Propagating Gravity Current in a Uniform Channel as a Laboratory Model for Salt Intrusion

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Abstract--The nature of a gravity current propagating along the rigid base of a channel of constant width and depth is investigated. The investigation is used to characterize the propagating gravity current, examining turbulent mixing particularly occurring above and immediately behind the current head, and quantifying the depth and speed of the current. Using special techniques developed from the photographic and video records in the laboratory, both the depth and speed of the current were accurately and precisely determined. The current depth is measured between 0.36-0.47 *H*, where *H* is the full water depth, whereas the non-dimensional front speed is found to be constant at 0.48±0.02, independent of all flow processes and external parameters. The application of the results to real cases in nature is discussed in the context of laboratory modeling for salt intrusion.

***Index Terms*-- gravity current, salt intrusion, turbulent mixing**

I. Introduction

Gravity current forms when a dense fluid intrudes its environment as a propagating dense current. The density difference between the dense fluid and the surrounding acts as a driving force of the opposing layers. Such a flow can be found in naturally occurring situations and man-made applications, as thoroughly discussed in [1]. A natural example is the inflowing saltwater from a sea intruding the mouth of an estuary and overlying the freshwater stream from a river. In the laboratory, the dynamics of a two-dimensional, propagating gravity current is governed by a balance between buoyancy and inertial forces and is well described by the shallow-water approximation. Thus, particular care should be taken if the laboratory observations of flow of this type, as reported here, are to be applied to real cases in nature.

A basic theory for gravity currents propagating along a horizontal rigid boundary was originally proposed by [2], who considered the propagation of the dense and less dense currents as an exchange of a two-layer flow with no mixing. In this theory, the flow is assumed to be steady, inviscid and hydrostatic, and if energy is conserved the depth of the current occupies one-half of the full water depth. The Benjamin's half-depth, energy-conserving theory was supported by a number of laboratory experiments [3]-[4], but modern experiments, as given in [5], have demonstrated that the theory is no longer hold for the case of a partial-depth release, as the current depth has been found to be significantly less than half depth.

Many authors have since then investigated the properties of gravity current, hence the progress of research in this discipline is much although some issues associated with propagating gravity currents in nature remain unresolved. It is therefore challenging to examine the characteristics of gravity current. Thus, the main purpose of this study is to determine the depth and speed of the gravity current produced in a laboratory uniform channel of constant cross-section with no hydraulic controls, and to consider the propagating current in the channel as a laboratory model for saltwater intrusion. This paper is structured as follows. The experimental methods are all described in §2. The results are presented in §3, followed by discussion in §4. Conclusions are then given in §5.

II. Methods

All experiments were conducted in a horizontal tank of 5.3 m long and 0.2 m wide (Fig. 1a) available at the Geophysical Fluid Dynamics (GFD) Laboratory, Research School of Earth Sciences (RSES), the Australian National University (ANU) that was filled with freshwater of 0.2m deep. In each experiment, a vertical barrier spanning the width of the tank was placed in the centre to divide the tank into two long reservoirs of equal length. A density difference across the barrier was made by adding some measured amount of salt to the right reservoir. Both reservoirs were then stirred thoroughly to set up two homogeneous reservoirs containing water of differing densities. The pressures in the reservoirs were equalized at mid-depth to ensure a purely baroclinic exchange.

Each experiment was initiated by the removal of the barrier allowing gravity current heads to develop, with the dense current propagating along the base and the less dense current counter-flowing near the surface (Fig. 1b). To stop the exchange, the barrier was reinserted into the tank at a time when the current noses had nearly reached the tank endwalls. The progress of the experiment was observed using the shadowgraph technique, the digital video camera and digital still cameras. The initial and final free surface heights were accurately determined using a digital micrometer to within 0.02 mm. The sample densities both before and after each experiment were measured using a digital density meter to a precision of 0.1 kg/m^3. The initial density difference $\Delta\rho$ was varied such that a fractional density difference defined as $\Delta\rho/\rho_2 = (\rho_2 - \rho_1)/\rho_2$ lay in the range $0.01 \le \Delta\rho/\rho_2 \le 0.07$, where ρ_1 and ρ_2 are the initial densities of the fresh and saltwater reservoirs, respectively.

