

# **DAM REHABILITATION STUDY WITH PROCESS ORIENTED NUMERICAL FLOW MODELS**

**S Erpicum**, University of Liege, Belgium  
**P Archambeau**, University of Liege, Belgium  
**S Detrembleur**, University of Liege, Belgium  
**B Dewals**, University of Liege, FNRS, Belgium  
**M Piroton**, University of Liege, Belgium

## **Abstract**

In the global framework of climate change, hydraulic structures rehabilitation is an up-to-date subject requiring appropriate design and impact studies. In this scope, upgrading the release facilities of dams is an important point when both up and downstream consequences, often irreversible, of badly controlled rising of water in the reservoir, become awarded. Suitable numerical models, coupled with contemporary computational possibilities, allow engineers to forecast the complex situations induced on real structures by extreme events with increasing representativeness and accuracy. In this field, WOLF software, a process oriented free surface flows computation package completely set up by the HACH, has proved its efficiency and reliability for years by numerous theoretical, experimental as well as on real structures applications.

In this paper, the rehabilitation study of the Nisramont dam (Belgium) is presented. Due to its temporary primary tasks, the stilling basin downstream of the crest spillway has been designed for a short time use. It's the same with the 3 bottom outlets, which were never equipped with valves and are thus unusable for the reservoir management. In order to secure the structure and to make it comply with its definitive working objectives, while taking into account climate change observations, the HACH has been entrusted with evaluating up to date critical flood discharges and with designing a system in accord with these new values for the rehabilitation of the bottom outlets and the evacuation of the floods. Several construction options have been compared and optimized by means of the hydrodynamic software WOLF.

Keywords: dam rehabilitation, crest spillway, bottom outlet, stilling basin, computer calculation

## **1. Introduction**

In the global framework of climate change, hydraulic structures rehabilitation is an up-to-date subject requiring appropriate design and impact studies. In this scope, upgrading the release facilities of dams is an important point since any badly controlled rise of water level in the reservoir leads usually to both up and downstream consequences, often irreversible.

Suitable numerical models, coupled with contemporary computational possibilities, allow today engineers to forecast the complex situations induced on real structures by extreme events with increasing representativeness and accuracy. In this field, WOLF software, a process oriented free surface flows computation package completely set up by the HACH team, has proved its efficiency and reliability for years through numerous theoretical, experimental as well as on real structures applications.

In this paper, the rehabilitation study of the Nisramont dam (Belgium) is presented. Located on the Ourthe River, a few kilometers upstream of the town of La Roche, this 21-meter high dam came into service in 1958 and was, in a first time, dedicated to be used as a cofferdam during the construction of a downstream larger reservoir of 250 hm<sup>3</sup>. But this second dam was never built and Nisramont became a definitive reservoir of 3 hm<sup>3</sup> assuming the drinking water supply of a large part of the population of the south of Belgium and producing hydro-electricity.

Due to its temporary primary tasks, the stilling basin downstream of the three 12.5 m large notches of the crest spillway has been designed for a short time use. Similarly, the 3 bottom outlets have never been equipped with valves and are thus unusable for the reservoir management.

In order to secure the structure and to make it comply with its definitive working objectives, while taking into account climate change observations, the Ministère wallon de l'Équipement et des Transport (MET) - Direction des barrages de l'Est (D. 241) entrusted the HACH with evaluating up to date critical flood discharges and with designing a system in accord with these new values for the rehabilitation of the bottom outlets and the evacuation of the floods to the downstream river.

This study has mainly been carried out using software of the WOLF package, successively applied to model really observed extreme events on the structure, to define new peak flow discharge and to design the stilling basin.

## 2. Dam features

The Nisramont dam is a concrete gravity one (Figure 1), 21 m high with a crest 116 m long at level 276 m and a total volume of 22,000 m<sup>3</sup>. The construction phase finished in 1958. The reservoir area is 47 ha for a storage volume of +/- 3 million m<sup>3</sup>. The catchment basin surface is 74,000 ha.



Figure 1: Nisramont concrete gravity dam

The dam is equipped with a surface spillway composed of three notches 12.5 m wide with a crest at level 272 m. The notches opening is controlled by downward sluice gates, the cables command mechanism of which is located in the 2.6 m wide piers between the notches. The maximum reservoir water level is 275 m for a theoretical discharge of 427 m<sup>3</sup>/s with the 3 notches totally opened.

