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EXPERIMENTAL OBSERVATIONS OF THE FLOW STRUCTURES AT GRAVITY CURRENT FRONTS

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Abstract: Fully developed saline gravity currents with specific gravity of 1.003 intruding a fresh water body are generated with the lock-exchange scheme in a 9.0 m long, 65 cm wide and 60 cm deep tank for investigations. The laser-induced fluorescence (LIF) flow visualization technique is utilized to observe the detailed flow structures with special emphasis on the current head. Continuous fluid motions in the longitudinal and transverse planes starting at 2.2 m downstream from the gate opening are recorded by a professional digital video camera for frame-by-frame visual analyses and measurements. It is shown that the continuous generation of eddies is originated at the current front. The flow in the head is very complex and it has structures varying both in the longitudinal and transverse directions. The eddies generated at the front are then manifested, stretched and bended by the shear flow developed behind and between the lighter and heavier fluids to form large-scale rollers similar to Kelvin-Helmholtz vortexes developed in free shear layers but much short-crested. It is believed that the cross-stream ambient fluid entrainment actions at the foremost leading edge of the current initiate intense mixing and it may provide the needed instabilities at the flow interface, hence feeding the growth as well as creating the three-dimensionality of the subsequent large-scale rollers exhibiting the lobe-and-cleft features.

Key words: Gravity current, Characteristic head, Mixing, Laser-induced fluorescence (LIF)

1. INTRODUCTION

Gravity currents are density driven flows occurring in natural and man-made situations. It is types of phenomena of stratified fluids, happens when a denser fluid body intrudes into a less dense body of fluid or vice versa. An example is a fresh waterfront flowing down an estuary over a “salt water wedge” formed by the opposing dense salty current. Both the fresh current at the surface and the salty current at the bottom are types of gravity currents. Comprehensive information on gravity currents can be found in Simpson (1997), in which he summarized that as gravity current advances, a characteristic head, so called front, is formed at the leading edge of the current and it is slightly raised above the bottom surface; intense mixing occurs between the front of the current and its surroundings. A sketch of a typical gravity current advancing on a horizontal plane is shown in Fig. 1. According to Simpson (1997), the head of the current H is approximately two times as deep as the following flow depth h and the nose, i.e. the foremost leading edge, of the current is about 1/8 of the current head. The current induced mixing is considered to be caused by two types of instability; they are (1) billows, which roll up in the region of velocity shear above the front of the dense fluid, and (2) a complex shifting pattern of lobes and clefts, which are formed by the influence of the ground on the lower part of the leading edge. Hence, the characteristics of the head would control the fluid mixing behavior, current propagation velocity as well as the current profile. Recent study by Yeh & Wada (2001) reveals further details of the gravity current flow field by utilizing the laser induced fluorescence (LIF) technique. They found that the billow formation at the gravity current front to be three dimensional and its features are more consistent with the lobes and clefts pattern indicated by Simpson (1997). The inverted roll-up and entrainment of the ambient fluid under the nose of the current were also observed by them. At the same time, they showed the leading edge of the current to be irregular due to formation of counter-rotating, mushroom-shaped eddies, and the flow following the front may have periodic formation of large-size eddies. Even many studies have inspected the fundamental characteristics of the advancing head; definite information about the complicated mechanisms of the three-dimensional unsteady flow field led by the front is still ambiguously. The present study investigates experimentally its features for further insights.

