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AIR DEMAND OF BOTTOM OUTLETS: INSIGHTS FROM SCALE MODEL TESTS AND PROTOTYPE MEASUREMENTS *

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1. INTRODUCTION

Bottom outlets (BOs) are a key safety feature of high-head dams. Their main purpose is the regulation and – if required - a fast drawdown of the reservoir water level in case of floods, structural damage of the dam or maintenance works. Additional purposes include residual flow release, flood diversion or sediment flushing. The large energy heads at the gate lead to a high-speed free-surface flow in the BO tunnel with flow velocities up to some 50 m/s for high dams. These large flow velocities and the high turbulence levels lead to considerable air entrainment and air transport, possibly resulting in negative pressures in the BO. This can cause problems with gate vibrations, cavitation and flow chocking. Sufficient air supply via an aeration chamber can mitigate these problems. Available design equations for the required air demand to prevent excessive negative pressures are based on scale model tests and prototype measurements. Most of these equations express the air demand β as a function of the Froude number at the vena contracta F_c. However, measured and predicted β-values show a large scatter. Some of the scatter can be explained by the different flow patterns. The remaining scatter can be explained with the neglect of crucial parameters in the design equation like the air vent loss coefficient ζ or the tunnel length L. This project aims to investigate the

* *Aération des vidanges de fond: Résultats des essais sur modèle à échelle réduite et des mesures en prototype*

effect of those parameters with small-scale model tests. The employed scale model exceeds most previous model studies in terms of energy head H_E and water discharge Q_w. Nevertheless, scale and model effects still need to be addressed carefully. Detailed prototype data are crucial for the validation and upscaling of model results. Therefore, this project additionally includes air demand measurements at three bottom and one middle outlet(s) in southern Switzerland.

2. SCALE MODEL TESTS

2.1. MODEL SETUP AND INSTRUMENTATION

A physical bottom outlet model was built at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich (Fig. 1a). Two pumps provide a maximum energy head at the gate of H_E = 30 m w.c. at a water discharge of $Q_w \approx$ 600 l/s. The rectangular sharp-crested gate is 0.2 m wide, 0.25 m high and the downstream tunnel extends to a height of h_t = 0.3 m (Fig. 1b). The horizontal BO tunnel has a maximum length of L = 20.6 m which can be varied due to detachable elements. The aeration chamber is connected to a circular air vent of diameter d = 0.15 m which can be throttled with an orifice plate to vary the loss coefficient ζ of the whole aeration system. A similar air vent is located at the tunnel end to measure the airflow into or out of the tunnel. All channel walls consist of PVC or acrylic glass with a hydraulic roughness of k = 0.003 mm.

Q_w is measured with an inductive flow meter with an accuracy of ±0.5% of the measurement value (MV) and ±0.4 l/s absolute error. The air flow velocity in the air vent $U_{a,o}$ is measured with a thermal anemometer while the air flow velocity at the tunnel end $U_{a,u}$ is measured with a bidirectional vane anemometer. The thermal anemometer has an accuracy of ±2.5% of MV and the vane anemometer has an accuracy of ±1.5% of MV ±0.2 m/s. From the measured velocity, the air discharges $Q_{a,o}$ and $Q_{a,u}$ are computed assuming a logarithmic velocity profile. The cross section above the air-water mixture is blocked with a gate at the tunnel end. Consequently the air has to be supplied through the second air vent which allows for a precise measurement of $Q_{a,u}$. A total of 40 relative pressure sensors with a measurement range of ±100 mbar and an accuracy of ±1 mbar are installed at the invert and the soffit along the tunnel centerline to measure both the water (subscript *w*) and air pressures (subscript *a*), respectively.

The following parameters were varied in the model tests: The relative gate opening a/a_{max} was increased from 0.1 to 1 in steps of 0.1. For each a/a_{max}, H_E was varied from 5 to 30 m w.c. in steps of 5 m w.c. and six ζ-values were tested, ζ = 0.7, 2.7, 9, 19, 28 and 57. All parameter combinations were tested for tunnel lengths of L = 20.6, 12.6 and 6.6 m. Combinations of H_E > 20 m w.c. and ζ > 10 could not be measured due to strong flow pulsations. Large relative gate openings of a/a_{max} > 0.8 led to a drowning of the aeration chamber and were thus excluded from the measurements.

