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Junction Chamber at Vortex Drop Shaft: Case Study of Cossonay

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ABSTRACT

The drainage network of the city of Cossonay (Switzerland) is currently being adapted for future needs. In particular, it is required to drain increased storm discharges due to a population augmentation and to provide an adequate concept to overcome unfavorable geotechnical conditions. Vortex drop shafts are sewer manholes commonly applied in steep urbanized topographies to connect conduits across large elevation differences. In Cossonay, the existing 48 m high vortex drop shaft, with a diameter of 1.5 m, allowed the storm discharge to flow from the city to a watercourse issued at half of the valley height. The discharge capacity was initially assumed as 4.1 m³/s, but frequent pulsations and choking phenomena implied a reduced effective capacity of around 3.0 m³/s. A new planned vortex drop shaft will collect the supercritical inflows of four collectors in the old City Centre and spill them through a shaft of roughly 120 m height, restituting the flow at the valley bottom. It was pre-designed using FLOW-3D simulations to estimate the hydraulic features of the incoming flows and to predict the hydraulic behavior of the upper elements (before the water enters the shaft). The simulation thus included a novel junction chamber type and a steep inlet channel before the spiral intake. The numerical simulations provided a first layout of the structure that was then validated by physical model tests. The physical model was built at the Laboratory of Hydraulic Constructions (LCH) of École Polytechnique Fédérale de Lausanne (EPFL).

Keywords: *Sewer. Fall manhole. Vortex drop shaft. Physical model. Numerical model. Design discharge.*

1. INTRODUCTION

Fall manholes are commonly used in drainage systems of steep topographies. They convey discharges by connecting collectors at considerably different elevations to dissipate energy and generate adequate flow conditions in the drainage systems. Depending on the elevation difference between upper and lower collectors, two fall manhole types exist. For smaller differences of elevation, up to 7 m, a classical drop manhole (SIA 1980) is adopted. Conversely, if drop height results are larger than 5 m, vortex drop shafts are applied (Gisonni and Hager 2012).

Vortex drop shafts efficiently dissipate the flow energy. They consist of three components: intake structure, vertical shaft, and outlet structure. The intake structure orientates the flow, among others, from horizontal to vertical. Furthermore, it produces an annular stable vortex flow in the shaft. For supercritical flows, Kellenberger (1988) proposed a spiral intake type in which the flow is forced to adhere to the walls. Drag along the shaft is responsible for the relevant energy dissipation.

Herein, the authors describe the vortex drop shaft that is to be added to the storm water net of Cossonay. The new structure will replace the existing vortex drop shaft to meet geotechnical and hydraulic requirements. In particular, the old vortex drop shaft has to be substituted for the following reasons:

- The air transport was not secured because of the presence of an orifice at the toe, and, consequently, choking and pulsations phenomena occurred.
- The growth of the population and the larger storm water flows required the vortex drop shaft design to increase discharge capabilities to 12.61 m³/s.
- The tailwater gallery placed at the toe of the old vertical shaft returned the storm water flow in the water course "Rochettes". This stream flows along a slow landslide, resulting in the erosion of river bed and banks. Possible river restoration works were discarded because they cannot guarantee that the water course will be stabilized. Conversely, a new and higher vortex drop shaft allows for overstep of the entire landslide area.
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The new concept (Fuchsmann and Périsset 2013) considers a vortex drop shaft with a larger drop height of 120 m located outside of the landslide area. It will be placed in the city centre where both storm water collectors and sewers arrive. The necessity to minimize the construction volume and to ensure adequate flow conditions entering the inlet structure (Pfister et al. 2013) provided motivation for a common junction chamber for all arriving collectors. This solution allows for a steep and short inlet channel to accelerate the flow before entering the spiral intake. This concept seems novel and no design rules are available, so it was necessary to carry out a comprehensive design. The design was composed by three phases:

1. A preliminary hydraulic design of the individual components;
2. A FLOW-3D simulation of the inlet structure (Dorthe 2013, 2014), including the junction chamber and the inlet channel (Figure 1); and
3. Physical model tests at the Laboratory of Hydraulic Constructions (LCH) of École Polytechnique Fédérale de Lausanne (EPFL).
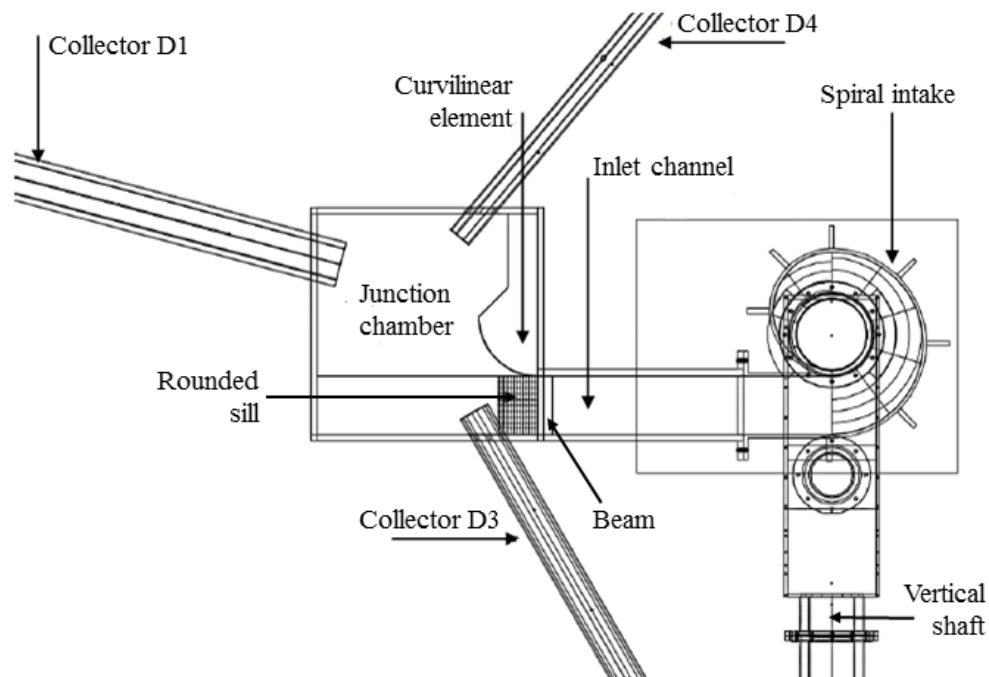

Figure 1. Plan view of the inlet structure (modified from Fuchsmann et al. 2015)

2. PRELIMINARY HYDRAULIC DESIGN

A preliminary hydraulic design (Dorthe 2013, 2014) was performed to assign minimum dimensions to the individual components of the vortex drop shaft. This stage was preparatory for further numerical and physical model tests.

Shape and dimensions of the junction chamber were chosen to guarantee an adequate volume to join the incoming flows. The chamber is almost square-shaped (Figure 2a), and it was orientated to facilitate the flow inlet towards the steep inlet channel. Moreover, a curvilinear element was added in proximity to the channel inlet to orient the flow. The first draft of the curvilinear element was shaped according to Army Engineer Waterways Experiment Station (WES) "entrance with roof curve" (ASCE 1957). The position of junction chamber with reference to the collectors was defined so that all the inflows merged at one point and no jet was directly oriented towards the inlet channel. The inlet channel allows the establishment of a stable supercritical flow needed to homogenize the flows, prevent hydraulic singularities, and ensure stable annular flow along the vertical shaft (Kellenberger 1988). This recommendation implies that Froude numbers should be larger than $F = 2.50$ at the outlet cross-section. The channel length L_c and width b were 10.0 m and 2.0 m, respectively, and the slope was $S_c = 20\%$.

The supercritical spiral intake (Figure 2b) was designed according to the standard of Kellenberger (1988). Hager (1990) recommends uniform and stable free-surface flow at the entrance of the spiral. The elevation difference between the intake and the outlet structures gives the shaft height. The required shaft diameter D_s is related to the discharge capacity, herein with $Q_M = 12.61$ m³/s as (Kellenberger 1988)

$$Q_M = [g \cdot (D_s/1.25)^5]^{0.5} \tag{1}$$

Equation (1) results in $D_s=2.18$ m. After that, a shaft diameter $D_s=2.40$ m was chosen to assign a discharge margin to the vortex drop shaft.

