

COMMISSION INTERNATIONALE  
DES GRANDS BARRAGES

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VINGT DEUXIÈME CONGRÈS  
DES GRANDS BARRAGES  
*Barcelone, juin 2006*

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**LOW HEAD STILLING BASIN WITH SIDE DISSIPATION BEAMS FOR  
IMPROVED DISSIPATION EFFICIENCY <sup>(\*)</sup>**

Dusan CIUHA  
*Grad. Civ. Eng.*

*IBE, Consulting Engineers*

Jure MLACNIK  
*Grad. Civ. Eng.*

*HIDROINŠTITUT, Institute of Hydraulic Research*

SLOVENIA

1. GENERAL

The present paper gives an example of an extremely changed operation of low head hydro power plant which shows that in flood water conditions the operation of the stilling basins is hydraulically unsuitable and provokes harmful consequences. The paper also presents the mode of such hydraulic improvement. In planning of such improvement by hydraulic model research the leading hypothesis was fulfilled according to which in the stilling basin with 2D dissipation a 3D dissipation of energy was achieved. This result was achieved by invention, development and use of a new structural solution – a side dissipation beam. Its effect on the increased dissipation efficiency of the stilling basin in which it has been built was determined by a model and partly approved on a prototype.

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<sup>(\*)</sup> *Amélioration de l'efficacité de la dissipation d'énergie dans un bassin d'amortissement à faible chute grâce à des poutres latérales.*

Low head hydraulic dam structures usually consist of a number of spillways positioned between side walls. Due to the available total head from the reservoir water level to the tailwater level, a portion of the potential approach energy in a spillway is transformed into kinetic energy which exerts a strong influence on the dynamic flow conditions and on the erosion downstream of the dam structure. In order to ensure the most effective dissipation in the stilling basin, a number of solutions is already known, but under the bottom limit value of the Froude number and - in our practical case - also at too low tailwater levels, such solutions have no effect and are therefore meaningless.

The original patented construction named "Side dissipation beam" has been designed by physical model tests in the hydraulic laboratory of the Institute of Hydraulic Research in Ljubljana. On each stilling basin side wall at least one dissipation beam is positioned longitudinally in the flow direction and protrudes from the side wall into the interior of the basin. The presented structure functions properly at low water heads, at very low Froude numbers and by negligible reduction of the cross-section area of the stilling basin.

The purpose of this invention is to improve the dissipation efficiency of the stilling basins of the small dam of the hydropower station Vrhovo on the Sava River in Slovenia. In the year 2002, such side dissipation beams were successfully applied in the 1<sup>st</sup> spillway. At critical discharges coinciding with lower than predicted downstream water levels they successfully stabilize the hydraulic jump inside the stilling basin. Side dissipation beams in the stilling basin ensure an effective dissipation of excess kinetic energy and thus prevent the bottom and banks of the downstream riverbed reach from extensive erosion.

The side dissipation beams can be applied either at the design stage of new hydraulic structures or as an economically acceptable refurbishment of the existing structures. For some more information see <http://www2.arnes.si/~ljhidri5>

## 2. DESCRIPTION OF THE FACILITY AND RELATED PROBLEMS

### 2.1. FACILITY DESCRIPTION

The Vrhovo Hydro Power Plant has been operating for a decade and represents the first upstream unit in the foreseen scheme of hydro power plants on the lower Sava River in Slovenia. The installed power of three bulb type generator sets is  $P_i = 43$  MW at operating head of 10 m and discharge of  $Q_i = 500$  m<sup>3</sup>/s.

The dam structure consists of five spillways of 15 m width. Each spillway block is 15 m wide and consists of a gated spillway with a radial gate with a

valve, of a reinforced concrete stilling basin with horizontal bottom of 20 m length (Type I by the Bureau of Reclamation, without accessories such as baffles and/or deflectors) and of a solid end sill.

