NUMERICAL SIMULATIONS OF HYDRAULIC TRANSIENTS IN HYDROPOWER PLANT JAJCE II

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Abstract:

Hydraulic transients in hydropower plant Jajce II (Bosnia and Herzegovina) were simulated with 1D unsteady pipe flow model. High accuracy of the model was accomplished with the use of non-conservative formulation of an unsteady pipe flow model incorporating a modified instantaneous acceleration-based unsteady friction model and second order flux limited numerical scheme. In order to apply the model, complex dual surge tank geometry needed to be represented with a unified surge tank. The numerical model was validated against the measured data on three simulation scenarios, defined with different turbine discharge reductions. Simulation results show a very good agreement between the computed and measured piezometric heads, both in amplitude and frequency of the oscillation.

1 Introduction

1.1 Hydropower plant Jajce II

Hydropower plant Jajce II is a conventional 30 MW hydroelectric power plant, situated in the central part of Bosnia and Herzegovina. The maximum operating water level of the plant reservoir is 328.5 m a. s. l., yielding maximal operating discharge of 79.8 m^3/s over the head of 49m. The electrical power is generated with three equal Francis turbines. The water reaches the turbines through a tunnel (2840m long, 5.5m in diameter) and three parallel penstock pipes (41m long, 3.2m in diameter). A surge tank is installed above the point of the tunnel branching into penstock pipes. Being somewhat specific to this hydropower plant, a pipe perpendicular to the main tunnel connects the surge tank to a smaller secondary surge tank with an overflow device.

A schematic 3D drawing of the hydraulic infrastructure of the hydropower plant is given in Fig. 1.

1.2 Numerical modeling of hydraulic transients

For the purpose of 1D transient pipe flow simulation, friction losses are often estimated by the use of a standard friction term based on steady or quasi-steady state flow conditions, which then exhibit insufficient damping and significant discrepancies in phase shift of head traces between

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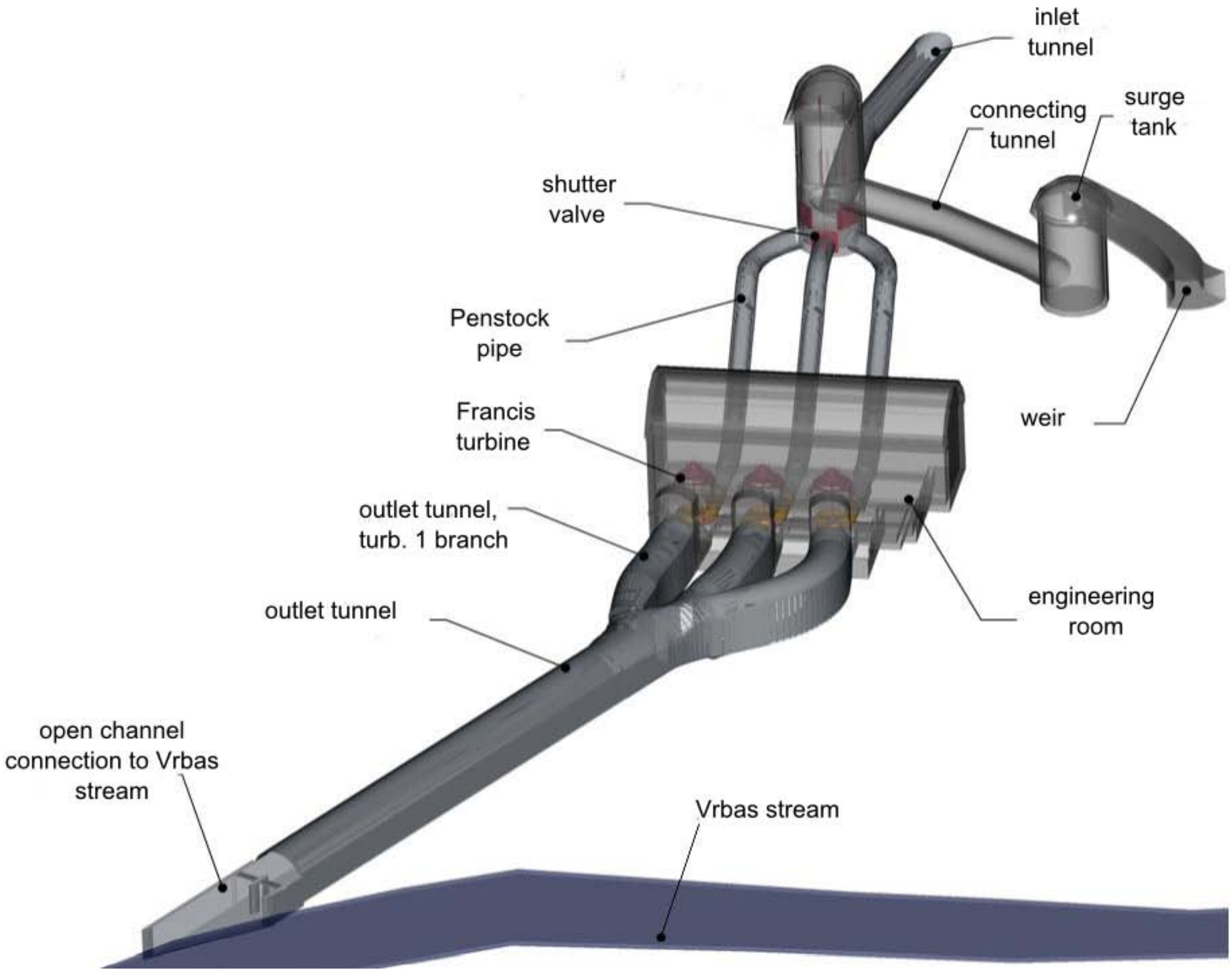