The dissipation chamber (Figure 2c) dissipates the remaining flow energy and de-aerates the flow. Flow pulsations and breakdown of the air circulation should be avoided by designing adequate chamber dimensions. Thus, the standard configuration according to Kellenberger (1988) is foreseen. The dissipation chamber resulted as 10.0 m long, 3.0 m wide, and 5.0 m high. The chamber was also equipped with a de-aeration system consisting in an aeration pipe placed on the chamber top. The aeration pipe diameter was $D_a = 1.40$ m.
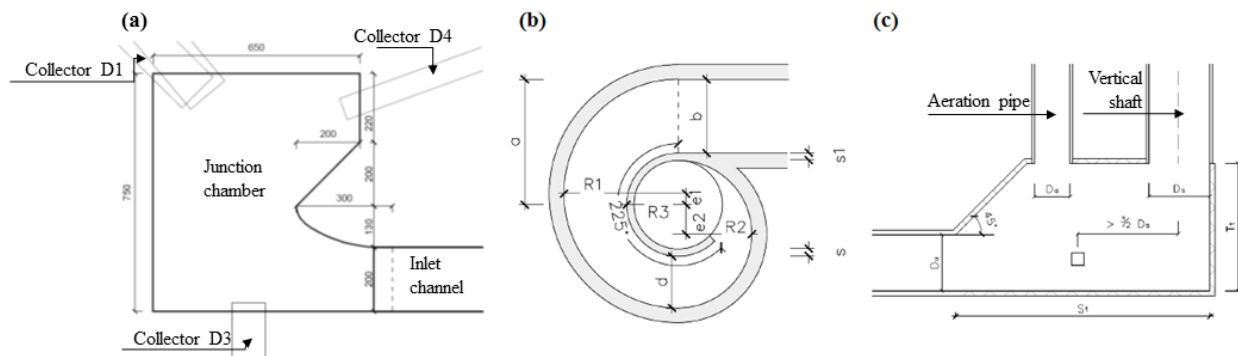

Figure 2. Sketches of vortex drop shaft components for the hydraulic preliminary design: (a) junction chamber, (b) spiral intake and (c) dissipation chamber (modified from Dorthe 2014)

3. NUMERICAL SIMULATION

A numerical FLOW-3D simulation was performed (Dorthe 2013, 2014) to verify the hydraulic behaviour of the structure resulting from the preliminary hydraulic design. The numerical model involved the collectors, the junction chamber, and the inlet channel. The junction chamber joins flows delivered by four collectors. The spiral intake, the vertical shaft, and the outlet structure were not simulated. Their performance depends strictly on the approach flow

conditions generated by the end of the inlet channel. If the simulated upper part of the system works adequately, then assume that the lower part will also operate as foreseen.

At first, numerical simulation did not show an optimal operation of the inlet structure derived by the preliminary design process. The free-surface in the junction chamber was irregular, and shock waves occurred along the inlet channel. Consequently, the flow orientation towards the spiral intake was poor, and Froude numbers of the flow entering the spiral intake were not in the achieved range. For these reasons, some modifications were introduced and tested by further simulations. In particular, the following changes were included:

- The curvilinear element in the junction chamber was simplified to a circular shape.
- An ogee-like sill (Fig. 1) was inserted to generate a critical section at the channel inlet and to increase the water volume in the junction chamber. The profile was designed to avoid sediment deposition in the chamber.
- A horizontal beam (Fig. 1) was inserted with the goal to break the flow rotation.
- The inlet channel slope was increased to 30% to accelerate the flow and, thereby, make the free-surface more regular.
- The altitude of the chamber invert was raised to tranquilize the flow in the junction chamber and to gain adequate flow acceleration along the inlet channel.
- The global inlet structure was rotated by 30° with reference to three collectors to optimize the flow stability at the inlet channel.
-

The above modifications were partially combined so that four set-ups were tested:

(1). Corresponding to the initial set-up. Its hydraulic performance results were not optimal.
(2). Including modifications of the junction chamber and the inlet channel but without any global rotation. The modelling highlighted an improvement in terms of free-surface flow pattern.
(3). As (1) but with a global rotation. The hydraulic behavior was better than in set-up (1).
(4). As (2) but with a global rotation. A pronounced improvement regarding flow stability and regularity was observed in the junction chamber and the inlet channel.

