over a granular bed having a Coulomb rheology between two infinite parallel planes obtained by numerical simulations with the analytical solution of [14] in terms of sediment concentration (left panel), velocity profiles (middle panel) and particle pressure (right panel) profiles.

Figure 1 shows the comparison of the numerical solution with the analytical solution from [14] in terms of sediment concentration (left panel), velocity (middle panel) and particle pressure (right panel) profiles. In the analytical solution, the sediment concentration profile is a step function with no particles in the upper half of the domain and with the maximum packing concentration in the lower half. The two-phase numerical model, based on continuous assumptions, is not able to reproduce exactly this sharp sediment concentration transition. This is due to the fact that the sediment concentration profile is obtained using the momentum balance between the gravity and the permanent contact contribution to the particle pressure. Despite this slight discrepancy, the numerical solution in terms of velocity profiles is in very good agreement with the analytical solution. Because the granular phase viscosity is directly related to the particle pressure, the key issue for the granular rheology model is to accurately predict the particle pressure hydrostatic profile. The comparison presented

in the right panel shows that even if the agreement in sediment concentration profile is not perfect, the particle pressure profile is very close to the analytic solution. This explains the very good numerical prediction of the velocity profile.

A second benchmarking case has been used but is not presented here. It concerns the pure sedimentation of a suspension of non-cohesive spherical particles for which experimental data are available. The agreement between the numerical simulation results and the experiments is very good.

3 Applications : Scour at an apron

In this section we present the application of model to the development of the scour downstream an apron. Following the numerical study of [16] and [1], the problem has been simplified.

The sediment bed is made of sand, density $\rho^a = 2650 \text{ kg.m}^{-3}$ and diameter $d = 0.25 \times 10^{-3} \text{ m}$. The fluid is water with density $\rho^b = 1000 \text{ kg.m}^{-3}$ and kinematic viscosity $\nu^b = 10^{-6} \text{ m}^2.\text{s}^{-1}$. The flow depth is fixed to $h_0 = 0.15 \text{ m}$, and the initial bed depth is $h_b = 0.05 \text{ m}$. As initial condition, the velocity of both phases, the sediment concentration, the TKE and the TKE dissipation variables (ε or ω) are set based on one-dimensional simulation results using funkySetFields.

