Experimental Study of the Effect of the Spreading Buoyant Gravity Current on the Coastal Environment

Dhafar Ibrahim Ahmed, Noureddine Latrache, and Blaise Nsom

***Abstract*—The experiments of injection gravity currents were completed in a rectangular basin by release the fresh water over a salty water surface at rest. The surface flow of lighter liquids horizontally can be considered as a special case of a two dimensional gravity current, and the spreading law of the fresh water is validated by using image processing technique to record the progress of the injection current. The jet fluid was colored and the digital video can have a variation of light intensity in order to obtain the shape of the outer boundary of the gravity current and its distance from the source point with relation to time, initial, or flow parameters of the jet source.**

***Index Terms*—Experimental results, gravity current, lighter fluid discharge, flow regimes, image processing.**

I. Introduction

Gravity currents can be found in oceanic and river systems. The density differences between fresh water river efflux and saline oceanic water can lead to a river plume and a salt wedge. The spreading of buoyant jets in calm, and stratified environment with a linear density has been the theme of consideration for a few decades. A gravity current generally defined as the flow of one fluid into another by a density differences, temperatures variation, and dissolved substances or suspension particles [1], [2]. The discharge of pollutants, and oil spillage on the sea or ocean extremely cause negative environmental impacts [3].

Von Kàrmàn [4] is the first one derived a theoretical formula for the spreading speed based on the Bernoulli equation assuming an ideal fluid and irrotational flow. Since the 1950s, the gravity current have been studied widely in laboratory experiments. The spreading is caused by a steady source of dense fluid, the outer boundary of the gravity current will always change with time, when the bottom is horizontal and the ambient is calm.

The radial spreading on a horizontal boundary was firstly approached by Sharp [5] who presented plots for the estimation of the dimensionless distance from the impingement point to the front of the gravity current, as a function of a dimensionless discharge flow rate and a dimensionless time. His experimental results refer to spreading on the free surface or on the bottom arising from the impingement of positively buoyant jets discharged horizontally upwards or downwards in a calm homogeneous ambient fluid.

The gravity current was described by Huppert and Simpson [6] of a denser fluid into a lighter fluid over a rigid plane when the ambient fluid is viscous and at rest. Huppert and Simpson defined three regimes: (i) the slumping regime, (ii) the inertial regime and (iii) the viscous regime. Fannelop and Waldman [7] proposed four solutions of the oil slick over water: (i) the first regime is the slumping of the oil slick (L ~ t), (ii) the second regime is the equilibrium between the inertia and the gravity forces (L ~ t^2/3), (iii) the third regime is the equilibrium between the viscous and the gravity forces (L ~ t^1/4) and (iv) the fourth regime is the equilibrium between the viscous forces and the surface tension effects (L ~ t^3/4).

The following studies have usually followed the force balance analysis employed by Fay [8] for spreading of oil on the sea surface. The spreading of fluid due to a constant source of buoyancy on the surface or on the bottom of a calm ambient was investigated experimentally and theoretically by several investigators [8]-[12].

The present study aim at displaying the results of laboratory experiments concerning the spreading of two dimensional gravity currents represented by injection the lighter fluid (fresh water) over a calm free surface of denser fluid (salty water) that it is like the process of coastal discharge of effluents. This study considers the spreading of a gravity current of fresh water with density ρ and initial speed Uo upon the free surface of an ambient liquid (salty water) with density $\rho+\Delta\rho$, at rest in a basin. The investigation is performed in a two dimensional configuration with the help of the spatiotemporal diagrams technique, we measured the time evolution of the progress x, and the spreading y of the gravity currents and these estimation have been characterized by scaling laws.

II. Experimental Setup and Procedure

A. Setup

The experimental device used to investigate the spreading of gravity currents over the free surface of a miscible denser liquid at rest was designed and built in our laboratory, it as shown in (Fig. 1). A transparent basin made from Plexiglas containing the static ambient liquid, of 700L (3m long, 0.49 m wide and 0.49 m deep). A bowl of 240L used to prepare the ambient fluid by introducing the quantity of salt corresponding to the concentration needed into a given volume of water. The solution prepared (salty water) is then poured into the previous basin. A reservoir of 60L equipped

Manuscript received December 19, 2015; revised February 20, 2016.

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DOI: 10.7763/IJET.2017.V9.957

with a floodgate and which releases the gravity currents into the basin.

