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Source: Journal of Coastal Research, 36(sp1) : 450-458

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.450

Journal of Coastal Research	SI 36	450-458	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Initial spreading behaviour of water released from a swinging gate lock

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ABSTRACT

Gravity currents are important phenomena that play a critical role in the advection of fluids in natural and man made environments. Boat locks, which are a common feature on many coastal waterways, are one type of system that can generate gravity currents. These locks usually have a set of vertically hinged gates at each end which, when opened, permit water from within the lock to exchange with the outside water in the form of gravity currents. By using the results from a series of laboratory experiments the properties of these gravity currents were examined when the lock water was heavier than the outside water. It was found that the swinging action of a lock gate had a significant influence on the rate at which the water initially leaves the lock as a slumping gravity current, with the initial speed of the flow being dependent upon the gate's opening speed. However, the final velocity achieved by the gravity current was independent of the gate opening speed; indicating that the total amount of entrainment of water into the flow was independent of opening speed.

ADDITIONALINDEXWORDS: *slumping phase, vorticity*

INTRODUCTION

Gravity currents occur when one fluid is allowed to flow into another (of different density) under the influence of gravitational acceleration. These are common and important phenomena that occur in many natural and man-made situations, including sea breezes, dense gas dispersion in the atmosphere, turbidity currents, the spreading of oil on the sea surface, pyroclastic flows from erupting volcanoes, and river inflows into estuaries, oceans and lakes (e.g. SIMPSON, 1997). Additionally, gravity currents also form during the heating and cooling of rooms (REES *et al.*, 2001), in water treatment plant clarifiers (e.g. MARLE and KRANENBURG, 1994), and in the operation of water regulating lock structures that are designed to modify and control estuarine and lake systems (e.g. LEWIN. 1995, and ZIGIC *et al*., 2001).

Navigational locks, which separate two adjacent bodies of water and are used to lift and lower vessels from one water level to another, are a further source of gravity currents (e.g. KERSTEMA *et al.*, 1994, MAUSSHARDT and SINGLETON, 1995, and USACE, 1995). Locks have a central chamber with gates at each end that can be closed to isolate the chamber from the adjacent waters. The filling and emptying of the chamber (to respectively lift or lower the water level and a vessel in the chamber) is usually carried out using a series of valves set in the gates, chamber walls and/or floor (e.g. NATALE and SAVI, 2000). Alternatively, the gates themselves can act as valves; that is, they can be opened slightly to allow water either to enter or exit the chamber, before being fully opened to allow for vessel navigation.

An example of the process of moving a vessel through a lock and the mixing processes that can occur is depicted in Figure 1. In this figure it is assumed that the vessel is moving from a lower saltwater downstream level to a higher fresher upstream level. This situation may arise when a lock separates a lake from an estuary (e.g. MAUSSHARDT and SINGLETON, 1995). In this example it will be assumed that initially the water inside the lock is that of the downstream side, and that the gates are open. This allows the vessel to move into the chamber (Figure 1a). The gates behind the vessel are then closed and water from the higher upstream side is pumped into the lock so the lock fills (Figure 1 b) until the hydrostatic pressures on either side of the upstream gate are matched. This closely corresponds to the vertical level of the upstream side being reached, but is not exactly the same as the water densities are different. During this filling stage KERSTEMA *et al.* (1994) noted that the fresher water entering the chamber produced an

