INTRODUCTION

In water conveyance systems, mainly including hydropower systems and water supply systems, throttled surge tanks are commonly used to realize reliable water hammer control; throttles can also dampen surge in these tanks and ease the regulation of turbines. Usually, for the throttled surge tank, one or more throttles are designed at the intersection between the surge tank and the main conduit to reduce surge amplitude and accelerate surge damping. In some cases, a relatively short linking tunnel or shaft is also used between the tunnel and the surge well instead of a simple throttle, and particularly, diaphragms can be installed in order to increase the head loss in some cases; this linking tunnel or shaft presents the same function as a throttle. By comparison with the hydraulic characteristics and operating stability of a simple surge tank, Borkowski concluded that the head loss for water entering or exiting a surge tank through the throttle is a key parameter for operating stability, water hammer, and surge control. For hydropower systems with throttled surge tanks, the effect of the
hydraulic resistance coefficient of the tank on the control of operating conditions was revealed by Wang et al., and throttles were proved to have a positive effect on governor stability. Furthermore, Vereide et al. highlighted that, for the surge tank, the throttle has an insignificant effect on governor stability for normal disturbances in grid frequency. In hydraulic vibration analysis, Kim introduced short linking pipe length for normal disturbances in grid frequency. In hydraulic tank, the throttle has an insignificant effect on governor stability, and Kendir and Ozdamar achieved an approach for quick optimal sizing of the air chamber volume and the corresponding head loss characteristics.

Smith reported that the orifice's head loss coefficients for its optimal design with an appropriate layout. Ward suggested that part of the surrounding pipe should be reinforced to avoid damage caused by cavitation, considering the orifice influence length and the corresponding head loss characteristics.

Therefore, it is important to understand the complete nature of the throttle's head loss coefficients in the surge analysis of the throttled surge tank and thus obtain clear guidance for its optimal design with an appropriate layout. Ward-Smith reported that the orifice's head loss coefficients depend not only on flow direction but also on the detailed design of the connections, the topology of the connection itself, and the relative Reynold's number. Arshenevskii et al. summarized the typical hydraulic regimes at the junction of the surge tank and introduced their mathematical models to define specific energy differences. Based on a simple experiment with a 12-meter-long straight pipe and four different throttle types for the surge tank, Prenner and Drobi investigated and ascertained the influence of the throttle on the transmission of pressure in the tunnel. Lai et al. introduced Gardel's head loss formula to represent the velocity head and momentum exchange at the T-junction of the surge tank and analyzed their effects on the critical sectional area of the downstream surge tank. The hydraulic resistance coefficient of throttled surge tanks was investigated by means of computational fluid dynamics (CFD), and further comparative analysis was carried out with a model test for a given case.

As can be seen in Figure 1, there is an obvious difference between the cross section and layout features of the different throttle types. Generally, four different methods can be used to accurately obtain their head loss characteristics: the specification-based method, the empirical-expressions-based method, the CFD-based method, and the experiment-based method. In fact, the throttle's head loss coefficients are revealed by experimental research in conjunction with CFD simulation, and further surge analysis is presented.

2 | EXPERIMENTAL SETUP

2.1 Typical throttle types and analysis of their head loss coefficients

In water conveyance systems, the typical throttles used can be of three main categories (Figure 1): a simple throttle (type A), a relatively short linking tunnel or shaft (type B), and more than one throttle (type C).
empirical-expressions-based method have been obtained using a significant amount of experimental data.

In CFD simulations, different numerical boundaries and turbulence models have an inevitable effect on the accuracy of the head loss coefficients; in some instances, this can be verified by experimental research. Therefore, to reveal the throttle’s head loss characteristics in detail and improve the accuracy of surge analysis, experimental research is preferred.

2.2 Typical flow regimes at the junction of the surge tank

In Figure 2, the surge tank point includes an upstream pipe (section 1-1), a downstream pipe (section 2-2), and a surge well (section 3-3); considering both transient and steady states, there are 12 typical flow regimes at this point.

Figure 2(A)–(F) show all the possible diffluence and confluence flow regimes at the T-junction of the surge tank in the transient state. Figure 2(G)–(L) present all the possible steady flow regimes that can be also considered special cases for the transient flow regimes. In experimental research, by assuming stable reappearance of the above 12 flow regimes, the head loss characteristics can be analyzed in detail based on collected experimental data.

