# Storage tunnels to mitigate hydropeaking

W. Richter
*Institute of Hydraulic Engineering and Water Resources Management, Graz University of Technology, Graz, Austria*

G. Zenz
*Institute of Hydraulic Engineering and Water Resources Management, Graz University of Technology, Graz, Austria*

ABSTRACT: The optimization of hydraulic systems in diversion tunnel power plants can provide significant economic and ecological benefits. By designing these systems as storage tunnels with differential surge tanks, power plants can be improved to handle surge and sunk compensation to mitigate hydropeaking by optimizing the associated construction costs, allowing for increased flexibility and improved storage management.

## 1 INTRODUCTION

New diversion power plants with tunnel water conveyance systems are currently designed and constructed as new as well as replacements for old power plants in terms of re-commissioning.

The transportation of water in tunnels offers the opportunity to go underground and thus utilize both economic and ecologic advantages, such as preserving protection zones and reducing fluctuations in water levels. For example, the Romanche-Gavet hydropower project (97 MW, 560 GWh/year), consisting of 6 old power plants and 5 reservoirs were replaced with a diversion power plant in one river section. Table 1 refers to Alpine hydropower projects utilizing underground storage infrastructure.

Table 1. Overview of underground storage of hydropower plants (Richter, 2022)

| Power plant | Type of underground storage | Volume | Installed capacity | Standard production capacity | Design discharge |
|---|---|---|---|---|---|
| | | $m^3$ | MW | GWh | $m^3/s$ |
| Innertkirchen (CH) | Storage tunnel and hydropeaking compensation basin combined in tailwater | 60,000<br>20,000 | 390 | 720 | 64 |
| Fieschertal (CH) | Storage tunnel headwater | 64,000 | 64 | 144 | 15 |
| Forbach PSH (G) | Storage cavern in tailwater for expansion | 200,000 | 50 | | 16.9 TU<br>15.7 PU |
| Nassfeld PSH (A) | Storage cavern in tailwater for expansion | 175,000 | 31.5 | 50 | 11.6 TU<br>9.2 PU |
| Obervellach II (A) | Storage tunnel in headwater and hydropeaking compensation basin in tailwater | 60,000<br>60,000 | 38 | 125 | 9.0 |
| Salvesenbach (A) | Storage tunnel | 10,000 | | 17 | 1.0 |
| Stanzertal (A) | Storage tunnel headwater | 51,000 | 13.5 | 52.2 | 12 |
| St. Anton (IT) | Storage tunnel in as hydropeaking compensation basin in tailwater | 95,000 | 90 | 300 | 18 |
| Starkenbach (A) | Storage tunnel | 4,700 | 17.8 | 17.8 | 0.85 |

The following example projects already show the effectiveness of storage tunnels in power water ways.

Obervellach II power plant project - currently under-construction - will replace an old cascade of power plants in the Möll valley in Carinthia. The project has a storage tunnel in parallel with the main tunnel and in balance with a retention basin with the same volume to allow an energy shift by storage operation by keeping the inflow and outflow to the river system at the same quantity.

The Stanzertal hydropower plant is operated with a 4.6 km long storage tunnel in the main pressure tunnel, which allows for energy to be shifted to peak periods. The approved pumped-storage hydropower plant (PSH) Forbach in the Black Forest in Germany will feature a 200,000 m³ tailwater storage expansion by a mostly unlined storage cavern attached to the existing river retention basin to enable efficient pumped storage operation in combination with the existing upper reservoir with 14 hm³.

The St. Anton hydropower plant near Bolzano was renovated with a 95,000 m³ storage tunnel in the tailrace for compensation of water level fluctuations. As part of the expansion of the Innertkirchen 1 hydropower plant, the tailrace was equipped with a storage tunnel and a balancing basin to reduce water level fluctuations in the Hasliaare river.