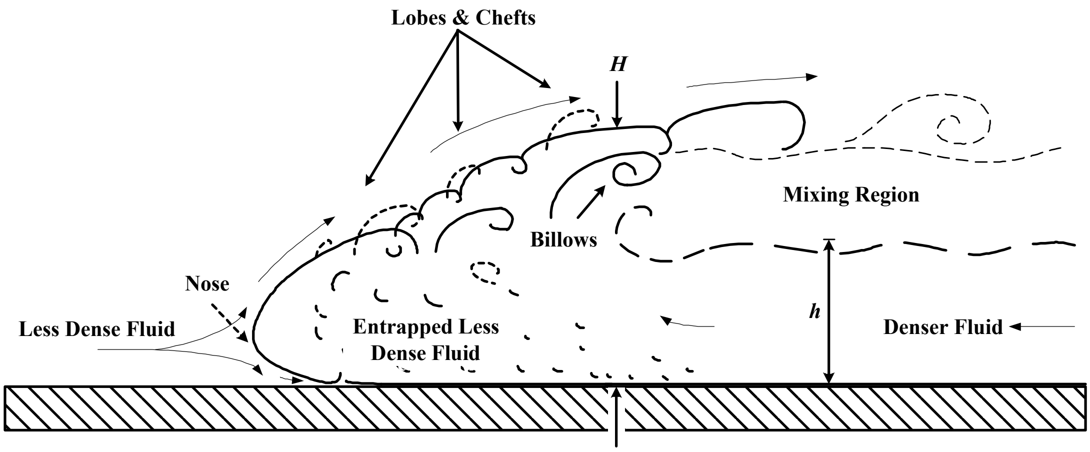

Fig. 1 Sketch of a typical gravity current front advancing along a horizontal plane

2. EXPERIMENT

The facility of the present study is constructed particularly for the investigations of gravity current in a controlled environment (Mok et al., 2002). The dimension of the experimental tank is 9.0 m long, 65 cm wide and 60 cm deep. Views and schematics of the facility are shown in Figs. 2 and 3, respectively. The structures of the tank are steel with anticorrosive painting. To ensure a smooth and uniform surface throughout the tank, the sidewalls and bottom floor are constructed with 12 mm thick temper glass plates. The entire tank is elevated with the bottom floor at 1.2 m from the laboratory ground. This setup together with the tank's glass walls and floor allow the shinning of laser light sheet from the side or below the tank for application of laser-induced fluorescence technique (LIF) for flow structure observations. It is emphasized that a transparent tank floor with sufficient dry working space underneath it is essential for introduction of laser light sheet and observations in the planes of all directions.

The generation of gravity currents in the designed water tank uses the lock-exchange scheme, which is commonly utilized for this type of studies (e.g. Wood & Simpson, 1984 and Yeh & Wada, 2001). The tank is divided into two chambers of 5.4 m and 3.6 m long by a stainless steel gate. The longer front chamber is filled with fresh water while the shorter back chamber is filled with uniformly mixed saline water. The densities of both fresh water and saline water are measured by a high-resolution hydrometer (ELE, No.943578) in the experiments. Before experiments, the uniformly mixed saline water is prepared in a stainless steel reservoir of 1.5 m in diameter and 1.2 m deep installed on a 2 m high platform behind the tank. A mixer (Toshiba, BMP-150B1) fixed above the reservoir is used to continuously stir the fresh-water and table-salt mixture for about one hour during preparation and then the solution is let to sit for at least 24 hours before being fed to the back chamber for usage. Generation of gravity currents for observation is made by vertically lifting the gate instantaneously by a pneumatic cylinder for a fixed distance, usually approximately one-third of the total water depth, above the bottom of the tank. This partial gate-opening setting can minimize free-surface disturbance at the gate and can control the generated current depth (Wood & Simpson, 1984 and Yeh & Wada, 2001). Observations of the fully developed gravity current are done at a far distance downstream of the gate in the front chamber.

