RESERVOIR BED SEDIMENT RESUSPENSION INDUCED BY GRAVITY CURRENTS

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ABSTRACT – Observations have shown that gravity currents, a horizontal buoyancy driven flow generated by density differences commonly observed in lakes and reservoirs, may be an important agent of sediment resuspension, playing an important role for water quality of these ecosystems. We ran laboratory experiments in a rectangular tank to characterize the sediment resuspension induced by gravity currents. Results showed that, considering a fine and cohesive sediment and a density difference of 25 kg/m³ between ambient and gravity current fluids, the incorporation of entrained sediment in the current did not play a significant role on the momentum of the gravity current, keeping the gravity current in the same flow regime. However, the sediment was strongly resuspended during the passage of the gravity current over the erodible bed, indicating a significant vertical and horizontal transport process. The strongest transport of sediment particles occurred during the passage of the gravity current head, followed by a minor longitudinal transport of the suspended particles in the flow body.

Palavras-Chave – Correntes de gravidade, ressuspensão de sedimento, reservatórios e lagos

1. INTRODUCON

Environmental monitoring is of fundamental importance for a sustainable natural resources management. The study of sediment transport in lakes and reservoirs helps controlling the water quality and the loss of water storage capacity (Fan and Morris, 1992; Schleiss et al., 2016; Matty et al., 1987). In addition, sediment transport may have a significant influence on greenhouse gas emissions (Bastviken et al., 2004; Huttunen et al., 2006; Bernardo et al., 2017) and distribution and accumulation of heavy metals along thermally stratified lakes and reservoirs (Sigg et al., 1987). Sediment deposited in reservoir beds act as a sink for contaminants (Pourabadehei and Mulligan,2016).

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A significant proportion of sediment comes from inflowing rivers. Most of the time the sediment concentration and the colder river water creates dense inflows, which after a plunge point are predominantly transported downward as gravity currents. Gravity currents are commonly defined as a horizontal buoyancy driven flow generated by density difference, producing small acceleration in the vertical direction. They have a characteristic head formed at the front of the flow, where eventually breaking waves may be observed just behind the gravity current head. Sediment are carried by the gravity current over long distances. And older sediments, which already deposited along the length of the reservoir, may be resuspended and further advected towards the dam. The fine-grained material that deposited along the reservoir is strongly influenced by shear-stress induced by gravity currents, which may be transported horizontally or also be resuspended, vertically in the water column.

The lake bed roughness and sediment particles incorporation may introduce internal stress, which favor the gravity current energy loss. Observations have shown that gravity currents may be an agent of sediment transport, playing an important role on sea floor change (Kneller et al., 1999) and contaminant resuspension (Pourabadhel et al., 2016). Although many observations suggest that gravity currents play a crucial role on the sediment dynamics in lakes and reservoirs, the mechanisms of transport and resuspension of sediment particles induced by gravity currents has got less attention (Zordan et al., 2018).

In order to investigate the horizontal transport of sediment particles of sediment caused by the gravity currents propagation, the present study objective is to analyze the sediment transport induced by gravity current flows based on laboratory experiments ran in a rectangular acrylic tank, and using an image analyzer. The main purpose is to analyze the physical mechanism of gravity currents to generate horizontal and vertical movements of sediment particles and help for the understanding of sediment transport in reservoir and lakes.

2. LITERATURE REVIEW

In many situations (Ungarish, 2011) the horizontal buoyancy driven flow generated by density difference associated to river-reservoir systems allows to apply the Boussinesq approximation ($R = \rho c/\rho a \approx 1$, in which ρ_c and ρ_a are the gravity current and ambient density, respectively). In this case and further assuming the inviscid flow theory (Benjamin, 1968), the initial potential energy from the gravity current is entirely converted into kinetic energy, which leads to the following energy balance:

$$U = Fr\sqrt{g'\,h_o}\,, \tag{1}$$

in which U is the front velocity of the gravity current, h_o is the water level behind the gate (Figure 1), $g' = 9.81\ (\rho_c - \rho_a)/\rho_c$ is the reduced gravity, and Fr is the densimetric Froude number, that correlates the inertial force to the acting gravitational force due to density difference. Laboratory experiments have shown an intrinsic dependence of Fr and other pertinent quantities (Keulegan, 1958):

$$Fr = f\left(\frac{x}{h_o}, Re, \frac{B}{h_o}\right), \tag{2}$$

in which x is the travel distance, B is the tank width, and $Re = Uh_o/\nu$ is densimetric Reynolds number, where ν is the water viscosity of the denser fluid.