2.3 Design of the experimental setup and adjustment of typical flow regimes

For conducting experimental research on the head loss coefficients of a surge tank’s throttle, a general and complete experimental setup was designed and built in a laboratory; its layout is outlined in Figure 3.
The experimental setup consists of auxiliary pipes with valves, a backwater area with triangular weirs, and a surge tank with upstream and downstream pressure pipes, so all the possible flow regimes can be successfully achieved and kept stable by operating the valves. Specifically, the transient flow regimes shown in Figure 2(A)–(F) with different discharge ratios are easily realized by adjusting valve opening, and the experimental flow rate is measured via orifice-plate flowmeters or triangular weirs. As a precondition to measure the volumetric flow rate entering or exiting the surge tank and passing through the main conduits, the orifice-plate flowmeters were designed and installed at appropriate sections along the upstream and downstream pipes. To avoid the effect of auxiliary pipes and accurately reproduce the flow regimes of the surge tank’s prototype, the surge tank used in the experiments was constructed employing adjacent upstream and downstream pipes whose lengths were 10 times greater than their diameters, including the designed transition pipes and inclination angles. To experimentally obtain the head loss coefficients for the different flow regimes under various operating conditions, three measuring sections were set in the experimental setup shown in Figure 3. A loop pipe was used to connect the four pressure taps evenly located along the pipe circumference with their corresponding piezometric tubes.

In this setup, both a surge tank with a single pipe (Figure 4) and a surge tank with two branches can be simulated and tested using two optional parallel auxiliary branches.

As aforementioned description, with the reasonable adjustment of all the valves to exhaust the pipelines completely at first, all the 12 flow regimes in Figure 2 can be realized in this experimental setup conveniently and steadily by adjusting the corresponding valves. Particularly in order to keep the water level balance in the surge tank for each flow regime, the valve 7 is served as a discharge valve for the flow regimes with water entering the surge tank and the valve 6 is a water supplement valve for the flow regimes with water exiting the surge tank. Considering a surge tank with a single pipe system, take a typical flow regime (A) in Figure 2 for example: with the valves 2, 5, 6, and 8 always in closing state and the valve 1 always in opening state, the valve 3 is setting in a relatively large opening, and simultaneously the valves 7 and 9 are adjusted to a reasonable opening to keep the water level balance in the surge tank, therefore, a typical flow regime (A) with a definite discharge ratio is built for experimental research; with the premise of the water level balance in the surge tank, the opening of valve 9 is adjusted from full opening to 0 while the opening of valve 7 is from 0 to full opening, and then, different discharge ratios can be realized in this flow regime; as the opening of valve 9 is equal to 0, this critical state of flow regime (A) is just the steady flow regime (G), while the opening of valve 7 is equal to 0, this critical state of flow regime (A) is just the steady flow regime (K). Similarly, the other 5 transient flow regimes can also be steadily produced by the combination of different valves.

3 | MATHEMATICAL MODEL OF THE SURGE TANK BASED ON EXPERIMENTAL DATA

3.1 | Definition of the head loss coefficients

Along flow direction, the head loss between sections \(i\) and \(j\), \(\Delta h_{ij}\), is obtained based on the Bernoulli equation,

\[
\Delta h_{ij} = E_i - E_j = Z_i + \frac{P_i}{\gamma} + \frac{\alpha_i V_i^2}{2g} - \left( Z_j + \frac{P_j}{\gamma} + \frac{\alpha_j V_j^2}{2g} \right)
\]
where the subscripts $i$ and $j$ represent sections $i$-$i$ and $j$-$j$, respectively; $E$ is the total water energy at each section; $\gamma$ is the bulk density of water; $Z$, $P/\gamma$, and $(Z + P/\gamma)$ are the gravitational potential energy, pressure potential energy and piezometric head, respectively; $P$ is the absolute pressure; $g$ is the acceleration due to gravity; and $\alpha V^2/(2g)$ is the velocity head. Here, the correction coefficient, $\alpha$, equals 1 for an even velocity distribution at the corresponding section.