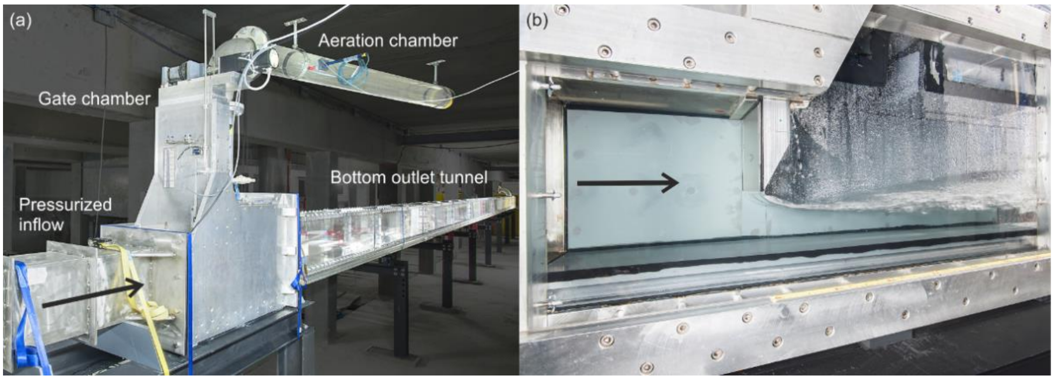

Fig. 1
(a) Physical scale model of a bottom outlet at VAW, (b) gate chamber
(a) Modèle à échelle réduite d'une vidange de fond à la VAW, (b) chambre de la vanne

2.2. AIR DEMAND IN MODEL TESTS

The air discharge $Q_{a,o}$ through the aeration chamber increases with increasing H_E and attains a maximum for moderate relative gate openings 0.4 ≤ a/a_{max} ≤ 0.6 (Fig. 2a). The maximum is shifted towards smaller a/a_{max} for increasing H_E.

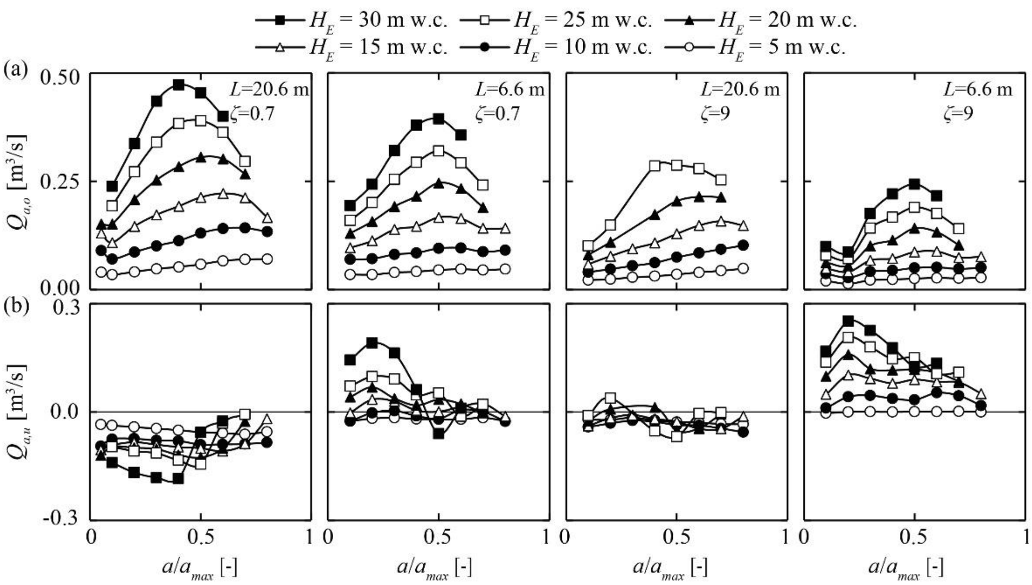

Fig. 2
(a) $Q_{a,o}$ and (b) $Q_{a,u}$ for different values of a/a_{max}, H_E, L and ζ
(a) $Q_{a,o}$ et (b) $Q_{a,u}$ pour des valeurs différentes de a/a_{max}, H_E, L et ζ

