Vortices at intake works of pump-storage schemes

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Physical model testing for two new major pump-storage hydropower scheme projects were performed at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). One, the 600 MW Nant-de-Drance pump-storage scheme between the Emosson and Vieux-Emosson reservoirs, is located in the Valais Alps. The other one, the 1'000 MW Linth-Limmern pump-storage scheme between the Limmernsee and Muttsee reservoirs, is located in the Glarner Alps. Pump-storage schemes, like ordinary hydropower schemes, are equipped with water intakes. Secondary flow and vortex formation above the intakes were investigated according to the operation conditions in generating mode for the upper basin, respectively in pumping mode for the lower basin for various discharges and water levels. The detailed velocity fields around and inside the vortices were measured using ultrasonic velocity profilers UVP. The geometry of the intake structures could be optimized through minor structural modifications in order to keep the intake operations outside the critical limit of air entrainment. Vertical velocity profiles along the vortex cores were also measured using ultrasonic velocity profilers. The velocity measurements highlighted the risk of frazil ice crystal entrainment, which could lead to the obstruction of the metallic intake grid.

Keywords: pump-storage hydropower scheme, water intake, vortex, frazil ice entrainment, velocity field, ultrasonic velocity profiler UVP

1 INTRODUCTION

In January 2008, the total installed capacity of hydropower schemes greater than 300 KW in Switzerland amounted to 14'200 MW. Today some 1'610 MW are available for pump-storage [1].

Within the frame of major upgrading of existing hydropower schemes with storage reservoirs in Switzerland, two distinct new projects are currently under final investigation: the Nant-de-Drance and the Linth-Limmern pump-storage schemes. These two projects, once completed, will practically double the existing pump-storage capacity in Switzerland.

Physical model testing for these pump-storage hydropower scheme projects were performed at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) [2-5]. Pump-storage schemes, like ordinary hydropower schemes, are equipped with water intakes. Secondary flow and vortex formation above the intakes were investigated in both physical model studies considering the operation conditions in generating (turbining) mode for the upper basin, respectively in pumping mode for the lower basin for various discharges and water levels.

2 CASE STUDIES

2.1 Nant-de-Drance pump-storage scheme

The Nant-de-Drance pump-storage scheme, located in the Valais Alps (Figure 1), consists of the installation of an underground pump-turbine plant between the existing reservoirs of Emosson (1'930 m a.s.l.) and Vieux-Emosson (2'205 m a.s.l.). The power station is composed of four production units with a total power of 600 MW and is fed by two pressure tunnels of 6.5 m in diameter.

2.2 Linth-Limmern pump-storage scheme

The existing Linth-Limmern hydropower scheme, located in the Glarner Alps (Figure 1), has at present an installed capacity of 340 MW.

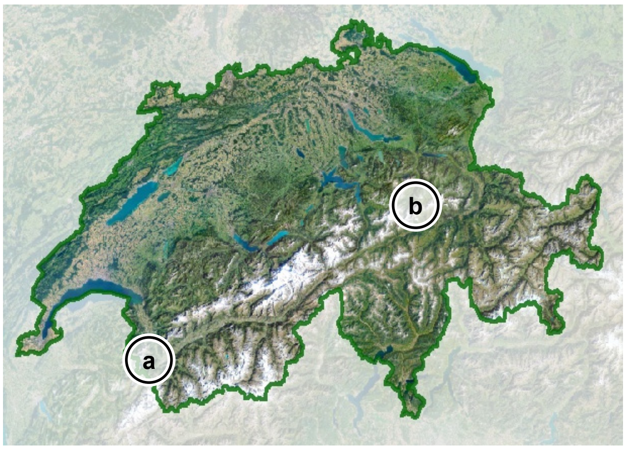

Figure 1: Location of the Nant-de-Drance (a) and the Linth-Limmern (b) pump-storage schemes projects.

The extension project "Linthal 2015 KW Limmern" foresees a new underground pump storage powerhouse able to pump water from the lower basin (Limmernsee, 1'857 m a.s.l) into the upper basin (Muttsee, at present at 2'446 m a.s.l.). During peak hours, the stored water can again be used for generating energy. The single upper basin intake guides the water into a conduit of 8 m in diameter, which feeds the power station composed of four units with a total power of 1'000 MW. The lower outlet (in generating mode) is composed of two separate works.

