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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/103823

Vorgeschlagene Zitierweise/Suggested citation:
Chauchat, J.; Nguyen, K. D.; Guillou, Sylvain (2006): Numerical simulation of the water-sediment mixture flow in a cyclic channel by a two-phase model. In: Technische Universität Dresden, Institut für Wasserbau und technische Hydromechanik (Hg.): Strömungssimulation im Wasserbau (Flow Simulation in Hydraulic Engineering). Dresdner Wasserbauliche Mitteilungen 32. Dresden: Technische Universität Dresden, Institut für Wasserbau und technische Hydromechanik. S. 229-236.

Numerical simulation of the water-sediment mixed flow in a periodic open channel by a two-phase model

J. Chauchat, S. Guillou and K. D. Nguyen

The two-phase approach (fluid-solid) is an interesting one in modelling sediment transport process. This paper presents the application of such a model for simulating water-sediment mixed flows in a periodic open channel, for which some experimental data are available. Particularly, the results obtained by the model show the importance of turbulence in the transport process. Thus, a drift velocity, which is due to the correlation between the instantaneous particle distribution and the fluid velocity fluctuations, is introduced. This is necessary to improve the numerical results.

1 Introduction

Management of coastal zones and estuaries requires more and more accurate models for cohesive sediment (mud) transports to cope with various problems (e.g. wetland protection and restoration, maintenance of navigation channels, impacts of construction works, dispersion of pollutants, etc.). Nowadays, there are mainly two approaches for sediment transport modelling : single and two-phase flow ones. In the first approach, sediment is considered as a passive scalar. The solid particles move at the same velocity as that of the fluid ones, except on the vertical, a settling velocity for the sediments is introduced as a function of the concentration. Usually a virtual bottom is considered under which a bed layer model can be used to take into account the consolidation processes. Therefore, exchange fluxes of sediment between the water column and the bed layer are imposed. In the two-phase approach, the suspension is treated as a mixture of fluid and solid particles. Conservation equations for mass and momentum are successively solved for each phase. The computational domain extends from the true non-erodible bottom to the free surface. Therefore interactions between fluid-solid particles and fluid-bottom will be naturally taken into account

The two-phase flow concept is an interesting approach, but presently it is not very developed. This is because the physical processes related to sediment transport are very complex, in which many problems are not parameterised yet. In this paper, we present an adaptation of a two-phase flow model (*Barbry et al.*, 2000), to a periodic open channel, in which the phenomenon such as the suspended-sediment transport, the sedimentation and the consolidation have been experimentally studied. Particularly, the influence of the drift velocity as well as of its parameterisation on modelling of suspended-sediment transports
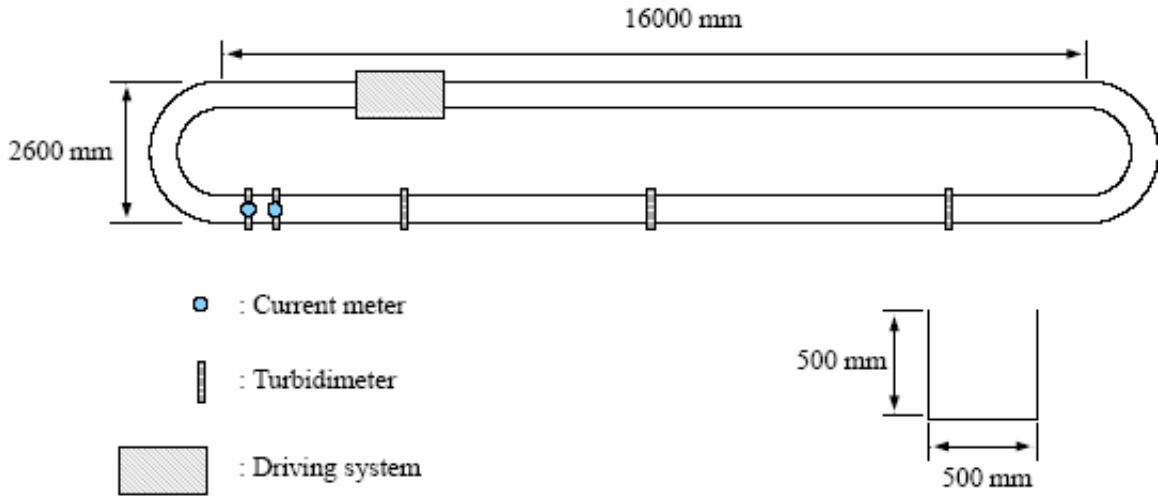
and sedimentations will be analysed.

