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Numerical modelling of the Vaugris reservoir on the Rhône with Telemac 3D

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***Abstract*— Production of hydroelectricity, a clean, renewable form of energy, is growing constantly and could be optimised both by carrying out works to improve existing power plants and by taking certain technical aspects into account when building new facilities.**

This approach is already underway, in particular through the launching of studies to rehabilitate existing facilities, although they do not systematically incorporate technological advances that would enable energy production to be optimised.

The PENELOP2 R&D project aims to improve and promote this approach applied to low-head hydropower schemes, which represent the largest proportion of hydroelectricity generated in France and around the world, with the goal of substantially improving performance. The pilot site of the project is the Vaugris dam on the Rhône river. This construction is composed of a spillway on the right bank, the power plant (with 4 generating sets) and a lock on the left bank.

To meet the objectives of the project, and study hydraulic losses, a numerical model of the currents through the Vaugris reservoir was constructed with Telemac 3D. The model was calibrated and validated for various modes of operation of the plants using current and water level measurements. The capacity of the model to simulate the current field in the complex geometry of the water chamber, with the inclusion of its main geometric features, intones, bulb turbine, is also analysed.

I. INTRODUCTION

Climate change and deteriorating air quality have led the international community to take into account the impact of human activities on the environment. In France, following the introduction of a "Climate Plan" in 2004, the law of 13 July 2005 stipulated that the country would have to reduce its greenhouse gas emissions by 3% per year. It also called for France to diversify its sources of energy production by developing renewable energy (RE).

Hydropower, unlike other types of RE such as wind and solar, provides a continuous and predictable supply. Production can be adapted more quickly to respond to network requirements. Hydropower is therefore the most widely used and competitive type of RE found on the market and accounted for 85.9% of RE production in France in 2007.

Low-head hydropower schemes are those that operate on a run-of-the river basis on rivers with a high discharge and head of less than 20m. They consist of a dam to create a reservoir, a water intake to channel the flow, a power plant to house the turbine (often a bulb unit) and finally a tail race to return water to the river downstream. The total length of these facilities is often less than 100-200m.

Low-head turbines are extremely sensitive to the quality of flow. Any loss of uniformity caused by disturbance at the intake is immediately felt at the turbine and results in production losses that can quickly become significant.

Certain low-head facilities thus experience difficulties when the flow of water is disturbed, and consequently a loss of efficiency and head (of the order of a few per cent). These problems affect the entire facility, including the upstream and downstream sections and turbines, and therefore require thorough investigation and analysis. Reducing the problems that cause disturbances in the hydraulic passage could significantly improve energy production and would enable the capacity of new facilities to be optimised right from the design stage.

PENELOP2 (*Performance ENergétiques, Economiques, et environnementaLes des Ouvrages de Production hydroélectrique de basse-chute* – Energy, economic and environmental performance of low-head hydro production structures) is a collaborative research project being conducted by a consortium of companies and university laboratories including the Compagnie Nationale du Rhône (CNR), Alstom Hydro France, Sogreah Consultants, In Vivo Environnement, Actoll, JKL Consultants and Grenoble INP. PENELOP2 is approved by the Tenerrdis compete-tiveness cluster, with funding granted in the framework of the 9th *Fonds Unique Interministériel* (FUI) programme. The aims of the project may be grouped under four general headings:

- Understanding, qualifying and quantifying inadequate performance at hydropower plants on site.
- Devising new systems for representing in detail what is observed on site.
- Systematically studying the origins and consequences of disturbances in flows.
- Studying ways of monitoring these disturbances and proposing innovative processes and technologies for controlling and correcting them.

Sogreah's Hydraulic Modelling and Software division is responsible for the numerical model design and construction aspects, and is to produce all the models of the reservoir. One of the keys to success will be to link up the various 3D models of flows upstream, downstream and in the water chamber correctly with those of flows in the turbine and draft tube designed by Alstom.

Vaugris dam on the Rhône was chosen as pilot site as its power losses resulting from head losses in the head race leading to the turbine have been clearly identified by the operator, the Compagnie Nationale du Rhône (CNR). The power plant adjoining the dam, which has a capacity of 18 MW, comprises four bulb units and has a maximum head of about 7m.

