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Front Velocity of Gravity Currents down a Slope in a Stratified Environment

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Abstract

Gravity currents in stratified environments are frequently encountered in many natural and engineering environments. Experiments are conducted in a linearly density stratified flume to study the front velocity of gravity currents down a ramp. Our results show that the gravity current is highly impacted by the stratification of the ambient water. Three development stages of the gravity currents are observed, i.e., acceleration stage, deceleration stage and separation stage. By taking into account the influence of linear stratification, a formula is derived based on the thermal theory to determine the accelerating velocity of the gravity current.

Key Words: Gravity current; Front velocity; Stratification.

Introduction

A gravity current is the flow driven by the density difference between the flow and its ambient environment [1]. It is a very important phenomenon in many aspects of natural and engineering process. The reader can refer to the book of Simpson [2] to find the extensive existence of gravity currents.

Gravity currents in clear water have been studied for many years [1, 3, 4]. For a gravity current propagating over a flat bottom in a uniform environment, Huppert and Simpson [5] proved that the full lock-exchange gravity current experiences four well-defined stages. Once the lock is released, as the initial density contrast between the current and the ambient water is relatively large, the gravity current firstly goes through a short acceleration stage, during which its front velocity rapidly increases from zero to the maximum value. Then, the slumping stage follows this short acceleration stage, in which the gravity current travels at nearly constant value for about O (5-10) lock lengths. This stage ends when the reflected ambient lighter fluid catches the front of the gravity current. A temporary balance is reached between the inertial and buoyancy force and the gravity current starts to slow down. In this inertia-buoyancy stage, the front velocity of the gravity current behaves as $t^{-1/3}$. As the gravity current constantly mixes with ambient lighter water, its density declines and thus decreases the driving force, which subsides the effect of the inertial force. The turbidity current enters the next stage when a new balance is reached between the buoyancy and viscous force. In this stage, the front velocity evolves as $t^{-4/5}$. These development stages of the gravity current have been recognized by many researchers [1, 4]. For the gravity current down a slope in the uniform environment, the previous studies [6,7] demonstrated that the lock-exchange gravity current experiences a short acceleration stage followed by a deceleration stage. A classic thermal theory [6] was proposed to successfully determine the movement of the gravity current.

Most of the previous researches about the front velocity of the gravity current were conducted in a uniform ambient. Nevertheless, the stratification of the ambient water is also frequently encountered in the real geophysical environments [8, 9], which greatly changes the motion of the gravity current. Until now, little study considered the effect of both the slope and the ambient stratification on the front velocity of the gravity current. In this study, experiments were conducted in a linearly density stratified flume to study the front velocity of gravity currents down a slope. Based on the classic thermal theory, new formulas were proposed to describe the motion of the gravity current in such an environment.

Experimental set-up and procedures

Full lock-exchange experiments were carried out in a rectangular plexiglass flume of width W = 15 cm, length L = 280 cm and height H = 46 cm, as shown in Figure 1. A perspex board was built on the end of the flume to create the slope. A flat disk connected with the outer two-tank setup was placed in the bottom of the flume to produce a linearly stratified environment by overflowing. Some interfaces were preset on the other side of the slope to let the fluid pass so the stratified water can fill all the area of the flume. The stratification of the ambient environment was conformed by measuring the density of the water samples, which were taken by a syringe at 5 cm vertical intervals. Our measurements presented a good linear density stratification of the water in the tank, with the water at the bottom 1013.61 kg/m^3 and the the water at the top of the ramp 1003.92 kg/m^3. The dense fluid (density: 1007.07 kg/m^3) dyed with potassium permanganate was then slowly injected into the head tank. In the process of producing the stratified environment, we kept the lock 2 closed and the opening height of the lock 1 being 4 cm. Then, by suddenly lifting up lock 2, the gravity current can be created and it propagates down the slope. The development of the gravity current was recorded by a digital camcorder with a resolution of 4928 pixel × 3264 pixel at a frame rate of 25 fps.

Experimental Results

The front location of the gravity current (x_f), defined as the distance from the foremost of the current to the top of slope, can be easily get by analyzing the videotape. Then, we can calculate the front velocity by $u_f = \mathrm{d}x_f$ / dt.