FIG. 1 – Experimental configuration

The experimental configuration is presented on Figure (1). It is an oval channel of 38 meters of length with a rectangular cross section of 0.5 m of width (SOGREAH). Currents are generated by 8 vertical disks in rotation (1.1 m diameter) partially immerged. Current velocities are measured by the mechanical current meters and suspended-sediment concentrations are gauged by five turbidimeters. The experimental results used here were obtained for a mean mixture velocity of 7 cm/s and an initial homogeneous concentration of 30 g/l.

2　Mathematical background

In the two-phase model used, mass and momentum conservation equations (Eq. 1) and (Eq. 2) are written considering the Eulerian approach for each phase (solid and fluid). Where $\alpha_k, \mathbf{u_k}, \rho_k$ is the volume fraction, the velocity vector and the density of phase k. $\mathbf{g}$ is the acceleration of gravity. $p_k, \overline{\overline{\tau_k}}$ represents the pressure and stress tensor respectively. $\mathbf{M_k}$ is the momentum exchanged between fluid and solid phases (Eq. 3) such as drag force (Eq. 5).

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla.(\alpha_k \rho_k \mathbf{u_k}) = 0 \tag{1}$$

$$\frac{\partial(\alpha_k \mathbf{u_k})}{\partial t} + \nabla(\alpha_k \mathbf{u_k} \mathbf{u_k}) = \frac{1}{\rho_k}\{-\nabla(\alpha_k p_k) + \nabla(\alpha_k \overline{\overline{\tau_k}})\} + \alpha_k \mathbf{g} + \mathbf{M_k} \tag{2}$$

$$\mathbf{M_k} = p_{ki}\nabla\alpha_k - \bar{\bar{\tau}}_{ki}\nabla\alpha_k + \mathbf{M_k'} \tag{3}$$

$$p_{ki} = p_f - \frac{1}{4}\rho_f \mid \mathbf{u_f} - \mathbf{u_s} \mid \; ; \; \bar{\bar{\tau}}_{ki} = \beta\bar{\bar{\tau}}_f \tag{4}$$

$$\mathbf{M_s'} = -\mathbf{M_f'} = \frac{3}{4}\frac{\alpha_s\rho_f C_D}{d}\mid\mathbf{u_{rel}}\mid\mathbf{u_{rel}} \tag{5}$$

$$\mathbf{u_{rel}} = \mathbf{u_f} - \mathbf{u_s} + \mathbf{u_d} \tag{6}$$

$$\mathbf{u_d} = -\bar{\bar{D}}\frac{\nabla\alpha_s}{\alpha_s} + \bar{\bar{D}}\frac{\nabla\alpha_f}{\alpha_f} \tag{7}$$

$$D_{ij} = t_c(u_{rel_i})\overline{u'_{fi}u'_{sj}} \; ; \; t_c(u_{rel_i}) = t_f\gamma_c(u_{rel_i}) \; ; \; t_f = \frac{3}{2}c_\mu\frac{k_f}{\varepsilon_f} \tag{8}$$

$$\gamma_c(u_{rel_i}) = \left(1 + C_\beta\sqrt{(u_{rel_i})^2/\frac{2}{3}k_f}\right)^{-0.5} \tag{9}$$

$$\overline{w_f'^2} = u_*^2 D_f C_v e^{-1.34z/h} \tag{10}$$

The formulae proposed by *Clift and Gauvin* (1970) is used to estimate the drag coefficient C_D, whereas, the one proposed by (*Graham*, 1981) is employed to model the amplification factor β for viscous strain. This parameter takes into account the non Newtonian characteristic of the flow when α_s reach high values. The total mass conservation $\alpha_f + \alpha_s = 1$ should be ensured. The kinematic and dynamic conditions are imposed on the free surface. On the bottom, a reflection condition for the pressure and a no-sleep condition for the mixed velocity are specified.

Following *Deutsch and Simonin* (1991); *Kaftori et al.* (1996); *Greimann and Holly* (2001), a drift velocity is introduced ($\mathbf{u_d}$) in the equation for the relative velocity (Eq. 6). This velocity is a result of a diffusive flux caused by the correlation between the instantaneous particle distribution and the fluid velocity fluctuations. Here the drift velocity is given by equation (Eq. 7) where t_c is the integral time scale associated with the duration that a particle spends in a fluid eddy, t_f is the integral turbulent fluid time scale. k_f and ε_f are the turbulent kinetic energy and the dissipation of turbulence respectively. $c_\mu = 0.09$ is the classical $k - \varepsilon$ model constant for the fluid phase. γ_c is a coefficient typically lower than unity, meaning that the correlation time scale (t_c) is lower than the turbulent fluid time scale. The parameter C_β expresses the fact that the diffusive effect is more efficient in the flow direction than in the transversal direction, so $C_\beta = 1$ in the flow direction and $C_\beta = 2$ in the orthogonal direction. The main issue is to estimate the correlation $\overline{u'_{fi}u'_{sj}}$. *Greimann and Holly* (2001) assumed that the