## 2.2. PROBLEMS DESCRIPTION

In flood water conditions and by increased discharge the Sava River brings along great amounts of floating material (debris, trees, bushes, etc.). This material accumulates on the dam, in front of the gates of the spillways. It jeopardizes the operation of the gates and the evacuation of flood waters. This floating material must be permanently flushed with water flow which can only be achieved by demanding gates manoeuvres performed by the plant operators. This means that the discharge must be asymmetrically increased in one or in a pair of the 5 spillways. Such a mode of unsymmetrical gates operation is uncomformable to the operational capacity of the structure; however, it will be impossible to avoid it in the future. The stilling basins of the spillways have been designed only for symmetrical gates operation and consequently they do not bear any overloading. Behind the asymmetrically opened spillway the tailwater level is lower than predicted due to the water level of the 2<sup>nd</sup> conjugate depth and the hydraulic jump “washed” out from the stilling basin in the riverbed which is non-resistant to erosion - see the situation on Fig. 1.



Fig. 1

The result of unsymmetrical spilling is unstable operation of two of the five spillways

*Le résultat de l'évacuation asymétrique est le fonctionnement instable de deux des cinq évacuateurs de crue*

The consequences of hydrodynamic overloads on the downstream riverbed result in a highly increased erosion of the river bottom and river banks downstream of the structure. Till the year 2002, the river bottom (carbon slate) was scoured for over 8 m below the original bottom level.

During the plant operation period, the peaks of flood waters achieved several times only some 100 m<sup>3</sup>/s lower values of the flood discharge with a 100-year return period amounting to  $Q_{100} = 3100 \text{ m}^3/\text{s}$  in the dam section. At that time the non-dissipated flows severely damaged the river banks in a length of up to 1 km downstream of the dam. The banks were always consolidated by a rockfill which was each time stronger than the previous one.

### 3. HYDRAULIC MODEL RESEARCH

In order to establish the most suitable way of such conditions improvement the company of "Savske Elektrarne Ljubljana" (Sava Power Generation Company) entrusted to the "Institute of Hydraulic Research" in Ljubljana a hydraulic model research which was implemented on physical hydraulic models of 1:38 and 1:25 scales and on the structure of the Vrhovo Hydro Power Plant.

#### 3.1. POSSIBLE MEASURES OF HYDRAULIC CONDITIONS IMPROVEMENT

The research firstly gave the reasons of damage caused by erosion in the downstream riverbed. With the aim of how to provide regular functioning of the stilling basins after reconstruction, different combinations of reconstructive measures such as tailwater level increase, prolongation and/or deepening of the stilling basin, installation of baffles and deflectors in the stilling basins and specific discharge decrease, have been studied. Any such reconstruction would be possible, however with large civil construction interventions, high costs or production decrease. All the above given reconstruction measures are shown to be practically unacceptable due to the purpose of the reconstruction being unachieved or due to the inappropriateness as regards technical and economical point of view. In the reconstruction measures block, no additional secondary stilling basin was treated since the approach according to which the existing stilling basin would be eliminated, would be unprofessional.

The original hypothesis according to which a suitable solution should be found leads to the conclusion that only a three-dimensional (3D) dissipation of energy, which is from physical logic point of view more efficient than the two-dimensional (2D) one, would be useful, still, a wetted cross section of the stilling basin as well as the undimmed discharge section without any structures which would prevent free discharge of the spillway should be preserved.

In the enumerated solutions, with the exception of baffles, the energy dissipation is 2D. Only with baffles the dissipation is 3D, but the baffles in this concrete case do not represent a suitable solution. Since the Vrhovo HPP operates with relatively shallow and short stilling basins with small heads which means with very low values of Froude number, in this very case the already known rule that in the stilling basins of Type I no baffles can be installed in order to increase dissipation has been confirmed.

### 3.2. RESEARCH WORK ON SIDE DISSIPATION BEAMS

The invention, research and application of side dissipation beams which shall be installed to the side walls of the stilling basin new alternatives of successful and economically viable improvement of unsuitable hydraulic conditions at unsymmetrical operation of the spillways on the dam have turned up. The improvement of the stilling basin dissipation efficiency by side beams hasn't been known in the current hydro technical practice. In the stilling basin into which they are built such side beams provide more efficient 3D dissipation of energy (instead of the 2D dissipation in the stilling basin without beams). Such dissipation is achieved by disruption of the in-flowing water streamlines to the stilling basin, first convergent to the stilling basin axis and immediately after that, in a fanlike formation, divergently under the beam causing formation of eddy currents with longitudinal and diagonal axis. Practically no reduction of the stilling basin wetted cross section and no obstruction of the floating material course from the stilling basin represent just some of the other important advantages of the side beams application.