Pressure tunnels for hydro power generation with medium head and high discharge rates often have greater lengths and necessarily large cross-sectional areas, which also contain a large volume of water. Traditionally, the hydraulic use of pressure tunnels is mostly intended for the transport of water from the reservoir to the surge tank and then to the turbines via the pressure shaft. In hydropower plants with large storage reservoirs, the volume proportion of the tunnel is in general small and serves purely for transport. The pressure tunnel is part of a hydraulic pressure system, changes in flow might occur very quickly due to the rapid propagation of pressure waves, with accompanying compensatory oscillations in the surge tank.

The additional use of the water conveyance system as a storage volume for short-term storage such as daily storage or flood peak compensation can significantly increase the usable water volume. This can make the operation of a hydroelectric power plant more flexible, especially in alpine catchment areas. For small or medium-sized diversion power plants, the operation can be based on the electricity demand and be adapted by the intermediate storage in the tunnel. In combination with the requirements of compensating for flood and low flow in the river as well as the residual water flow, the storage of water volume can offer advantages for the operation.

Additionally, by using bypasses with energy dissipators around turbines, the power regulation of the machines and the water flow rate can be decoupled. This can be used for environmental flow compensation in case of load rejections. Specifically designed regulated energy dissipators are currently investigated to ensure stable control circuits in combination with environmental benefits.

## 2 TUNNEL STORAGE CONCEPT

In addition to the amount of water and the head, the ability to store water efficiently determines the effective generation of renewable energy by hydroelectric power plants. In some cases, the storage reservoir can be effectively supplemented by hydraulic storage utilization implemented in the water transport tunnel. Tunnel systems are particularly used in storage power plants, diversion power plants, or pumped-storage power plants. For small or medium-sized diversion power plants, an adapted operation can be carried out based on the electricity demand through the intermediate storage in the tunnel. New power plants or revitalization projects are also subject to higher requirements for flood and low flow compensation. These can be partially or entirely relocated to the tunnel for their damping effect, enabling flexible participation in grid control services with higher ecological acceptability. In pumped-storage power plants, the capacity of the storage reservoirs usually prevails, and they can provide peak power without flood or low flow impact, especially with sufficiently large reservoirs downstream, making them an ideal storage and load balancing technology for the energy transition. The combination of tunnel storage in the head race tunnel and compensating reservoir downstream also enables turbines to operate beyond the amount of water available, in order to operate the storage volumes during peak power times or during low water seasons without negative impacts on river flows. Any suspended sediment accumulations in storage tunnels can also be addressed through daily emptying in a bypass.

## 2.1 *Diversion power plant with bypass energy dissipator*

The combination of a tunnel storage with a bypass that includes an energy dissipator allows for flexible operation to maintain the hydropeaking compensation through the water volume in the diversion tunnel. An adequate bypass system enables the decoupling of the power-controlled turbine operation and water flow. This allows for steep power gradients of the units and flat flow gradients to meet the requirements of hydropeaking compensation in the river system. Figure 1 shows a schematic section through a diversion power plant with a tunnel storage in the head race, a tunnel storage surge tank, and an energy converter in the power cavern. The tunnel is shown in the empty state. A control element after the intake enables independent control of the storage volume. An aeration shaft enables that the ventilation of the storage tunnel takes place and not through the intake structure ensuring safe operation. By using the energy dissipator downstream, a possible compensation basin can be optimized in size since in this case, storage water can pass from the head race even when the turbines are throttled. In particular, by holding the hydropeaking compensation in the tunnel, the level in the compensation basin can be lower, thus ensuring higher energy generation, which is relevant for medium-head systems with high flow rates. The energy dissipator in the turbine bypass allows the hydropeaking compensation volume to be maintained in the head race tunnel. The dissipator depicted corresponds to the pressure regulator of the turbines in the Tonstad power plant (960 MW) in Norway, which are successfully used for pressure surge reduction. Dissipators or pressure regulators were built in many power plants associated with Francis turbines, especially in the first half of the 20th century. Pressure regulators in Austria are, for example, in operation in Rodundwerk I (1943) pumped-storage power plant and Limberg I pumped storage power plant (1955). Possible further designs of a control element in the bypass are modified cone jet valves and axial piston valves.

