Regulation of Flow Downstream of Weirs

By Boualem Hadjerioua[1], Tony Rizk[2], Emmett M. Laursen[3] and Gary Hauser[2]

Abstract

Reregulation weirs are one means adopted by the Tennessee Valley Authority (TVA) to provide continuous improved minimum flow and wetted area for aquatic life downstream of hydroprojects during off-generation periods. A series of low-level pipes through the weirs, where some are fitted with regulating float-actuated valves, maintain essentially constant releases over a full range of weir pool elevations. Previous designs of such float-controlled mechanisms were based on physical modeling. This paper describes such a flow-regulating system and presents a quick and reliable analytical technique to determine float movement and pipe discharge rate at different headwater conditions. Data obtained from a full-scale model of the TVA South Holston labyrinth weir pipe and valve assembly were used to develop this analysis. Results of the analytical model were found to compare well with experimental data.

Introduction

Block-loaded operation of peaking hydroelectric plants, where the plants operate for only a few hours each day, results in essentially zero flow downstream for periods of several hours each day. TVA plans to construct reregulating structures downstream of some river when the peaking plant to provide a sustained minimum flow in the

[1] Graduate Student, University of Arizona, Dept. of Civil Eng., and Eng. Mech., Tucson, Arizona.

[2] Tennessee Valley Authority Engrg. Lab., Norris, Tennessee.

[3] Professor Emeritus, University of Arizona, Dept. of Civil Eng. and Eng. Mech., Tucson, Arizona.

turbines are not operating.

TVA is using various types of weirs with controlled and uncontrolled low-level pipes at dams where minimum flow objectives must be met (Hauser, et al.1991). The use of control valves and pipes in a reregulating structure was first introduced by TVA in 1984 at the Clinch River weir below Norris Dam (Harshbarger, 1985).

Experimental Data

A full-scale physical model of a section of the South Holston reregulating weir, shown in Figure 1, was tested at the TVA Engineering Laboratory. For each length of rod L1 tested, float movement and pipe discharge rates were measured at several different headwater elevations. Data from that experimental work was used to verify the analysis described in this paper, which generalizes design for these control systems for similar applications.

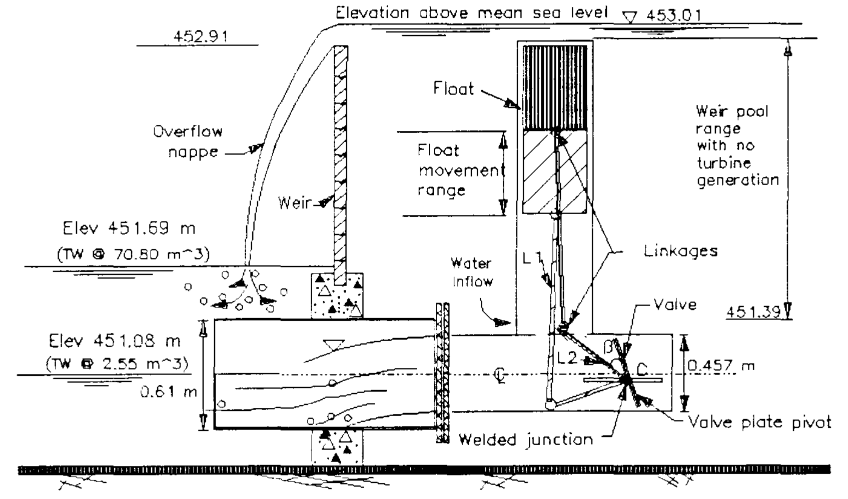

Figure 1. Pipe and Valve Assembly

Mathematical Problem Formulation

The flow regulation problem can be defined as follows:
For any given rod length, L1, determine:

1. The submergence ($^*L_{fsub}$) at which the float starts to move; this gives starting time of valve opening.
2. The relation between headwater levels upstream of the weir and discharge through the valved pipe for a range of headwater levels.

The analysis was developed assuming that:

---

[*] All symbols are defined in Appendix II.Notation

a. The system is frictionless.

b. An average constant coefficient of pipe discharge can be used for the whole range of heads.