Figure 3 shows a comparison of the set-ups (1) and (4). The inlet cross-section of the channel is affected by a shock wave on the right channel wall for set-up (1) (Fig. 3a). This shock wave is absent in set-up (4), among others, due to the horizontal beam (Fig. 3b). Similarly, the middle and outlet cross-sections were initially characterized by the occurrence of surface irregularities (Fig. 3c, e), which were reduced in set-up (4) (Fig. 3d, f).

These qualitative impressions are supported by comparison criteria considering the free-surface regularity, the flow orientation, and the hydraulic stability. The first criterion relates to the transverse flow depth standard deviation. This parameter was used for quantifying the dispersion of flow depths around the average value by considering three inlet channel cross-sections. The second criterion includes the flow orientation by means of the velocity vectors angle α at the channel outlet with reference to the channel axis. The third criterion was based on the Froude number F_u at the channel outlet cross-section. The corresponding values of these criteria are listed in Table 1. As visible, the modifications included in set-up (2) allowed homogenizing the free-surface in comparison with the un-modified set-up (1). At the same time, the global rotation employed in set-up (3) improved the flow orientation. Overall, the set-up (4) seems most preferable, being characterized by sufficient a Froude number F_u. Accordingly, set-up (4) was retained for further investigations.
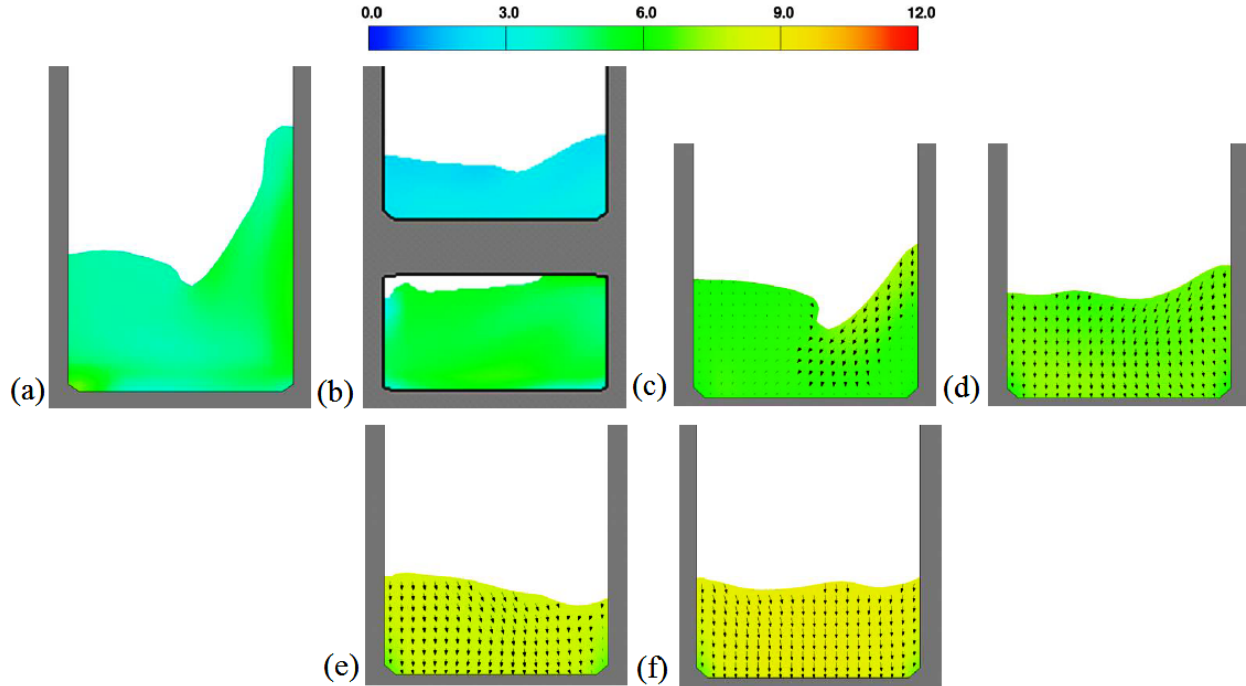
Figure 3. Simulated transverse velocity and free-surface profiles at different inlet channel cross-sections for set-ups (1) and (4), namely (a) and (b) inlet cross-section for set-ups (1) and (4), (c) and (d) middle cross-section for set-ups (1) and (4), and (e) and (f) outlet cross- section for set-ups (1) and (4) (modified from Dorthe 2014)