The gravity current time dependency consequently implies that Fr is a function of time. However, when gravity current reaches the stagnant ambient, it is accelerated and rapidly enters the inertial slumping regime, an intermediate non-self-similar inviscid phase, in which it is characterized by a constant velocity of the gravity current. The shear stress between the current front and the stagnant ambient favors the expansion of the gravity current head, which also intensifies vorticity by vortex stretching (Cochran et al., 2019). Observation have suggested that the initial velocity of the gravity current front ($x = 0$) is independent of Re and B/ho (Keulegan, 1958), which leads to the follow equation:

$$Fr = Fr_o + \beta\left(Re, \frac{B}{h_o}\right)\frac{x}{h_o}. \tag{3}$$

Laboratory experiments have shown that in this regime condition $Fr = 0.46$ (Keulegan, 1958) until a viscous-buoyancy regime is reached. However, if Re is not too low, the inertial slumping regime may be followed by the inertial-buoyancy self-similar phase, which is characterized by a decrease of volume due to intense mixing behind the head of the gravity current. Due to the mixing, the Re decreases, and the regime can reach the viscous phase, characterized by a strong deceleration of the gravity current due to the dissipation of energy generated by viscous forces.

In highly turbulent flows generated especially by gravity current evolution, the velocity fluctuation associated to the horizontal velocity of the gravity current favors the increase of shear stress at lake bed, which play a critical role in the transport of sediment particles (Zordan et al., 2018)

3. METHODS

Laboratory experiments were ran in an horizontal, rectangular, and acrylic channel 2.0 m long, 0.1 m wide, and 0.5 m high, that was filled with fresh water up to 0.2 m depth (Figure 1). A gate was placed at 13 cm distance from the left side end-wall of the tank, dividing the ambient fluid from the denser fluid of the gravity current. In this study denser fluid for the gravity current was produced by adding dissolved salt into the water ($\Delta\rho = 25$ kg/m³). Water densities were measured three times by a 50 ml pycnometer to ensure fluid homogeneity.

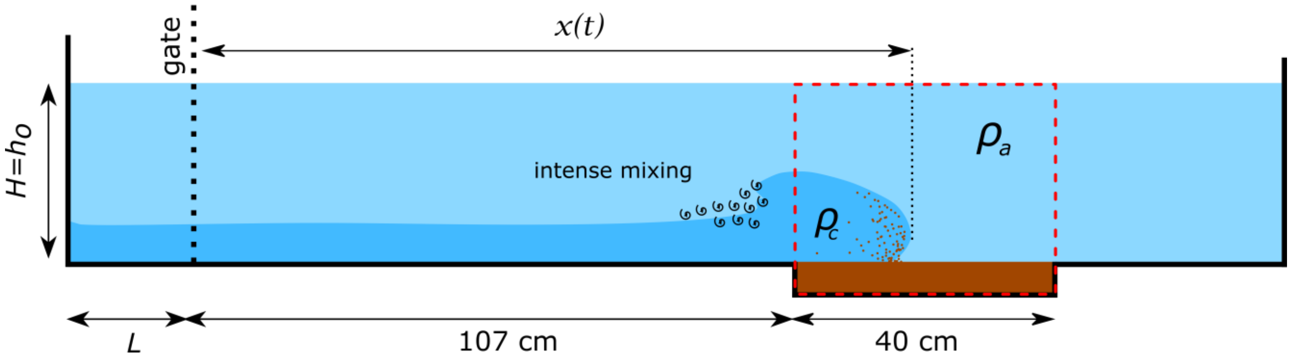

Figure 1 – Side view of the experimental set-up. Red dashed box indicates the region where video was recorded.

The 40 cm erodible bed was positioned at 1.2 m from the left side end-wall of the tank, with 2 cm depth below the bottom surface (Figure 1). The material used as the sediment in the experiment was sawdust from selected imbuia, treated with formaldehyde, material already used in other experiments to better simulate the cohesive force of sediment in reservoirs and lakes (CEHPAR, 1981). When the gate was vertically removed, the denser fluid flowed in one direction along the bottom of the system whilst the lighter one flowed in the opposite direction along the top boundary due to differences in the hydrostatic pressure. A video camera was fixed perpendicular to the flow looking at the sediment bed region, red dashed area indicated in Figure 1.

