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On the dynamics of open-channel flows in the laboratory for educational use of hazard mitigation and science teaching

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Abstract

Flows generated in the laboratory are commonly used to model flows in nature. Among those, gravity currents internally driven by a density difference and surface waves mechanically driven by a simple device in the laboratory are produced using a channel of either constant or varying width. In gravity current experiments, the dynamics of a two-dimensional horizontal flow is examined and the results are compared to similar flows in the open oceans or estuaries. It was found that the non-dimensional speed of the current is 0.45 ± 0.03, close to a value of 0.5 predicted by internal hydraulic theory and the height of the current indicates a loss of energy of about 10% due to vertical mixing. In other series of experiments on water waves, the speed of a surface gravity flow is found to be influenced by the water depth but is independent of external energy supply. The non-dimensional speed of the surface flow, characterized by the theoretical speed for the flow, is 0.97 ± 0.01, implying that frictional effects have either a small or no influence on the flow. Discussion on laboratory open-channel flows are aimed at introducing hazard mitigation and science teaching at schools and in universities.

Keywords: open-channel flows; hazard mitigation; science teaching; gravity currents; surface water waves

1. Introduction

Laboratory open-channel flows are common to model large-scale flows in nature with some limitation. The apparatus utilised allows us to perform conceptually simple experiments in which it is possible to make accurate measurements of some important quantities including flow travel time, speed and depth relevant to the flow dynamics in the laboratory. In a series of experiments using a rectangular channel of uniform cross-section, saltwater and freshwater are allowed to exchange after a barrier initially separated the waters with different properties is withdrawn. The resulting flow is widely known as density-driven gravity currents. Information about these currents is of significant interest in most geophysical situations. For example, mutual intrusion at the mouth of an estuary where freshwater discharge from a river meets landward intrusion of saltwater from an adjacent sea locally induces the formation of front [1], causing environmental problems as various pollutants may be carried by the discharge of a river stream flowing into the coastal ocean [2]. In the same manner, [3] addresses an issue about how salt intrusion needs to be

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carefully managed since it may pose potential risks for water supply in the surrounding environment, particularly if the intrusion intrudes too far to the near land. At a larger scale such as in the open oceans, propagating gravity currents can transport sediments [4] and distribute fluid properties, such as salt and heat between parts of the oceans. In other series of experiments on water waves using the same apparatus, freshwater at a fixed depth in the channel is mechanically disturbed by a simple device constructed and controlled using an electronic circuit placed outside the channel. After the circuit is switched on, a surface gravity wave is generated and propagated near the surface along the channel. The characteristics of this wave is examined in terms of its speed whether it is affected by a given water depth inside the channel or by an external parameter such as the energy supply. This type of wave is also of fundamental significance as it is used to model tsunamis commonly generated by large earthquakes occuring at a great depth below the sea surface [5]. Information about the dynamics of the surface flow can be used to better understand tsunamis and to complete what is needed in predicting arrival time of the P-wave as part of tsunami early warning system development [6]. Thus, the open-channel flows can be used to promote hazard mitigation and science teaching at schools and in universities relevant to efforts for disaster risk reduction program.

2. Theory

2.1. Gravity currents

Gravity currents form when a fluid of a single density intrudes into another fluid of a different density. The density difference drives the horizontal flow of the currents both in the laboratory open-channel and in the environment [7], where the denser fluid propagates along the base underlying the less dense fluid flowing in the opposite direction near the surface. Under some circumstances, gravity currents could be considered as a two-layer flow in which there were no mixing between the fluid within the dense current and that of the surrounding [8]. Internal hydraulic theory provides basic assumptions made for the current, where the current would have the height equal to a half of the water depth and the dimensionless speed of 0.5 if there were no dissipation due to mixing and frictional effects [9]. The dimensionless speed is here derived from the observed speed divided by the characteristic speed U of the current defined as

$$U = \sqrt{g'D} \qquad (1)$$

where $g' = g\Delta\rho/\rho_o$ denotes the reduced gravity, g is the gravitational acceleration, $\Delta\rho$ is the density difference, ρ_o is the reference density, and D is the water depth.

