Numerical modelling with Wolf2D of the sedimentation problem at the entrance of a lock on the river Meuse.

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Abstract

This paper presents the resolution of a practical hydraulic engineering problem thanks to effective numerical tools. A sedimentation study of the lock of Hun (river Meuse, Belgium) is completed using solid transport models integrated in a finite volume free surface flows solver. The silting of the lock entrance is successfully modelled and various layout modifications of the site are tested to predict their effects and to see to what extent they could improve the actual situation. The analysis of the results shows that a regular dredging of the lock entrance is ineluctable.

Keywords: bed load, suspended load, sediment transport, numerical modelling, finite volume, river flow

1 Introduction

In the field of flow modelling, numerous models are available, and it is now possible to accurately represent many phenomena such as solid transport, pollutant transport,… Engineers have access to a broad range of tools they didn't have a few decades ago. Many problems in hydraulics can be studied thanks to numerical simulations. In this paper, the application of a sediment transport model in a quasi-3D flow modelling tool to a lock site on the river Meuse is presented.

Many mathematical models which represent complex phenomena like solid transport need the knowledge of several parameters in order to run properly. When establishing these models, the scientists often rely on well instrumented experiments. But in many practical problems, the needed data are frequently missing and the parameters appearing in the models equations can hardly be calibrated. In fact, engineers have access to a huge quantity of models, but frequently have to adapt them or make working hypotheses in order to solve the problems they face. Having good models is an essential part when studying a problem, but the engineers feeling stays essential in the studies, because their experience is necessary to link theoretical models and practical problems (choice of the parameters, resolution scheme,...).

2 Problem setting

For many years, sediments coming from the river Meuse aggregate at the entry of the lock of Hun. The resulting deposition impedes fluvial traffic which is using the lock. As a result, a regular dredging is required in order to maintain the site accessibility.

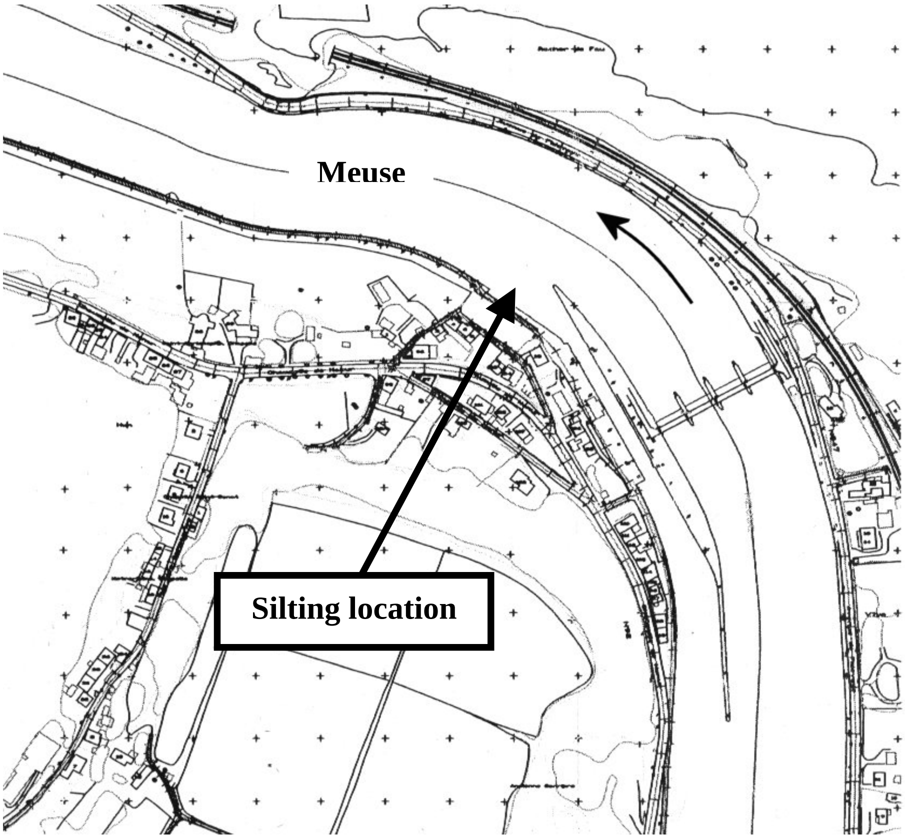

Figure 1: Site map

A numerical sedimentation study has been carried out in order to assess if geometrical modifications of the site would reduce the sediment deposition. In order to accurately represent deposition effects and location, at least a bidimentionnal study is needed.

