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Evaluating 3D hydraulic conditions to favor sediment transport and erosion through a reservoir: the case study of Champagneux run-of-river dam on the Rhône River, France

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Abstract— **By decreasing the velocity of the flow and turbulence, reservoirs controlled by dams are likely to force inflowing sediments to settle. This process can be more or less temporal and intensive, depending on particle size and the reservoir characteristics. To reduce the reservoir sedimentation and prevent a disruption of sediment continuity, one possible option for dam operators is to recover favorable flow conditions either for routing inflowing sediments or to remobilize previous deposits. In the case of cohesive sediments, one of the main challenges to deal with is that deposition and erosion thresholds are often radically different as a result of deposit consolidation. For the last 30 years, the Champagneux run-of-river dam (Rhône River, France) has experienced significant deposition processes affecting mainly fine sediment fractions. As a dam operator, CNR has wanted to determine hydrodynamic conditions to favor transport and erosion of fine fractions of sediment. In fact, this simple question covers many points of complexity, and thorough analyses on shear stress evaluation have been conducted by CNR. The purpose of this communication is to present hydraulic methodology and results to define those conditions in the case of the Champagneux dam.**

The evaluation of bottom shear stress throughout the reservoir and for different hydrological and operating conditions relies on a hybrid approach combining (1) a TELEMAC-3D free surface numerical model of the whole reservoir, (2) a physical scale model 1/35 limited to the downstream part of the reservoir and (3) a FLUENT CFD numerical model of the dam area. Even if those 3 models have been initially deployed in the frame of a more general project, this experience has shown that such a comprehensive approach is required to obtain relevant values of the shear stress and flow velocity close to the river bottom. Final goal is to achieve a correlation of numerical results with critical thresholds coming from core sampling lab-tests. For the dam operator, such a comprehensive survey provides useful information to enhance the management of the reservoir and feedback obtained will contribute to an optimization of the methodology for other similar cases.

I. INTRODUCTION

By decreasing the velocity of the flow and turbulence, reservoirs controlled by dams are likely to force inflowing sediments to settle. This process can be more or less temporal and intensive, depending on particle size and the reservoir characteristics [2]. To reduce the reservoir sedimentation and prevent a disruption of sediment continuity, one possible option for dam operators is to recover favorable flow conditions either for routing inflowing sediments or to remobilize previous deposits [1]. In the case of cohesive sediments, one of the main challenges to deal with is that deposition and erosion thresholds are often radically different as a result of deposit consolidation [3]. For the last 30 years, the Champagneux run-of-river dam (Rhône River, France) has experienced significant deposition processes affecting mainly fine sediment fractions. One essential challenge that CNR has to deal with as the dam operator is to determine the hydrodynamic conditions likely to ensure the remobilization of fine-grained deposits.

To achieve this objective, the approach favored by CNR relies on a hybrid model to quantify the shear stress values (τ) corresponding to different hydrologic and operating conditions. It exists several ways to know this shear stress near the bottom. On the one hand the theoretical expression of shear stress τ in turbulent boundary layer at equilibrium can be calculated with …:

$$\tau = \rho\nu\frac{\partial U}{\partial z} - \rho < u'w' > \qquad (0)$$

With ρ water density, ν kinematic viscosity, U velocity field vector and u', w' average fluctuation of velocity.

- Measurement of speed fluctuations by vertical Acoustic Doppler Velocimetry (ADV): the shear stress is related to measures u' and w' for different z.

- Measurement of average velocity by vertical ADV: the shear stress is connected to vertical gradient U (introduced in this article).

On the other hand, the development of Navier-Stokes equations with free surface assumption leads to the theoretical relation between the local hydraulic radius R_h and the energy slope J (requires measuring upstream and downstream average speed).

$$\tau = \rho g R_h J \qquad (1)$$

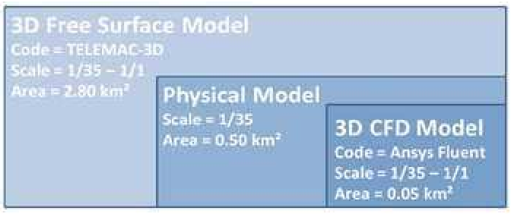

Figure 1. Hybrid modelling concept

Such issue is however far from being trivial and requires addressing following concerns:

- Even if measurements in the field should be possible, these methodologies rely on a uniform regime, which is never obtained *in situ*.
- Numerical models have to be calibrated by physical model to determine realistic shear stress values and compare it to critical shear stress values obtained from lab test on undisturbed core samples.

