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Gravity currents over a rigid and emergent vegetated slope

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ABSTRACT

Lock-exchange experiments are conducted to investigate the effects of emergent vegetation on gravity currents flowing down a slope. Rigid and emergent cylinders are used to represent vegetation such as reeds in aquatic environments. The results show that the head of gravity currents without cylinders forms a semi-elliptic shape, similar to the flat bed case. For the slope-induced gravity, however, the head of gravity currents gradually grows and accelerates. A steeper slope without cylinders causes the evident entrainment and subsequent energy dissipation of gravity currents with ambient fluid. When the cylinder population becomes denser, developments of the head become slower, and the semi-elliptic head can be only seen at the very front end. As the density reaches 6.9%, the interface between the saltwater and freshwater performs an inclined straight line, corresponding to the pervious theoretical derivation. The gravity current event could go through two different routes under the similar toe speeds. The current head without cylinders grows along the downslope path, and the enrollment and mixing with ambient fluid could occur at the edge of the head; while the currents within dense cylinders (~6.9%) has a nearly constant thickness and a smaller and more streamlined head at the very front end. As the cylinder density increases, the front speed of gravity currents transforms from acceleration to deceleration phases. The experimental results reveal that the head would accelerate over the downslope course if the cylinder density is less than 2%.

1. Introduction

Gravity-driven convective currents are flows mainly produced from the horizontal density differences in fluid [1,2]. In aquatic environments, gravity currents play an important role to transport nutrient and chemical substances between the nearshore and the main water body when the external momentum (wind and river flows) is absent [3–5]. The flows can arise from heterogeneous temperature distributions and subsequent density gradients in water body [6,7]. For example, emergent and floating vegetation can block some solar radiation and lead to lower water temperature in vegetated regions than open water regions during daytime [8–10]. The differential heating due to vegetation shading thereby results in the variation of water densities, driving gravity currents from the open water to the vegetated area along the surface, returning to the open water along the bottom during daytime, and reversing the circulation patterns during nighttime [11]. Similarly, a topographic slope can lead to warmer water in shallows than in deep parts during daytime [12,13]. As a result, the induced circulation that flows from the shallow water to the deep water along the water surface and underflow uphill over the sloping bottom toward the onshore is generated [14]. Other examples and application of gravity currents can be referred to Simpson [15].

Lock-exchange experiments have been used to study gravity currents for several decades [16]. Fluids of different densities are initially at rest and separated by a partition and then released suddenly by removing the partition. On a flat bottom and infinite water depth, the horizontal current speed U was firstly derived by von Kármán [17] using the potential flow theory, which is given by:

$$U = \sqrt{2g'h}, \qquad (1)$$

where $g' = \frac{\rho_1 - \rho_2}{\rho_1}$, ρ_1 and ρ_2 are densities of the denser and lighter fluids, h is the depth of the current. Benjamin [18] combined mass, momentum and energy conservation to derive the steady propagation of a gravity current in a cavity, which is:

$$U = \sqrt{g'\frac{H}{4}}, \qquad (2)$$

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where H is the height of the cavity. In these studies, U is independent of time due to lack of energy sources and sinks. Shin et al. [16] showed that the energy and momentum can be transferred if the denser fluid does not occupy the entire water depth, i.e. partial-depth lock release.

Lock-exchange flows over an inclined boundary draw less attention rather than the cases on a flat bottom. However, gravity currents over a slope are commonly encountered in geophysical environments such as the sinking of surface-cooled in coastal regions and snow avalanches [19,20]. According to the type of buoyancy source, gravity currents traveling down a slope can be generated by continuously supplying with buoyancy fluxes or releasing a fixed volume of fluid. The two different source types perform different flow patterns. For a constant-flux flow, current speeds are only the function of inflow fluxes and irrelevant to the bottom slope as long as the slope is larger than 5 degrees [21]. On the other hand, Beghin et al. [22] proposed a model to describe the flow produced by releasing a finite volume of heavy fluid and verified with experimental data. Their results show that the currents first go through an acceleration phase followed by a deceleration phase. This model, known as the thermal theory, becomes the basis for many following studies, which attempted to include the entrainment and detrainment processes in downslope gravity currents [23–25]. Although these studies have gained a solid understanding of gravity current behavior, few studies discuss flow patterns in the presence of obstructions such as vegetation canopy.

Huppert and Woods [26] studied the gravity-driven flows in porous layers and showed that current speeds down a slope can be related to permeability, void fraction, and variations of height of gravity currents. Tanino et al. [27] revealed that gravity currents decelerate with time as the current front moves into the vegetation canopy over a flat bottom. In the drag-dominated region, the current speeds are given by:

$$U = \sqrt{\frac{2n_v}{C_D a L} g' s H}, \tag{3}$$

where n_v is the porosity of the vegetation canopy (the ratio of volume occupied by water to total volume), a is the frontal area of the vegetation stems per unit volume, L is the horizontal frontal length, C_D is the drag coefficient, and s is a scale constant, which is 0.6 obtained in Tanino et al. [27]. Zhang and Nepf [7] combined the equation derived in Shin et al. [16] and Tanino et al. [27] to discussed flow patterns when vegetation canopy only occupied half of the flow domain. They concluded that the current speed entering the canopy and exchange flowrates both decrease with increasing vegetative drag and also decrease gradually over time. However, to the best of authors' knowledge, gravity currents traveling down a slope in the presence of vegetation canopy have not been studied yet.