2.2. Surface gravity waves

Gravity waves can be naturally occurring at the free surface of a sea of uniform depth and width, from which a class of surface gravity waves is named. The basic assumption usually made for these waves is that the free surface displacement is relatively small compared with both the wavelength of the wave and the depth of the water [10]. Further assumptions can be made by neglecting viscous and rotation effects, and stratification. Two limiting cases applied for surface gravity waves are deep-water approximation and shallow-water approximation. As many argue that a tsunami wave generated by a geophysical disturbance in an open ocean propagates with an extremely long wavelength, then the shallow-water approximation is best assumed to be appropriate for the propagation of tsunamis in oceanic and coastal regions [5, 10, 11]. Within this context, the characteristic speed V of the shallow-water waves is given by

$$V = \sqrt{gD} \qquad (2)$$

where g is the gravitational acceleration and D is the water depth. It is then clear from equation *(2*) that the dynamics of the surface gravity waves is independent of density variation.

3. Methods

All runs in both types of water wave experiments in this study were performed in the laboratory using a tank of uniform cross-section with the size of 10 cm wide x 30 cm high x 200 cm long available at the Laboratory of Basic Electronics, Instrumentation and Earth Sciences, Physics Department, The State University of Surabaya. For accurate measurements of depths and densities, a digital micrometer gauge being able to measure water depths to within ± 0.01 mm and a hydrometer being able to measure water densities to within ± 10^{-4} g/cm^3 were used. Travel times taken by gravity currents and surface currents along a distance between two fixed points in the channel were separately measured by a digital stopwatch to within 0.1 s and digital ultrasonic sensors to within 0.001s for comparison. Experimental photos and videos were taken during an experiment for each run using a digital still camera Nikon D3100 and a video camera Samsung PL 120.

For the gravity current experimens, the initial condition was such that the tank was divided into two reservoirs of water with different densities filled into either side of a barrier placed either in the middle of or close to the end of the tank. Each run was initiated by rapidly sliding the barrier out of the tank, after which the head of the dense current collapsed, developed and intruded into the freshwater reservoir. While propagating along the base, the dense fluid was continuously mixed with the less dense fluid forming a mixed layer clearly visibly seen at the interface between the two fluids. For completeness, density difference and water depth were varied to test the sensitivity of the results to changes in both dynamic variables.

For the surface gravity wave experiments, the initial condition was such that the tank was filled with water at a fixed depth and no barrier was placed inside the tank. Instead, a simple tool able to move up and down was immersed in the water and was connected to the mechanics electronically controlled from outside the channel by a circuit. When this circuit was turned on by selecting a voltage of fixed energy supply, then the surface flow developed and propagated along the surface. For completeness, water depth and the voltage were varied to examine if the two parameters affect the flow.

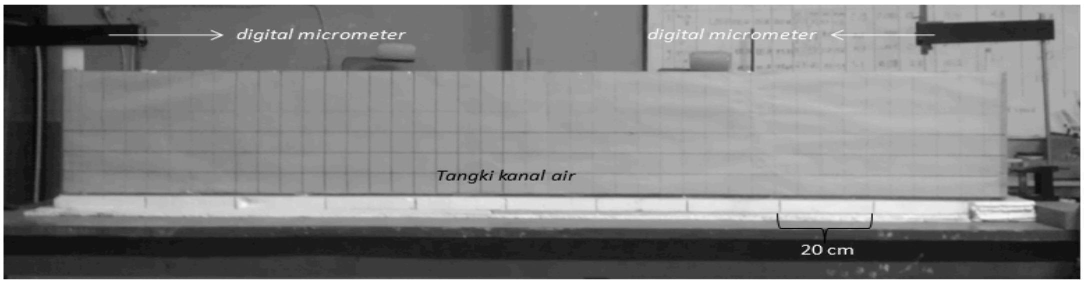

Fig. 1. A laboratory open-channel of uniform width used for gravity current and surface gravity wave experiments.

4. Results and Discussions

4.1. Gravity current experiments

A total of nine runs were performed in the gravity current experiments, where the results for all runs are given below in Table 1. Both the fractional density difference and the total water depth influence on the flow speed. The non-dimensional speed, however, is independent of any parameter, as it is found to be 0.45 ± 0.03 on average, consistent with the previous work of [9] and close to the predicted value of 0.5 for the idealised case of steady, non-dissipative gravity currents proposed by [8]. The fact that in all runs the observed depth is less than the half depth of the water confirms that there is a loss of energy through both viscous dissipation and turbulent dissipation while the dense current propagating along the channel base. A further consideration of the loss based on conservation of mechanical energy gives an estimate of order 10% for the loss.

