Radomil Květon, Peter Dušička

Hydro Dynamical Model of the Water Structures Ladce – Ilava – Dubnica – Trenčín and Kostolná – Nové Mesto – Horná Streda

The Váh cascade of hydroelectric power plants has been constructed over 70 years. Individual power plants and entire groups of power plants were designed and built with different hydraulic parameters such as size of channels, discharges through power plants, etc. Therefore, the hydraulic structures of the Váh cascade are complicated. The hydraulic structures Dolné Kočkovce - Ladce - Ilava - Dubnica - Trenčín and Trenčianske Biskupice - Kostolná - Nové Mesto - Horná Streda are the groups of channel hydro power plants on the Váh Cascade. Our department has made terrain measurements and research on this water structure system last year. The results of measurements were used for the better calibration of hydro dynamical model of these water structures. The presented paper describes this process.

Key words: Hydro Power Plant, Water Work, Hydraulic Parameters, Terrain Measurements

1. INTRODUCTION

Groups of channel hydropower plants (HPP) of the Váh cascade Ladce – Ilava – Dubnica – Trenčín and Kostolná – Nové Mesto – Horná Streda are hydraulically interdependent. Going along the stream of the Váh River, the group of hydropower plants Ladce – Ilava – Dubnica – Trenčín begins in the reservoir Dolné Kočkovce and ends in the reservoir Trenčianske Biskupice and the group of hydropower plants Kostolná – Nové Mesto – Horná Streda begins in the reservoir Trenčianske Biskupice and ends in the reservoir Drahovce (Sĺňava). Both groups of HPPs are the oldest of the Váh Cascade groups. Therefore the installed capacity of these HPPs is 150 respectively 180$m^3.s^{-1}$. The reservoirs Dolné Kočkovce and Trenčianske Biskupice have small storage volume for regulating operation of lower situated HPPs. For this reason is the regulation operation of the HPPs enabled by flow regulation, which is provided by the large reservoir Nosice situated above the concerned stage of the Váh cascade (above the reservoir Dolné Kočkovce).

In the view of mathematical modelling are for these groups easily applicable modelling methods verified on other channel hydropower plants. These methods are based on decomposition of modelling system into separate sections with independently defined boundary conditions. This enables simultaneous verification of complex methods for obtaining more realistic description of interaction between natural Váh riverbed (together with water reservoirs) and artificial channels of hydro power plants. The modelling results will be progressively applied for other parts of the Váh hydroelectric system aiming to obtain fully developed hydrodynamic model.

An important part of the modelling is also to verify the hydraulic characteristics of channels - the roughness coefficient of wetted perimeter.

The presented paper describes terrain measurements with intention to obtain these hydraulic characteristics at groups of hydropower plants Ladce – Ilava – Dubnica – Trenčín and Kostolná – Nové Mesto – Horná Streda. Both concerned groups of channel HPPs operate practically synchronously in tandem operation. Therefore the terrain measurements at the derivation channels had to be synchronous. The measurement had been performed simultaneously on both groups with the aim to achieve steady water levels in channels, as well as in reservoirs.

2. HYDRAULIC LINKS WITHIN THE CONCERNED STAGE OF THE VÁH

Concerned stage of the river Váh is situated between the water structure (WS) Dolné Kočkovce down to water structure Drahovce and it is fully energetically utilized. The two mentioned groups of hydropower plants (Ladce – Ilava – Dubnica – Trenčín and Kostolná – Nové Mesto – Horná Streda) are in this stage. Every hydropower plant of the groups is directly hydraulically linked to upstream HPP or reservoir. This means that the backwater of downstream HPP reaches the upstream HPP. Also the HPPs are operated simultaneously, meaning that these HPPs operate with discharge, which is let in the whole scheme at the entry of this stage by the first intake channel and hydropower plant (pilot HPP). In this case it is the HPP Ladce.

Fig. 1 WS Dolné Kočkovce – weir and intake structure of the intake channel for HPP Ladce

Fig. 2 HPP Ladce

Fig. 3 HPP Trenčín

Fig. 4 WS Trenčianske Biskupice – weir and intake structure of intake channel for HPP Kostolná

Fig. 5 HPP Kostolné

Fig. 6 HPP Horná Streda

The intake channels of the HPP group Ladce – Ilava – Dubnica – Trenčín have trapezoid cross-section with bottom width about 18,3 m and water-side slope 1:1,75. They are sealed by facial concrete sealing. The bottom width of outlet channels varies from 8 to 15,4 m. There is no channel lining under the minimal operation water level and the slope of the banks is 1:3. The maximal turbine capacity of HPP Ladce (after reconstruction) and HPP Trenčín is 2 x 90 m^3s^{-1}. The maximal turbine capacity of HPP Ilava and HPP Dubnica is 2 x 75 m^3s^{-1}.

