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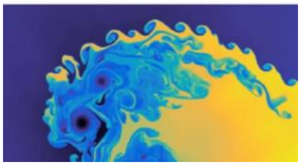

Effects of bottom obstacles on the front velocity of gravity currents: a case study

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Abstract

The present study aims to analyze the effect of bottom obstacles on the propagation of gravity currents in a rectangular channel. Two lock-exchange experiments were set up. They consisted of a freshwater tank with a lock-gated compartment for denser saltwater that, when released, produces the interaction of both fluids in the form of a density current. The first experiment was a lock-release over a flat bottom, while the second experiment has thin bottom obstacles along the channel. The flow in the tank was recorded with cameras using dye concentration as a tracer for the denser fluid. Open-source image analysis was used for computing relevant flow variables such as current front velocity, Froude number and front height. Comparison between results of both experiments showed the tendency of the gravity current to be slowed down by the placement of bottom obstacles. Results also suggest a correlation between barrier impacts and the level of turbulence and instability generated in the system during collisions. It was concluded that bed geometry of the channel plays a major role in gravity current dynamics.

Keywords: gravity current; lock-exchange; bottom obstacle; front velocity.

1. Introduction

Gravity currents are flows consisting of a fluid propagating horizontally under a less dense ambient fluid under gravitational action. Since gravity currents are driven by density differences, they are often called

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density currents. Some examples of gravity currents in nature are avalanches, turbidity (sediment-laden) currents and cold fronts.

A standard way of studying gravity currents in laboratory is by lock-exchange experiments. Lock-releases consist of two fluids with different densities contained in a rectangular horizontal channel and separated by a lock gate that is rapidly removed allowing for the propagation of the denser fluid below the less dense ambient fluid. The denser fluid is usually a saline mixture while the ambient fluid is freshwater.

In order to compare theoretical formulations with experimental results, the lock-exchange flow in the channel is recorded with cameras using dye concentration as a tracer for the denser fluid. Then, by using image analysis techniques, it is possible to reconstruct the temporal and spatial evolution of the density fields (see, e.g., Shin et al., 2004; Marino et al., 2005; Fragoso et al., 2013; Nogueira et al., 2014). However, numerical modeling has also been implemented in gravity current studies (e.g., Cantero et al., 2007; Ooi et al., 2009).

The first studies of gravity currents propagating over bottom obstacles were performed by Rottman et al. (1985). Later, Lane-Serff et al. (1995) analyzed the problem in more depth for a triangular ridge by comparing laboratory measurement and shallow water theory. Employing a combination of numerical simulations and shallow water theory, Gonzalez-Juez and Meiburg (2009) tried to extend the findings of Rottman et al. (1985) and Lane-Serff et al. (1995) for an isolated square ridge. Their main finding was that the current flux downstream of the obstacle is approximately constant in space and time. However, for a series of identical obstacles, Tokyay et al. (2011) found that the drag force is time-dependent and dominated by the recirculation downstream of each ridge. More recently, Wu and Ouyang (2020) used three-dimensional simulations to generalize the problem for a rectangular ridge and studied the effect of obstacle aspect ratio on the propagation of the gravity current.

The present study aims to analyze the effect of bottom obstacles on the propagation velocity of the gravity current. Lock-exchange experiments were set up in the laboratory using salinity to create the density difference. A finite volume of dyed saltwater was rapidly released from the lock gate, and the gravity current was recorded using a camera. The recorded frames were analyzed using suitable image analysis software and variables such as current front speed, Froude number and Reynolds number were reconstructed for the experimental runs. The process was performed for two experiments, one considering a flat bottom and the other with two thin bed obstacles. Finally, a comparison between relevant variables of both experiments was conducted.