Downstream of the notches, the spillway has a Creager type profile followed by a constant slope channel 5.3 m long being connected by an arched profile to the downstream +/- 0.33% constant slope stilling basin. This basin, 42.7 m wide, is at level 261.2 m upstream and ends with a profiled sill 1.2 m high located 32 m downstream of the spillway foot.

The bottom outlets are made of octagonal holes through the dam 3 m high and 3 m wide for a surface of 7.46 m<sup>2</sup>. Each outlet is located in the axis of a surface spillway notch. On the reservoir side, the level of the outlets is 262.2 m. Their exit in the stilling basin, it is at level 261.2 m. Their length being 17.2 m, the conduits have a constant slope of 5.8 % to downstream. The three outlets are closed in their upstream section by a fixed plug made of concrete plates leaned against dam face. Therefore, it is at present not possible to manage the reservoir water level by using the bottom outlets. Moreover, the regular increase of the leaks of water through the plugs suggests proceeding to their rehabilitation by making them maneuverable.

### 3. The WOLF package

The WOLF free surface flows computation package, completely developed by the HACH team, includes in the same development environment the resolutions of the 1D Saint-Venant equations, the 2D shallow-water equations as well as a physically based hydrological model and powerful optimisation capabilities based on Genetic Algorithms. The interactive and unique user-interface, with high performance pre- and post-processing, allows monitoring 3-D large-scale runs graphically while they proceed, as well as generation of 3D videos. Each code handles general multiblock meshes, dealing with natural topography and mobile bed simultaneously, for any unsteady situation with mixed regimes and moving hydraulic jumps.

By this way, WOLF deals with all free surface hydraulic phenomena, from hydrological runoff and river propagation to extreme erosive flows on realistic mobile topography, such as gradual dam breaching processes. It has moreover proved its efficiency and reliability for years by numerous real applications [1, 2].

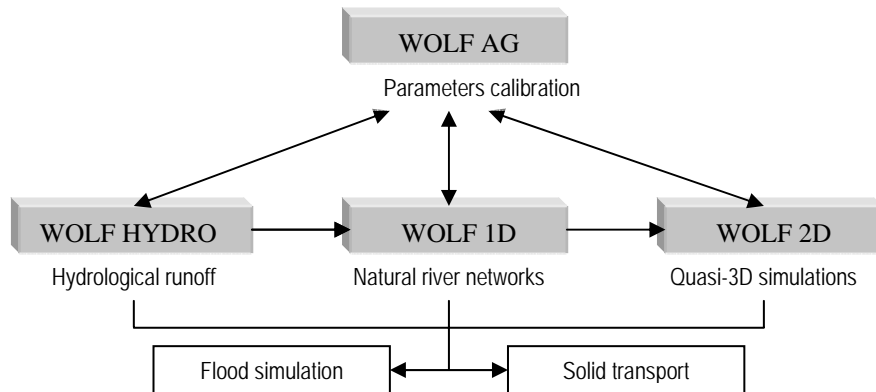


Figure 1 : General organization of WOLF computation units

### 4. Study area numerical model

Input information at the basis of a process oriented free surface hydraulic modelization is an accurate Digital Elevation Model (DEM) of the whole study area, the topography gradients being the main flow engine as well as the main responsible of the local disturbances. It is also the location of the global energy dissipation. A great attention has so been paid to the realization of the digital elevation model of the Nisramont catchment, the reservoir, the structure itself and the downstream river for a total area and a discretization level in accordance with considered phenomena.

The data used to built the DEM came from different sources:

- topographic maps from the Institut Géographique National (IGN) for the whole study area,
- topographic drawings of the reservoir before filling operation,
- dam construction drawings,
- downstream river cross sections through the main bed,
- a global DEM of the dry areas from an airborne laser acquisition stage with an accuracy of 1 point per square meter and 15 cm in elevation,
- several pictures of the structure from its building phase to present.

All these sources, when digitalized and positioned in the same geographic coordinates system (Belgian system Lambert 72), made a strong basis for the generation of a DEM distributed on a regular grid to be directly used in the solvers of the WOLF package.

Three different distributed DEM have been built. A model of the catchment with 100 m meshes, a model of the reservoir and the dam with meshes of 1 m and a more accurate model of the dam, release structures, stilling basin and downstream river discretized with square meshes 25 cm in side (Figure 2). A two-dimension DEM of the Ourthe River downstream of the structure, made up of cross sections spaced out of 25 m and covering a 600 long section, completed this set of three-dimensional representations for specific calculations.

