Experimental studies on intake headloss of a blasted lake tap

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Abstract. In existing reservoirs, construction of an intake is sometimes achieved by so-called lake tapping, a submerged tunnel piercing by blasting out the rock plug at the intake. The blasting process involves phases of rock, water, air and gas released from the explosive charge; the resulting entrance profile often differs from design assumptions. The intake headloss is a factor of concern for power generation. For a vertical intake formed by lake tapping, experiments have been carried out in a 1:30 physical model to examine the effect of entrance shapes on intake headlosses. The purpose is that, if there is potential to reduce the headlosses, the originally blasted intake shape would be modified. In the model, five alternative shapes are evaluated. The test results show that to enlarge the vertical shaft area is the most effective way to reduce the intake headloss; to further blast out a narrow channel upstream does not give much effect. Bearing in mind the risk of free-surface vortex at the intake, the influence of the intake modifications on vortex is also checked.

1. Background
The Akkats power station, situated on the Lule River in North Sweden, was commissioned in 1973. It was originally equipped with one 150-MW generating unit (G1) operating at a 45 m gross head and a 385 m\textsuperscript{3}/s turbine flow. Due to a number of incidents and breakdown that led to unexpected long shutdown periods and limited power output, the single unit was replaced with two 75-MW units with higher turbine efficiency. One unit (G3) takes the place of G1; the new unit (G2) is placed to its left in the extended power plant. Figure 1 shows the layout of the power station after the refurbishment.

For construction of the new generating unit, a separate tunnel was built, running from the reservoir to the tailwater. It was performed while maintaining the normal reservoir water level and unit G1 was in normal operation. The tunnel was first excavated to below the reservoir bottom and only a protective plug of 6-m natural rock was left. Before its commissioning, the final rock plug was then blasted out at one time to allow water to suddenly flow into the tunnel from the lake. The way that the protective plug was removed is usually referred to as lake tapping [1]. The tunnel was pre-filled with water to mitigate the blasting impacts. A stone pit was prepared below the intake to trap the blasted rock materials and prevent them from entering into the tunnel [2].

Lake tapping is the submerged piercing of a tunnel at its intake. The reservoir is connected to the tunnel and the power station is put into operation without lowering the reservoir water level or building a cofferdam around the tap hole. The blasting process involves a mixture of rock of various...
sizes, water, air and gas produced from the explosive charges and is not well understood due to its complexity. Affected also by the prevailing hydraulic conditions, the resulting intake shape is highly irregular, which was also the case in Akkats.

![Figure 1](image)

**Figure 1.** Layout of Akkats hydropower station after refurbishment. (1) new intake, (2) plant extension with new unit G2, (3) tailrace tunnel, (4) new access road, (5) transport road, (6), (7) gate depository, (8) construction tunnel/surge gallery, (9) tailrace, (10) cofferdam.

The vertical intake shaft was designed to have a nominal area of 100 m². However, field control measurements showed that the lake tapping gave only 87.6 m². Corresponding to normal reservoir water stages, the water depth above the intake is approximately 9.5 m. At full loading, the turbine discharge of unit G2 amounts to \( Q_2 = 200 \text{ m}^3/\text{s} \). The cross-sectional area of the tunnel is 80.24 m².

In spring 2012, unit G2 was to be put into operation. During the commissioning, a large vortex occurred unexpectedly at the intake. Estimated 30–40 cm below the water surface, its diameter amounted to 4–5 m. With the help of empirical formulas for critical submergence, one could state that the intake water depth was, in relation to the intake diameter, not large enough to avoid vortex [4]. The vortex formation limited the power output of G2 and gave also rise to other consequences, including generation of swirling flow further into the tunnel and vibration in the unit. There was also a risk that the flow transported some of the blasted rock materials downstream in the tunnel.

Another major issue of concern was the head loss at the blasted intake. The occurrence of the vortex itself caused extra head loss; the irregular entrance geometry of the intake was probably also a contributing factor. Analysis of the plant operation data showed that, at the full turbine effect, the piezometric head loss between the reservoir and the turbine amounted to about 1 m. After examinations of the echo-sounded intake profile, it was considered possible to reduce the headloss by means of geometrical modifications.