2. Materials and methods

To compare the velocity of the gravity wave and its height for scenarios with and without a bottom step, two experiments were carried out in the laboratory of environmental engineering at the Federal University of Paraná (UFPR). The experiments consist of a freshwater tank with a lock-gated compartment for saltwater that, when placed in contact with freshwater, interacts in the form of a gravity current. The tank was 22 cm high and 2 m long, and the vertical barrier was placed 13 cm from the left end wall. This lock was filled with dyed saltwater with a density of 1020 kg/m³ in experiment 1 (E1) and 1016 kg/m³ in experiment 2 (E2). These values were obtained with the help of a pycnometer and an analytical balance. The rest of the tank was filled with freshwater with a density of 1000 kg/m³. In the first experiment, there were no obstacles, and the gravity wave flows without hindrances, as shown in Figure 1.

Then, the experiment was repeated with the obstacles: two steps spaced 9.5 cm apart and 1.8 cm high, the first 29 cm and the second 38.5 cm long. The first step was positioned 47 cm from the barrier, as it can be seen in Figure 1. Both scenarios were recorded keeping camera distance and position unchanged between experiments. These recordings were cropped, maintaining only the area of the tank occupied by the water solutions. Moreover, frames before the release of the lock were excluded, in favor of appropriately assessing current velocity and evolution. Specifically for the video documenting E2, a white mask was positioned over the obstacles, as a way of ensuring the correct interpretation by the software. The edited videos were then analyzed via the Dyenamic software (Bueno et al., 2021), computing the relevant variables and generating plots.

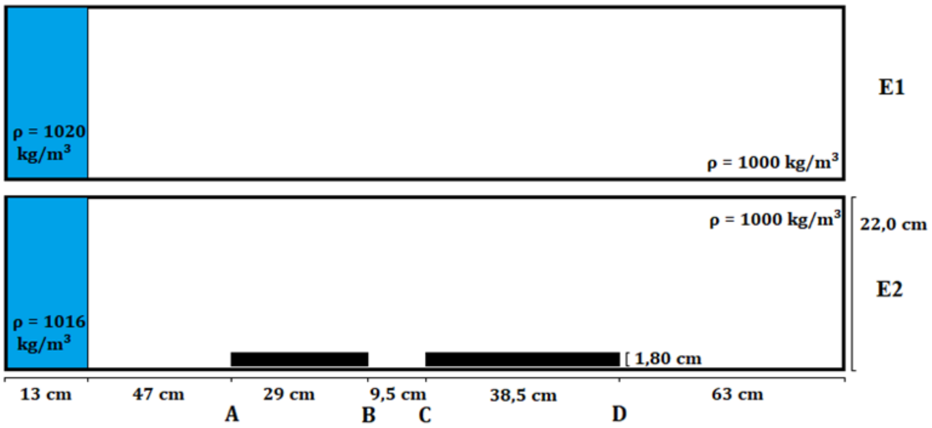

Figure 1: Tank dimensions and schematics of the experiments.

The variables considered in the analysis were: mean front velocity, u_f, measured at the head of the current; average front height, h_f; and Froude number, Fr_f. The Froude number is a dimensionless quantity, used in stratified flows to evaluate the degree of stratification (Embid and Majda, 1998). It can be calculated as

$$\mathrm{Fr}_f = \frac{u_f}{\sqrt{g' h_f}} = \sqrt{\left[\frac{(1-\phi)(2-\phi)}{(1+\phi)}\right]}, \quad (1)$$

where g' is the reduced gravity, obtained by multiplying the gravitational acceleration, g, by a ratio between the difference in stratified layer's densities and a reference density value (Mayer and Fringer, 2017).

Using the aforementioned definition, Benjamin (1986) determined that the front Froude number could be computed as a function of ϕ, as shown on equation (1). In this case, ϕ represents the fraction the front height h_f and the tank height H. This relation was used to model expected values of the front velocity, given only the density differences and the measured front heights.