Table 1. Numerical values of criteria used for comparing set-ups for a discharge of $Q = 12.61$ m³/s (from Dorthe 2014)

Criteria	Set-up (1)	Set-up (2)	Set-up (3)	Set-up (4)
Free-surface regularity, standard deviation				
at the channel outlet (at $1.00 \cdot L$)	0.07 m	0.05 m	0.06 m	0.03 m
at $0.75 \cdot L$	0.14 m	0.08 m	0.11 m	0.06 m
at $0.50 \cdot L$	0.15 m	0.11 m	0.12 m	0.09 m
Flow orientation				
α	1.8°	1.5°	1.1°	1.1°
Hydraulic stability				
F_u	2.8	3.1	2.9	3.1

4. PHYSICAL MODEL INVESTIGATION

The significance and complexity of the vortex drop shaft – including aspects related to air transport along the shaft – requested for a verification of its hydraulic comportment in physical model tests. Thus, a physical model was built at the *Laboratory of Hydraulic Constructions* (LCH) of EPFL Lausanne (Fig. 4). The model reproduced the complete structure (set-up (4) from numerical simulations). The Froude similarity was applied as typical for gravity driven free-surface flows. A geometrical scale factor of 1:7.82 was chosen.

The experimental set-up (Fig. 4) consisted of the junction chamber and the inlet channel (made of painted formwork plates). Three (out of four) transparent PVC pipes (collectors) spilled their discharges into the chamber. The fourth collector was not physically modelled, being considered not relevant due to its small discharge. Thus, the discharge conveyed by this collector was summed proportionally to the other three. The collector lengths were equal to $15 \cdot D$ to ensure adequate flow conditions at the chamber. A supercritical spiral-type intake was provided at the end of the inlet channel. The vertical shaft was made up with a transparent PVC pipe. At the toe of the shaft, the dissipation chamber

made of PVC was provided. The chamber was equipped with an aeration pipe to secure adequate de-aeration of the flow. Finally, a PVC tailwater conduit with a slope $S_o = 1.5\%$ was the tailwater gallery.

The main hydraulic parameters were measured and recorded for each run. In particular, the total discharge in the individual collectors was measured by using electromagnetic flowmeters with a full scale accuracy (FS) of 0.5%. The flow depths in the junction chamber and along the inlet channel were measured by point gauges. A micro-propeller was used to record the velocities along the inlet channel and the spiral intake. Free-surface profiles along the spiral intake were discretized by using a point gauge. The rotational flow angles along the vertical shaft were also recorded. The dynamic pressures were recorded in the dissipation chamber with piezometers. Flow depths were measured inside the dissipation chamber and along the tailwater conduit. Finally, air velocities in the aeration pipe were measured by an anemometer.

