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VENTING OF TURBIDITY CURRENTS: WHEN TO ACT?

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ABSTRACT

During floods, sediments are transported from watersheds into reservoirs, slowly decreasing water volumes and this leading to economic losses. Thus, in the long term, sedimentation endangers reservoirs' sustainability. Sediments can also block low-level hydraulic structures such as bottom outlets and powerhouse intakes and cause abrasion of gates and turbines. Additionally, the trapped sediments induce downstream starvation and thus the impoverishment of the river's morphology and ecosystem. Many measures are taken to deal with the sedimentation of reservoirs. Among the most common methods is venting turbidity currents approaching the dam. In fact, these sediment-laden currents carry the major part of sediments found near the dam and thus their evacuation before they settle can be a very effective method to reduce sedimentation. However, dam operators lack information and guidelines to perform efficient venting operations. The present research experimentally and numerically investigates the venting of turbidity currents applied with different timings of outlet opening: (1) before the current reaches the outlet, (2) after the current has reached the outlet and climbed up to the top of the dam, and (3) after the upstream reflection of the muddy lake has begun. The high data acquisition frequency offers the possibility to examine temporal variations of inflow and outflow concentrations and discharges and thus variations of the efficiency of venting in time during the tests. In addition, the experimental results are extended numerically for a better understanding of the effect of opening timing on venting. Results show that opening the outlet before the current reaches the wall can be more efficient than opening after the current has reached the wall. Outputs of this study lead to crucial information for dam operators dealing with reservoirs facing high sedimentation rates due to the formation of turbidity currents.

Keywords: Reservoir sedimentation; turbidity currents; venting; bottom outlets; timing.

1 INTRODUCTION

The management of reservoirs to ensure their sustainability is a task that requires technical intervention on many levels. It includes works of maintenance, management of operations under different hydrological conditions, adaptation to possible changes in demands, and most importantly making sure the capacity of reservoirs is not significantly reduced. Sedimentation is a serious problem affecting reservoirs worldwide (Schleiss et al., 2016).

In order to reduce the impact of sedimentation, different methods exist to remove the deposited sediments. One of the most common techniques is to open the outlets and drawdown of the water level, causing retrogressive erosion and moving sediments towards the downstream river. This method is called free-flow flushing (Brandt, 2000). Another method is to mechanically dredge (wet or dry) the sediments, transporting them from upstream to downstream of the dam or other dump areas. However, these methods can be harmful for the downstream environment since large amounts of sediments are introduced in the river in a short time compared to the natural transport process (Espa et al., 2016). Other methods take place in the watershed to bypass or block sediments (Kantoush and Sumi, 2010).

In some cases, however, sediment-laden flows form and plunge below the clear water surface of the reservoir due to their higher density. They are called turbidity currents. Depending on the reservoir's geometry, the sediment concentration and also temperature differences (between the current and the clear water), a turbidity current can travel long distances until reaching the dam. The current then rebounds, its kinetic energy is transformed into potential energy and it climbs up the dam before reflecting upstream. A muddy lake is formed during this process and if no low-level outlets or intakes are opened, the sediments of the muddy lake settle and consolidate. Sediments depositing close to the dam not only reduce the reservoir's capacity but can also obstruct/abrade hydraulic structures (e.g., low-level outlets, turbines, intakes). In order to avoid such consequences, a direct transit or venting of turbidity currents reaching the dam through outlets is the most adequate technique if well performed. Besides reducing the amount of sediments in the vicinity of the dam, venting can be beneficial for the downstream environment and relatively economic since it is performed using relatively low outlet discharges.

However, this technique requires information on the turbidity currents and thus their monitoring, which can be costly. Moreover, guidelines on the operational conditions that can lead to high release efficiencies are also needed. In this context, several knowledge gaps exist and optimal conditions to perform efficient venting have not been sufficiently investigated. Researchers have highlighted the importance of this technique in the past (Bell, 1942; Chen and Zhao, 1992; Fan and Morris, 1992; Morris and Fan, 1997; Müller and De Cesare, 2009; Nizery et al., 1952; Schneider et al., 2007) but very few have performed quantitative research on the subject (Yu et al., 2004; Lee et al., 2014; Chamoun et al., 2017). Based on literature and particularly on field data, some influential parameters can be determined. Among these parameters is the timing of the outlet opening.

In the present work, venting of turbidity currents is investigated using an experimental set-up, as well as a numerical analysis. The effect of the opening timing of a bottom outlet on the amount of sediments that are evacuated is studied. The experimental model and procedure are firstly described, followed by the tests' boundary conditions and experimental results. The numerical model is then briefly described and more insight on the operation of venting under different timings is given.