Based on the defined reference velocity, $V_R$, at a given reference section with sectional area $A_R$ and total volumetric flow rate, the head loss coefficient, $\zeta$, between sections $i$-$i$ and $j$-$j$ is:

$$\zeta = \frac{\Delta h_{ij}}{V_R^2/2g} = \frac{E_i - E_j}{V_R^2/2g}$$  \hspace{1cm} (2)$$

In transient states, the head loss coefficients for each flow regime are analyzed based on experimental data under different discharge ratios at the T-junction of the surge tank; the discharge ratio, $q_s$, is defined as:

$$q_s = \frac{Q_b}{Q_t}$$  \hspace{1cm} (3)$$

where $Q_t$ is the total volumetric flow rate at the corresponding section, and $Q_b$ is the split volumetric flow rate at the adjoining section. Experimental results indicate that, during the rising and declining of the water level in a surge tank, the throttle’s head loss coefficients are not constants but vary with the discharge ratio. The relationship between $\zeta$ and $q_s$ is fitted by square regression analysis based on the least squares method:

$$\zeta = a q_s^2 + b q_s + c$$  \hspace{1cm} (4)$$

where $a$, $b$, and $c$ are the fitted coefficients of the quadratic equation.

For different hydraulic systems with throttled surge tanks, the throttle’s head loss coefficients obtained from experimental data are consistent with those for prototype surge tanks. In order to perform relatively exact surge analysis and then economically optimize the surge tank, the obtained head loss coefficients for water entering or exiting the surge tank should be inputted to the detailed hydraulic transient analysis to exactly reflect the time evolution of the water level in the surge tank.
3.2 Mathematical model of the surge tank

Figure 5 shows a typical throttled surge tank point. Based on the characteristics method, the general equations for the water level fluctuations in the throttled surge tank are:

\[ C^+ : H_p = C_p - B_{pq} Q_{ps} \]  \hspace{1cm} (5)

\[ C^- : H_{p1} = C_{m1} + B_{m1} Q_{p1} \]  \hspace{1cm} (6)

\[ H_{p1} = H_p \]  \hspace{1cm} (7)

\[ H_p = Z_{ps} + R_s \left| Q_{ps} \right| Q_{ps} \]  \hspace{1cm} (8)

\[ Q_{p1} = Q_{p} + Q_{t} \]  \hspace{1cm} (9)

\[ A_s \frac{dZ_{ps}}{dt} = Q_{ps} \]  \hspace{1cm} (10)

where subscripts \( n \) and 1 represent the specified sections; \( H_p \) and \( Q_p \) are the unknown piezometric head and volumetric flow rate for the specified sections at time \( t \), respectively; \( C_p, B_p, C_m, \) and \( B_m \) are constants calculated from the known piezometric head and volumetric flow rate for the given sections at time \( t - \Delta t \); \( Z_{ps} \) is the water level in the surge tank; \( A_s \) is the area of the surge tank; \( Q_{ps} \) is the volumetric flow rate entering or exiting the surge tank; and \( R_s \) is the resistance coefficient passing through the throttle, which is defined as \( R_s = \frac{1}{2g \phi^2 A_o^2} \), with known throttle area, \( A_o \), and recommended flow coefficient \( \phi = 0.6-0.8 \). \hspace{1cm} (28)

With the obtained resistance coefficient, \( R_s \), for the water flow passing through the throttle, the boundary of the surge tank can be easily solved. The throttle’s head loss, \( \Delta h \), is considered a minor loss and depends on flow direction and the head loss coefficient. Based on Equation (8), an extended derivation is recommended to introduce experimental data regarding the throttle’s head loss coefficients into the mathematical model of the surge tank:

\[ \Delta h = H_p - Z_{ps} = R_s \left| Q_{ps} \right| \]  \hspace{1cm} (11)

Considering the velocity at the throttle, \( V_o \), corresponding to the throttle’s area, \( A_o \), the head loss coefficient, \( \zeta_o \), is:

\[ \zeta_o = \frac{\Delta h}{V_o^2/2g} \]  \hspace{1cm} (12)

Then, in Equation (11):

\[ R_s = \frac{\zeta_o}{2g A_o^2} \phi = \frac{1}{\sqrt{\zeta_o}} \]  \hspace{1cm} (13)

By introducing the definition of the throttle’s head loss coefficient, Equation (2), we obtain:

\[ \zeta_o \frac{Q_{ps}^2}{2g A_o^2} = \zeta \frac{Q_t^2}{2g A_R^2} \]  \hspace{1cm} (14)

For the flow regimes in Figure 2(A)–(D), the volumetric flow rate at section 1-1 or 2-2 corresponds to the total volumetric flow rate, \( Q_t \), and then, \( Q_t = Q_{ps}/q_s \). Thus, by combining this expression with Equation (4), the derived resistance coefficient, \( R_s \), is:

\[ R_s = \frac{1}{2g A_R^2} \left( a + \frac{b}{q_s} + \frac{c}{q_t^2} \right) \]  \hspace{1cm} (15)