Figure 1. Schematic 3D drawing of the hydraulic infrastructure of the hydropower plant Jajce II.

experimental and calculated data [1]. In order to address aforementioned issues, the modified instantaneous acceleration-based (MIAB) formulation of an unsteady friction model was derived [2], which relates the unsteady component of friction to the instantaneous local and convective acceleration. Since the Brunone unsteady friction coefficient [3] used in the MIAB model varies with time and space [4-5], the model needs to be expressed in a non-conservative formulation in order to correctly evaluate the characteristic fields in the numerical approximation [6], which leads to better numerical approximation of measured head traces. The numerical model was tested by using measured data obtained from hydropower system Jajce II.

2 Mathematical model

2.1 One-dimensional unsteady pipe flow

The tunnel and penstock flow were modeled with the use of a one-dimensional unsteady pipe flow Allievi model. The basic governing equations for 1D unsteady pipe flow, as defined in [7], are:

$$\frac{\partial H}{\partial t} + \frac{c^2}{gA}\frac{\partial Q}{\partial x} = 0 , \qquad (1)$$

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + J_s + J_u = 0 , \qquad (2)$$

where indices t and x denote time and space (along the conduit length), H denotes the piezometric head, Q denotes discharge, c denotes wave speed, g denotes gravity acceleration, A denotes pipe cross-section area, while J_s and J_u represent head losses per unit length due to steady and unsteady friction losses, respectively. The steady friction losses are obtained as follows:

$$J_s = \frac{f_s Q|Q|}{2DA}, \tag{3}$$

where f_s represents Darcy friction factor and D denotes the pipe diameter. For the unsteady friction term J_u , a definition from [2] is used:

$$J_u = \frac{k}{2}\left(Q_t + c\Phi_A |Q_x|\right), \tag{4}$$

where Φ_A represents the sign of Q and k stands for the Brunone friction coefficient defined as:

$$k = \frac{\sqrt{C^*}}{2}, \tag{5}$$

and:

$$C^* = \begin{cases} 0.0476 & \text{Re} < 2300 \\ 7.41 \cdot \left(\text{Re}^{\log 143 \cdot \text{Re}^{-0.05}}\right)^{-1} & \text{Re} \geq 2300 \end{cases}, \tag{6}$$

where Re = uD/v is the Reynolds number, u denotes flow velocity and v denotes fluid dynamic viscosity. As proposed in [2], the unsteady friction model can be split into two parts:

$$J_u = \frac{1}{2}\left(k_p \cdot \frac{\partial Q}{\partial t} + k_A \cdot c\Phi_A \left|\frac{\partial Q}{\partial x}\right|\right), \tag{7}$$

where the two unsteady friction coefficients k_P and k_A are defined as $k_P = k$ and $k_A = 1.5k_P$.