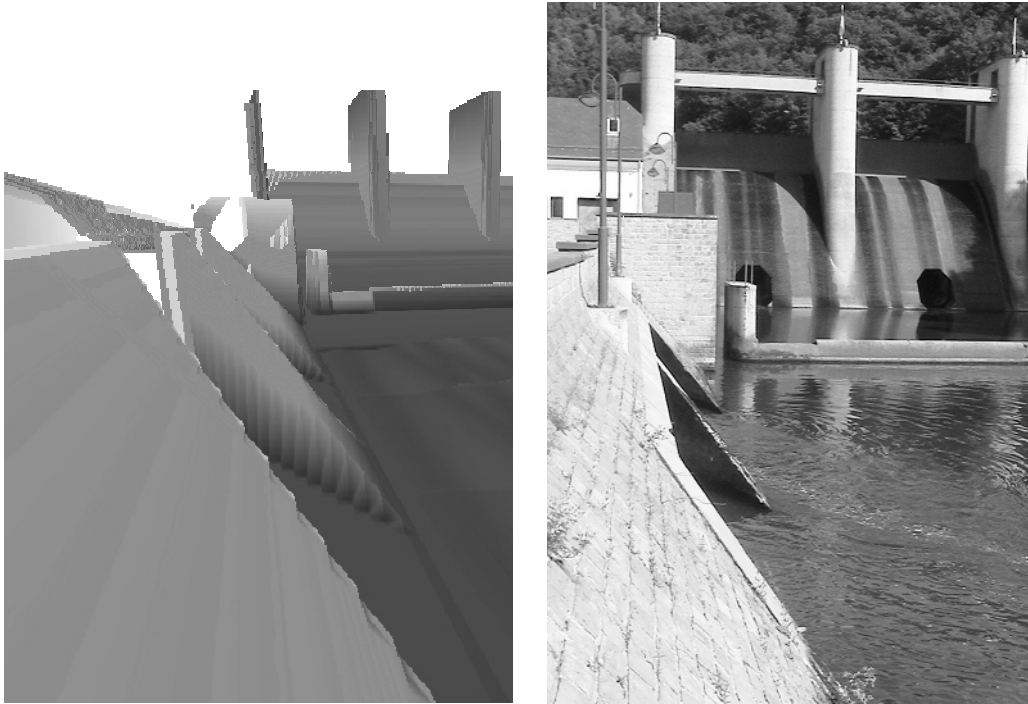


Figure 2: 25 cm digital elevation model of the dam and near downstream

The different models are bordered in the downstream river at the level of a gauging station from the SETHY<sup>1</sup>, the rating curve of which supplies reliable boundary condition values. The lateral extension of the DEMs has been determined in such a way that the flow limits corresponds to a real topographic upward slope for all tested discharges, both in the reservoir as well as in the River Ourthe downstream.

## 5. Hydrologic study

The first step of the study consisted in a hydrologic evaluation carried out on two complementary stages: firstly a statistical analysis of the discharge data in the reservoir from the structure opening to the year 2001, secondly a numerical simulation of hydrologic flow on the catchment using the solver WOLFHydro and starting from rain data given by Intensity - Duration - Frequency curves (IDF curves) of the nearest meteorological station.

Following the application of the Gumbel probability distribution to the 43 available annual maximum inflow values in the reservoir, the 1000-year flood has been evaluated to 320 m<sup>3</sup>/s, with a 70% (IC 70%) confidence interval between 286 and 360 m<sup>3</sup>/s, while the 95% (IC 95%) confidence interval forecast values are situated between 256 and 412 m<sup>3</sup>/s. The 10,000-year flood is estimated to 405 m<sup>3</sup>/s.

These values have been confirmed by the deterministic modeling of flood events on the catchment area starting from statistical rain data and using the solver WOLFHydro.

In conclusion of this hydrological study, regarding the spillway, its maximum capacity equals the new 10,000-year flood and is thus acceptable. On the other hand, the locking of a gate gives a security up to only a 200-year flood. This involves equipping the bottom outlets to recover a part of the release capacity in this case and therefore a sufficient security for the structure.

The design flood finally taken into account for the stilling basin rehabilitation is the 1000-year one increased in the 95% confidence interval up to 375 m<sup>3</sup>/s.