The intake channels of the HPP group Kostolná – Nové Mesto – Horná Streda have also trapezoid cross-section with varying bottom width from 16 to 19 m and water-side slope 1:1,75. They are sealed by facial concrete sealing. The bottom width of outlet channels varies from 12 to 16 m. There is no channel lining under the minimal operation water level and the slope of the banks is 1:3. The maximal turbine capacity of all HPPs in this group is 2 x 90 m^3s^{-1}.

The disposition of the HPPs is in hydraulic point of view a channel derivation, whereby the dominant dimension of the channel is its length. From physical point of view can be specific profiles (the intake object of HPP Ladce at water structure Dolné Kočkovce, the orifice of the outlet channel of VE Trenčín with reservoir Trenčianske Biskupice, the intake object of HPP Kostolná at water structure Trenčianske Biskupice, the orifice of the outlet channel of VE Horná Streda with reservoir Drahovce and all HPPs) considered as singular points. It is possible to define hydraulic parameters and time behaviour of the flow in these points. For the hydraulic solution of the flow regime can be both groups of HPPs divided in separate stages as following:

- Dolné Kočkovce – Ladce (intake channel for HPP Ladce),
- Ladce – Ilava,
- Ilava – Dubnica,
- Dubnica – Trenčín,
- Trenčín – Trenčianske Biskupice (outlet channel of HPP Trenčín reservoir Trenčianske Biskupice),
- Trenčianske Biskupice – Kostolná (intake channel for HPP Kostolná),
- Kostolná – Nové Mesto,
- Nové Mesto – Horná Streda,
- Horná Streda – Drahovce (outlet channel of HPP Horná Streda to reservoir Drahovce).

After separation can singular points be considered as boundary profiles and known time behaviour of hydraulic parameters in these profiles can be considered as boundary conditions for flow computation.

3. METHODOLOGY OF VERIFICATION OF ROUGHNESS COEFFICIENT IN DERIVATION CHANNELS

Verification of roughness coefficient is possible only by direct measurement during operation in these approaches:

a. steady state measurement – steady non-uniform flow in channel, attained by continuous start on required flow rate through hydropower plant – minimizing of wave transition effects in channel,

b. unsteady state measurement – unsteady non-uniform flow (used only in case, when attaining of steady state is not possible, results are less precise).

4. MEASUREMENT OF ROUGHNESS COEFFICIENT BY STEADY STATE

Measurement by steady state consists of next steps:

- attaining of steady state without any flow before the beginning of measurements – steady water levels in derivation channels and compensation reservoirs are necessary not only for the probes calibration but also as initial conditions for mathematical modelling
- attaining of steady flow state.

Frequency of data acquiring (water level measurement), once per minute, is usually sufficient for major part of hydrodynamic processes.

Conditions for attaining steady flow state vary in order to type of derivation channel and measured profiles must be situated in sufficient distance from impounding structures in channel.

For roughness coefficient calculation of measured stage by steady non-uniform flow has been the segment solution method and its appropriate formulas for hydraulic characteristics:

$$\Delta z = Q^2\left[\xi\left(\frac{1}{S_d^2}-\frac{1}{S_h^2}\right)+\frac{l}{K_p^2}\right] \qquad (1)$$

$$K_p^2 = S_p^2 C_p^2 R_p$$

$$S_p = (S_d + S_h)/2$$

$$O_p = (O_d + O_h)/2$$

$$R_p = S_p / O_p$$

$$C_p = \frac{1}{n} R_p^{1/6}$$

where

Δz - water level elevation change on the stage z_h-z_d

Q - steady flow rate

ξ - expansion or contraction loss coefficient

S_d, S_h - flow area of downstream and upstream profile

l - length of stage

K_p - average flow-rate module

S_p - average flow area

C_p - velocity coefficient by Manning

R_p - average hydraulic radius

O_p - average wetted perimeter

O_d,O_h- wetted perimeter of downstream and upstream profile *n* - roughness coefficient