In this paper, the behaviors of exchange flows over slopes within and without rigid and emergent vegetation are examined. The lock exchange experiment is a simplified condition to the typical field conditions, and a tank was separated into two same-sized reservoirs to ensure the constant differences of fluid densities. In this study, a vertical partition is set up in the middle of an inclined tank which is significantly different from previous studies that the denser fluid is confined in a small lock. Since the geometric configuration is different as previous studies, the mathematical description of front propagation is firstly derived and compared with our experiment observations. The vegetative drag is then included in the mathematical formulation, and speeds and patterns of gravity currents over a vegetated slope are then performed.

2. Mathematical formulation

The flow domain shown in Fig.1 is assumed as a two-dimensional triangular cavity with the origin at the tip, and x and $z(=-S_0x)$ are the horizontal and vertical coordinates, respectively, where S_0 is the bottom slope and $x = 0$ at the lock (center of the cavity), and $z = 0$ at the water surface. In this work, we consider the cases without vegetation and with rooted and rigid emergent vegetation. The horizontal momentum equation with rooted and rigid emergent vegetation can be written as [28]:

$$n_v \frac{Du}{Dt} = -n_v \frac{1}{\rho}\frac{\partial P}{\partial x} - \frac{C_D a u\sqrt{u^2+w^2}}{2} + n_v \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}\right), \tag{4}$$

where u, w are horizontal and vertical velocities, P is the hydrostatic pressure, ρ is the fluid density, and ν is the kinematic viscosity of the fluid. Without vegetation, the vegetative drag term is dropped, and n_v is equal to unity. In this study, the toe speeds u_{toe} of gravity currents in the lower (moving down the slope) and upper layers shown (moving to the tip of the tank) in Fig.1 are of interest. Since the time scale for the lock exchange experiment is $\sim$O (10 s), by using molecular viscosity of water ($\approx 10^{-6}\,m^2\,s^{-1}$) the boundary layer thickness ($=\sqrt{\nu t}$) is $\sim 3.2\times10^{-3}$ m, far less than the water depth in the lock-exchange experiment, which indicates that the viscous effect can be ignored. Therefore, the inertia is mainly balanced with horizontal pressure gradient (buoyancy) in Eq. (4) in the absence of vegetation. Scaling the inertia term as $u\partial u/\partial x \sim u_{toe}^2/L$ (L is the longitudinal frontal length starting from the lock), Eq. (4) becomes:

$$\frac{u_{toe}^2}{L} = -C_1 \frac{1}{\rho}\frac{\partial P}{\partial x}, \tag{5}$$

where C_1 is a scale constant, and L for the upper and lower layers are denoted as L_{upper} and L_{lower} respectively.

The flow is assumed hydrostatic as previous studies adopted [18,27]. The hydrostatic pressure P in the lower ($-H \leqslant z \leqslant -(H-\eta(x,t))$) and upper layers ($-(H-\eta(x,t)) \leqslant z \leqslant 0$) can be expressed as:

$$P_1(x,z,t) = P_0(x,t) - \rho_1 g(z+H), \tag{6}$$

$$P_2(x,z,t) = P_0(x,t) - \rho_1 g\eta - \rho_2 g(z+H-\eta), \tag{7}$$

where P_0 is the pressure at the bottom. The spatial and temporal variations of water depth can be neglected, and mass conservation thus leads to the zero net flux at each vertical cross section [27], which yields:

$$n u_{lower}\eta = -n u_{upper}(H-\eta), \tag{8}$$

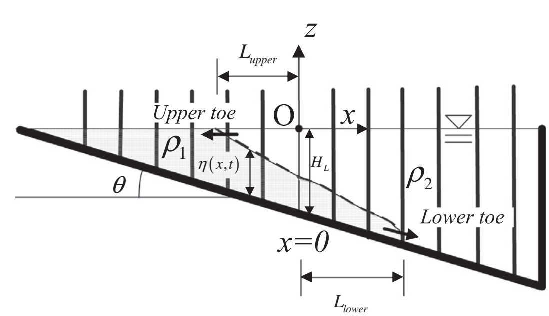

Fig. 1. Schematic of a lock-exchange experiment within cylinders. The lock is positioned at $x = 0$, i.e., the center of the tank, with water depth of H_L. $\eta(x, t)$ is the interface profile. L_{lower} and L_{upper} are the horizontal length of the interface from the lock in the lower and upper layers. ρ_1 and ρ_2 are the density of the denser and lighter fluids.