## 6. Hydrodynamic study

### 6.1. Flow conditions in the reservoir

Even if the multiblock computation capacities of the solver WOLF2D allow to compute in a single way geometrically important areas with strongly varied topography, a first set of simulations regarding only the reservoir have been carried out in order to specify inflow conditions upstream of the dam. These

<sup>1</sup> Service d'Etudes Hydrologiques (Hydrologic studies division) - Direction Générale des Voies Hydrauliques - Ministère wallon de l'Équipement et des Transports

results have been used in a second time as upstream boundary conditions for the all the detailed simulations of the release structures hydraulic behavior.

This approach in two stages is fully justified by savings of CPU time it provides by reducing the number of calculation meshes or by a decrease of the unsteady waves propagation length in the numerical model.

## 6.2. Model validation: the flood of January 3<sup>rd</sup> , 2003

In order to validate the proposed approach for the specific case of this study as well as to fit roughness coefficient values of the different soils, i.e. the only unknown of the numerical model, the solver has been applied to the simulation of a real flood event, which occurred at the beginning of year 2003.

The observed peak flood for this event was 240 m<sup>3</sup>/s, i.e. a 100-year flood. For this discharge, the 3 gates of the spillway were partially opened. However, this peak appeared during the night, and so no picture of the flow is available for comparison. On the other hand, during the day of January 3<sup>rd</sup>, just before noon, a 175 m<sup>3</sup>/s discharge on the spillway has been reached. The flows on the spillway have been photographed. This discharge has thus been used to validate the numerical model.

The simulation domain has been cut into 4 blocks using calculation meshes from 25 cm to 1 m in size (Figure 3). A block has been defined upstream of the dam (A), another on the spillway (B), a third one covered the stilling basin area (C) and the last one represented the natural river down to the downstream boundary condition (D). Classical shallow water equations, i.e. the ones written in Cartesian coordinates, have been solved everywhere except in the second block where the expression in curvilinear coordinates has been used. In blocks B, C and D, the calculation unknowns are the water depth and the specific discharge in the mean flow plane while in block A the water depth and the flow velocities have been chosen as main unknowns in order to correctly compute the total head upstream of the structure.

The only boundary conditions imposed to the model were the horizontal discharge distribution in the reservoir upstream of the dam and the free surface elevation in the river 600 m downstream. Here clearly appears the originality and the benefits of a unified modeling from upstream to downstream, in particular for the objective computation of the head-discharge curve of the spillway, provided that the flow remains continuous through the release structure.

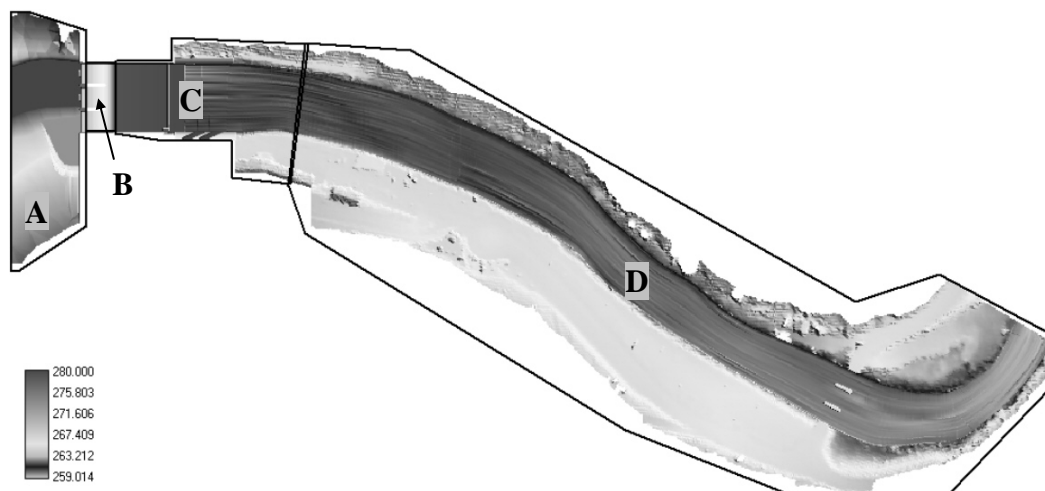


Figure 3: Simulation domain topography and definition of the different computation blocks

Several simulations have been carried out, testing different values of the structures roughness coefficients in their physically representative interval of variation. The extreme sensitivity of the results, above all regarding the hydraulic jump location in the stilling basin, rapidly appeared. In addition, it is impossible to correctly compute the hydraulic jump location in the stilling basin without using the curvilinear coordinates expression of the shallow water equations.