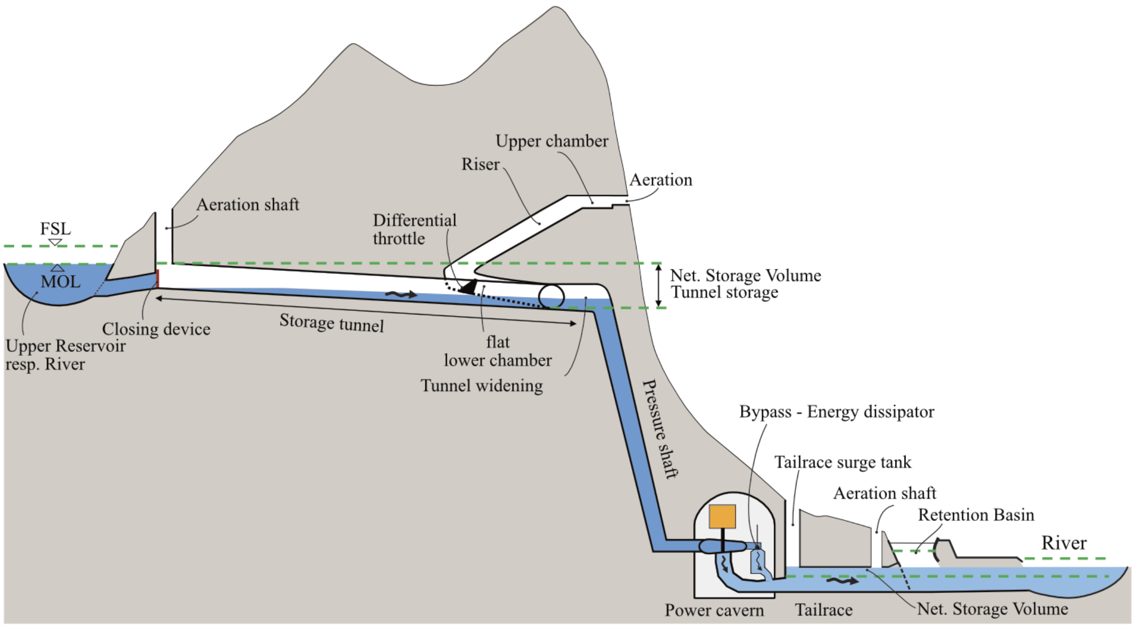


Fig. 1: Schematic longitudinal section of a diversion power plant with tunnel storage and differential storage surge tank, bypass with energy converter, optimized compensation basin, and optimized surge tank concept. (Richter et. al, 2022 modified).

## 3 HYDRAULIC REQUIREMENTS

### 3.1 *General requirements*

Due to its operation as a storage tunnel, the hydraulic flow behavior of the tunnel changes from pure pressure flow to a free surface flow and vice versa. Thus, the requirements for the design and dimensioning of the tunnel and the surge tank are crucial. The head race tunnel must therefore be designed to ensure safe flow between pressurized flow and free surface flow. These boundary conditions, as well as the necessary venting before the intake structure, influence the design of the surge tank and the necessary inclination of the pressure tunnel. Venting in the tunnel prevents air blowouts when the power plant is unloading and the surge tank is upsurging. An ideal, possibly low inclination of the storage tunnel can be determined specifically for each system. A gentle inclination enables high heads even with partial filling, therefor the inclination can be in the range of 0.1% to 0.2% (Design and operation of the Stanzertal hydro power plant headrace tunnel as reservoir, 2015). However, even lower inclinations in the range of the energy line gradient can also be effective.