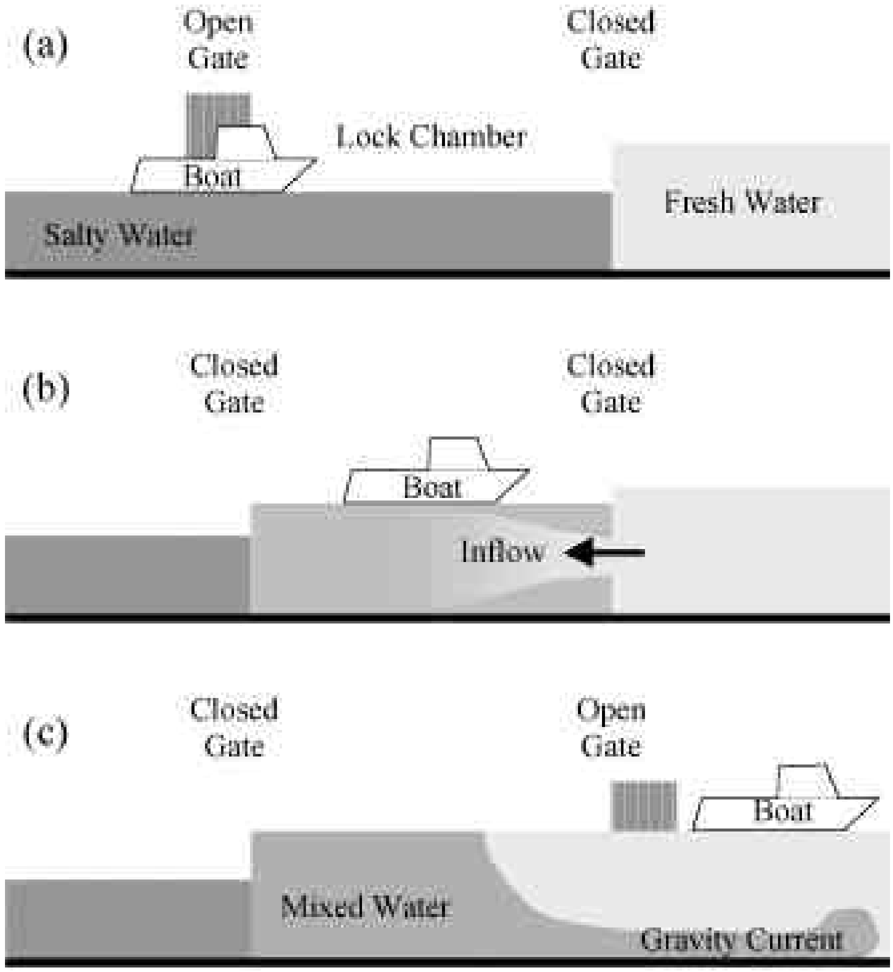

Figure 1. Example of a boat lock operation cycle. (a) Boat enters the lock with water inside the lock equivalent to that of the downstream side. (b) After boat has entered the lock, the gates are closed and the water level raised by filling the lock with upstream water under strong mixing conditions so that the lock water was completely mixed. In this case water enters the chamber through valves in the gates. (c) Upstream gates are opened to allow vessel exit and a bottom gravity current forms.

internal density structure ranging from a light surface layer to a homogeneous mixture whose density falls somewhere between that of the upstream and downstream sides. It is anticipated that the amount of mixing that occurs within the lock will depend upon a number of parameters including the filling method, density differences, filling velocity and filling time. When the upstream gates are opened (to let out the vessel) an exchange flow forms (Figure 1 c). Here, less dense upstream water will flow into the chamber as a surface gravity current and the relatively heavier lock water will slump out of the chamber as a bottom gravity current. This process will proceed in reverse as a vessel moves in the opposite direction. Therefore, the net result of a lock structure is to generate intermittent gravity currents both insiode and outside of the lock chamber, which in turn will influence water properties around that lock.

Previous research on lock-induced gravity currents where the gate separating the two fluids was raised vertically has shown three main phases following flow initiation (SIMPSON, 1997). The first is the ‘slumping phase’ that immediately follows the removal of the gate. During this stage the lock fluid collapses down into the receiving ambient and progresses outwards along the bed as a bottom gravity current, and the receiving ambient water replaces the water lost from the lock chamber. The front of the bottom gravity current moves with constant speed and maintains nearly constant depth. The second phase (referred to as the ‘similarity phase’) occurs after the head of the gravity current has advanced about eight lock lengths (ROTTMAN and SIMPSON, 1983), and is marked by the front advancing at a rate dependent upon time. This corresponds to a disturbance (in the form of a bore) being generated at the end wall of the lock overtaking the front of the current. The third phase is reached only if the gravity current velocity drops sufficiently to cause viscous forces to dominate the flow dynamics (SIMPSON, 1997).

HALLWORTH*et al*. (1996) observed that there was little entrainment into the head of the current during the slumping phase, even though horizontal vortical structures (including Kelvin-Helmholtz instabilities) were present. ALAHYARI and LONGMIRE (1996) and HÄRTEL *et al*. (1999) also found that the evolution of flow during this phase is governed by the emergence of intense start-up vortices that form in a similar manner to those observed for unstratified vortex sheets of finite extent. The properties of these vortices were found to be only weakly dependent upon the ratio of flow buoyancy and viscous forces.

Previous studies of lock-exchange gravity currents have focused on the case where horizontal vortices were present. However, numerous situations arise when vertically oriented vortex structures may be significant. A particular and important example occurs during the opening of vertically hinged swinging boat lock gates (which is the focus of this paper). In this situation the opening of the gates separating the lock chamber and the receiving ambient will impart momentum into the water column and generate vertically oriented vortices. This phenomenon appears to have been paid little (if any) attention to date, despite having potentially significant environmental impacts that may develop through enhanced bed velocities and the long-lasting nature of vortex structures which can permit extended travel of undiluted water. The aim of this paper is to report upon a novel experimental study designed to investigate and qualify the initial slumping phase behaviour following the opening of a vertically hinged swinging lock gate, which separated a lock chamber filled with dense water from a fresher water channel. The results show that the swinging action of the lock does influence the slumping phase dynamics when compared to the tradition vertical lift gate case.