Figure 2 shows the front velocity of the gravity current down a slope in the linearly stratified environment and Figure 3 shows the experimental snapshots. Once the lock is released, the gravity current firstly experience a short acceleration stage driven by the density gradient, in which the front velocity increases from zero to the maximum value. A velocity shear is produced at the interface between the gravity current and the ambient water, which generates the Kelvin-Helmholtz instabilities and turbulent billows, as shown in Figure 3. The ambient lighter water is then entrained and mixed with the gravity current [10,11] and thus its density constantly decreases and the driving force of the gravity current declines, correspondingly.

As the gravity current further moves down the slope, the density gradient that drives its movement continuously declines due to the decrease of the gravity current's density and the increase of the ambient water's. Figure 2 shows that the deceleration stage can be further divided into two phases. In the first phase, the front velocity only slightly decreases. In the second phase of the deceleration stage, as the inertial force and buoyancy force

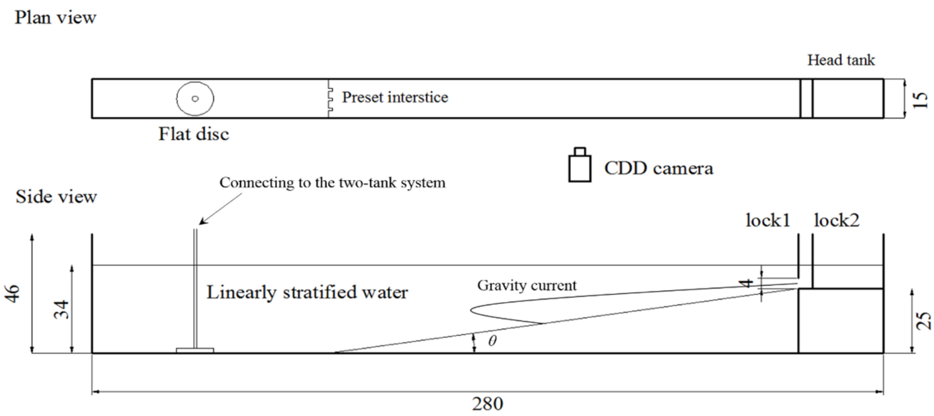

Figure 1: Plan and side views of the experimental tank. θ is the angle of the slope. All measurements are in cm.

gradually loses its control on the gravity current, the viscous force becomes significant in which the front velocity reduces rapidly. Our experimental results also show that in the second phase of the deceleration stage, the tail of the gravity current is increasingly expanded. The dense fluids of the gravity current also gradually penetrates into the ambient environment horizontally as the presence of the density variation at different depth.

When the density difference between the gravity current and the ambient water disappears, the gravity current stops to descend along the slope. The foremost of the gravity current is separated from the slope and starts to intrude into the ambient environment at where both densities of gravity current and ambient water reach equal. The intrusive head has a very thin layer with a very slow speed.

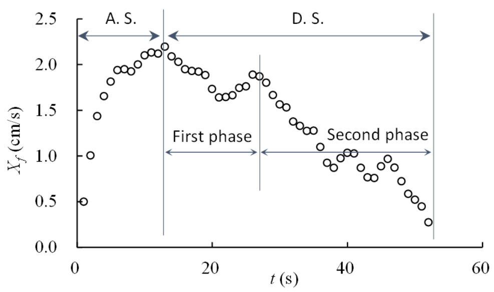

Figure 2: Front velocity of gravity current down a slope in linearly stratified environment. A.S. represents the acceleration stage and D.S. the deceleration stage.

As the gravity current moves down the slope, the density contrast that drives its development constantly declines. When the driving force cannot overpass the effect of the friction, the gravity current starts to decelerate. Figure 2 shows that the deceleration stage can be further divided into two phases. In the first phase, the front velocity only slightly decreases. In the second phase of the deceleration stage, a new balance is reached between the buoyancy force and the viscous force and the front velocity reduces obviously.

When the density difference between the gravity current and the ambient water disappears, the gravity current stops to descend down the slope. The foremost of the gravity current leaves the slope and starts to intrude into the ambient environment horizontally. The intrusive forward has a very thin nose with a very slow speed. The controlling force of the gravity current in this stage is the viscous force. The development process of the gravity current in the different stages is shown in Figure 3. Since the velocity of the horizontal intrusion is very low, we only focus on the front velocity of the gravity current in the acceleration and the deceleration stages in this study.