#### 3.2.1. *Shape and position of side dissipation beams*

The side beams shape and position have been determined after a series of model tests of dissipation efficiency performed on side beams of different shapes and positions in different hydraulic conditions. Final beam shape is very simple since it is straight-lined with rectangular cross section of  $B \times H = 0.8 \times 1.0$  m and it runs along the complete side wall of the stilling basin.

#### 3.2.2. *Impact on increased stability of the stilling basins operation*

With experiments performed on a physical 1:25 scale model at different hydraulic boundary conditions and for both stilling basin regimes those minimal tailwater levels have been determined by comparison at which the stilling basin is operating in a stable/unstable way. In other words, by these measurements the tailwater level value was determined as a measure of the stilling basin dissipation efficiency. It has been confirmed that the stilling basin with side beams operates more stably in all regimes and in different boundary conditions.

The results are given in Fig. 2 in the dependence of the gate opening  $a$  (m) showing the middle value of results obtained in both regimes. A comparison of boundary lines height shows that the side beams installation in the stilling basin allows maximum 1.2 m lower tailwater level  $SV$  (m) in the area of critical specific discharges  $30 < q < 45 \text{ m}^2\text{s}^{-1}$  and with gate openings  $3.5 < a < 5.5 \text{ m}$ . In the areas of lower and higher discharges where the decreased dissipation in the stilling basin is not necessarily provided the effect of side beams is smaller.

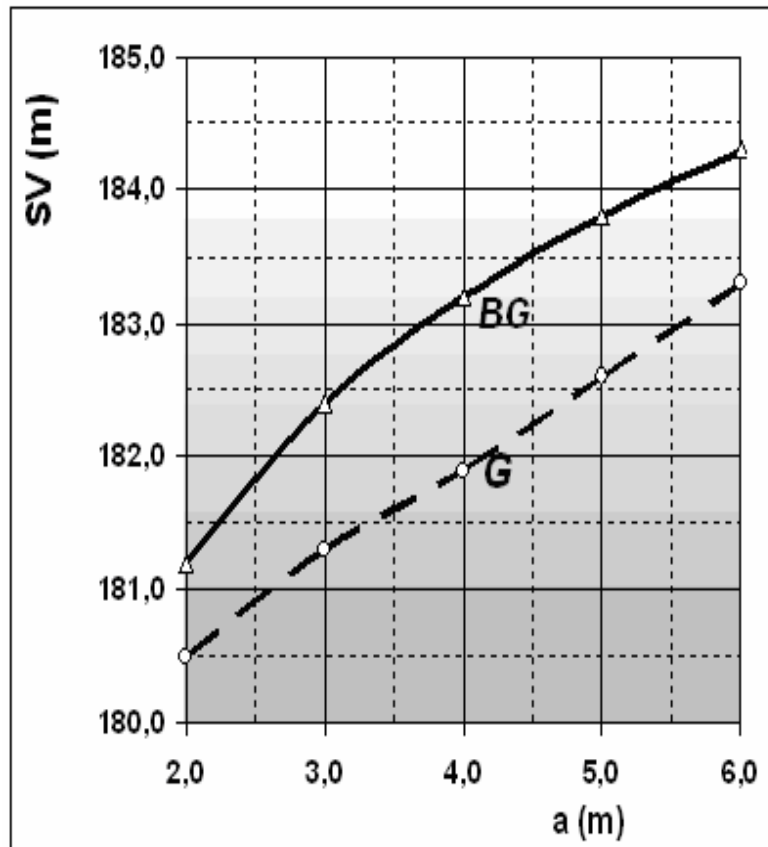


Fig. 2

The border lines of stable (above the line)/unstable (under the line) operation of stilling basin of the Vrhovo HPP model (scale 1:25) at different tailwater levels  $SV$  and different radial gate openings “ $a$ ”

*Les lignes de limite du fonctionnement stable (au-dessus de la ligne)/instable (au-dessous de la ligne) du bassin d’amortissement sur modèle de la centrale hydroélectrique Vrhovo (échelle 1:25) avec différents niveaux des eaux aval  $SV$  et différentes ouvertures des vannes secteur “ $a$ ”*

----- line BG: stilling basin without dissipation beams  
 - - - - - line G: stilling basin equipped with dissipation beams

----- ligne BG: bassin d’amortissement sans poutres de dissipation  
 - - - - - ligne G: bassin d’amortissement muni des poutres de dissipation

### 3.2.3. *Impact on the riverbed erosion decrease*

A test of the stilling basins operating efficiency can be made also on the basis of a qualitative comparison of the riverbed degradation size hollowed down by the water course in the bottom of the riverbed following the two simultaneously observed stilling basins, one equipped with side beams and the other without them. In this case a qualitative comparison means that the pool size in a hydraulic model is not similar to the size of the pool in nature consisting of another material which can not be used in a model.

