1. INTRODUCTION

The groups of the channel hydropower plants (HPP) of the Váh Cascade at Ladce – Ilava – Dubnica – Trenčín and Kostolná – Nové Mesto – Horná Streda are hydraulically interdependent. Going along the stream of the Váh River, the Ladce – Ilava – Dubnica – Trenčín and Trenčianske Biskupice - Kostolná - Nové Mesto - Horná Streda water structures are groups of channel hydro power plants on the Váh Cascade. Last year our department made terrain measurements and conducted research on this water structure system. The results of the measurements were used for the improved calibration of the hydro dynamical model of these water structures. The presented paper describes this process.

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2. ABSTRACT

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 the sizes of channels, discharges through power plants, etc. Therefore, the hydraulic structures of the Váh cascade are complicated. The Dolné Kočkovce - Ladce - Ilava - Dubnica - Trenčín and Trenčianske Biskupice - Kostolná - Nové Mesto - Horná Streda water structures are groups of channel hydro power plants on the Váh Cascade. Last year our department made terrain measurements and conducted research on this water structure system. The results of the measurements were used for the improved calibration of the hydro dynamical model of these water structures. The presented paper describes this process.

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3. KEY WORDS

• Hydro Power Plant,
• Water Work,
• Hydraulic Parameters,
• Terrain Measurements.
system with the aim of obtaining a fully-developed hydrodynamic model.
An important part of the modelling is also the acquisition versus
the verification of the hydraulic characteristics of channels - the
roughness coefficient of a wetted perimeter.
The presented paper describes terrain measurements with the
intention of obtaining these hydraulic characteristics at the Ladce
Streda groups of hydropower plants. Both of the relevant groups
of channel HPPs operate practically synchronously in a tandem
operation. Therefore, the terrain measurements at the derivation
channels have to be synchronous. The measurements were performed
simultaneously on all groups with the aim of achieving steady water
levels in the channels as well as the reservoirs.

2. HYDRAULIC LINKS WITHIN THE RELEVANT
STAGE OF THE VÁH
The relevant stage of the Váh river is situated between the
Dolné Kočkovce water structure (WS) down to the Drahovce
water structure, and it is completely utilized energetically. 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 an upstream HPP or reservoir.
This means that the backwater of a downstream HPP reaches
an upstream HPP. Also, the HPPs are operated simultaneously,
which means that these HPPs operate with a discharge which
is let in the whole scheme at the entry of this stage by the first

Fig. 1 WS Dolné Kočkovce – weir and intake

Fig. 2 HPP Ladce structure of the intake channel for HPP Ladce

Fig. 3 HPP Trenčín

Fig. 4 WS Trenčianske Biskupice – weir and intake structure of
intake channel for HPP Kostolná
intake channel and hydropower plant (pilot HPP). In this case it is the HPP Ladce.

The intake channels of the Ladce – Ilava – Dubnica – Trenčín HPP group have a trapezoidal cross-section with a bottom width of about 18.3 m and a water-side slope of 1:1.75. They are sealed by facial concrete sealing. The bottom width of the outlet channels varies from 8 to 15.4 m. There is no channel lining under the minimal operational 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 m³s⁻¹. The maximal turbine capacity of HPP Ilava and HPP Dubnica is 2 x 75 m³s⁻¹.

The intake channels of the Kostolná – Nové Mesto – Horná Streda HPP group also have a trapezoidal cross-section with a varying bottom width from 16 to 19 m and a water-side slope of 1:1.75. They are sealed by facial concrete sealing. The bottom width of the outlet channels varies from 12 to 16 m. There is no channel lining under the minimal operational water level, and the slope of the banks is 1:3. The maximal turbine capacity of all the HPPs in this group is 2 x 90 m³s⁻¹.

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

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

3. METHODOLOGY OF THE VERIFICATION OF THE ROUGHNESS COEFFICIENT IN THE DIVERSION CHANNELS

The verification of the roughness coefficient is possible only by direct measurement during operations with these approaches:

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

b. unsteady state measurement – unsteady non-uniform flow (used only in a case when attaining a steady state is not possible; the results are less precise).
4. MEASUREMENT OF THE ROUGHNESS COEFFICIENT BY A STEADY STATE

The measurement by a steady state consists of the following steps:
- attaining a steady state without any flow before the beginning of the measurements – steady water levels in the diversion channels and compensation reservoirs are necessary not only for calibrating the probes but also as initial conditions for mathematical modelling
- attaining a steady flow state.

The frequency of acquiring the data (water level measurement) once per minute is usually sufficient for most of the hydrodynamic processes.

