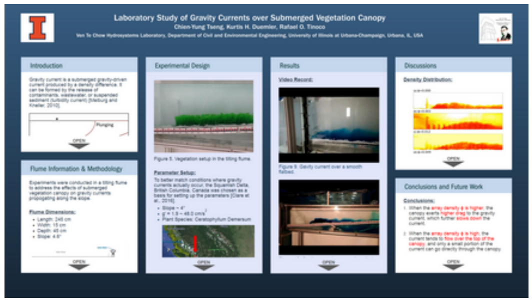
Laboratory Study of Gravity Currents over Submerged Vegetation Canopy



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INTRODUCTION

Gravity current is a submerged gravity-driven current produced by a density difference. It can be formed by the release of contaminants, wastewater, or suspended sediment (turbidity current) [Meiburg and Kneller, 2010].

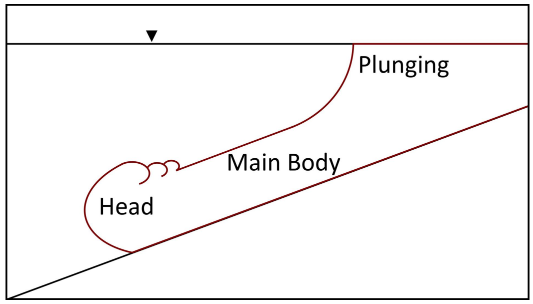


Figure 1. Sketch of the gravity current [Tseng and Chou, 2018].

Significance of Turbidity Current

- Agents of sediment transportation and carbon circulation [Liu et al., 2013].
- Sedimentation in reservoirs [Cesare et al., 2001].
- Damage to the seafloor equipment.   ex: submarine cable [Dengler et al., 1987].

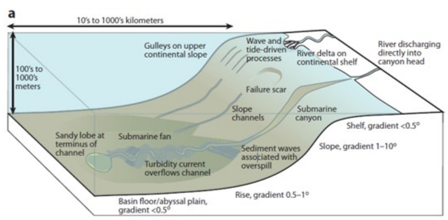


Figure 2. The sketch of turbidity current occurance environment [Meiburg and Kneller, 2010].

Past Turbidity Current Studies

Numerous studies were done to investigate the physics of vertical flow structure, current head propagation, and entrainment:

Laboratory experiments:

- Parker et al., 1987
- Garcia, 1993
- Kneller, et al. 1999
- Sequeiros et al., 2009
- Sequeiros et al., 2010

Numerical simulations:

- Kassem and Imran, 2001
- Choi and Garcia, 2002

These studies focused on the leading head and main body of gravity currents over a simple smooth bed.

Effects of Aquatic Vegetation

In the natural aquatic system, the presence of vegetation can significantly alter the mean and turbulent flow structure, affecting current mixing [Nepf, 2012].

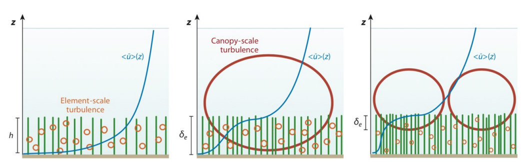


Figure 3. Vegetation effects on flow structure under different array densities [Nepf, 2012].

Past Gravity Current Studies with Vegetation

In recent years, more and more laboratory experiments were conducted to study the effects of complex bottom topography on gravity currents by using rigid cylinder arrays to model aquatic plants canopy.