The model river bed behind the stilling basins has been build up with a material of uniform grain size of 0.3 m – 0.6 m. Several comparative tests were carried out at nominal water level, by individual spillway discharge of  $500 \text{ m}^3\text{s}^{-1}$  and by open radial gates for  $a = 4.0 \text{ m}$ . Between individual tests only the tailwater level was different but constant during the whole testing period.

The difference in the riverbed degradation size is most visible in case of such common tailwater level where the hydraulic jump in the stilling basin equipped with beams is stable while in the stilling basin without beams the hydraulic jump escapes out of the stilling basin. This result shows very large changes of the riverbed degradations behind both stilling basins at a given time period in longitudinal profile.

Behind the stilling basin without side beams the riverbed degradation is over 9 m deep already after 6 hours of operation and over 13 m deep after 24 hours of operation while the riverbed degradation behind the stilling basin with side beams reaches 6 m at the maximum in 24 hours of operation.

The results of these tests show that the side dissipation beams in no case deteriorate the hydrodynamic conditions behind the final sill of the stilling basin. In cases as well when both stilling basins operate in the same regime, stable or unstable, the riverbed degradation behind the stilling basin equipped with side beams is smaller.

A model operation (model scale 1:38) of the two of five spillways is given in Fig. 3 for unsymmetrical operation of the two of five spillways at equal hydraulic boundary conditions for both stilling basins: upstream and downstream water levels and radial gates openings at the spillways. The left hand stilling basin is equipped with side dissipation beams and operates stably while the right hand stilling basin is without beams and operates unstably.

Fig. 4 shows the riverbed degradations behind the stilling basins after 24 hours of the spillways operation (time for nature) for the case represented in Fig. 3. The smaller one is formed behind the right hand stilling basin equipped with side dissipation beams which resulted in higher dissipation efficiency.



Fig. 3

Asymmetrical operation of spillways: the left hand stilling basin with side dissipation beams operates stably while the right hand stilling basin is without beams and operates unstably (model scale 1:38)

*Le fonctionnement asymétrique des évacuateurs de crue : le bassin d'amortissement du côté gauche muni des poutres de dissipation latérales ont un fonctionnement stable, tandis que le bassin d'amortissement du côté droit sans poutres a un fonctionnement instable (modèle à l'échelle 1:38)*



Fig. 4

Width of riverbed degradations behind the 2<sup>nd</sup> and 4<sup>th</sup> stilling basins after 24 hours of spillway operation (prototype time) for the case represented in Fig. 3  
*Largeur de la fosse d'érosion du lit de la rivière derrière le 2<sup>ème</sup> et le 4<sup>ème</sup> bassin d'amortissement suite au fonctionnement des évacuateurs de crue pendant 24 heures (temps réel) pour le cas présenté à la Fig. 3*



#### 4. FIELD TEST OF BEAMS EFFICIENCY

With transmission of the beams efficiency from the model (1:38) into nature different aeration grades of the water course in a model and in a prototype by watering the beams with a two-phase water-air mixture shall be considered. The model similarity degree hasn't been strictly defined yet, but when hydrological conditions permit, tests of parallel operation of the spillways on a prototype are foreseen.

After side beams installation into the 1<sup>st</sup> spillway of the Vrhovo HPP a comparative observation of both spillways regimes has been performed, however, till now only in a single hydrological situation. During testing the radial gates were successively opened, i.e. in the 1<sup>st</sup> spillway where in the relevant stilling basin side beams were installed and in the 2<sup>nd</sup> spillway without beams. The operation of the gates opening was going on, till the stilling basin operation became unstable. Both tests were performed at equal headwater and tailwater hydraulic boundary conditions. This was provided by constant combined (turbine and spillway) discharge in the dam section reaching about 1000 m<sup>3</sup>/s during both tests.