This communication focuses firstly on the hybrid modelling approach deployed for obtaining relevant shear stress values in the reservoir and bounding uncertainties for its evaluation. Then TELEMAC-3D methods for shear stress values are compared with outputs from Computational Fluids Dynamics (CFD) FLUENT.

II. HYBRID MODELLING

A. Overall context and methodology

First it should be specified that the results presented hereafter were obtained in the frame of a more general project which included in particular following investigations: characteristics of flow dynamics in a diversion area, evolution of spillway conveyance according to various gate openings, impact of deposits on the spillway capacity, spatial heterogeneity of reservoir deposits, and susceptibility to erosion of deposits. Due to the multiple objectives of the project, deploying a physical model only didn't appear sufficient for addressing those complex issues. Consequently, the option considered consists in a hybrid modelling approach combining (1) 3D numerical modelling of the whole reservoir, (2) a physical model at 1:35 corresponding to the downstream part of the reservoir and (3) a 3D local numerical model representing the dam area (Fig. 3). The objectives and the main principles of each model are specified in next paragraphs.

B. 3D numerical modelling of the whole reservoir

TELEMAC-3D (T-3D) is the large-scale model deployed for the whole reservoir. This model allows a suitable representation of the flow velocity distribution induced by the river bend upstream of the dam. T-3D provides also upstream boundary conditions to the physical and CFD models with regard to the flow velocity. Outputs provided correspond to situations ranging from low flows to the design flood. One of the main interests of T-3D is to calculate bottom shear stress values in the whole reservoir and with a high resolution. For shear stress calculation, a proper calibration of the vertical velocity profile is required and can be obtained from experimental measurements provided by the physical model (see Fig. 3).

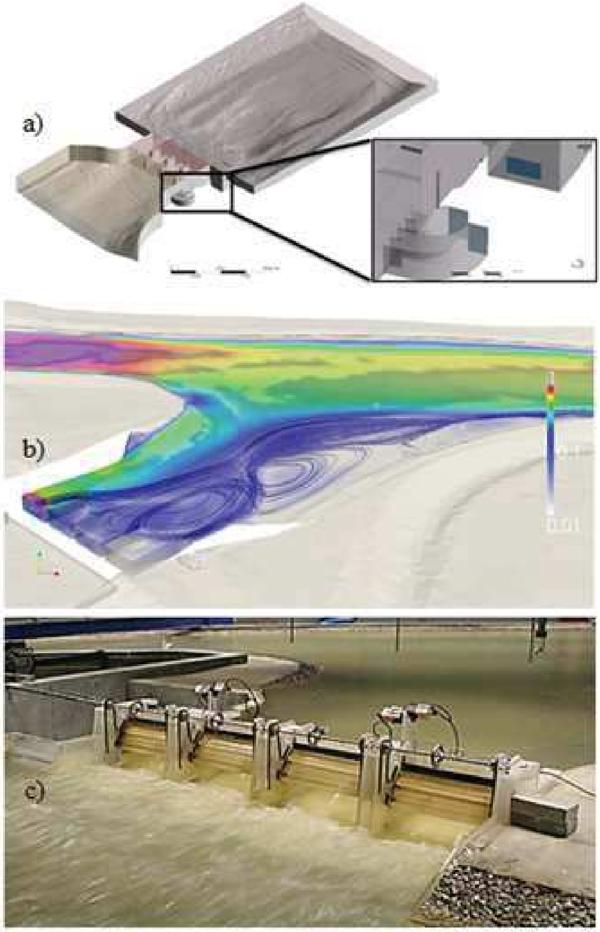

Figure 2. Hybrid model consisting of a) view of 3D CFD Fluent mesh, b) TELEMAC-3D velocity fields and c) downstream view of physical model

T-3D solves the Navier-Stokes averaged and unsteady equation (URANS) for a single incompressible fluid (including the 3 components of the average flow velocity field). The numerical method used to discretize the equations is the Finite Element Method. Friction (wall laws) includes source terms.

