ADVANCES IN SPILLWAY DESIGN USING FUSE GATES:
APPLICATION TO THE MONTSALVENS DAM (*)

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1. INTRODUCTION

From May 1997 to December 1998, important rehabilitation works were carried out at the Montsalvens arch dam. The evolution of safety requirements since the construction of the dam achieved in 1921 together with ageing effects of the hydromechanical equipment made the works necessary to ensure a satisfactory dam behavior under normal and exceptional conditions [1].

Strengthening of the left bank abutment, subject to plastic deformation, included extensive drilling and shotcrete works to increase its stability conditions.

(*) Développements récents dans la conception d'évacuateurs de crue par l'utilisation de hausses fusibles : Application au barrage de Montsalvens.
The nearly 2 000 m² rock surface was provided with drainage pipes and anchors to prevent the formation of water pressures within the rock mass as well as local block instabilities.

The installation of additional monitoring instrumentation both in the dam and the abutments will allow to follow the behavior of the structures and verify the effectiveness of the strengthening measures.

To increase the spillway capacity, the rehabilitation works included the replacement of the radial gates, the lowering of the overflow sill crest and the installation of Hydroplus fuse gates. With a height of 5.05 m, the fuse gates of Montsalvens dam are the tallest installed in Europe and the first in Switzerland.

From the concept of an auxiliary spillway equipped with Hydroplus fuse gates up to construction details, the report will present the different aspects related to the design, construction and installation of Hydroplus fuse gates.

2. THE MONTSALVENS SCHEME

2.1. THE POWER PLANT

The Montsalvens scheme situated on the Jogne river, a tributary of the Sarine in the Fribourg Canton, is owned and operated by the "Entreprises Électriques Fribourgeoises (EEF). The construction of the plant started in 1918 to provide peak power to the rapidly growing regional energy market.

The double curvature arch dam closes a 70 m narrow gorge impounding a reservoir of 12.6 million m³ of total storage capacity. A 1 680 m long headrace tunnel with a flow section of 6.5 m² supplies the 438 m long penstock. The above ground powerhouse equipped with 5 Francis units of 4.8 MW each generates 62 GWh per year. The gross head of the plant varies between 96 and 122 m with a total nominal discharge of 25 m³/s. Seated into operation in 1921, some of the hydromechanical and electrical components of the plant were successively upgraded and adapted to present standards including namely the replacement in 1987 of the two 1.8 m diameter penstocks by a single 3.0 m diameter pipe.

2.2. DAM AND APPURTEMENT WORKS

The construction of the 52 m high and 110 m crest length arch dam designed by H.E. Gruner signed the beginning of the development of double curvature arch dam in Europe. The width of the variable radius arches increases at both abutments to optimize the strength distribution in the rock foundations. At the crest level (el. 802.30 m a.s.l.), the crown width is 2.0 m increasing to 3.0 m
at the abutments and to 22.50 m at the dam base. The cement used for the concrete varied between 250 kg/m³ below el. 765 m a.s.l. and 220 kg/m³ for the upper part with a total placed concrete volume of 26,000 m³. The dam construction was performed in five blocks using hydraulic concrete compacted with pneumatic hampers separated by 1 m wide shear slots. Precast masonry blocks were used as formwork for both the upstream and downstream dam faces.

The dam foundation consists of thin layers of Malm limestones dipping subvertically with a joint system of variable orientation. During construction works, the left bank excavations disclosed an old preglacial valley nearly parallel to the present riverbed. In addition to a modification of the dam geometry, including the construction of a gravity abutment, the left bank of the dam had to be founded on the rock buttress situated in between the preglacial and the actual valley. The general layout of the dam and the appurtenant structures as configured prior to the rehabilitation works are schematically shown in Figure 1.

Prior to the rehabilitation works, the dam was equipped with a 57 m³/s capacity bottom outlet located at the dam base and two spillways with a maximum capacity of 75 m³/s each, equipped with radial gates installed in 1920. The spillway on the right bank was completed in 1945, following erosion damages occurred in 1944 on the rock buttress below the left bank spillway. The capacity of this spillway was thus reduced by closing one of the two bays and moving the radial gate from the left to the right spillway.