### 3.2 *Requirements for the surge tank*

A surge tank for hydraulic separation between pressure surge and mass oscillation of the penstock is necessary in hydropower plants featuring tunnel systems of a certain length to ensure the controllability of the turbines (Thoma, 1910). To prevent the surge tank from showing a resonance event due to independent control processes, it must have a sufficiently large horizontal cross-section that interacts with volume changes caused by switching operations with head changes affecting the power output. Particularly for large flow rates and lower heads, the stability criterion for the surge tank shaft may require large horizontal cross-section areas. This criterion is usually calculated according to Thoma or Svee (Thoma, 1910 and Jaeger C., 1949) or (Svee, 1972 and Leknes, 2016). A flat surge tank tunnel with surge tank chambers arranged at an angle in the head height range of the power plant has very large cross-sections, which thus meet the stability criterion for adequate controllability and also store water. Since the frictional losses in the pressure shaft, which have an adverse effect on stability, are not considered in Thoma's criterion, a safety factor must be multiplied by it. Values of 1.5 [-] to 1.8 [-] are proposed (Jaeger, 1958). More precise calculations of the required cross-section can be carried out using calculation formulas from Svee, 1972 or Leknes, 2016, or with 1D numerical stability calculations. Short pressure shafts and operating ranges in which the efficiency gradient of the turbines increases (before the optimal efficiency value) have a favorable effect on stability. A decreasing efficiency gradient of the turbines (after the peak load value) has an unfavorable effect on the required stability cross-section. Thus, for diversion power plants with low or medium head heights, the safety factor of 1.5 [-] for the stability cross-section typically used can be reduced, or best being calculated in terms of 1D numerical simulations.

The surge tank also reduces the pressure surge load on the pressure tunnel and allows for quick start-up and shutdown of the hydraulic machines, with the inertia of the water masses in the tunnel enabled by the water volume in the surge tank. The water in the pressure tunnel is accelerated by the water level and thus pressure difference between the surge tank and the reservoir. It must ensure both start-up without the water column separation and shutdown without the surge tank overflowing. For the start-up operation, a different condition arises for tunnel storage surge tanks compared to the usual high-pressure systems. For storage tunnel operation the tunnel may have a free surface flow. However, the water column must not separate creating macro cavitation, prevented by the lower chamber design on low head level in connection to the tunnel. It is important that the pressure tunnel cross-section is widened before the transition to the pressure shaft in order to compensate for the varying flow velocities without causing the flow to break.

The specific representation of a possible tunnel storage surge chamber from a 3D CFD simulation in the emptying state (Fig. 2) shows a low-lying lower chamber with a free water level that is able to drop into the tunnel without flow separation during the downsurge. Due to the low tunnel inclination and the surge tank, any intermediate switching operations are also enabled.

In the event of shutdown or emergency shutdown, the differential surge tank arrangement allows the kinetic energy in the gallery and surge tank to be damped by the upsurge via the overflow weir and the differential throttle. The overflow height thus defines the pressure maximum for the mass oscillation at the surge tank base. A differential chamber is provided directly after the lower chamber separated by the differential throttle. The two chambers are provided as inclined tunnels, the latter being designed on the required volume from the mass oscillation and the stability criterion. From a construction point of view, both chambers can thus be excavated up from the same access. The deep differential chamber significantly reduces the dynamics of water flowing back from the surge tank to the basin in case of shutdown. The throttle is necessary to efficiently dampen the mass oscillation and separate water from the lower chamber as much as possible in case of a shutdown. The throttle must be sized to an optimum diameter, leaving enough air in the upper chamber to retain volume in the event of shutdown. Several constructive design variations of a surge tank surge chamber are conceivable.