Scaling of the Slumping Phase

Several studies have found that the most notable feature of shallow-water lock exchange gravity currents during the initial slumping phase (when initiated by the vertical lifting of a lock gate) is the uniformity of a constant Froude number (Fr) based on the water depth (H). SIMPSON (1997) discusses how by equating the decrease of potential energy with the increase of kinetic energy the speed of propagation of the gravity current head (U) can be described by:

$$Fr = \frac{U}{(g'H)^{1/2}} = C = 0.5 \qquad \textbf{(1)}$$

where g' = g(r0 - r1)/r1 is the reduced gravity, g is the acceleration due to gravity. r0 is the initial density of the lock water, r1 is the density of the ambient water, and C is a theoretical constant. Using an extensive range of laboratory experiments BARR (1967) found that for a rectangular lock and channel C = 0.46, while HACKER *et al*. (1996) obtained C = 0.456, and KNELLER *et al*. (1999) derived C = 0.41 from detailed Laser Doppler Anemometry measurements. The data presented by THOMAS *et al.* (1998) indicate 0.4 < C < 0.5. HARTEL *et al*. (1999) employed a series of direct numerical simulations and found C = 0.53 when there was a fixed lid on the system.

The differing values of C appear to arise from the scale of the experiments, which influence the mixing between the two fluids and the gravity current Reynolds number:

$$\mathrm{Re} = \frac{Uh}{\nu} \qquad \textbf{(2)}$$

where h is the vertical thickness of the gravity current and *v* is viscosity. This scale feature has been found to be important in describing the mixing that occurs within the gravity current flow (e.g. SIMPSON and BRITTER, 1979, GARCIAand PARSONS, 1996, HUQ, 1996, KNELLER *et al*., 1999 and HARTEL *et al.*, 2000a,b). HARTEL *et al*. (2000a) found that properties of the gravity current nose were not significantly influenced by the three-dimensionality of the flow, and that as Re increases, so does Fr. It is important to note that Eq. [1] applies for stationary receiving environments and that it must be modified if the receiving water is flowing or experiencing turbulent motions (e.g. LINDEN and SIMPSON 1986). Additionally, modifications are required if the bed is sloping or made of a porous material. This implies that Eq. [1] may not be applicable when the lock gate is swung open, as this opening process will impart kinetic energy into that lock and ambient water masses, in addition to that resulting from vertical lift gate induced slumping.

EXPERIMENTAL METHODOLOGY

The lock-exchange experiments undertaken in this investigation were performed in a glass-sided, smooth metal-floored channel, 7 m in length and 0.45m wide. A single lock gate was placed 0.7m from one end of the tank (ie the lock length l_o = 0.7 m). In this study two types of lock gates were used. The first was a vertical lift gate as used in the classical lock exchange experimental studies (e.g. see Simpson, 1997). The second was a gate hinged against one side of the tank so that it could be swung open about the vertical axis. The speed at which the gate was opened was controlled by a variable speed motor, rope and pulley system. For all experiments the gate was moved from an initially closed state (normal to the tank side) to a fully open state (where it was parallel to the tank side). The swinging gate experiments were the primary focus of this study with the vertical gate experiments conducted for comparative purposes.

Each experiment was conducted as follows: the tank was filled with tap water to the desired depth H and the lock gate closed. Salt was then dissolved into the lock chamber to create the desired density difference (Δρ) between the lock and tank water. The water densities were derived from conductivity and temperature measurements made using an Orion Model conductivity/temperature meter. For visualisation purposes, food colouring was diluted into the lock water. Once the water on both sides of the lock had become stationary, the gate was opened and the progress of the lock exchange gravity current recorded on video for later analysis. For this study the focus was on the mean gravity current properties, with little attention placed upon the flow patterns within the lock.

Results from 2 vertical lift gate and 9 swinging gate experiments will be presented in his paper. The parameter varied in the swinging gate experiments was the gate opening speed with constant l_o = 0.7 m and H = 0.5 m and near constant g'. Table 1 summaries the conditions of the experiments and some of the results found.

RESULTS AND DISCUSSION

Vertical Lift Gate

The experiments conducted with the vertical lift gate arrangement resulted in flow patterns resembling that of the classical lock-exchange induced gravity current (e.g. see HUPPERT and SIMPSON, 1980 and SIMPSON, 1997). Following the opening of the gate, lock water slumped and progressed along the tank bed as a bottom gravity current, where the classical enlarged head and associated lobe and cleft structures were observed. Following the head were Kelvin-Helmholtz billows and the stratified trailing body structure of the current. While the tank was too short to observe the second and third phases, this was not critical, as the initial slumping phase was the focus of this study.