2 EXPERIMENTAL SET-UP AND MATERIAL

The experimental set-up is formed by a long (L = 8.55 m) and narrow flume (b = 0.27 m) with a 1 m height. A mixing tank serves the purpose for the preparation of the water-sediment mixture (Figure 1.e). The flume is divided into three parts: (i) the head tank located in the upstream part of the flume and connected to the mixing tank using two pipes, a ''pumping pipe'' (Figure 2) that serves to pump the mixture from the mixing tank into the head tank and a ''restitution pipe'' used to siphon the mixture back into the mixing tank; (ii) the main flume which has a length of 6.7 m represents the reservoir in which the turbidity current is triggered; and (iii) a downstream compartment that receives residual clear water from the main flume while the turbidity current advances. The inlet consists of a tranquilizer of 4.5 cm height (Figure 1.c). It links the head tank to the main flume when the sliding gate is opened. A wall (0.8 m height for the 2.4% slope and 0.92 m for the 5% slope) is placed at 6.7 m from the inlet. It represents the dam with a rectangular outlet placed at its bottom (Figure 1.b). The outlet is centered on the width of the flume. It has a height of 12 cm and a width of 9 cm. A downstream tank is located at the exit of the outlet and receives the vented turbidity current.

Note that for the cases where the outflow is larger than the inflow and in order to avoid the decrease of the water level in the main flume, a part of the spilled clear water in the downstream compartment of the flume is pumped back into the main flume through a ''recirculation pipe''. A diffusor placed above the inlet (Figure 1.c) receives this ''residual'' water and homogeneously divides it over its height.

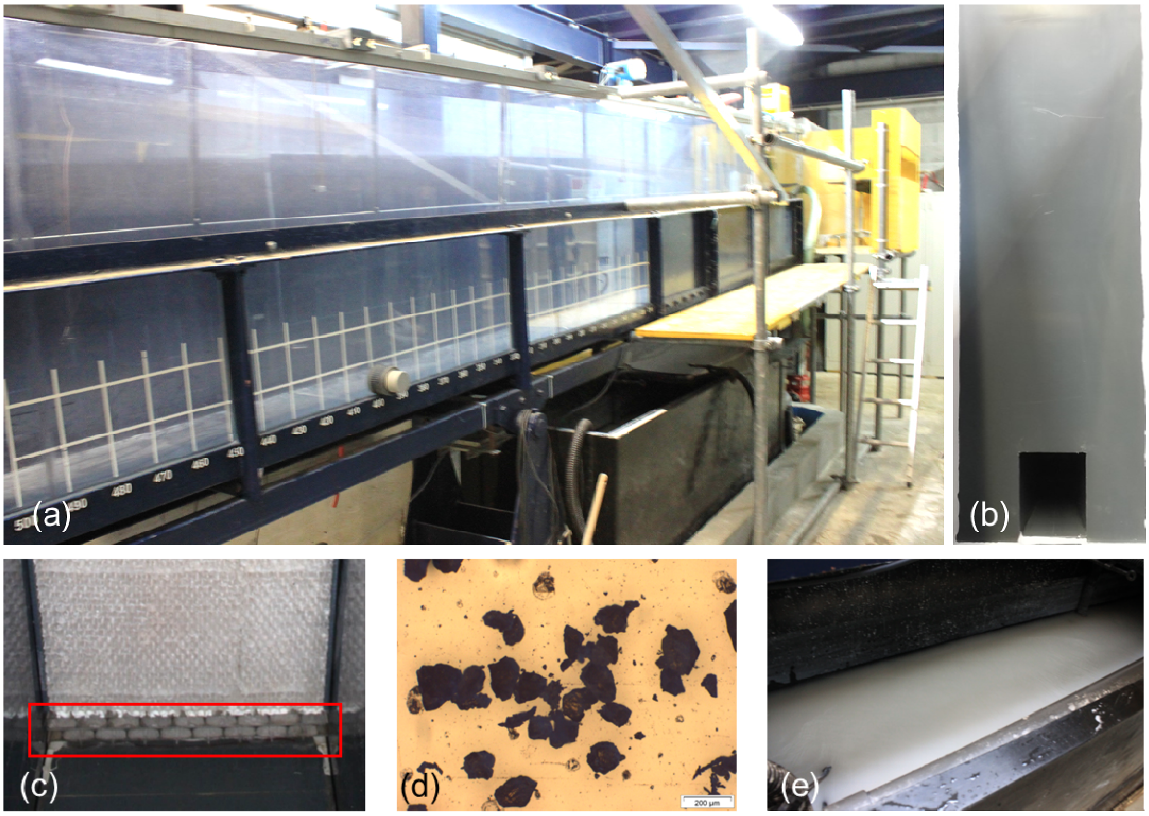

Figure 1. Experimental set-up showing (a) the main flume (b) the bottom outlet and the wall (c) the inlet highlighted in red below part of the diffusor (d) a microscopic photo of the sediment material and (e) the sediment-water mixture in the mixing tank before the beginning of a test.

2.1 Sediment material

A thermoplastic polyurethane (polymer) powder is used to simulate the sediments contained in the turbidity currents. It has a particle density of ρ_s = 1160 kg/m^3 and diameters of d_{10} = 66.5 μm, d_{50} = 140 μm, and d_{90} = 214 μm, where d_x represents the diameter for which x% of the sediments have smaller diameters. As shown in the microscopic photo, the sediments are angular (Figure 1.d). The settling velocity is thus not only estimated using Stokes' Law (appropriate for spherical particles) but also using an empirical formula proposed by Cheng (1997) for natural sediments. An average settling velocity v_s = 1.5 mm/s is considered.