Strickler roughness coefficient value for concrete areas has been chosen equal to 70, and the one of the downstream natural bed of the Ourthe River to 27. These values lead to the results with best agreement regarding the hydraulic jump location in the stilling basin (Figure 4 - A), water heights in the downstream river, in particular along banks (Figure 4 - B), the location and geometry of the cross-waves, and the dry area at the piers foot (Figure 5 - C and D).

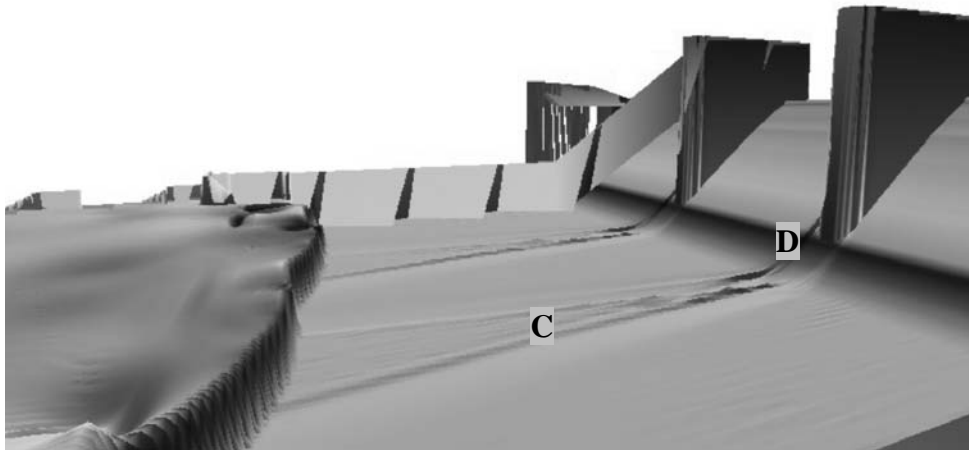


Figure 4: Simulation of the January 3<sup>rd</sup> 2003 flood event - 175 m<sup>3</sup>/s - Solver validation

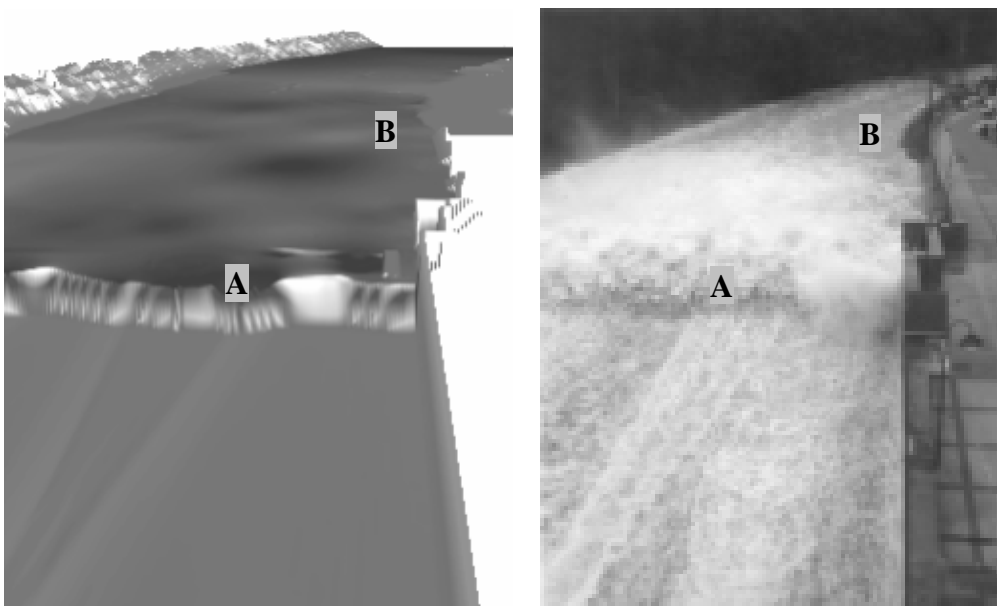


Figure 5: Simulation of the January 3<sup>rd</sup> 2003 flood event - 175 m<sup>3</sup>/s

### 6.3. Outlets rehabilitation

One of the goals of this study is to set up a system allowing the use of the three conduits under the dam as bottom outlets without compromising the actual behavior of the other release facilities. Because of the security criteria to respect regarding an accidental reservoir emptying, such a system means at least to include:

- a gate for regulation of the released discharge,
- a security gate to quickly and securely close the outlet in case of accident,
- an upstream stoplog to put out of water the system in case of maintenance and reparation operations,

none of these added elements negatively interacting with the working of the existing release facilities.

