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Terrain Measurements and Calibration of Hydro Dynamical Model of the Hydropower plant Madunice

The simplest part of Vah hydroelectric system from the point of view of mathematical modelling is the water work Drahovce - Madunice. Modelling methods verified on other channel hydro power plants are easily applicable on this hydroelectric system. Last year was made by our department terrain measurements and research on this water work. The results of measurements were used for the better calibration of hydro dynamical model of this water work. The presented paper describes this process.

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

I. INTRODUCTION

The water work Drahovce - Madunice is the simplest part of Vah hydroelectric system from the point of view of mathematical modelling (Fig.1). Modelling methods verified on other channel hydro power plants are easily applicable on this hydroelectric system. These methods are based on decomposition of modelling system. The system is decomposed to separate sections with own defined boundary conditions. At the same time we can verify complex methods to obtain more realistic description of interaction between natural Vah riverbed (together with water reservoirs) and artificial channels of water power plants. The results from the modelling of the hydro power plant (HPP) Madunice will be applied to the other parts of Vah hydroelectric system. The goal of this application is to get a complex hydro dynamical model of the catchments of the river Vah.

An important part of the modelling is also obtaining respectively verifying of hydraulic characteristics of channels - the roughness coefficient of wetted perimeter.

The presented paper describes terrain measurements with intention of obtaining these hydraulic characteristics at water work Drahovce – Madunice.

II. DESCRIPTION OF CONDITIONS AT WATER WORK VD DRAHOVCE - MADUNICE

Water work Drahovce - Madunice is a water work of the 1.category. It is situated on the river Váh between the river km 101,90 to river km 119,20. The weir Drahovce is situated in river km 113,40. Water work Drahovce – Madunice is a multipurpose work. The most important purposes are the hydropower utilization and flood protection of local area. Water work Drahovce – Madunice consists of these structures:

- reservoir Sĺňava,
- weir Drahovce,
- intake channel,
- hydropower plant,
- navigational lock,
- outlet channel.

III. HYDRAULIC BONDS WITHIN THE INVOLVED REACH OF THE VÁH CASCADE

The stage of the river Váh, between the water work Drahovce and water work Kráľová, is energetically utilized only in its upstream stage under the water work Drahovce by hydropower plant Madunice. Water flows from the reservoir Drahovce in intake channel to hydropower plant Madunice. A view on the intake structure of HPP Madunice intake channel and weir Drahovce is in the figure 2.
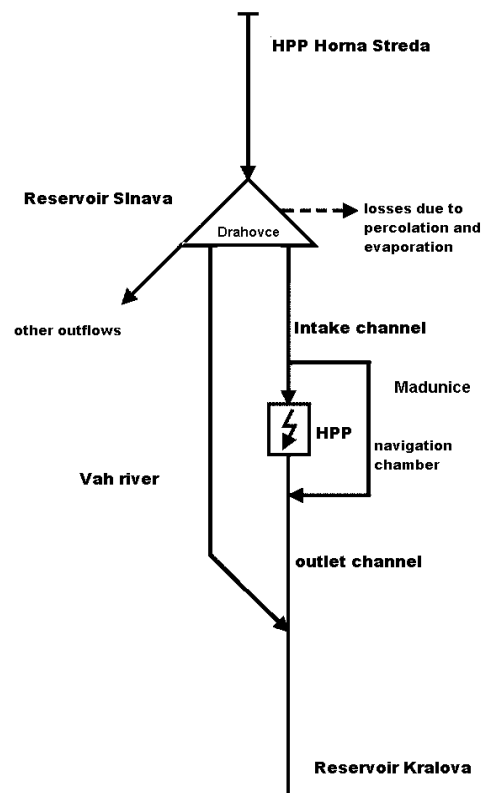
Fig. 1 Scheme of water work Drahovce – Madunice

Fig. 2 Intake structure of HPP Madunice intake

Fig. 3 The hydropower plant Madunice

The intake channel has trapezoid cross section with bottom width 15,25 – 60 m, slope of upstream face 1 : 1,75. It is sealed with concrete face sealing. The length of the channel is 6,542 km.