3 THEORETICAL CONSIDERATIONS

3.1 Vortices on water intakes

Referring to their intensity, vortices on water intakes can be classified into six types, reaching from non coherent surface swirls to eddies with continuous core and air entrainment. A vortex is considered to be critical when the air core reaches the intake. In order to avoid such situations, a minimal submersion has to be guaranteed. For a first approach, Knauss (1987) [6] proposes an empirical formula to calculate this critical water depth above the intake:

$$\frac{h_t}{D} > 2.3 \cdot F_p + 1 \qquad (1)$$

$$F_p = V \Big/ \sqrt{g \cdot D} \qquad (2)$$

With F_p the Froude number of the intake, V the mean velocity in the conduit, D the hydraulic diameter of the conduit, and h_t the water depth referred to the conduit axis.

The values of V, h_t and D vary according to the position within the intake structure due to intake inclination, vertical and lateral contraction and finally change of the conduit cross section from rectangular to circular. Thus, the verification of the critical water depth over intake structures has to be carried out for several cross sections (Figure 2), namely at the end of lateral (A) and vertical (B) contractions and at the entrance into the circular conduit (C).

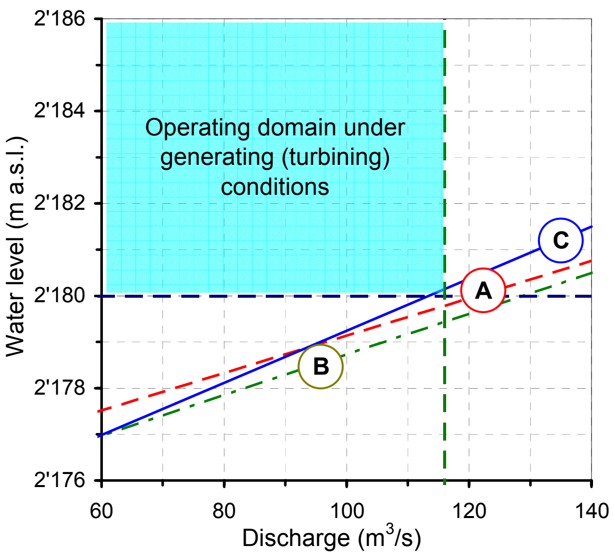

Figure 2: Relation between discharge and critical submersion depth for three cross sections (A), (B), and (C) of the Vieux-Emosson intake structure.

The theoretical considerations reveal the existence of a critical minimal water depth that has to be maintained during generating mode at full capacity. This condition will thus be verified experimentally.

3.1 Frazil ice particle entrainment

If water temperature falls below the freezing point and no ice layer covers the lake surface, frazil ice can form. If wind or currents agitate the water, these ice crystals can be entrained vertically along the water column and transported towards the intake [7].

Frazil ice can easily adhere to the metal bars of the trash rack that have high thermal conductivity, not only on their contact surfaces but also between them [8]. The accumulation of frazil ice and their growing can lead to rapid and complete blocking of the entrance section [9].

The lake of Vieux-Emosson is situated at 2'200 m a.s.l. where extreme climatic conditions can occur. In particular negative temperature peaks of -10 to -15 °C and clear, cold nights favour frazil ice formation. Furthermore, primary and secondary flow conditions due to generating and pumping modes contribute to thermal mixing of the water and therefore to frazil ice production.

In order to define whether frazil ice can be entrained by vertical flow, the different forces applying on an ice particle have to be analyzed. Ice crystals usually form disks of less than 1 mm in diameter, but after growing these disks can reach 15 mm and also coalesce to near spherical shapes [8].

The ice disk thickness is 5 to 10 times smaller than its diameter. A one-dimensional model allows equilibrating active and resisting forces, that is to say disk weight *P*, buoyant force F_A and drag force F_T.

$$P = \rho_i \cdot g \cdot \overline{V} \qquad (3)$$

$$F_T = \frac{1}{2} \cdot C_T \cdot S \cdot \rho_w \cdot V_z^{\,2} \qquad (4)$$

$$F_A = \rho_w \cdot g \cdot \overline{V} \qquad (5)$$

with $\overline{V}$ the ice particle volume, S the projected section of the disk in flow direction, C_T the drag coefficient, V_z the relative velocity, g the gravity acceleration, ρ_i and ρ_w the volumetric mass of the ice particle respectively of water.