3 Numerical tools

For this study, the quasi-3D flow modelling software Wolf2D has been chosen. In this solver, classical depth-integrated equations are solved in combination with moment of momentum equations by the finite volume technique [2].

Wolf2D includes two modules to model the solid transport: one for the bed load, the other for the suspended load. In the bed load model, the solid discharge is supposed to be in equilibrium with the flow at any time. Several equations provide the solid discharge as a function of the hydraulic characteristics of the flow [1]. A well-known and widely used formula is the Meyer-Peter-Muller one:

$$q_b = 8\sqrt{(s-1)\,g{d_{50}}^3}\left[\frac{R_{hb}\xi_M J}{(s-1)\,d_{50}} - 0.047\right]^{3/2}, \tag{1}$$

where q_b is the solid discharge, s is the sediments density, g is the gravity, d_{50} is the mean particle size of the sediments, R_{hb} is the hydraulic radius of the river bed, ξ_M is a roughness parameter, and J is the friction slope.

The erosion (or deposition) rate is then computed as

$$\overline{S_s} = \frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y} \tag{2}$$

In the suspended load model, the flow can be unsaturated or over-saturated. This enables to take into account the loading or unloading delay for the sediments. Nevertheless, this implies the use of an additional unknown, the sediment concentration. This one can be computed thanks to the following advective-diffusive equation [4]:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}\left(uC - \varepsilon_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(vC - \varepsilon_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(wC - \varepsilon_z \frac{\partial C}{\partial z}\right) = S_s, \tag{3}$$

where C is the local concentration, u, v and w are the sediments velocities in the x, y and z directions. u and v are equal to the corresponding flow velocities, w is the sum of the vertical flow velocity and the sediment settling velocity. ε_i ($i = x, y, z$) are the turbulent diffusion coefficients and S_s is the local sediment source term.

In a general way, the concentration profiles are non-uniform over the water depth, but for practical use, depth-integrated models (with the mean concentration as unknown) are commonly used. Integration of equation (3) leads to

$$\frac{\partial h\overline{C}}{\partial t} + \frac{\partial h\overline{uC}}{\partial x} + \frac{\partial h\overline{vC}}{\partial y} - \overline{\varepsilon}_x \frac{\partial}{\partial x} h \frac{\partial \overline{C}}{\partial x} - \overline{\varepsilon}_y \frac{\partial}{\partial y} h \frac{\partial \overline{C}}{\partial y} = \overline{S_s} \tag{4}$$

In some models, a moment equation for the concentration is added in order to get a better representation of the concentration profiles.

The source term in equation (4) depends on flow condition and sediment concentration. In the software Wolf2D, the following source term has been chosen [3]:

$$\bar{S}_s = \alpha w_s \left(C_{\acute{e}q} - \bar{C} \right), \tag{5}$$

where $C_{\acute{e}q} = k \left(\frac{|\bar{u}|^3}{h w_s} \right)^m$; α , k and m are parameters. More details on this source term can be found in [3].

In both bed load and suspended load models, the Exner equation (continuity) is used to compute bed level changes:

$$\frac{\partial Z_b}{\partial t} + \frac{S_s}{(1-p)} = 0\,, \tag{6}$$

where Z_b is the bed elevation and p is the bed porosity.