This site is to be used to validate the numerical models by comparing their results with measurements taken on site, and to quantify the impact of current patterns on the performance of the power plant. Subsequently, the models will be used to improve the efficiency of the generating sets by testing different geometrical configurations (shape of the invert, contraction, etc.).

The Telemac modelling system was designed initially to study free-surface flow only [1]. The model of the reservoir presented here is to be used to validate the techniques for taking into account confined flows and submerged structures in a first attempt to produce a comprehensive representation of the flows involved.

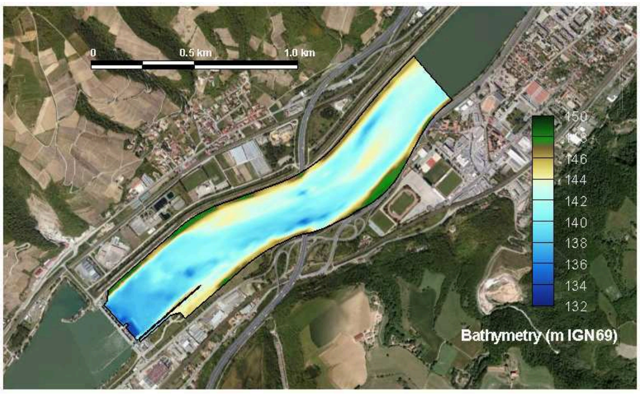

Figure 1. Footprint and bathymetry of the reservoir model.

II. MODEL OF THE RESERVOIR

A. *Footprint and bathymetry*

All the data required for constructing the model were supplied by the CNR, including bathymetric surveys upstream and downstream of the dam and drawings of the power plant with its hydraulic equipment. The model footprint covers the entire low-water bed of the Rhône over a distance of about 2km upstream the dam [2]. The model also includes the lock approach channel on the left bank (Fig. 1).

B. *Grid and boundary conditions*

The horizontal grid comprises more than 6500 nodes and 12600 elements. The mole area between the dam and the plant was represented in particularly fine detail as it is here that recirculation is liable to occur, causing loss of capacity in bulb unit 4, which is next to it. The size of the mesh segments varies from 1m to in the immediate vicinity of the water intakes for the four bulb units to 50m upstream of the model, with 3m for the area adjacent to the mole and storage dam (Fig. 2).

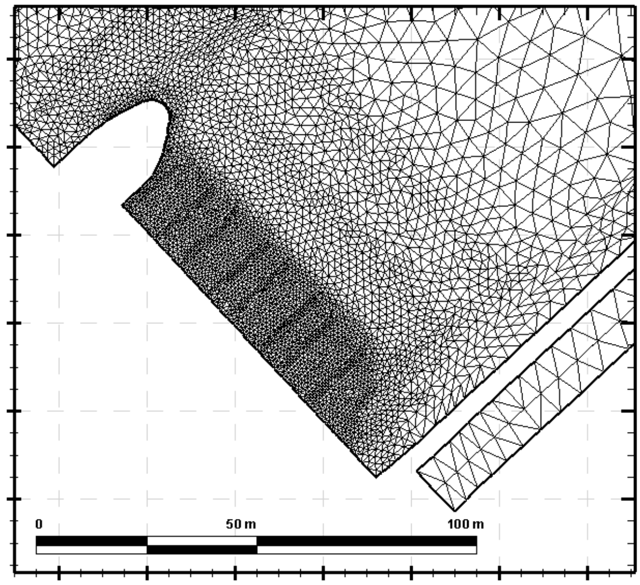

Figure 2. Horizontal grid resolution upstream of the power plant bulb units.

The 3D grid is built on the basis of the horizontal grid, which is reproduced 20 times along the water column. The model's boundary conditions are not of the usual kind. The velocity distribution upstream of the power plant depends directly on the discharges passing through each bulb unit. It is therefore necessary to prescribe discharges downstream of the model, at each bulb unit. The same type of condition is prescribed upstream and the only place where the free surface is controlled is the lock on the left bank of the model.

