SOLUTIONS FOR UPGRADING THE HYDRAULIC SYSTEM OF TONSTAD HPP

W. Richter, K. Vereide and G. Zenz

Abstract: The pressurized tunnel system of the 960 MW Tonstad hydropower plant (HPP) is a characteristic example of the Norwegian design philosophy. The use of a pressurized sand trap in the downstream end of the tunnel system allows the use of unlined tunneling in the long upstream headrace tunnel. The sand trap is constructed together with the surge tank equipped with a gate in the main riser. Investigations of upgrading of the installed capacity have been made for the power plant. The surge tank and the pressurized sand trap are identified as limitations for the upgrade. This paper describes the purpose and design of the surge tank and sand trap, and potential solutions to allow the power plant upgrade. These solutions include retrofitting of the surge tank and the sand trap, a digital twin protection system, and expansion of the tunnel cross section with a new tunnel in parallel.

1 Introduction

The 960 MW Tonstad hydropower plant (HPP) is considered for upgrading of the installed capacity. The transformers are due for renewal, and this has triggered investigations of potential increase of the installed capacity of the existing units in the power plant. More specifically, it is considered to increase the installed capacity of the four existing 160 MW units to 190 MW. In addition, the largest unit of 320 MW unit has already been prepared to allow 340 MW. If all the upgrading is realized, it will raise the installed capacity from 960 MW to 1100 MW. However, this upgrade requires that the existing power waterway including surge tanks and sand traps can allow worst-case operation without danger of damaging incidents as reported previously [1]. The main limitation is the long waterway comprising over 30 km of tunnels, two intake reservoirs, and eight secondary brook intakes. The power plant is equipped with three pressure shafts, three sand traps, and three surge tanks (Fig. 1) that also function as gate shafts equipped with sliding gates. The limitations first encountered in the combined surge tank and pressurized sand trap in the downstream end of the headrace tunnel system. Upgrading of the installed capacity, without measures in the waterway, can cause low water pressure and free surface flow through the normally pressurized sand trap, effectively flushing the trapped sand and gravel down into the turbines. Several solutions considered to allow the power plant upgrade are presented in this paper such as; (i) possible upgrading of the existing surge tanks and sand traps including results from physical model tests, (ii) the functionality of a waterway protection system based on a digital twin, and (iii) possible pressure tunnel upgrade with an additional tunnel.

1.1 Hydraulic system of Tonstad HPP

The Tonstad HPP is shown in Fig. 1. It is an unlined pressure tunnel system in addition to two main intakes that are in continuation of upstream hydropower plant schemes on the river Sira and the river Kvina. Both rivers contain several upstream reservoirs and HPPs. The main upper reservoirs Ousdal (Sira river) and Homstøl (Kvina river) are designed with the same maximum reservoir capacity level of 497 m a.s.l, but have different (i) storage volume, (ii) length of the unlined pressure tunnel before the junction and thus different head loss, (iii) different inflow magnitude and variability, as well as (iv) different discharge from upstream hydropower plants. One of the main factor determining the behaviour of this complex hydraulic system, is the hydraulic resistances of the various tunnels. This determines how much water is taken from each reservoir depending on the respective water levels, and finally if the resulting pressure in the pressurized sand traps is sufficient to avoid free surface flow. Fig. 1 depicts the original sand trap's layout as well as the ramp and ribs that are suggested for retrofitting [2]. The power plant was constructed with drill and blast method and the utilisation of the crushed rocks as layer for the construction road inside the tunnel during excavation. These sediments and the influx of sediments from the intakes are excluded before the steel lined section of the penstocks after the surge tanks. The surge tank riser is equipped with a sliding gate that can be closed to allow access to the sand traps for emptying of the trapped material.