The front speed of the gravity current and the sediment resuspension was measured using an open-software designed to investigate the dynamic of gravity current and sediment transport, Dyenamic (Bueno and Bleninger, 2020). The software allows the analysis of the evolution of the gravity current and the visualization of sediment transport frame by frame based on specified thresholds of gray scale values. The software is capable to separate the threshold values of sediments from those of the gravity current. The concentration values and the video analysis enable estimating physical indices to analyze the current and sediment dynamics.

A calibration was performed to improve the output results generated by Dyenamic, adjusting the shades of the current and the environment and improving the quality of the analysis. The calibration procedure was carried out by varying the threshold values of the grayscale, until a satisfactory distinction between current and ambient fluid, as well as sediment particles. The software provides information according to the dynamics of the gravity current, which includes snapshots of processed images (Figure 2). In addition, the heights of the current the highest speed points of the head were analyzed where there was no visible interference due to the erodible bed.

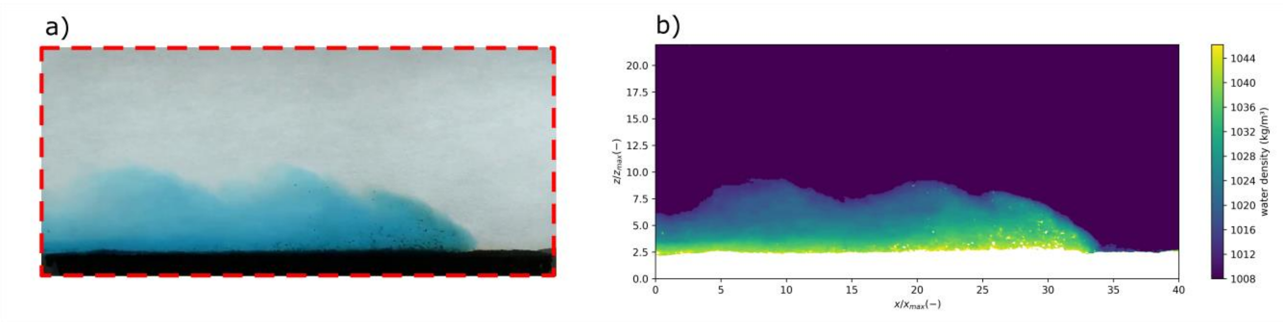

Figure 2 - Gravity current flowing under the erodible bed ($x = 154$ cm). a) snapshot from video and b) digitalized image processed by the Dyenamic.

4. RESULTS

The front position of a gravity current is defined as the prominent point of the gravity current, which often varies between 15% and 40% of the underflow depth depending on the Froude number regime (Groenenberg, 2007). In this experiment, the gravity current speed was measured at 1.5 cm from the erodible bed. The evolution of the head front suggests a constant velocity which indicates that the current is probably in the inertial-slumping or inertial-buoyancy phase (Figure 3). Apparently, the propagation of the current along the erodible bed does not indicate that the gravity current was influenced by the sediment particles, which could result in a deceleration of the gravity current front (Bhaganagar and Pillalamarri, 2017).

