Spillway with improved dissipation efficiency
- side dissipation beams

Dušan Ciuha
IBE, Consulting Engineers
Hajdrihova 4
Ljubljana
Slovenija

Jurij Mlačnik
Institute for Hydraulic Research
Hajdrihova 28
Ljubljana
Slovenija

Abstract

Low head hydraulic 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 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 of the side walls of the stilling basin 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 "works" 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 on the stilling basins of the small dam of the hydropower station Vrhovo on the Sava River in Slovenia. There in the year 2002 the side dissipation beams have been successfully applied in the 1st 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 prevents the bottom and banks of the downstream riverbed reach from extensive erosion.

The side dissipation beams can be applied either at the design of new hydraulic structures or as an economically acceptable refurbishment of existing structures.

Some more information about dissipation beams see: http://www2.arnes.si/~ljhidri5.

1. Introduction

The present paper gives an example of an extremely changed operation of low head hydro power plant which shows that at flood water conditions the working of stilling basins is hydraulically unsuitable and brings 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 increased dissipation efficiency of the stilling basin in which it has been built was determined by a model and partly approved on a prototype.

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 dam structure showed in **Figure 1** consists of a dam with five spillways of 15 m width and of a turbine structure with three bulb type generator sets. The installed power is Pi = 43 MW at operating head of 10 m and discharge of Qi = 500 m^3/s. 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.

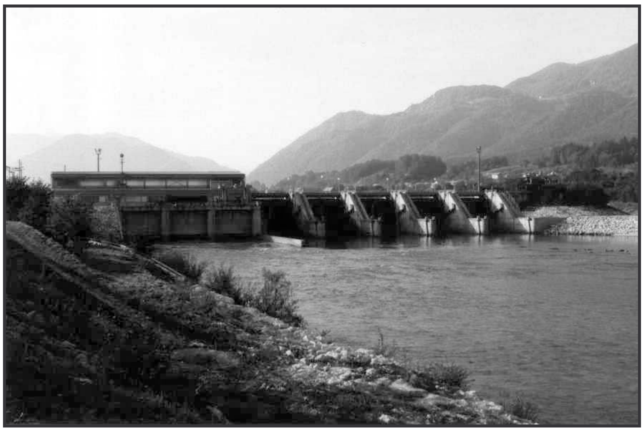

Fig. 1. The Vrhovo Hydro Power Plant

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 flushing with water flow which can only be achieved by demanding manoeuvres with gates of the plant operators. This means that the discharge must be unsymmetrically increased in one of the 5 spillways. Such a mode of unsymmetrical gates operation is unconformable to the operational capacity of the structure; however, it will be impossible to avoid it in the future. The stilling basins of the spillways are designed only for symmetrical gates operation and consequently they do not bear any overloading. Behind the unsymmetrical opened spillway the tailwater level is lower then predicted due to the water level of 2nd conjugate depth and hydraulic jump "escape" out from the stilling basin in the riverbed which is non-resistant to erosion. The consequences of hydrodynamic overloads on the downstream riverbed result in 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 several times achieved only some 100 m^3/s lower values of the flood discharge with 100-year return period which amounts to $Q_{100} = 3100\ m^3/s$ in the dam section. At that times nondissipated 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 Plant Utility) confided to the "Institute of Hydraulic Research" in Ljubljana a hydraulic model research which was implemented on a physical hydraulic model of a 1:38 scale and in 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 working 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 an unachieved aim (purpose) of the reconstruction or due to an 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 Side dissipation beam

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 convergently 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

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 $B_*H = 0.8_*1.0$ m and it runs along the complete side wall of the stilling basin. Side dissipation beams in the model is given in **Figure 2** and in the prototype in the first spillway in **Figure 3**.