B. Measurement Technique

Techfluid 2150 flowmeter aiming at controlling and measuring the flow rate of the gravity current as it is released from the previous reservoir. An injection channel (600 mm long and 17 mm wide) manufactured in transparent glass and which links the reservoir to the basin. An instrumentation equipment comprising: an observation system consisting of one SONY CCD XC-ST51/ST51CE black and white camera equipped with a resolution of 768x576 pixels. The viscosity of the salty water was measured against the concentration using an Ostwald viscometer.

A light source made of 50 Hz- 500w projector lamp was placed in front of basin. The experiments were conducted in the dark laboratory room to avoid other light sources disturbing on the experiments. A small red soluble dye quantity of Rhodamine B was used as tracer in order to visualize the flow of gravity current (Fresh water) in the reservoir and its agent is introduced for video-photographic analysis purpose.

C. Experimental Procedure

The flow rate of gravity current was varied from 30 L/h, 70 L/h, and to 110L/h. The release of gravity current of lighter fluid represented by the density ρ equal 1000 kg/m3 injected on the top of a basin surface containing a static denser fluid represented by a salty water with density ρ+Δρ equal 1040 kg/m ³. The dye had no effect on the density of salty water and viscosity because the dye was a conservative with similar density to fresh water. Experiments took place under the same conditions with temperature ranging from 17 to 23 ℃. The reduced gravity and viscosity are fixed respectively at 0.38 m/s ² and 10-6 m2/s.

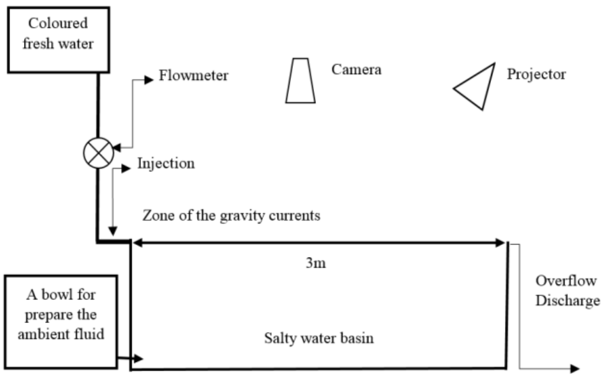

Fig. 1. Schematic of the experimental setup

III. The Dimensional Analysis

The horizontally flow injection of lighter fluid region is due to the initial momentum flux M_0, specific fluxes mass (Q_0 the initial flow), and the flow of lighter fluid over a calm surface of denser fluid formed immersed bulk due to the buoyancy flux B_0.

$$Q_{\circ}=\frac{\pi d^{2}}{4}U_{\circ},M_{\circ}=U_{\circ}Q_{\circ},B_{\circ}=Q_{\circ}g',g'=\frac{\Delta\rho}{\rho}g$$

where U_o indicates the initial fresh water injected velocity, Q_o the initial flow rate and d represented the width of injected channel, g' is initial visual acceleration of gravity at the injection source, g is acceleration due to gravity, Δρ denotes the difference densities between fresh and ambient salty water, and ρ the uniform fresh water density.

Therefore, the initial (at the channel exit) parameters Q_o,M_o,B_o,g' are used for flow analysis with a possible dependence on the densimetric Froude number Fr_o (Initial Froude number) and Reynolds number Re(Initial Reynolds number).

$$Fr_{\circ}=\frac{U_{\circ}}{\sqrt{g'd}},\mathrm{Re}_{\circ}=\frac{\rho U_{\circ}}{\mu}$$

The range of initial injection densimetric Froude numbers Fr_o from 0.36 to 1.32 was studied and the flow was transmitted progressively from laminar to the turbulent, with the Reynolds number Re_o from 481 to 4434.

IV. Visualization and Image Processing

The visualization is realized by adding rhodamine B in gravity current which can give the variation of the light intensity recorded by a camera. The recorded images are analyzed in order to extract the position of gravity current boundary. The image processing is based on the filtering of noise and binarization of image sequences as shown in Fig. 2 and to exact the spatiotemporal interface position of the gravity current.

Fig. 2. Image captured by a camera: (A) initial frame without flow Io, (B) frame with a colored gravity current flow, and (C) image obtained by difference and filtering processes.

The captured video frames with current development are subsequently converted into greyscale matrices, in the region of the basin surface and then converted into instantaneous density field as shown in Fig. 3.