3 PROCEDURE

At the beginning of each test, the main flume was filled with clear water up to the height of the downstream wall and the water-sediment mixture was simultaneously prepared in the mixing tank. The latter was equipped with a submerged pump that keeps the sediments suspended before and during the test. After adding the adequate mass of sediments, the mixture was pumped into the head tank and recirculated between the two compartments for a few minutes. This procedure ensures the homogeneity of the mixture and lasts until reaching the fixed concentration of the test in the head tank. The recirculation was then stopped and the sliding gate was opened triggering a turbidity current inside the main flume. Due to its higher density, the latter advanced on the bed of the flume below the clear water. Depending on the timing of opening tested, the bottom outlet was operated and the evacuated flow reached the downstream tank where discharge and concentration were measured.

3.1 Measurements

Several measuring instruments are employed throughout the tests. The different parameters monitored and the locations of the instruments are summarized in Table 1 and Figure 2. Inflow conditions in terms of discharge and concentrations were kept as steady as possible during one test and between the different tests. Temperature measurements serve to check that density differences between the mixture and the clear water is majorly due to the suspended sediments and not affected by temperature differences. More details about the measuring techniques and accuracy can be found in Chamoun et al., (2017).

Table 1. List of the measuring instruments and parameters measured.

Instrument	Parameter	Location
Turbidity probe	Concentration C_{TC} and C_{VENT}	Head tank; Downstream tank
Flowmeter	Discharge Q_{TC}, Q_{VENT} and Q_{res}	Pumping, venting, and recirculation pipes
Depositometer	Deposition	62 different points at the bed of the flume
Level probe	Water level	Head tank; main flume
UVP transducer	Velocity profile	2.8 m, 4.1 m, 5.5 m, 5.8 m, 6.0 m, and 6.2 m from the inlet
Thermometer	Temperature	Head tank; Downstream tank
Camera	Photos/videos	Facing the channel

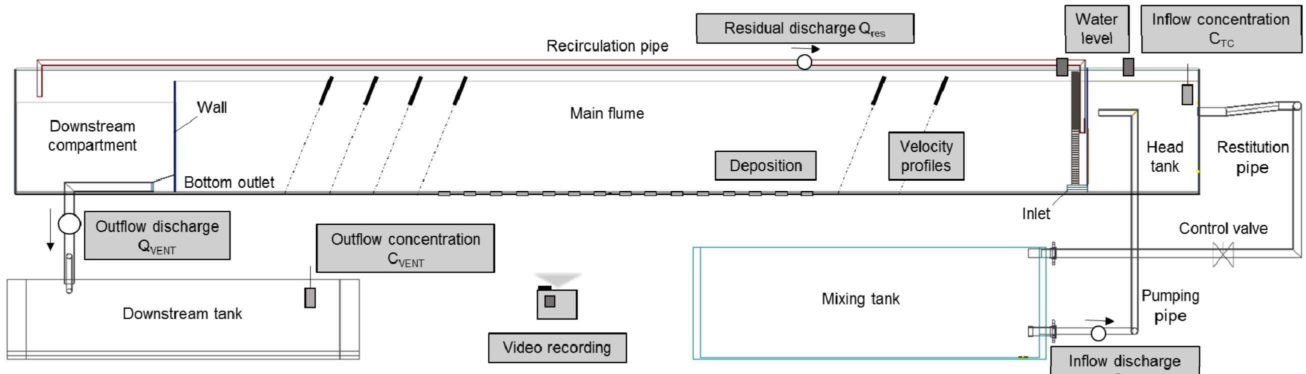

Figure 2. Scheme of the experimental set-up summarizing the different measurements (in gray highlight).

4 EXPERIMENTAL RESULTS

4.1 Tests

The characteristics of the tests considered for the present paper are listed in Table 2. Two different bed slopes are used: 2.4% and 5%. The initial concentration C_{TC} and density ρ_{t0} of the turbidity currents are shown. The tested ratio Φ between outflow discharge and turbidity current inflow discharge is 115% for all the cases. Three different timings of outlet opening are tested: (i) before the arrival of the turbidity current to the bottom outlet, at a distance d/h = 5, where d is the distance from the outlet and h is the height of the outlet (12 cm); (ii) after the arrival of the turbidity current to the bottom outlet and when it has climbed up the wall and reached its top (~ 30s after arrival); and (iii) after the formation of the muddy lake and the beginning of the reflection of the turbidity current upstream (~ 60s after arrival).