3. Results

The calibration for image processing in Dyenamic was challenging since, as shown on Figure 2, background illumination was not uniform. There were dark regions at both ends of the tank, behind the lock compartment ($x < 15$ cm) and at the right end ($x > 170$ cm), defining the origin ($x = 0$ cm) at the left wall. The significant reduction in brightness in these regions generated noise over the captured flow images, compromising software interpretation, so they were labeled noise zones (NZs). Given this difficulty, the subsequent analyses exclude the area located beyond the 170 cm threshold. In other words, canal length was considered, pragmatically, 170 cm. Also, given the NZ at the lock region of the tank, lock height had to be considered as a constant value of 21.5 cm, and consequently front height computations were compromised. Moreover, the effect of NZs on the estimated average front height was evaluated by comparison between observed and calculated values. It was found that mean values were slightly affected, and flow behavior was consistent with observations. In this way, qualitative analysis of this variable was viably conducted. In Appendix A, several photos of the gravity currents for both experiments are presented.

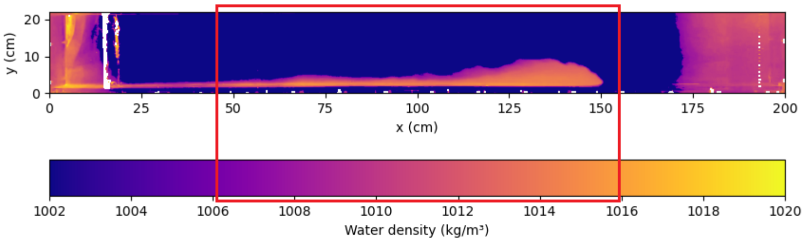

Figure 2: Example frame displaying the noise zones on each extremity of the tank. In red, the region of interest for this study.

In order to analyze some of the effects of the placement of bottom obstacles over the propagation of the gravity currents, front velocity, Froude number and average height were computed throughout the extent of the tank. Through trial and error, it was determined that the optimal height for the observation of patterns was $y = 5$ cm above the bottom of the tank. This value is used, therefore, as the evaluation height of forthcoming results and discussion.

In respect to the first experiment,**Erro! Fonte de referência não encontrada.** shows the observed and modeled front velocity after the release of the lock, as the blue series. Furthermore, Figure 3 displays the observed and modeled front velocity during the second experiment, as the green series. In the figure, the vertical dashed lines represent the placement of the obstacles. As it can be seen in this figure, temporal resolution was defined as 1 s, in order to reduce the analysis' computational time and demand.

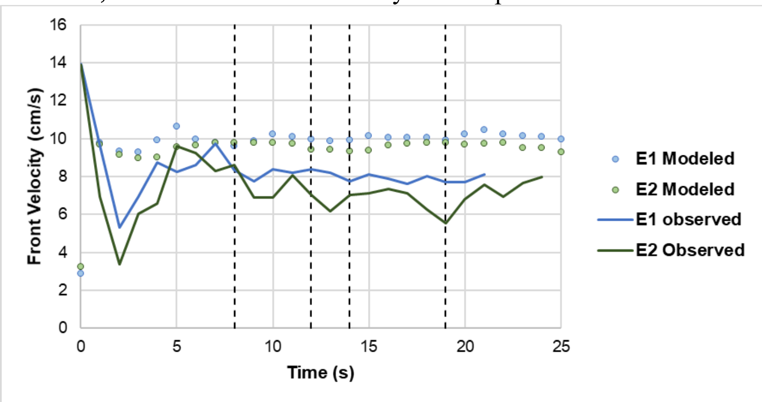

Figure 3: Front velocity development during the first (blue) and second experiment (orange). Above, vertical lines are related, in the respective order, to lengths A, B, C and D.

The software also provided the wave height after processing the two videos. From the output data, the graph in Figure 4 was plotted, which shows the variation of front height (h) as a function of time, where the dashed lines represent the beginning and end of both bottom steps.