Figure 2 presents a plot of the position of the gravity current head as a function of time following the lifting of the lock gate (data from Exp. 1 – see Table 1). The figure shows how the gravity head current progressed with a constant velocity throughout its travel. Using this data and the initial conditions (see Table 1) it was found that C = 0.47, which is in keeping with previously published data. The results of the two vertical lift experiments indicated the suitability of the experimental facility for studying lock release gravity currents.

Table 1. Summary of experimental conditions.

Experiment Number	Gate Type	*H* (m)	*g'* (ms^{-2})	*V* (ms^{-1})	*U* Measured (ms^{-1})	*C*
1	Vertical	0.5	0.012	-	0.37	0.45
2	Vertical	0.5	0.012	-	0.37	0.45
3	Swinging	0.5	0.009	0.065	0.034	0.49
4	Swinging	0.5	0.009	0.033	0.031	0.47
5	Swinging	0.5	0.009	0.025	0.031	0.47
6	Swinging	0.5	0.009	0.018	0.031	0.47
7	Swinging	0.5	0.012	0.247	0.037	0.47
8	Swinging	0.5	0.010	0.235	0.037	0.52
9	Swinging	0.5	0.010	0.059	0.037	0.52
10	Swinging	0.5	0.012	0.042	0.037	0.48
11	Swinging	0.5	0.011	0.028	0.037	0.50

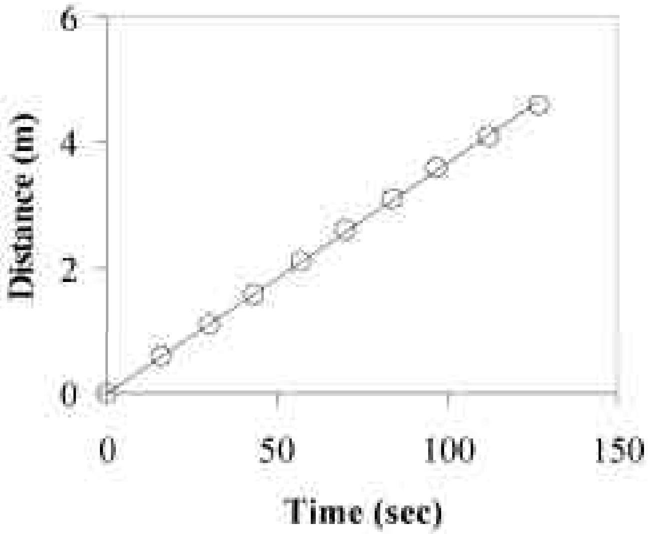

Figure 2. Plot of the gravity current front as a function of time for a vertical lift gate experiment. The open circles represent the experimental data and the solid line is a line of best fit to that data with the form d = 0.037t, where t is the time after the gate is the lifted and d is the distance travelled by the head of the gravity current, and a squared correlation coefficient of 0.9997.

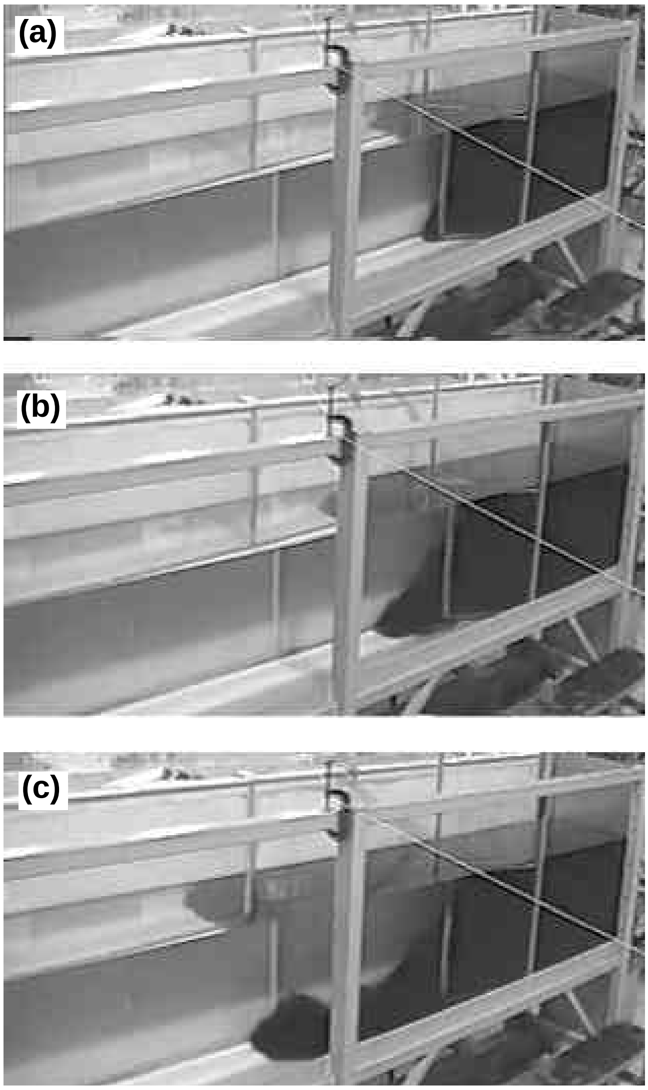

Figure 3. Spreading behaviour of a lock water into the tank for $V = 0.022\ ms^{-1}$ and $UT = 0.11\ ms^{-1}$ and H = 0.5 m. The images were recorded at times corresponding to (a) 10 sec, (b) 14 sec and (c) 24 sec after the gate opening process commenced. NB. The spreading rate velocities are not presented in this paper.