The sudden increase of $Q_{a,o}$ for $a/a_{max} \approx 0.05$ is caused by the transition to spray flow. At large a/a_{max} the air flow rate is decreasing again, especially for large H_E. This is due to the transition to foamy flow with the tunnel almost flowing full at the tunnel end. The reduced cross-sectional area above the air-water mixture for foamy flow allows less air to be dragged along with the flow. $Q_{a,u}$ is negative for moderate a/a_{max}, low ζ value and long tunnel, indicating a net air flow out of the tunnel at the downstream end. For foamy flow conditions $Q_{a,u}$ increases to zero, whereas spray flow leads to a slight decrease of $Q_{a,u}$ (Fig. 2b). An increase in ζ drastically reduces $Q_{a,o}$, while simultaneously increasing $Q_{a,u}$, resulting in a net air flow into the tunnel from the downstream (Fig. 2). The decrease in $Q_{a,o}$ and the increase in $Q_{a,u}$ are even more pronounced for short tunnels as air can enter more easily from the downstream tunnel end.

The minimal air pressure in the gate chamber $p_{a,min}$ depends on $Q_{a,o}$ and ζ. With all other parameters kept constant, an increase in ζ leads to a simultaneous decrease of $Q_{a,o}$ and $p_{a,min}$. The magnitude of decrease of each quantity in turn depends on a/a_{max}, H_E and L.

3. PROTOTYPE MEASUREMENTS

3.1. TEST SITES

The two BOs of the arch dam Malvaglia and the BO and middle outlet (MO) of the arch dam Luzzone in the Canton of Ticion, southern Switzerland were equipped with measurement devices. All outlets are usually operated once a year to flush sediments out of the reservoir. Additionally, a mandatory function test requires the test of small gate openings once a year. All three outlets are equipped with sluice gates. Luzzone features a maximum static head $H_{o,m}$ of 224 m w.c. for the BO and 120 m w.c. for the MO. Malvaglia has two BOs, an old and a new one with $H_{o,m}$ = 94 m w.c. and $H_{o,m}$ = 91 m w.c., respectively. The new BO was specifically built to flush sediments from the intake vicinity. The old BO features a circular tunnel with a diameter of d = 4.3 m, whereas the new BO has a 2 m wide, 2.5 m high horseshoe profile. Both outlet tunnels join a common outlet tunnel (d = 5.6 m) to which the spillway is also connected (Fig. 3). The tunnel conjunction is well aerated what leads to effective tunnel lengths of L = 67 m and L = 82 m for the old and new BO. Up to now only measurements during a function test in Malvaglia could be conducted.

3.2. PROTOTYPE INSTRUMENTATION

The instrumentation applied at Malvaglia Dam and their accuracy are listed in Table 1, and a sketch of the measurement setup is shown in Fig. 3.

The following parameters were measured:

- $Q_{a,o}$: To measure the air flow velocity $U_{a,o}$ in the air vent, vane anemometers were mounted at two locations in the center of the air vent cross section. $Q_{a,o}$ was calculated assuming that the measured velocity $U_{a,o}$ corresponds to 110% of the mean air velocity in the air vent.
- p_a: Absolute pressure sensors were installed in both gate chambers, in the middle of both tunnels and at the tunnel conjunction.
- Air velocity at the end of the outlet tunnel $U_{a,u}$: Bidirectional vane anemometers were installed in the upper half of the tunnel cross section at the end of both tunnels to measure air flowing out of or into the BO tunnel.
- Air temperature T_a: Temperature sensors were installed at two locations in the air vent; in the horizontal part and at the end of the air vent in the new BO.

Additionally, video cameras were installed in both gate chambers and at the tunnel conjunction.

Table 1
Overview on measurement devices and accuracy, symbols refer to Fig. 3

Symbol	Type	Name	Range	Accuracy
U1, U2	unidirectional vane	Höntzsch ZS25-mn120	1.4 - 120 m/s	± (1.5% of MV + 0.6 m/s)
U3 - U5	bidirectional vane	Höntzsch ZSR25-mn120	–60 - 60 m/s	± (1.5% of MV + 0.6 m/s)
U6, U7	bidirectional vane	Schiltknecht Air	–40 - 40 m/s	± (1.5% of MV + 1 m/s)
P1 - P5	absolute pressure sensor	Keller PAA-26 W	700 - 1200 mbar	± 2.5 mbar
R	flow direction indicator	VAW-made	0 - 360°	± 2°
T1, T2	Air temperature	Arthur-Grillo MTA90-P	–30 - 40°C	± (0.25% of MV + 0.15°C)