The domain is 4 km long, integrating Champagneux dam and its reservoir, and the entry of the headrace channel. The edge length of mesh was set to 20 m in the reservoir, but was decreased to [0.5-2] m nearest to the dam. The 3D model presented 10 horizontal levels whose spacing is ruled by a logarithmic profile refined near the bottom. Consequently the 3D grid comprises about 395,000 nodes and 776,190 elements.

The computational area presented 5 liquid boundaries. At the inlet, discharge measurements were forced in TELEMAC-3D (V6P2 release). A discharge was imposed on each 4 gates of Champagneux dam. At the headrace channel outlet, water level was imposed. Turbulence model chosen is k-ϵ, with 2 kinds of wall law (smooth friction with Reichard law, and rough friction with Nikuradse law).

C. *Physical model at 1:35*

The physical model (PM) is the local model used for determining with an appropriate accuracy the hydrodynamic flow conditions nearby dam area. Discharges considered range from frequent floods to the design flood. Investigations performed concern particularly the spillway discharge coefficient and an evaluation of its possible evolutions due to the sediment dynamics. The physical model is also used to measure the vertical velocity profile (Fig. 3) with Acoustic Doppler Velocity (ADV), to calibrate the turbulence model of T-3D and evaluate precisely the head loss due to the dam crossing. Model and natural free surface flow similarities are guaranteed according to a Froude similitude.

D. *3D numerical model of the dam area*

FLUENT (CFD) is the micro-local model deployed to simulate a broad range of flow situations with respect to the spillway gates opening. The code solves 3D URANS equations with finite volume numerical method. The domain comprises air and water so a transport equation on volume fraction is added according to the Volume of Fluid (VOF) method. Compared to T-3D, the main benefits of CFD are to (1) allow a multiphase modelling and directly account for air/water interactions at the free surface, (2) limit assumptions concerning the flow regime of the gates as the downstream of dam is simulated, and (3) obtain comprehensive modelling results with a very high spatial resolution. In the frame of this project, scale effects have been also investigated to evaluate if they can be reasonably neglected.

E. *Modelling strategy followed for minimizing uncertainties*

First, it should be kept in mind that the geometric data of the models have been unchanged during a given simulation so as to better highlight and understand the hydrodynamic processes. A mobile bed numerical model is currently operated to take into account sedimentary processes from a more detailed manner. It is also essential to note that the modelling strategy relies on cross-validation of models which requires a strict coordination between modellers throughout the calibration process. The model construction is indeed based on an iterative approach meaning in particular that assumptions specific to a given model have to be validated from outputs provided by the other ones. Such process is obviously constraining but acceptable with regard to the hydraulic safety issues at stake. In order to take full advantage of the hybrid model and facilitate interactions as well as subsequent comparisons, a formal methodology has been followed:

- All models use the same input data such as bathymetry, flow rates and gate openings observed during calibration events… Although time-consuming in the preliminary steps of the project, such approach provides huge benefits for the analysis of results in the ultimate stages of the project.
- The calibration of models is performed simultaneously and according to the same time scheme for achieving effective interactions and possibly adapting the methodology to unexpected concerns.
- The calibration process includes following steps: (1) a blind calibration of physical model and 3D numerical models using field data measured with Acoustic Doppler Current Profiler (ADCP), (2) an inter-comparison of results obtained for a given situation and (3) a reverse calibration of 3D models if significant discrepancies are eventually highlighted.
- The post processing work is performed on a common set of output parameters measured exactly at the same locations and all simulation results are compared at scale 1:1.

III. SHEAR STRESS EVALUATION BY AVERAGE VELOCITY VERTICAL PROFILES

A. *Hybrid modelling phase*

Determining the bottom shear stress is a very challenging issue, especially owing to the impossibility for measuring this parameter in situ. This parameter has been evaluated from an indirect manner using experimental observations performed on the physical model. The option considered consists in determining the friction velocity *U** from the shape of the vertical profile of velocity. In the frame of this project, the velocity profile has been measured with a Vectrino II (ADV), which can be deployed for water depth above 1 mm at 1:35. The scale 1:35 has been chosen indeed for minimizing uncertainties and this option leads finally to obtain a standard deviation of 2% when simulation results are upscaled to 1:1.