The water intake structure supplying the headrace tunnel is located on the right bank in between the dam abutment and the right bank spillway. Additional details on the scheme construction and the initial behavior are given in [2] and [3]. Figure 2a) shows a general view of the downstream dam face, whereas a schematic cross section of the crown cantilever including the bottom outlet is given in Figure 2b).
Fig. 1
General layout of the Montsalvens dam and appurtenant structures
Représentation générale du barrage de Montsalvens et des ouvrages annexes

1. Left bank spillway
2. Gravity abutment
3. Bottom outlet
4. Arch dam
5. Intake
6. Gate chamber
7. Right bank spillway
8. Gallery
9. Tailrace canal
10. Jogne River
11. Downstream protection

1. Évacuateur rive gauche
2. Culée rive gauche
3. Vidange de fond
4. Barrage-voûte
5. Prise d'eau
6. Bâtiment de la prise d'eau
7. Évacuateur rive droite
8. Galerie
9. Canal de fuite
10. La Jogne
11. Protection aval
3. DESIGN OF THE SPILLWAY REHABILITATION WORKS

A flood safety analysis completed in 1995, indicated an insufficient discharge capacity at the Montsalvens dam. Combined with the need to replace the nearly 70 years old radial gates, alternatives for the rehabilitation and substantial upgrade of the spillways were examined within a feasibility study.

A preliminary analysis revealed that the capacity increase from 150 m$^3$/s to 346 m$^3$/s peak outflow discharge had to be achieved preferably on the left bank spillway, due to the access and construction difficulties on the right bank one. Furthermore, due to the risk of erosion damages, priority had to be given to the operation of the right bank spillway in order that the left one could be operated only in case of exceptional events.
Based on the previous conditions, various design alternatives were considered for the upgrade and rehabilitation of the left bank spillway. From the replacement of the existing radial gates with an equipment of the same type up to the installation of an inflatable weir or of fuse gates, several alternatives were evaluated at a feasibility level. The main criteria considered for the comparison of the solutions, included construction costs, safety, maintenance and operational reliability.

Following the detailed evaluation of the various design alternatives, and considering the exceptional operation of the left bank spillway, the installation of 4 Hydroplus fuse gates turned out as the most suitable solution due to the following main aspects:

- High operational reliability comparable to a free overflow sill.
- Reduced operational and maintenance costs if compared to conventional gates.
- Reduced construction costs of both the civil and steel structures if compared to a conventional solution.

Although the Hydroplus system has proven to be effective for several applications, the main design problems to be faced by the first Swiss application may be summarized as follows:

- Approval by the Swiss dam supervision authority considering the fact that the fuse gates would be the highest in Europe (5.05 m).
- Behavior of the fuse gates under exceptional loads including ice formation, floating debris and earthquakes.
- Detailed hydraulic and stability behavior during the tilting sequence.

The Swiss dam supervision authority was involved from the early design stages in order that any requested investigation or suggestion could be planned and included within the design process. It was finally accepted by the authority to consider the Hydroplus fuse gates as reliable as a free overflow sill in order that a blockage of the gates can be excluded.

As regards the operational safety of the fuse gates under exceptional loads, constructive measures had to be taken to exclude any additional horizontal load due to ice formation or floating debris. Finally the gates have to be fully operational without any structural damage for horizontal loads up to 10 % of the gravitational acceleration.

The hydraulic and stability behavior of the fuse gates under different operational conditions has been investigated with the support of two hydraulic model studies as described in chapter 5. The finally adopted design of the modified spillway is shown in Figure 3. The numbers indicated on the fuse gates correspond to the finally adopted tilting sequence.
Fig. 3
General characteristics of the left bank spillway: a) Plan view (numbers on fuse gates correspond to the tilting sequence) and b) Longitudinal cross section
Caractéristiques générales de l'évacuateur de crue en rive gauche: a) Vue en plan (les numéros sur les hausses fusibles correspondent à la séquence de basculement) et b) Coupe longitudinale

a) 1. Lateral deflector
   2. Bridge
   3. Abutment
   4. Spillway chute
   5. Sill
   6. Approach zone

b) 1. Deflector crest
   2. Normal operating level
   3. Hydroplus fuse gates
   4. Concrete ballast
   5. Float
   6. Water aeration system
   7. Alluvial deposits
   8. Rock abutment
   9. Actual rock profile

a) 1. Déflecteur latéral
   2. Passerelle
   3. Appui du barrage
   4. Coursier de l'évacuateur
   5. Déversoir
   6. Zone d'approche

b) 1. Crête déversante
   2. Niveau normal d'exploitation
   3. Haussse Hydroplus
   4. Lests en béton
   5. Flotteur
   6. Système d'injection d'air
   7. Alluvions
   8. Rocher
   9. Profil actuel du rocher
4. HYDROPLUS FUSE GATE CONCEPT