correlations of the fluid-solid velocities are equal to the correlations of the fluid velocities $\overline{u'_{fi}u'_{sj}} = \overline{u'_{fi}u'_{fj}}$, for dilute cases. This assumption may overestimate the fluid-solid correlation, because the sediment has not a fully respond to the fluctuations of the fluid. However, to model this correlations in wall-bounded flows, it would be necessary to solve transport equations for each component of $\overline{u'_{fi}u'_{sj}}$ (Simonin, 1991). Here, the fluid correlation on the vertical direction is estimated by the formulation proposed by Greimann and Holly (2001) (Eq. 10). Where u_* is the shear velocity, $C_v = 1.51$ is a constant and $D_f = \sqrt{\kappa/\kappa_c}$ is a damping factor of the turbulence due to the presence of sediment. κ_c designate the Von Karman constant for clear water and κ is the Von Karman constant in presence of sediment.

The model used here is a modification of the one proposed by Barbry et al. (2000). Succinctly, it uses a fractional step algorithm, coupled with a finite difference formulation, and an adaptative eulerian mesh in order to fit the computed mesh to the free water surface (Guillou et al., 2000). The periodic boundary condition is treated with an overlapping-zone technique. The presence of the driving system is modelled by introducing a volumic forcing term in the horizontal equation of momentum conservation. The forcing term is evaluated using a fixed-point algorithm and by imposing the specified velocity (Guillou, 2005). The mesh is composed of 66 nodes in the horizontal direction and 21 nodes in the vertical direction with a refinement near the bottom. Here, the cohesive properties of the sediment are not considered and the particules are $15\,\mu m$ diameter with a density of $2650\ kg/m^3$.

3   Results and Discussion

Figure (2) shows the velocity field at two different moments. The initial condition is set at rest. The velocity field converges to a stationary state after few minutes. Obviously, the flow in such a configuration is fairly reproduced. Then, an initial well-mixed concentration of $30\ g/l$ of sediments is introduced in the open channel. Figure (3) shows the numerical and experimental comparison of the velocity profile. The numerical profile is in a good agreement with the measures, ensuring that the model correctly reproduces the vertical hydrodynamic structure of the flow.

Figure (4), and (5) show the experimental and numerical concentration profiles at different moments without and with the drift velocity, respectively. Figure (4) shows the formation of two distinct interfaces : one near the bottom, and another near the water surface. In the lower layer, the concentration reaches $500\ g/l$
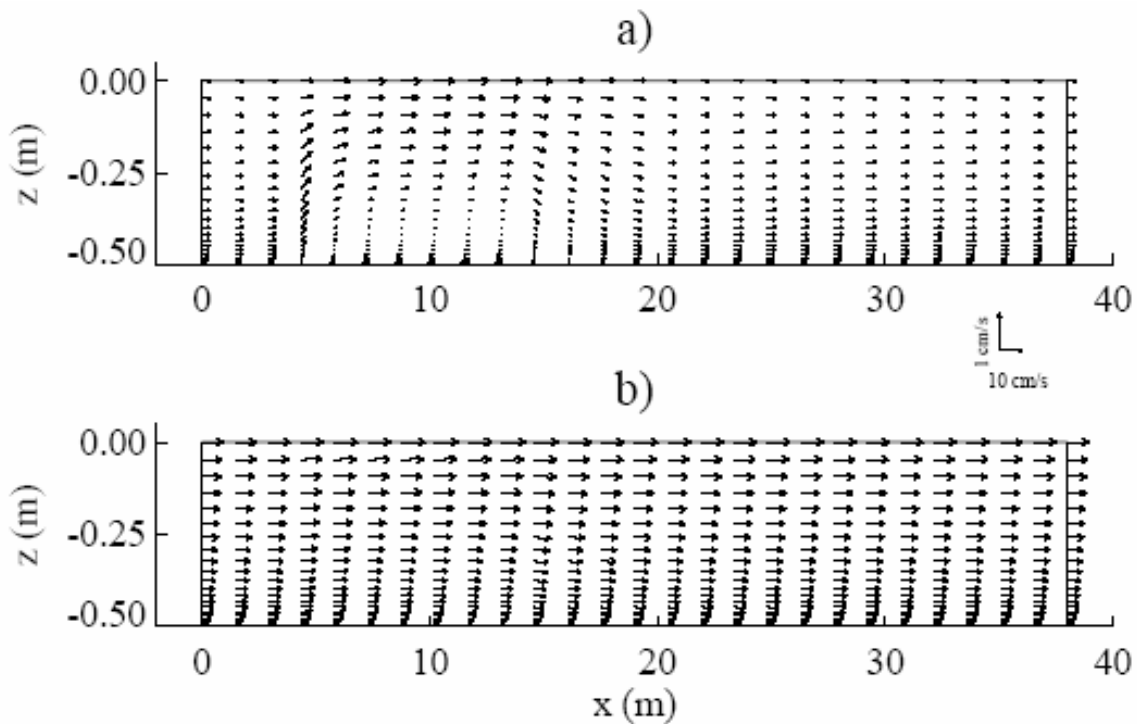
a)