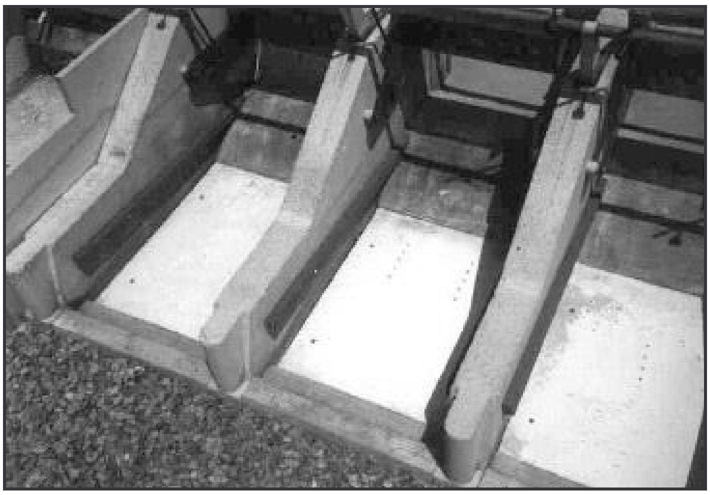

Fig. 2. Side dissipation beams in the model in 1:38 scale

Fig. 3. Side dissipation beams in the 1^{st} stilling basin of the Vrhovo HPP dam

3.2.2 Impact on increased stability of the stilling basins working

With experiments performed on a model in different hydraulic boundary conditions and for both stilling basin regimes those minimal tailwater levels have been determined by comparison at which the stilling basin working is stable/unstable. 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 working more stable in all operating regimes. The measurements results are given in the dependence of the gate opening (discharge) showing the middle value of results of both regimes. A comparison of boundary lines height shows that the side beams installation into the stilling basin allows more than 1.0 m lower tailwater level in the area of critical specific discharges. In the areas of the lowest and highest discharges where the decreased dissipation in the stilling basin is not necessarily provided the effect of side beams is smaller.

3.2.3 Impact on the riverbed erosion decrease

A test of the stilling basins working efficiency can be made also on the basis of a qualitative comparison of the plunge pool size hollowed down by the water course in the bottom of the riverbed following the two simultaneously observed stilling basins, one with side beams and the other without them. All model tests represent such a qualitative comparison of the stilling basins working efficiency. 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 bottom behind the stilling basins has been build up with a material of uniform grain size of 0.3 – 0.6 m. Several comparative tests were carried out at nominal water level, by individual spillway discharge of Q = 500 m^3/s and by open radial gates for a = 4.0 m. Between individual tests only the tailwater level was different but constant during the whole testing period.

The results of these tests show that 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 plunge pool behind the stilling basin equipped with side beams is smaller.

The difference in the plunge pool size is most visible in case of such 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 escape out of the stilling basin. The tailwater level for both stilling basins is the same. This case is graphically presented in **Figure 4** where a change of the plunge pool behind both stilling basins is given at a given time period. Behind the stilling basin without side beams the plunge pool is over 9 m deep already after 6 hours of operation and over 13 m deep after 24 hours of operation while the plunge pool behind the stilling basin with side beams reaches less than 6 m at the maximum in 24 hours of operation.

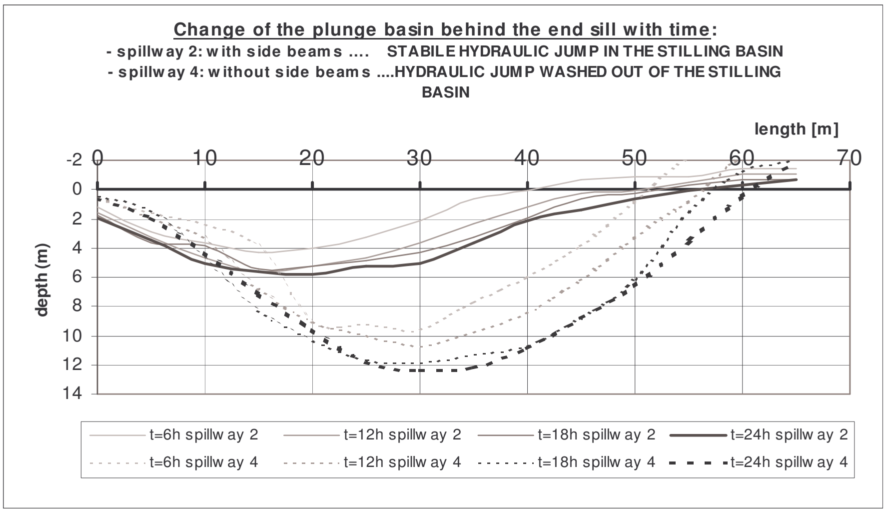

Fig. 4. 2 cases of the plunge pools during the 24 hours of spillways operation: the deeper one is behind the 4th spillway which is without side dissipation beams

3.2.4 In-site test of beams efficiency in the spillway of the Vrhovo HPP

With transmission of the beams efficiency from the model (1:38) into nature (1:1) different aeration grade of the water course in a model and in a prototype by watering the beams with a two-phase water-air course shall be considered. The model similarity degree hasn't been strictly defined yet, but someday in future when hydrological conditions permit, tests of parallel operation of the spillways on a prototype are foreseen. Such tests where model deviations will be determined are relatively simple; however, till now there haven't been sufficient discharges big enough, between 1400 and 1900 m^3/s, available for testing.