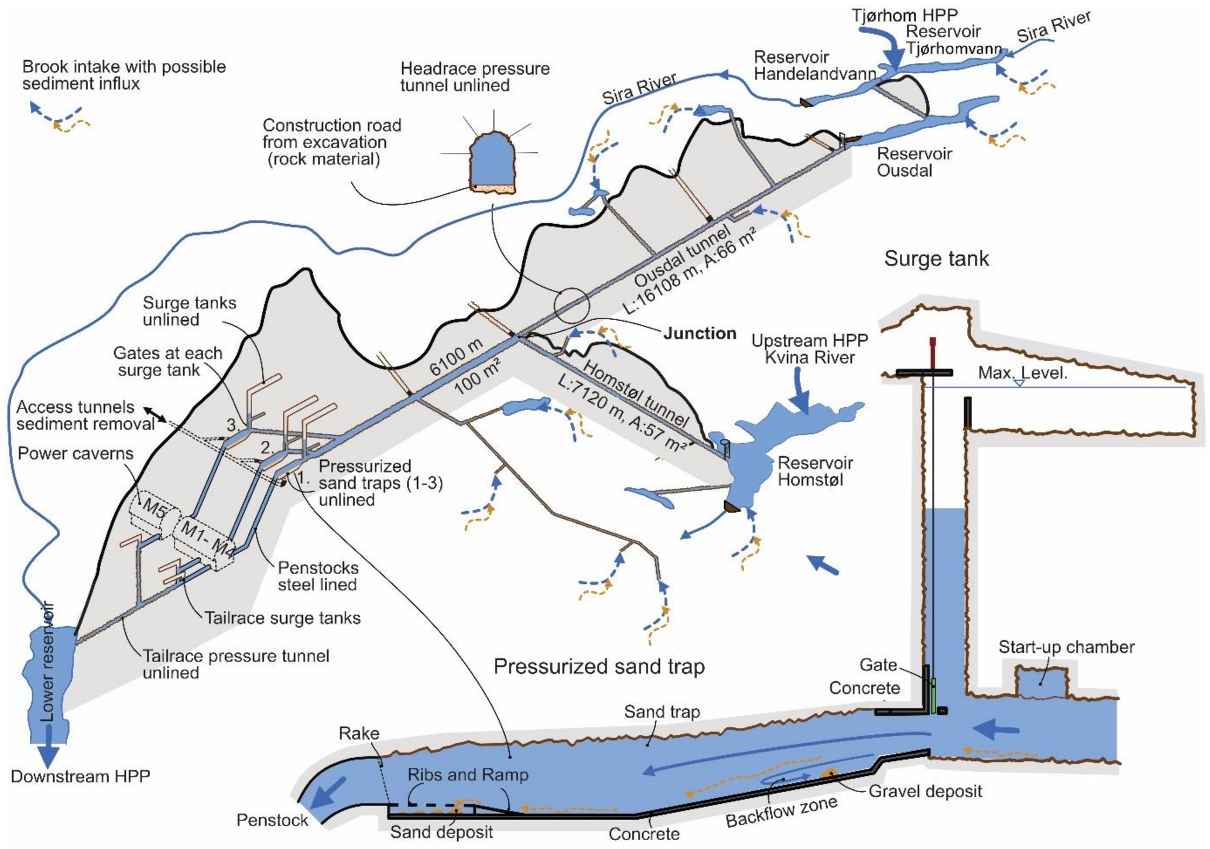

Fig. 1: Tonstad Hydropower scheme - characteristic Norwegian layout, surge tank with pressurized sand trap and proposed upgrade with ribs and ramp design.

Table 1 describes the simplified hydraulic properties of the unlined headrace tunnels as given by the construction drawings, and the averagely assumed Darcy friction loss factor of f = 0.06 [-]. The water inflow in the brook intakes is neglected to consider the worst-case situation highlighting the problem. The head losses in the system is calculated for the design discharge of 240 m³/s, it shows that 44% discharge comes from the Ousdal reservoir and 56% water flow from the Homstøl reservoir.

The lower capacity of the Ousdal tunnel is unbeneficial since this reservoir also has the highest annual inflow. This means that in times of high inflow the reservoir level in Homstøl needs to be lowered, or the gates in Homstøl have to be closed, to drain more water from Ousdal. However, these measures lead to sub-optimized operation with high head loss. The high head loss may again result in free surface flow through the pressurized sand trap.

Table 1: Hydraulic properties of unlined headrace tunnels at design discharge and without inflow into the brook intakes

	A	L	Q	Q	Friction factor	Headloss
Connection	m²	m	m³/s	%	f	m
Ousdal - Junction	66	16,100	107	44	0.06	14
Homstøl - Junction	57	7,100	133	56	0.06	14
Junction - Surge Tank	100	6,100	**240**	100	0.06	10
Sum		**29,300**				**37**

The key hydraulic structure considered in this paper is the combined surge tank and pressurized sand trap. Because of the construction of the surge tank and sand trap, immediately next to each other, they influence each other, and the design is more complex compared to a separate construction. The combined structure provides; (i) water hammer mitigation, (ii) mass oscillation mitigation, (iii) hydraulic stability, (iv) reduced acceleration and (v) deceleration time for flexible power plant operation, (vi) the emergency closing function with gates inside the main surge tank riser as well as (vii) protection against sand, gravel and other debris from entering the pressure shaft (Fig. 2).

