HYDROELECTRIC STRUCTURES AND THE DESIGN OF SURGE CHAMBERS

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Summary

The principles, design, and application of surge chambers in water conveyance systems such as found in waterpower and pumping installations and pumping mains are described from both theoretical and practical points of view. Surge chambers are needed to protect against water- hammer pressure pulses and to limit these to conduits designed for high pressures. Low-pressure conduits in the conveyance system are generally interconnected to a surge chamber where they join high-pressure conduits such as penstocks and pumping mains. Long-period surge oscillations also occur, but are less troublesome than high-frequency water-hammer pulses (see *Water Power Engineering*).

1. Introduction

A surge chamber or surge tank is one of the smaller, but essential, hydraulic components in a water conveyance system and is generally required in one or other form in a hydroelectric power development or a pumping main.

Between a reservoir, the head pool, and the tail pond, the following components are in a typical hydroelectric installation: the intake works, the low-pressure conveyance (some form of canal/tunnel combination), the surge tank or surge chamber, the high-pressure conduit, the turbine and generator installation, and the tailrace. Sometimes another low-pressure conveyance follows the turbines, especially in underground power stations. Another surge shaft or chamber may be incorporated ahead of the low-pressure conduit leading to the outlet in the river downstream.

Surge chambers are important components for decoupling the high-pressure conduits from the low-pressure conveyances. At their junction, the surge chamber introduces a free water surface by means of a tee-connection. High-pressure water-hammer impulses are not able to pass this point and hence are confined to the high-pressure conduit between the surge chamber and the hydroelectric plant. Low-pressure surges are all that remain in the low-pressure conveyance upstream of this point. However, in a throttled surge tank, some of the transient pressure is transmitted to the low-pressure system.

This article deals primarily with surge chambers in hydroelectric power plants, but brief reference is also made to surges in pipelines (see *Appendix 1. Hydroelectric Structures*). Water hammer and surges occur not only in hydroelectric power penstocks, but also in pumping mains and gravity pipelines.

2. Water Hammer and Surge Suppression

These two hydraulic phenomena are manifestations of unsteadiness in a conduit connected on one side to a free water surface and on the other side to a closing device or flow constriction. The presence of a free water surface may give rise to surges, which are slow oscillations of the water column due to gravity and inertia effects. The action of a closing device or flow constriction gives rise to rapid elastic oscillations in the water column and the conduit, which is known as water hammer.