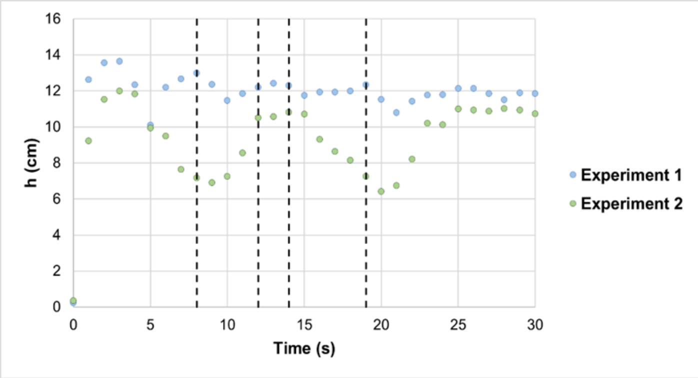

Figure 4: Wave height during the first (blue) and second (green) experiments. Vertical dashed lines represent points A, B, C and D in Figure 1.

4. Theoretical Assessments

The lock-exchange experiments were able to show, in a controlled way, what may happen in an environmental flow where there is a difference in fluid densities causing a gravity current. Assuming a hydrostatic approximation, a higher piezometric pressure is expected inside the denser fluid than in the fluid above it (Benjamin, 1968). Because of this, the formation of a current is expected as clearly shown in the conducted experiments. However, environmental stratified flows usually do not occur over flat beds. In search of a more extensive comprehension of naturally occurring gravity currents, it was proposed the comparison between the E1 and E2, with the main difference being the presence of bottom obstacles. In fact, E2 is yet a rough approximation, since natural stratified flows appear on more complex bathymetries (Kullenberg, 1977).

Subsequently to these introductory considerations concerning the experiments, it is important to assess the fundamental role of the image processing methodology in this case study. The analysis of relevant variables for gravity current studies demands collection of data in space and time, since lock exchanges are, by definition, transient processes. Literature-wise, this can be accomplished either with 2- and 3-dimensional models, or laboratory experiments recordings coupled with image processing and analysis (e.g., Shin et al., 2004; Marino et al., 2005; Cantero et al., 2007). The last approach was selected in this study, with one significant difference from the wide literature available on the subject: the use of open-source and readily available software. Indeed, Dyenamic (Bueno et al., 2021) proved to be a viable tool for the analysis of gravity current dynamics. Standardized results and datasets were obtained, allowing for a reasonable comparison of different experiments.

5. Discussion

In a prior evaluation of the presented results, it is possible to note the tendency of the gravity current to be slowed down by the presence of bottom obstacles. Initially, the time necessary for the current on experiment 1 to reach NZ was 20.5 s. In comparison, the current obtained on experiment 2 took 23.5 s to reach the same distance. Moreover, front velocities were considerably slowed in the latter case.

Indeed, current initial density was different between the two experiments. This means that, theoretically, lower values of front velocity observed in E2 could be related to both the presence of the obstacles and the variations in density, which produce different reduced gravities. In order to assess the importance of those effects, equation (1) was applied to model expected values of front velocity, considering only the variation of reduced gravity in the experiments.

Figure 3 shows that, using the Froude number definition, and considering only the density variation of each experiment and measured front heights, more modest differences in front velocity between E1 and E2 were expected. The measured velocity series display, especially in regions close to the obstacles, much higher velocity contrasts than the expected. Given these results, it is realistic to assume that, in the studied case, the variation of the lock density does not affect front velocity as the bottom obstacles do.

Moreover, Figure 3 can be used as a way of comprehending qualitatively the mixing processes in the experiments. According to Benjamin (1968), in gravity current flows with no energy loss, without mixing, Froude number is expected to be 0.5. Since Fr_f and u_f are directly related, lower Froude number values imply lower velocities and, therefore, higher mixing between the fluids. According to the results, both E1 and E2 observed velocities were below the expected values, indicating higher mixing ratios than anticipated. Also, mixing was higher in E2 than in E1, notably in the obstacle discontinuity and immediately after the second obstacle.

