Surge Tank Behavior in the Presence of a Traveling Pressure Wave

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ABSTRACT

This research aims to analyze the response of surge tanks under traveling pressure waves. The study involves measuring the maximum amplitude of mass oscillation within surge tanks of varying diameters and pipe friction levels, establishing the relationship between pipe friction and oscillation amplitude, and examining how surge tank diameter influences pressure suppression. The study found that increasing the surge tank diameter reduces the maximum water surface level (Z_{max}) up to a certain point, which is a diameter of 7 meter, beyond which further increases in diameter the Z_{max} remains almost constant. Additionally, higher tunnel roughness leads to a linear relationship between Z_{max} and friction factor with negative slop dampening the pressure fluctuations in an effectively way.

INTRODUCTION

Water hammer, a phenomenon caused by the sudden closure of valves or abrupt turbine shutdowns, results in significant pressure surges that can damage fluid transport systems (Nakayama, 2018; DFT Inc., 2019). This research investigates methods to mitigate these surges, focusing on the use of surge tanks in hydraulic power plants to absorb and dissipate excess pressure. Historical incidents, such as the Sayano-Shushenskaya explosion (Figure 1) and the Oigawa Power Station accident (Figure 2), illustrate the catastrophic consequences of water hammer (Bunn, 2012; Bonin, 1960). By employing the rigid water column theory, this study aims to determine the relationship between tunnel friction and oscillation amplitude and examining how surge tank diameter influences pressure suppression.

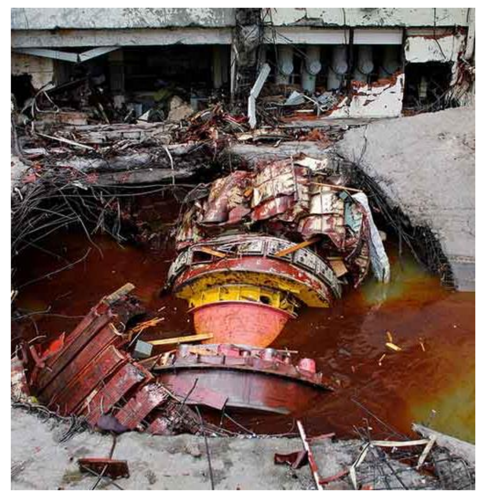

Figure 1: Sayano-Shushenskaya explosion (Lupa et al. , 2022).

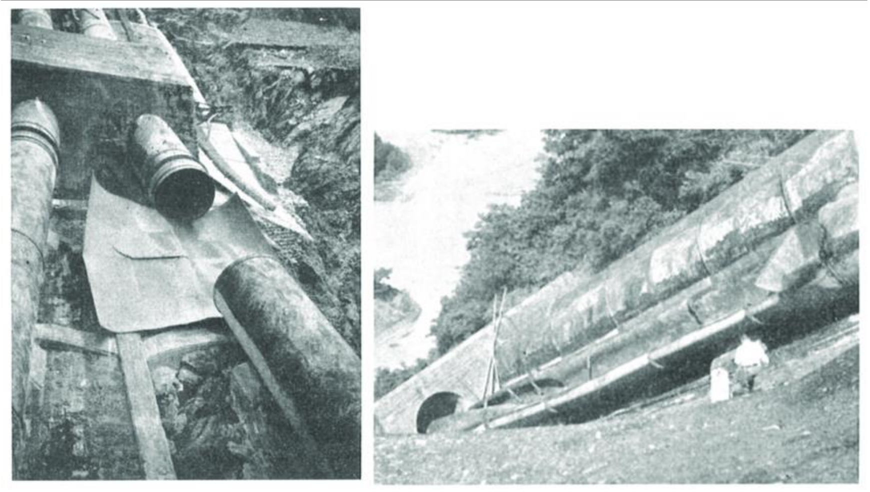

Figure 2: Oigawa Power Station accident (Lupa et al. , 2022).

