Prevention of air-entrainment at the outlet of a pumped storage plant – large scale model tests

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Abstract: *To avoid the generation of air-entraining vortices at a projected outlet structure in an existing reservoir of a pumped-storage plant, large-scale model tests were conducted. The model, with a scale of 1:18, had the considerable dimensions of 30 m in length and 16 m in width.*

Due to the complex shape of the reservoir, the many inlets and outlets, and numerous operating conditions, very complex flows occurred. Depending also on the water level, the direction of flow approaching the outlet was always changing. This made it hard to find a solution for all operating conditions and water levels that avoided air-entraining vortices. However, with the suggested measures it was possible to maintain operation down to a quite low drawdown level without air-entrainment.

Keywords: *air-entrainment, vortex, inlet.*

1. INTRODUCTION

To increase capacity, a new outlet structure is projected in an existing reservoir of an Austrian pump storage plant. Due to the complex shape of the reservoir and the large number of different operating and flow conditions, air-entrainment vortices could possibly develop at the new outlet. To avoid air entrainment, large scale hydraulic model tests have been conducted. Air-entrainment can have many negative effects: on the one hand it can lead to a loss of energy or reduction of discharge and on the other hand it could harm the duct system due to vibrations or cavitation, which could mean a temporary drop out.

Generally speaking, vortices can develop when flow to an outlet is asymmetric. In our case, due to the shape of the reservoir, flow towards the new outlet is very asymmetric and furthermore varies with the water level and depends on the specific operating condition. The picture below shows an illustration of the topography of the basin (all heights mentioned refer to nature scale!).

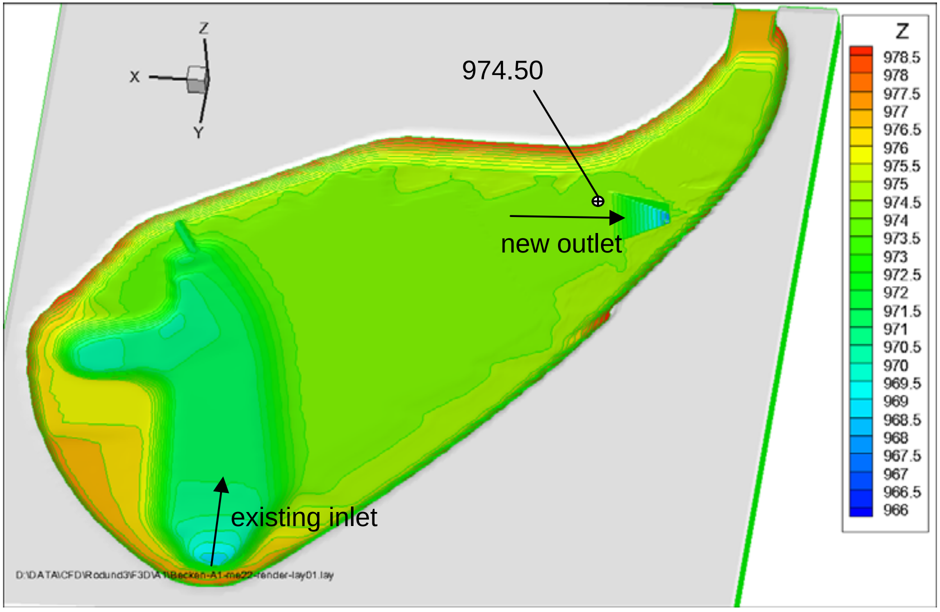

Figure 1 3D-illustration of the reservoir topography

Strictly speaking both structures shown in Fig. 1 can work either as an inlet, leading water from the reservoir down to a power plant, or as an outlet, while pumping water into the reservoir. Concerning the development of air-entrainment vortices at the new structure, only the case when it works as an outlet is of interest here.

The reservoir with its built-in structures is depicted in Fig. 2. There are 4 structures in the basin: the first one is a conduit which connects the reservoir to another one next to it. The second one, situated in the northern area of the reservoir, is the existing in-/outlet structure (called “2-in”). The third, new structure, “3-out” is projected in the southern area. Furthermore, there is a canal, from which water can also come into the reservoir.