The order of these structures from upstream to downstream is important. The sand traps need to be located downstream the surge tanks, to avoid two-way flow and large velocities through the sand trap owing to the mass oscillations. If located downstream the surge tank, the flow is always one-directional and will never be higher than the maximum turbine flow. In addition, if the surge tanks including the gates are placed upstream, the emergency gates can also be used for maintenance purposes of the sand trap and the pressure shaft. This is particularly useful for the Tonstad HPP as the sand traps are cleaned each year, and to avoid having to dewater the entire headrace tunnel system that is more than 30 km long and takes two weeks to dewater. A challenge of this construction is that the transient flow in the surge tank influences the inflow into the sand traps. In addition, the cross section at the entrance of the sand trap has a contraction to limit the necessary size of the gates. This yields larger flow velocities with disturbances from the upstream transients into the sand trap, resulting in reduced trap efficiency.

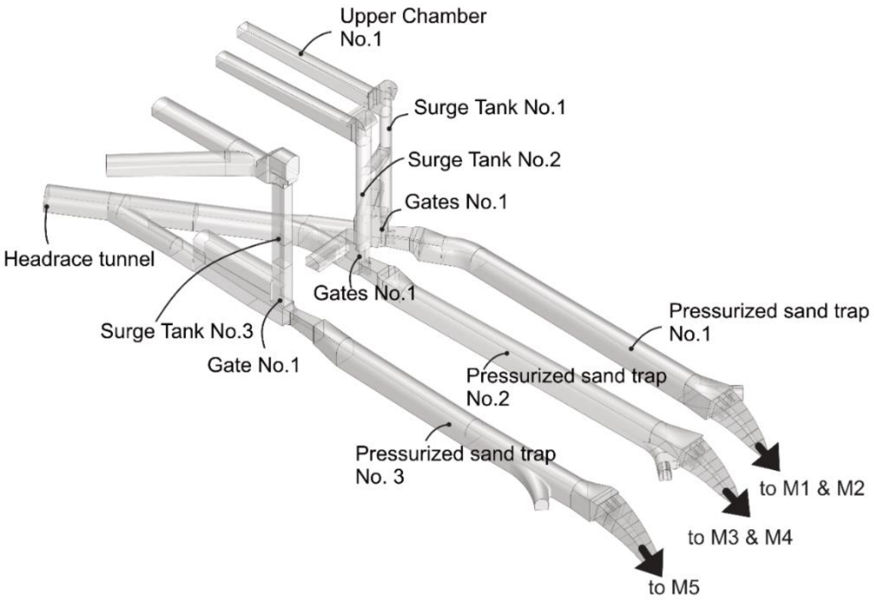

Fig. 2: Tonstad surge tank and pressurized sand trap system

Moreover, for large transients, the water level in the surge tank may become so low that air intrusion and free surface flow may occur in the downstream sand trap. Such cases have occurred with resulting flushing of the sediments trapped in the sand trap down into the pressure shaft and the turbines. Necessary measures and operation restrictions have later been introduced to mitigate such incidents. The transition from the concreted part of the gate section at the surge tank towards downstream into the unlined section of pressurized sand trap is shown in Fig. 3. The unlined sand trap with the concrete bottom is shown in Fig. 4, with the upstream view direction towards the gate section after the manual removal of trapped sediments.

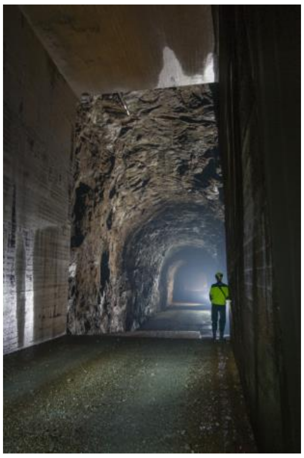

Fig. 3 Concrete gate section, view downstream

Fig. 4 Unlined pressurized sand trap, view direction upstream

2 Possible hydraulic upgrade solutions

2.1 Hydraulic system upgrade

A minimum water level in the surge tanks for steady state operation is now required for safe operation avoiding free surface flow in the sand traps. This water level is significantly above the pressure tunnel crown level. With geometrical and hydraulic improvement of the surge tank a significant discharge upgrade for the existing tunnel system is reasonable. An upgrade of about 25% discharge leading to about 20% power upgrade seems possible [3] [4]. Due to higher friction losses a lower water level in the surge tanks and sand traps has to be acceptable. This includes specifically during start-up and also for steady operation at maximum discharge. To allow this, an enlargement of the lower chamber of the surge tanks is necessary. In addition to the expansion of the lower chamber in the surge tanks, an operational restriction is necessary. When operating at maximum power, the gates in both Homstøl and Ousdal has to be open, to drain water from both reservoirs. If some gates are closed, and water is only drained from one reservoir, the head loss will again be too high and result in free surface flow in the sand traps. This leads to further aspects of hydraulic power water way upgrades.