The theoretical approach admits that the disks are positioned perpendicularly to the vertical flow velocities. This conservative hypothesis can be justified by the fact that the ice disks will orientate parallel to major horizontal velocities in the eddy. This model allows calculating critical velocities for frazil ice particle entrainment, for disks with a thickness/diameter ratio of 0.1 and for spheres

(Figure 3).

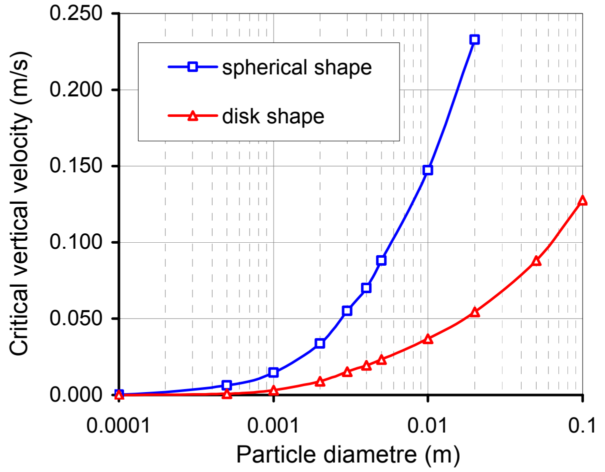

Figure 3: Critical velocity for frazil ice particle entrainment.

Physical modelling thus consists in quantifying the limits of the vertical velocity range for frazil ice entrainment.

4 PHYSICAL MODELING

4.1 Experimental set-up

The physical models of the Nant-de-Drance and the Linth-Limmern intake structures have been built at scales ranging from 1:36 to 1:42. This scale range allows representing the behaviour of swirling flow in an adequate way [11], [12], [13]. In order to reveal possible model effects and to evaluate the robustness of the results, supplementary test series have been run with higher flow rates.

The limits of the physical model were selected in a way that the substantial influences of the topography on the flow conditions can be considered and the model delimitation leads to no substantial influences. The intake works have been built in PVC and the reservoir topography with a rigid cement covered structure (Figure 4). Every conduit can be run individually and independently in generating, as well as in pumping mode. The reservoir level is controlled by an overflow weir.

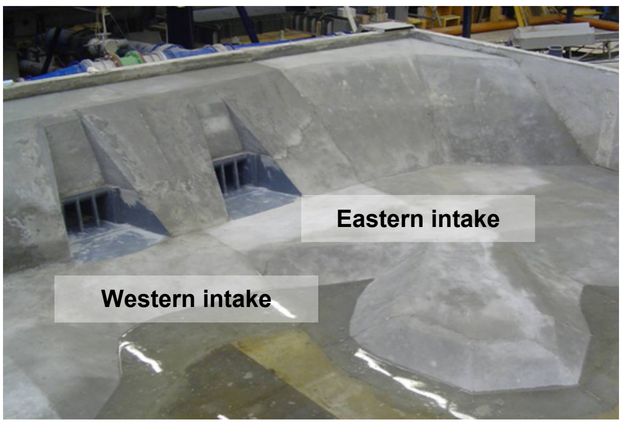

Figure 4: Hydraulic model of the two adjacent intakes inside the lower Limmernsee basin of the Linth-Limmern pump-storage scheme project.

The models have been exploited considering Froude similarity. The Reynolds number is considered only for head losses at the intake entrance.

4.2 Measuring technique

For the quantitative evaluation of eddies, 2D velocity measurements have been carried out using UVP (Ultrasonic Velocity Profiler). Two rows of four sensors have been placed perpendicularly in order to obtain a network of 16 measuring points (10 cm x 10 cm, Figure 5). A hydrogen bubble generator installed upstream the measurement area allowed to trace the flow [14], [15].

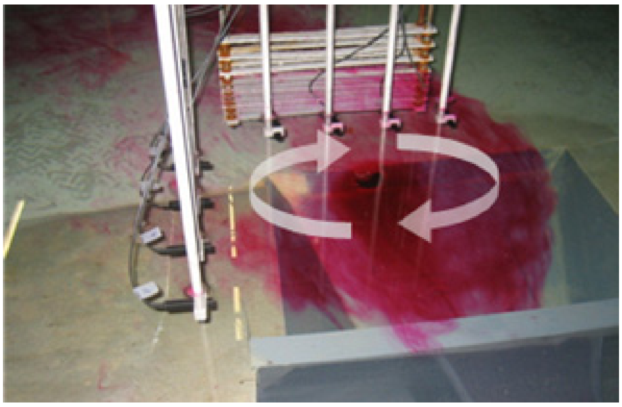

Figure 5: Measurement frame with 4x4 US transducers for vortices flow field mapping. A hydrogen bubble generator (in the back) was used for local hydrogen seeding supply.