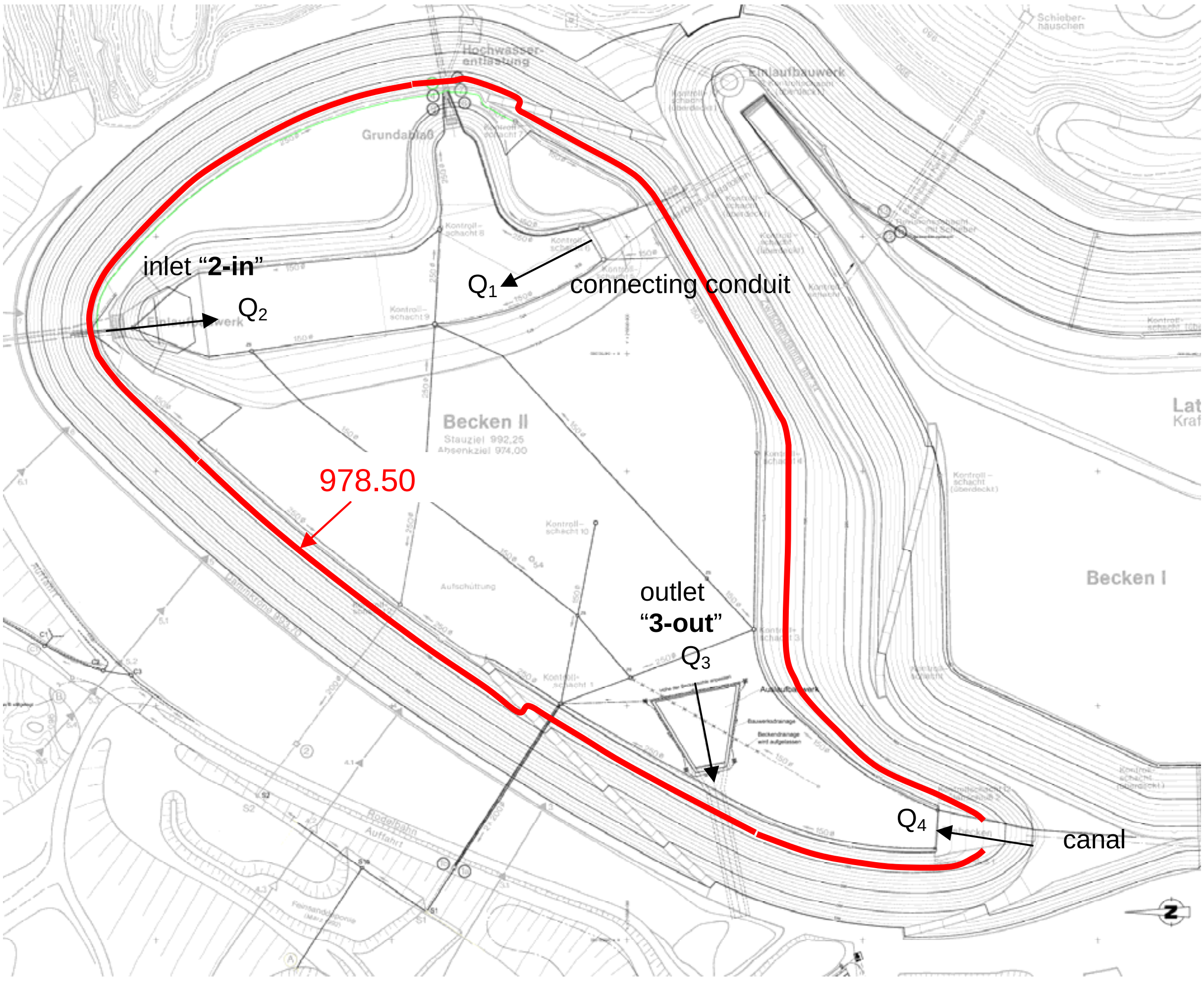

Figure 2 plan view of the reservoir

2. PHYSICAL MODEL

It is recommended by several researchers, *e.g.* Knauss (1972), that a physical model should not be smaller than a scale of 1:20 in order to reproduce the development of air-entrainment vortices. The scale chosen here was 1:18. Another recommendation is to increase the inflow velocity. To meet this concern additional model tests were conducted with increased discharges.