Those experimental data has been also used for validating the ability of the 3D numerical models to represent properly the whole velocity field of the flow obtained by the complete resolution of URANS system. In addition, qualitative observations demonstrate the convergence of the general flow pattern for the 3 models, with regard to the position of the recirculation cells in particular.

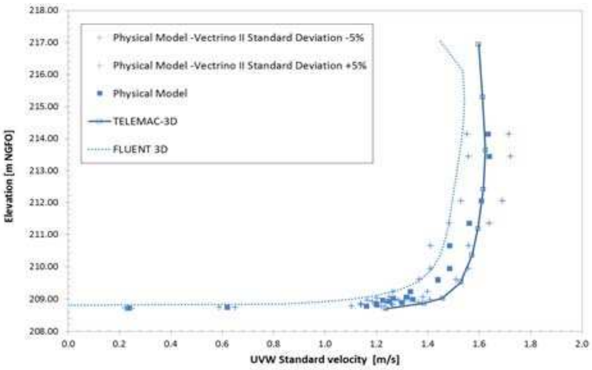

Figure 3. Inter-comparison of vertical profiles of velocity

During the calibration process, the wall law (friction coefficient) and the type of turbulence model (by an assessment of vertical evolution of velocity) have been adapted when required. A series of tests were also performed to demonstrate that options using either a Reichard law (smooth friction plan)

$$\frac{U}{U^*} = \frac{1}{\kappa}\ln(1+\kappa y^+) + 7{,}8\left(1 - e^{\frac{y^+}{11}} - \frac{y^+}{11}e^{-0{,}33y^+}\right) \qquad (2)$$

where κ=0.41 is the Von Karman constant, y^+ is the dimensionless distance to the wall, or a Nikuradse law (rough friction regime) lead to much more accurate results compared to calculation based on an vertically-averaged velocity depending on a Strickler friction law. These friction laws suppose that the speed at the wall on a mesh is not quite taking to the wall (otherwise it would be null) but it is taken into the boundary layer at a distance *y*.

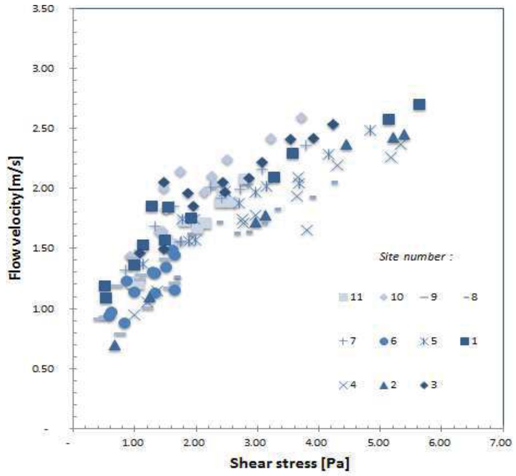

Figure 4. Flow velocity vs. shear stress at core sampling sites

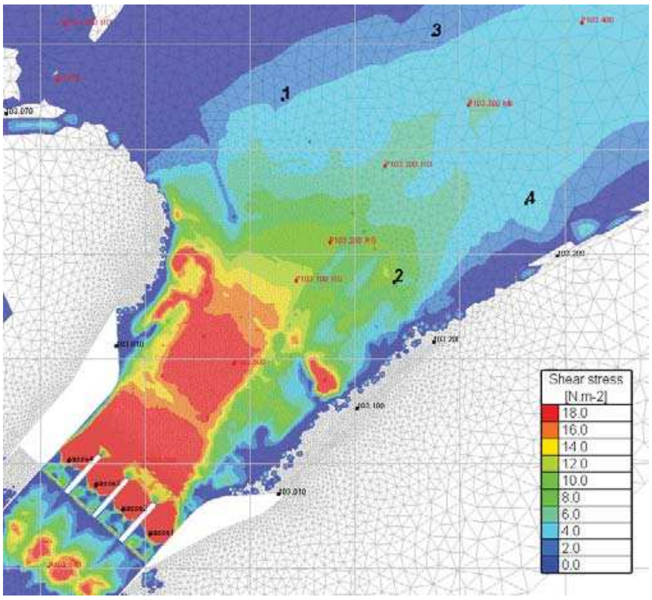

Figure 5. Shear stress distribution from T-3D calculations and location of core samples considered for erosion tests.