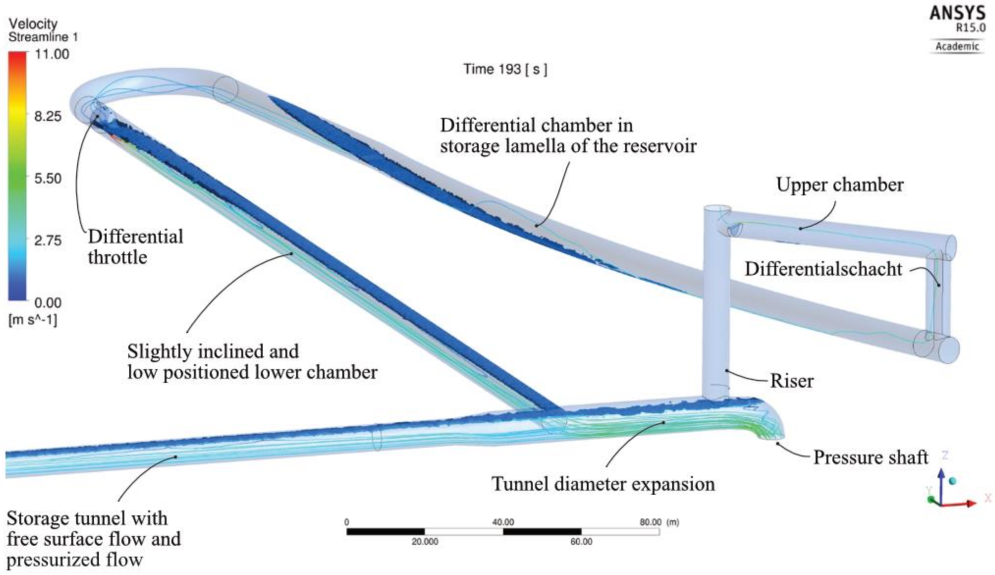


Fig. 2: 3D view, surge shaft surge chamber, emptying process, expansion of the surge shaft before the transition to the pressure shaft, effect of the differential throttle (Richter et. al, 2022 modified).

Since a vertical surge shaft is unthrottled, and connected directly at the transition to the pressure shaft, the design enables ideal pressure pulse reflection. The shaft has very low inertia values and thus can physically respond quickly to pressure surges. This design can also be omitted if it is demonstrated that the pressure surge can be sufficiently mitigated by the inclined gallery and ventilation of the lower chamber is assured. Figure 3 shows a horizontal differential throttle with a lower loss coefficient in outflow direction compared to filling direction defining a differential throttle.

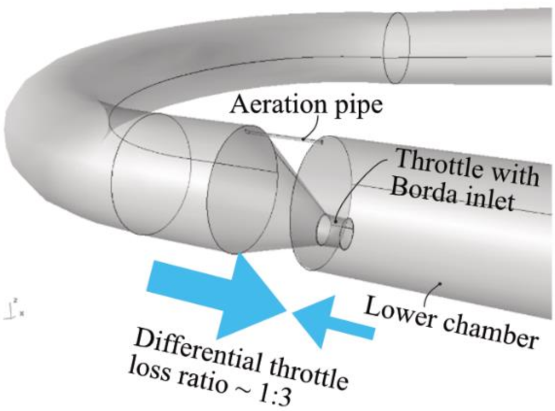


Fig. 3: 3D view, horizontal differential throttle with aeration pipe (Richter et. al, 2022 modified).

### 3.3 *1D numerical simulation*

The hydraulics of pressure tunnel systems are being investigated efficiently in a goal-oriented approach by means of 1D numerical simulations. The transient processes such as mass oscillation and pressure surge events are calculated for the headrace waterways and in particular the surge tank, that are designed for most unfavorable transient operations. In order to model the free surface flow in the pressure tunnel appropriately, adequate 1D numerical simulations are demanded. Based on a Master's thesis at the Institute of Hydraulic Engineering and Water Resources Management at the Graz University of Technology, the hydraulics of a tunnel reservoir of a medium-sized hydropower plant were studied. The 1D numerical simulation software Wanda V4.2 was evaluated for these problems (Wechtitsch, 2014).