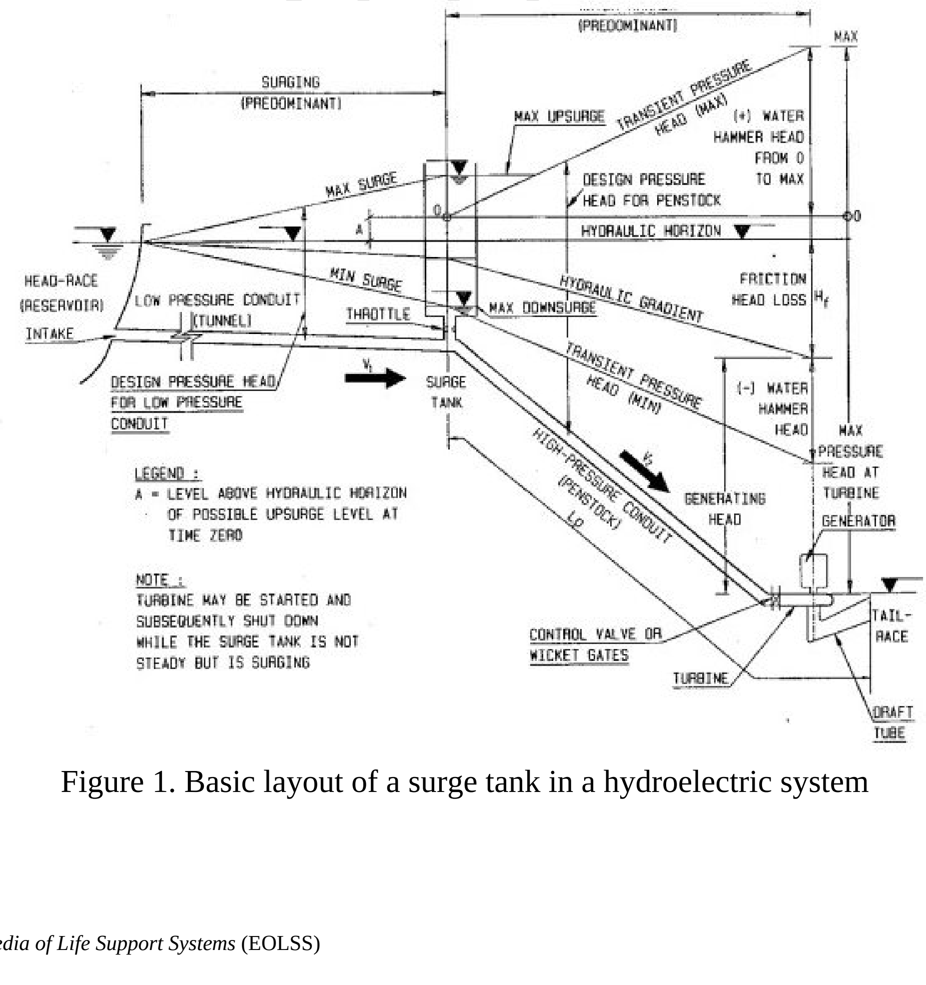

Figure 1. Basic layout of a surge tank in a hydroelectric system

Because the two phenomena are often confused, they are explained separately in the following sections. Either or both may cause serious malfunction or even destruction of the system, and for this reason it is necessary to incorporate a surge chamber that has the function of controlling and separating the two effects and confines surging to the low-pressure conduit or tunnel and water hammer to the high-pressure conduit or penstock. In Figure 1 the basic layout of a surge tank in a hydroelectric system is shown, while in Figure 2 the use of surge chambers in a pumping line is illustrated.

3. Design of Surge Chambers

The surge chamber can have several forms. It could be a vertical drop shaft to the junction of the pressure conduit with the low-pressure conveyance, or it could be a surge chamber located inside the rock mass at that point. In a pumping main, surge chambers are also often located between the pump station and the delivery reservoir to prevent water-hammer oscillations. These may occur if the pumps should fail, and the water column in the pipeline separates and vapor pockets could be formed. The water column in the surge chamber is then available to fill the vapor pocket, which is caused by subatmospheric pipeline pressures. Instead of the classical surge chamber open to atmosphere, it may be designed as an air-pressure vessel.

4. Functioning of Surge Chambers

Surge chambers operate in the following manner. The reservoir level fixes the hydraulic head at one end of the line. The surge chamber alleviates water-hammer overpressure or responds to negative pressures due to water column separation, by influx or efflux of water. It reduces the effective length of the longitudinal water column in the conveyance pipeline, and, according to the rigid-column theory, also the magnitude of the under-pressure and over-pressure surges. Furthermore, it reduces the rigid-column length, which is exposed to sudden water-hammer pressure rises and falls, to that portion of the conveyance situated between the surge chamber and the power house (or pump station, as the case may be).

The connection between the surge chamber and the conduit may be throttled to reduce the surge oscillations more rapidly. In pumping mains, an air-accumulator vessel situated close to the discharge side of the pumping station is more economical to construct than a surge chamber. Although the same principles apply to an air accumulator as for a surge tank in terms of suppressing water hammer, the air accumulator is more sophisticated to operate and needs close supervision for continuous correct operation.

5. Water Hammer

Water hammer occurs in a penstock or a high-pressure conduit downstream of the surge tank's location (between the surge tank and the turbine station, or in a pumping main ahead of the surge tank (or surge suppresser) between the pump station and the surge tank.

