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Numerical and Experimental Study of Favre Waves after Hydropowerplant Trigger with TELEMAC-3D

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Numerical and experimental study of Favre waves after hydropowerplant trigger with TELEMAC-3D

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***Abstract*—CNR is the first producer of exclusively renewable energy in France, operating and managing 18 hydroelectric power plants on the Rhône River. When turbines shut down because of electric incidents, the stop is very sudden and generates a wave that raises the upper channel water level. This step is called trigger or disjunction.**

To improve the knowledge of these wave phenomena is essential for CNR in order to implement suitable actions both at the barrage and power plant with respect to each specific development constraint (warning of sudden water release in the downstream reach, automatic backup, intrinsic security).

Previous modelling studies with 1D and 2D models of the actual trigger test carried out with a 500 m^3/s discharge at Chautagne scheme in April 2010 showed some limitations including excessive dampening of reflected waves and underestimation of secondary waves amplitude. The aim of this study is to carry out the modelling of this test with the TELEMAC-3D software in order to get better results. Tasks consist of 3D model meshing, model calibration for trigger conditions, comparison of results with real test measurements, discussion on methods, analysis of the main parameters and extrapolation to a trigger test with a 700 m^3/s discharge.

I. INTRODUCTION

The of hydro-electric development scheme of the Rhone River is based on a regulation barrage and a power plant equipped with turbines. Electrical incidents (mechanical failure in the turbine or in the electrical network, etc…), or unfavourable hydraulic conditions can lead to a quick stopping of one or more turbines and thus stop the plant and its production. This phenomenon is also called trigger or disjunction. To avoid destruction of the machines due to overspeed, the flow that supplies hydraulic turbines is automatically cut off by valves. The discharge is then suddenly reduced to zero, creating a positive wave propagating in the upstream channel and a negative one in the downstream channel of the plant. The wave is called wave disjunction or swelling. As a consequence, the positive wave will temporarily increase the standard water level of the upper channel (i.e. the usual operating water level) and consequently affects security issues (e.g. flooding of banks equipments and structures, spillage over levees). The numerical study of this phenomenon is crucial for CNR in order to improve the understanding of the wave propagation and to prevent occurrence of any incidents.

The paper is divided in four parts. First, the Chautagne development scheme features are explained. Second, the experimental trigger is described. Third, the TELEMAC modelling is presented. Finally, 2D and 3D results are analysed, limits of optimization are listed and improvements are proposed.

II. OBJECTIVES

The simulation of disjunction waves using TELEMAC-2D model (shallow water or Boussinesq equations) gives a good representation of the first passage of the primary wave amplitude and frequency. This model also has its limitations:

- The dampening of reflected waves is too strong;
- The amplitude of the wave from the second pass at the plant is underestimated compared to the expected results.

In addition, the secondary waves are not modelled by the Saint Venant equations, because these assume a hydrostatic pressure distribution. That’s why 3D modelling seems necessary to reproduce this phenomenon.

Study objectives are:

- to realize a 3D exploratory approach from the existing 2D model and evaluate it by comparing with the experimental test data recorded on 29 April 2010 (500 m3/s);
- To extrapolate the trigger test to the maximum discharge of the power plant.

III. CHAUTAGNE SCHEME

Chautagne hydropower plant is located in the Rhône River valley (in the eastern part of France), between Geneva (Switzerland) and Lyon. It was built in 1980. Chautagne follows the typical CNR development scheme. Indeed, it is composed of the following structures:

- A hydropower plant (Usine d’Anglefort: US) with a total installed capacity of around 90 MW. It comprises two bulb-upstream units with a maximum power station discharge of 700 m^3/s.

- A barrage (BarraGE de retenue de Motz: BGE) equipped with five sector gates. When upstream discharge is higher than the power plant maximum discharge, the gates start opening. During major floods, the gates cannot regulate the water level anymore since they are completely opened.
- A lock for yachting navigation purposes (US).
- A reservoir (retenue RE) which is 5.7 km long. The tributary Fier River (FI) converges into this part of the river course.
- A headrace channel (Canal d'amenée CA) from reservoir to hydropower plant which is 5.3 km long.
- A tailrace channel (Canal de Fuite: CF) which is 3.4 km long.
- The natural river course (Vieux Rhône: VR) in which a minimal discharge has always to be maintained during dry season. During floods most of the flow goes through this natural river.