In order to represent flows immediately upstream of the power plant as accurately as possible, the boundary condition downstream of the model is modified to take into account the submerged inlet of the bulb units. To do so, the real flow sections are calculated and the normal velocities at these outlets are prescribed as a function of the required discharges.

III. MODEL OPERATION

A. *Available measurements*

A campaign of velocity measurements (ADCP readings) was carried out on 25 November 2010 by the CNR [3]. These measurements were taken on 8 profiles downstream of the plant and 11 profiles upstream in two different plant configurations. In the morning G2 and G4 (right bank next to the dam) were operating at full capacity and G1 (left bank) was providing additional capacity to reach close to 800m³/s (Fig. 3). In the afternoon, G2 was replaced by G3 (configuration not shown here). Throughout the measurement period, discharge at the dam was nil.

According to the in-house tests performed by the CNR laboratory, the ADCP devices used gave results with a level of uncertainty of around 5% concerning discharges in steady conditions, based on the average of a series of 4 successive transects. The uncertainty with regard to the instantaneous velocity values is of the order of 10%.

The upstream velocity profiles P1 (profile 1) to P4 demonstrate the influence of the bulb units on the velocity distribution in the section. From P1 to P8, the velocities are higher on the LB (power plant side). The velocities on the following (P9 to P11) are uniform over the entire section. On profile P1, the closeness of the reinforced concrete affects the ADCP compass, as shown by the differences between the ADCP and GPS paths.

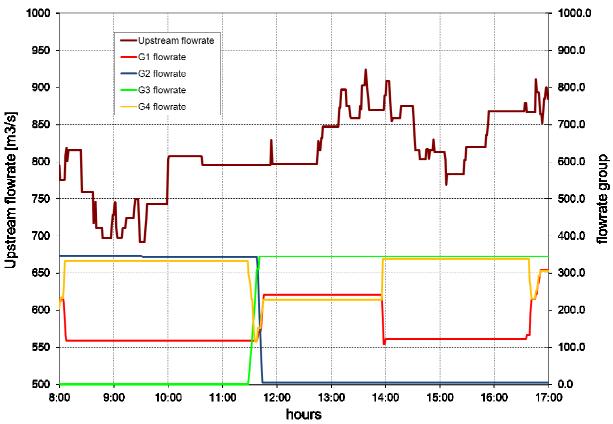

Figure 3. Flow rate of the Rhône and through the bulb units on 25/11/2010.

The measurements and model are exploited in the rest of this article in the power plant's morning operating configuration.

B. Results

In order to avoid the effects of boundary conditions on the model (wave reflection during changes in power plant configuration), it is only run here under stationary discharge conditions. The ADCP profiles exploited are shown in Fig. 4. These profiles are the most representative of the lack of flow uniformity upstream of the bulb units. Fig. 5 to Fig. 8 compare the current intensities indicated by the model results and the measurements.

The lack of spatial uniformity in the velocities immediately upstream of the bulb units appears to be well reproduced by the model. While the discharges flowing through bulb units 2 and 4 are practically the same, the current distribution is not symmetrical and tends to show that the effect of the feeder canal is significant.

The contraction of the current on the right bank and along the mole produces a local increase in velocity opposite bulb unit 4. Fig. 7 and Fig. 8 show that the current tends to become uniform upstream even if the impacts of the dam on the right bank and of the power plant are still perceptible.

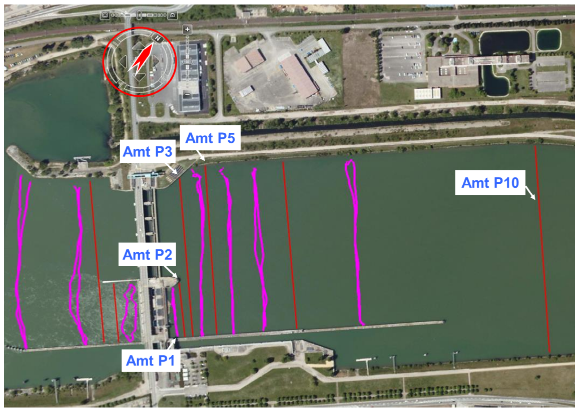

Figure 4. Location of the ADCP profiles upstream of the power plant.