In the 2<sup>nd</sup> spillway without beams the radial gate was raised up to opening  $a_2 = 2.3$  m (maximum discharge was  $Q_2 = 310$  m<sup>3</sup>/s), while in the 1<sup>st</sup> spillway with dissipation beams the gate was raised up to  $a_1 = 3.9$  m opening (maximum discharge was  $Q_1 = 480$  m<sup>3</sup>/s), where the stilling basin operation became unstable. The tests performed showed that the effect of side beams in nature is similar to the effect of side beams used in a model.

Unfortunately, due to a too low discharge of the Sava River, up to now the foreseen test with parallel and simultaneous operation of both stilling basins, which would enable direct comparison of hydraulic efficiency of both stilling basins regimes hasn't been implemented yet.

#### 5. CONCLUSION

By hydraulic model research a higher dissipation efficiency of the stilling basin in which side dissipation beams were installed has been approved in two ways.

1. Greater dissipation efficiency of the stilling basin with beams has been established by a series of comparative model tests of checking stilling basin operating stability in different hydraulic boundary conditions in comparison with operation of a stilling basin without side beams. The stilling basin operating stability is presented, as an interdependence of the gates opening and the tailwater level by equal other boundary conditions. The results, which are given in

Fig. 2 show that the stilling basin with beams can operate in a stable regime at lower tailwater levels.

2. The dissipation efficiency of side beams has been determined also indirectly in a model – in a qualitative way by means of erosion efficiency of the water course exerted to the bottom of the tailwater streambed where the measure of the stilling basin efficiency is represented by the final size and depth of the riverbed degradation hollowed out by the water course in a given time period and changing its material in a material of uniform grain size. In all operating regimes the riverbed degradation was always smaller behind the stilling basin with side beams, which resulted in a higher efficiency of the stilling pool. For the case where the differences are the greatest, the conditions are given in Fig. 3 and 4.

The increased dissipation efficiency of the stilling basin in which side beams have been installed, established by model research, enables stable operation of the stilling basins at relatively lower tailwater level. At the same time, this enables partly unsymmetrical operation of the spillways. The increased dissipation efficiency of the stilling basin decreases frequency and duration of unstable stilling basin operation and consequently decreases the possibility of damage caused by erosion in the river bottom and river banks downstream of the dam. This measure so fulfils the purpose of reconstruction. Beside the fact that among all measures studied, side beams showed to be the most efficient reconstruction measure, it is not negligible to say that side beams are very simple structures which can be easily installed into the existing stilling basins.

The side dissipation beams can be applied also at the design stage of new hydraulic structures as economical and acceptable structures.

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## SUMMARY

The paper gives some interesting answers to the question how to increase the dissipation efficiency of stilling basins at low energy heads or at very low Froude numbers, i.e. at specific hydraulic boundary conditions. In the case of common stilling basins (Type I by the Bureau of Reclamation, without any accessories such as baffles and/or deflectors) operating in such conditions only relatively weak dissipation efficiency can be achieved despite comparatively great stilling basin size. The dissipation efficiency of the stilling basin has been researched on an actual case of extensive deepening of the riverbed downstream from the dam and riverbank damage arising in the downstream course of the Vrhovo Hydro Power Plant on the Sava River. The hydraulic model research, as well as establishing the hydraulic conditions operating at the hydropower plant, has been performed on 1:38 and 1:25 scale physical hydraulic models.

The purpose of the first part of the research was to determine the reasons for the hydro-dynamic overloads of the riverbed. It was proved that such overloads were a result of unsymmetrical opening of radial gates on the spillways, which resulted in an unstable operation of the stilling basin provoking a hydraulic jump being washed out from the stilling basin into the downstream unconsolidated riverbed.

The purpose of the second part of the research was to determine civil construction measures to improve the dissipation efficiency of the asymmetrically operating stilling basins with due consideration of important constraints such as relative simplicity of civil construction works and feasibility of reconstruction measures with an acceptable level of investment costs. This research produced no adequate solution. It has been proved that for improvement of critical hydraulic conditions practically no classical civil construction measure is adequate.

In the third part of research the original hypothesis has been changed. This original hypothesis according to which a suitable solution should be found, led to the conclusion that only a three-dimensional (3D) dissipation of energy, which is from physical logic point of view more efficient than the two-dimensional (2D) one, would be useful, still, the wetted cross section of the stilling basin as well as the discharge section should be preserved. The invention, research and application of side dissipation beams to be installed on the side walls of the stilling basin as new alternatives for successful and economically viable improvement of unsuitable hydraulic conditions at unsymmetrical operation of the spillways is described.