(a) **(b)**

Fig. 2 Views of experimental facility; (a) front view, (b) back view

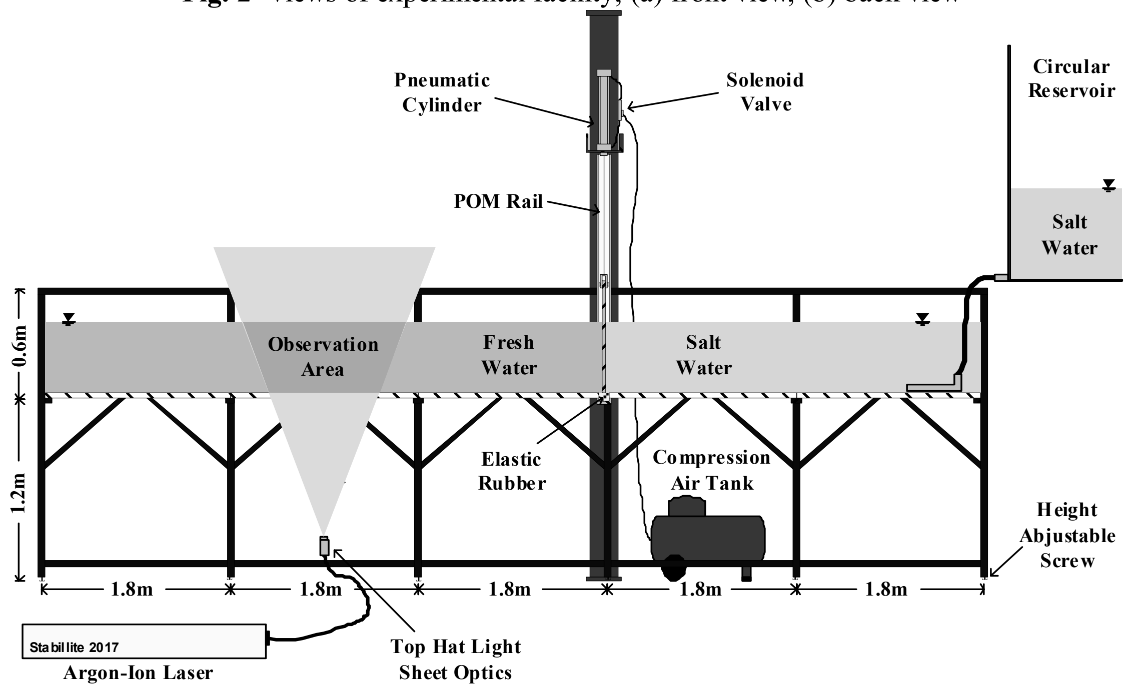

Fig. 3 Schematics of the gravity-current tank

Detailed profiles of the fully developed current with emphasis on the mixing mechanism of the current head are visualized through LIF technique, in which a 10-Watt Argon-ion laser (Spectra Physics, Stabilite 2017 System) operated in the 457.9-528.7 nm wavelength range (the green spectrum) is used. The laser emits a 1.4 mm diameter laser beam to a Dantec fibre optics system equipped with a top hat light sheet optics module of sheet angle 40-degrees (Dantec, 9080X0421) connecting to the end of a 10 m long single-mode fibre cable. The optics converts the laser beam into thin light sheet, which can be placed at desirable location to illuminate the saline water dyed with fluorescein (Disodium salt, $C_{20}H_{10}O_5Na_2$) so that flow details in various planes (longitudinal and transverse) of gravity currents can be revealed. The brighten flow field is recorded by a professional digital video camera (Sony, DCR-VX2000) with 25 frames per second recording ability. The recorded video signals are then fed into a computer for frame-by-frame analyses and measurements.

3. RESULTS AND DISCUSSION

Observations of the flow structures in a fully developed gravity current front were done by repeating experiments. The depths of both the fresh and saline water in the front and back chambers were set at 0.45 m throughout all experimental runs. The densities of the saline and fresh water were ρ_s = 1002 kg/m^3 and ρ_a = 999 kg/m^3 respectively, hence giving a specific gravity of 1.003 to the saline water. Gravity current was generated by vertically lifting the gate instantaneously for 0.15 m above tank bottom, i.e. one-third of the 0.45 m water depth. Observations of the current front were made starting from 2.2 m downstream of the gate, approximately 15 times the gate opening, in the front chamber. It is believed that this distance is enough for the transient disturbances caused by gate opening to subside, therefore imposing minimum effects on the observed currents. It is also noted that the 3.6-m long back chamber provides sufficient length so that flows in the observation area will not be disturbed by reflections from its end wall. The repeated experiments were synchronized in time by letting $t = 0$ sec. at gate opening.

The sequential fluid motions of the gravity-current head in a longitudinal vertical plane illuminated by a 1.4mm thick Argon-ion laser light sheet along the center of the tank are shown in Fig. 4 with a time step of 0.427 sec. between each picture. The area size covered by the pictures is approximately 15cm longitudinal by 10 cm vertical. The Reynolds number and the densimetric Froude number of this flow are $R = Uh/\nu = 1750$ and $F = U/\sqrt{(g'h)} = 1.146$ respectively, where U is the average advancing speed of the current head, ν is kinematic viscosity of the fluid and $g' = (\rho_s - \rho_a)g/\rho_a$ is the buoyant acceleration with g being the gravitational acceleration. Figure 4(a) is taken at t = 57.28 sec. after the gate opening and the right edges of this and other pictures in Fig. 4 are at 2.2 m downstream of the gate. The characteristic head of the saline current is made visible by the laser illuminated fluorescence shown in gray shades while the fresh water is shown in white.