2.2 Sand trap upgrade

Additional discharge and increased flexibility of the power plant increases also the transport of sediments in the power water way with the demand of safe exclusion and the safe trapping of gravel grains, which has been investigated in physical model test at Graz University of Technology with the geometric scale of 1:36.67, resulting in a proposal for retrofitting. The physical model test was planned upon previous investigations via 3D CFD simulations of the sediment settling behaviour and flow patterns [2], [5], [6]. The model setup in the flume with a 30 cm width is shown in Fig. 5.

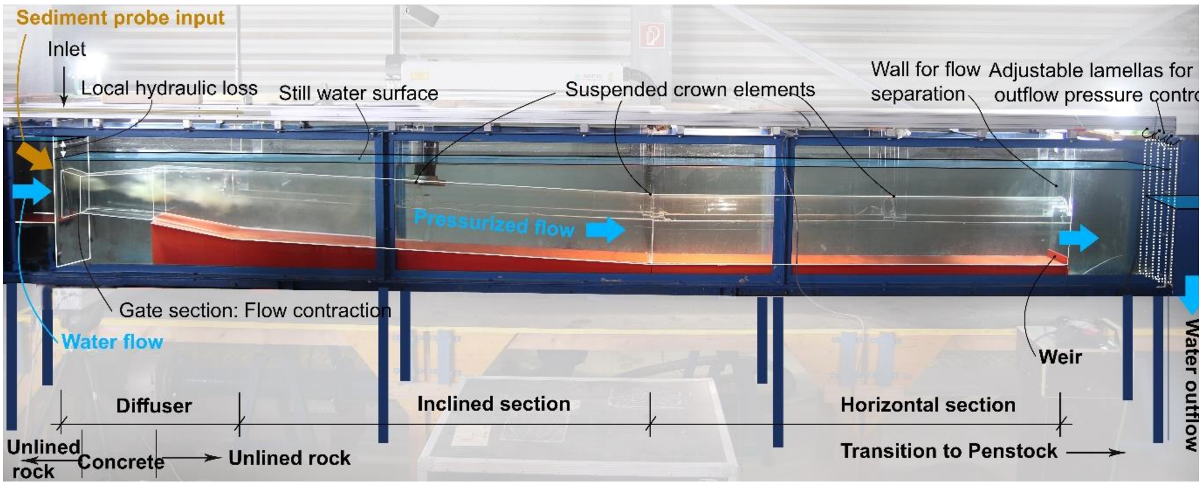

Fig. 5 The physical scale model test with 1:36.67 geometrical scale and 1:1 velocity and sediment scaling in the 30 cm wide flume of the hydraulic laboratory ([2], modified)

The geometry of the model test was defined with the ideal dimensions of the scaled construction drawings without tunnel roughness. However, this approach focuses on the hydraulic turbulences introduced by the gate section. The scaling of the physical test was determined for 1:1 velocity, keeping also the sediment size to 1:1 as prototype size [2]. The sand is introduced into the model's inlet by a probe, where it is then moved in suspended flow. 0.5 l cups of sand with grain sizes ranging from 0.3 to 1.0 mm were used to add sand to the system as defined volume unit at various time rates of influx. Fig. 6 shows the sediments in the pressurized sand trap no. 3 directly in front of the rake to the pressure shaft. This figure and also inspection results indicate that sand particles are being flushed through the turbine. Fig. 7 depicts the representation of the similar situation with sand in the physical model test at the downstream end of the sand trap, visualizing the flushing of sand over the weir. The sand is accumulated as a dune, vortex flows that transiently appear create a high capability of lifting sand particles over the weir.

Fig. 6 Prototype sand accumulation before rake to pressure shaft ([2])

Fig. 7 Model test sand accumulation respectively to the prototype, visualizing of the vortex flow lifting sand particles ([2], modified)

To allow the settling of sand particles on the bottom of the sand trap without blasting the bottom, a structure was developed consisting of a slightly inclined ramp and ribs with the prototype dimensions of 1 m width and 1 m gap. The rib dimensions have been implemented in other sand traps in Norway [7]. Fig. 8 depicts the geometry that lead to safe trapping of sand particles. Further hydraulic investigations of the flow around the ribs have been contributed at NTNU, Trondheim [8].