For the flow regimes in Figure 2(E) and Figure 2(F), the volumetric flow rate at section 3-3 corresponds to \( Q_t \) and satisfies \( Q_t = Q_{ps} \). Thus, the derived resistance coefficient, \( R_s \), is:

\[ R_s = \frac{1}{2g A_R^2} (aq_s^2 + bq_s + c) \]  \hspace{1cm} (16)

Therefore, in hydraulic transient analysis, based on the obtained instantaneous volumetric flow rates at sections 1-1, 2-2, and 3-3, the instantaneous flow regime at the surge tank point can be clearly defined. The experimental data for the throttle’s head loss coefficients for different flow regimes are organized according to Equations (15) and (16), and then employed for surge analysis. In Equation (15), for the particular case of \( q_s = 0 \), the boundary condition for the surge tank point satisfies \( \Delta h = 0 \) and \( H_p = Z_{ps} \), contrarily to Equation (15). Based on the characteristics method, all the boundary conditions can be easily simulated for different elements, for example, the reservoir, series pipelines, the surge tank, bifurcation pipes, the turbine, and tailwater, and a mathematical model.
for the entire hydro-mechanical system can be built for advanced surge analysis.

4 | ANALYTICAL APPLICATION IN SURGE ANALYSIS

4.1 | Two schemes for a throttled surge tank

A pumped-storage power system mainly consists of two pump-turbine branches sharing a headrace tunnel, an upstream throttled surge tank, and a long penstock. The headrace tunnel is 640.3 m in length with a diameter of 6.2 m, and the penstock is 1159.5 m in length with a diameter of 5.4 m. The throttled surge tank is 9.0 m in diameter and presents an upper chamber of 1940.0 m bottom elevation and a 216.2 m² cross-sectional area. The throttle exhibits the two schemes shown in Figure 6 (details on dimensions are presented in Table 1); for scheme DS2, the centerline length of the L-shaped linking tunnel is 21.06 m. In Table 1, i is the slope of upstream tunnel, \( L_1 \), \( L_2 \), and \( L_3 \) are the lengths of upstream connecting tunnel, bottom tunnel of the surge tank and downstream connecting tunnel respectively, \( H_1 \) and \( H_2 \) are the heights from the bottom of inverted cone to the centerline of the tunnel, and the height of inverted cone.

4.2 | Numerical simulation of the head loss coefficients

Before comprehensive experimental research, the orifice's head loss characteristics can be preliminary revealed via CFD simulation.\(^2^3,3^1\) Considering the advantages on the numerical simulation of flow detachment and swirling flow etc, the realizable \( k-e \) turbulence model was used in combination with the SIMPLE algorithm to realize velocity-pressure coupling, and the TGrid mesh was generated concurrently with necessary refinement for some regimes with violent changes in the flow patterns. All the monitoring sections were 5 pipe diameters away from the surge tank point. In Figures 7 and 8, after the reference section 1-1 is presented, the obtained throttle's head loss coefficient under flow regimes (G) and (I) are presented along with the obtained velocity nephograms. Additionally, possible flow detachment, vortex formation, and swirling flow is clearly evidenced in the different nephograms presented, which can clarify the difference observed for the head loss coefficients.

As can be observed in Figures 7 and 8, when water enters the surge tank, because of the obvious uneven velocity distribution at different cross sections in the surge tank of scheme DS1, its head loss coefficient is notoriously greater than that of scheme DS2; the opposite is observed when water exits the surge tank mainly due to the existing swirling flow along the pressure tunnel for scheme DS2. Because the velocity distribution at different cross sections of water entering the surge tank is worse than that of water exiting the surge tank for scheme DS1, the throttle's head loss coefficient for water entering the surge tank is notoriously greater than that when water exits the surge tank; the opposite is observed for scheme DS2 because the velocity distribution at different cross sections of water entering the surge tank is better than that of water exiting the surge tank.

4.3 | Experimental results for head loss coefficients

4.3.1 | Steady flow regimes

Based on the experimental setup for the two aforementioned schemes, experiments were carried out to determine the head loss coefficients for the 12 typical flow regimes. In Table 2, for a throttle diameter of 4.3 m, the head loss coefficients for water entering and exiting the surge tank

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FIGURE 6  Two throttle schemes: (A) Scheme DS1 and (B) Scheme DS2
were obtained for the steady flow regimes (G)–(J). By employing the known area of the reference section, $A_R$, and the throttle's area, $A_o$, the flow coefficient, $\phi = \frac{A_o}{\sqrt{A_R}}$, could be also calculated.