Concerning the maximum velocity simulated with T-3D, the main trends highlighted correspond to a −7% underestimation upstream of the dam and a +10% overestimation in the close vicinity of the spillway. The overall results are still comprised in a +/- 10% interval which is quite satisfactory. Scale effects and sensitivity tests on calibration parameters and modelling options (especially with regard to wall laws, friction regime, turbulence model, meshing…) have been also performed and results obtained lead to consider that the uncertainty on shear stress values is near 25%. Those investigations demonstrate that the major benefits of the hybrid approach deployed are (1) the possibility to calculate relevant bottom shear stress values in the entire reservoir, (2) with a high resolution and a relatively good level of confidence and (3) by taking into account a large panel of hydraulic situations (see Fig. 4 and Fig. 5).

B. *Validation cases by experiment*

Simulation results from T-3D were also used for comparing the *in situ* sediment dynamics understanding in the reservoir. Investigations performed have mainly focused on the possible relations between the reservoir deposits distribution and the flow pattern. In many areas, the deposition of non-cohesive particles observed in-situ is clearly explained by the limitations due to the transport capacity of the flow. The calculation of the Rouse number, which determines how a particle of a given size is likely to be transported by the water flow, provides indeed consistent results compared with the distribution of deposits within the reservoir. Similar conclusions have been obtained by comparing the sedimentation pattern with the distribution of the coarsest particles likely to be transported as bed-load.

IV. SPECIFIC ANALYSIS BASED ON CALCULATION METHOD OF SHEAR STRESS

Qualitatively, flow patterns are identical between TELEMAC-3D and FLUENT but there is a fundamental discrepancy for calculation method of shear stress value.

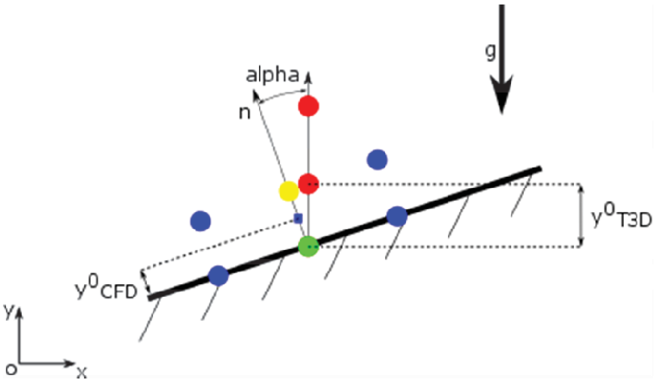

Figure 6. Diagram of positioning of computing nodes for the T3D solver (red) and FLUENT solver (blue) to calculate the stress at the wall (green).

A source of error is also the numerical method of calculating the friction velocity compared to the meshing method of numerical models. As shown in Fig. 6, T-3D has not its nodes cells directly on the normal to the walls because the extrusion of the mesh is in the direction of gravity (except in places where the normal to the sides of the river are collinear with the vertical). The definition of stress at a wall requires it to be proportional to the velocity gradient calculated in the direction normal to the wall. Reichard's law in Eq. (2) connects the shape of the velocity profile at the wall stress: the velocity profile is fully determined by the value of the speed of the first point and the distance to the wall. The solver T-3D assimilate the height of the first layer point y_{T3D} to the distance along the normal to the wall and the velocity value of this as being the point of the yellow dot.