In the hydraulic engineering laboratory of the Graz University of Technology, hybrid model tests (numerical and physical) were used to calibrate the 1D numerical simulations using large surge chamber models (Richter, et al., 2013). Flow transitions from pressurized flows to free surface flow occur in surge tanks, especially in the lower chambers. The experience of the hydraulic behavior of the lower chambers will be applied to both the hydraulics of the pressure tunnel and the design of storage tunnel surge tanks.

### 3.4 *Case study for storage tunnel featuring a storage surge tank*

1D simulations are carried out on the basis of a case study. Load cases for start-up and shut-down as well as stability simulations are performed. Penstocks usually have large flow cross sections and high Reynolds numbers. For back-calculations of existing flow losses in headrace tunnels, Strickler coefficients are usually determined in Austria. For transient 1D numerical calculations these roughness values are converted into equivalent sand roughness. The Strickler coefficient of smooth concrete pressure tunnels was converted from measurements of the pressure tunnel of the Lünerseewerk PSH from $D_i$ 3.05 m, $K_{ST}$ = 85 $m^{1/3}/s$ to $K_S$ = 0.276 mm (Buchegger, 1961). Due to the neglection of the Reynolds number in the Strickler approach, the Strickler coefficient decreases for the same roughness for larger pressure tunnel cross-sections.

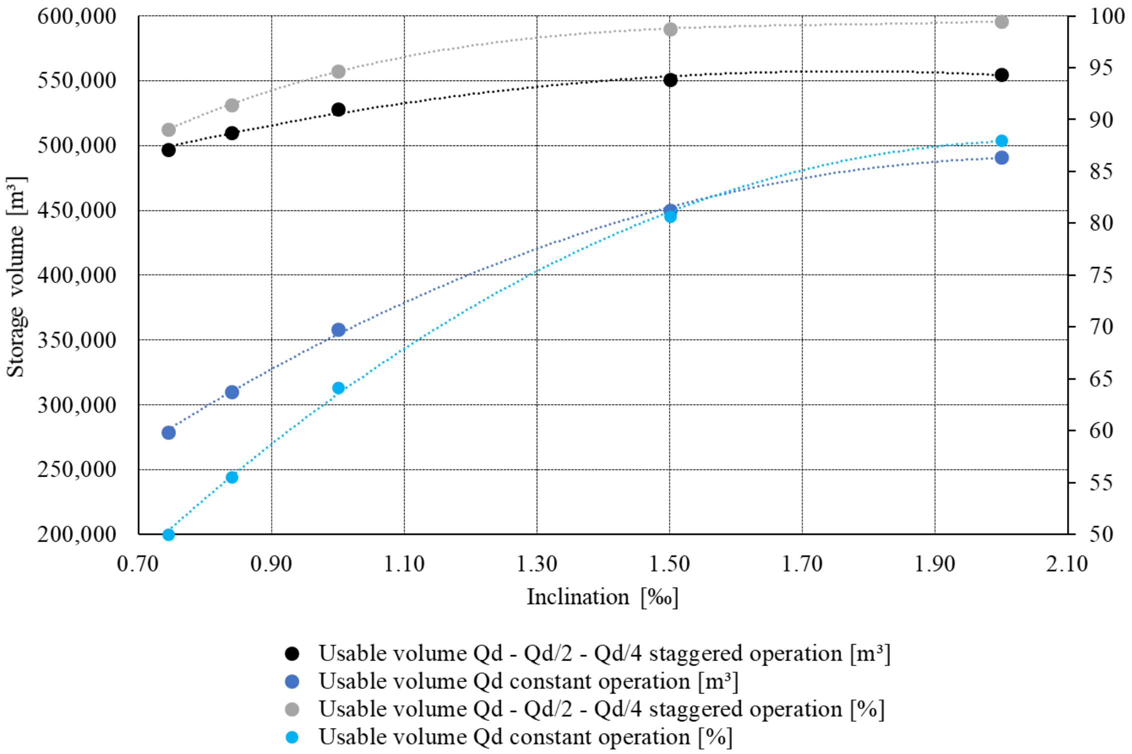


Fig. 4: Drainage of storage galleries, useful volume and useful fraction, case study, (Richter et. al, 2022 modified).