Since the system of equations (1)-(2), with equations (3)-(4) or (7) is not written in the classical conservation form, non-conservative formulation (as laid out in [6]) was derived in order to reach a sufficiently accurate solution.

The reservoir was modeled as a water storage tank, with a local hydraulic loss on the grill at the tunnel entrance. That is, the piezometric head at the tunnel inlet can be calculated as:

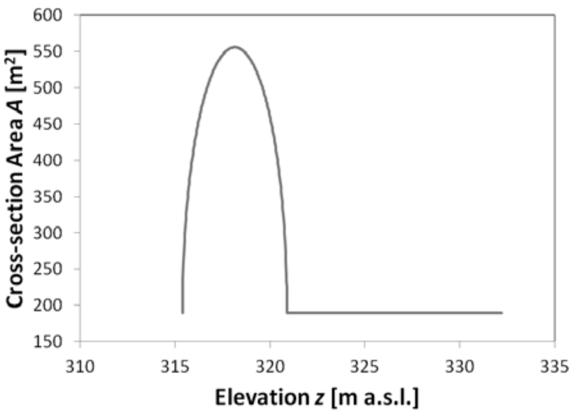

Figure 2. Equivalent unified surge tank geometry defined with cross-section area per elevation.

$$H = H_{st} - (1-\zeta)\frac{Q^2}{2gA^2}, \tag{8}$$

where Q denotes discharge at the tunnel entrance, A denotes the pipe cross section area, ζ represents local hydraulic loss derived from measured data which include all local losses between the tunnel and reservoir, and H_{st} represents the water level in the reservoir [7].

2.2 Equivalent unified surge tank

Due to the complicated two-tank design of the surge tank facility of hydropower plant Jajce II, a simplification was needed in order to successfully use the 1D flow model. Therefore, this rather complicated surge tank facility was represented with a single unified, volumetrically and hydraulically equivalent, surge tank (Fig. 2), which allowed for the use of a standard surge tank model, as it is commonly employed in hydraulic transients modeling.

For the standard surge tank model, only water level H_{st} is tracked over time and its variation is defined with the ordinary differential equation:

$$\frac{dH_{st}}{dt} = \frac{Q_{st}}{A_{st}}, \tag{9}$$

where $A_{st} = A_{st}(H_{st})$ is the surge tank cross section area at the level of H_{st} ([7]).
Discharge into and out of the surge tank Q_{st} is calculated with the use of the expression:

$$Q_{st} = \text{sgn}(H_{bst} - H_{st}) \cdot C_D \sqrt{2g|H_{bst} - H_{st}|}\ ,\tag{10}$$

where C_{DA} denotes the surge tank discharge coefficient (taken as C_{DA} = 0.8 m^2) and H_{bst} represents the piezometric head in the tunnel below the surge tank. The sign of Q_{st} indicates the direction of the water flow at the surge tank entrance:

- $Q_{st} > 0$ water flows into the surge tank,
- $Q_{st} < 0$ water flows out of the surge tank.

Outflow discharge at the surge tank overflow is calculated with the use of standard weir flow formula ([8]). The crest of the surge tank weir is at the level of 332.2 m a. s. l. The surge tank inlet is modeled as an orifice with the hydraulic loss coefficient obtained through a calibration procedure conducted on a series of measured data.
The above described model simplification of the surge tank facility was crucial for the success of 1D unsteady pipe flow application and represents one of the principal challenges of this research.

3 Numerical model

The mathematical model given above was formulated in the non-conservative form and second order flux limited numerical scheme was applied to the proposed formulation, as explained in [6].
The numerical model was implemented in in-house developed software STRAN [9]. The scheme of the elements of the numerical model is given in Fig. 3.
The reservoir was modeled as a water storage tank with a local hydraulic loss on the grill at the tunnel entrance. Tunnel and pipe wall roughness, as well as grill loss coefficient, were defined with the use of measured surge tank and tunnel entrance steady-state water levels.
In the numerical model, the turbines are represented with the Dirichlet boundary conditions of known discharge values.

4 Model validation

The numerical model described in this paper was validated against the measured data on several simulation scenarios, defined with different turbine discharge reductions:

1) turbine discharge reduced from 100% to 50%;
2) turbine discharge reduced from 100% to 30%;
3) turbine discharge reduced from 100% to 10%.