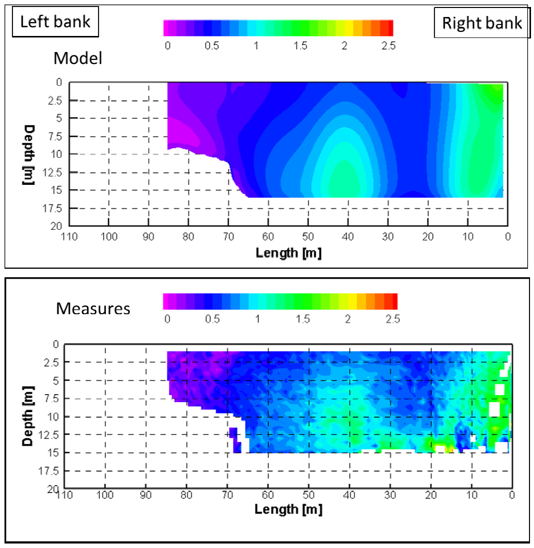

Figure 5. Comparison of model results with measurements for profile 1.

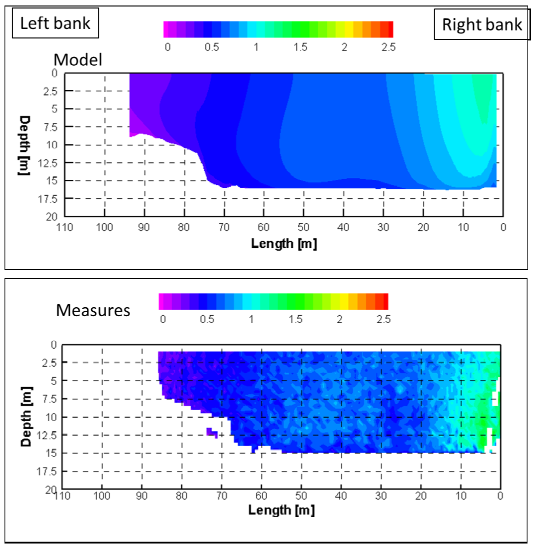

Figure 6. Comparison of model results with measurements for profile 2.

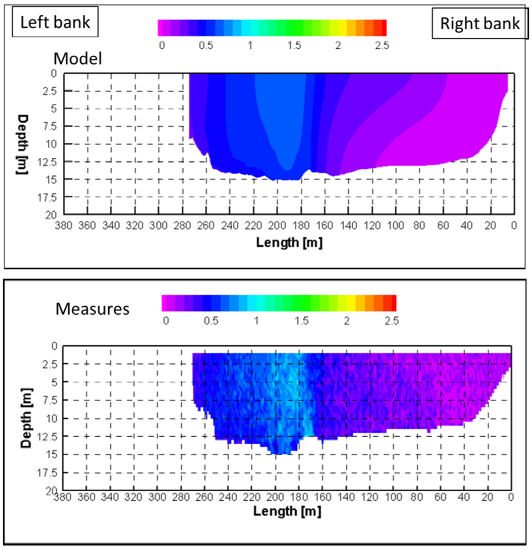

Figure 7. Comparison of model results with measurements for profile 3.

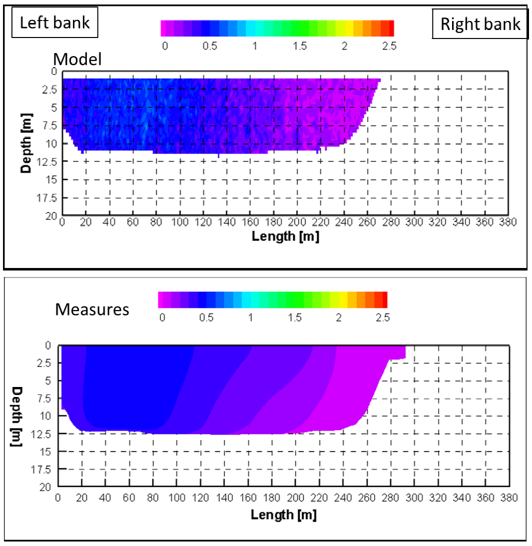

Figure 8. Comparison of model results with measurements for profile 5.