4.1. BASIC PRINCIPLE

The Hydroplus fuse gate concept applied to Montsalvens dam consists of a set of four independent overspilling straight-crested units placed on the left spillway sill to increase its flood discharge capacity from 75 to 300 m$^3$/s. The units are overtopped by moderate floods. When a flood higher than 250 m$^3$/s occurs (i.e. 70-year flood), the first unit starts to overturn. For the 1 000-year flood, the four units tilt solely as a result of an increasing upstream water level, so that the whole sill is free for flow release. For floods intermediate between these two extremes, the units overturn one after the other in a predetermined order (see Fig.4).

![Diagram](image_url)

**Fig. 4**
Montsalvens Dam: Tilting sequence of the fuse gates during a 1 000-year flood, with the right bank spillway out of order

*Barrage de Montsalvens: séquence de basculement des hausses fusibles pendant une crue de 1 000 ans, avec l'évacuateur rive droite hors service*

<table>
<thead>
<tr>
<th>A</th>
<th>Discharge (m$^3$/s)</th>
<th>A</th>
<th>Débit (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Time (h)</td>
<td>B</td>
<td>Temps (h)</td>
</tr>
<tr>
<td>C</td>
<td>Inflow</td>
<td>C</td>
<td>Débit de crue entrant</td>
</tr>
<tr>
<td>D</td>
<td>Outflow</td>
<td>D</td>
<td>Débit de crue sortant</td>
</tr>
<tr>
<td>I-IV</td>
<td>Fuse gates tilting</td>
<td>I-IV</td>
<td>Basculement des hausses</td>
</tr>
</tbody>
</table>
The process of Monsalvens Dam fuse gates is based on:

- free-standing gravity units, 5.05 m-high, 2.57 m-wide, set side-by-side on the auxiliary spillway to form a watertight barrier,
- each unit, made of construction steel, bears against stainless steel abutment blocks located at the downstream edges. Each unit is ballasted with reinforced concrete blocks to resist hydrostatic pressure,
- a drain hole is provided per unit to remove any leakage along the interface,
- the units are equipped with an horizontal seal to ensure watertightness of the interface and a vertical seal to ensure watertightness between adjacent units,
- each unit is fitted with a well which admits water to the underface when the headwater reaches a specified reservoir level. The four units have the top edges of their well set at different heights.

When the drain hole cannot discharge the whole inflow of the well, pressure starts to build up beneath the fuse gate and eventually causes it to tip off the sill platform. This triggering system is very precise and leaves an ample safety factor (ratio of the stabilising moment to the overturning moment) until the reservoir level reaches the elevation activating a given element. In normal operating conditions, the safety factor is equal to 2.6 at normal water level (water level at the fuse gates crest). It remains equal to 1.7 even just prior to lift-off.

4.2. ADAPTATION OF THE GENERAL CONCEPT TO MONTSALVENS DAM FUSE GATES

The auxiliary spillway of Monsalvens is particular insofar as its width is extremely narrow compared to its height. This geometry leads to relatively high approach flow velocities to the spillway after the tilting of the first two fuse gates. Fuse gates Nr 1 and Nr 2 were designed with standard wells and Nr 3 was located between them in order that the draw down of the water profile triggered by the tilting of fuse gate Nr 1 does not affect the tilting of fuse gate Nr 2. The setting of the top edges of the standard wells take into account the water profile (see Fig. 5).
To account for the lowering of the water surface in the spillway and for the three-dimensional flow conditions after the tilting of the first two fuse gates, the wells of fuse gates Nr 3 and Nr 4 were modified. A surge chamber was installed on each side of their wells (see Fig. 6). The surge chamber is in contact on one side with the reservoir, and on the other side with the inlet well supplying the pressure beneath the bottom of the fuse gate.