By comparing the results presented in Table 2 with the specified flow coefficient for surge tanks ($\phi = 0.6$–$0.8$; see Section 3.2), the obtained flow coefficients ranged from approximately 0.6–1.0; for scheme DS1 (type A), $\zeta_{3i} > \zeta_{3i}$ ($i = 1, 2$), while for scheme DS2 (type B), $\zeta_{3i} < \zeta_{3i}$ ($i = 1, 2$), and $\zeta_{31}$ (DS1) $> \zeta_{31}$ (DS2) ($i = 1, 2$), while $\zeta_{3i}$ (DS1) $< \zeta_{3i}$ (DS2) ($i = 1, 2$), which is in agreement with the simulation results. Therefore, for two or more different throttle types, the experimental method could exactly distinguish their differences in head loss characteristics for water entering and exiting the surge tank. This proves the suitability of the specification-based method and most importantly, also demonstrates the advantage of obtaining more accurate flow coefficient for different throttle types experimentally.

Further comparative analysis indicated that, for flow regimes (G) and (I), the head loss coefficient differences between experimental results and simulation results presented evident variations. For water entering or exiting the surge tank, a significant amount of turbulence, including flow detachment, vortex formation, and swirling flow, often occurs, promoting local unsteadiness that effects the energy analysis at the monitoring section of the CFD simulation. In the downstream, monitoring sections of Figures 7 and 8 can be observed that the best agreement between the experimental and numerical results is found for water exiting the surge tank of scheme DS1 in Figure 8(A) (difference below 5%); in contrast, the largest difference (about 20%) is found for water exiting the surge tank of scheme DS2 in Figure 8(B). This indicates that the chosen turbulence model, mesh, and boundary conditions present an inevitable influence on CFD results.

### Table 1 Dimensions of the throttled surge tank

| Scheme       | $i$ (%) | $L_1$ (m) | $L_2$ (m) | $L_3$ (m) | $H_1$ (m) | $H_2$ (m) |
|--------------|---------|-----------|-----------|-----------|-----------|-----------|
| DS1 (type A) | 5.219   | 9.0       | 10.6      | 9.0       | 3.9       | 3.0       |
| DS2 (type B) | 6.867   | 9.0       | 10.4      | 9.0       | 6.4       | 2.35      |

**Figure 7** Velocity nephograms for flow regime (G): (A) Scheme DS1 with $\zeta_{31} = 8.002$ and (B) Scheme DS2 with $\zeta_{31} = 6.010$

**Figure 8** Velocity nephograms for flow regime (I): (A) Scheme DS1 with $\zeta_{31} = 4.398$ and (B) Scheme DS2 with $\zeta_{31} = 8.477
4.3.2 Transient flow regimes

After the above analysis on the throttle’s head loss coefficients under steady states, the head loss coefficients under transient states are now analyzed based on experimental research. In Table 3, the head loss coefficients for water entering or exiting the surge tank are analyzed considering the typical flow regimes (A)–(F) for scheme DS2 and a throttle diameter of 4.3 m.

In particular, based on scheme DS1, experimental research for different throttle diameters was conducted and the head loss coefficients for each throttle diameter were obtained. Figure 9 shows the curves for the throttle’s head loss coefficient, $\zeta_{13}$, under flow regime (A) and $\zeta_{31}$ under flow regime (C) for different schemes and throttle diameters. The presented test data correspond to the sampled data of the throttle’s head loss coefficient for scheme DS2 with a throttle diameter of 4.3 m.

It can be proven that a quadratic equation based on square regression is the best fitting curve and that the throttle’s head loss coefficients vary with discharge ratios under transient states. Considering the particular case when the discharge ratio equals 1, the calculated throttle’s head loss coefficients are close to the experimental data for steady flow regimes (G–J) with a relative error below 5%. The increase in the throttle’s diameter in scheme DS1 evidently results in a decrease in the throttle’s head loss coefficients at different discharge ratios; this is particularly evident for large discharge ratios.