It is clear from the pictures in Fig. 4 that large-scale eddies or billows develop on the upper surface of the head and grow in the upstream direction. These eddies are believed to be originated at the front interface by baroclinic torque, which is created by the unparallel density and pressure gradients as suggested by Yeh (1991, 1995). The formed eddies are then manifested, stretched and bended by the shear flow developed behind and between the lighter and heavier fluids to form large-scale billows or rollers similar to Kelvin-Helmholtz vortexes developed in free shear layers as indicated by Simpson (1997) but they are much short-crested and have more of the lobe-and-cleft features, hence three-dimensional, due to the inherently vortical flow at the gravity current head as observed and pointed out by Mausshardt *et al.* (1994) and Yeh & Wada (2001). A view of the transverse vertical plane at 2.35 m downstream of the gate taken at t = 65.36 sec. after the gate opening is shown in Fig. 5. The shown plane is at approximately 9 cm behind the current nose. The irregular interface in the

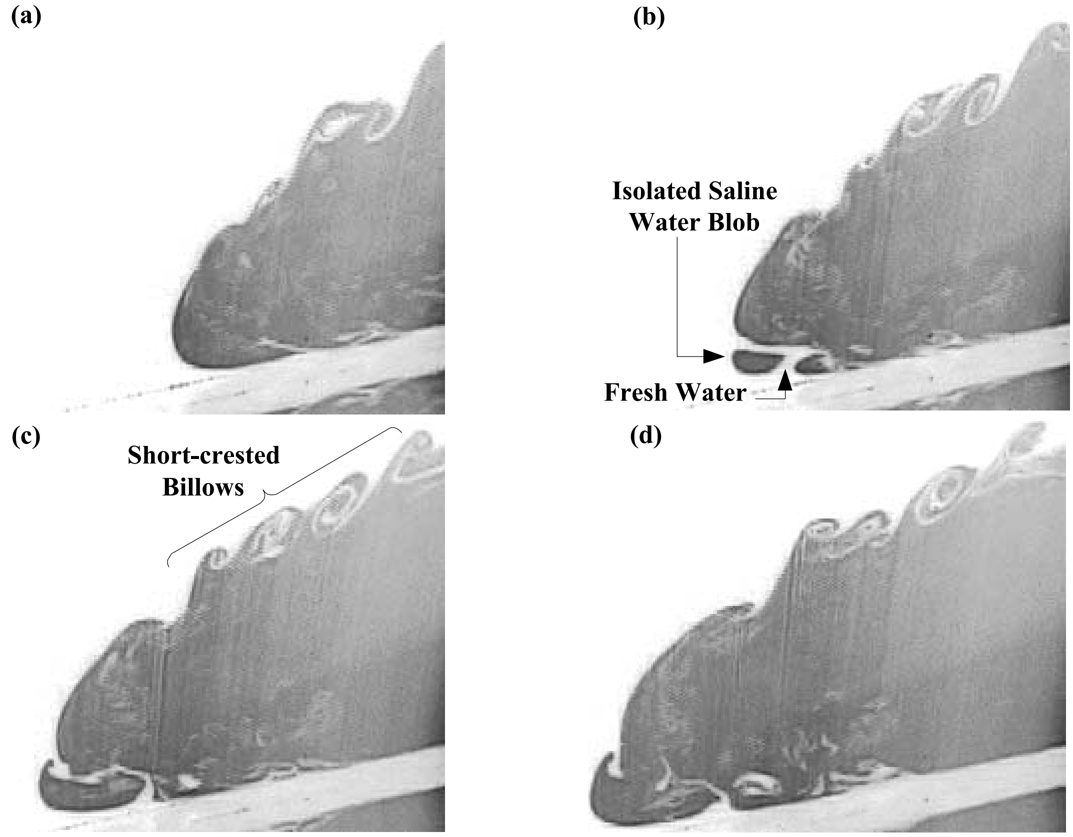

Fig. 4 Sequential views of the flow structures in a saline current front along the longitudinal vertical plane in the center of the tank at 2.2 m downstream of the gate, the Reynolds number R = 1750 and the densimetric Froude number F = 1.146, the time step of each picture is 0.427 seconds and the viewing area is about 15cm$\times$10cm