Final formula for roughness coefficient computation, obtained by adjusting upper formulas (1):

$$n = \sqrt{\frac{\Delta z - Q^2 \xi \left(1/S_d^2 - 1/S_h^2\right)}{l}} \frac{S_p}{Q} R_p^{2/3} \qquad (2)$$

Analysis of this formula (2) shows, that the final computation error is relied on accuracy of difference measurement between upstream profile (zh) and downstream profile water level elevation (zd). In regard to limited precision of measurement (centimetres) and other surround influences such as water surface waving (e.g. caused by wind), it is needed to attain maximal difference of measured water levels, what is succeeded in formula (1) by maximal flow rate in channel and maximal length of measured stage.

Very important parameter, which is affecting the precision of the calculations, is the flow rate Q. The value of the flow rate is not measured directly, but it is determined from the power output of the HPP according the functionality determined by guarantee measurements. Based on measurements in 2005 and the state of the channels by their revision we have to point out that this way of the flow rate determination is inaccurate. Mostly the value of hydraulic loss coefficient in turbine intake will be in many cases considerably higher.

5. MEASUREMENT OF ROUGHNESS COEFFICIENT BY UNSTEADY STATE

Measurement results by unsteady state can be used only for indirect assessment of roughness coefficient from several different scenarios of measurements.

For data processing is used a hydrodynamic model (HDM) for modelling unsteady non-uniform flow according to scheme:

calibration of the HDM for maximal flow rate scenario,

verification of the HDM for other scenarios.

For solution of connection of inlet channel to the compensation reservoir was used a mathematical model of reservoir based on volume balance

$$V_{t+\Delta t} = V_t + \sum Q_{pri}.\Delta t - \sum Q_{odt}.\Delta t \qquad (3)$$

where V - water volume in reservoir

$t, \Delta t$ - time and time step

Q_{pri} - inflow to reservoir

Q_{odt} - outflow from reservoir

and known reservoir volume curve *V* = *f(h)*, which enables backward computation of water level in reservoir from volume of reservoir.

Used HDM is based on numerical solution of Saint-Venant partial differential equation system as follows:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q_\ell = 0 \qquad (4)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (\beta Q V)}{\partial x} + gA\frac{\partial h}{\partial x} = gA(i_0 - i_e) + q_\ell v_\ell$$

where

Q - flow rate [m^{3}s^{-1}]

A - flow area [m^2]

q_l - density of lateral side inflow or outflow [m^{2}s^{-1}]

x - profile distance from the beginning (x=0) in flow direction [m]

t - time [s]

V - average section velocity [ms^{-1}]

h - water level [m]

g - gravitation acceleration [ms^{-2}]

β - correction factor reflecting the influence of non-uniform velocity distribution

i_0 - bottom gradient

i_e - power line gradient

v_l - velocity component of side inflow or outflow in direction of axis x [ms^{-1}]

For conversion of foregoing equation system to numerical solution by the finite differences method has been used Preissmann implicit scheme with weight coefficient 0,67.

6. TERRAIN MEASUREMENTS (MEASUREMENTS „IN SITU“)

Measurements in real conditions (measurements “in situ“) were realized for the purpose of calibration and verification of the hydrodynamic model of the groups of channel hydro power plants:

1. Ladce – Ilava – Dubnica – Trenčín and
2. Kostolná – Nové Mesto – Horná Streda.

Both considered groups of channel hydro power plants are operated simultaneously (in tandem). Thus the terrain measurements of the water level in channels had to be performed simultaneously and at the same time on both groups of HPPs.

At the beginning of the July 2005 took place a survey of the derivation channels and water structures at considered stage of the river Váh (from weir Dolné Kočkovce to Drahovce). It has been determined 12 measuring profiles at the HPP group Ladce – Ilava – Dubnica – Trenčín and 10 at the HPP group Kostolná – Nové Mesto – Horná Streda.

Both groups of HPPs had been operated according to the agreement with HPP dispatch centre of Slovenské elektrárne a.s., Vodné elektrárne o.z. Trenčín. The measurement and determined operation scenarios were following:

- July 25, 2005 (Monday) installation of measuring probes in selected profiles of the derivation channels,
- July 26, 2005 (Tuesday) discharge of HPPs: 150 m^3s^{-1},
- July 27, 2005 (Wednesday) discharge of HPPs: 120 m^3s^{-1},
- July 28, 2005 (Thursday) discharge of HPPs: 90 m^3s^{-1}.