In order to quantify the results obtained, Table I gives the discharge, cross-section and mean velocity calculated from the ADCP measurements and obtained from the model. All these results show that circulation inside the reservoir is accurately represented by the model.

To analyse flows immediately upstream of the power plant in greater detail, a new model of bulb unit 4 at Vaugris is now presented.

IV. Model of Bulb Unit 4 at the Power Plant

The purpose of this model is to consider the civil works part of bulb unit 4 of the power plant upstream of the turbine.

A. Footprint and construction

In order to represent flows on the right bank of the power plant as accurately as possible, a local model of flow inside bulb unit 4 (connected to the dam) was built. In addition to this initial approach, the feasibility of using Telemac for this type of modelling must be validated by additional work using a confined-flow model (OpenFOAM). The long-term aim is to combined the model of the reservoir and that of bulb unit 4 in a single model.

TABLE I. Discharge Q (m^3/s), cross-section S (m^2) and mean velocity U (m/s) from measurements (MS) and model (MD).

	Profile 1		Profile 2		Profile 3		Profile 4		Profile 5	
	MS	MD	MS	MD	MS	MD	MS	MD	MS	MD
Q	944	796	789	796	761	789	857	785	797	789
S	1527	1256	1264	1349	2955	3451	2874	3201	2927	3226
U	0.62	0.63	0.62	0.59	0.26	0.23	0.30	0.25	0.27	0.24
	Profile 6		Profile 7		Profile 8		Profile 9		Profile 10	
	MS	MD	MS	MD	MS	MD	MS	MD	MS	MD
Q	799	796	815	794	804	791	823	792	810	789
S	2947	3194	3014	3158	2917	3042	2623	2694	2522	2688
U	0.27	0.25	0.27	0.25	0.28	0.26	0.31	0.29	0.32	0.29

The model footprint is shown on Fig. 9. The model extends from the screens upstream of the power plant (i.e. the downstream boundary of the previous 3D upstream model) to the turbine bulb.

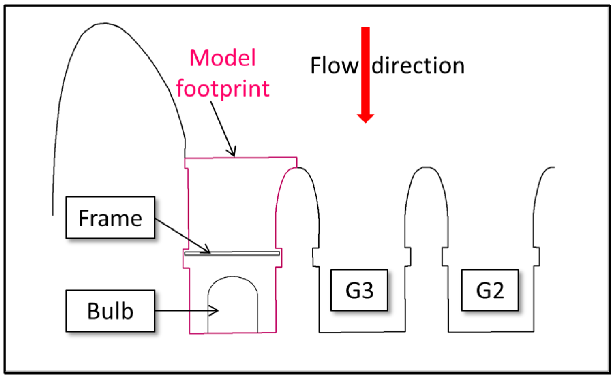

Figure 9. Diagram showing the footprint of the model of bulb unit 4 of Vaugris power plant.

This type of model requires several adaptations of the code to take into account the confined flow inside the power plant and the turbine bulb. The contraction at the bulb unit inlet is forced by prescribing a spatially varying pressure field. The hypothesis chosen is that of hydrostatic pressure in order to set the free surface elevation at the desired level.

In parallel with this free surface processing, friction is taken into account in the boundary condition of the equations of motion by calculating the shear velocity u_* in rough friction conditions. Finally, for this initial approach, the turbulent viscosity is modified with this proximity of the upper "wall", still applying the same type of processing that is normally used on the bottom of the domain.

Further downstream the water chamber is taken into account in the usual manner with a free surface that changes both spatially and in time. Finally, the outflow condition is modified by subtracting the planned area of the turbine bulb from the flow section. The 3D grid is shown in Fig. 10.