b)

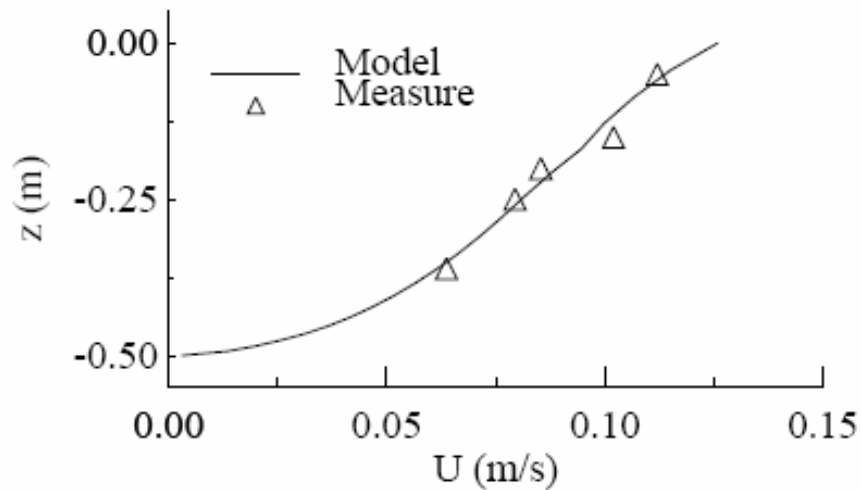FIG. 2 – Velocity field : a) t = 4 min and b) t = 33 min