cross-stream direction confirmed the short-crested billow and the three-dimensional lobe-and-cleft characteristics in the following flow of the current. The uneven transverse saline water depth would also create fluctuations in the cross-stream pressure gradient hence creating cross-stream flows or circulations, therefore complicating the flow structures within the current front. In addition, there are small slanted white streaks originating at the tank bottomas shown in both Figs. 4 and 5. These streaks represent fresh water trapped underneath the saline current at the nose as it advances along the bottom. They are stretched by the current flow field near the bottom as they rise up within the saline water domain by buoyancy. Further analyses on the pictures shown in Fig. 4 indicate that the entrainment of ambient fluid into the saline current could happen as early as at the foremost leading edge, i.e. the nose, of the current. Figure 4b shows that fresh-water blob can suddenly enter the illuminated viewing plane at the leading part of the current hence isolating a saline water blob in the front from the main current body. The saline water blob then increases in size and develops into a 'mouth' like pattern and eventually merges back with the main current front through longitudinal stretching and bending (Fig. 4d). The facts that the sudden entrance of the fresh water blob as well as the size increase of the isolated saline water blob indicate that the supply must come from the cross-stream direction but not from directly below and behind. These observations allow one to conclude that the three-dimensional characteristics of a gravity current flow field must be originated at the front and the ambient fresh water entrainment there is probably more significant than those from the bottom trapped underneath the current. Actually, the large white streaks which go all the way from the bottom to the interface appear near the right edge of Fig. 5 are probably results of cross-stream flow actions due to irregular front profile. It is believed that these cross-stream ambient fluid entrainment actions at the foremost leading edge of the current may provide the needed instabilities at the flow interface, hence feeding the growth as well as creating the three-dimensionality of the subsequent large-scale rollers exhibiting the lobe-and-cleft features. In fact, this is consistent with the results of the linear-stability analysis concentrating on the foremost part of the front by Härtel et al. (2000a), which are based on direct numerical simulation data of two-dimensional lock-exchange flows by Härtel et al. (2000b). They found that the existence of a vigorous linear instability that acts in a localized way at the leading edge of the front and originates in an unstable stratification in the flow region between the nose and the stagnation point located slightly below the nose. The complex flow structures at the foremost part of the front can best be demonstrated by the picture shown in Fig. 6 which is taken also at t = 65.36 sec. after the gate opening as that in Fig. 5 with the same coverage area as in Fig. 4. The significant amount of fresh water entrainment shown by sporadic distribution of white patches in various shapes and sizes in the very leading part of the current head indicates intense mixing occurring as early as at the leading front and this confirms the possibilities of ambient fluid entrainment from various directions and it leads to unstable stratification resulting in subsequent eddy formation and growth. It can be seen in Fig. 6 that the roll-up action of a small-scale eddy occurs at location very near the nose, which is followed by a series of similar eddies along the interface with growing sizes.

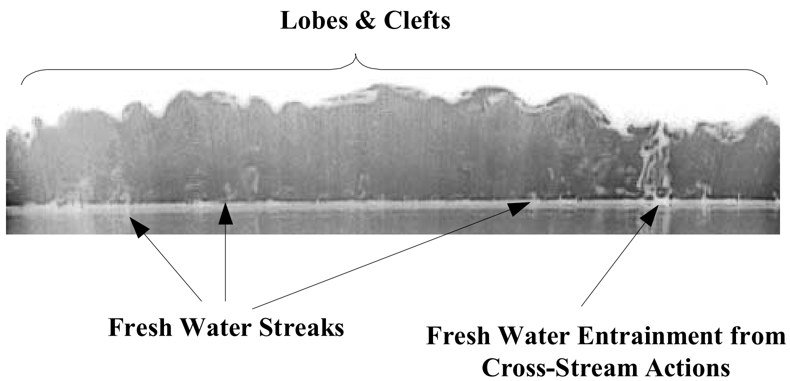

Fig. 5 View of the flow structures in a transverse vertical plane at 2.35 m downstream of the gate taken at t = 65.36 sec. after the gate opening, the shown plane is at approximately 9 cm behind the current nose with R = 1750 and F = 1.146

4. CONCLUSION

The flow structures in the characteristic head of gravity current are revealed by LIF observations along the longitudinal and transverse vertical planes. It is found that the flow structures there are very complex and three dimensional leading to heavy entrainment of ambient fluid through various directions starting as early as at the leading front of the current. This results in the creation of an unstable stratification condition at the front favourable for subsequent eddy generation and growth, thus leading to the formation of the short-crested billows exhibiting the lobe-and-cleft features, which are further magnified by the shear flow actions following the current front. Furthermore, the lobe-and-cleft features shown near the head and in the following flow create fluctuations in the pressure gradient in both longitudinal and transverse directions, therefore further complicating the flow structures and mixing behaviours. At last, it is noted that even the present study provides additional insights to the flow behaviours at the gravity current front, further investigations at a greater depth are required to provide complete explanations.