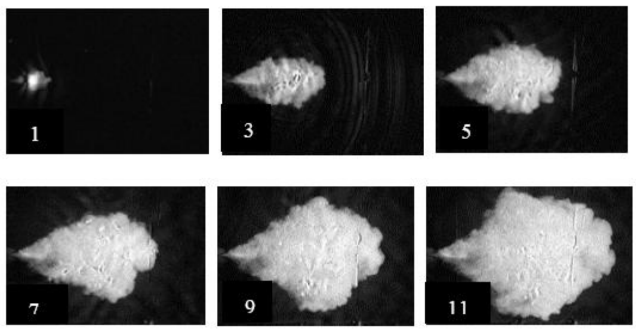

Fig. 3. Snapshot of gravity currents obtained by image processing.

V. Results

A. Shape of Gravity Currents

The techniques of image processing to characterize fully experiments of spreading gravity current in our work. The two dimensions profiles of the gravity current showed that the flow is non-axisymmetric and the evolution of the front position showed a power law with time, as shown a horizontal plane coordinate system x-y according to Fig. 4, Fig. 5 and Fig. 6, represented the outer boundary of injection current. An image analysis applied to investigate the gravity currents developing over a horizontal free surface of the basin. Immediately after the injection of lighter fluid on the basin, a gravity current of was formed and the injection zone depending on the flow rate.

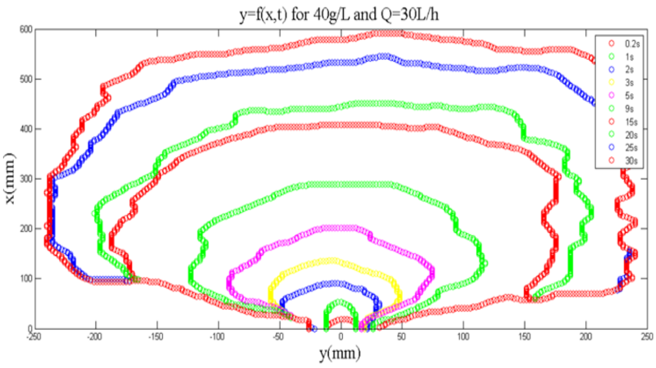

Fig. 4. The profile of gravity currents outer boundary $y=f(x, t)$ for Q= 30L/h

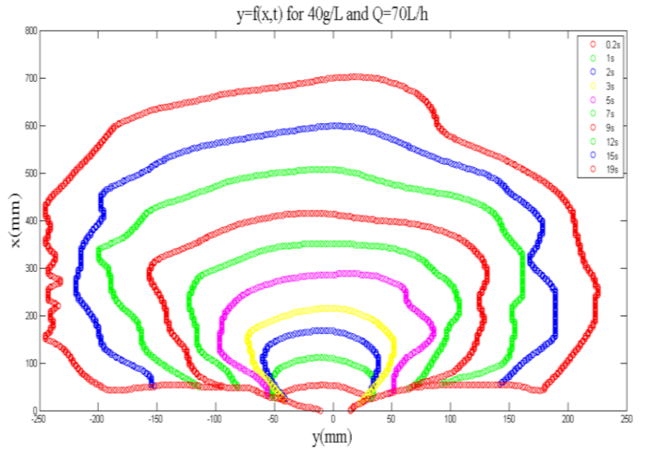

Fig. 5. The profile of gravity currents outer boundary $y=f(x, t)$ *for* Q=70L/h

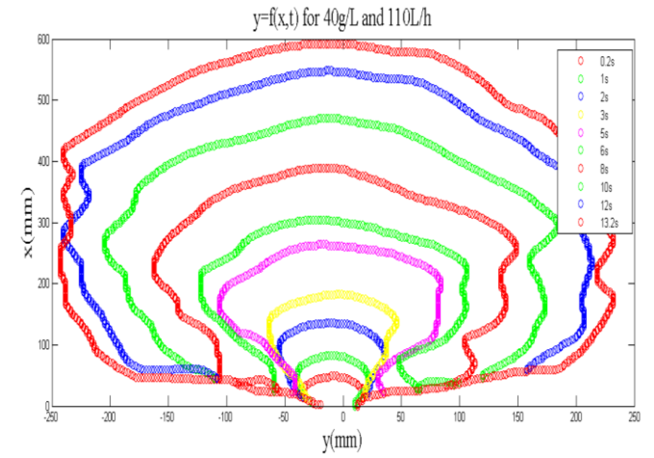

Fig. 6. The profile of gravity currents outer boundary $y=f(x, t)$ *for* Q=110L/h

B. *Front Positions of Gravity Currents*

The shape of gravity currents for every flow depends on the volume of fresh water was released, also consideration the time periods to configuration the gravity currents varies due to differences in velocities. During the interval of time, the gravity current travels with constant velocity, depending on the initial height and modified acceleration due to gravity. Observation of the flow structures in a fully developed gravity current front were done by repeating experiments. These experiments, however, served to emphasize the importance of including the effect of the ambient fluid on the gravity current.