2. Akktas hydraulic model

To work out solutions for suppression of the vortex formation and at the same time to reduce the head loss of the intake, a physical hydraulic model was built summer 2012, in which different countermeasures were evaluated for their suitability (figure 2). The model was constructed in a scale of 1:30 and was based on the Froude Law of gravity similarity. To correctly reproduce the
approaching flow and the vortex at intake G2, the reservoir area included was sufficiently large, 300 m long and covering the whole river width of about 300 m. The two-bay spillway and the intake to unit G3 were also built in. Figure 3 shows the longitudinal profile of intake G2 and its relation to the spillway and intake G3.

Figure 2. Akkats scale model (1:30) with a blasted intake to new generating unit G2.

Figure 3. Longitudinal profile of intake G2 and its location in relation to spillway and intake G3.

The final solution chosen for vortex mitigation was construction of a curtain wall on the downstream side of the intake, covering the whole water depth and stretching from the intake edge to the dam front. The wall, consisting of five separate steel sections anchored onto the reservoir bottom, suppressed effectively the rotation; only minor unsteady vortices were left above the intake. An opening was left between two neighbouring sections so as to reduce forces acting on each wall section. During January 2013, the implemented solution was tested under full loading and the result was in good agreement with the model tests.

Though no comparison measurement was made, the wall curtain eliminated a certain amount of the head loss. To make further improvement, five geometrical modifications of the entrance were examined (figure 4 and 5). The idea was to achieve reduction of the head loss by enlargement of the
intake cross-section [3]. The modifications were made on the upstream side of the intake, not on its downstream side. The reason was twofold. The downstream side was needed to install the curtain wall; the lake rapping already produced a reasonable shape on this side.

Case A: existing entrance geometry (area 87.6 m²) after the lake tapping (reference case)

Case B: blasting of the shaft's upstream edge to an area of 100 m² (design area)

Case C: further enlargement of the shaft by blasting out its upstream edge to an area of 140 m²

Case D: based on Case C, blasting out of a sloping channel, with an inclination angle of 67°

Case E: based on Case C, blasting out of a sloping channel, with an inclination angle of 45°

Case F: based on Case C, blasting out of a sloping channel, with an inclination angle of 22.5°

Figure 4. Six examined entrance profiles in the model.
Figure 5. Sketch of six entrance configurations examined to reduce intake headloss. In Case C, the rock above the tunnel’s upstream end is totally removed, resulting in a vertical upstream edge.

3. Instrumentation and measurement

As compared to the reference case, the change in headloss that an intake modification introduces might be small. That was the reason why high measurement accuracy was required for both flow rate and water pressure in the model. All the measurements were computerised. Magnetic flow meters were installed to separately monitor the inflow to the model and the turbine flow rates. Piezometric heads were measured at a few locations in the reservoir and along the tunnel. The data from two locations were used to analyse the headloss across the intake (figure 6). Point m was located 115 m upstream of the intake axis; point n was at the end of the tunnel, at a distance of 65 m from the axis.

Figure 6. Measuring points m and n for headloss calculations of unit G2.

The piezometric head change, $\Delta H$, between the two points is equal to

$$\Delta H = (Z_m + y_m) - \left( Z_n + \frac{p_n}{\rho g} \right)$$

(1)

where $Z_m$ = reservoir bottom elevation above datum, $y_m$ = reservoir water depth, $Z_n$ = tunnel centreline elevation above datum, $p_n$ = tunnel water pressure, $\rho$ = water density and $g$ = gravitational acceleration. The total head loss, $h_t$, in between is written as

$$h_t = E_m - E_n = \Delta H + \frac{V_m^2}{2g} - \frac{V_n^2}{2g}$$

(2)
where $E =$ total specific energy and $V =$ flow velocity. As the flow pattern was complicated across the intake, no efforts were made to distinguish between local and frictional losses; the focus was the total headloss. The headloss coefficient, $\alpha$, is defined as

$$\alpha = \frac{2gh}{V^2}$$  \hspace{1cm} (3)

Eight typical flow cases, denoted as FC1 to FC8, are examined (table 1). The spillway was closed during the tests. Unit G2 operates both separately and in combination with unit G3. HWS and LWS refer to the highest and lowest water stages of the reservoir’s legal operation range, corresponding to +259.5 and +258.0 m a.s.l., respectively.