Swinging Gate

The derivation of Eq. [1] assumed that the lock water could freely slump into the receiving water. Consequently, if the slumping process is modified in some way than Eq. [1] may not be valid. Figures 3-5 present a series of images collected during and following the opening of the swinging gate under different opening speed conditions but with the same initial depth and density conditions. Figure 3 presents images from when the gate was opened with V = 0.2 UT, where UT is the theoretical velocity derived from Eq. [1] when C = 0.5. That is:

$$U_T = 0.5(g'H)^{1/2} \quad \textbf{(3)}$$

As the lock is opening, lock water collapsed into the tank though the continually expanding gap that developed between the tank sidewall and the outer gate edge (Figure 3a). In response to this slumping, conservation of volume required fresh tank water flow back into the lock chamber. As mentioned above, this into-lock flow process was not the focus of this study and therefore it will not be discussed further in this paper. The slumping lock water flowed radially outward into the tank until it reached the side of the tank where the gate was hinged (Figure 3b). This spreading process acted to slow down the longitudinal gravity current speed when compared to that calculated from Eq. [1]. After the gate was fully opened (Figure 3c) the gravity current accelerated away and eventually formed into the classical bottom gravity current. As evident in the images, strong vertical vortices were not evident at this slow V.

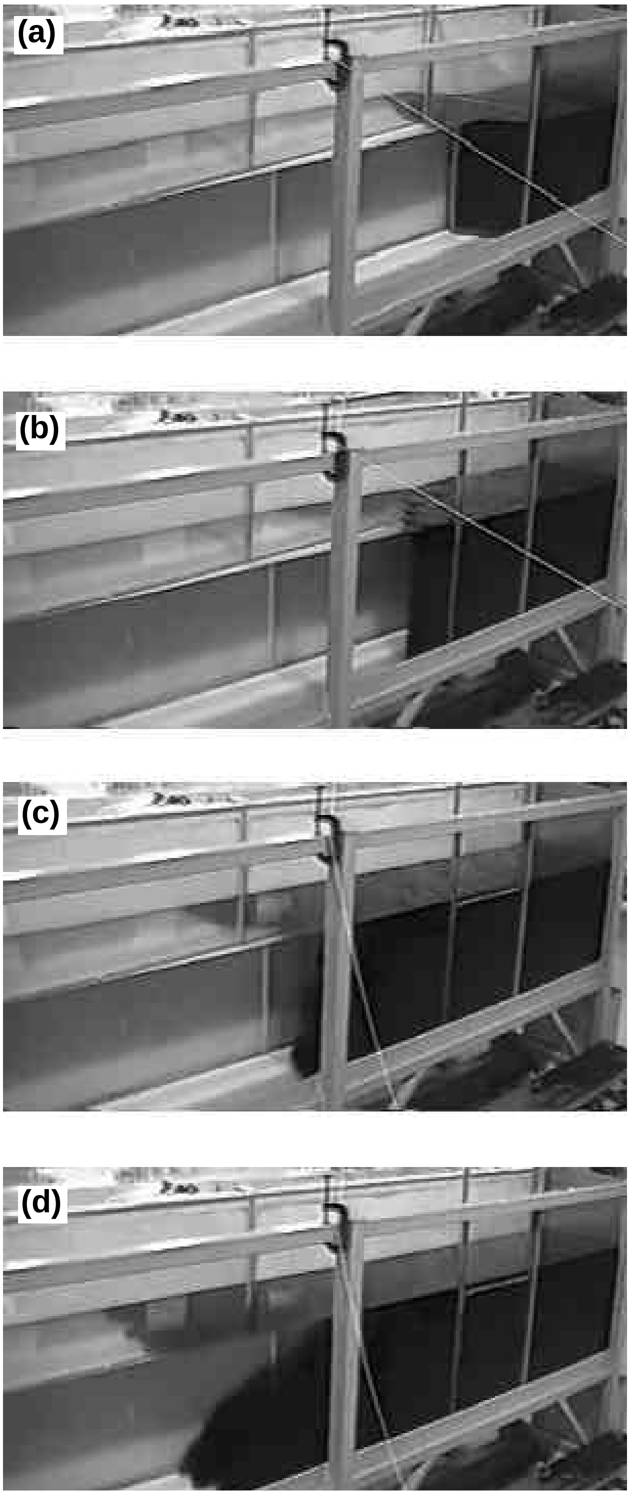

Figure 4. Spreading behaviour of a lock water into the tank for V = 0.24ms-1 and UT= 0.11 ms-1 and H = 0.5 m. The images were recorded at times corresponding to (a) 0.1 sec, (b) 3 sec (c) 6 sec and (d) 12 sec after the gate opening process commenced. NB. The spreading rate velocities are not presented in this paper.