IV. EXPERMIENTAL TRIGGER

A. *Hydraulic scheme*

The model is delimited by the CNR works:

- Upstream: barrage/hydropower plant of Seyssel (SY) and the tributary FIER River (FI);
- Downstream: barrage of Motz (BGE) and hydropower plant of Chautagne.

B. *Disjunction test in April 2010*

1) *Chronology*

TABLE I. DISJUNCTION CHRONOLOGY

Initial conditions, before disjunction	
Initial incoming discharge at 9:37 am	759 m^3/s
Initial turbine discharge in hydropower plant of Chautagne	500 m^3/s
Discharge through the barrage of Motz	185 m^3/s
Initial water level upstream hydropower plant	251.74 m NGFO
Disjunction	
Turbines stopping	09 :37 :03
Barrage opening	09 :54 :00

2) *Experimental measurements*

7 sensors with an adapted frequency sampling rate (Δt = 1 s) were implemented along the Chautagne scheme (Fig. 1). Therefore the short period secondary waves phenomenon could be recorded. During study the comparison was always done regarding these measurement points.

3) *Experimental results*

The speed of wave propagation was 9.8 m/s, the period was 49 min for the primary waves and 15 seconds for the secondary waves. The waves reached the headrace channel inlet in about 13 minutes (where secondary waves could be clearly recorded).

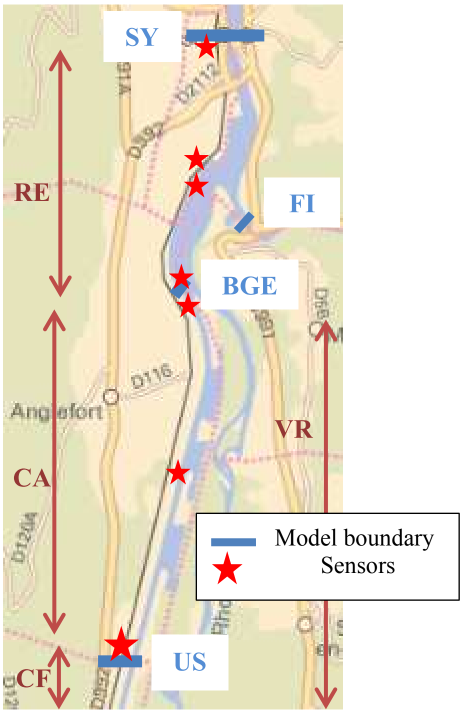

Figure 1. Chautagne scheme

V. THEORETICAL ASPECT CONCERNING THE FAVRE WAVES

Different physical phenomena are distinguished:

- Primary waves (which are related to the propagation along the channel of rapidly changing boundary conditions of flow);
- The secondary Favre waves overlapping primary waves;
- Other "side effects" phenomena such as the amplification of the wave to the right bank (which are a consequence of modulation and primary waves)

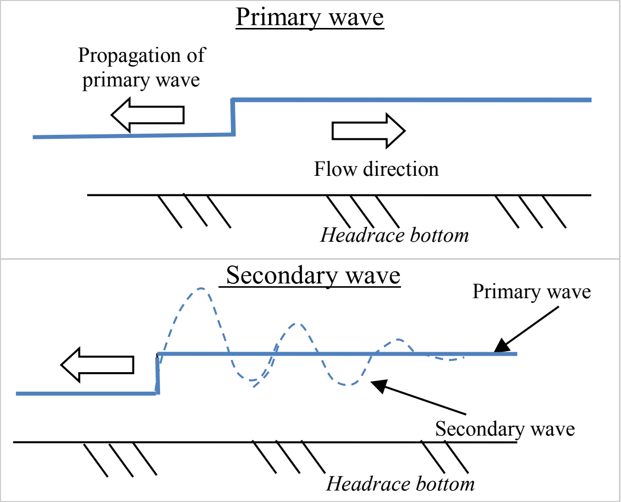

Figure 2. Schematic representation of Favre waves.