The throttle’s head loss coefficients under the 12 flow regimes and the extended mathematical model for the surge tank obtained using experimental data were utilized in the detailed surge analysis of the two most unfavorable cases, named WCT and WCP, that the 12 flow regimes experience at the T-junction of the surge tank. For case WCT, the water levels in the upper and lower reservoirs were 1940.0 and 1355.0 m, respectively, in turbine mode the two units presented a load acceptance equal to the rated output, and when the water flow rate entering the surge tank was maximum, the two units performed load rejection by simultaneously closing the wicket gates. For case WCP, the water levels in the upper and lower reservoirs were 1903.0 and 1400.0 m, respectively, in pump mode the two units started pumping, and when the water flow rate exiting the surge tank was maximum, the two units ceased working with the wicket gates performing no actions. The closing and opening laws of the pump-turbines were as follows: wicket gate linear opening time in turbine and pump mode of 30 seconds, wicket gate broken closing time in turbine mode of 35 seconds (time at broken point: 2.6 seconds; relative opening at broken point: 0.65), and wicket gate linear closing time in pump mode of 30 seconds.

In the experimental research and numerical simulation, the effect of the short linking tunnel for scheme DS2 is included in the obtained throttle’s head loss coefficients. In addition, the recommended flow coefficient in the codes basically refers to the T-junction, and the head loss along the short linking tunnel can be ignored by compared with that of T-junction. Therefore, it is rational to regard the linking tunnel as a node with the ignorance of its water inertia in order to introduce the experimental data into further surge analysis.

After detailed sensitivity analysis for throttle diameters of 3.5, 3.9, and 4.3 m based on experimental data from scheme DS1, surge analysis with a throttle diameter of 4.3 m for each scheme based on experimental data was performed. In addition, for comparison purposes, a constant flow coefficient, $\varphi = 0.7$, was also introduced into the surge analysis for these
two schemes instead of experimental data. The maximum and minimum water levels in the surge tank for cases WCT and WCP are presented in Table 4; the water level in the surge tank and the piezometric head at the bottom tunnel versus time for case WCT are shown in Figure 10.

The results indicate that, for the two schemes with a throttle diameter of 4.3 m, because of a significant difference in terms of head loss coefficients, there are evident differences in the surge and piezometric head at the bottom tunnel. The difference in maximum water level is 1950.52 − 1948.78 = 1.74 m, and the difference in minimum water level is 1867.95 − 1865.94 = 2.01 m. When the flow coefficient for water entering and exiting the surge tank was considered equal to 0.7, the surge and piezometric head at the bottom tunnel presented significant differences with the results of the experimental research.

In summary, to achieve an economical and safe design for the surge tank's top/bottom elevation with reasonable safety margin in a surge tank system, the maximum and minimum water levels in the tank should be accurately evaluated. In most cases, considering the evident surge differences for the most unfavorable cases caused by using the head loss characteristics obtained from different methods, it is crucial to accurately compute the throttle's resistance coefficients for different throttle types in surge analysis. Based on comparative analysis, experimental research can provide exact head loss coefficients for different throttle types. By introducing experimental data into the surge tank's mathematical model, relatively accurate surge analysis including throttle type and size optimization can be performed to achieve improved design in engineering applications.

5 | CONCLUSIONS

For throttled surge tanks in hydropower systems, the throttle's head loss coefficient is often obtained based on design specifications or empirical formulae, and an approximate
value has to be inevitably used in most cases, even for commonly used throttles with typical layouts. In addition, when CFD simulations are used to obtain the throttle's head loss coefficients, the accuracy of this approach depends on the mathematical models and numerical boundaries employed. Herein, after defining the typical flow regimes at the throttled surge tank, a general and complete experimental setup, including a surge tank and necessary pipelines, was built in the laboratory and the throttle's head loss coefficients for the 12 typical flow regimes were obtained for a given throttled surge tank with different throttle types. It was demonstrated that the throttle's head loss coefficient varies under different flow regimes and that the discharge ratio is of importance. Additionally, an extended mathematical model for the surge tank was developed with the introduction of experimental data for the throttle's head loss coefficients. Finally, via a detailed case analysis, it was found that the experimentally obtained flow coefficients for different throttle types are more accurate and clearly reveal the difference of throttles’ head loss characteristics; this was also confirmed via CFD simulations for the different throttle types.

It is concluded that detailed surge analysis provides relatively accurate solutions for the economical and safe design of surge tank top/bottom elevation with reasonable safety margin.

**ORCID**

Jianxu Zhou [https://orcid.org/0000-0002-4306-5491](https://orcid.org/0000-0002-4306-5491)

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