This technical modification represents an important innovation to the Hydrouplus System and an adaptation of the general concept to the particular case of Montsalvens. The water level inside the surge chamber and upstream of it are almost identical. This surge chamber makes it possible to recover the kinetic energy of the flow.

The modification therefore allowed the designer to avoid the problem of the low streamline level along the inlet well of fuse gates Nr 3 and Nr 4 when the adjacent fuse gates have tilted. Surge chambers permit to define the tilting level of the fuse gates independently from the approach conditions (i.e. fuse gates tilting is calibrated according to the impounding level with the exception of the head losses in the approach channel).
Fig. 6
Fuse gate fitted with a surge chamber: a) perspective view and b) Vertical section
Hausse fusible avec chambre d'équilibre: a) perspective et b) coupe verticale

A  Water level in the well  
B  Water level near the well  
C  Inlet well  
D  Surge chamber  
E  Drain hole  
F  Underface (pressure chamber)  
G  Horizontal seal  
H  Ballast blocks  

A  Niveau d'eau dans le puits  
B  Niveau d'eau contre le puits  
C  Intérieur du puits  
D  Chambre d'équilibre  
E  Purge  
F  Chambre de mise en pression  
G  Joint longitudinal  
H  Lests en béton

5. MODEL STUDIES

The particular approach and restitution flow conditions of the left bank spillway associated to the alternative selection of Hydroplus fusegates convinced the designers to submit this particular work to hydraulic model tests. Regarding the information attended from the experimental study, a general and a detailed model were realized. A summary of the experimental setups, respective aims of both models, and main results related to the fuse gates functioning is presented below.

5.1. GENERAL MODEL 1:30

The first model at geometric scale 1:30 was carried out in the Laboratory of
Hydraulic Constructions at the Swiss Federal Institute of Technology in Lausanne. This model included part of the reservoir with the approach zone geometry, the left bank spillway, the impact area of the water jet and part of the downstream riverbed including the bottom outlet restitution.

The aim of the experimental device was to investigate the following main aspects, respecting the Froude similarity:

- Approach flow conditions to the left bank spillway.
- Ski jump and deflector optimization in order to promote the water jet aeration and to limit the scouring in the impact area.
- Scouring zone delineation at the impact of the jet.
- Selection of the optimum tilting sequence of the Hydroplus fuse gates.
- Determination of the hydraulic characteristics of the spillway at the various tilting sequences.

5.2. Detailed Model 1:10

Following the geometrical definition of the spillway, a second model at scale 1:10 was built in the chute of the Maigrange scheme owned by the electrical company. For this model 4 fuse gates 0.505 m high and 0.257 m wide were built according to a preliminary design provided by Hydroplus.

The purpose of this second experimental study, realized by the engineer office Ribi in Fribourg, were to ensure the operational conditions of the fuse gates and in particular:

- Accurate verification of the hydraulic behavior of the fuse gates and of the tilting sequence.
- Evaluation of the stability and tilting characteristics including the definition of the ballast weight in order that each tilting occurs at the required reservoir level.
- Analysis of the hydraulic effect of floating debris on the fuse gates.
- Evaluation of the operational reliability of the fuse gates under normal and exceptional conditions including the influence of seal leakage.

5.3. Experimental Results

The main observations and results related to the fuse gates [4], [5], [6], can be summarized as follows.

The flow asymmetry due to the successive opening configurations during the tilting sequence induces the development of jets towards the rock cliff at the chute outlet. In order to rectify this negative effect, a lateral deflector was
provided and optimized experimentally along the right guide wall at the left end of the chute (Fig. 3a).

The lateral deflector mounted on the ski jump had then to be considered when defining the tilting sequence of the fuse gates. As a matter of fact, the flow expansion from the openings located on the right side of the spillway reaches the deflector wall perpendicularly, resulting in a vertical jet. Thereby, the initially foreseen tilting sequence of the fuse gates had to be modified in order to provide optimal flow conditions on the chute. By giving the tilting priority to the gate located on the left extremity, the efficiency of the lateral deflector has so been preserved, as shown in Figures 7 and 8.