After side beams installation into the 1st 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 1st spillway where in the relevant stilling basin side beams were installed, and in the 2nd spillway without beams. The operation of the gates opening was going on, till the stilling basin working became unstable. Both tests were performed at equal headwater and tailwater hydraulic boundary conditions. This was provided by constant combined discharge in the dam section reaching in the time of both tests about 1000 m^3/s.

Fig. 5. Example of unstable stilling basin working at Vrhovo HPP spillway (2nd spillway without side dissipation beams)

Figure 5 gives an example of unstable stilling basin working in the 2nd spillway, while **Figure 6** represents an example of a stable working of the stilling basin with side beams in the 1st spillway.

In the 2nd spillway without beams the gate was raised up to a_2 = 2.3 m (Q_2 = 310 m^3/s) opening, while in the 1st spillway with dissipation beams the gate was raised up to a_1 = 3.9 m (Q_1 = 480 m^3/s) opening, where the stilling basin working 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.

Fig. 6. Example of stable stilling basin working at Vrhovo HPP spillway
(1st spillway equipped with the side dissipation beams)

4. Conclusions

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 working stability in different hydraulic boundary conditions in comparison with the working of a stilling basin without beams. The stilling basin working instability is presented as an interdependence of the gates opening and the tailwater level by equal other boundary conditions. The results shows, 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 plunge pool 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 plunge pool 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 **Figure 4.**

The increased dissipation efficiency of the stilling basin in which side beams have been installed, established by model research, enables stable working 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 working 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.

Literature

1. BRADLEY, J. N. and A. PETERKA, 1957: *The hydraulic design of stilling basins*, Am. Soc. Civ. Engrs. Proc. ASCE, Journal of Hydraulics Division, Vol 83., 84/1958
2. CHOW, Ven Te, 1959: *Open-Channel Hydraulics*, McGraw-Hill, New York.
3. PETERKA, A. J., 1964: *Hydraulic Design of Stilling Basins and Energy Dissipators*, Engineering Monograph No. 25, U.S. Bureau of Reclamation, D. C.
4. U.S. Department of the Interior, Bureau of Reclamation, D. C., 1976: *Design of gravity dams.*
5. U.S. Department of the Interior, Bureau of Reclamation, D. C., 1987: *Design of small dams.*
6. VISCHER, D. L. and HAGER, W. H., 1997: *Dam Hydraulics*, Wiley, Chichester

The Authors

Dušan Ciuha finished his undergraduate studies in 1977 at the Hydraulics Division of the Faculty of Civil and Geodetic Engineering of the University of Ljubljana, Slovenia. In 1978, he came to the Water Management Institute as a researcher and between 1987 and 1991 he worked as a manager of Hydraulic Laboratory Department. Since 1995 he has been employed in the Institute for Hydraulic Research as a research councilor and between 1997 and 1998 as a manager of the Institute for Hydraulic Research. Since 2004 he has been working in IBE, Consulting Engineers. His experience covers most of all physical modeling of hydraulic phenomena and field observations and measurements in the domain of hydraulics, hydrology and hydrographic surveys.

http://www.izum.si/scripts/cobiss?ukaz=BASE&bno=99999&id=7 (Slovenian national bibliographical service, search for Dušan Ciuha)

Jurij Mlačnik finished his undergraduate studies in 1987 at the Hydraulics Division of the Faculty of Civil and Geodetic Engineering of the University of Ljubljana. He started working as a researcher in hydraulic laboratory of Institute for Hydraulic Research (at that time Water Management Institute) in 1988. Since 2000 he works as a manager of Institute for Hydraulic Research. His experience covers most of all physical modelling of hydraulic phenomena and field measurements in domain of hydraulics, hydrology and hydrographical surveys. He also deals with mathematical modelling in field of hydraulics and in most recent period he is making a great effort in introducing hybrid models into the Slovenian hydraulic research practice.

http://www.izum.si/scripts/cobiss?ukaz=BASE&bno=99999&id=7 (Slovenian national bibliographical service, search for Jurij Mlačnik)