From the results reported here, if the total water depth and the density difference are known, then both the current depth and speed hence in nature flux of saltwater penetrating into the land can be estimated. This knowledge is important as the demand 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 reduces the availability of healthy water near and below the surface to a minimum level, thereby giving rooms to saltwater to intrude into the land.

Table 1. A list of the results for the non-dimensional speed of the gravity current experiments.

No	ρ_o (g/cm^3)	ρ (g/cm^3)	$\Delta\rho/\rho_o$ (%)	g' (cm/s^2)	D (cm)	U (cm/s)	U^* (cm/s)	U^*/U
1	0.9978	1.0072	1.0	9.214	10	9.60	4.34	0.45
2	0.9978	1,0273	3.0	28.915	10	17.01	7.60	0.45
3	0.9978	1.0464	5.0	47.636	10	21.83	10.10	0.46
4	0.9978	1.0084	1.0	10.390	10	10.19	4.35	0.43
5	0.9978	1.0278	3.0	29.405	10	17.15	7.64	0.45
6	0.9978	1.0472	5.0	48.420	10	22.01	10.13	0.46
7	0.9978	1.0070	1.0	9.017	20	13.43	6.24	0.46
8	0.9978	1.0276	3.0	29.209	20	24.17	10.84	0.45
9	0.9978	1.0468	5.0	48.028	20	30.99	14.42	0.47

4.2. Surface gravity wave experiments

A number of runs were completed for the surface gravity waves and the corresponding results are listed in Table 2 below. General features extracted from the table are as follows. The observed speed V^* is determined by the water depth, as is also the case for the theoretical speed V for the flow of this type. However, the non-dimensional speed of the flow defined in the last column shows no dependence upon the water depth, that is 0.97 ± 0.01, on average for all cases reported. This value for the speed implies that in all runs effects of bottom and sidewall friction are relatively small compared to inertial forces that drive the flow horizontally along the water surface, making the assumption of inviscid fluid for the water waves sensible. Another interesting finding is that there is no correlation between the change in external source of energy given by a voltage applied to the mechanics inside the water and the dynamics of the flow, hence the flow speed. As these experiments are used to model tsunamis generated in the open oceans by submarine earthquakes with a rasionable magnitude of the quake, then the dynamics of tsunamis is likely affected only by the ocean depth at which the tsunamis are induced.

Table 2. A list of the results for the non-dimensional speed of the surface gravity waves.

No	Voltage (volt)	Depth (cm)	Length (cm)	Time (s)	V (cm/s)	V^* (cm/s)	V^*/V
1	2.0	5.16	157.69	2.254	71.04	69.96	0.98
2	3.0	5.16	157.69	2.255	71.04	69.93	0.98
3	5.0	5.16	157.69	2.255	71.04	69.93	0.98
4	2.0	10.27	157.69	1.611	100.22	97.88	0.98
5	3.0	10.27	157.69	1.611	100.22	97.88	0.98
6	5.0	10.27	157.69	1.611	100.22	97.88	0.98
7	2.0	15.01	157.69	1.361	121.16	115.86	0.96
8	3.0	15.01	157.69	1.361	121.16	115.86	0.96
9	5.0	15.01	157.69	1.361	121.16	115.86	0.96

5. Conclusions

Laboratory experiments are used to model both gravity currents and surface gravity waves in nature. The experiments utilise a channel of uniform cross-section such that it is possible to generate the flows in the channel using shallow-water approximation. The primary aims of the experiments are to promote hazard mitigation and disaster-related science in support of programs for minimising disaster risks and maximising public awareness of science at schools and in universities. Within this context, gravity current is a good model for a river discharge flowing into the coastal ocean and salt intrusion penetrating into the land while the shallow-water waves are candidates for modeling tsunamis in the open oceans. The results for gravity current experiments are given in terms of the speed and the height. The non-dimensional speed is found to be 0.45 ± 0.03, in good agreement with a value of 0.5, the non-dimensional speed predicted by internal hydraulic theory. In all runs, the measured height is less than the half depth, implying that some of mechanical energy is lost through viscous dissipation and turbulence as friction and mixing are always present in the flow. A loss of energy available for the flow on order 10% is best estimated to irreversibly mix the fluids. The results for the surface gravity wave experiments are given in terms of the flow speed. The non-dimensional flow speed is found to be 0.97 ± 0.01, very close to the theoretical speed of the long surface water waves, indicating that frictional effects are at a minimum level. The speed is influenced by the water depth but is independent of any external supply of energy, somewhat surprising results and therefore they are likely to be applied to real cases in nature with caution.

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