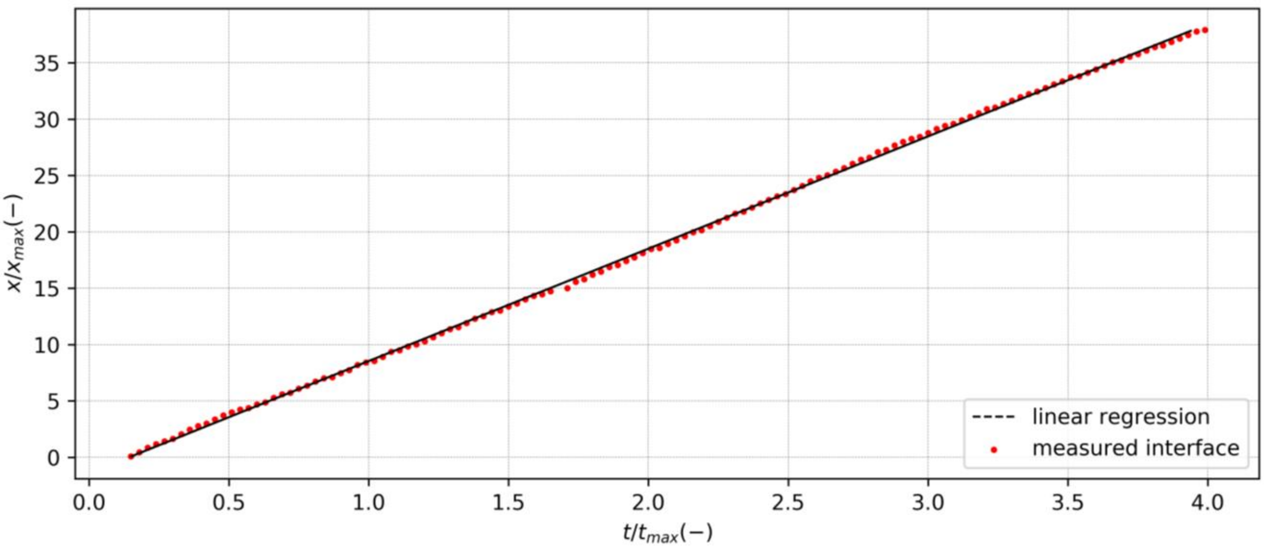

Figure 3 - Time evolution of the gravity current front location. x- and y-axis are normalized by the time and special scale of the erodible bed

The average velocity of the front *U* is calculated as the slope of the linear regression function, which suggests a mean speed of approximately 9.96 cm/s. The coefficient of determination of the fitted function is 0.99. Since the linear regression model accounts for most of the variance of the measured values, we may assume that the regime of the flow is inertial.

Laboratory experiments have suggested that an initial phase with constant-velocity persists until a transition occurs when a disturbance caused by a bore reflection from the lock back wall catches up the front (Marino et al., 2005). From that point, the current tends to be self-similar, in which the current depth increases towards the rear of the head. Once the current enters the similarity regime (inertial-buoyancy phase), there is a distinct difference between the height of the head and the depth of the current flow, which is followed by a gradual deceleration due to mixing and detrainment observed behind the gravity current head.

The densimetric Froude number, estimated by equation 1, is approximately constant and consistent with previous measurements (Marino et al., 2005; Shin et al., 2004). The current head remained at almost constant height during the evolution over the erodible bed with intense mixing behind the head. A linear regression using the least squares method indicates an average Froude number of $\overline{Fr} = 0.519$ with 0.029 standard deviation.

The slope of the linear regression (-0.002) indicates a small variation compared to the theoretical estimates for the self-similar regime, which indicates that the gravity current is probably in the constant-velocity phase or in an intermediate regime with a slight deceleration. The extrapolation of the linear regression, indicates that the initial densimetric Froude number (equation 3) is $Fr_o = 0.54$, which corroborates with theoretical values (Figure 4)