4 Study of the lock of Hun

4.1 ***Data***

Before starting to solve the problem, it is required to gather all necessary data. Unfortunately, all of these data are not always available, and it is therefore sometimes necessary to put forwards hypotheses in order to solve the problem without the missing data.

In the case of the lock of Hun, we basely need three kinds of data: hydraulic (water levels, discharges), geometric (site geometry, topography and bathymetry,...) and sedimentary (sediment concentrations, solid inflows,...). The hydraulic data were in sufficient quantity (discharges and free surface levels). Precise maps of the site were given, showing the river limits, the dam and lock positions. A general map of the river bathymetry was also available, but had to be completed. Two boat surveys were carried out at different times to assess the bed evolution. Almost no sedimentary data were available. A sediment sample has been taken on the site and showed a non-uniform grain size distribution. No information was available about the sediment concentration in the flow.

4.2 ***Modelling***

The following resolution scheme is divided in several steps. First, we start with a purely hydraulic simulation of the flow (no sedimentation effects). Then, the bed load model is added to the simulation and the results are analysed. After that, the suspended load model is tested and compared to the bed load. Finally, various geometry changes are tested to assess their effect on the sediment deposition.

As high deposition rates occurs during floods, a discharge of 400m^3/s is chosen, which corresponds to a mean discharge during a flood period. A water height is used for the downstream flow boundary condition. A relation between the river discharge and the water surface level at the downstream end of the simulation domain could be extracted from the available data. For the 400m^3/s discharge, the corresponding water height is 4.43m.

Figure 2 shows the result, where we can see appearing a zone with low-velocity currents at the entrance of the lock. These ones are the probable cause of the sedimentation because a velocity diminution implies a sediment deposition.

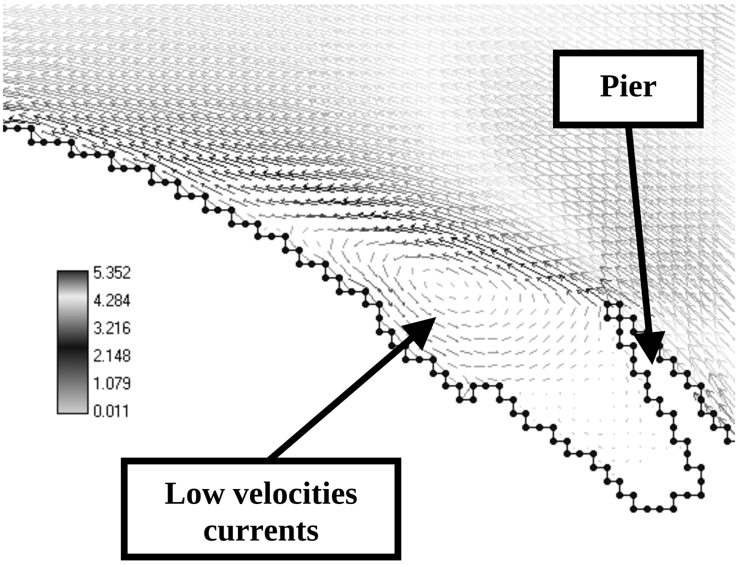

Figure 2: Specific discharge (m²/s)

In the next step, a first modelling of solid transport has been carried out with the bed load model (a flat bed has been chosen as initial condition to test the model). Figure 3 shows the resulting deposition:

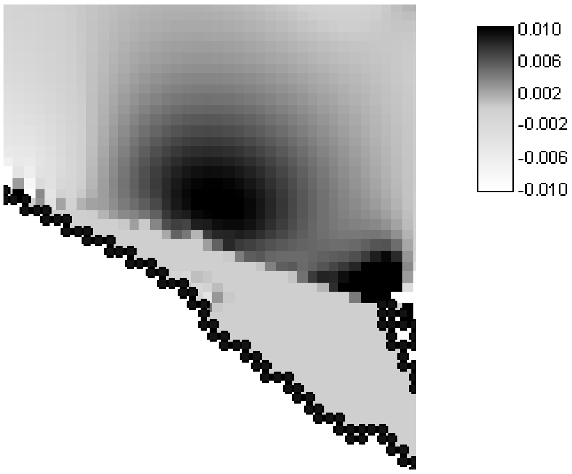

Figure 3: Deposition with bed load model (cm)