Two solutions have been successively considered to equip the bottom outlets. The first one consisted in equipping each conduit separately, the second one in building a water intake tower in the reservoir including the regulation and closing system and in feeding each conduit through a pipe network.

Hydrodynamic impacts in the reservoir and on the spillway have been studied for both cases by numerical simulations of different working situations and different discharges.

Finally, the cost and realization difficulties attached to the second solution in comparison with the first one have led it to be forsaken.

After calculation of the potentially evacuated discharges and corresponding times to empty the reservoir, the diameter of the gates to be placed in the conduits has been chosen by the

Administration by also relying on the Ourthe River classified discharge curve at the level of the dam. The chosen system is made up for each outlet of a water intake, protected by a grille followed by a convergent and two successive butterfly gates at the minimum conduits level, and discharging downstream of the dam. This system is designed to allow the release of up to more or less 50 m<sup>3</sup>/s for a water level in the reservoir at 275 m.

The combined use of the three bottom outlets allows a reservoir emptying in a period of more or less 16 hours. It also permits, in case of an exceptional situation, to offset a third of the maximum release capacity of a spillway notch.

#### 6.4. Stilling basin design

It is important to underline the particular geometry of the stilling basin in its current configuration. A sill higher than the riverbed, followed by a concrete slab, characterizes it at its downstream extremity. "Classical" stilling basins have instead an extremity step to compensate for the topography level difference between the buried apron and the natural riverbed, step that artificially causes an important increase of the downstream water level in comparison with the supercritical flow coming from the spillway. This induces the expected regime change to dissipate excess energy of the flood and imposes to the flow a higher downstream water height, which acts in the same way. In the current configuration, the sill can be felt by the flow as a limited topography not acting enough as an incentive towards a regime change.

On the other hand, the stilling basin is under designed for the floods expected on the spillway with a relatively important recurrence, as it has been shown by calculation in this study and in the reality by the events of these last years. In the scope of the bottom outlets rehabilitation, the problems of dissipation capacities of the stilling basin become worse by the potential increase of discharges through the dam management facilities.

It is however obvious that the design flood of the stilling basin is directly dependent on the river discharges, and not on the cumulated release capacities of the structure (spillway and bottom outlets). Within this framework, after analysis and modeling of the current structure behavior, a first design of a stilling basin with a flat bottom has been realized as an extreme situation before the calculation of the required dimensions for an efficient stretching and deepening of the present basin. This latter solution seems indeed the less expensive and easier one to realize.

The two stages listed above have in a first time been approached in one-dimension using the solver WOLF1D, prior to a final validation by two-dimensional simulations using WOLF2D.

The final solution meets all the constraints, linked to the stilling basin operations as well as to the hydroelectric power station ones, rejecting its water downstream of the dam. It consists in removing the sill, stretching out the basin of 30 m towards downstream and deepening this new section of 1 m. A step 50 cm high and 3 m long ends the system (Figure 6).