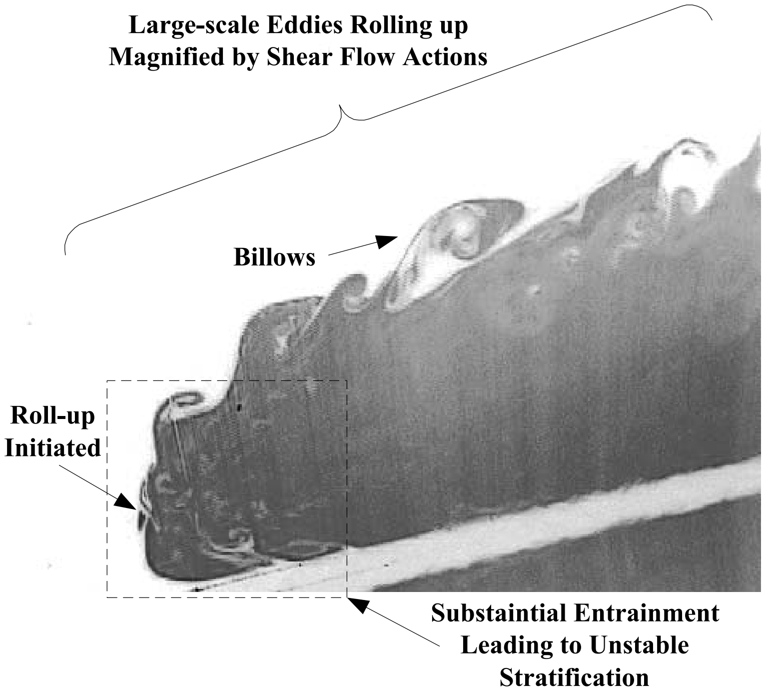

Fig. 6 view of the flow structures in a saline current front along the longitudinal vertical plane in the center of the tank at 2.2 m downstream of the gate, the Reynolds number R = 1750 and the densimetric Froude number F = 1.146, the viewing area is about 15cm×10cm

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REFERENCES

Härtel, C., Carlsson, F. and Thunblom, M., 2000a. Analysis and Direct Numerical Simulation of the Flow at a Gravity-Current Head. Part 2. The Flow-Front Instability, *J. Fluid Mech.* Vol. 418, pp. 213-229.

Härtel, C., Meiburg, E and Necker, F., 2000b. Analysis and Direct Numerical Simulation of the Flow at a Gravity-Current Head. Part 1. Flow Topology and Front Speed for Slip and No-Slip Boundaries, *J. Fluid Mech.* Vol. 418, pp. 189-212.

Mausshardt S., Yeh H. and Grandinetti C., 1994. Laboratory Observations of Gravity Currents and Internal Bores, *Fourth International Symposium on Stratified Flows*, L.E.G.I., Grenoble, France.

Mok, K. M., Ieong, K. K. and Yeh, H., 2002. Experimental Facility for Gravity Currents, *Proceedings of the 16th National Conference on Hydrodynamics*, ed. Zhou, L. D., Shao, W. M., Zhan, J. M., Li, Y. P. and, Zhao, F., Ocean Press, Shinghai, pp. 816-822.

Simpson, J. E., 1997. *Gravity Currents: In the Environment and the Laboratory*, 2nd Edn. Cambridge University Press.

Wood, I. R. and Simpson, J. E., 1984. Jumps in Layered Miscible Fluids, *J. Fluid Mech.*, Vol. 140, pp. 329-342.

Yeh, H., 1991. Vorticity-Generation Mechanisms in Bores, *Proc. Roy. Soc., Lond. A*, Vol. 432, pp. 215-231.

Yeh, H., 1995. Free-Surface Dynamics, In *Advances in Coastal and Ocean Engineering*, ed. L.-F. Liu, Vol.1, World Scientific, Singapore, pp. 1-75.

Yeh, H. and Wada, K., 2001. Descriptive Hydrodynamics of Lock-Exchange Flows, In *Advances in Coastal and Ocean Engineering*, ed. P. L.-F. Liu, Vol.7, World Scientific, Singapore, pp. 203-240.