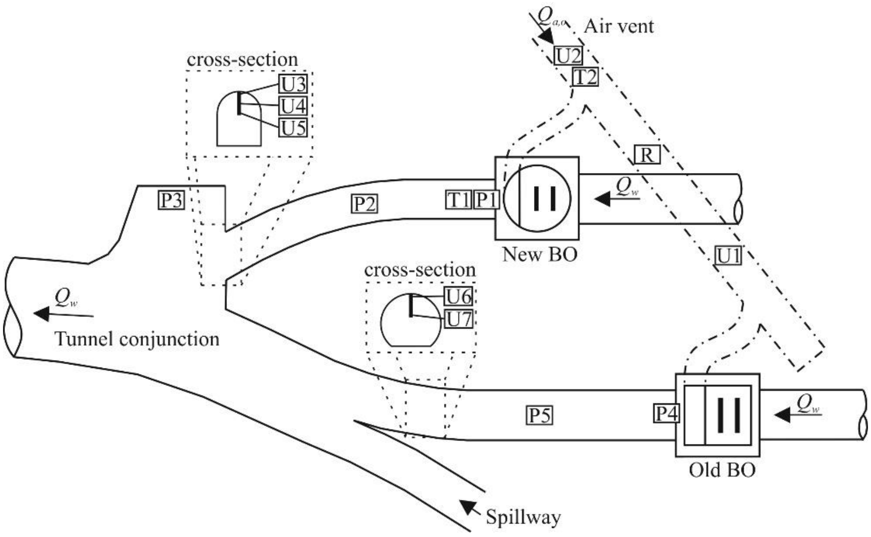

Fig. 3
Sketch of the measurement setup at Malvaglia Dam (not to scale)
Esquisse de la configuration de mesure au barrage Malvaglia (pas à l'échelle)

Two different gate openings were tested for both BOs: a = 0.05, 0.1 m for the old BO and a = 0.1, 0.2 m for the new BO, respectively. Only one BO was in operation at a time. The reservoir water level varied from 980 to 980.9 m asl. during the test, resulting in an average static pressure head of H_E = 84.7 m w.c. for the old BO and H_E = 81.6 m w.c for the new BO. An average air temperature T_a of 9°C was used to calculate ρ_a, resulting in ρ_a = 1.12 kg/m^3 at ~900 m asl. To show the overall trend, the measurements were averaged over 5 s in the following figures. Additionally, the original 10 Hz measurements are shown as thin lines. To calculate characteristic numbers (e.g. β, ζ), the measurement were averaged over the duration of each gate opening. ζ was calculated as $\zeta = 2\Delta p_a/(\rho_a U_{a,ov}^2) - 1$, where Δp_a is the air pressure drop in the gate chamber $\Delta p_a = p_a(t{=}0) - p_a(t)$. The Q_w-values for the calculation of $\beta = Q_{a,o}/Q_w$ were provided by the dam operator.

3.3. RESULTS OF BOTTOM OUTLETS MALVAGLIA

Table 2 summarizes the measurement results and Fig. 4 shows detailed results for the new BO. If only the new BO is in operation, an equal amount of air is supplied through the air vent and the old BO tunnel (U1 and U2 in Fig. 4a). $U_{a,o}$ is slightly higher for a = 0.1 m compared to a = 0.2 m. This can partly be explained by the transition from spray flow to free-surface flow for a = 0.2 m (Fig. 5). The sudden rise in $U_{a,o}$ during the closing of the gate is also caused by a more intense spray formation for a < 0.1 m. For spray flow, i.e. a = 0.1 m, air is flowing out of the tunnel end, whereas for a = 0.2 m air is entering the tunnel from downstream (Fig. 4b). $U_{a,u}$ is significantly lower than the air-water mixture velocity of ~12 m/s (estimated after [1]). The drop of p_a is clearly visible in the gate chamber (P1) and to a lesser extent after half of the tunnel length (P2) (Fig. 4). At P1, more pronounced pressure transients were observed, particularly during gate closure, whereas these transients have already disappeared at P2. No considerable variation in pressure can be observed in the tunnel conjunction (P3), showing that the conjunction is sufficiently aerated from downstream.