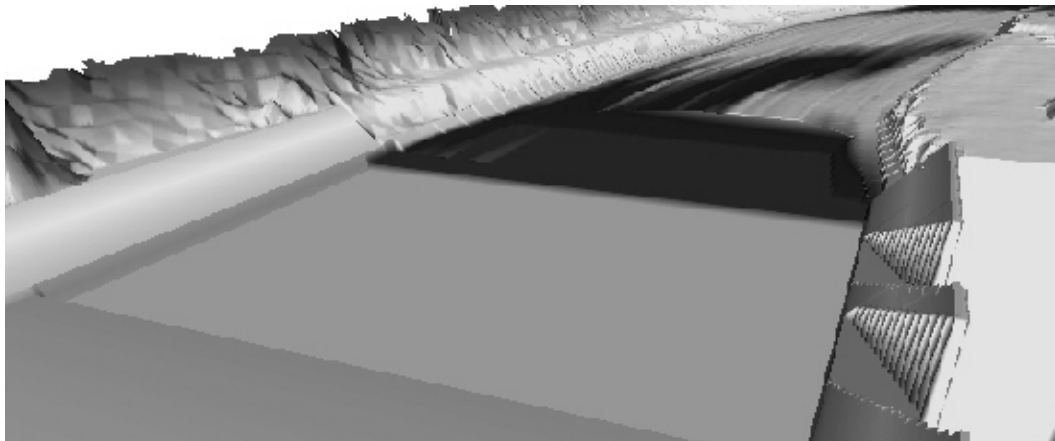


Figure 6: 3D view of the final geometry of the stilling basin

The results of the final simulation of a 1000-year flood release confirm the good behavior of the whole structure, discharging only through the surface spillway (Figure 7) or using a combination of this one with the bottom outlets.

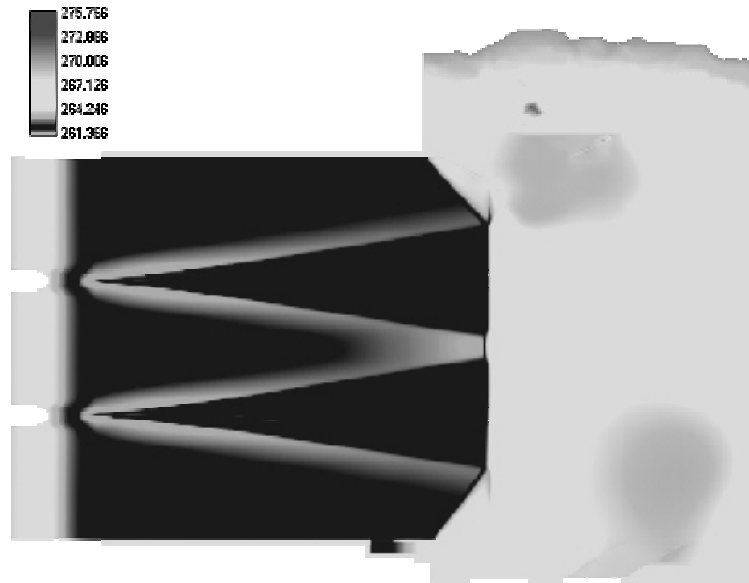


Figure 7: Simulation of the design flood on the final geometry - Free surface elevations (m)

## 7. Conclusions

Recent advances in the set up of efficient and robust numerical models coupled to the current computers calculation capacities allow today hydraulic engineers to tackle more and more practical problems in a reliable and accurate way.

The WOLF software package of the HACH, presented in this paper, has in this scope been successfully applied to the rehabilitation studies of the Belgian Nisramont dam.

After an update of the extreme inflow values entering the reservoir by a statistical method completed with a deterministic calculation, the proposed two-dimensions numerical approach has been validated through the simulation of two flood cases really observed on the structure. The hydrodynamic impact on the behavior of the surface spillway of the different rehabilitation solutions of the bottom outlets has then been assessed. In the same scope, the real operation mode of the present stilling basin has been analyzed before optimizing a new design in accordance with the up to date working constraints of the complete structure.

The solution finally accepted to rehabilitate the bottom outlets, simple and less expensive in terms of new structures, consists in equipping each conduit separately with two butterfly gates and a stoplog sliding on the upstream face of the dam. The release of water is located downstream in the stilling basin without inducing important risks in the Ourthe River in case of reservoir emptying. The working of the bottom outlets doesn't disrupt the flows on the surface spillway nor the stilling basin or hydropower station operation. The same observations remain valid for the new piers in the notches axis necessary to operate the stoplogs.

Regarding the stilling basin, the chosen solution consists in a simplification of the current structure by removing the end sill and by lengthening and deepening the apron towards downstream. A step at the exit realizes in a security way the end of the structure. This geometry has been numerically tested for a lot of flood discharges up to the 1000-year one as well as for a dual operation of surface spillway and bottom outlets.

By completely setting up all the models described in this paper and by having at its disposal a large test laboratory to validate the original mathematical formulations approaches and the resolution schemes on physical applications, the HACH is able to propose coupled approaches for all hydraulic design studies. They consist in numerical simulations at a large scale of the structures with sophisticated but perfectly mastered solvers, completed if needed by physical models more limited and thus more detailed, with as a global goal to optimize the study periods as well as realization means while guaranteeing maximal reliability and accuracy of the results.

## 8. References

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