Figure 4 presents a series of images collected when V = 2UT. For this type of experiment the opening of the gated caused lock water to be ‘flung’ out into the tank water (Figures 4a-d), before slumping into a bottom gravity current. As the gate was opened the reduction in pressure behind the opening gate dragged lock water into the tank and pushed the tank water away as a forced surface wave (Figure 4a). The fresher tank water could therefore move into the lock over the entire depth, which is different to the traditional slumping process where the receiving water could only flow over the lock water. The lock water then proceeded to spin out over the entire depth into the tank (Figure 4b). At this stage strong vortical structure were evident at the edge of the spreading flow with the water surface undergoing oscillations resulting from the opening process. The lock water moved about 1 m into the tank before slumping (Figure 4c-d). Eventually the flow developed into a normal gravity current where no strong vertically orientated vortices were evident (about 5 m). This pattern differs significantly from the vertical lift experiments, where the initial dominant vortices were orientated horizontally and the flow slumped immediately upon the opening of the gate.

One significant implication of the results presented in Figure 4 is that the velocities near the bed are likely to be elevated when a strong vortex is present. Therefore, in coastal water bodies the bed could experience increased scour and channel modification, which in turn could lead to elevated suspended sediment loadings.

For comparison, Figure 5 presents a series of images collected when V = 0.5 UT. For this type of experiment the lock water slumping speed was closer to that of the gate opening speed compared to Figure 3 and 4. That is, the slumping process experienced less hindrance from the opening gate process. The slumping lock water initially spread radially and outwards over the tank floor as it left the expanding gap (Figure 5.a). The lock water then progressed along the tank floor and approached the traditional flow pattern (Figures 5.b and c). Strong vertical vortices were not evident in this situation.

The images presented in Figures 3 - 5 show that the swinging gate action resulted in a very different flow pattern to that of a vertical lift gate situation. Figure 6 presents the spreading rate results derived from a series of experiments conducted with very similar initial density differences but differing V (Experiments numbers 3-6 as given in Table 1). When the ratio V/UT is large (ie gate opening speed was relatively fast compared to the slumping speed) the gravity current generated by the opening of the gate initially had a high velocity before gradually decelerating to a near constant velocity after about 4 m. As detailed in Table 1, this near-constant velocity corresponds to that derived from Eq. [1] and gave C = 0.49. These results indicate that the opening of the gate imparted initial momentum into the