HPP Madunice is created as a peak hydropower plant with maximal turbine capacity 3 x 100 = 300 m^3s^{-1}. Maximal head is 18,36 m, minimal head 11,71 m and installed power output 43,2 MW. Length of service time in a common year is around 3600 hours. A view on the HPP Madunice is in the figure 3.

Water flows from HPP Madunice in an outlet channel. This channel has trapezoid cross section with bottom width 57,00 m, slope of upstream face 1 : 3. It is fortified by rock base and spreaded rocks. The orifice of outlet channel to Váh is by chute with slope 1 : 10. Minimal hydrostatic water surface in the outlet channel is fixed by the stemming at level 139,40 m a.s.l.

A view on the chute at the end of the HPP Madunice outlet channel is in figures 4 and 5.

It is a derivation canal hydropower plant from the hydraulic engineering point of view, where length is the dominant dimension of the canal. Upstream boundary of the derivation canal is formed by the Drahovce reservoir and downstream boundary by the chute at the end of the outlet channel.

In a physical point of view are the intake to the channel by the reservoir Drahovce, hydropower plant and the chute at the end of the outlet channel, singular points. In these points it is possible to define hydraulic parameters of the flow and its behaviour in time. Thus by the analysis of hydraulic regime and hydraulic bonds, whole scheme cannot be solved at once. The scheme is divided in separate stages:

- Drahovce – HPP Madunice (intake channel of HPP Madunice)
- HPP Madunice – chute (outlet channel of HPP Madunice).

Fig. 4 The chute at the end of the HPP Madunice outlet channel (downstr.view)

Fig. 5 The chute at the end of the HPP Madunice outlet channel (upstream view)

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

IV.   METHODOLOGY OF VERIFICATION OF DERIVATION CANALS ROUGHNESS COEFFICIENT

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

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).

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 canals 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 canal:

a. stage Drahovce – Madunice (intake channel of HPP) – inflow to reservoir Drahovce must be the same as flow trough HPP Madunice,

b. outlet channel of HPP Madunice – its orifice is in natural riverbed – measured profiles must be situated in sufficient distance from impounding structures in channel (dikes).

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:

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

$$K_p^2 = S_p^2 \cdot C_p^2 \cdot R_p \qquad (1)$$

$$S_p = (S_d + S_h)/2$$
$$O_p = (O_d + O_h)/2$$
$$R_p = S_p / O_p$$
$$C_p = \frac{1}{n} \cdot R_p^{1/6}$$

where
Δz — water level elevation change on the stage z_h - z_d
Q — steady flow rate
ξ — coefficient   for widening of channel 0,028
       for constriction of channel 0,056
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):

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

Analysis of this formula (2) shows, that the final computation error is relied on accuracy of difference measurement between upstream profile (z_h) and downstream profile water level elevation (z_d). 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.

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

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

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 $V = f(z)$, 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:

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

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

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.

V. 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 inlet and outlet channel of HPP Madunice. Measurements took place in September 13~16 2004, while on September 13 had been measurement devices installed and on September 14, 15 and 16 was the measurement in progress. By the measurements had been the water level regime examined depending on the operation of HPP Madunice in chosen profiles of inlet and outlet channel.
For water levels measurements were used pressure probes from company MERET Bratislava. Probes had worked in real time. Their time step was set on one data record per one minute. Installation of probe in protection pipe on the channel bank is shown in figure 6.
Used chainage of the probes placement (measured profiles) was used according to operation manual of water work Drahovce –

Madunice – in the downstream direction, where km 0,000 is situated in the intake structure axis of the inlet channel on the weir Drahovce. Five measured profiles were situated in the inlet channel.