OBJECTIVES

This research aims to analyze the response of surge tanks under traveling pressure waves. It focuses on determining the relationship between surge tank diameter and pressure suppression in a tunnel and considering the impact of tunnel friction. The study involves measuring the maximum amplitude of mass oscillation (Z_{max}) within surge tanks of varying diameters and pipe friction levels, establishing the relationship between pipe friction and oscillation amplitude, and examining how surge tank diameter influences pressure suppression.

METHODOLOGY

This research uses the rigid water column theory to analyze surge tank response under traveling pressure waves. A MATLAB code was developed to solve the following equations. The momentum equation between the reservoir and the surge tank described by: $l_e \frac{1}{g}\frac{dV}{dt} + Z \pm h_f = 0$, where l_e is the equivalent length which is is composed by the pipe length and the equivalent length of the energy losses at the tunnel entrance and the surge tank junction, V is the velocity within the tunnel, Z is the water level in the surge shaft, and $h_f = f\frac{L}{D}\frac{v^2}{2g}$ is the tunnel head loss. The second equation is the continuity at the tank junction: $A_1 V = A_2 \frac{dZ}{dt} + Q$ where A_1 and A_2 are the cross-sectional areas of the tunnel and surge tank, respectively, V is the flow velocity at tunnel, and Q is the flow rate to the turbine. At the initial the shutoff turbine is accounted considering Q = 0.

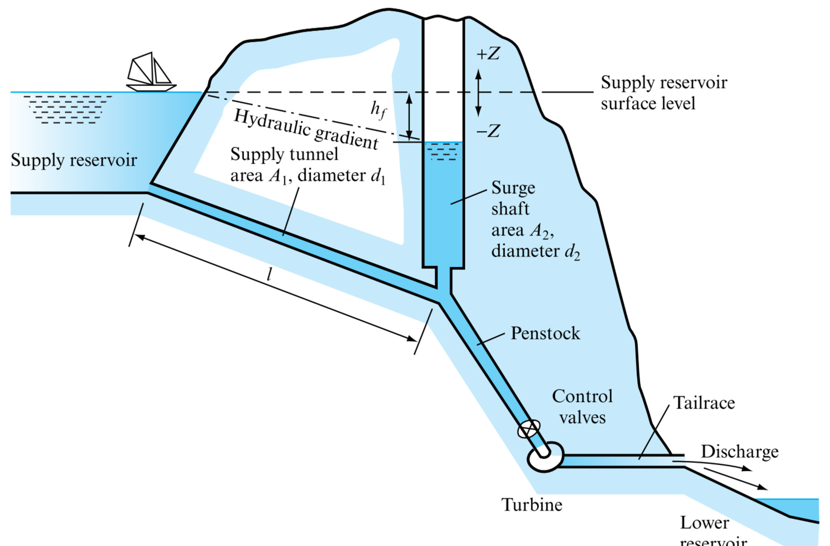

Figure 3: Schematic of a surge shaft layout in a hydroelectric scheme (Douglas, 2006)

On the other hand, the finite difference method will be applied to solve these one-dimensional equations. The momentum equation is discretized as follows: $V^{n+1} = V^n + \frac{g}{l_e}\left[-Z - \frac{4fl_e}{d1} \cdot \frac{V^n|V^n|}{2g}\right]\Delta t$. In this expression, Δt represents the time step, with the superscripts n and n+1 indicating the current and next time steps. Similarly, the continuity equation is discretized as $Z^{n+1} = Z^n + \frac{A_1}{A_2} \cdot 0.5(V^{n+1} + V^n)\Delta t$. The steady state condition (velocity and head loss) as initial condition was obtained considering ρ=998,2 kg//m^3. μ=1.002 x 10^{-3} N.s/m^3, the flow rate is 2 m^3/s, the minor loss coefficient for tunnel inlet and surge tank junction are K_1=0.004 and K_2=0.19, respectively. The tunnel diameter is 1.25m and the surge tank diameter is 2.4m. The tunnel length until to surge tank is 200 m and the roughness is 0.015 m. After that, the transient solution was developed changing the tank diameter from 0.1m to 10 m to analyze the relationship between mass oscillation and surge tank diameter. Additionally, the tunnel roughness variation from 0.001m to 0.03m is considered to determine the impact of pipe friction on mass oscillation.