Vertical velocity measurements have been carried out with UVP as well, this time perpendicular to the water surface in the center of vortices. Flow velocities have been recorded only when eddies were highly developed.

5 EXPERIMENTAL RESULTS

The following results concern exclusively vortices in front of the intake structures. Two problems are analyzed: the first deals with eddy formation and potential air entrainment, and the second reveals the risk relative to frazil ice entrainment.

5.1 Assessment of vortex formation

Vortices above the intakes have been analyzed qualitatively, considering eddy type, dimension and persistence. Observations have been made for possible operation conditions (discharges and reservoir water levels).

Based on these results, critical configurations have been selected and analyzed quantitatively by 2D UVP measurements.

An example of such observations and measurements results are given for the Vieux-Emosson reservoir in Figure 6. Technical solutions allowing an improvement of the swirling flow behaviour have been proposed and optimized thanks to the hydraulic model tests.

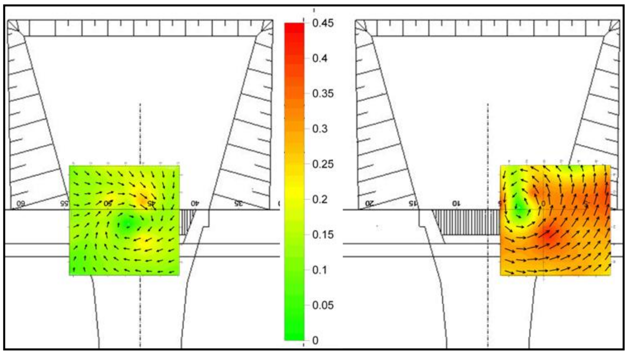

Figure 6: Formation of vortices in generating mode at the water intakes of Vieux-Emosson. Top: dye injection. Bottom: horizontal measured flow field at an intermediate level.

5.3 Evaluation of frazil ice entrainment

Figure 7 shows an example of the vertical velocities measured in the core of the vortices for several reservoir water levels. Velocities of 0.05 to 0.10 m/s can easily entrain frazil ice disks of some 5 cm in diameter. The frazil ice forming on the water surface, with a size of 1 mm, can therefore be entrained towards the trash rack of the intake structure. Solutions to reduce the risk of blocked trash racks must be considered.

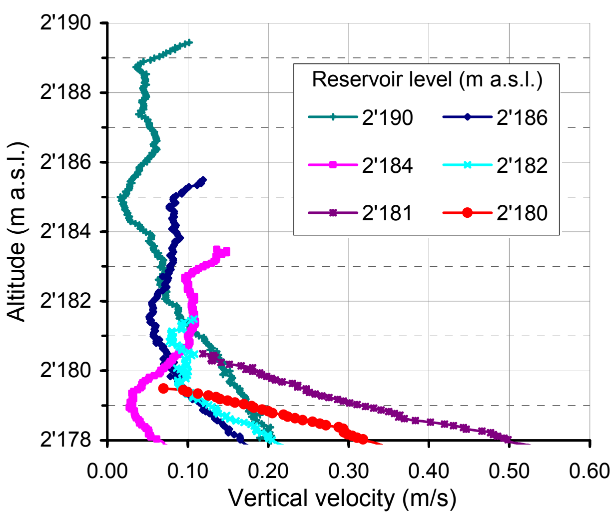

Figure 7: Vertical velocity inside the vortex core to assess frazil ice entrainment in the Vieux-Emosson model.

6 CONCLUSIONS

UVP measurements applied to physical models of the intake structures of the pump-storage schemes Nant-de-Drance and Linth-Limmern allowed exploring the velocity fields associated with vortex formation. Based on the detailed results of these tests, problems have been identified and solutions have been proposed and optimized.

In order to reduce the frequency and persistence of eddies, the excavation niches have been enlarged. The vortex intensity could be reduced by implementing small walls above the intake platform (Nant-de-Drance) or by placing a concrete crossing beam over the intake (Linth-Limmern).

The risk of trash rack blocking due to frazil ice has been revealed and both constructive solutions (spacing between bars, protection layers or coatings, possible heating) and exploitation measures (potential underwater frazil ice detection, flushing by reverse current) have been proposed.

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