Two probes were installed on the upstream side, 15 m and 100 m above the intake structure of the inlet channel (above the coarse rack). Probe location, directly above and under the coarse rack of the intake structure, had been chosen with purpose to determine local hydraulic loss. This loss is being considerable mostly by clogging of the coarse rack (fig. 7) and it causes decreasing of water level at the beginning of the intake channel. This results in increase of hydraulic losses in the intake channel and thus lowering the head used by HPP Madunice. Final result is decrease of power output and electric energy generation in HPP Madunice.

In the outlet channel including natural riverbed of Váh were 3 measured profiles situated. Besides these probes, 2 probes were installed in natural riverbed of Váh and 1 below the chute at the end of the outlet channel. These probes monitored the water level beyond the chute to enable analysis of the chutes influence on chute overflow discharge and the influence of the chutes impounding by water from natural riverbed of Váh (below the confluent of the outlet channel and natural riverbed).

The measurement proceeded according to in advance prepared and approved program. The measurements were complicated by the fact that one aggregate had been shut down due to repairs. The capacity of the HPP was 2 x 100 m^3s^{-1} = 200 m^3s^{-1}. The operation of the HPP Madunice had been according to agreement with HPP dispatch centre of Slovenské elektrárne a.s., Vodné elektrárne o.z. Trenčín, such as to ensure during the operation in every day of the measurement the achievement of steady state for minimum of 4 hours (steady flow rate through the HPP Madunice). This agreement was for a scale of discharges with the operational start from standstill in 20 minutes: 180 m^3s^{-1} (September 14 2004), 130 m^3s^{-1} (September 15 2004) and 80 m^3s^{-1} (September 16 2004). Before the operation start (7:00) was since midnight zero discharge to set the hydrostatic water level. Real flow rates achieved during measurements were 190 m^3s^{-1} (September 14 2004), 132 m^3s^{-1} (September 15 2004) and 82 m^3s^{-1} (September 16 2004).

The power operator recorded in real time (in 1 minute intervals) following data:
1. water level at reservoir Drahovce,
2. Upstream water level at HPP Madunice,
3. downstream water level at HPP Madunice,
4. flow rate in HPP Madunice.

These data served as underlay for following measurement evaluation and for calibration and verification of the hydrodynamic model of the inlet and outlet channel of HPP Madunice.

Fig. 7 Intake structure of the inlet channel of the HHP Madunice inlet channel

Fig. 6 Probe protection pipe on the bank─ clogging of coarse rack

VI.   ACHIEVEMENTS

After the data processing of terrain measurement records, has been the method of following processing divided in these steps:
- calculation of the roughness coefficient of the outlet channel – steady flow rate state had been attained – segment solution method has been used for calculation (4.1),
- calculation of the roughness coefficient of the inlet channel – steady flow rate state had not been achieved for operational reasons (repairs on upstream group of HPPs and economically disadvantageous release of idle discharges by other HPP objects) – simulation on the hydrodynamic model had been used for calculation (4.2).

Results of roughness coefficient computation for the outlet channel are shown in following table.

day	flow rate	downstream profile		upstream profile		roughness
		profile	water level	profile	water level	coefficient n
	$m^3.s^{-1}$		m a.s.l.		m a.s.l.	
14.9.2004	190	10	140,45	8	140,73	0,0224
15.9.2004	132	9	140,27	8	140,37	0,0220
16.9.2004	82	9	139,27	8	140,02	0,0206

Then, for outlet channel was for next processing used average value of the roughness coefficient n = 0,022. Value of the roughness coefficient for the inlet channel has been after consideration of technical state of the inlet channel set as increased according to design value (0,015). It has been experimentally designed on value n = 0,020 and consequently verified by modelling on the hydrodynamic model.

VII.   CONCLUSION

The measurements at water work VD Drahovce – Madunice enabled refinishing of the methodology of roughness coefficient in derivation canals assessment. The correct assessment of the roughness coefficient in derivation canal is necessary for quality increase of the hydrodynamic models output.

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