We can see a siltation at the entrance of the lock. Nevertheless, it seems that this deposition mainly occurs in the main flow. Indeed, as the bed load model is explicitly based on an equilibrium between solid load and flow conditions, the current can not be oversaturated when entering the low-velocities zone (lock entrance), and the deposition occurs practically instantly at the interface between the main flow and the low-velocities zone. Therefore, there is no sediment left in the flow for silting in the lock entrance.

The bed load model gives a first representation of the sediment deposition. In order to take into account the unloading time which clearly play a major role in this problem, a suspended load model is needed. But in order to apply this model, the parameters in the source term (5) must be determined.

The analysis of the sediment transport equations (4), (5) and (6) shows that the value of the parameter k in the source term don't modify the repartition of the silting, but only changes the sedimentation rate. Indeed, this one is directly proportional to k.

The value of k to be used can be determined if we know the solid discharge in the river Meuse. Nevertheless, even if this one is unknown, it is possible to compare several configuration of the site geometry by using an arbitrary value for k, as the repartition of the silting is not influenced. This solid transport model therefore allows to compare different geometrical configurations even when the sedimentary data is limited.

The parameter α must also be determined. The loading and unloading delays depend on this parameter. It will therefore have an influence on the sediments repartition. α can easily be determined if we know the sediment concentrations field. Otherwise, another method is needed to estimate it. In the problem of Hun, several simulations of the topography evolution have been tested with a broad range of α values. The results have been compared with available topographic surveys in order to determine which value gives the best results. This is a very delicate operation because many other factors (which have an influence on the bathymetry), such as fluvial traffic and lockage currents, can not be taken into account. As the precision on this parameter is rather limited, a sensitivity analysis will also be done to confirm the conclusions of the study for slightly different values of α.

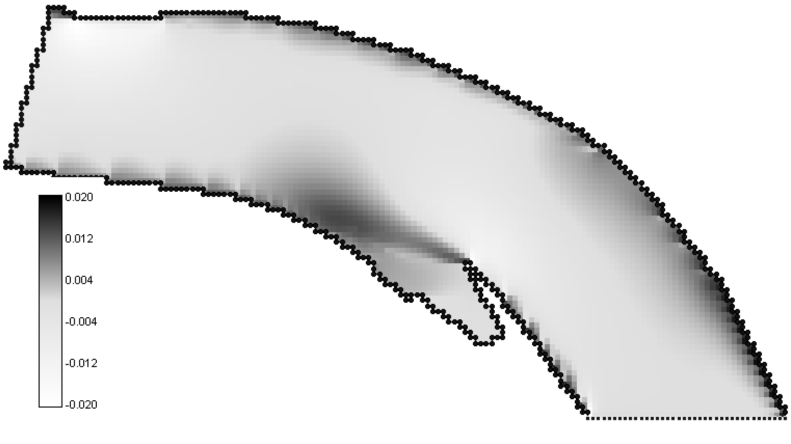

Figure 4: Sediment deposition with suspended load model (cm).

The initial bed topography is a flat bed. The results of the suspended load model (Figure 4) show a more realistic repartition of the depositions than with the bed load model, because the deposition is better distributed in the lock entrance.

4.3 Study of site geometry modifications

Using the suspended load model, numerous modifications of the site geometry have been tested. For each of these situations, the importance of the sediment deposition has been quantified, enabling a meticulous comparison of the various solutions.

One of the problems in this study is to find an objective method in order to compare the different solutions. The first question is the choice of the initial bathymetry. In order to limit its influence on the results, a flat bed was chosen. With this initial condition, the various geometries can be compared by looking at the bed evolution. The simulated time is kept constant for all the simulations. It is then possible to quantify the sediment deposition. In this study, this is done thanks to two criteria:

- Maximum height of deposition
- Volume of sediment deposition in the entrance of the lock

The first geometry change was to lengthen of the pier. The aim of this modification is to provide a guide for the water flow and reduce the variation of the river width at the lock entrance.