The front of the two dimensional gravity currents obtain by inconstant jet flow of fresh water over salty water. Through used the scaling law by applied the power fitting for measurements the exponents in a series of all experiments will get the functional forms of the positions x and y together with time relationships and this leads to study the spreading is changeable problem since the gravity current grows with time and the outer boundary variations as shown that in Table I. As well as observed the variation of distances with time can see in Fig. 7 and Fig. 8.

TABLE I: Scaling Laws Obtained for the Spreading of Fresh Water

Q	Re	Fr	Spreading Law (x-direction)	Spreading Law (y-direction)
30	481	0.36	$x=52t^{0.69}$ [1.8<t(s)<18.6] $x=96t^{0.48}$ [18.8<t(s)<30.2]	$y = 64.6t^{0.67}$
70	3587	0.84	$x=68\ t^{0.63}$ [1<t(s)<9.4] $x=91t^{0.56}$ [9.6<t(s)<19.6]	$y=113\ t^{0.60}$
110	4434	1.32	$x=63t^{0.49}$ [0.2<t(s)<2.6] x=38.9t [2.6<t(s)<11]	$y=90\ t^{0.70}$

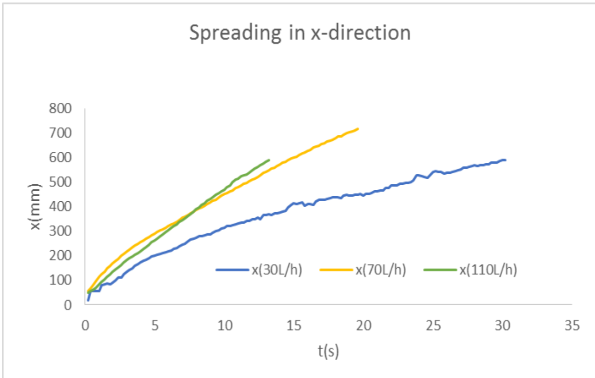

Fig. 7. Evolution of spreading front in x-direction.

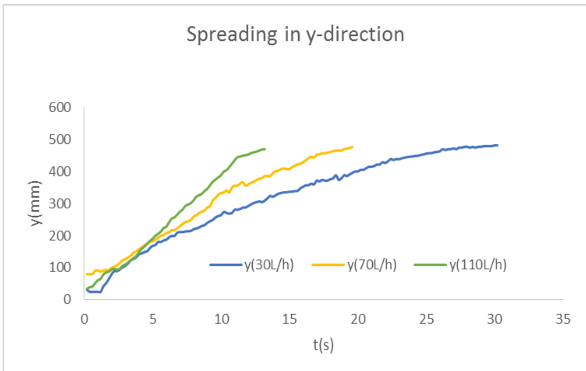

Fig. 8. Evolution of spreading front in y-direction.

That means there are two kinds of movements are featured in the layers of oceanic water: (1) laminar or layered motions, when adjacent layers do not mix, and (2) turbulent or rotational motions, when velocities continuously baulk according to a value and direction around the average in every flow point. Oceanic water surface is subject to continuous fluctuations from periodic and non-periodic forces.

These forces include gravity currents (generated by dense and level gradients), friction, and tide creating forces, centrifugal forces and the inertia and deflecting forces of Earth rotation. The formation of oceanic gradients in surface layers predominates during the lightest times of day and year, and they are destroyed during dark periods.

VI. Conclusion

The experimental results were compared with Huppert [11], the front of the two dimensional gravity currents obtained by a constant fresh water injection over the salty water surface basin. Also the gravity current jet of the fresh water over salty water is studied experimentally and it's for initial Reynolds number and initial Froude number, as shown as the Table. I the alteration of flow regimes was in viscous regime x~t^0.6 approximately this confirmed experimentally by Britter [8] .The outer boundary of gravity current spreading on the salty water free surface is almost non-axisymmetric and the same thing for jet zone. The front positions distances from the jet source to the outer boundary of the gravity currents are correlated with spatiotemporal diagram and showing the balancing between buoyancy and, either drag (viscous spreading) or inertia.

Acknowledgment

This work is part of the author's PhD thesis in the field of Coastal Engineering at UBO (Université de Bretagne Occidentale).

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