Generally speaking, the current front produced in experiment 1 developed higher average heights than the current front in experiment 2. In Figure 4, front height of the E2 remained lower than in E1 for all time points. This can be in part an effect of the density difference that was slightly lower for E2. In addition, front height in E2 shows a strong variation when the current reaches the obstacles, while E1 produces more homogeneous values. A preliminary analysis suggests that the increase in front height in E2 just after the collision with the first barrier is due to the turbulence generated and the possible vortices formed as a result. This is opposite to what would be expected in the absence of barriers, where the front height would gradually decrease along the flow. The lowest value of velocity, occurring in both experiments 2 seconds after lock release, is considered as related to the turbulence produced by the release, and so is not directly related to gravity current processes.

In the second barrier, where the current already has lower translational kinetic energy after the dissipation of the first barrier, part of the mass get accumulated in the space between the barriers (obstacle discontinuity, or OD), which lead a decrease in height. Furthermore, at the end of the second barrier, the wave can be analyzed in two layers. The lower layer collides with the bottom, generating vortices that promote mixing, reducing the concentration by dilution and adding to the upper layer, increasing the wave height. This elevated mixing ratios can be further justified by the measured front velocity values, which are reduced in the OD region. This means that, in the area, the current is not only moving in the preferential direction, along the tank.

Immediately after the second obstacle, both current height and velocity decrease. This can be related to the turbulence induced by the end of the obstacle. Subsequently, the current assumes a behavior similar to the OD region. Nevertheless, the mass remains freely occupying the tank bottom space, since there is no other barrier in sequence. Front velocity and height can, this way, be increased, as shown on Figure 3 and Figure 4.

To accurately analyze the number of vortices formed in each collision with the obstacles, more precise software and greater time discretization would be necessary. This would allow for the correlation of barrier impacts with the level of turbulence and instability generated in the system during collisions.

In natural environments, implications of the observed behaviors are important. Since, in some water bodies, gravity currents function as a transporting agent of sediment and nutrients (Bueno e Bleninger, 2018; Koller et. al, 2019), the concentration of these parameters is heavily influenced by the dynamics of the currents. The presence of OD in the bed of a water body, as shown above, can induce accumulation of mass. This could create regions in environments where nutrient concentration is elevated, for example. Also, the lower velocity values found for E2 can suggest that, in areas with bottom obstacles, sediment transport by density currents is difficulted. The understanding of these processes and interaction can be important, for instance, to the comprehension of the changes in reservoir beds over time.

Notwithstanding, some limitations were observed. Mainly, lighting discrepancies throughout the tank caused noise in the results. Consequently, maximum front height analysis was affected. Alongside, results obtained in NZs had to be disregarded. As a matter of fact, this issue could have been resolved by providing uniform lighting or focusing the analysis on the region of interest. However, some considerations and simplifications provided a framework for analysis and discussion of the observed effects of bottom obstacles.

6. Conclusions

Comprehension of stratified flows is crucial in natural aquatic environments such as estuaries and fjords, where layer density differences are elevated. Unfortunately, an accurate mathematical modelling of those environments and flows is a difficult task. To circumvent this problem, one possible option is the simplified simulation of these processes in controlled laboratory conditions. This paper suggests that using lock-exchange experiments of gravity currents in a water tank allows for studying the influence of conditions such as the bathymetry on these flows in a comparative way. A comparison between the first reference gravity current experiment and a second experiment with the presence of bottom obstacles provided insights on the influence of bathymetry over the currents in a rectangular channel.

Results showed that, in the second experiment, front velocity was significantly lower, causing the flow to reach the end of the channel with overall lower front speed and in a longer period of time. In natural environments, these lower speeds could be interpreted as reduced impacts on bed sediment, i.e., lower erosion rates. Additionally, higher Froude numbers were related to the flow over bottom obstacles in experiment 2. Since the velocities were smaller, this was explained via the reduction of mean head height observed over the obstacles. This way, effectively, higher mixing ratios were observed on E2, especially in the OD and after the obstacles. As a result, it is clear that bed geometry of the channel plays a major role in gravity current dynamics. In natural environments, therefore, these conditions must be properly considered. Otherwise, analysis of the effect of stratified flows will be incomplete.

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