VI. SCHEME MODELLING

1. *Mesh*

The domain is 15 km long and is meshed with node located every 15 m (Δx). This resolution was calculated according to the wave speed (*C*) and the time for stopping the hydropower plant. The secondary waves are very quick and have a runtime of 15 s (*T*). It was assumed that between 5 and 10 observations (*n*) during plant stopping were enough to measure waves. Consequently the mesh resolution was calculated with:

$$\Delta x = \frac{C.T}{n} \underset{n=10}{\Longrightarrow} \Delta x = 15.6\,m \qquad (1)$$

The 2D grid comprises about 26 000 nodes and 50 000 elements. This mesh has been generated by Matisse. With regard to the 3D model, 6 horizontal levels are generally used in this study. Consequently, the 3D grid comprises about 150 000 nodes and 750 000 elements. 4 liquid boundary segments (SY, FI, BGE, and CE) are applied.

A. *Calibration*

The model calibration is very important because it determines numerical model reliability. At first, the calibration is done with the 2D model. Then 2D calibration coefficients are reused in the 3D model after a validation step (dependent to the water depth discretization, i.e. horizontal level number). For the calibration process five steady state discharges ranging from 436 m^3/s to 1300 m^3/s and two flood events with peak flows of 2400 m^3/s and 2070 m^3/s were selected. Water levels were imposed at the downstream hydropower plant (CE) and at the other three liquid boundaries (SY, FI and BGE).

The modelling of the turbulence was realised with a constant viscosity of $5.10^{-3} m^2/s$. Calibration was focused on the bottom coefficient, which was computed following Strickler's law. The model was divided into different Strickler zones as specified in Fig. 3.

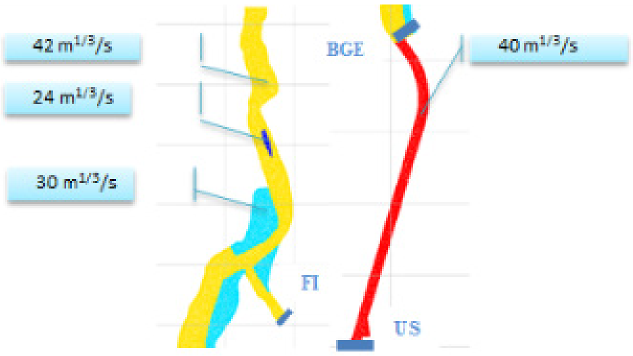

Figure 3. Strickler coefficients

The comparison of computed and measured water levels shows a maximal error of 15 cm for the steady state conditions, however for the lowest discharge the error is less than 5 cm. For the flood events the upstream power plant water level during the peak flow is overrated with 15 cm,. Nevertheless the results match the measurements fairly well allowing to validate the numerical model. For the next step of the study, an average error between 5 and 15 cm has to be taken into account.

The Strickler coefficients from the 2D calibration were used in the 3D model, and the calibration procedure was applied again in order to check the model behaviour in 3D. A similar calibration quality could be reached.

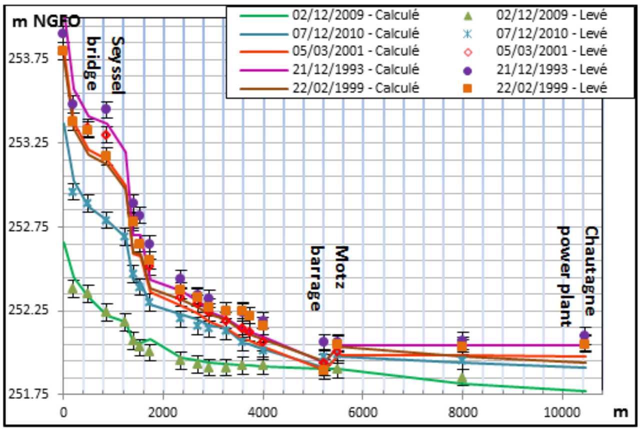

Figure 4. Calibration of steady state in 3D model

VII. DISJUNCTION TEST MODELLING

The disjunction is studied in this part. Water levels throughout the model were calculated to improve the knowledge about these phenomena. During the disjunction, the model was controlled by flow boundary condition. Thus, 2 different kinds of boundary condition setups were used. On the one hand, the initialization (normal boundary conditions), on the other hand the disjunction (only flows).

A. *Initialization*

A hydraulic model in subcritical flow is controlled by a downstream water level, consequently a water level was imposed on the power plant. For the initialization the unsteady state before the disjunction took place was taken from measurements. The model simulated a whole day prior to the disjunction until 9:30 a.m. The simulation of these 30 hours took only 8 minutes on 32 computational cores.