Table 2
Overview of the measurement results in Malvaglia

name	Q_w [m^3/s]	a [m]	a/a_{max} [-]	F_c [-]	$Q_{a,o}$ [m^3/s]	Δp_a [mbar]	ζ [-]	β [-]
new BO	2.5	0.1	0.08	52	17.7	5.2	2.6	7.1
new BO	5.0	0.2	0.15	36	15.0	3.9	2.8	3.0
new BO	2.5	0.1	0.08	52	17.1	6.3	3.7	6.8
old BO	2.4	0.05	0.03	61	15.2	7.5	5.8	6.3
old BO	5.0	0.1	0.06	43	27.1	23.7	5.8	5.4
old BO	2.4	0.05	0.03	61	11.7	4.5	5.9	4.9

For the old BO no transition to free-surface flow was observed for the larger gate opening a = 0.1 m. On the contrary, the old BO showed an even stronger spray formation for a = 0.1 m (Fig. 5). Consequently $Q_{a,o}$ increased with increasing a for the old BO.

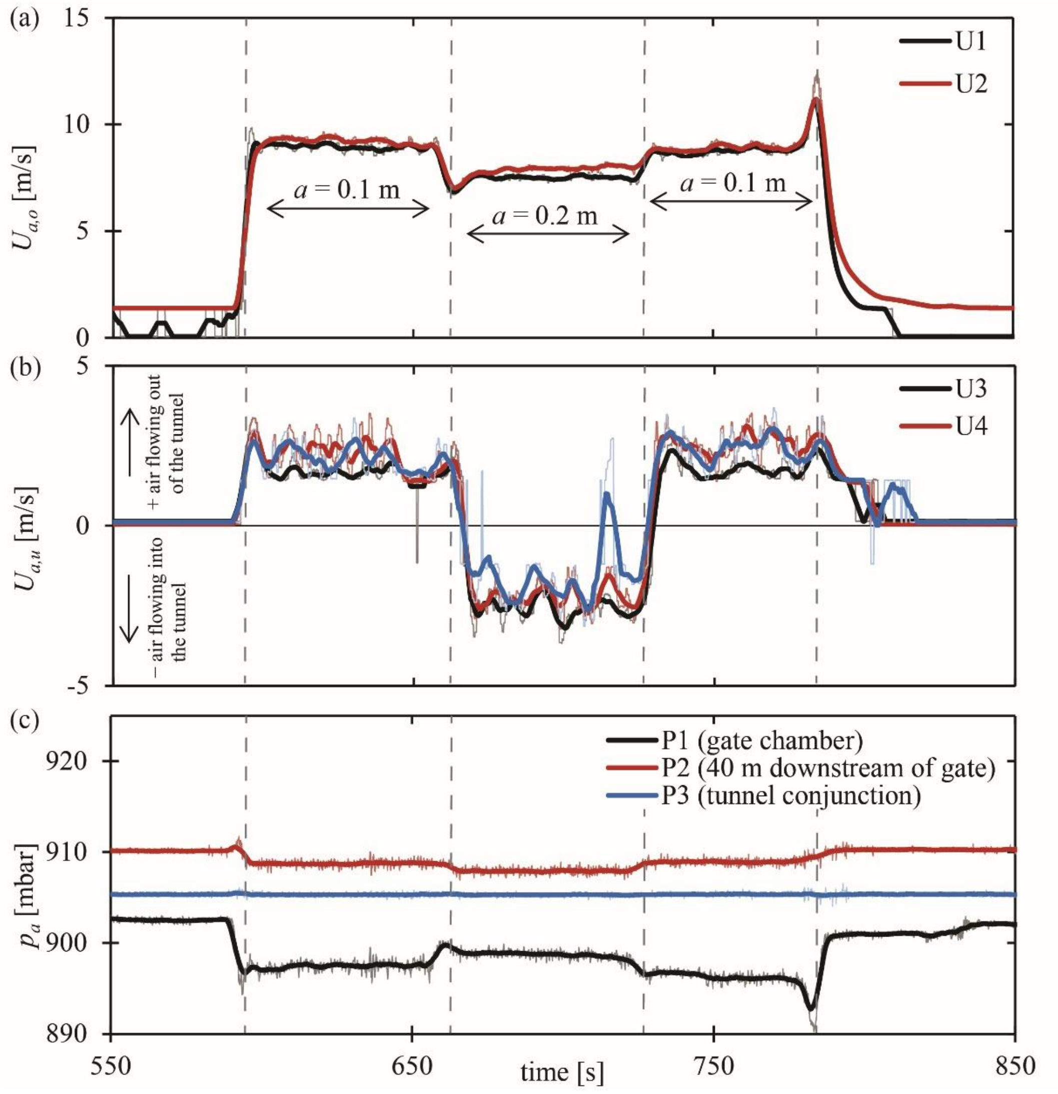

Fig. 4

Measurements for the new BO (a) $U_{a,o}$, (b) $U_{a,u}$ and (c) p_a at different locations