The following Eqs. (1) to (3) give the values of the pressure oscillations, Hwh, due to water hammer for both sudden and slow valve closure times.

$$\textit{For sudden valve closure}, \; tc \le t: \mathrm{Hwh} = \pm \frac{CV}{g} \qquad (1)$$

where *tc* is less than or equal to 2Lp/C, *V* = flow velocity at time zero, *Lp* = penstock length (length of waterway open to atmosphere at either end and includes length of penstock, spiral casing, and draft tube), Hwh = max. water-hammer amplitude.

$$\textit{For slow valve closure}, \; tc > t: \mathrm{dHwh} = \pm \frac{CdV}{g} \qquad (2)$$

where *tc* = valve closure time ≫*t*, *C* = sonic velocity in system, *dV* = flow velocity change in time,
t = 2*Lp*/*C*, dHwh = incremental head rise or fall.

$$\textit{Another formula used is} \quad \frac{H_{\max}}{H_o} = \frac{K}{2} \pm \sqrt{(K + K/4} \qquad (3)$$

where *K* = L.Vo/(g.Ho.tc), + positive water hammer for load rejection, – negative water hammer for load acceptance.

This head rise (or fall) due to water hammer acts over the full waterway length, or over that portion of the pumping main lying between pump station and surge tank. The shorter this length can be made, that is the closer the surge tank is located to the turbine (or pump) station, the more economical it is for the project. The water hammer over- (or under-) pressures, requiring a higher class of penstock or pipeline, are thus restricted over as short a length as possible. The magnitude of the water hammer pulses is both positive and negative, for flow reduction and for flow increase.

The *water-hammer* pulsing period, Twh, is equal to:

$$\mathrm{Twh} = \frac{4Lp}{C} \qquad (4)$$

where *Lp* = length of pipeline, *C* = sonic velocity in filled conduit:

$$C = \frac{\sqrt{(g/\rho)}}{\sqrt{(1/K + cD/Eth)}} \qquad (4a)$$

th = pipe wall thickness
K = bulk modulus of water
E = elastic modulus of pipe wall material
D = pipe diameter (internal)
g = gravitational acceleration

ρ = specific mass (density) of water
c = joint fixity, taken as equal to 0.9

The amplitude envelope of the water-hammer pulse is not constant and varies along the length of the penstock, *Lp,* as shown in Figure 1. It varies from the maximum upsurge value at the surge tank to the maximum water hammer, Hwh, at the turbine end, oscillates, and decays exponentially with time, due to friction and turbulence losses.

6. Surges

Oscillations of much longer periodicities than the short-period water hammer pulses occur over the length of low-pressure conduit between the reservoir and the surge tank (for the case of a hydroelectric power installation) and may also occur in a pumping main between the surge tank and delivery reservoir (in the case of a pumping installation).

Such long-period oscillations are known as surges and are due to gravity effects in a pipeline connecting with a free water surface reservoir at either end. The magnitude of the surge head above the equilibrium value due to small changes in the flow rate is given by

$$dHs = \pm \frac{L}{g} \cdot \frac{dV}{dt} \qquad (5)$$

where L = the length of the conduit stated above, dV = velocity change in the time increment $t = dt$, dHs = the incremental head rise or fall.

Therefore, the maximum value of the surge head caused by complete flow stoppage or resumption is

$$Hs = \pm\ LV / g \cdot tv \qquad (6)$$

where V = the rated flow velocity, tv = valve closure/opening time, Hs = maximum surge amplitude.

The above two equations give the value of the surge head for, respectively, a small adjustment in flow and a complete flow reversal, such as may be caused by the closure or opening of a valve situated at the end of a conduit that connects the reservoir with the surge tank as shown in Figure 1. The same effect is created by the starting or stopping of a pump in the portion of the pipeline (shown in Figure 2) between the surge tank and the delivery reservoir.

In a penstock delivering high-pressure water to a turbine in a hydroelectric installation, the initial surge magnitude, dHs, is positive for control valve closure, and for valve opening it is negative. Thereafter, the surges oscillate and diminish until a new static or dynamic equilibrium level is maintained. The surge magnitude is a maximum in the surge tank and zero at the reservoir and varies linearly in between in proportion to the distance from the reservoir (Figure 1).

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Biographical Sketches

J.M. Jordaan is a retired civil engineer with experience in hydraulic structures design for the Department of Water Affairs and Forestry in Pretoria, South Africa.

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