![Flow over the spillway after tilting of the first fuse gate with a reservoir water level at 802.10 m a.s.l.: a) Top view and b) Downstream frontal view](image)

**Fig. 7**

Flow over the spillway after tilting of the first fuse gate with a reservoir water level at 802.10 m a.s.l.: a) Top view and b) Downstream frontal view

Écoulement sur l'évacuateur après basculement de la première hausse fusible (niveau de retenue à 802,10 m s.m.) : a) Vue de dessus et b) Vue de face depuis l'aval
Fig. 8

Longitudinal profiles and cross sections on the chute of the spillway after tilting of the first fuse gate, with a reservoir water level at 802.10 m a.s.l.

*Profils en long et en travers sur le coursier de l'évacuateur de crue après le basculement de la première hausse, avec un niveau de retenue à 802,10 m s.m.*

1, 2 Cross sections  1, 2 Profils en travers
A, B, C Longitudinal profiles  A, B, C Profils en long
X, Y Distances in m  X, Y Distances en m
Z Altitude in m a.s.l.  Z Altitude en m s.m.

The tilting will then occur respecting the sequence 1-3-2-4 in conformity to the numeration shown on Figure 3. Furthermore, it could be verified that the deflector will not be an obstacle on the fuse gates trajectories when washing out.

By floods, the water increase in the reservoir will first lead to the overtopping of the fuse gates and then to their successive tilting. The five
independent rating curves of the spillway corresponding to the possible operational conditions had so to be defined. The experimental approach is justified in this case by the presence of the inlet wells above and behind the gates screen (Fig. 6) and by the three-dimensional character of the flows at the various tilting stages. The obtained rating curves are presented in Figure 9 in comparison with the theoretical ones. It appears that the hydraulic capacity of the spillway is greater than forecasted, due to the underestimation of the effective discharging width. As a matter of fact, the location of the inlet wells and the tightening lateral walls in retreat of the gate screen (Fig. 6) induce an acceleration before the flow reaches the opening section. Therefore the contraction effect at this place is reduced. With a capacity of about 300 m³/s, the left side spillway allows therefore the evacuation of extreme floods in conformity with the guidelines of the Swiss dam supervision authority.

Fig. 9
Rating curves of the left bank spillway. Comparison of the experimental and theoretical results

Relations niveau-débit de l’évacuateur de crue en rive gauche. Comparaison entre les résultats expérimentaux et l’approche théorique

A Water discharge in m³/s
B Water level in m a.s.l.
C Top of dam level
D Theoretical rating curves
E Experimental rating curves

A Débit en m³/s
B Niveau d’eau en m s.m.
C Niveau de la crête du barrage
D Relations niveau-débit théoriques
E Relations niveau-débit expérimentales

The evaluation of the stability and tilting characteristics could be provided including the definition of the ballast weight in order that each tilting occurs at the required reservoir level. For the gate Nr 3 and Nr 4 (Fig. 3), fitted with a surge
chamber, a particular problem was to mobilize the entire kinetic energy for the supply of the inlet well. The adjunction of lateral deflectors, visible in Figure 6a), revealed to be very effective in this case and were adopted for the gates construction.

Qualitative tests performed with floating debris put in evidence that an accumulation of wood trunks behind the fuse gates could affect the tilting conditions. In order to warrant the required functioning, it was decided to install a floating beam shortly upstream of the spillway.

The operational reliability of the fuse gates under normal and exceptional conditions was examined when considering the influence of seal leakage. The hydraulic model tests put in evidence the importance of a good imperviousness of the horizontal joints and the necessity to provide a good planarity of the foundation slab.

6. SPILLWAY CONSTRUCTION

6.1. CIVIL WORKS

The civil works [6], [7], started in 1997 with the dismantling of the existing gates and the demolition of part of the civil structures down to the rock foundation. A stoplog was installed to protect the job site from the reservoir. In case of an exceptional flood, blasting of the stoplog would have been necessary to provide the necessary discharge capacity to prevent a dam overtopping.

Figure 10 shows the start of the concreting works on the spillway chute following the completion of the demolition works.

Regarding the design of the modified spillway structure it should be mentioned that the crest of the overflow sill does not follow a Creager shape but is horizontal to obtain the necessary surface for the positioning of the fuse gates as shown in Figure 3.