Valeurs mesurées pour la nouvelle VF (a) $U_{a,o}$, (b) $U_{a,u}$ et (c) p_a aux lieux différents

4. DISCUSSION

Both the model and prototype data demonstrate the significant influence of the flow pattern on $Q_{a,o}$, $Q_{a,u}$ and p_a. The scale model data also clearly show the importance of L and ζ for the aforementioned quantities. The importance of ζ is also supported by the prototype data, i.e. the fact that the new BO exhibits larger β-values than the old BO despite smaller F_c and less intense spray can be attributed to the smaller ζ-value.

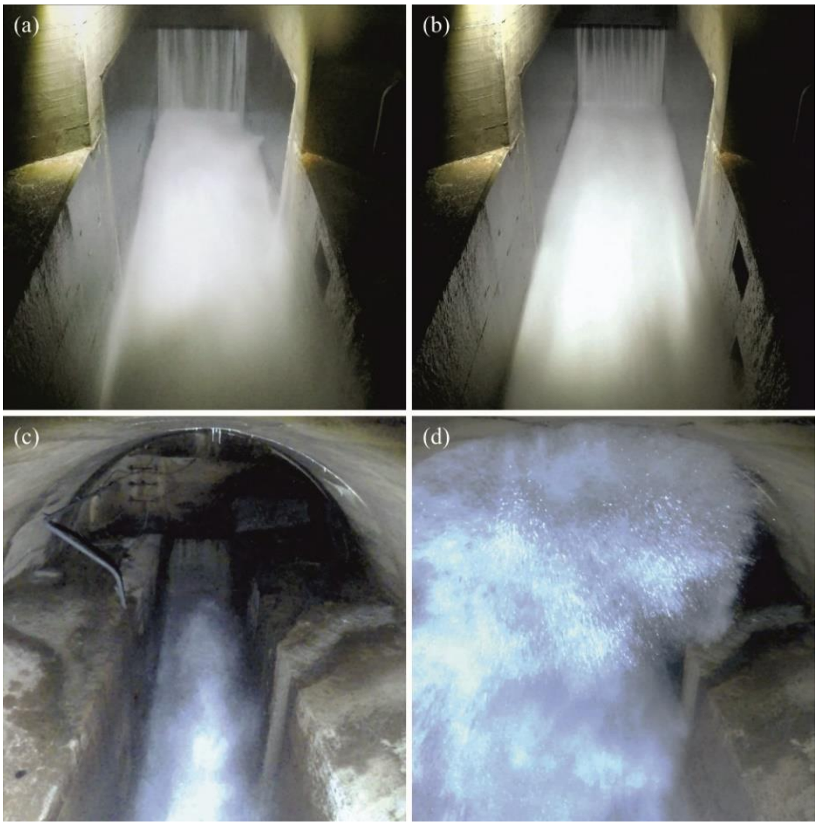

Fig. 5
Bottom outlet sluice gate in operation (a) new BO a = 0.1 m, (b) new BO a = 0.2 m, (c) old BO a = 0.05 m and (d) old BO a = 0.1 m.
Vanne de vidanges de fond (VF) en opération (a) nouvelle VF a = 0.1 m, (b) nouvelle VF a = 0.2 m, (c) vielle VF a = 0.05 m and (d) vielle VF a = 0.1 m.