The physical model had overall dimensions of 30 x 16 m. To build the model accurately, bricks were positioned along the major contour lines and levelled exactly. The two inlet/outlet structures made of plexiglass, the conduit and the canal were placed at their positions. Then the model was filled with compacted sand and the surface concreted. The reservoir was built up to a level of 978.50 m which is 4 m above the surface of the reservoir.

The new outlet structure has a trapezoidal shaped ramp that leads from the reservoir surface at 974.50 m down to the bottom of the inlet at 967.00 m (see Fig. 3). The drawdown-level of the reservoir is intended to be very low at 975.50, only 1 m above the reservoir surface. With such a small water cover between the water level and the outlet axis it is expected that air-entrainment vortices could develop.

Figure 3 outlet "3-out"

Based on Froude law of similarity that can be used here, because inertia forces and gravity are dominant, the following conversion factors can be derived:

Table 1 conversion factors

length l:	l_{Nature}	=	M_l	x l_{Model}	(l_{Nature}	=	18	x L_{Model})
area A:	A_{Nature}	=	$M_l^{\ 2}$	x A_{Model}	(A_{Nature}	=	324	x A_{Model})
volume V:	V_{Nature}	=	$M_l^{\ 3}$	x V_{Model}	(V_{Nature}	=	5832	x V_{Model})
time t:	t_{Nature}	=	$M_l^{\ 1/2}$	x t_{Model}	(t_{Nature}	=	4.24	x t_{Model})
velocity:	v_{Nature}	=	$Ml^{1/2}$	x v_{Model}	(v_{Nature}	=	4.24	x v_{Model})
discharge:	Q_{Nature}	=	$M_l^{\ 5/2}$	x Q_{Model}	(Q_{Nature}	=	1374.6	x Q_{Model})

3. OPERATING CONDITONS

Disregarding cases when the new structure works as an inlet into the reservoir the following operating conditions were examined in the model tests (m³/s in nature, l/s in model scale; positive values mean flow into the reservoir):

Table 2 Operating conditions

	Q1		**Q2**		**Q3**		**Q4**		**waterlevel**		
	conduit		**2-in**		**3-out**		**canal**		**from**	**to**	**direction**
	m³/s	l/s	m³/s	l/s	m³/s	l/s	m³/s	l/s	m	m	
case 5	0	0	80	58	-110	-80	0	0	978.50	975.50	down
case 5a	0	0	0	0	-110	-80	0	0	978.50	975.50	down
case 6a	0	0	0	0	-110	-80	75	55	978.50	975.50	down
case 6b	0	0	80	58	-110	-80	75	55	975.50	978.50	up
case 7a	65	47	0	0	-110	-80	0	0	978.50	975.50	down
case 7b	65	47	80	58	-110	-80	0	0	975.50	978.50	up

The regular operating conditions are case 5 and 5a, the other cases are special operating conditions which occur only once a year. So the model tests concentrated on that cases. As mentioned before, additional model tests were conducted with increased discharges (up to 130%) in order to enforce the development of vortices.

4. MODEL TESTS

Before a test was started the reservoir was filled up to the starting water level. The discharge at the inlets and the outlet was increased within approximately 20 seconds, starting from a quiet water surface, because that also enforced the development of vortices. The main aim of the investigation was to develop measures to prevent the development of air-entrainment vortices. Therefore a huge number of model tests with different structures to direct flow, such as groynes, walls and piles, were tested. In particular for case 5a – turbine operation of structure “3-out” - more than 100 series were conducted until the optimal configuration was found. Here, the initial situation and the final solution are presented.