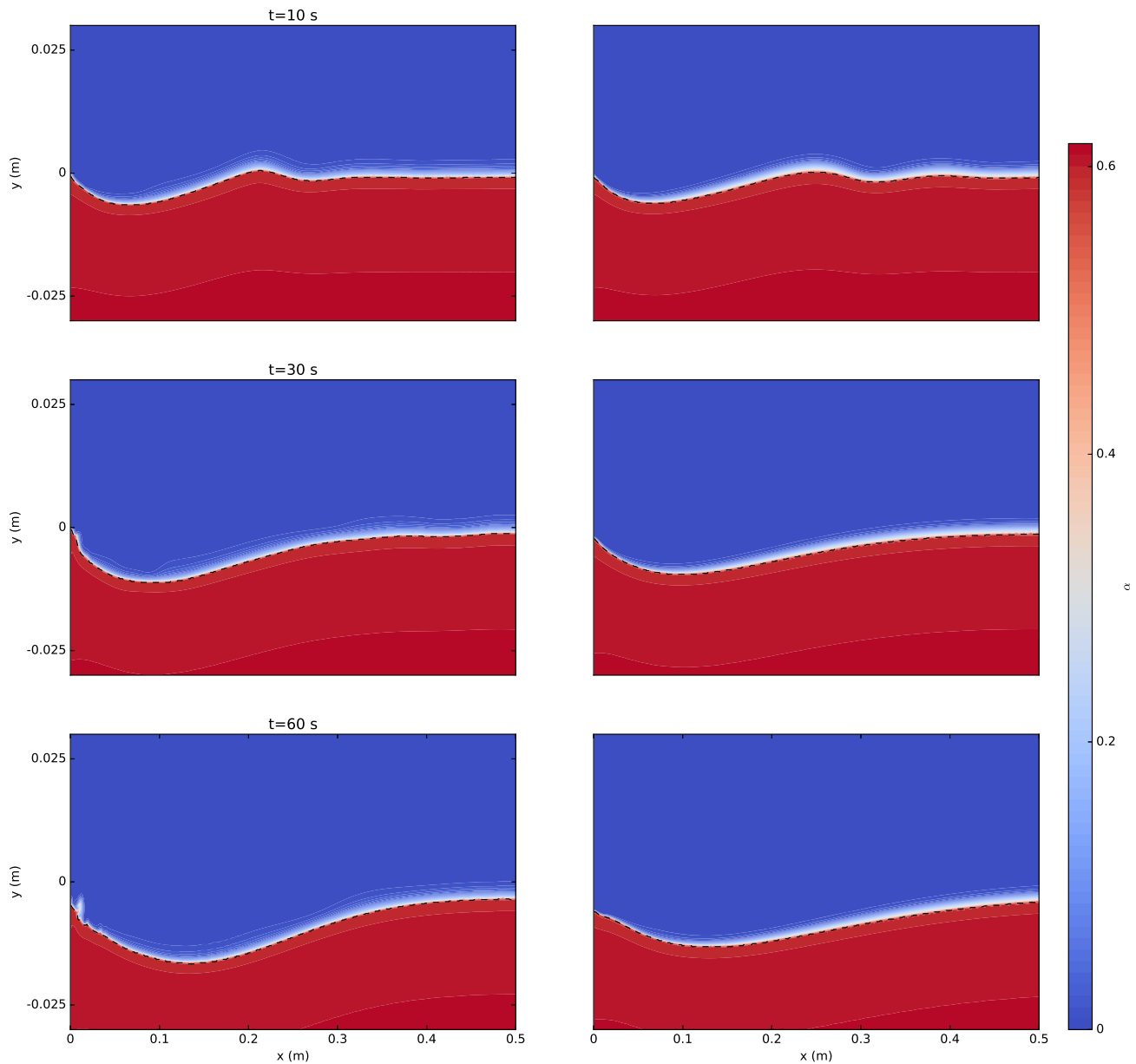


Figure 2: Sediment concentration contour at different time during the scour process using $k-\varepsilon$ and kinetic theory (left panels) and $k-\omega$ and $\mu(I)$ granular rheology (right panels).

According to experimental studies [17, 18], the development of the scour hole is rapid at the initial stage, and eventually reaches an equilibrium state. The result presented in figure2 show the scour mark using two combinations of turbulence and granular stress models, the $k-\epsilon$ with the kinetic theory on the left and the $k-\omega$ with the granular rheology on the right panels. The time evolution of the scour mark has been compared with previous two-phase numerical results and the proper scaling laws are retrieved by sedFoam.

This test case shows the capabilities of the proposed two-phase flow model to deal with multi-dimensional flow configurations. Further work is needed to improve the model validation as well as the model sensitivity to flow turbulence and rheological parameters. This requires more detailed experimental data that, to the best of our knowledge, are not available at present.

4 conclusions

A comprehensive two-phase flow model for sediment transport applications has been presented. The proposed model provides different options for the modeling of flow turbulence (mixing length, $k-\epsilon$ or $k-\omega$) and inter-granular stress (kinetic theory of granular flows or dense granular flow rheology). The dense granular flow rheology is implemented using a regularization technique and is verified against an analytical solution for the laminar bed-load problem. The application on scour allows to illustrate the multi-dimensional capabilities of the solver. In light of these model applications, some questions remain on the optimum values of the turbulence model coefficients, which will need more high resolution measurements, for a wide range of flow conditions. The open-source numerical model presented here is expected to facilitate this endeavor in the future.

As a general conclusion, the aim of this contribution is to provide a comprehensive two-phase flow sediment transport modeling framework to the scientific community. Intense efforts have been made to ensure its reliability and numerical robustness. This numerical tool is suitable to address various physical problems for which the classical sediment transport approach is not working very well or require more model assumptions. However, the readers are reminded that two-phase flow simulations are still relatively time consuming and require finer spatial resolution and smaller time steps than classical sediment transport models. We encourage more contributions to the model development from the community effort, and we will be delighted to integrate them in the future releases of sedFoam.

5 Code availability

The code is available at <https://bitbucket.org/sedfoam/sedfoam> and the python package for postprocessing of the tutorials is available at <https://bitbucket.org/sedfoam/fluidfoam>.

Post processing was done using Python-scripts including the pyof/fluidFoam package.

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