At first the initialization was run with TELEMAC-2D. The difference between the models will be explained later. The comparison of computed and measured water levels (ΔZ) for the initialization run is presented in Table II for different locations of the model (Fig. 1).

At 9:30 a.m the water level. is close to the reality (average ΔZ about 3 cm). Moreover, the headrace channel discharge calculated at 9:30 am is about 500 m^3/s, similar to the ADCP measurements. Therefore the last time step of this initialization was used as the first of the trigger modelling.

TABLE II. INITIALIZATION SUMMARY

	Z [m NGFO]		Init 5 [m NGFO]			
Measurement Point/Station	08:30	09:30	08:30	ΔZ	09:30	ΔZ
P1 Seyssel Bridge	252.33	252.53	252.47	*0.14*	**252.56**	***0.02***
P2 leisure center	251.96	252.06	252.13	*0.17*	**252.09**	***0.03***
P5 BGE upstream	251.96	252.03	252.09	*0.13*	**252.04**	***0.01***
P7 CA entrance	251.94	252.02	252.04	*0.10*	**252.01**	***0.00***
P8 mi- CA	251.84	251.94	251.82	*-0.02*	**251.87**	***-0.06***
P9 lock upstream	251.57	251.73	251.64	*0.07*	**251.78**	***0.05***
P13 100m CE upstream	251.54	251.70	251.59	*0.05*	**251.76**	***0.06***
P14 CE upstream	251.59	251.74	251.67	*0.08*	**251.74**	***0.00***

B. Disjunction

To start disjunction modelling, simulation was run with TELEMAC-2D to get an idea of the results. Then a simple 3D model was run with default setup parameters in TELEMAC-3D. The optimization of this case has been studied in a second phase. Again only flow boundary conditions were used (Fig. 5). Default setup parameters were chosen for TELEMAC-2D run.

- Strickler's friction law with different zones as shown in Fig. 3.
- Constant turbulence model with a constant viscosity of 5.10^{-3} m^2/s.
- The solver was chosen by default with "solving normal equation".
- Shallow water equations were used in this model. A quick sensitivity test between Saint Venant and Boussinesq did not show any significant difference.

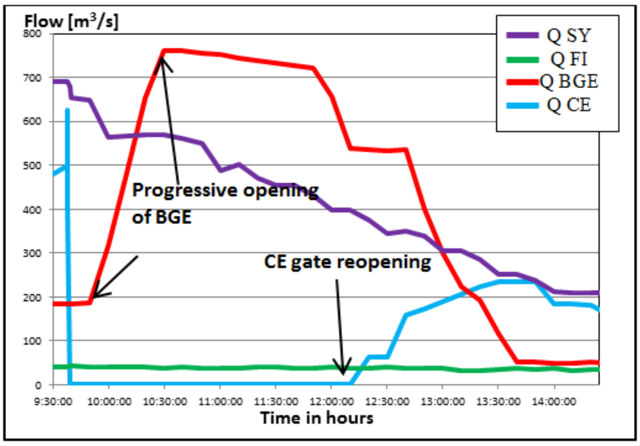

Figure 5. Boundary conditions during trigger test

For the TELEMAC-3D run, parameters were chosen similarly. Additional key-words like 2D continuation, 6 horizontal levels and no friction on lateral boundaries were added to the 3D model.

The time step (Δt) has been calculated according to Courant number C_r. This number must be less than 1 for rapidly changing flows.

$$C_r = C\,.\frac{\Delta t}{\Delta x} < 1 \xrightarrow[\Delta x = 15m]{} \Delta t < 1.4\ s \tag{2}$$

Consequently, **Δt = 1s**.

Both simulations (2D and 3D) were run with continuation on 2D or 3D initialization. Results were extracted at different locations; the study mainly focused on the upstream US sensor (6) and on the inlet of CA sensor (7).