RESULTS AND ANALYSIS

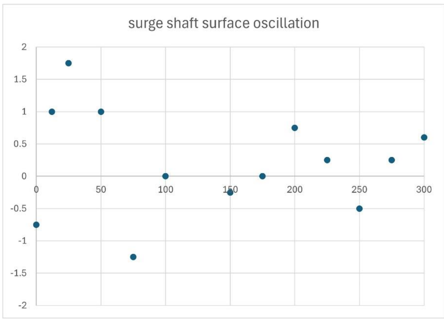

Figure 4: Surge tank water surface oscillation for a diameter of 2.4 m (Douglas, 2006)

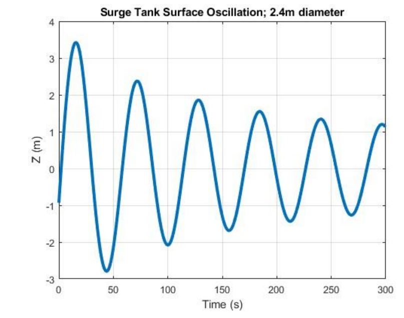

Figure 5: Simulation of surge tank water surface oscillation for a diameter of 2.4 m using rigid column water theory

Numerical simulation (Figure 5) show overprediction when is compared with water surface oscillation obtained by Douglas, 2006. In general, there is not a shift in the time evolution as well as the pattern is captured very well.

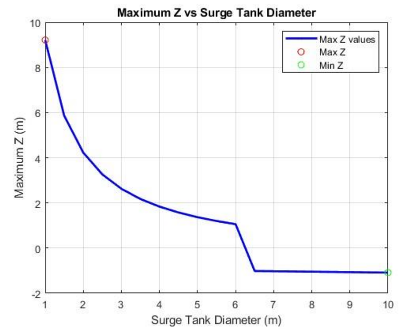

Figure 6: maximum water surface elevation in surge tank in terms of tank diameter

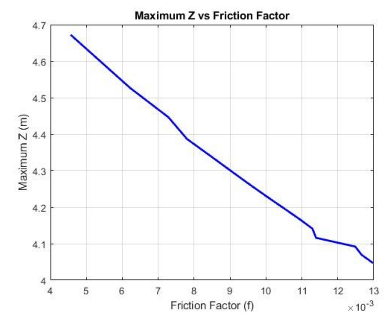

Figure 7: maximum water surface elevation in surge tank varying pipe roughness

The numerical simulation (Figure 6) showed the maximum water surface in surge tank (Z_{max}) has an exponential-like relationship with tank diameter variation. After a sudden drop in Z_{max} from 6 to 7-meter of tank diameter a constant water level is observed. Further increases have minimal impact on pressure suppression.

RESULT AND ANALYSIS

The figure 7 denotes the relationship between Z_{max} and friction factor. The simulation demonstrated that as tunnel roughness increases, the friction factor increases, leading to a decrease in Zmax, which suggests that the increased friction helps to slow down and reduce the pressure fluctuations within the surge tank. The observed relationship is linear.

CONCLUSIONS AND RECOMENDATIONS

This study analyzes the impact of surge tank diameter and pipe friction on pressure oscillations in the penstock. The results indicate that a specific diameter was identified where pressure suppression is optimized. Increasing the diameter beyond the 7-meter tank diameter the pressure oscillation has minimal impact on Z_{max}. On the other hand, tunnel roughness leads to decrease in the water surface oscillation amplitude in the surge tank, suggesting that higher friction within the tunnel contributes to damping pressure waves following a linear relationship. These findings show the importance of selecting an optimal surge tank diameter and considering tunnel roughness to effectively manage pressure surges in hydraulic systems. Future work could explore the impact of tunnel materials and surge tank configurations on pressure oscillation behavior.

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