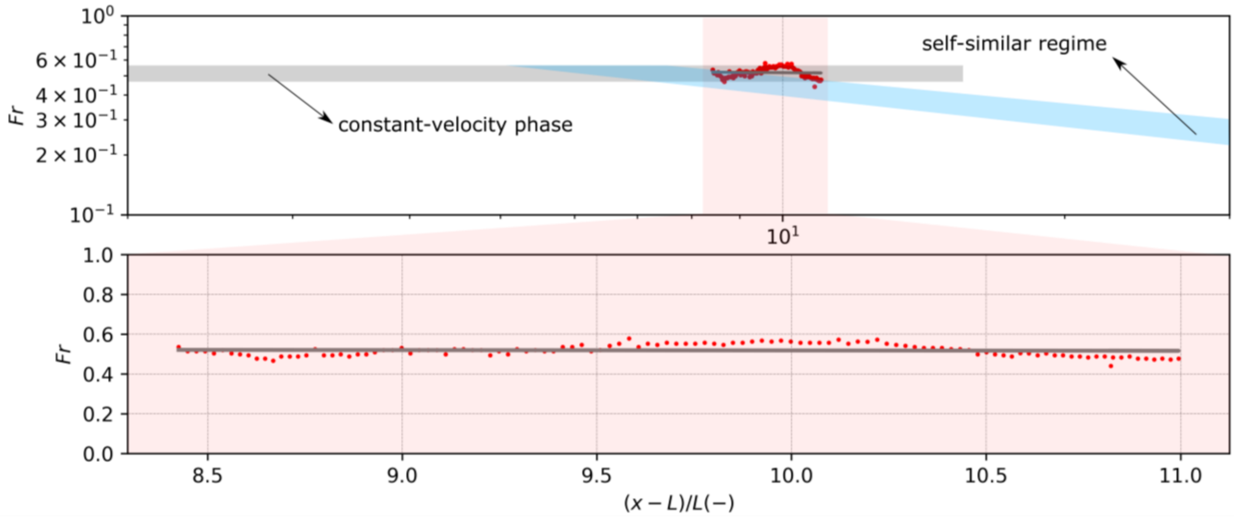

Figure 4 - Evolution of the dimensionless front velocity. The theoretical estimates for the constant-velocity phases and the self-similar regimes are indicated by green and blue boxes, respectively.

Assuming that the gravity current is located in the constant-velocity phase, the small decrease of the Froude number compared to values obtained in the literature (Marino et al., 2005) does not indicates that the regimes have reached a self-similar regime. We observed that the sediment bed did not play a significant role on the front evolution.

The sediment variation, which characterize the area occupied by sediment particle from the front view of the tank, at $x = 20$ cm (middle of the erodible bed) is plotted against time (Figure 5). The gravity current front reaches the middle of the erodible bed position after exactly 2.162 seconds, thereafter the transported sediment is detected by the software. The initial peak is due to the gravity current head passage that resuspends and transports sediments downward, followed by a minor longitudinal transport of the suspended particles in the flow body. At the end, the resulting transport from vertical and horizontal components, deposited particles outside the investigation area.

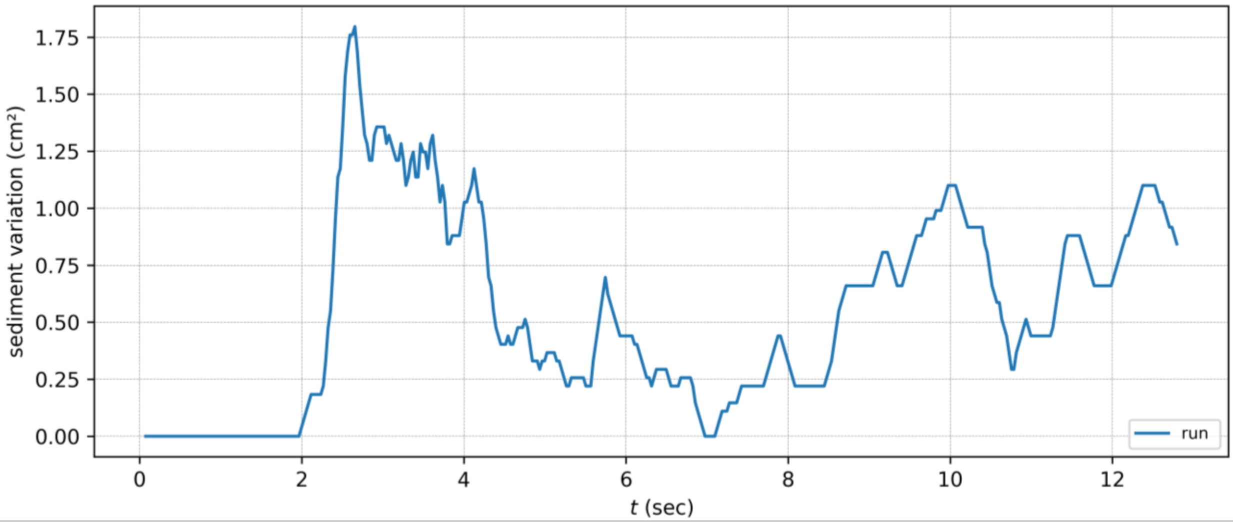

Figure 5 - sediment resuspension observed at 140 cm from the left-hand side end of the tank.

5. CONCLUSION

In this experiment, we demonstrated the efficiency of gravity currents to resuspend sediment particles even when the sediment does not play an important role in the dynamic of the gravity current. Although we did not explore the physical forces involved to the resuspension, we demonstrate a preliminary characterization of sediment resuspension induced by gravity currents. We explore the influence of bottom roughness of the erodible bed on the gravity current evolution, and concluded that, considering our bed condition, the incorporation of bed particles into the gravity currents does not influenced the evolution of the gravity current. For future analysis, the number of experiments will be expanded, demonstrating the influence of gravity current with different densities on the sediment resuspension. The height of the head will be also taking into account as a facilitator of the sediment transport.

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