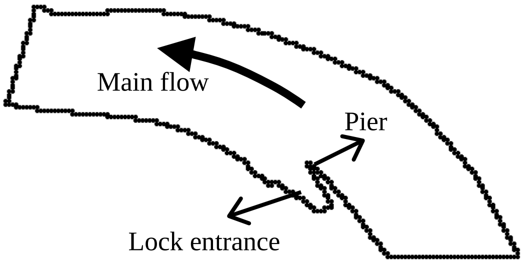

Figure 5: Initial configuration

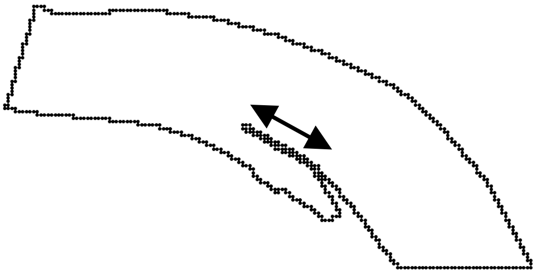

Figure 6: pier lenghtening

The following figures show the results for these two configurations.

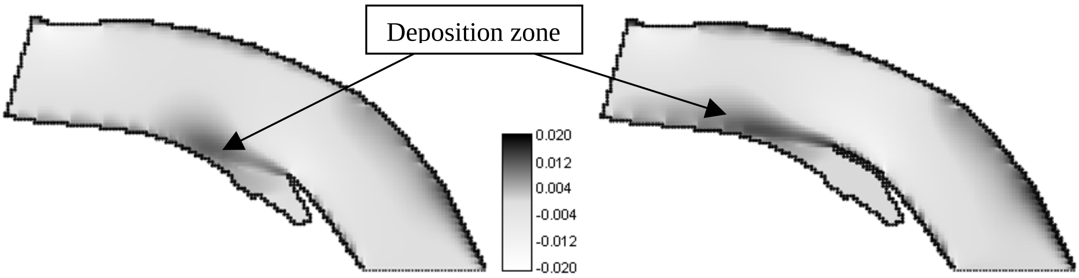

Figure 7: Comparison of sediment deposition before and after the pier lenghtening (cm)

In the modified configuration, the deposition zone is more widespread and is slightly shifted downstream. But the maximum height of deposition is only reduced by 4%. The improvement of the situation is therefore rather limited.

Other changes have also been tested: the river section reduction downstream of the lock (Figure 8), the flow deviation upstream of the lock exit (Figure 9), and many others…

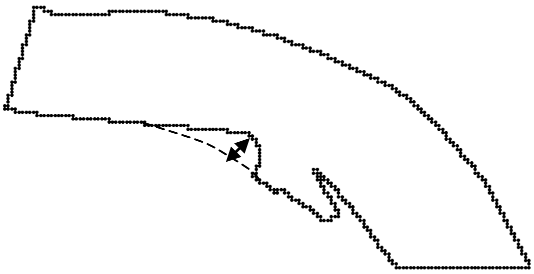

Figure 8: geometry modification

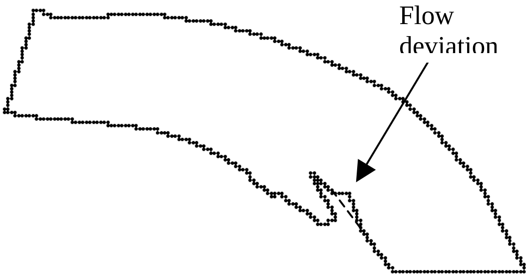

Figure 9: geometry modification

The analysis of the simulations shows that none of the tested geometries lead to a significant improvement.