Several discharges Q were tested. Herein, the scenarios included in Table 2 are considered. These values correspond to discharges between 50% to 140% of the design discharge Q_d. The discharge of scenario D exceeds the vortex drop shaft discharge capacity, $Q = 16.00$ m³/s according to Eq. (1). For this "overload" scenario, which is of interest regarding the reliability of the structure, no particular phenomena (such as pulsations, choking, or insufficient de-aeration) occurred, and the annular air-water flow in the vertical shaft was preserved. This evidence seems to suggest that vortex drop shafts designed following the literature recommendations may guarantee a safety in terms of discharge capacity.
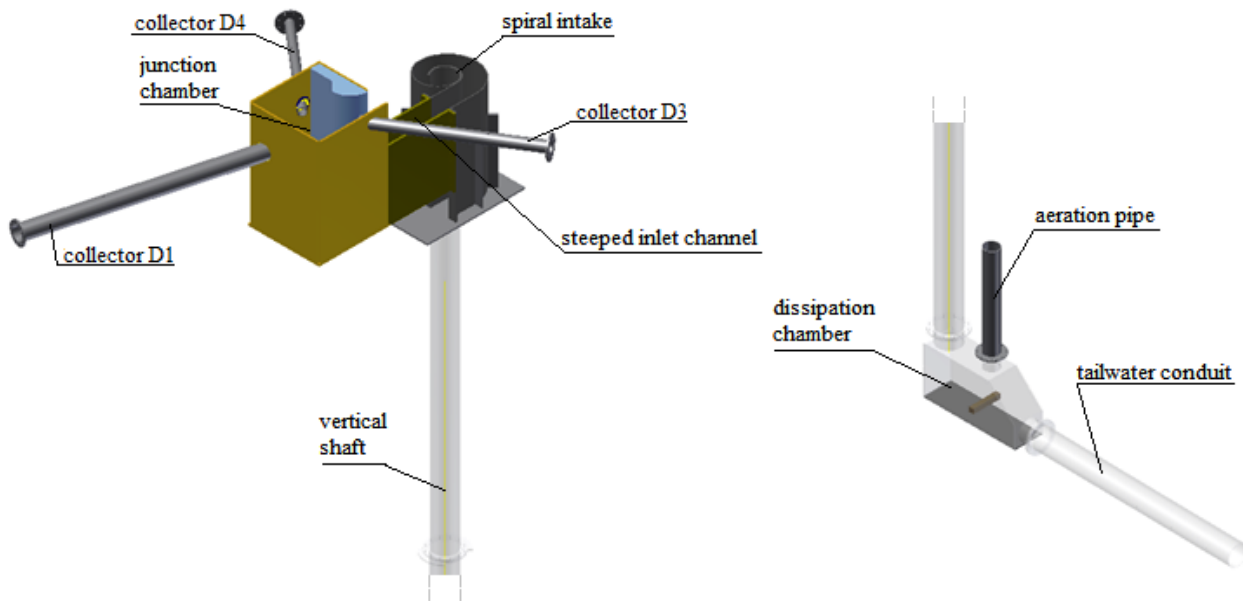

Figure 4. Sketch of the physical model (modified from LCH 2015)

Table 2. Test program

Scenario	Discharge [m³/s]
A: 50%·Q_d	6.43
B: 75%·Q_d	9.54
C: 100%·Q_d	12.70
D: 140%·Q_d	17.39

4.1. Hydraulic performance

4.1.1. Junction chamber and inlet channel

Figure 5a shows the free-surface profiles for scenarios A to D. No data are recorded below the collectors because their presence hindered the instrumentation placement. The free-surface appears regular, being almost horizontal from point D to point G (Fig. 5b), confirming the results of the numerical simulation corresponding to the set-up (4). Water surface level differences are below some 0.6 m in scenario D when ignoring the area near the curvilinear element (point B). There, the free-surface was affected by a swell induced by the impact of flow on the curvilinear element. Nonetheless, the swell height was such that it remained in the chamber. More importantly, the flow coming from the collector D1 was not affected (no hydraulic jump was observed) despite the water level being close to its top. This is due to the large momentum of the collector flow, requiring a larger conjugated depth than available.
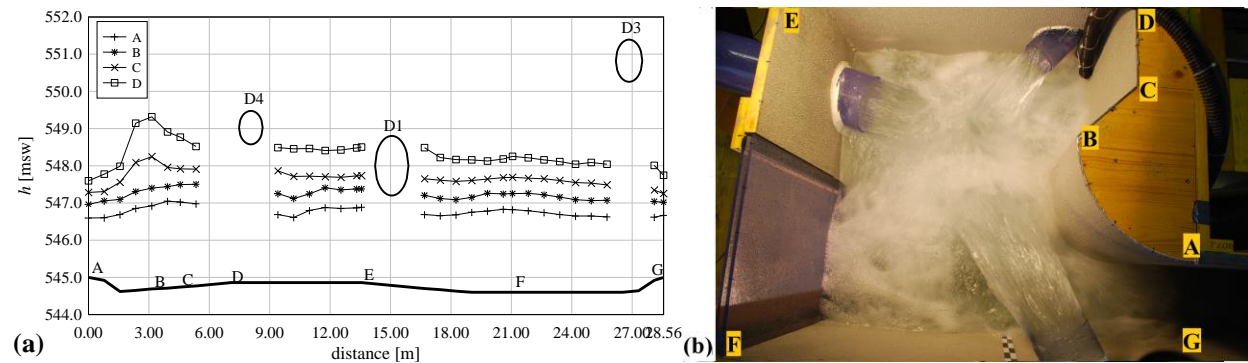