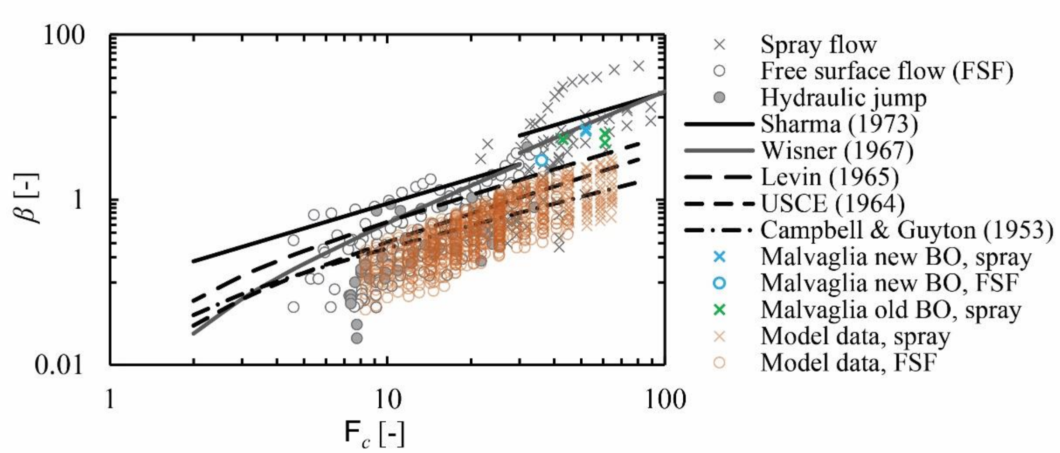

Fig. 6
Comparison of prototype data from literature [2] and design equations with model data and new prototype measurements
Comparaison des mesures en prototype de la littérature [2] et des équations avec des mesures du modèle à échelle réduite et nouvelles mesures en prototype

The new prototype air demand data are moderate to high compared with existing prototype measurements (Fig. 6, [2]). The large scatter in the model data is due to the varying ζ and L. Actually the model data for a given combination of ζ and L is reasonably described by a power law relation $\beta = a\mathrm{F}_c^{\,b}$, where a, b are dependent on ζ and L. While the model data shows a good agreement with existing prototype data and equations for free-surface flow, the model data tend to underestimate β for spray flow conditions. Indeed the gas Weber number and the Ohnesorge number indicate that the secondary disintegration of droplets is subject to scale effects i.e. the spray is less pronounced in the model. Additionally the model sluice gate has no gate slots which are a main cause for spray formation [8].

5. CONCLUSIONS

A systematic physical scale model study on the air demand of bottom outlets was performed. The results show that the air demand decreases with increasing air vent resistance and decreasing tunnel length. The flow pattern has a decisive influence on the air demand with the maximum air demand occurring for spray flow. The highest air discharge was observed for free-surface flow. New prototype measurements conducted in two bottom outlets in Switzerland support the main findings of the scale model test. Differences were observed for spray flow conditions, where the local gate geometry plays a crucial role.

ACKNOWLEDGEMENTS

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SUMMARY

Bottom outlets (BOs) are a key safety feature of high-head dams. The high-speed free-surface flow in the BO tunnel leads to considerable air entrainment and air transport, resulting in negative pressures in the outlet tunnel. Current knowledge does not allow a coherent design of the air vent needed to mitigate problems due to negative pressures as e.g. gate vibrations and cavitation. Extensive model test conducted in this project showed that: (i) the flow pattern strongly influences the air demand with spray flow resulting in maximal values; (ii) the air demand decreases with increasing air vent loss coefficient, while the air pressure consequently decreases; and (iii) a shorter tunnel length reduces the air demand as air can enter more easily from the downstream end. New prototype data collected in two BOs in Switzerland support these findings.

Des vidanges de fond (VF) sont des structures importantes pour des grands barrages. L'écoulement à surface libre à grande vitesse mène à l'entraînement et transport de l'air résultant en pressions négatives dans le conduit. La connaissance actuelle ne permet pas une conception cohérente du conduit d'aération lequel est pourtant nécessaire pour atténuer les problèmes de vibration des vannes et de cavitation. Des expériences extensifs sur modèle à échelle réduite mênés dans ce projet ont montré le suivant : (i) le régime d'écoulement influence fortement la demande d'air avec un maximum pour le régime « spray », (ii) la demande d'air diminue pour une augmentation du coefficient de perte du conduit d'air tandis que par conséquent la pression diminue et (iii) un conduit plus court diminue la demande d'air parce que l'air peux entrer plus facile par la fin du conduit en aval. Les résultats principaux des essais sur modèle à échelle réduite sont soutenus par des nouveaux essais de prototype.

KEYWORDS

AERATION, BOTTOM OUTLET, FIELD TEST, MALVAGLIA, LUZZONE, PHYSICAL MODEL,

AERATION, ESSAI EN PLACE, LUZZONE, MALVAGLIA, MODELE PHYSIQUE, VIDANGE DE FOND