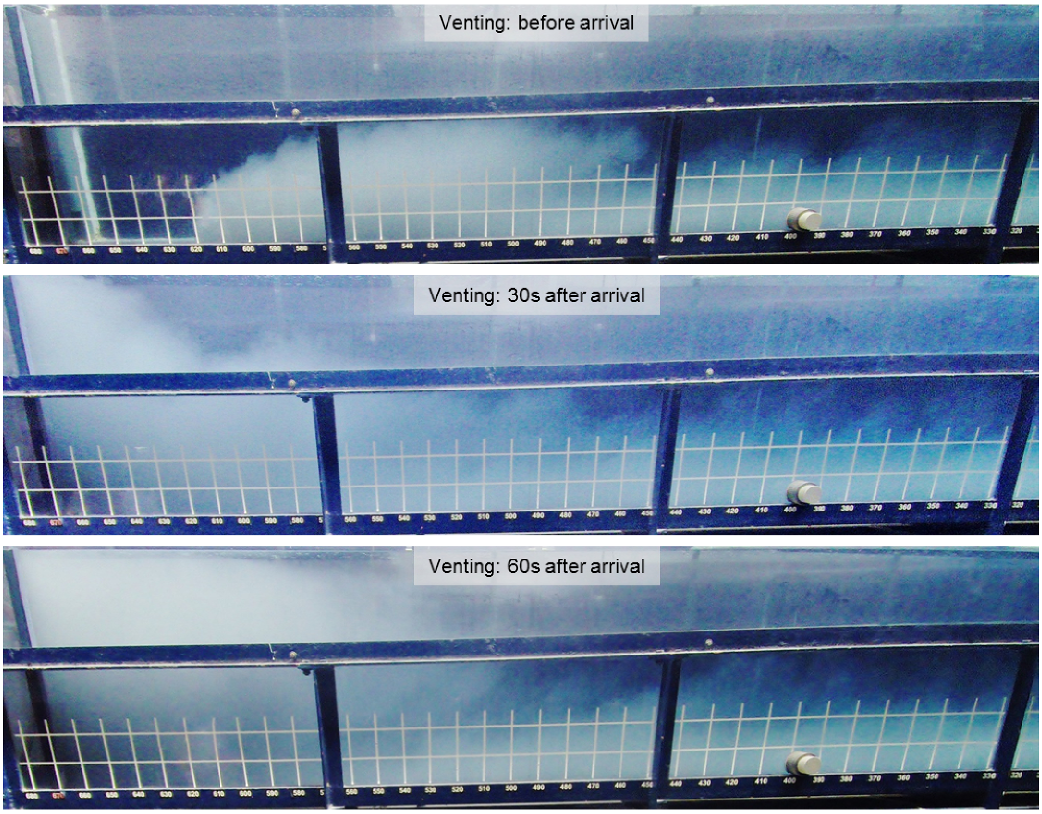

Figure 3. The different outlet opening timings tested (2.4% slope).

Table 2. Characteristics of the tests.

Test number	Slope s (%)	Initial concentration C_{TC} (g/l)	Initial density ρ_{t0} (kg/m^3)	Venting degree Φ (%)	Timing of outlet opening
T1.b	2.4	20.0	1002.4	115	Before d/h = 5
T1.a30	2.4	27.4	1003.4	115	After 30 s
T1.a60	2.4	28.0	1003.5	115	After 60 s
T2.b	5.0	27.8	1003.5	115	Before d/h = 5
T2.a30	5.0	26.0	1003.2	115	After 30 s
T2.a60	5.0	26.2	1003.3	115	After 60 s

4.2 Outflow concentration

The outflow concentration was measured at the downstream tank where the vented current is restituted. The frequency of the measurement is high enough (2.75 Hz) to detect the detailed temporal variation of the outflow concentration. As shown in Figure 4, the concentration increases once the vented current reaches the downstream tank before slightly decreasing and becoming quasi-steady. This behavior is observed for all the tests with more or less the same trend, and only with different slope of the phase preceding the quasi-steady state.

Outflow concentrations were used to deduce two important parameters, which are the reduced gravity acceleration of the turbidity current while approaching the wall and the height of aspiration of the outlet . Both require the value of the density of the turbidity current in the approaching phase right before venting starts (in the vicinity of the wall). However, this value was not measured. Therefore, the highlighted part of the outflow concentration (Figure 4) is averaged and considered as representative of the concentration of the body of the current reaching the wall. The concentration at the approaching phase is called C_{app}. The height of aspiration h_L represents the height that the outlet can reach above its central axis to vent the dense fluid approaching it. It is expressed as such (Craya, 1949; Gariel, 1949; Fan, 1960):

$$\left[\frac{\Delta\rho}{\rho_w}\frac{g(-h_L)^5}{Q_{VENT}^2}\right]^{1/5} = -1.2 \qquad [1]$$

where $\Delta\rho = \rho_{tapp} - \rho_w$ represents the density difference between the approaching turbidity current ρ_{tapp} and the clear water ρ_w and g is the gravitational acceleration. According to Graf and Altinakar (1995), the density of the turbidity current approaching the outlet is $\rho_{tapp} = C_{app}\rho_s + (1-C_{app})\rho_w$ and thus the reduced gravity acceleration of the current is $g'_{app} = g[(\rho_s-\rho_w)/\rho_w]C_{app}$.