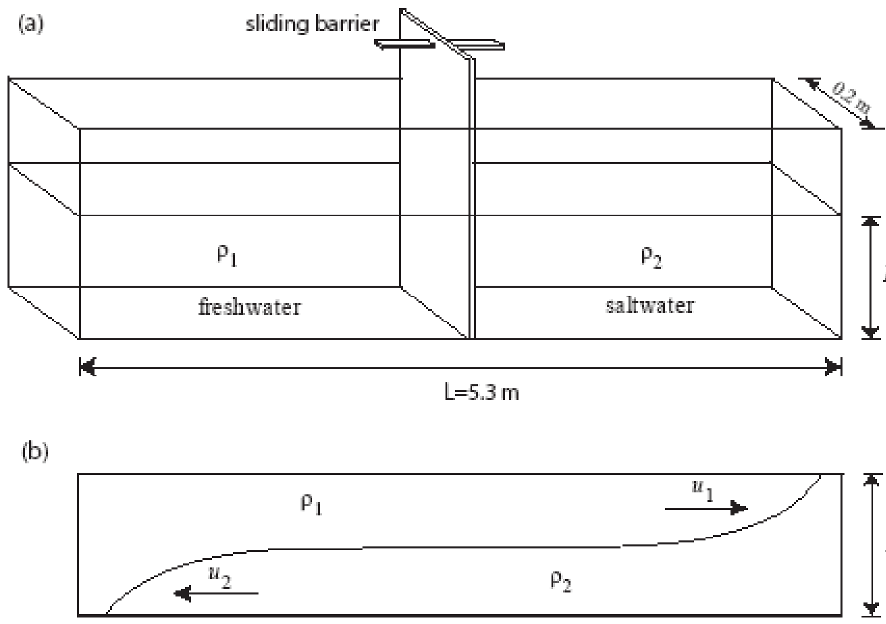

Fig. 1. Sketches of (a) apparatus used for experiments of lock-release gravity currents and (b) typical propagating gravity currents in the laboratory channel.

III. Experimental Results

A. Flow Observation

When the barrier was removed, a characteristic head of gravity current developed. As time progressed, the (bottom) dense current advanced along the base of the tank and the (surface) less dense current propagated in the opposite direction. The front shape of the current head was nearly the same regardless of the density difference, and it was maintained when the bottom current advanced steadily along the channel base. In all experiments, the flows were visually observed to be symmetric.

The region behind the head was unstable to small disturbances leading to overturning motions, and hence mixing between the fluid within the dense current and that of the surroundings. The mixing process occurred when billows grew relatively large in size and subsequently collapsed, carrying away the mixed fluid that was continually replaced by the fluid from the rear. Thus, the sharp front could be sustained at a fixed shape and the corresponding front speed was nearly constant. As the dense current moved forward, interfacial mixing also took place along the upper surface of the following current although it was much less intense than that above the head.

B. The Current Depth

The depth of a gravity current can be estimated from visual observations, where a photograph was taken at a time when the nose of the dense current had nearly reached the left endwall. The average of the possible current heights is taken as the best estimate for the current depth (Fig. 2) in which the current depth is estimated between 0.38 H and 0.47 H, with H being the full water depth. The results are compared with those obtained at different stages of an experiment (when the head was situated in the middle and close to the left endwall). It was found that the non-dimensional current depth is approximately constant for various stages of an experiment. This finding also applies to experiments with different fractional density differences.

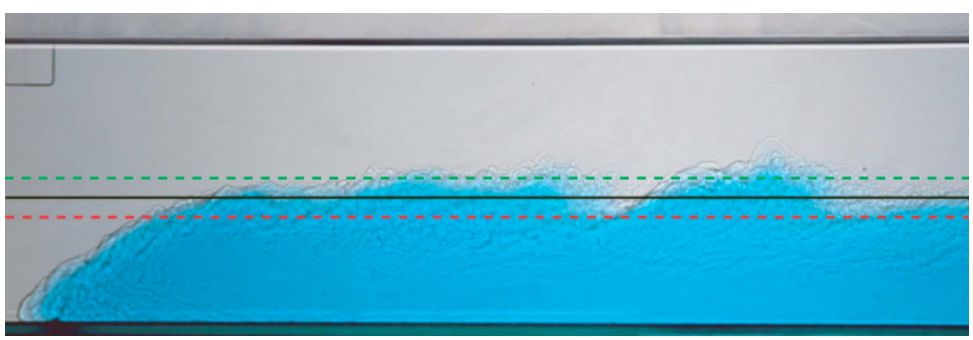

Fig. 2. Estimate of the depth of a gravity current, from the minimum (lower dashed-line) and maximum (upper dashed-line) current heights with the average (solid-line) being used as the current depth.