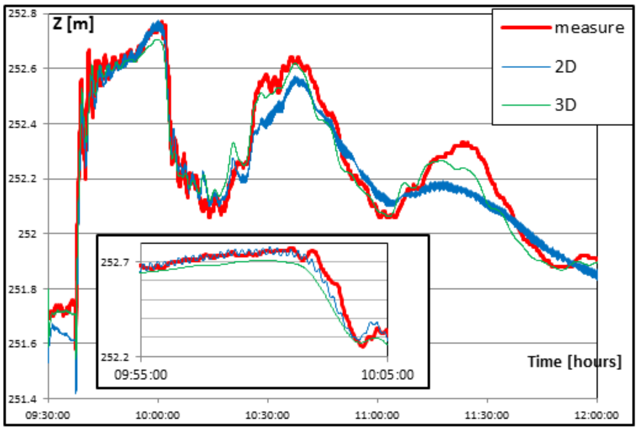

Figure 6. Comparison 2D vs. 3D models at upstream powerplant.

The 2D model shows attenuation of the reflected waves and underestimated amplitude. The first wave peak is perfectly reached by the 2D model; the 3D model is also close even if there is a Δz of 5 cm. Generally the 3D model reproduces the waves better than 2D model. Amplitude and frequency of the model results are almost in line with the measured signal. The amplitude of the reflected wave is quite acceptable even if the model results show a small attenuation; this could be improved with an optimization program.

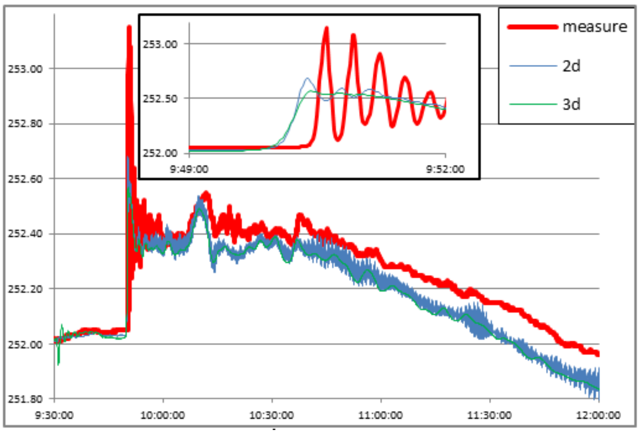

Figure 7. Comparison 2D vs. 3D models at inlet of headrace channel.

The 2D model shows instabilities on the secondary waves (see the zoomed detail in Fig. 7). Some oscillations appear overlaying the general curve, but they might be linked to numerical instability. The primary wave is well simulated by the 3D model. Afterwards a specific study is performed on the representation of secondary waves.

VIII. OPTIMISATION PROGRAM (1)

A. *Key-words effect*

A large optimization program is set up to improve the representation of the disjunction wave and to mitigate the difference between simulation and measurements. This program is based on different key words available with TELEMAC-3D:

- Number of horizontal levels: 6 to 10;
- Horizontal levels position: equidistant or close to free surface;
- Modelling continuation: 2D or 3D;
- Non-hydrostatic or hydrostatic version;
- Horizontal and vertical turbulence model: constant viscosity, mixing length, Smagorinsky, K-Epsilon, K-Omega;
- Solvers.

Most of the tests are displayed on Fig. 8 and Fig. 9. Not all the tests performed with the different solvers are shown, because the results are almost the same.