FIG. 3 – Velocity profile at t = 35 min

after 30 minutes. Hence, a highly concentrated sediment bottom is formed. On Figure (5) there is no distinct interface observed on the concentration profiles. After 15 minutes, the numerical results are in a good agreement with the measures yet. However, at 30 minutes the numerical results slightly diverge from
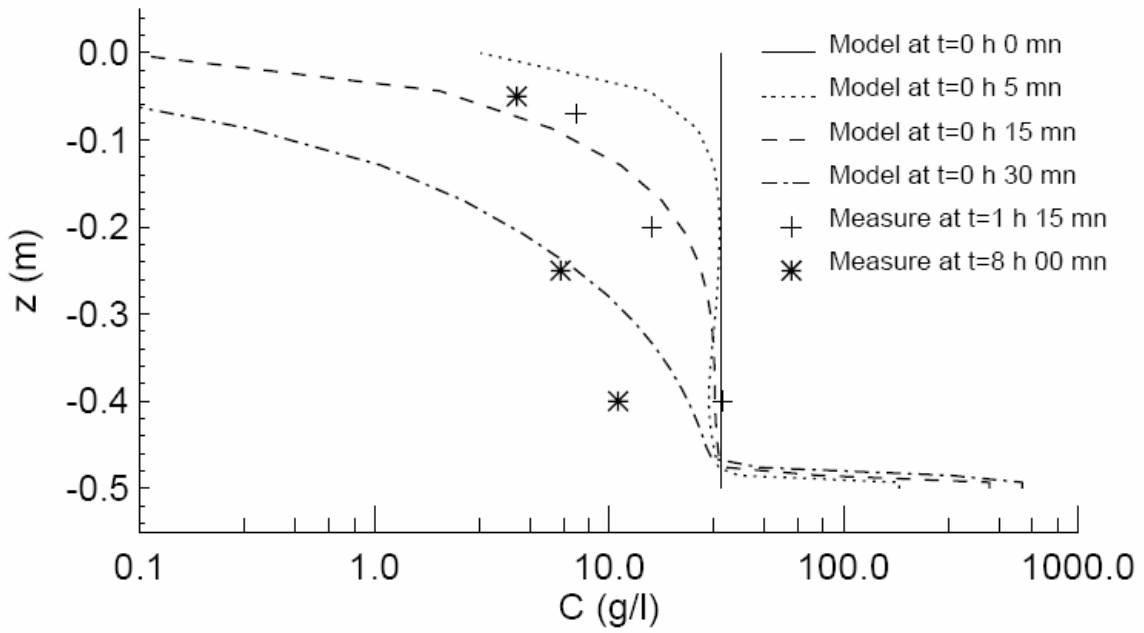
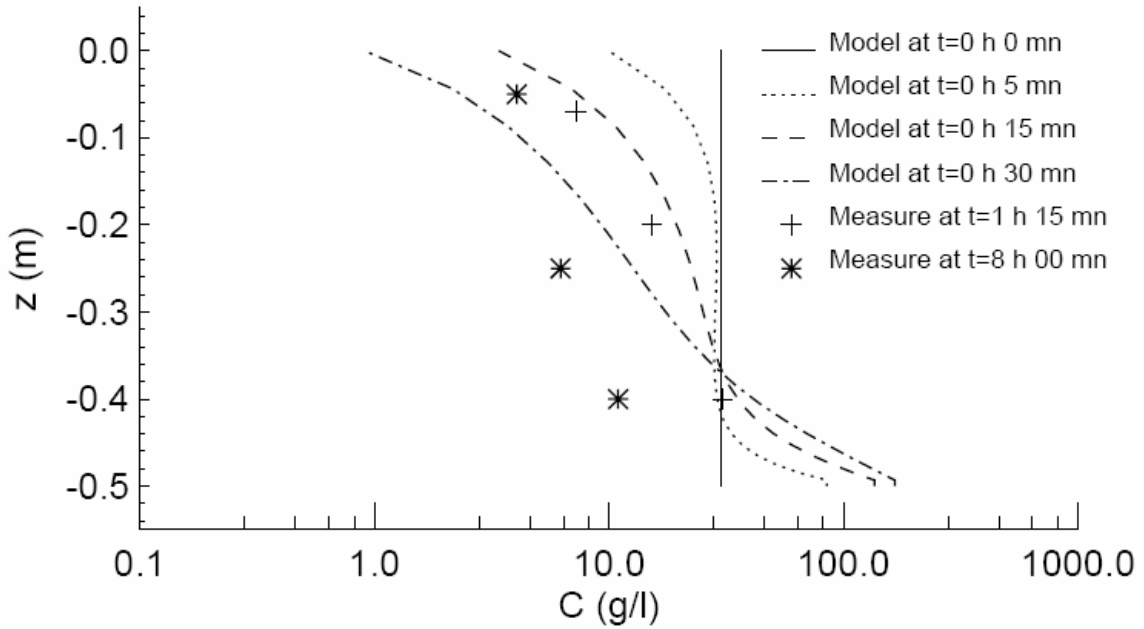FIG. 4 – Concentration profiles at different moments without drift velocity

FIG. 5 – Concentration profiles at different moments with drift velocity

the measures, especially in the lower part of the channel, where the gradient of sediment concentration is very low in comparison with the experimental data.

The qualitative comparison between the two simulations, with and without drift velocity, shows the impact of this parameter on the behaviour of suspended sediments. Without drift velocity, the sediment concentration diminishes in the upper layer of the channel and the concentration profiles do not fit the experimental measures. It was observed experimentally that a large part of the sediments is kept in suspension by the flow. When the drift velocity is included, the concentration profile in the upper part of the flow is closed to the observations at 15 minutes, showing that this parameter is essential to correctly simulate the behaviour of suspended sediments.

However without drift velocity, in the lower part of the flow, the concentration profiles obtained correspond to the classical order of magnitude near the bottom. The lower part of the concentration profiles obtained with the drift velocity model is open to criticism. It is necessary to keep in mind that the closure relationships used in equation (Eq. 10) are valid for dilute flows, which is obviously not the studied case here.

4 Conclusion

In conclusion, the two-phase approach is a promising one to simulate suspended-sediment transports and sedimentation processes, even if it needs an important CPU time. All the parameters for the sediment transport modelling are not yet studied and understood. These preliminary results show the importance of the drift velocity in modelling the behaviour of suspended sediment by a two-phase approach. Obviously the role of drift velocity in sediment transport merits to be more studied in the future. A possible researching direction would be the development of a turbulence sub model for the solid phase for a correct parameterisation of turbulent interaction between fluid-solid and solid-solid particles.

Acknowledgements

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