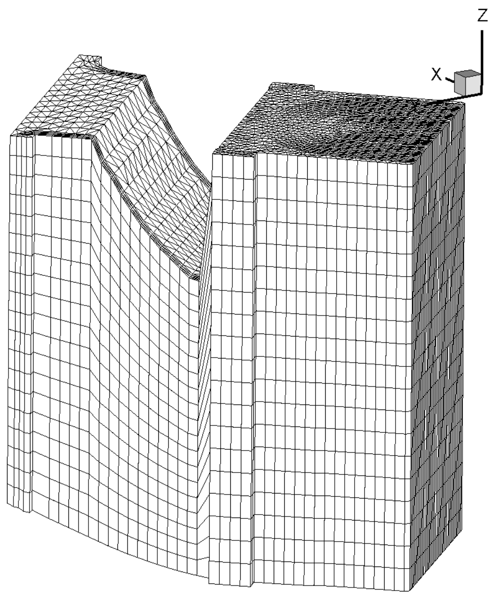

Figure 10. Three-dimensional grid of the model of bulb unit 4 incorporating free surface forcing to represent the contraction.

B. *Preliminary results*

The first results are promising (Fig. 11). The flow characteristics are accurately represented. A new campaign of measurements is to be carried out, incorporating a frame supporting numerous ADCP and ASFM sensors in the stop log groove. This campaign will enable the pertinence of this type of modelling to be assessed.

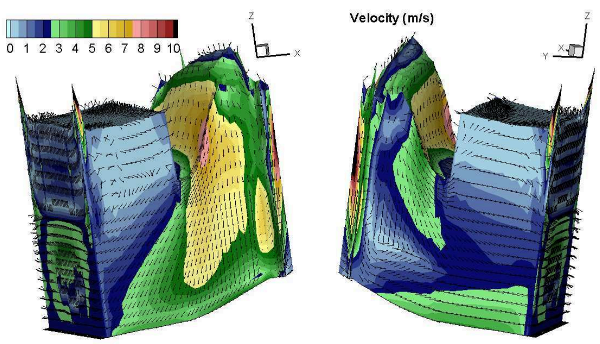

Figure 11. Intermediate result concerning flows inside bulb unit 4.

V. Conclusion

The market for renovating and optimising low-head power plants is set to develop continuously as a result of the increased importance that the international community is giving to renewable energy, especially hydroelectricity. It is necessary to carry out in-depth analysis and identify disturbance factors in order to ensure gains in performance. Indeed, low-head turbines are extremely sensitive to the quality of flow. Any loss of uniformity caused by disturbance at the intake is immediately felt at the turbine and results in production losses that can quickly become significant.

On the basis of this work, it was possible to build various complementary operational models. The first measurements performed throughout the reservoir were used to qualify the model upstream of Vaugris power plant. Velocity mapping should now help to identify the initial factors that are disturbing flow.

Rough modelling of one of the plant's bulb units should help to fine-tune the representation of flows around the power plant when the various models are linked up. However, this is the limit of validity of the Telemac software as a bulb unit consists of numerous complex features (Fig. 12).

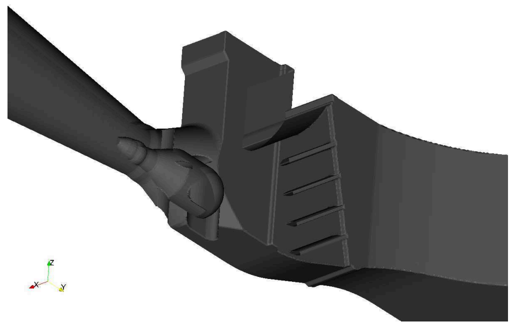

Figure 12. Representation of bulb unit 4 at Vaugris power plant using the OpenFOAM software.

It is by multiplying these approaches, which combine on-site measurements and numerical models, that pertinent solutions will be found for fine-tuning hydraulic assessments of low-head schemes. Numerical modelling is now recognised as a reliable way of representing physical phenomena and a technical reference in assessing projects. However, all these approaches are a challenge for the scientific modelling community, which only joint programmes like PENELOP2 can handle.

Acknowledgement

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