4.1. Initial situation

In case 5 and 5a a large air-entraining vortex developed in front of the outlet “3-out”. It developed because water mainly flowed at the left side of the building around it and then coming back from the right side. This flow situation was visualized with swimming light objects: they were exposed to the flow and photographed with a camera mounted on the laboratory’s ceiling with a long-time shutter speed taking interval pictures. They leave a stripe on the picture whose length is dependent on their speed.

Figure 4 air entraining vortex at 3-out (left case 5, right case 6b)

The pictures below show the lights flowing around the outlet, turning around the building clockwise and then establishing the vortex in front of the outlet. The pictures indeed were taken when discharge at inlet and outlet were the same (80 l/s) at drawdown level of 978.50, but they are also characteristic for the other situations of case 5 and 5a, also at higher water levels and with different inlet and outlet discharges.

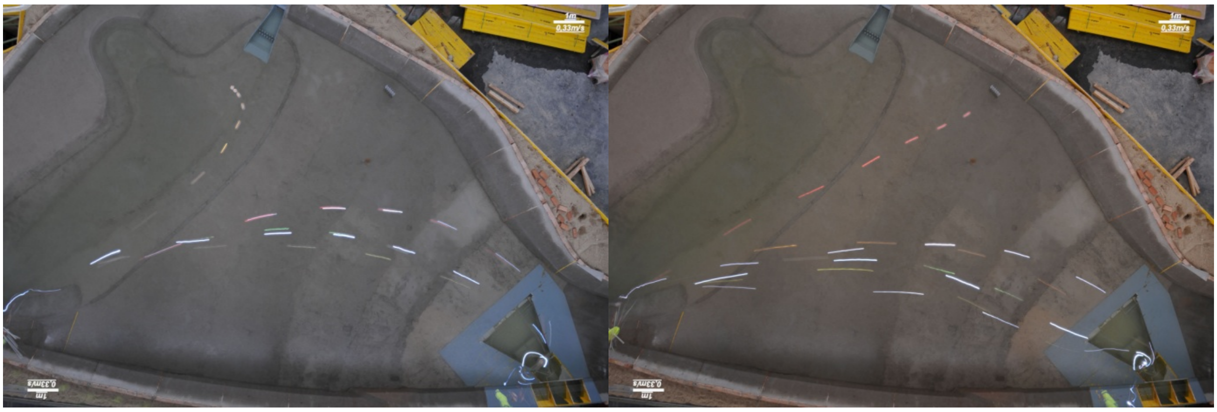

Figure 5 flow visualisation case 5a, Q_2 = 80, Q_3 = -80 l/s, W.l. 975.50 m

In addition to the model tests CFD-simulations were carried out which are not described here in detail, but were useful to visualize the flow field around the outlet, especially when compared with the final proposal.