The power plant dimensions for the case study are defined as follows:

- Gross head: 64 m
- Expansion water flow: 130 m³/s
- Storage gallery length: 13 700 m, D = 7.2 m, $K_{ST}$ = 80 $m^{1/3}/s$
- Gross gallery volume: 557 800 m³
- Expansion capacity: 66 MW
- Pressure shaft: L = 80 m, D = 6 m, KST = 110 $m^{1/3}/s$

Due to the low head and the relatively high discharge in the pressure tunnel, the required stability cross-section for the surge chamber is 888 m² with a safety factor of 1.5 [-].

Fig. 4 shows the evaluation for the usable volume of the case study as a function of slope. A distinction is made between emptying at design water discharge (Qd) and staggered emptying discharge $Q_d – Q_{d/2} – Q_{d/4}$. In the case of emptying with $Q_d$, the water column separates at a point, whereby emptying degrees of 50% - 65% are achieved. With staggered emptying between 90% - almost 100% can be achieved depending on the inclination. The friction slope for pressure discharge is 0.74 ‰, which can be a minimum design slope specification.

Thus, depending on the plant, it is possible to reserve both a part of the storage tunnel for flexible power plant operation and a partly for hydropeaking compensation.

### 3.5 *Design criteria for storage tunnel surge tanks*

For the hydraulic dimensioning of storage tunnel surge tanks, the following parts are to be designed by means of transient simulations:

- Lower chamber for the most unfavorable opening load case, or a resonance load case in storage tunnel operation, to avoid separation of the water column.
- Upper chamber, or inclined shaft to the most unfavorable shutdown load case, in connection with the throttle dimensioning to avoid overflow.
- The horizontal water surface area in the surge chamber is designed for the stability criterion in a 1D numerical stability analysis.

Due to the low inclination, storage tunnels have low internal pressures, especially in diversion power plants. When a storage tunnel surge tank with differential effect is arranged, higher pressures are generated only briefly. Therefore, for specific pressure tunnel situations and with good geological conditions, an unlined pressure tunnel can offer hydraulic stability and enough volume as well as design and economic advantages. The throttle generates a differential effect. Since the lower chamber overlaps in height with the pressure tunnel, startup events can be permitted until a free level discharge is reached in the pressure tunnel if the design is appropriate. In particular, a low positioned lower chamber also allows increased flexibility in operation with free surface flow discharge with respect to cyclic power plant operations. 3D numerical flow simulations and/or physical model tests are recommended to investigate a concrete design hydraulically with respect to transient effects of filling and emptying, as well as the behavior of the air. In addition, 1D numerical stability simulations allow an economic design of the surge tank cross-sections.

## 4 DISCUSSION

Power plant constructions in times of climate crisis, resource efficiency and energy generation in particular are reconsidered in comparison with the energy input for construction and operation. Since low inclined pressure tunnels, which are designed as storage tunnels, are also exposed to a low maximum internal pressure, the tunnel lining can be optimized due to geotechnical requirements. Thus, in load-bearing rock, unlined pressure tunnels can also be designed in a targeted manner, taking the criterion of internal pressure versus mountain water table into account. For the hydraulic design of diversion power plants with a defined inflow level, it may also be advisable to design the headrace tunnel for free surface flow operation as normal operation mode.

## 5 SUMMARY

Diversion power plants with headrace tunnels can offer both economic and ecological advantages in terms of hydropeaking compensation by increasing flexibility and enabling reservoir management if the hydraulic design is optimized as storage tunnels with differential surge tanks.