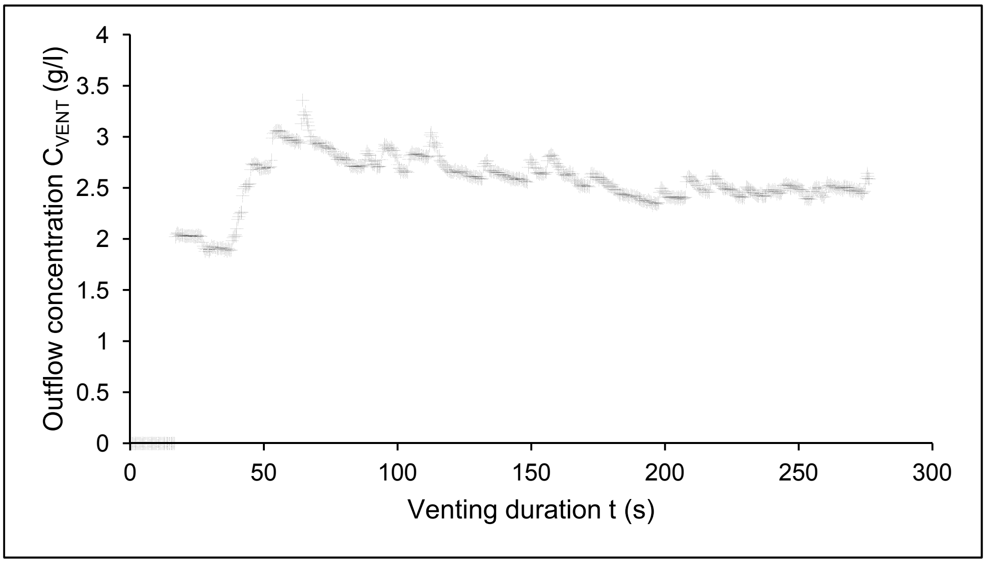

Figure 4. Variation of outflow concentration as a function of time during venting (Test T2.b).

4.2.1 Height of aspiration

As shown in Eq. [1], the height of aspiration depends on the density of the turbidity current reaching the outlet (C_{app}) and the discharge of the outlet. Based on the results shown in Table 3, the zone of influence of the outlet during venting is limited to a height of 21.2 cm on average with very similar values for the different tests. This height corresponds to 25% of the total water depth in the flume. This shows that the effect of venting is very local and that the timing of opening does not affect the height that the bottom outlet can reach out to evacuate from the turbidity current/muddy lake.

Table 3. Height of aspiration of the outlet for the different tests.

Test number	Height of aspiration h_L (cm)
T1.b	22.1
T1.a30	21.2
T1.a60	19.4
T2.b	21.4
T2.a30	21.4
T2.a60	21.8

4.3 Venting release efficiency

The release efficiency of venting is evaluated based on the ratio between the total mass of sediments vented M_{VENT} and the total mass of sediments introduced into the reservoir (main flume) by the turbidity current M_{TC}. In Figure 5, this efficiency is plotted in time for the 2.4% and 5% slopes. For both slopes, during the beginning of venting, the efficiency obtained when operating the outlet before the arrival of the current is lower than the cases where the outlet is opened after the arrival of the current. However, the curves of T1.b and T2.b increase faster and the efficiency obtained in a longer term tends to surpass that obtained when the outlet is opened after the arrival of the current.

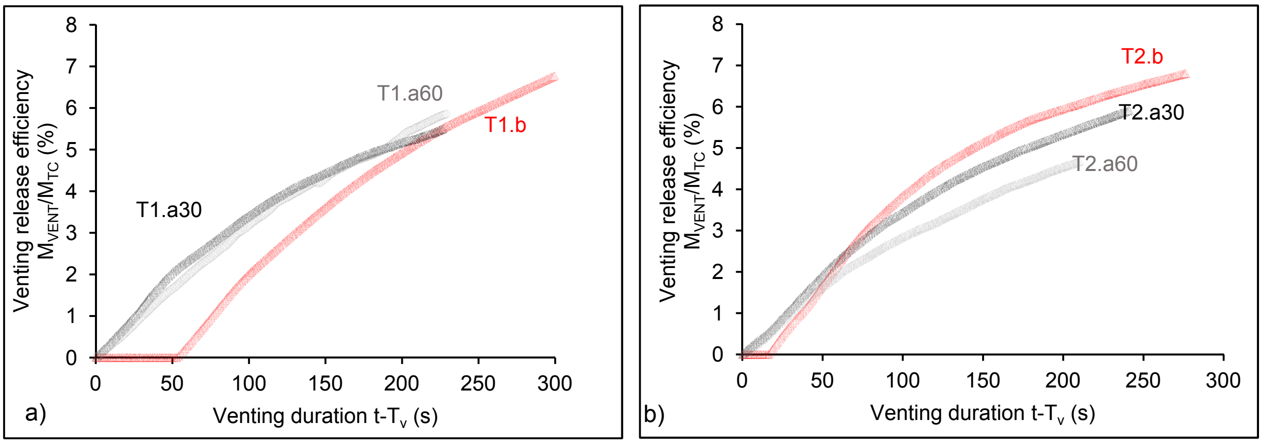

Figure 5. Venting release efficiency as a function of venting duration for the 2.4% slope (left) and the 5% slope (right) (tests numbering according to Table 2).

This is observed in particular for the 5% slope where venting before the arrival of the current gives higher efficiencies starting t-T_v = 60s, where T_v is the time corresponding to the beginning of venting. In order to take into account the major parameters that can affect the efficiency, such as the height of aspiration h_L and the reduced gravity of the approaching current g'_{app}, a normalized time defined by Chamoun et al. (2017) and expressed by $\bar{t} = (t-T_v)^2 g'_{app}/h_L$ is used in Figure 6.