Study	Year	Current Setup	Experiment sets	Model and Method	Findings	Approach
Tanino and Nepf, Water Resource Research	2005	Lock-exchange current on flat bottom	1. Salt water with blue dye 2. Different initial concentration 3. Different density of the array	Random array of emergent cylinders	Velocity profile changes with increasing canopy density.	Lab Exp
Ho and Lin, Advances in Water Resources	2014	Lock-exchange current on a slope	1. Well-mixed salty water 2. Different initial concentration 3. Different slopes 4. Different array density and element diameter	In-line, uniformly distributed array of emergent cylinders	Provides semi-empirical formulae to predict the front speed and subsequent propagation time.	Lab Exp
Testik and Yilmaz, Physics of Fluid	2015	Continuous flux current on flat bottom	1. Non-Newtonian fluid mud gravity current 2. Different mud concentration 3. Different density of the array	In-line array of emergent cylinders	Semi-empirical parameterization for the drag coefficient per cylinder is obtained.	Lab Exp
Soler et al., Sedimentology	2017	Lock-exchange current on flat bottom	1. mixed natural sediment into reservoir water 2. Different initial concentration 3. Different density of the array	Random array of PVC emergent cylinders	The propagation of gravity currents and the patterns of deposition were found.	Lab Exp

Table 1. Past studies of gravity current over emergent vegetation canopy.

Study	Year	Current Setup	Experiment sets	Model and Method	Contribution	Approach
Tokyay et al., Journal of Geophysical Research-Ocean	2014	Lock-exchange current on flat bottom	1. Different types of 2D obstacle 2. Different position of 2D obstacle 3. Different 2D obstacles' height	2D submerged cylinders numerical simulation	Discussion of frontal velocity, structure of the gravity current, bed friction velocity, and mixing effect.	3D LES
Zhou et al., Journal of Fluid Mechanics	2017	Lock-exchange current on flat bottom	1. Different density of the cylinder arrays 2. Different configuration of the cylinder arrays (in-line and staggered) 3. Fix submerged ratio (H/h=5.4)	Submerged cylinders lab experiment for calibration & Numerical simulation	1. Discuss the dynamics of (i) through-flow, (ii) over-flow, (iii) plunging-flow, and (iv) skimming-flow. 2. Frontal velocity difference in different flow regimes.	Lab Exp (calibr) & 3D LES
Cenedese et al., Environmental Fluid Mechanics	2018	Lock-exchange current on flat bottom	1. Different ratio of current height and cylinder height 2. Different stream-wise density of the cylinders	Staggered distributed submerged cylinders	Discussion of the convective instability and mixing effect in a sparse and dense configuration.	Lab Exp

Table 2. Past studies of gravity current over submerged vegetation canopy.

Most of the studies mentioned above are based on the lock-exchange flow setting on a flat bed, where the propagating ability is limited by the constant initial current volume.

Motivations and Purposes of the Study

However, in the natural environment, gravity currents can be consistently discharged into ambient water for a considerably long time. Also, due to the gravity effect, the gravity current tends to move downstream along the river slope or the continental shelf, and the sloping bottom can provide a consistent propagation mechanism for the gravity current.

In order to better represent to the real natural environment, the range of shallow submergence (the ratio of water depth to the canopy height < 5 [Nepf, 2012]) is going to be considered in this study.

The present study aims to use both rigid, uniform, acrylic rods and flexible, non-uniform, plastic vegetation to study the submerged canopy effect on gravity currents with unlimited propagation ability on a constant sloping topography.

FLUME INFORMATION & METHODOLOGY

Experiments were conducted in a tilting flume to address the effects of submerged vegetation canopy on gravity currents propogating along the slope.

Flume Dimensions:

- Length: 245 cm
- Width: 15 cm
- Depth: 45 cm
- Slope: 4.6°

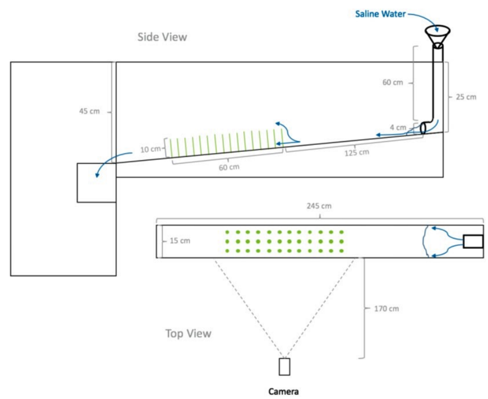


Figure 4. Sketch top view and side view of the gravity current flume.