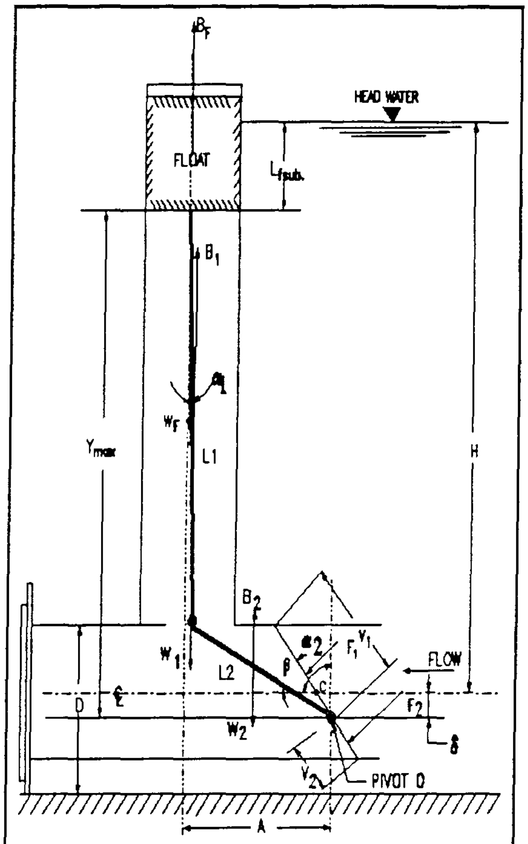

Figure 2. Free Body Diagram of the Pipe and Valve

Problem Definition

The objectives of this study is to obtain a mathematical description of the relationships among the headwater, valve opening, and discharge through the regulating pipe. As the pool lowers, the valve opens sufficiently slowly so that, for computational purposes, a quasi-static equilibrium state may be assumed at each headwater level during the opening period. This assumption is reasonable for this system in light of the physical data. Summing moments of the forces in Figure 2, about the valve plate pivot, results in

$$(B_F-W_F)M_F+(B_1-W_1)M_1+(B_2-W_2)M_2+(F_2)M_{p2}-(F_1)M_{p1}=0 \quad (1)$$

where

M_F, W_F, and B_F are, respectively, moment arm, weight and buoyancy of the float.
M_1, W_1, and B_1 are, respectively, moment arm, weight and buoyancy of rod L1.
M_2, W_2, and B_2 are, respectively, moment arm, weight and buoyancy of rod L2.
M_{p1} and M_{p2} are, respectively, moment arms of the forces F_1 and F_2.

Computation of Float Movement

The float movement is defined by:

$$Y_{mov}=Y_{\max}-Y \tag{2}$$

where Y is computed from Equation (1) for each weir headwater level, distance from the"horizontal" centerline of the pivot to the bottom of the float.

Computation of Flow Through a Valved Pipe

When power is generated, the water level rises in the reregulating pool above the weir, raising the float in the riser pipe and shutting the valve. The projected area of the valve plate is about equal to the interior pipe area. When the weir pool level lowers, the float drops and opens the valve. As the angle α_2 increases, the valve plate rotates, and additional flow passes through the pipe. The pipe discharge equation is:

$$Q_{flow} = V * A = C_d * A_{flow}\sqrt{2gH} \tag{3}$$

where

A_{flow} = cross-sectional area of the pipe less projected area of the valve;
V = flow velocity;
C_d = coefficient of discharge
H = vertical distance from headwater level to pipe centerline; and
g = acceleration of gravity.

After algebraic manipulation and considering leakage, Equation (3) yields:

$$Q_F=C_d\sqrt{2g}\frac{\pi}{4}\sqrt{H}\Big[D^2-\big[(D-2\epsilon)\,(V_1\cos(\alpha_2-\beta)+(V_2\cos(\alpha_2-\beta)\big]\Big]+C_{leak}\sqrt{H} \tag{4}$$

where ε is the thickness of the nut holding the valve to the pipe, and C_{leak} is the coefficient of leakage determined experimentally.

Results

When the valve is closed, the only flow through the pipe is due to minor leakage. The moment of the hydrostatic pressure forces were estimated for the upper and lower portions of the valve plate about its pin. The discharge coefficient, determined experimentally, was 0.489 for the opening mode and 0.6 for the fully open valve. As an example, application of the model is illustrated where L1 is 0.762 meter. Figures 3 and 4 show experimental and analytical results for float movement and discharge respectively, through the pipe for the range of headwater elevations. Comparison of similar data for other lengths of L1 also indicate good agreement between analytical values and experimental data.