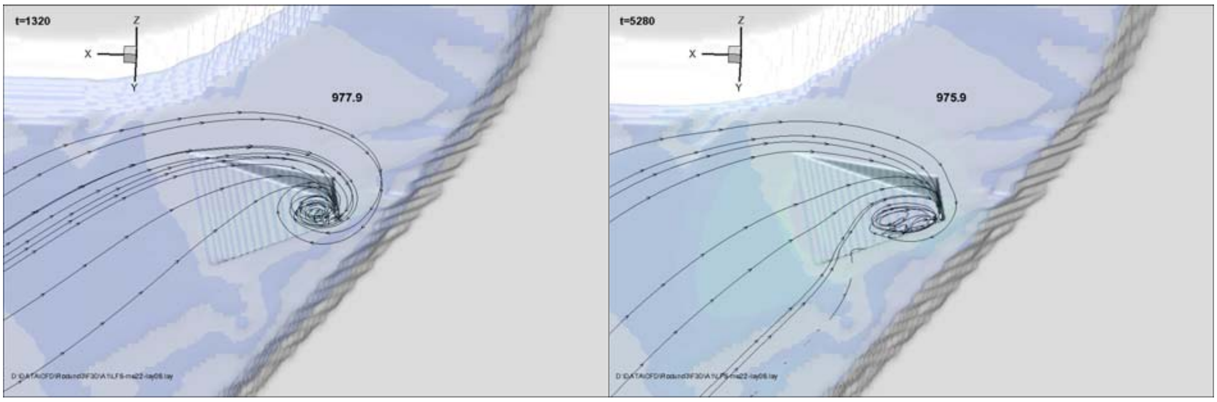

Figure 6 flow visualisation case 5 (from CFD-simulation)

4.2. Optimisation Process

During the model tests it came out that a groyne or a wall at the left side of the intake has a positive effect on the flow field, as it leads the flow towards the outlet. But in case 6 to 7 it turned out that this was not sufficient, because vortices developed somewhere else. Thus, different kinds of piles or rows of piers were added above the front of the outlet. All combinations of walls and groynes with piers had to be tested in all cases of operation and what seemed to be good in one case often turned out to be worse in another, because the flow field strongly varied between the different cases. It was very tricky to find a solution especially for case 5 and 5a, so that no air entrainment took place. In the end 2 constructions were proposed: one is a combination of a wall with holes with a row of piles at the outlet ceiling (called “A37”), shown in Fig. 7; the other one is a kind of floating grid or girder made of wood (called “G02”).

4.3. Final Proposal “A37”

This arrangement, a combination of a curved wall with holes at the left side before the outlet, and a row of 5 piers – 4 short piles and one long pier with gaps in between – seems to be quite unusual at the first glance, but it proved to be very effective, as it almost completely prevented the development of air entraining vortices in all test cases. Only a small surface vortex, which did not entrain air, developed once for a short time and disappeared again quickly.

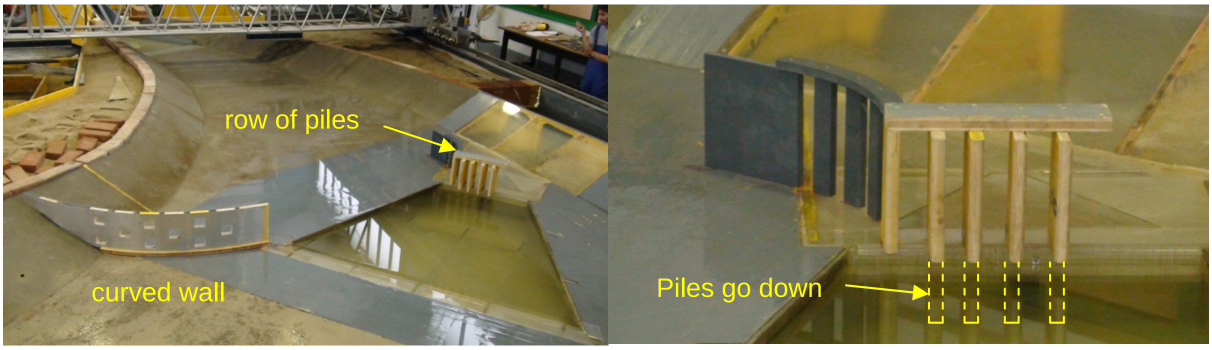

Figure 7 final proposal “A37”

The effects on the flow field can be clearly seen in the following figures: flow coming from the left side is now directed towards the outlet, the lower part heading directly into the outlet. The upper part above the bottom of the reservoir flows through the row of piles and is directed by them in a large circle around the piers, thus avoiding a concentrated swirl.