A retrospective correction would assume that the velocity calculated at the first node is similar to the yellow dot node and the distance to the wall is corrected by $y_{T3D} \cos(\alpha)$, where α is the angle between the normal to the wall with the vertical direction. The shear stress would be increased as the same rate would be closer to reaching the wall. An estimate value of the relative error submitted is made by calculating the same velocity to the first cell wall of the two constraints generated by a distance $y_{T3D} \cos(\alpha)$ and y_{T3D}. The relative error plotted in Fig.7 is therefore:

$$\frac{\left(\tau(y^0_{T3D} cos(\alpha), U) - \tau(y^0_{T3D}, U)\right)}{\tau(y^0_{T3D}, U)} \quad (3)$$

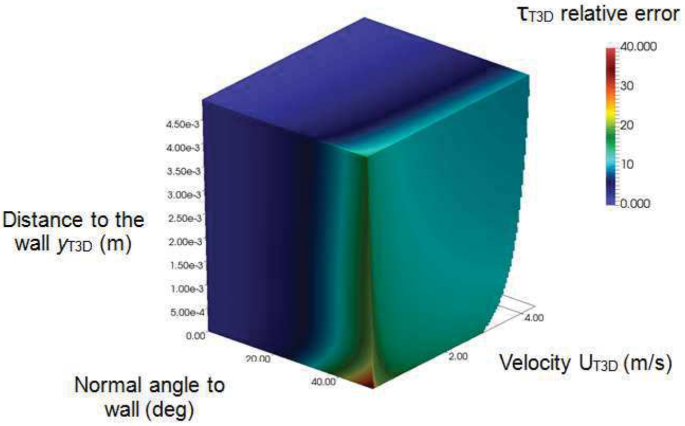

Figure 7. Relative error between the corrected stress τ (y_{T3D} cos (α), U) and stress calculated by T-3D based on a velocity range in the first compute node, the distance to the wall of the first node and the angle of the normal to the α wall.

In this parameter range and the conditions of distance to the dimensionless wall $y^+ > 1$ and wall stresses below 50 $N.m^{-2}$, the stress calculated by T-3D underestimates maximum of 5% of the corrected stress τ (y_{T3D} cos (α), U) for angles less than 20°, 10% for angles less than 30° and up to 40% for angles up to 50°. This source of underestimating shear stress seems to be relevant in this topic as it would mainly take place in the areas where deposits are located.

V. PERSPECTIVES

The Preston pipe method is an alternative way of directly measuring the bottom shear stress [4]. Shear stress rate U^* is connected to the difference between total and static pressure measured near the bottom. Ongoing tests at CNR laboratory based on pressure gradient measurements performed at scale 1:35 may help decreasing significantly the bounds of current uncertainties, in particular for gradually varied regime.

VI. CONCLUSION

The hybrid modelling approach deployed in the Champagneux dam case combines one physical model and two 3D numerical models used for assessing the erosion hazard of reservoir deposits. Such option is very constraining and challenging but provides unparalleled benefits for evaluating, with a high resolution and a relatively good level of confidence, relevant bottom shear stress values in the entire reservoir for a large panel of hydraulic situations. The models calibration is based on a cross-validation strategy that requires a formal organization and a strict coordination of modelling activities. It’s worth noting in particular that all models use the same input data and are calibrated simultaneously and according to the same time scheme. Moreover, the post processing work is performed on a common set of output parameters measured exactly at the same locations and all simulation results are compared at scale 1:1.

It is a major importance to remind that shear stress library (for a large range of discharge) is only assess throughout numerical calculation of friction velocity (T-3D) at scale 1:35 to 1:1 or by wall law (FLUENT) at scale 1:35. Even if values do not present discrepancy, it is crucial to perform some complementary investigations to address properly sediment related issues (morphodynamic simulations):

- To validate numerical method by comparison with a direct measure of shear stress (see paragraph V.) at scale 1:35 in gradually varied regime.
- To transpose methodology from scale 1:35 to 1:1 limiting uncertainties.

Finally, the comparison between erosion lab-tests and simulations results will lead to assess the erosion hazard of reservoir deposits. As a first approach, the diagnosis performed is based on the calculation and the spatialization of the relative deviation between the critical shear stress and the effective shear stress corresponding to a given flood event. Complementary investigations considering an approach based on a 3D hydro-sedimentary model will currently perform to improve this preliminary approach.

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