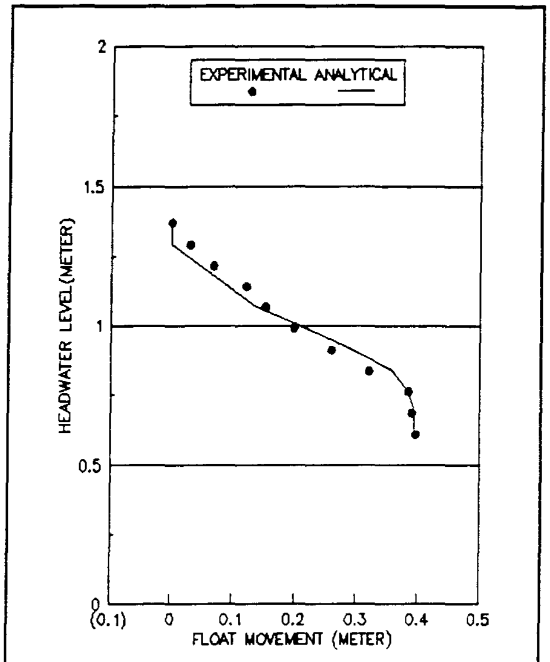

Figure 3. Float Movement (0.762 Meter Rod)

Conclusion

The mathematical analysis describing the behavior of a float-actuated valve developed in this study performed reasonably well when compared to experimental data obtained from a full-scale physical model of the pipe and valve assembly for the TVA South Holston labyrinth weir. The analytical procedure presented provides a quick and reliable technique to determine movement of a float and pipe discharge rate at different headwater levels, pipe diameters, and connector rod lengths. The mathematical analysis provides a reliable design and eliminates the need for laboratory studies, thus saving time and money. Such low-flow control devices offer a relatively simple mechanism for reliable and automatic flow regulation to meet minimum-flow criteria using weirs downstream of hydro-plants that are operated intermittently for power.

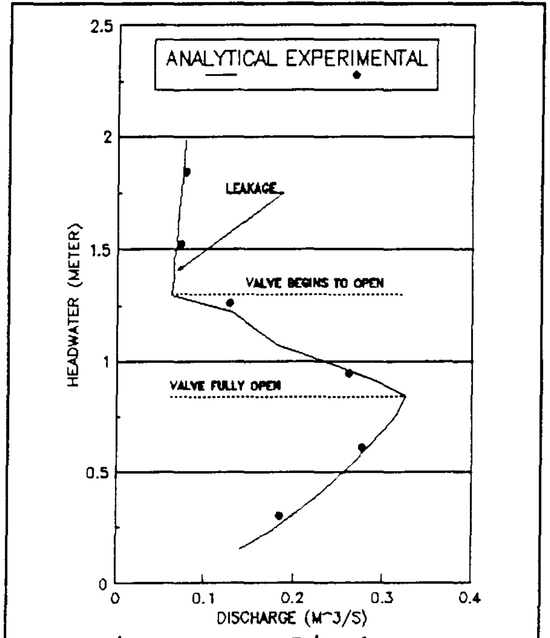

Figure 4. Discharge (0.762 Meter Rod)

APPENDIX I. REFERENCES

1. Harshbarger, E. Dean (1985). "Field Evaluation of the Clinch River, Hydraulic Characteristics," WR28-1-590-116, TVA Engineering Laboratory, Norris, Tennessee.

2. Hauser, G. E., R. M. Shane, J. A. Niznik, and W. G. Brock (1991). "Innovative Reregulation Weirs for Improving Minimum Flow and Dissolved Oxygen in Dam Releases," Proceedings of the ASCE National Conference on Hydraulic Engineering, Nashville, Tennessee.

3. Shane, Richard M. (1985). "Experimental Clinch River Flow Reregulation Weir, Field Evaluation Interim Report," WR28-4-590-118, TVA Engineering Laboratory, Norris, Tennessee.

APPENDIX II. NOTATION

The following symbols are used in this paper:

A_{Flow} = float cross-sectional area of the flow;
B_F, B_1 and B_2 = buoyancy of the float, rod L1 and L2 respectively;
F_1, F_2 and D = pressure forces, and pipe diameter;
H = headwater above pipe centerline;
LF, M_1 and M_2 = moment arm of the float, rod L1, rod L2 respectively;
L_{fsub} = critical float submergence;
L_{p1} and L_{p2} = moment arm for the pressure forces F_1 and F_2 respectively;
L1 and L2 = vertical and horizontal rod lengths, respectively;
Q_F = total discharge including leakage;
V_1 and W_2 = upper and lower length of the valve from the eccentric axis of rotation, respectively;
W_F, W_1 and W_2 = weight of the float, rod L1 and L2 respectively;
Y = distance from the "horizontal" centerline of the pivot to the float;
Y_{max} = distance from the valve pivot to the bottom of the float (closed position);
Y_{mov} = float movement;
α_1 = angle between the "vertical pipe" centerline and rod L1;
α_2 = angle between the pivot and rod L2;
β = angle between the valve and rod L2 and;
δ = distance from centerline of the horizontal pipe to axis of rotation.