The best reduction of the maximum height of sediment deposition was only 10%. For the volume criterion, the reduction is not significant but in some case, the deposition location is shifted downstream and is therefore less disturbing for the fluvial traffic. Nevertheless, the improvements are rather limited for all of the tested configuration. As a consequence, a regular dredging of the site remains the best solution.

4.4 Influence of the discharge

In order to compare the different solutions, the same discharge has been used for all simulation. Nevertheless, it is interesting to analyse how the river discharge influences the sediment deposition.

The simulations have been performed with a broad range of discharges, and the results lead to the following conclusion: the sediment deposition

- considerably increase for high discharges
- is very small for low discharges (nearly negligible)

This shows that the major part of deposition occurs during flood periods.

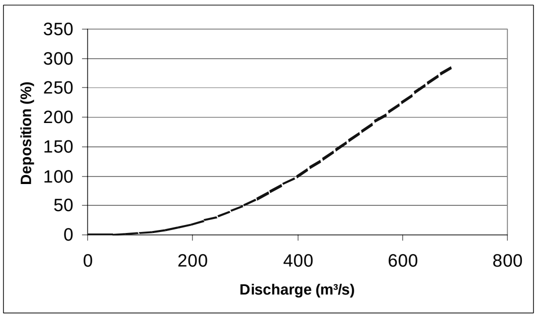

Figure 10: Sediment deposition (100%=deposition for Q=400m³/s)

As an example, the analysis of the discharges for the year 2003 – 2004 shows that according to the model, the deposition during January 2004 (31 days) is about 15 times the total deposition for the period between the 15th of March and the 15th of December 2003 (275 days)!

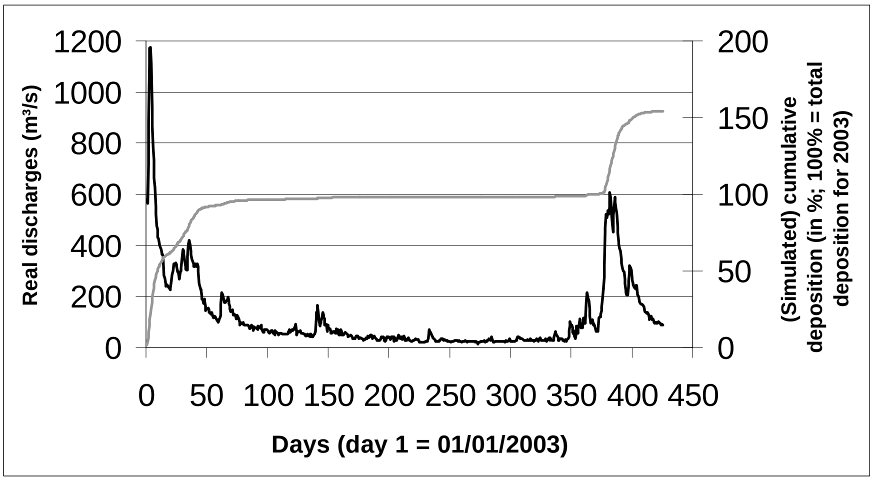

Figure 11: Discharge and cumulative deposition in 2003-2004

5 Conclusion

At the present time, a lot of numerical tools are available for hydraulic engineers and help them to solve the problems they face. In most of real problems, opposite to theoretical experiments, the lack of data is an additional difficulty which the engineers have to take account of.

The study of a lock site on the river Meuse has been solved thanks to a finite volume flow simulation software which includes solid transport models. Both a bed load and a suspended load models have been used. The suspended load model showed better results because it can take into account the loading and unloading delays. Some of the parameters values to be used in the simulations were calibrated thanks to the available data and the others were deducted from logical reasoning and working hypothesis.

Various modifications of the site geometry have been tested to see to what extend they reduce the sediment deposition: variation of the pier length, modification of the banks (both sides of the river), deviation of the main flow,… The results showed that none of the modifications bring a significant improvement and that a regular dredging of the site remains the best solution to the problem.

6 References

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