C. The Current Speed

The speed of a gravity current is evaluated by examining a series of photographs taken from the dense current view in one side of the channel, as shown in Fig. 3 below. The photographs show that the dimensionless speed, non-dimensionalized by $0.5(g'H)^{1/2}$, is approximately constant at 0.48±0.02. The same value of the front speed was also found in all other experiments over the ranges of the external parameters examined in this study. The uncertainty quoted here is due to the uncertainties in the measurements of the distance over which the front propagates and the time taken for the front to travel such a distance in the channel.

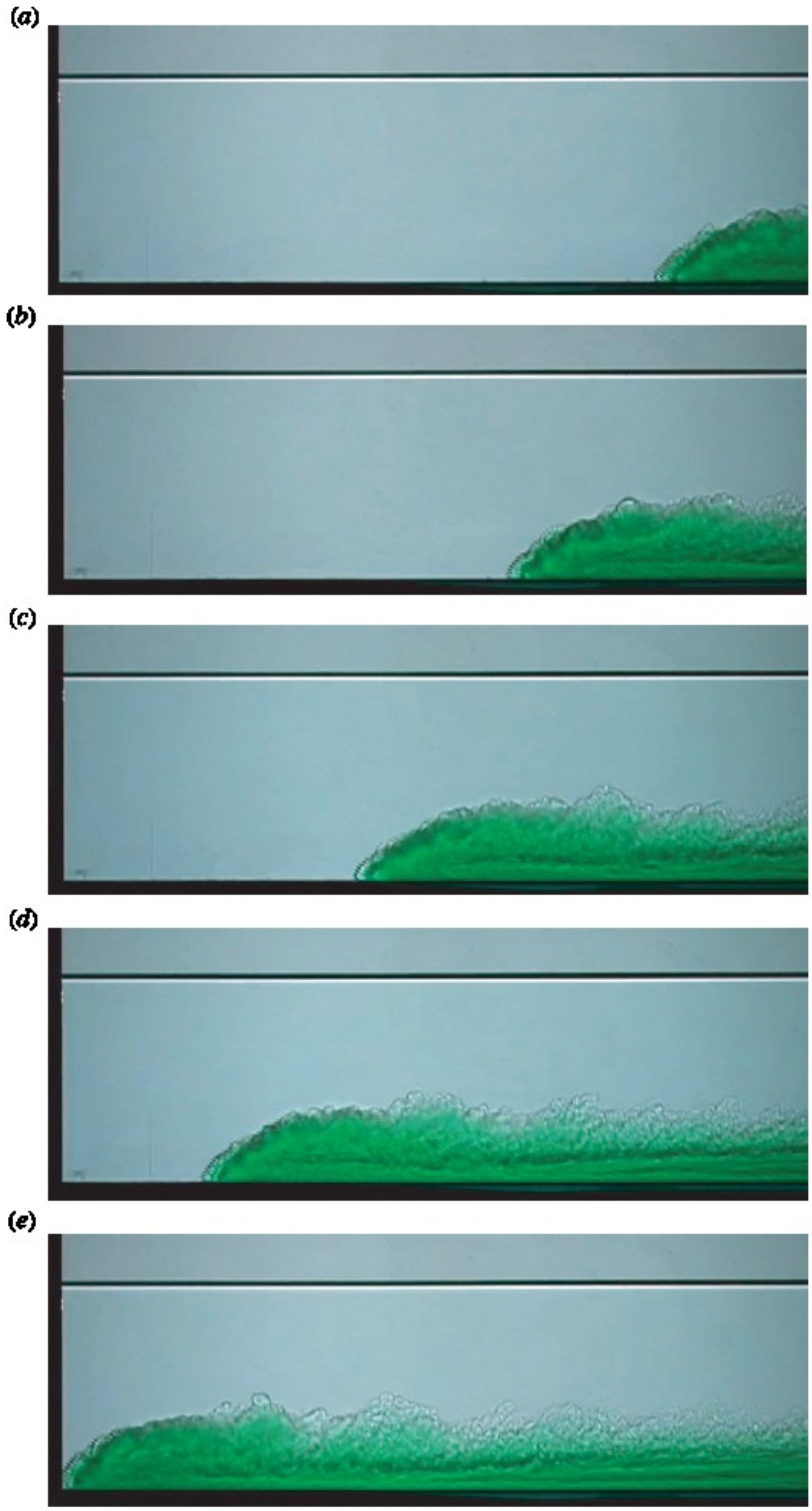

Fig. 3. Gravity current front propagating towards the left endwall from an experiment, where each frame was taken at an constant interval time. The distance between two consecutive frames was also approximately constant, suggesting that this front traveled at a constant speed, as theoretically predicted.