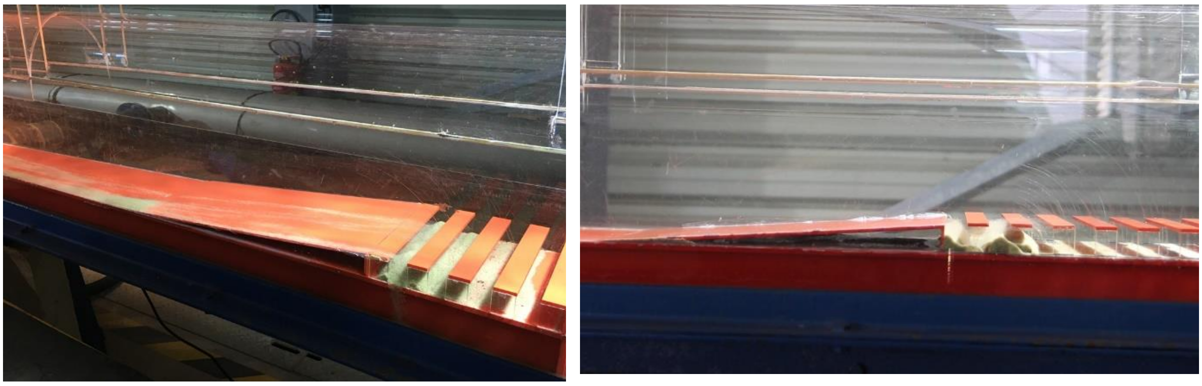

Fig. 8: Ramp and ribs solution for safely trapping of sediments as retrofitting proposal. Physical model test with 1:1 sediment and 1:1 velocity scaling ribs and ramp solution at weir ([2])

2.3 Digital twin

Tonstad HPP is currently controlled by a digital twin, referred to as the supreme governor. This digital twin was developed to safeguard the pressure in the waterway and reduce the inaccuracy between power setpoint and actual produced power from the five units [9].

The digital twin was installed in 2012 when Tonstad HPP started delivering frequency restoration reserves (FRR) to the transmission system operator (TSO). The FRR was controlled remotely and directly by the TSO with up to 100 MW power changes. Since these power changes could encounter at any time and without notice, it was determined that additional safety measures were necessary.

The functionality of the digital twin is shortly explained in the following. The digital twin consists of a 1D numerical model of the power plant, with focus on the power waterway and the turbine units. When a new setpoint for one of the units is given by the power plant operator or remotely by the TSO, the effect of the setpoint is firstly simulated by the digital twin, to determine if it is safe or not. If the setpoint is harmless, it is allowed to pass to the unit. If the setpoint is considered harmful, the setpoint is divided into smaller setpoints that are distributed over a longer time, so that the resulting hydraulic transients are acceptable. Furthermore, since the produced power from the five units in Tonstad is dependent on the total head loss in the system, the digital twin calculates the new head loss situation, and makes an adjustment to the setpoint so that the actual produced power is closer to the setpoint given [10].

The digital twin also calculates, based on the current reservoir levels and brook intake inflow, the maximum possible power that can be produced from the power plant, without risk of free surface flow in the brook intake. This information is used by the power plant operators and the production planners to make real-time decisions on the operation control.

In conclusion, the digital twin allows safe operation of the power plant. However, this is based on restricting the power plant operation. If a new increase of the installed capacity is realized, these operational restrictions will become even more severe. Hence, an upgrade of the power water way is necessary to fully utilize the full operational range and maximum power in the case of an upgrade.

2.4 Upgrade of the power water way

Due to the imbalance of the power water way, an additional tunnel from Ousdal to the Junction (Fig. 1) can significantly improve the situation by lowering the hydraulic loss. A new tunnel can be excavated by a hard rock gripper TBM creating relatively smooth unlined rock walls. A friction factor of f:0.03 [-] is assumed [11]. Table 2 shows the improved friction losses by balancing the main tunnel losses with an additional tunnel with 17 m^2 of flow section by unlined TBM bored construction. This provides equal discharge from both reservoirs, improving substantially the capacity from Ousdal and reducing the total head loss of about 5 m at design discharge.