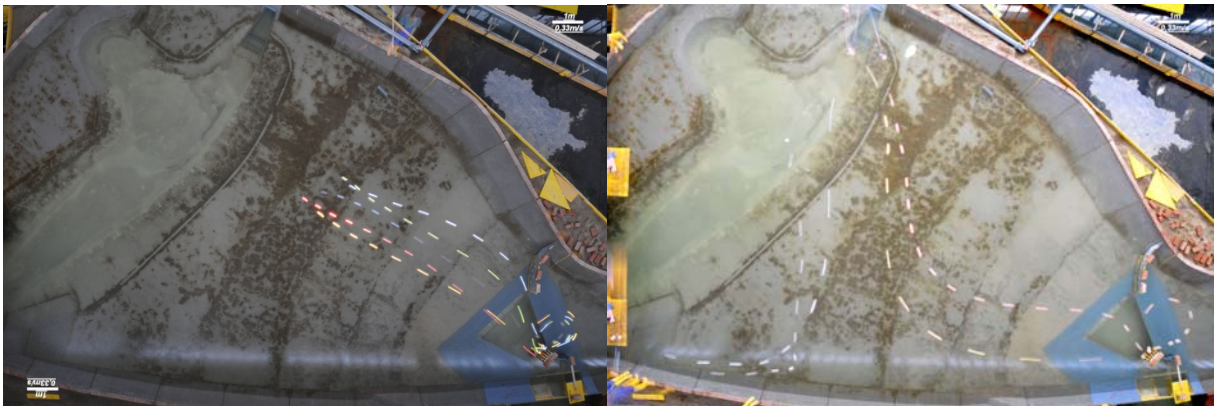

Figure 8 flow visualisation "A37" (left case 5, right case 7a)

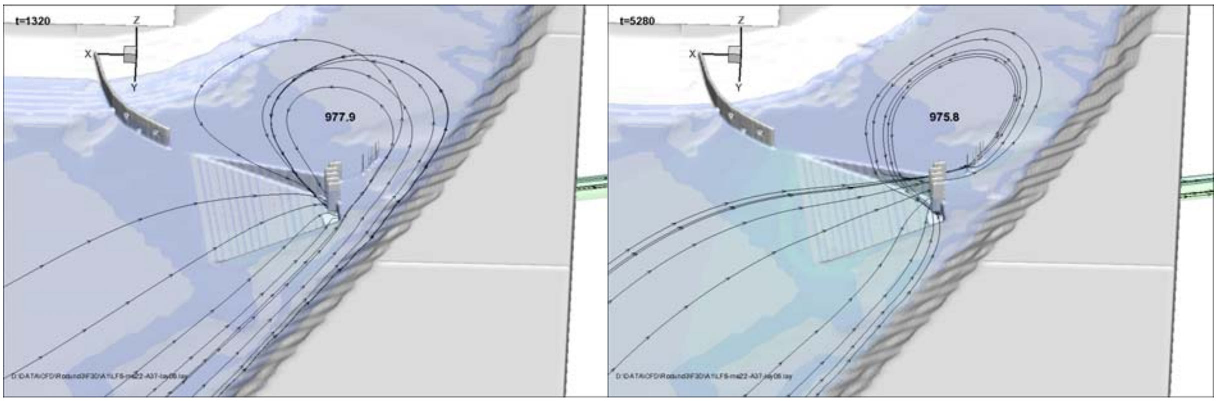

Figure 9 flow visualisation "A37" (from CFD-simulation)

4.4. Final Proposal "G02"

The solution with a floating grid guided by two pylons, shown in Fig. 10, was even better at reducing the development of vortices, as there were no surface swirls at all. However, for construction it was decided to build the first proposal "A37" for reasons of reliability in operation.

Figure 10 floating grid "G02"

5. SUMMARY

Hydraulic model tests have been conducted in order to detect air-entrainment vortices at a projected outlet in an existing reservoir of an Austrian pump storage plant. The experiments showed that air-entrainment vortices did develop with the original configuration. Many model tests with different modifications were carried out to avoid air-entrainment. Finally, two measures were proposed: one was a combination of a wall with a row of piles and the other one was a floating girder made of wood. With both constructions the development of air-entrainment vortices was avoided.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Knauss, J. (1972), *„Wirbel an Einläufen zu Wasserkraftanlagen“.* Technical report, Versuchsanstalt für Wasserbau der Technischen Hochschule München, 1972.