IV. Discussion

The gravity current depth is relatively difficult to measure in the laboratory as the region behind the head is unsteady and turbulent. However, the depth of the current can be best estimated from the photographic and video record [4], as also reported here. An alternative measure of the current depth can also be based on the total mass anomaly in the water column at a given position, as discussed in [5], in which considerable variations in the current depth were found between 0.35 H and 0.50 H across the range of the initial conditions. The latter is consistent with the theoretical prediction of the current depth based on the basic theory for a propagating gravity current [2]. Reference [6], using direct numerical simulations, calculated the current depth by integrating the non-dimensional density profile of the flow field at a given location and estimated it between 0.30 H and 0.40 H, not significantly different from the laboratory results of [5].

In the present experiments discussed here, the depth is estimated between 0.38 H and 0.47 H, consistent with the results of both laboratory measurements [5] and numerical simulations [6]. The present result for the depth suggests that the method for determining the current depth developed here is, to a first degree, reliable although the application of the result to real cases in nature is limited with caution.

The dimensionless speed reported here, 0.48±0.02, agrees well with those of previous results [5]-[7]-[8] and is very close to the theoretical speed for the ideal case of steady, dissipationless propagating gravity currents [2], in which the dimensionless speed is predicted to be 0.5. The conditions considered in the current experiments are, however, different from those of [2], in that both mixing and friction are present and cannot be completely ignored. Thus, the presence of these factors reduces the front speed from the predicted value slightly and induces a loss of mechanical energy through a mechanism of viscous dissipation while the current propagating, as reflected by the measured depth.

The experimental results for both the depth and speed of the gravity current generated in the laboratory channel here are expected to be applicable to natural situations in which fluids of different densities are exchanged. Such an exchange can be commonly found at the mouth of an estuary, for example, where freshwater discharge from a river meets the landward intrusion of saltwater from a sea. If the total depth of a two-layer exchange flow in the estuarine circulation and the density difference between water with different properties in the adjacent basins that drives the circulation are known, then both the depth and speed of the intruding saltwater can be estimated, hence flux of saltwater penetrating into the land can also be predicted. The salt intrusion needs to be carefully managed since it may pose potential risks for water supply in the environment, particularly if the intrusion extends too far to the land. The demand for water upstream for irrigation and domestic use, for instance, may lead to an over extraction of both freshwater at the surface and groundwater at a greater depth. Such an extraction significantly reduces the availability of healthy water near and below the surface to a minimum level, and thereby giving rooms to saltwater from the sea to intrude into the land.

Given human-induced influences on the environment, the likely changes in the availability of healthy water needs to be predicted accurately. Some fundamental questions such as whether changes in the rate at which a river stream flows to the sea or the level of salinity of seawater to which an estuary is linked may affect the estuarine circulation and to what extent such changes have an effect on the biological productivity remain challenging. What we can learn from this study is critical for those who live in and rely much on coastal waters. A likely grounded, public policy to reduce vulnerability to coastal floods, drinking waters and food supplies is thus vital. Research-based policy from the government can only be provided to the society if this issue is properly treated. It is also important to mention here that, because of its incredibly diverse ecosystem, estuarine research is interdisciplinary that involves not only physics, chemistry, and biology but also social and life sciences, and even goes far beyond these disciplines. As this issue is essential for human life, the need for a better understanding and preservation of this invaluable system is remarkably important, and thus is of fundamental interest.

V. Conclusions

Laboratory experiments are used to examine the nature of a gravity current generated in a simple channel of constant width and depth, where the apparatus used is able to show the essential features of a typical gravity current commonly found in nature. The apparent shape of the gravity current was observed to be consistent with the theoretical descriptions of a steadily advancing gravity current along a horizontal rigid boundary, as discussed in [2]. The current depth is best estimated to be 0.36-0.47H, in good agreement with previous results [5]-[6], whereas the dimensionless front speed is measured to be 0.48±0.02, independent of all parameters and processes responsible for mixing, very close to the theoretical value for the front speed suggested by [2] and further confirmed by [5]. Although the experimental results for both the depth and speed of the current obtained from this study are reliable and convincing, the experimental conditions in the case we consider here limits the application of the results to a wider situation in natural environments, in which more dynamical variables may come into play.

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VII. References

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