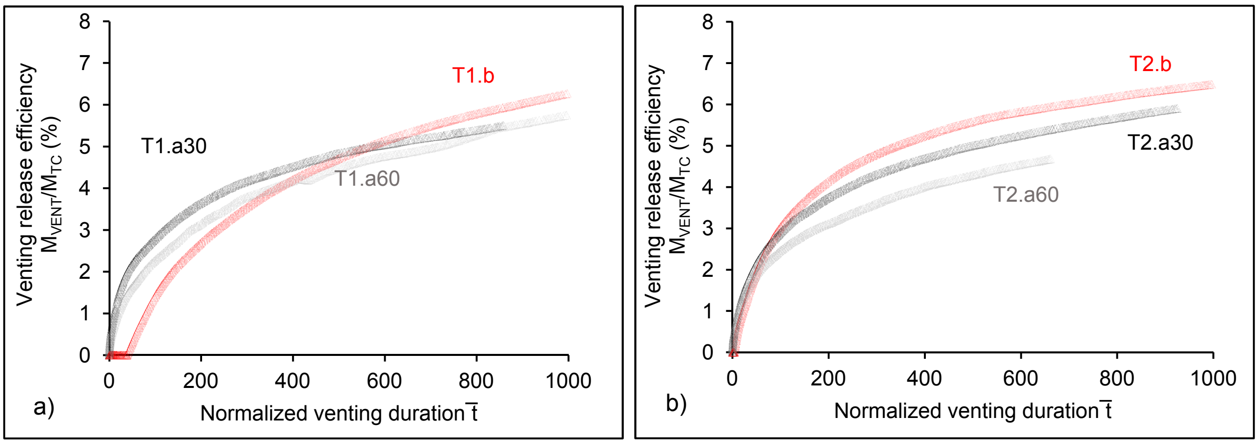

Figure 6. Venting release efficiency as a function of the normalized time for the 2.4% slope (left) and the 5% slope (right) (tests numbering according to Table 2).

The results now show a clearer trend. Log-shaped curves obtained for the different cases suggest that there are two phases in venting. The first phase where venting starts, the increase in efficiency is fast. The second phase, where the current has already climbed up the wall and started reflecting upstream, yields more and more steady efficiencies in time (especially that inflow and outflow have steady conditions in the present work). The graphs in Figure 6 show more clearly that venting before the current reaches the outlet, particularly for long-term operations, can be more efficient than venting after the current has reached the outlet.

5 NUMERICAL MODEL

5.1 Description

In order to extend the analysis based on some visual and unmeasured features, a 3D numerical model was built using ANSYS CFX Inc. The geometry of the numerical model represents the experimental set-up. The mesh is tetrahedral (516’997 elements) except for a hexahedral inflation applied at the bed.

One of the advantages of ANSYS CFX Inc. is that it offers the possibility for users to insert equations to better represent the specific phenomenon simulated. In the present case, equations for the drag coefficient (Cheng, 1997), the settling velocity of the sediments (Richardson and Zaki, 1997; Zhiyao, et al., 2008) and the mixture’s dynamic viscosity (Van Rijn, 1987) were added. An inhomogeneous multiphase model was used with the SST turbulence model. The sediment diameter of 140 µm (corresponding to the d_{50} of the material used experimentally) was used with a particle density, ρ_s = 1160 kg/m^3 and a uniform grain size distribution.

The geometry and boundary conditions applied are shown in Figure 7. The calibration of the numerical model was done based on the experimental results.

The numerical model was used to simulate the tests performed with the 5% slope. The release efficiency of venting was computed and the behavior of the vented flow in the vicinity of the dam was evaluated. The three cases of opening timing are called ‘’before’’, ‘’after 30s’’ and ‘’after 60s’’ hereafter.

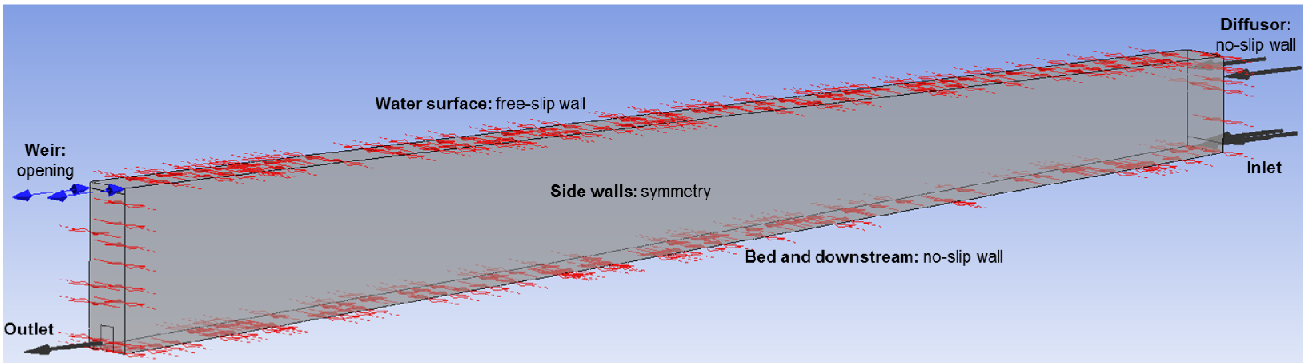

Figure 7. Geometry and boundary conditions used in the numerical model for the 5% slope.