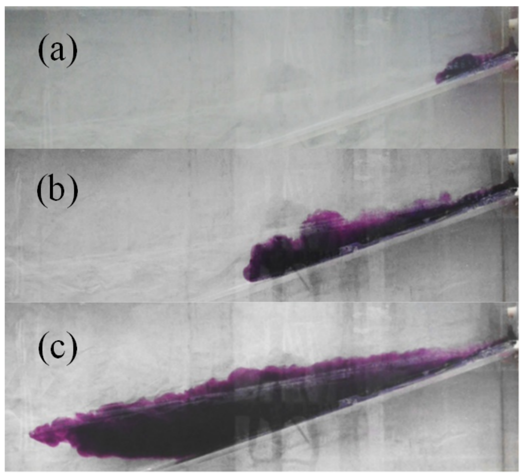

Figure 3: The typical development of the gravity current down a slope in a linearly stratified environment. (a) The acceleration stage, t = 2 s; (b) The deceleration stage, t = 12 s; (c) The separation stage, t = 55 s.

Front Velocity of The Gravity Current

In this section, we only focus on the front velocity of the gravity current in the acceleration stage. The classic thermal theory proposed by Beghin et al. [6] to describe the development of gravity currents down a slope has got much success [7]. For the gravity current in the acceleration stage, the following result can be obtained:

$$U_m = \left(\frac{1}{x_0}\right)^{\frac{1}{2}} \frac{x_0}{x}\left(\frac{x}{x_0} - 1\right)^{\frac{1}{2}} \sqrt{\frac{8\sin\theta S_1(\rho_{c0}-\rho_a)gfA_0}{(1+k_v)E^2S_2^2\rho_a}}, \quad (1)$$

The meanings of these symbols can refer to [6,11]. To extend Eq. (1) to determine the front velocity of gravity current in a linearly stratified environment, the stratification coefficient α_s is defined as follows:

$$\alpha_s = \frac{g'}{g_0{}'} = 1 - \frac{m\rho_s x_f \sin\theta}{\rho_{c0}-\rho_s}, \quad (2)$$

where

$$m = (\rho_B - \rho_s)\sin\theta/(H_a\rho_s), \quad (3)$$

Based on the thermal theory, we can re-derive Eq. (1) and obtain the front velocity of gravity current in the linearly stratified salt water as

$$u_f = \frac{P\sqrt{x_f(1-Wx_f)}}{x_f + x_0}, \quad (4)$$

where

$$W = \frac{m\rho_s}{\rho_{c0} - \rho_s}, \quad (5)$$

$$P = (1+\frac{\alpha_0}{2k})\sqrt{\frac{8x_0\sin\theta S_1(\rho_{c0}-\rho_s)g(c_a f A_0)}{(1+k_v)E^2 S_2^2 \rho_s}}, \quad (6)$$

In Eq. (3), all the parameters can be determined by the experiments except for the geometric configuration coefficient, which can be get by fitting with the experimental data. Fig. 4 shows the comparison result of the front velocity in the acceleration stage. The good agreement demonstrates that the above equation can be well applied to describe the movement of the gravity current in the acceleration stage.

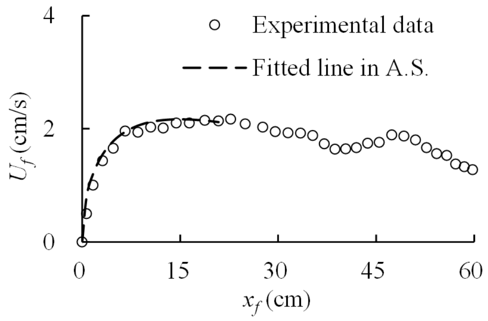

Figure 4: Comparison of the experimental data and the fitted line. A.S. means the acceleration stage.

Conclusions

This study presents the lock-exchange experiment of gravity currents down a slope in a linearly stratified saltwater. The front velocity of the gravity current changing with time is obtained by PIV techniques. The result shows that the development of the gravity current can be divided into the acceleration stage, the deceleration stage, and the separation stage. The stratification of ambient damps the gravity current greatly. A formula is proposed to calculate the front velocity of gravity current by considering the linear stratification. More experimental data of the gravity current in an inclined and linearly stratified environment are being processed by our research group.

Acknowledgments

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