Methodology

1. Fill with stagnant freshwater.
2. Mix saline water with blue dye.
3. Poure into a funnel placed on the top of the ramp.
4. A high speed camera is used to capture the current movement:

- Acquisition frame rate: 10 Hz (dt = 0.1 s)
- Exposure time: 1.5 ms ~ 8 ms
- Total frames N = 400

EXPERIMENTAL DESIGN

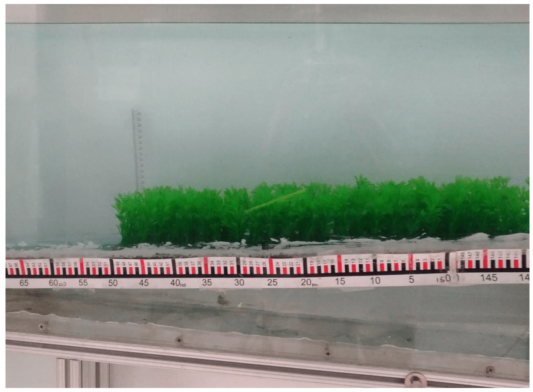


Figure 5. Vegetation setup in the tilting flume.

Parameter Setup:

To better match conditions where gravity currents actually occur, the Squamish Delta, British Columbia, Canada was chosen as a basis for setting up the parameters [Clare et al., 2016].

- Slope ~ 4°
- $g' = 1.9 \sim 48.0\ cm/s^2$
- Plant Species: Ceratophyllum Demersum

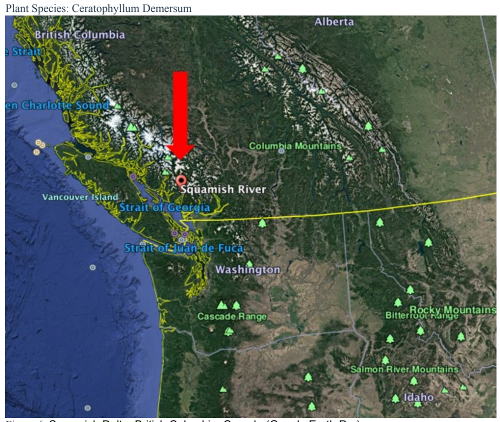


Figure 6. Squamish Delta, British Columbia, Canada (Google Earth Pro).

Obstacles Setup:

- Plant choice:

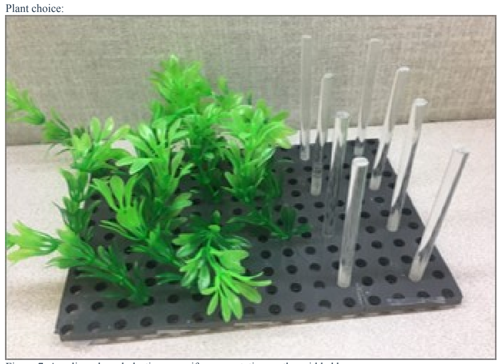


Figure 7. Acrylic rods and plastic non-uniform vegetation on the gridded base.

- Array density $\phi = (\pi/4)d^2/(s_x s_y)$
- $d = 0.64$ cm

- $s_x = s_y$ = 2.56 cm (4d), 3.84 cm (6d), 5.12 cm (8d)

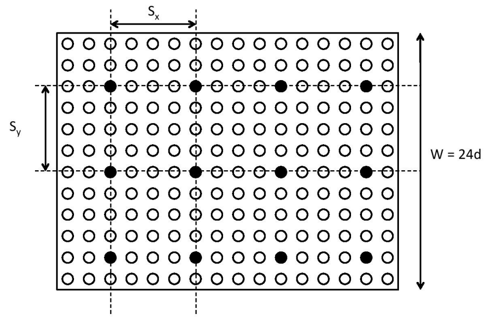


Figure 8. The sketch of in-line array configuration for the experiment, where d is the element diameter.