6 NUMERICAL RESULTS

6.1 Venting release efficiency

The results of the release efficiency of venting obtained numerically show quite similar trends in comparison with the experimental results. The efficiency ‘’before’’ is the lowest at the beginning of venting, then it increases faster than the two other cases until reaching efficiencies similar to the ‘’after 30s’’ case and higher than the ‘’after 60s’’ case. Opening the outlet 60s after the arrival of the current to the wall yields the lowest efficiencies.

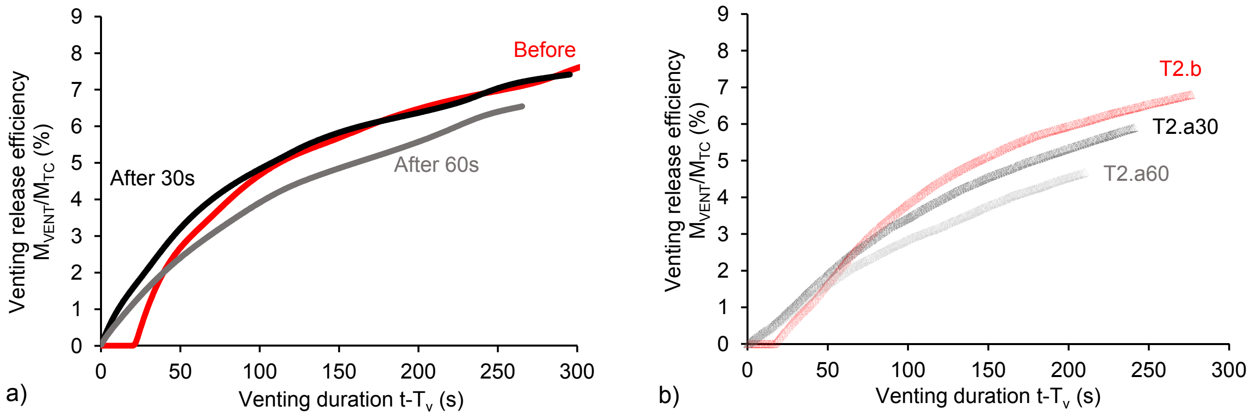

Figure 8. Venting release efficiency as a function of time for the three different timing cases obtained (a) numerically and (b) experimentally for the 5% slope.

A comparison was made between the ‘’before’’ and ‘’after 60s’’ cases based on the volume rendered sediment concentrations. Figure 9 shows that at t = 430s (venting started at t = 125s for the ‘’before’’ case and at t = 205s for the ‘’after 60s’’ case), the ‘’after 60s’’ case shows higher concentrations close to the outlet, while the ‘’before’’ case shows very low concentrations. The latter simply looks like the continuation of the linear decrease of concentrations close to the bed when moving from upstream to downstream. In order to better assess the difference between the two cases, sediment concentrations of ‘’before’’ case were subtracted from the sediment concentrations ‘’after 60s’’. Positive values (Figure 10) were obtained in the vicinity of the wall explaining the lower efficiencies obtained with the ‘’after 60s’’ case. In fact, in the latter case, the muddy lake is well developed before venting has started, rendering the suction of the current continuously reaching the outlet more complicated. Moreover, a kind of interflow seems to form in the ‘’after 60s’’ case due to the high reflection upstream.

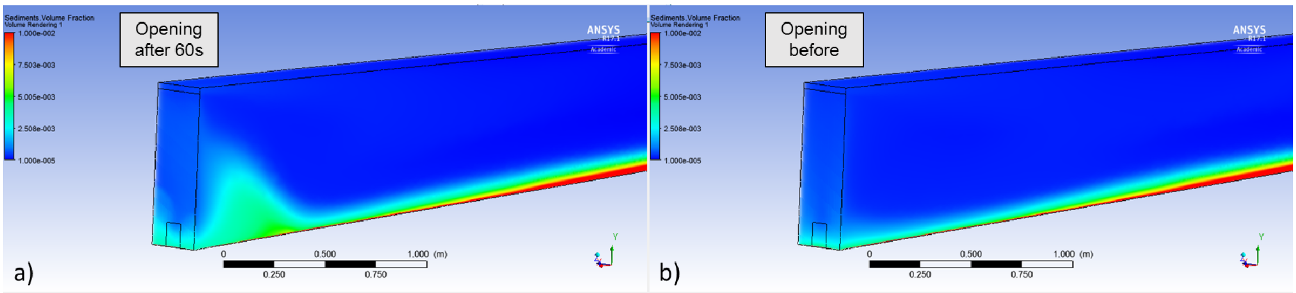

Figure 9. Rendered volumes showing the sediment concentration at t = 430s for the (a) ''before'' and (b) ''after 60s'' cases (slope 5%).