Figure 5. (a): Free-surface profiles detected in the junction chamber perimeter, (b) top view of the junction chamber flow pattern for scenario C

A supercritical flow profile was observed along the inlet channel. Flows are mainly accelerating along the first half of the channel and almost in the uniform flow regime along the second half (Figure 6). It is noticeable that the inlet flow depths at the inlet cross-section exceed the beam elevation and overtop it, at least for the herein presented discharges. The beam acts as a combination of a gate and a broad-crested weir. Froude numbers $F_u = V_u/(g \cdot h_u)^{0.5}$ between 2.42 (scenario D) and 4.10 (scenario A) were derived at the channel end. These values roughly support the outcomes of the numerical simulations, according to which the Froude number related to the design scenario was $F_u = 3.10$ (Table 1) against the physical model Froude value of $F_u = 2.70$.
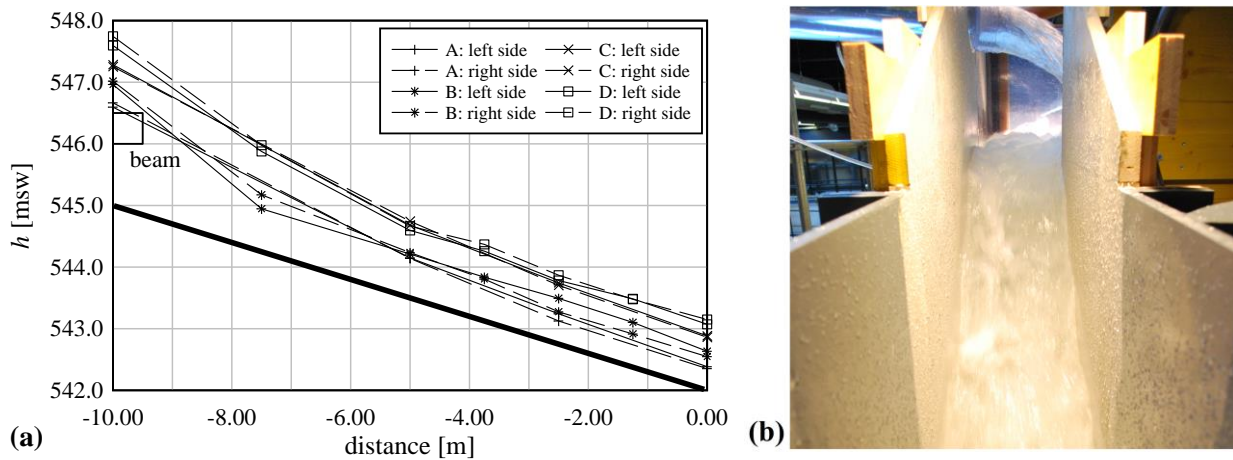

Figure 6. (a): Free-surface profiles along left and right sidewall of the inlet channel, and (b) view of the inlet channel flow under scenario D

Figure 7 shows the free-surface profiles along the external sidewall of the spiral intake. The supercritical approach flow generates a pronounced shock wave because of the abrupt deviation at the spiral intake. Hager (1990) observed only one, single-standing shock wave for highly supercritical approach flow (F_o = 5.70), whereas two maxima were observed for F_o = 1.80. Here, approached Froude numbers F_o were between 2.42 and 4.10, and two maxima were observed.
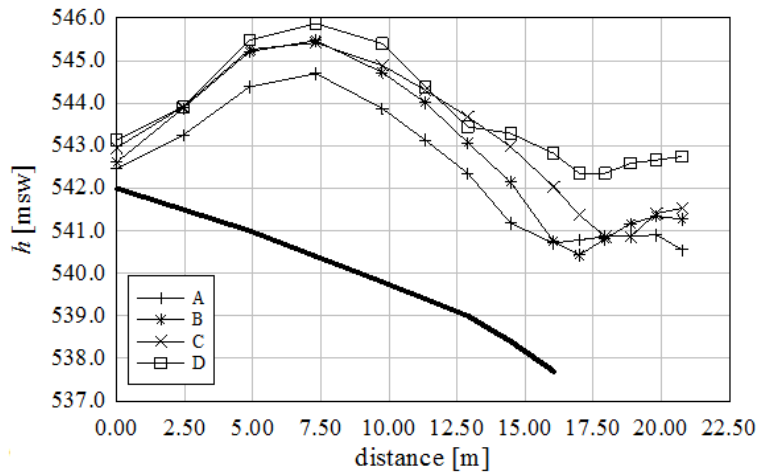

Figure 7. Free-surface profiles along the external sidewall of the spiral intake

4.1.2. Vertical drop shaft

The annular flow along the shaft was stable even under scenario D with a discharge exceeding the design value (Fig. 8). No collapse of the central air core or pulsations was observed. The approach flow was set in rotation by the spiral intake, producing the achieved annular flow in the shaft.