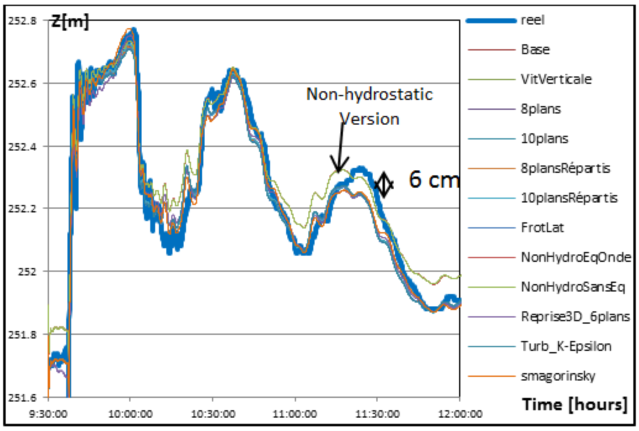

Figure 8. CE upstream models comparison

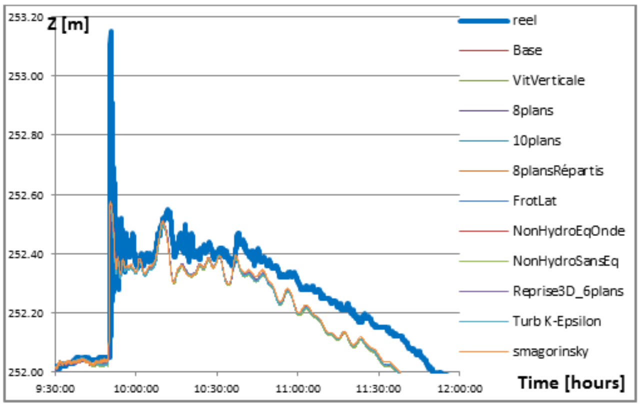

Figure 9. Inlet of headrace channel models comparison.

From the analysis shown in Fig. 8 some configurations could be dismissed:

- Particular level distribution is not appropriate to this test;
- Friction on lateral boundaries has no influence on the free surface level.

Further investigations:

- 3D continuation with restart file (equations solved at last time step);
- Non-hydrostatic version (starting hypothesis);
- Horizontal turbulence model: constant viscosity (5.10^{-3} m^2/s);
- Vertical turbulence model: mixing length;
- Steering word "Velocity profiles" at the discharge boundaries were calculated considering the water height.

At the inlet of the headrace channel, only the primary waves could be calculated by TELEMAC-3D: it should be necessary to find an alternative set of parameters to investigate this phenomenon.

B. *Key-words coupling*

These selected key words are gathered in one simulation. A quick test showed that considering only 6 horizontal levels was enough for this trigger test. Besides boundary conditions were modified and shifted to +10 minutes, because records gave average on last 10 minutes. The values of coefficient diffusion for velocity and depth were fixed to 1 in accordance with the calibration done on v5p9 version. Moreover, free surface gradient compatibility was reduced to 0.9 to avoid instabilities.

A new simulation was run with TELEMAC-3D considering the mentioned key-words concerning coupling and boundary conditions. The 2D model was also modified with the same key-words matching on TELEMAC-2D. Results were matching very well with the measurements as shown on Fig. 10 and Fig. 11.

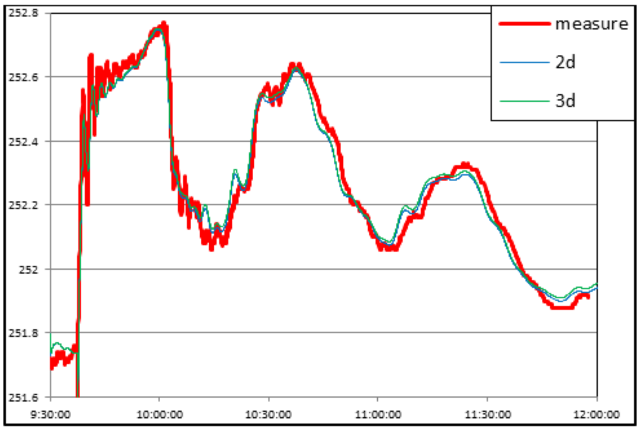

Figure 10. Comparison 2D vs. 3D optimized models at upstream of power plant

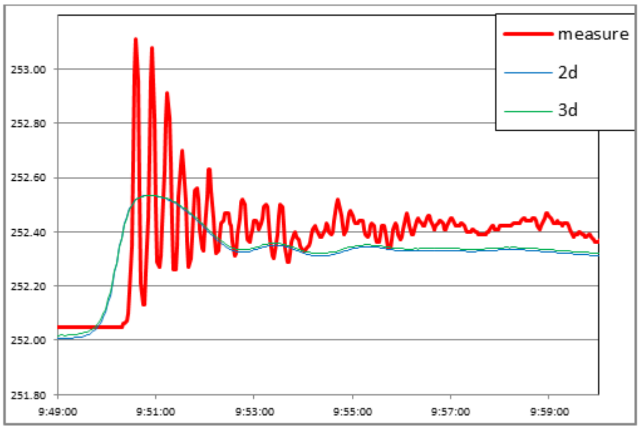

Figure 11. Comparison 2D vs. 3D models at inlet of headrace channel.