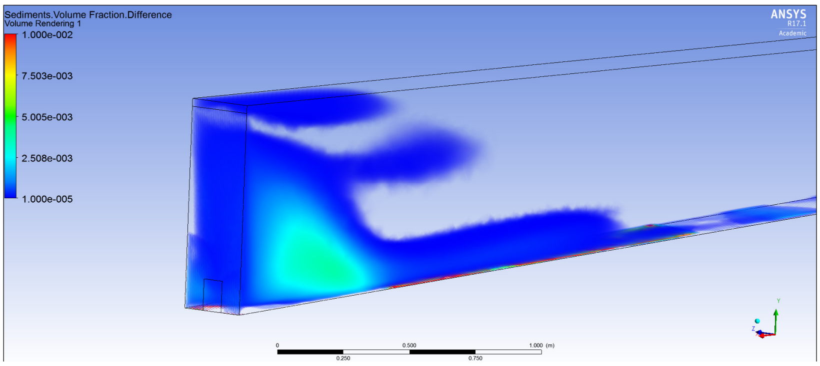

Figure 10. Difference between concentration values of the ''after 60s'' and ''before'' cases obtained numerically at t = 430s in the vicinity of the wall (slope 5%).

Furthermore, the sediment velocity streamlines during venting were computed to improve the understanding of the phenomenon (Figure 11). In fact, the streamlines obtained with the ''after 60s'' case are not well developed between the current and the outlet compared with the ''before'' case. Opening before the current reaches the outlet ensures a better suction of the current once it reaches the dam. Contrarily, when venting is timed after the formation of the muddy lake, parts of the sediments are stuck close to the outlet due to a recirculation (stagnant zone). This zone seems to force the continuously flowing turbidity current to bound over it and reach the outlet at higher levels rendering its transit more complicated and less efficient.

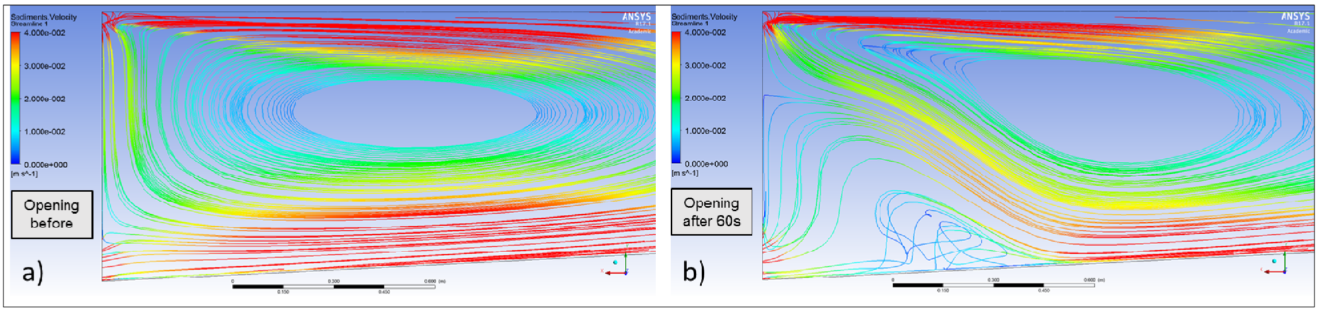

Figure 11. Streamlines in the vicinity of the dam for the case of venting ''before'' and ''after 60s''.

7 CONCLUSIONS

Reservoir sedimentation is an increasing problem that numerous reservoirs are facing worldwide. Preventing or reducing large amounts of sediments that can settle in reservoirs during floods is a must to ensure the sustainability of these structures.

Venting of turbidity currents is among the most economic and efficient mitigation techniques, if performed under optimal conditions. One of the most important operational parameters of venting is the timing of the opening of the outlets. This parameter is discussed in the present paper based on experimental and numerical data. Three different timings are discussed: opening the outlet before the arrival of the current to the dam, after the current has reached the top of the dam (before it starts reflecting upstream), and after the muddy lake has formed and began reflecting upstream.

Based on the calculation of the height of aspiration for the different tests, venting is shown to have a very local influence in terms of height where the aspiration level reached 25% of the total clear water depth. The venting release efficiencies are experimentally shown to be slightly more favorable when opening after the current reaches the dam, during a certain time at the beginning of venting. After this duration, efficiencies obtained in the case of opening the outlet before the arrival of the current to the wall become higher. It seems that the earlier the opening takes place, the longer the time it takes to produce higher efficiencies than the case of operating the outlet after the current has reached the dam. This suggests that opening the outlet when the current is the closest to the dam can be the best timing.

These trends were more or less identical numerically, particularly when comparing the efficiencies obtained when the outlet is opened before the current has reached the wall and the ones obtained after the muddy lake has started reflecting upstream. Sediment concentration contours and streamlines were computed numerically and show the formation of a recirculation zone upstream of the outlet that forces the continuously inflowing current to bounce and renders its suction more complicated. On the opposite, in the case where the outlet is opened before the arrival of the current to the wall, it is smoothly evacuated and streamlines are well developed.

Finally, the output of the present research can provide missing input for dam operators needing crucial information on the optimal conditions to perform venting and reduce sedimentation rates.

ACKNOWLEDGEMENTS

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