A storage tunnel surge tank consisting primarily of a shallow lower chamber with a necessary volume also allows for flexible hydraulic use of the tunnel volume. 1D numerical calculations show that a well-designed surge tanks can perform this function. This allows the free surface flow discharge in the tunnel to be independent of the cyclic load operations. In addition, the use of energy dissipators can decouple the power control of the machines and the hydraulic flow downstream. This allows upstream tunnel volume to be used for hydropeaking compensation as well. Simulations show that with staggered discharge and an optimized tunnel inclination up to nearly 100% of the tunnel storage volume can be utilized. However, current research on dissipators in control operation is necessary in order to safely manage the durability on the one hand and the flexible control capability of the overall system on the other hand. In addition, dissipators can achieve a reduction of the pressure surge load if designed appropriately. Specific investigations by means of 3D-numerical hydraulic simulations as well as physical model tests allow the most economical and structural safe and appropriate design of storage tunnel systems and surge tanks.

## 6 REFERENCES


Buchegger, W. 1961. *Fallhöhenverluste in der Wasserführung des Lünerseewerkes.* Jahrgang 51, Heft 5/6, Seiten 136 - 142: Österreichische Wasserwirtschaft.

Deltares. 2013. *Wanda 4.2, User Manual.* Delft.

*Die Oberstufe des Tauernkraftwerkes Glockner-Kaprun.* 1955. Zell am See: Tauernkraftwerke A.G.

Jaeger, C. 1949. *Technische Hydraulik.* Basel: Birkhäuser.

Jaeger, C. 1958. Contribution to the Stability Theory of Systems of Surge Tanks.

Leknes, E. 2016. *Comparison of the Svee and Thoma Stability Criteria for Mass Oscillations in Surge Tanks.* Masterthesis, NTNU Trondheim.

Müller, M., Kaderli, R., Keller, Y., Gehri, M., & Kost, M. 2016. Ausgleichs und Regulierbecken Innertkirchen Planung, Realisierung und Inbetriebnahme des ersten Beckens zur Reduktion von Schwall und Sunk in der Schweiz. *Konferenzbeitrag, 18. Waserbau - Symposium, Technische Universität München*, Obernach.

Richter, W. 2020. *Surge Tank Design for Flexible Hydropower.* Dissertation: Graz University of Technology.

Richter, W., Schneider, J., Zenz, G., & Innerhofer, G. 2013. *Hybrid Modelling and Development of a long Upper Chamber in a Surge Tank.* Proceedings of Hydro Congress, Innsbruck.

Richter, W., Schneider, J., Zenz, G., & Kolb, S. 2012. Hybrid Modelling of a Large Surge Tank. *Proceedings of 17th International Seminar on Hydropower Plants, Vienna*.

Richter, W., Zenz, G. Stollenspeicher für Ausleitungskraftwerke. *Österr Wasser- und Abfallw* 74, 383–388 2022. https://doi.org/10.1007/s00506-022-00879-0

Svee, R. 1972. *Fordelingsbasseng ved vannkraftverk; Formler til bestemmelse av svingegrenser og kritiske tverrsnitt, Surge tanks for hydropower plants – Equations for deciding the surge limits and critical areas Bericht - Norwegisch.* Trondheim.

Thoma, D. 1910. *Theorie des Wasserschlosses bei selbsttätig geregelten Turbinenanlagen.* Dissertation, Kgl. Technische Hochschule zu München: R. Oldenbourg.

Wechtitsch, R. 2014. *Modellierung von Stollenspeicher.* Masterarbeit, Institut für Wasserbau und Wasserwirtschaft, TU Graz.

Widmann, W., Lebesmühlbacher, T., Eder, A., & Knorpp, K. 2015. Design and operation of the Stanzertal hydro power plant headrace tunnel as reservoir. *Hydro Congress.* Bordeaux.