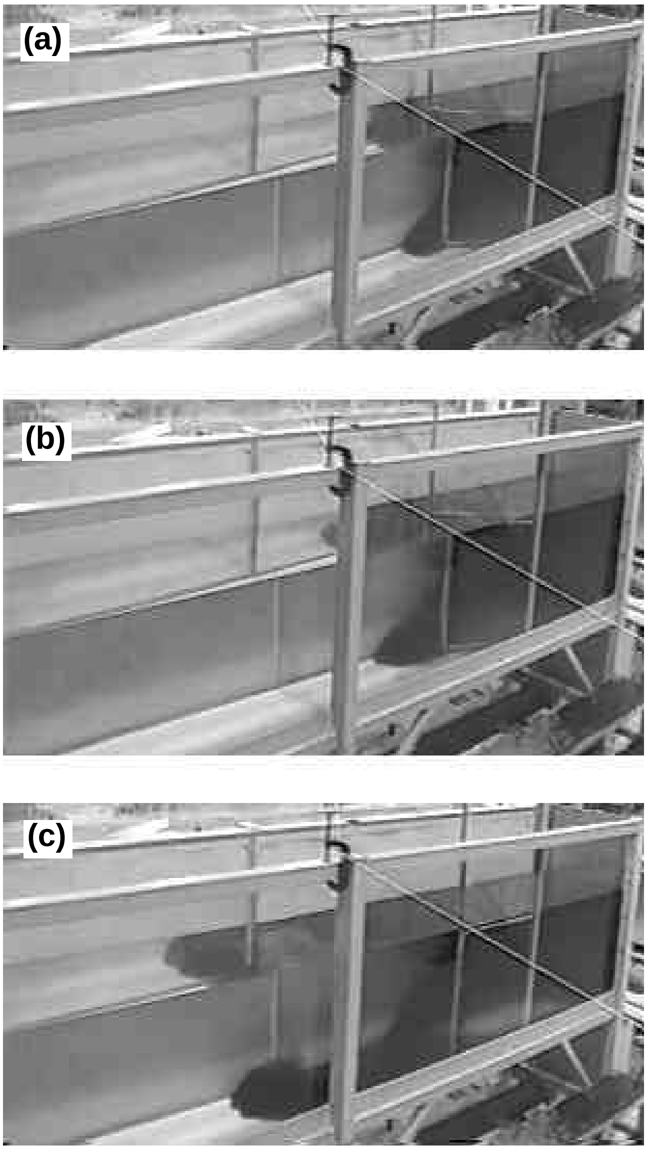

Figure 4. Spreading behaviour of a lock water into the tank for $V = 0.24ms^{-1}$ and $UT = 0.11\ ms^{-1}$ and H = 0.5 m. The images were recorded at times corresponding to (a) 0.1 sec, (b) 3 sec (c) 6 sec and (d) 12 sec after the gate opening process commenced. NB. The spreading rate velocities are not presented in this paper.

slumping phase in excess of that obtained from the potential energy difference between the lock and tank waters. That is, the lock water accelerated out faster than it could under the influence of gravitational acceleration alone. However, since the final velocity was close to that predicted by Eq. [1] it appears that the high levels of vorticity failed to significantly enhance entrainment into lock water over the length of the experiment. If it had then the density difference between the lock and tank waters would have been less and the gravity current speed would have been reduced. This is not necessarily a surprising result as vortical structures, while energetic, can be inefficient entrainment mechanisms (e.g. Lemckert and Forsyth, 2001).

When the ratio V/UT < 1 (ie gate opening speed was relatively slow compared to the slumping speed) the gravity current generated by the opening of the gate showed little sign of vorticity (Figures 3a and b). The flow pattern was dominated by the requirement for the flow to spread radially across the tank floor before it could solely move forward. This meant that the flow was initially slower that that predicted by Eq. [1] (see Figure 6), but that once the radially spreading pattern had become longitudinal only it could achieve a constant velocity of UT. Similar results were found for the other experiments presented in Table 1.

The results show that the gate opening velocity has little effect on UT, but it did strongly influence the method by which UT was reached. This can be explained by considering the density and vorticity of the fluid. Firstly, when the lock gate is opened in a horizontal swinging motion, it imparts an amount of vorticity into the fluid as indicated in Figure 4. This vorticity, along with the motion of the gate causes the fluid to rapidly accelerate out of the lock chamber, reaching speeds well above its limiting velocity. However, once the gate is fully open it can no longer continue to accelerate the liquid out of the chamber, and at this point the vorticity in the fluid starts to lose momentum. Once the momentum has decreased to a certain point, the density of the fluid becomes the dominant force, causing the fluid to slump to the bottom of the tank, where it forms a typical gravity current. This is consistent in all experiments where V > UT.

The independence of UT on the initial conditions indicates that the density of the gravity current head must be independent of V when UT is finally reached. This is because, it is the density difference at the point where UT is reached that determines the ultimate velocity and not actually that of the initial conditions. Therefore, while the gate speed does influence the initial spreading rates the amount of entrainment into the currents eventually becomes the same. This outcome suggests that an accelerating gravity current (UT < V) entrains more fluid than a decelerating current (UT > V).

CONCLUSIONS

The qualitative flow dynamics of lock-release gravity current generated using a gate that was swung open about a vertical axis was studied experimentally. The slumping phase of the gravity currents generated by this process was found to be strongly dependent upon the speed at which the gate was opened. High opening speeds (when compared to the natural slumping velocity) resulted in the lock water being flung out of the lock chamber with high levels of vorticity being imparted into the fluid. For slow opening speeds the water initially seeped out through the continually expanding gap between the lock wall and gate. It then spread radially into the tank before moving longitudinally through the tank.

While both the initial conditions, and the manner in which the limiting velocity is reached varies with the gate opening speed, the main characteristics of flow appear to be very similar once a steady state is reached. The limiting velocity and the distance taken to reach the limiting velocity does not alter with the opening speed of the gate.

From a management point of view, the outcomes of this study imply that the modelling of the gravity current flows generated by boat locks can be achieved using simple existing approaches rather than more complex ones that must include three dimensional effects and vorticity. However, if the main concern is associated with the environments immediately adjacent to the lock structure then considerable effort must be made to characterise the flow.

ACKNOWLEDGEMENTS

The authors wish to thank the Charles Allport for his assistance in setting up the experimental facility. This project was financially supported in part by the Australian Research Council Strategic Partnerships with Industry - Research and Training (SPIRT) Scheme (Project C89906860), a Griffith University Research Development Grant and the School of Engineering, Griffith University.