The conditions for attaining a steady flow state vary according to the type of derivation channel, and the measured profiles must be situated at a sufficient distance from the impounding structures in the channel.

For calculating the roughness coefficient of the measured stage by a steady non-uniform flow, the segment solution method and its appropriate formulas for hydraulic characteristics are used:

\[ \Delta z = Q \left[ \frac{2}{S_d} \left( \frac{1}{S_d} - \frac{1}{S_h} \right) \right] \]

\[ K' = S^2_c R_p \]  (1)

\[ S_p = (S_d + S_h)/2 \quad O_p = (O_d + O_h)/2 \quad R_p = S_p/Q_p \]

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

where \( \Delta z \) - water level elevation change at the stage \( z_h-z_d \)
\( Q \) - steady flow rate
\( \xi \) - expansion or contraction loss coefficient
\( S_p, S_h \) - flow area of downstream and upstream profile
\( l \) - length of stage
\( K_p \) - average flow-rate module
\( S_c \) - 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

An analysis of this formula (2) shows that the final computation error relies on the accuracy of the measurement of the difference between the upstream profile \( zh \) and the downstream profile’s water level elevation \( zd \). With regard to the limited precision of the measurement (centimetres) and other surrounding influences such as waves on the water surface (e.g., caused by wind), it is necessary to attain the maximal difference of the measured water levels, which is successful in formula (1) through the maximal flow rate in the channel and the maximal length of the measured stage.

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

5. MEASUREMENT OF THE ROUGHNESS COEFFICIENT BY AN UNSTEADY STATE

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

For data processing a hydrodynamic model (HDM) is used for modelling an unsteady non-uniform flow according to the scheme:
- calibration of the HDM for the maximal flow rate scenario,
- verification of the HDM for other scenarios.

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

\[ V_{t+\Delta t} = V_t + \sum Q_{in} \Delta t - \sum Q_{out} \Delta t \]  (3)

where \( V \) - water volume in the reservoir,
\( t, \Delta t \) - time and time step,
\( Q_{in} \) - inflow to the reservoir,
\( Q_{out} \) - outflow from the reservoir,
and the known reservoir volume curve \( V = f(h) \), which enables the backward computation of the water level in the reservoir from the volume of the reservoir.

The HDM used is based on the numerical solution of the Saint-Venant partial differential equation system as follows:
where $Q$ – flow rate [m$^3$s$^{-1}$]
$A$ – flow area [m$^2$]
$q_i$ – 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$^{-2}$]
$\beta$ – correction factor reflecting the influence of the non-uniform velocity distribution
$i_0$ – bottom gradient
$i_e$ – power line gradient
$v_i$ – velocity component of the side inflow or outflow in direction of axis x [ms$^{-1}$]

For the conversion of the foregoing equation system to a numerical solution by the finite differences method, the Preissmann implicit scheme with a weight coefficient of 0.67 was used.

6. TERRAIN MEASUREMENTS (“IN SITU” MEASUREMENTS)

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

1. Ladce – Ilava – Dubnica – Trenčín and

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

At the beginning of July 2005, a survey of the diversion channels and water structures took place at the stage considered of the Váh river (from the Dolné Kočkovce weir to Drahotice). Twelve measuring profiles at the Ladce – Ilava – Dubnica – Trenčín HPP group and 10 at the Kostolná – Nové Mesto – Horná Streda HPP group were determined.

Both groups of HPPs were operated according to an agreement with the HPP dispatch centre of Slovenské elektrárne a.s., Vodné elektrárne o.z. Trenčín. The measurement and determined operational scenarios were the 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$^3$s$^{-1}$,
- July 27, 2005 (Wednesday) discharge of HPPs: 120 m$^3$s$^{-1}$,
- July 28, 2005 (Thursday) discharge of HPPs: 90 m$^3$s$^{-1}$.

Other requirements for operation of the HPPs were:

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

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

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

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

The actual condition was significantly different from the originally projected conditions. The original roughness coefficient of the inlet channels (facial concrete sealing) had been approximately 0.013. According to the measurements, the present roughness coefficient was determined to be from 0.015 to 0.022. The original roughness coefficient of the outlet channels had been approximately 0.022. According to the measurements, the present roughness coefficient was determined to be from 0.022 to 0.030.

After 20 years of operation, the Kostolná – Nové Mesto – Horná...
Streda group of HPPs was inspected and repaired in the summer of 2005. The inspection confirmed the poor conditions of the water structures and showed the causes of deterioration of the hydraulic roughness in channels, which leads to decreasing the utilisation of the hydropower potential of the Váh river. The conditions in the channels are shown in the following figures. This work was supported by the Science and Technology Assistance Agency under Contract No. APVT-20-046302.

REFERENCES