Table 1. Typical prototype flow cases evaluated for intake headloss.

| Flow Case | Reservoir Water Stage (m a.s.l.) | Turbine G2 Flow Rate $Q_2$ (m$^3$/s) | Turbine G3 Flow Rate $Q_3$ (m$^3$/s) |
|-----------|---------------------------------|-------------------------------------|-------------------------------------|
| FC1       | HWS                             | 200                                 | 0                                   |
| FC2       | HWS                             | 200                                 | 100                                 |
| FC3       | HWS                             | 200                                 | 200                                 |
| FC4       | HWS                             | 100                                 | 0                                   |
| FC5       | LWS                             | 200                                 | 0                                   |
| FC6       | LWS                             | 200                                 | 100                                 |
| FC7       | LWS                             | 200                                 | 200                                 |
| FC8       | LWS                             | 100                                 | 0                                   |

4. Experimental results

The eight flow cases were tested for each intake configuration. For each flow case, repeated tests were made. Results of averaged $\Delta H$, $h_t$ and $\alpha$ values are shown in figure 7, 8 and 9, respectively. The $\Delta H$ and $h_t$ results correspond to prototype values.
Within the reservoir operation range (LWS–HWS), the energy loss is listed in table 2 for different intake geometries. Based on the results, the following conclusions are drawn.

- At the full loading $Q_2 = 200 \text{ m}^3/\text{s}$, the difference between the test results is somewhat larger for Case A than for the other cases.
- For Case A, $\Delta H$ varies between 0.67–0.76 m and $h_t$ between 0.35–0.44 m at $Q_2 = 200 \text{ m}^3/\text{s}$. At the half loading $Q_2 = 100 \text{ m}^3/\text{s}$, $\Delta H \approx 0.18 \text{ m}$ and $h_t \approx 0.10 \text{ m}$.
- Irrespective of the intake geometry and reservoir stage, the head loss of unit G2 is hardly affected by the operation of unit G3. This is almost expected, as the reservoir water area is large and the effect of the turbine flow of G3 is insignificant on the reservoir flow velocity.
• To enlarge the intake cross-sectional area is the most effective way to reduce the intake headloss. The area enlargement to 140 m$^2$ (Case C) has almost halved the existing energy loss at the full turbine load. The percentage reduction is even larger at lower turbine flow rates.

• To further increase the intake area in the form of a channel upstream does not give much effect.

### Table 2. Prototype energy loss within the reservoir operation range LWS–HWS.

| Case | $Q_2 = 200$ m$^3$/s | $Q_2 = 100$ m$^3$/s |
|------|-----------------|-----------------|
| A    | 0.401           | 0.102           |
| B    | 0.306           | 0.080           |
| C    | 0.220           | 0.049           |
| D    | 0.190           | 0.043           |
| E    | 0.166           | 0.040           |
| F    | 0.166           | 0.041           |

During the tests, certain vortex formations at the intake were observed. The vortices were however small and unsteady. The surface water was actually characterised by periodical alternations between vortex-free flow and vortices of varying sizes. The largest vortex recorded had a prototype diameter of ~2 m. The different intake geometries did not give rise to any noticeable difference in the vortex formation.

### 5. Concluding remarks

With the commissioning of the new unit at Akkats, free-surface vortex formation occurred unexpectedly at its vertical intake formed by lake tapping. Physical model tests were performed to work out countermeasures to mitigate the vortex. A curtain wall, consisting of five stand-alone sections, was anchored onto the reservoir bottom to suppress the vortex occurrence.

In the model tests performed, the intake geometry was modified with the purpose to find out a means for headloss reduction. It was demonstrated that to enlarge the intake cross-sectional area was most effective; the original headloss was reduced with 45% by a fairly simple modification of the intake. The examined intake configurations did not introduce any noticeable changes in the flow pattern above the intake. The intake geometry has not been modified in the prototype. The gain in the headloss reduction and power production must be weighed by the construction costs.

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