The improvement of the stilling basin dissipation efficiency with side beams is unknown in current hydrotechnical practice. Practically no reduction of the stilling basin wetted cross section and no obstruction to floating material being washed out of the stilling basin are just two of the other important advantages of the side beams application. The shape and position of the side dissipation beams have been finally determined after a series of model tests of dissipation efficiency in different hydraulic conditions. In all operating regimes, the impact on the increased stability of the stilling basin operation and on the reduction of riverbed erosion has been determined. When transposing beam efficiency from the models into full size prototype, different aeration conditions must be considered, perhaps using a two-phase water-air mixture.

## RÉSUMÉ

Ce rapport donne quelques réponses intéressantes à la question : comment mieux dissiper l'énergie dans des bassins d'amortissement de faible hauteur de chute ou ayant de très petits nombres de Froude, c'est-à-dire pour des conditions aux limites particulières? Pour des bassins de type classique, fonctionnant dans de telles conditions (classés Type I par l'USBR sans dispositifs accessoires tels que tranquilliseurs et/ou déflecteurs), l'efficacité de la dissipation ne peut être que médiocre malgré les dimensions plutôt grandes du bassin. L'efficacité de la dissipation d'énergie dans de tels bassins d'amortissement est étudiée à travers un cas réel d'affouillement important du lit de la rivière Sava à l'aval du barrage et de la destruction des berges à l'aval de l'usine hydroélectrique de Vrhovo. Des recherches sur modèle hydraulique ainsi que la

détermination des conditions hydrauliques régnant au droit de l'usine ont été menées sur des modèles hydrauliques à l'échelle 1/38 et 1/25.

Le but recherché dans un premier temps était de connaître les causes de la surcharge hydrodynamique du lit de la rivière. On a démontré que ces surcharges résultaient de l'ouverture asymétrique des vannes secteur de l'évacuateur avec pour conséquence une instabilité du fonctionnement du bassin d'amortissement rejetant le ressaut dans les matériaux meubles du lit naturel.

Dans un deuxième temps, on a cherché à établir les mesures de génie civil nécessaires pour améliorer l'efficacité de la dissipation d'énergie dans des bassins d'amortissement à fonctionnement asymétrique, en tenant compte des contraintes telles que la facilité de réalisation des travaux de génie civil et la faisabilité des travaux de reconstruction à un coût d'investissement acceptable. Ces recherches n'ont pas débouché sur une solution valable. On a démontré que pour améliorer les conditions hydrauliques critiques, pratiquement aucune méthode classique de construction ne convenait.

Dans un troisième temps, on a modifié l'hypothèse de départ. Cette hypothèse qui devait déboucher sur une solution acceptable, nous a conduit à conclure que seule la dissipation de l'énergie dans les trois dimensions (3D) serait plus efficace qu'une dissipation dans les deux dimensions (2D), ce qui est physiquement logique; cependant, le périmètre mouillé du bassin ainsi que la section d'écoulement devaient rester inchangés. Le rapport donne une description de l'invention, à savoir l'étude et l'installation de poutres latérales de dissipation sur les parois latérales du bassin d'amortissement. Cette invention apporte une solution nouvelle, performante et rentable qui modifie de façon satisfaisante les mauvaises conditions hydrauliques créées par un fonctionnement asymétrique de l'évacuateur.

L'amélioration de l'efficacité de la dissipation d'énergie dans un bassin d'amortissement au moyen de poutres latérales est inconnue en génie hydrotechnique jusqu'à ce jour. Une section mouillée pratiquement inchangée et une évacuation aisée des corps flottants vers l'aval du bassin du fait de l'absence d'obstructions, sont les deux principaux avantages de cette solution. La forme et la position des poutres ont été déterminées après examen des résultats d'une série d'essais sur modèle dans différentes conditions hydrauliques. L'amélioration de la stabilité de fonctionnement du bassin et la réduction de l'érosion du lit aval ont été vérifiées pour tous les régimes de fonctionnement. Pour passer du modèle au prototype, il convient de tenir compte des conditions d'aération qui sont différentes, conduisant éventuellement à l'utilisation d'un mélange bi-phase eau-air.