The exact information on turbine discharge change over time, for these three scenarios, is obtained from measurements. As an example, recorded turbine discharge transition corresponding with Scenario 1 is given in Fig. 4.

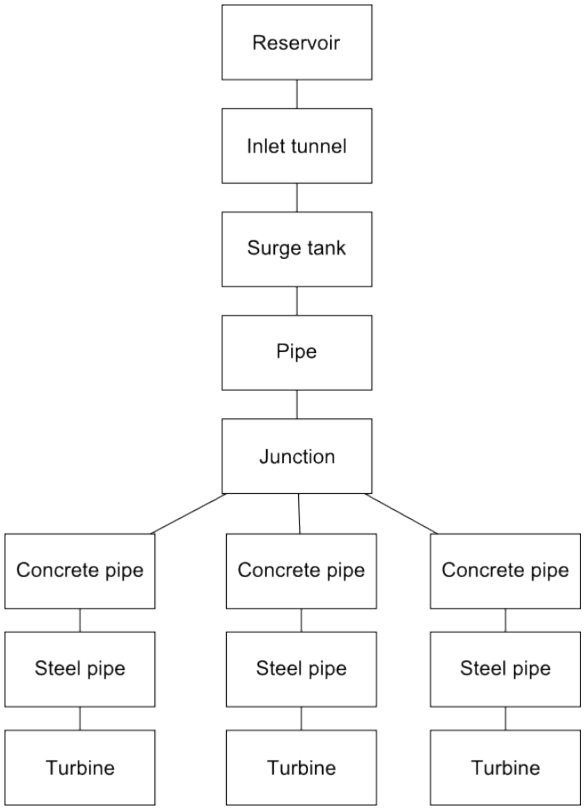

Figure 3. Diagram of the hydraulic system of hydropower plant Jajce II.

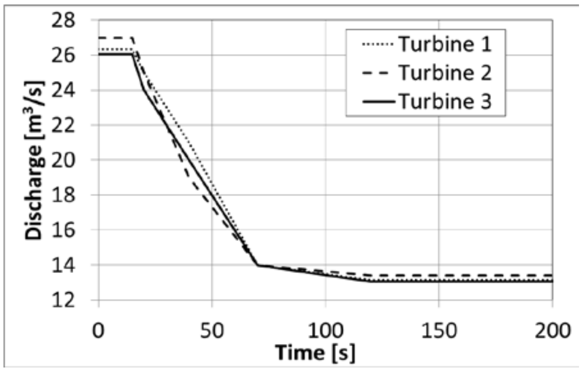

Figure 4. Turbine discharge reduction for the Scenario 1.

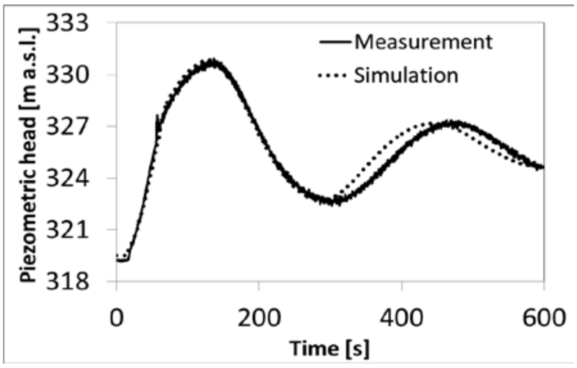

Figure 5. Computed and measured piezometric head at the turbine 1 – Scenario 1.

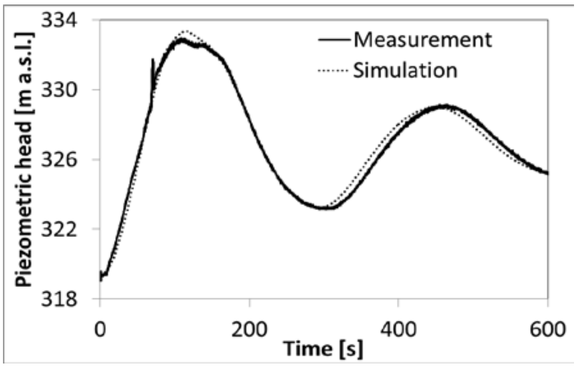

Figure 6. Computed and measured piezometric head at the turbine 1 – Scenario 2.