Figure 8. side view of the central air core at the inlet of the vertical drop shaft for scenario D

4.1.3. Outlet structure

The vertical jet issued by the shaft impinges on the dissipation chamber bottom and abruptly changes its direction to the horizontal. If the outlet structure works adequately, the energy of the impinging water mostly disperses, and the flow entering the tailwater gallery is subcritical.

The dissipation chamber showed an adequate performance. Pulsations or a breakdown of the air circulation was not observed, and the outflow from the shaft was never submerged despite the overload discharge in scenario D (Fig. 9b). Mixture air-water flow depth and pressure measurements were carried out in the dissipation chamber. Fig. 9a shows the average free-surface water levels inside the dissipation chamber for scenarios A to D. Obviously, the large inflows generated a relevant turbulence in the chamber, with flow depths touching the 45°-sloped chamber top.
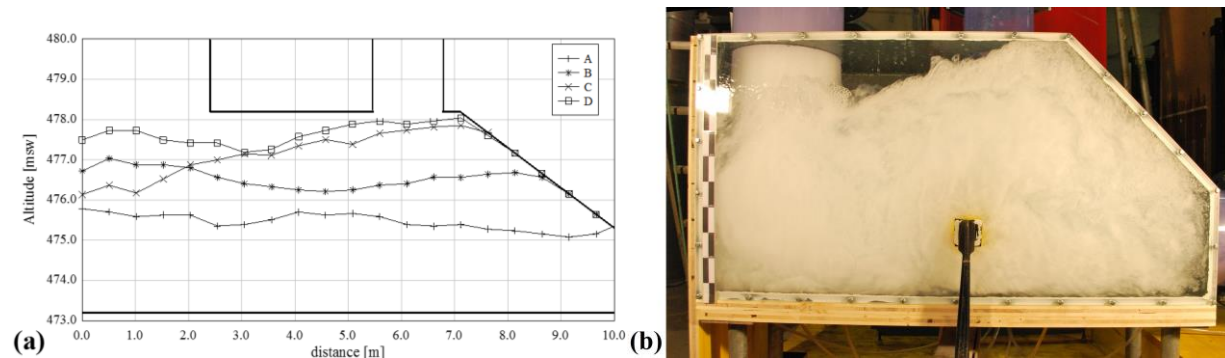

Figure 9. (a): Free-surface profiles in the dissipation chamber, and (b) mixture flow pattern for scenario D

5. CONCLUSIONS

A new vortex drop shaft is planned in Cossonay (Switzerland) with a design discharge of 12.61 m³/s, a total drop height of around 120 m, and a shaft diameter of 2.40 m. It replaces the existing vortex drop shaft, which was affected by several hydraulic and geotechnical constraints. The proposed concept herein combines several inflow collectors arriving at various elevations with a standard vortex drop shaft. A common junction chamber merges four collectors, minimizing the construction volume and providing only one single inlet channel. This technical solution has never been discussed systematically in the literature, so a detailed hydraulic design was required.

A preliminary "manual" hydraulic design indicated the geometry of all individual components according to the standard recommendations. In the frame of a numerical simulation, the hydraulic behavior of the inlet structure elements (collectors, junction chamber, inlet channel) was verified. The simulations showed which modifications to the inlet structure geometry were required, namely a global rotation of the structure to improve the flow features in the chamber, the set-up of the chamber with a sill and a beam, and the slope of the inlet channel.

Physical tests in a scale model (1:7.82) were carried out to verify the design of the entire structure. The overall performance of the vortex drop shaft was adequate. Choking and pulsations phenomena were absent during the design discharge run. Furthermore, the physical model results showed that vortex drop shaft discharge capacity was larger than the design value.

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