Other requirements for operation of HPPs were:

- Steady flow rate equal for every HPP, kept for minimum of 4 hours since 6:00 AM at every measuring day,
- At the first measuring day (Tuesday, July 26, 2005), since 0:00 AM to 6:00 AM, zero discharge at whole concerned stage and at 6:00 AM a gradual operation start of HPPs,
- Standard starting operation water levels with minimal differences during measuring days.

The measurement scenarios including all additional requirements were adjusted according to common operation corresponding to hydrologic parameters of the concerned stage of the river Váh and requirements of electric power system.

The measurement was realized as planned and the measured data were supplemented with measurement of the operator of the HPPs.

7. CONCLUSION

For estimation of hydraulic parameters were selected steady water level data measured at 10:00 AM. Unsteady water levels were substituted by adjusted trend lines for measurement at 9:00 to 10:00 AM. For computation were average geometric parameters of intake and outlet channels used. The computation methods are described in section 4 and 5.

The results of measurement and following computations at the groups of HPPs Ladce – Ilava – Dubnica – Trenčín and Kostolná – Nové Mesto – Horná Streda showed bad condition of operated water structures at considered groups of HPPs.

The actual condition was significantly different from originally projected conditions. Original roughness coefficient of inlet channels (facial concrete sealing) had been approximately 0,013. According to the measurements has been the present roughness coefficient determined from 0,015 to 0,022. Original roughness coefficient of outlet channels had been approximately 0,022. According to the measurements has been the present roughness coefficient determined from 0,022 to 0,030.

After 20 years of operation, in summer 2005, had been the group of HPPs Kostolná – Nové Mesto – Horná Streda inspected and repaired. The inspection confirmed bad conditions of the water structures and showed the causes of deterioration of hydraulic roughness in channels, which leads to decreasing of hydropower potential utilisation of the river Váh. The conditions in the channels are shown at following figures.

Fig. 7 Sediments behind intake structure Trenčianske Biskupice

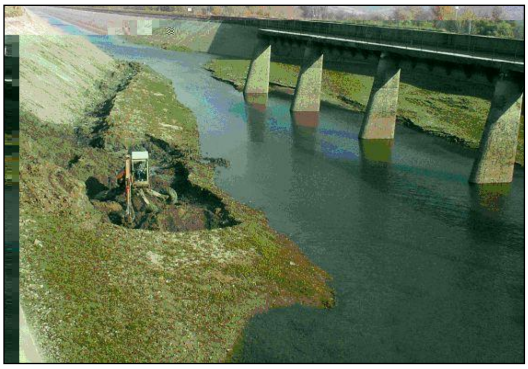

Fig. 8 Sediments in front of HPP Nové Mesto

Fig. 9 Sediments in front of HPP Horná Streda

Fig. 11 Car in intake channel

Fig. 10 Clams in intake channel

Fig. 12 Washing machine in intake channel

REFERENCES

[1] Dušička, Květon (2001): Application of 1-D Modelling in the Process Operating the Channel Power Plants of the Vah Cascade, Int. symposium on Water Management and Hydraulic Engineering, Miedzybrodzie Zywieckie, Poland

[2] Dušička, Květon (2002): 1-D Modelling in Process Operating the Channel Power Plants – Theory, Application and Results, Int. conference ICHE 2002, Hydro-Science and Engineering, Warsaw

[3] Kamenský, Květon, Šoltész (1998): Non-permanent Flowing Regime in Derivation Channel of Gabcikovo Water Work, Int. symposium on Water Management and Hydraulic Engineering, Dubrovnik

[4] Lopez (1978): Mathematical Modelling of Sediment Deposition in Reservoirs, Hydrology Papers, Colorado State University

ADDRESSES OF AUTHORS

Radomil Květon, Doc. Ing., PhD., Slovak University of Technology in Bratislava, Department of Hydraulic Engineering, Radlinského 11, Bratislava, SK 831 68, Slovak Republic, radomil.kveton@stuba.sk

Peter Dušička, Prof. Ing., PhD., Slovak University of Technology in Bratislava, Department of Hydraulic Engineering, Radlinského 11, Bratislava, SK 831 68, Slovak Republic, peter.dusicka@stuba.sk