After the completion of the downstream part of the modified spillway structure, the stoplog was removed and the remaining civil works on the spillway approach zone were completed within one month.
6.2. CONSTRUCTION AND INSTALLATION OF FUSE GATES

The detailed design, construction and assembling of the fuse gates was under the responsibility of Hydroplus International acting as supplier of the equipment. The fabrication of the fuse gates was subcontracted by Hydroplus to a local supplier. The consultant was charged with the preparation of the technical specifications and the quality supervision during the detailed design and construction phases.

Due to the significant height of the fuse gates and the required planarity of the base joint, it was decided to provide the base of the overflow sill with 200 mm large embedded stainless supports as shown in Figure 11 allowing a fine positioning of the fuse elements.

The fuse gates structures were assembled by welding 10-12 mm StE 37 steel plates locally reinforced with stiffeners to provide the necessary structure rigidity. Relatively small fabrication tolerances had to be respected in order to obtain the needed base planarity and to avoid any blockage of the fuse gate during tilting.
The nearly 4 tons steel structures were completely assembled, and painted in the factory prior to be placed by crane shortly upstream of the overflow sill. Only after the fine positioning of all four fuse gates, the embedded parts on the sill base were poured and definitely sealed.

Following the positioning of the fuse elements, the base and lateral rubber joints were mounted and the concrete ballast installed on the steel structure, increasing the final weight of each fuse element to nearly 20 tons.

To prevent the formation of ice in front of the fuse elements with a consequent modification of the horizontal loads, a water aeration system was provided at the base of the fuse gates. The circulation of water induced by the upward moving air bubbles avoids the formation of ice on the water surface in front of the gates.

A floating beam located shortly upstream of the spillway and moving along two vertical piers is used to prevent the impact of floating debris on the skin plate of the fuse gates. Furthermore, after the tilting of one fuse element, the floating beam avoids the blockage of the hydraulic section by debris.
Finally, the costs for the detailed design, fabrication and installation of the four Hydroplus fuse gates including joints, and spare parts were of CHF 480 000.- (US$ 320 000.-). The costs for the embedded parts and for the supervision during the fabrication and installation may be estimated of approx. CHF 50 000.- (US$ 35 000.-).

7. CONCLUSIONS

The necessary increase of the outflow capacity of the Montsalvens dam has been achieved by the installation of four Hydroplus fuse gates. This technical solution revealed to be the most suitable among various design alternatives. The main arguments for that choice are related to the operational reliability and to the construction and maintenance costs.

The experimental investigation of the project on two hydraulic models allowed to optimize its design and functioning. Important modifications could thus be provided, particularly concerning the tilting sequence of the fuse gates and the water jet deviation on the ski jump downstream.

Due to the fact that the surface profile near the gates is significantly affected by the first cleared openings, the last two tilting fuse gates had to be equipped with a surge chamber installed on the well supplying the pressure chamber located at the base of the gates. This technical modification represents a major innovation of the Hydroplus System.

The project will thus satisfy to all the severe safety conditions imposed by the Swiss dam supervision authority.

REFERENCES


SUMMARY

In the frame of the rehabilitation works carried out at the Montsalvens dam in Switzerland, the outflow capacity had to be increased from 150 to 346 m³/s. This condition could be satisfied by the installation of four 5.05 m high Hydroplus fuse gates on the left bank spillway. Hydraulic model tests were performed which allowed to improve and to optimize the technical solution.

The civil works were carried out from May 1997 to December 1998. A particular attention was put to the gates fabrication and to the base planarity in order to avoid any blockage during tilting.

RÉSUMÉ

Dans le cadre des travaux de réhabilitation du barrage de Montsalvens en Suisse, la capacité d’évacuation des crues devait être augmentée de 150 à 346 m³/s. Cette condition a pu être satisfaite par l’installation de quatre hausses fusibles de type Hydroplus, de 5,05 m de hauteur, sur l’évacuateur en rive gauche. Des essais sur modèle ont permis d’améliorer et d’optimiser cette solution technique.

Les travaux ont été réalisés de mai 1997 à décembre 1998. Une attention particulière a été portée à la fabrication des hausses et à la planimétrie de leur socle afin d’éviter tout blocage durant le basculement.