Due to optimization steps, the primary wave upstream of the plant is very well represented. Indeed, the period of the signal is correctly calculated for three oscillations visible in the Fig. 11 and the difference in the maximum amplitude is about 2 cm. The curves of 2D and 3D models overlap. The optimized 2D modelling converges to the same results as the 3D model. However, the results provided by TELEMAC-3D take the non-hydrostatic pressure distribution in the vertical axis into account; the model should in theory represent these secondary waves. The optimization of the 3D model must be continued in order to obtain these secondary waves.

IX. OPTIMISATION PROGRAM (2)

Besides the coefficients of velocity and water level diffusion imposed by the version and used for the calibration of the model, a refined mesh could be an alternative solution to get a better hydraulic behaviour. The alternative meshes were:

- Mesh modified at Δx = 5 m and Δt = 0.5 s with 588,378 nodes and 4,238,535 elements;
- Mesh modified at Δx = 1 m all along CA, as for the remaining area Δx = 15 m and Δt = 0.1 s and Δt = 0.01 s with 5,676,066 nodes and 28,197,810 elements.

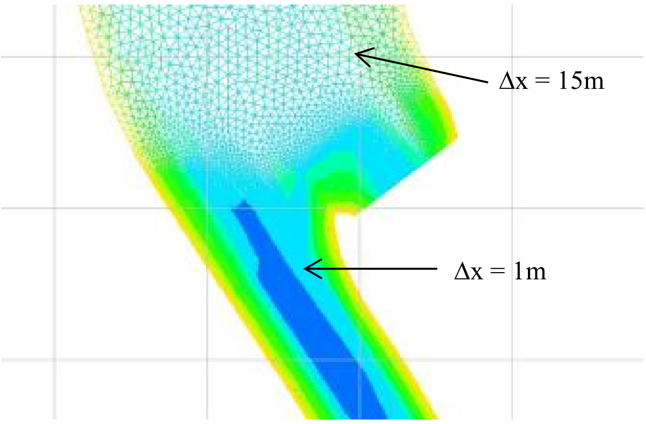

Figure 12. 3D models alternative meshed at inlet of headrace channel.

Only a refined mesh at 1 m with Δt = 0.01 s led to better results concerning Favre's waves modelling (Fig. 13). Indeed the frequency of the secondary waves is now visible in the 3D model results. However, the amplitude is not reached by this last run. A difference of about 50 cm occurred between the computed and measured peak amplitude.

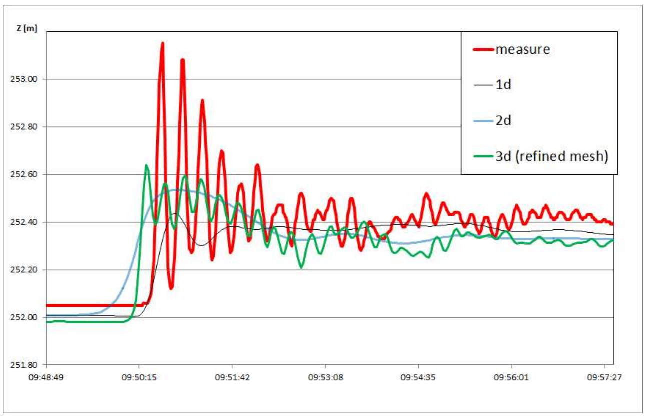

Figure 13. Best 3D Favre's waves representation at inlet of headrace channel.

X. CONCLUSION

The primary wave phenomenon is perfectly calculated by 2D and 3D models (with 6 horizontal plans only). However, the secondary wave phenomena could only be covered with an extremely refined mesh. This led to huge computing time. For 30 min simulation time with a time step of 0.1 s using 32 computational cores the server required 96 h and about 500 h with a time step of 0.01 s for the most refined model. Another future optimization is to refine the discretization of the water column by increasing the number of horizontal planes. Computation times observed here are probably incompatible with the engineering constraints. CNR wants to study the possibility of HPC (High Performance Computing) in the coming months.

Improved knowledge of waves disjunction, including secondary waves, on facilities of the Rhone valley is crucial for CNR to secure the safety for people and facilities. Farmers do not want to take responsibility for the real tests for trigger at high discharge. Also, the real tests mobilize a lot of resources and people. The numerical approach is a suitable way for the study of these phenomena in current operations. Today, as shown in Fig. 13, the calculations 1D-2D-3D do not supply conservative results. It would be promising to continue the study with further model configurations on Chautagne or with an alternative geometry of headrace channel (other development scheme on the Rhône River).

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