LITERATURE CITED

ALAHYARI, A. A. and LONGMIRE, E. K. 1996. Development and structure of a gravity current head, *Experiments in Fluids*, 20, 410-416

BARR, D. I. H. 1967. *Densimetric exchange flows in rectangular channels. III Large scale experiments*. Houille Blanche, 6, 619-31

LINDEN, P. F. and SIMPSON, J. E. 1996. Gravity driven flows in a turbulent fluid. *Journal of Fluid Mechanics*, 172, 481-497

GARCIA, M. H. and PARSONS, J. D. 1996. Mixing at the front of gravity currents. *Dynamics of Atmosphere and Oceans*, 24, 197-205

HACKER, J., LINDEN, P. F. and DALZIEL, S. B. 1996. Mixing in lock-release gravity currents. *Dynamics of Atmosphere and Oceans*, 24, 183-195

HALLWORTH, M. A., HUPPERT, H. E., PHILLIPS, J. C. and SPARKS, R. S. 1996. Entrainment into two-dimensional and axisymmetric turbulent gravity currents. *Journal of Fluid Mechanics*, 308, 289-311

HÄRTEL, C., MEIBURG, E. and NECKER, F. 1999. Vorticity dynamics during the start-up phase of gravity currents. *Il Nuovo Cimento*, 22 (6), 823-833

HARTEL, C., MEIBURG, E. and NECKER, F. 2000a. 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. *Journal of Fluid Mechanics*, 418, 189-212

HARTEL, C., CARLSSON, F. and THUNBLOM, M. 2000b. Analysis and direct numerical simulation of the flow at a gravity-current head, Part 2. The lobe-and-cleft instability. *Journal of Fluid Mechanics*, 418, 213-229

HUPPERT, H. E. and SIMPSON, J. E. 1980. The slumping of gravity currents. *Journal of Fluid Mechanics*, vol 99, 785-99

HUQ, P. 1996. The role of aspect ratio on entrainment rates of instantaneous, axisymmetric finite volume releases of dense fluid. *Journal of Hazardous Materials*, 49, 89-101

KNELLER, B. C., BENNETT, S. J. and MCCAFFERY, W. D. 1999. Velocity structure, turbulence and fluid stresses in experimental gravity currents. *Journal of Geophysical Research*, 104 (C3), 5381-5391

KERSTEMA, J., KOLKMAN, P. A., and REGELING, H.J. 1994. *Water quality control at shiplocks*. A. A. Balkema, USA

LEWIN, J. 1995. *Hydraulic gates and valves.* Thomas Telford, New York

LEMCKERT, C. J. and FORSYTH, C. 2001. Water column destratification using a pulsed jet system, 14th Australasian Fluid Mechanics Conference, Adelaide University, Adelaide, Australia, 10-14 December 2001.

LINDEN, P. F. and SIMPSON, J. E. 1986. Gravity driven flows in a turbulent fluid. *Journal of Fluid Mechanics*, 172, 481-497

MARLE, C. v. and KRANENBURG, C. 1994. Effects of gravity currents in circular secondary clarifiers. *Journal of Environmental Engineering*, 120 (4), 943-960

MAUSSHARDT, S. and SINGLETON, G. 1995. Mitigating salt-water intrusion through Hiram M. Chittenden Locks. *Journal of Waterways, Port, Coastal and Ocean Engineering*, 121 (4), 224-227

NATALE, L. and SAVI, F. 2000. Minimization of filling and emptying time for navigation locks. *Journal of Waterways, Port, Coastal and Ocean Engineering*, 126 (6), 274-280

REES, S. J., MCGUIRK, J. J. and HAVES, P. 2001. Numerical investigation of transient buoyant flow in a room with displacement ventilation and chilled ceiling system. *International Journal of Heat Mass Transfer*, 44, 3067-3080

ROTTMAN, J. W. and SIMPSON, J. E. 1983. Gravity currents produced by instantaneous releases of a heavy fluid in a rectangular channel. *Journal of Fluid Mechanics*, 135 (Oct.), 94-110

SIMPSON, J. E. 1997. *Gravity currents in the environment and the laboratory*. Second Edition, Cambridge University Press, United Kingdom

SIMPSON, J. E. and BRITTER, R. E. 1979. The dynamics of the head of a gravity current advancing over a horizontal surface. *Journal of Fluid Mechanics*, 94 (3) 477-491

THOMAS, L. P., MARINO, B. M. and LINDEN, P. F. 1998. Gravity currents over porous substrate. *Journal of Fluid Mechanics*, 366, 239-258

U.S. ARMY CORE OF ENGINEERS (USACE). 1995. *Hydraulic design of navigation locks*. US Army Corp of Engineers, Report No. EM 1110-2-1604

ZIGIC, S., KING, B. and LEMCKERT, C. J. 2001. A study to investigate the mixing between two systems connected by an automated bi-directional gated structure. *Estuarine, Coastal and Shelf Science*, In Press.