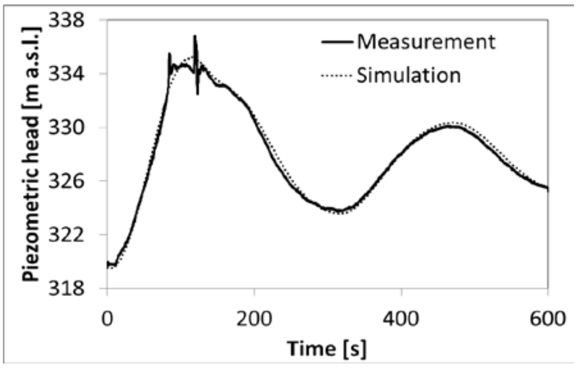

Figure 7. Computed and measured piezometric head at the turbine 1 – Scenario 3.

For all three scenarios, the water level in the reservoir equaled 327.63 m a. s. l. and total discharge equaled 79.34 m^3/s.

For the purpose of numerical model validation, the computed and measured piezometric heads at the turbine 1 for the three defined scenarios are compared (Figs. 5-7).

The results given above confirm the used numerical model as not only fully adequate, but very dependable and highly accurate. The oscillations of the piezometric head are successfully reconstructed, both in amplitude and frequency.

However, it is clear that the developed numerical model shows a somewhat better agreement with measured data for the more extreme transitions (Scenarios 2 and 3).

5 Conclusion

Standard transient pipe flow models mostly use the steady-state friction formulation, regardless of the unsteady nature of the transient flow itself. In order to improve the modeling methodology, modified instantaneous acceleration-based (MIAB) formulation of unsteady friction was used in the numerical simulations of hydraulic transients in hydropower plant Jajce II.

Besides, so as to enable the use of 1D pipe flow model, the rather complex dual surge tank of hydropower plant Jajce II was modeled with an equivalent unified tank.

Presented simulation results show a very good agreement between the computed and measured piezometric heads, both in amplitude and frequency of the oscillation. This proves the 1D transient pipe flow model with unsteady friction completely adequate and substantially accurate for hydropower plant hydraulic transients modeling, even when confronted with complex hydraulic system geometries. Furthermore, the success of the model shows the utilization of the unified surge tank model to be reasonable and sufficient.

References

[1] Daily, W. L., Hankey, W. L., Olive, R. W., Jordaan, J. M.: *Resistance coefficients for accelerated and decelerated flows through smooth tubes and orifices*, Transactions of the Japan Society of Civil Engineering, 78 (1956), 1071-1077.

[2] Vítkovský, J., Bergant, A., Simpson, A., Lambert, M., Martin, F.: *Systematic Evaluation of One Dimensional Unsteady Friction Models in Simple Pipelines*, Journal of Hydraulic Engineering - ASCE, 132 (2006), 7, 696-708.

[3] Bergant, A., Simpson, A., Vitkovsky, J. A. R.: *Developments in unsteady pipe flow friction*

modeling, Journal of Hydraulic Research, 39 (2001), 3, 249–258.

[4] Brunone, B., Ferrante, M., Cacciamani, M: *Decay of pressure and energy dissipation in laminar transient flow*, Journal of Fluids Engineering, 126 (2004), 6, 928-934.

[5] Bouazza, Z., Brunelle, P. E.: *A new friction model for transient pipe flows development of the frequency dependence approach of Brunone*, Proceedings of 9th International Conference on Pressure Surges, BHR, Chester, U.K., 2004, 391-404.

[6] Škifić, J., Maćešić, S., Črnjarić-Žic, N.: *Nonconservative Formulation of Unsteady Pipe Flow*, Journal of Hydraulic Engineering - ASCE, 136 (2010), 8, 483-492.

[7] Chaudhry, M. H.: *Applied Hydraulic Transients*, Van Nostrand Reinhold, New York, 1987.

[8] Agroskin, I. I., Dmitrijev, G. T., Pikalov F. I.: *Hidraulika*, Tehnička knjiga, Zagreb, 1969.

[9] Sopta, L., Mačešić, S., Črnjarić-Žic, N., Škifić, J., Družeta, S., Crnković, B.: *STRAN 1.0*, computer software package, Rijeka, 2010.