Table 2: Hydraulic properties of unlined headrace tunnels with additional tunnel as upgrade in balance of friction losses

	A	L	Q	Q	Friction factor	Headloss
Tunnel	m²	m	m³/s	%	f	m
Ousdal - Junction	66	16,100	96	40	0.06	**11**
Additional Tunnel Ousdal - Junction	17	16,100	25	10	0.03	**11**
			120	**50**		
Homstøl - Junction	57	7,100	120	**50**	0.06	**11**
Junction - Surge Tank	100	6,100	**240**	100	0.06	10
Sum		**29,300**				**32**

Table 3 shows a further improved proposal of an enlarge unlined TBM tunnel of 22 m² flow section from Ousdal to the junction allowing 25% higher discharge with 5 m higher head loss, but significant capacity increase.

Table 3: Hydraulic properties of unlined headrace tunnels with additional tunnel as an improved upgrade with 25% additional design discharge

	A	L	Q	Q	Friction factor	Headloss
Tunnel	m²	m	m³/s	%	f	m
Ousdal - Junction	66	16,100	105	44	0.06	**14**
Additional Tunnel Ousdal - Junction	33	16,100	64	26	0.03	**14**
			169	**70**		
Homstøl - Junction	57	7,100	132	**55**	0.06	**14**
Junction - Surge Tank	100	6,100	**300**	125	0.06	15
Sum		**29,300**				**42**

A main advantage of excavating TBM tunnels is the direct and effective energy investment of electrical power into power infrastructure.

2.5 Surge tank upgrade

Additional discharge upgrade is possible for the existing headrace tunnels if an upgrade of the surge tanks is realized. An upgrade demands mainly larger volumes for the lower chamber to allow the flow acceleration and avoiding free surface flow at the surge tank base and possible sediment movement. Since all three surge tank shafts are hydraulically connected a single large chamber can achieve the demands. Therefore, a new development; a semi-air cushion surge tank has been proposed [12]. The semi-air cushion design allows an optimized use of excavation volume by introducing a temporary air cushion that is created by delayed outflow of the pressurized air.

3 Conclusions

Unlined high head hydropower systems play a major role in the power production of Norway. The increased flexibility demand can efficiently be met by upgrading hydraulic water ways as investigated for the case of Tonstad HPP. Surge tank upgrades with increased chamber volume can lead to upgrade of the entire power water way system. Pressurized sand traps, as utilized in unlined hydro tunnel systems were found to be retrofitted with ramp and ribs structure to safely trap sediments in existing geometries. Additional tunnels can provide high capacity upgrade and also improve existing hydraulic capacity imbalance between the two main tunnels in the headrace system with significant power upgrade potential.

4 References

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Authors

Dr.techn. Wolfgang RICHTER
Graz University of Technology
Institute of Hydraulic Engineering and Water Resources Management
Stremayrgasse 10/II, 8010 Graz, AUSTRIA
Phone: +43 316 873 8352
Email: wolfgang.richter@tugraz.at

Adj. Ass. Prof. Kaspar VEREIDE
Sira-Kvina kraftselskap/NTNU
Vassbygget, 322, Valgrinda, S. P. Andersens veg 5, NORWAY
Phone: +4792698109
E-mail: kaspar.vereide@ntnu.no

Univ.-Prof. Dipl.-Ing. Dr.techn. Gerald ZENZ,
Graz University of Technology
Institute of Hydraulic Engineering and Water Resources Management
Stremayrgasse 10/II, A-8020 Graz, AUSTRIA
Phone: +43-316-873-8360
E-mail: gerald.zenz@tugraz.at

Wolfgang Richter is a project senior scientist and hydraulic researcher at TU Graz working on flexible surge tank design for hydropower plants and pumped storage schemes. His main field of research is physical and numerical modelling of surge tanks and transient flow in hydropower systems.

Kaspar Vereide is an Adjunct Associate Professor at NTNU and a Project Developer at Sira-Kvina kraftselskap. At NTNU, Vereide works as a with hydraulic design and hydraulic transients in hydropower plants. At Sira-Kvina power company he works with upgrading of existing hydropower plants and design of new hydropower plants

Gerald Zenz graduated in Civil Engineering from the University of Innsbruck, Austria. His doctoral dissertation dealt with wave propagation caused by blasting. Since the late 1980s he worked as a project engineer, project manager and finally as Business Unit Manager for Hydropower Plants, Dams and Civil Engineering. Since 2007 he is Professor and head of the Institute of Hydraulic Engineering and Water Resources Management at Graz University of Technology.