Experiment Runs:

- Current density: $\rho_{current}$ = 1.007 g/cm^3
- Ambient density: $\rho_{ambient}$ = 0.998 g/cm^3
- Reduced gravity: g' = 8.85 cm/s^2

Run	Slope	g'(cm/s^2)	Current volume (L)	Density ϕ	Obstacle type
#1	0.08	8.85	3	0.000	-
#2	0.08	8.85	3	0.010	Rigid cylinder
#3	0.08	8.85	3	0.018	Rigid cylinder
#4	0.08	8.85	3	0.042	Rigid cylinder
#5	0.08	8.85	3	0.006	Flexible vegetation
#6	0.08	8.85	3	0.010	Flexible vegetation
#7	0.08	8.85	3	0.024	Flexible vegetation

Table 3. List of parameters for each experiment set.

RESULTS

Video Record:

[VIDEO] https://www.youtube.com/embed/rT7UGD-u3Ug?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
Figure 9. Gavity current over a smooth flatbed.

[VIDEO] https://www.youtube.com/embed/li26MDZMU8I?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
Figure 10. Gavity current over acrylic cylinder array.

[VIDEO] https://www.youtube.com/embed/Q-ie2DlKK9E?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
Figure 11. Gavity current over plastic vegetation canopy.

High Speed Camera Record:

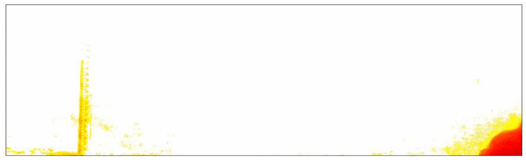
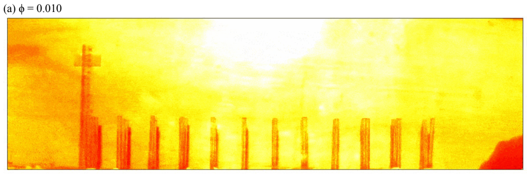
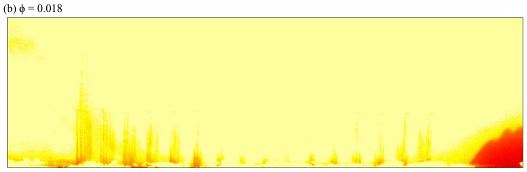


Figure 12. Animation of gravity currents over a smooth flatbed.

(a) $\phi = 0.010$



(b) $\phi = 0.018$



(c) $\phi = 0.042$

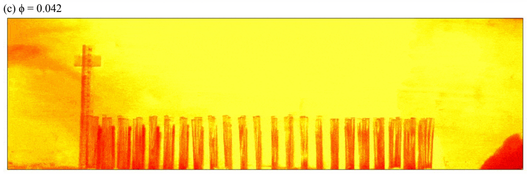
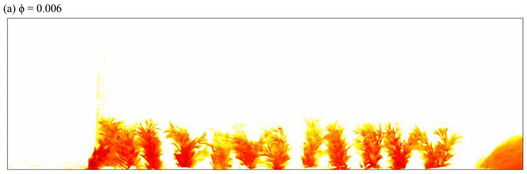
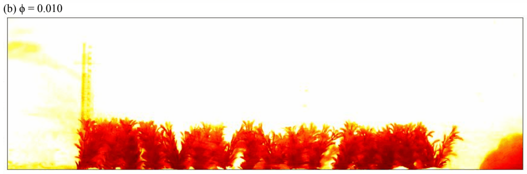


Figure 13. Animation of gravity currents over acrylic cylider array. (a) $\phi = 0.010$, (b) $\phi = 0.018$, (c) $\phi = 0.042$.

(a) $\phi = 0.006$



(b) $\phi = 0.010$



(c) $\phi = 0.024$

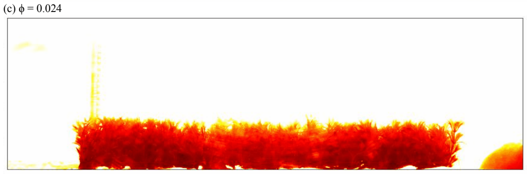


Figure 14. Animation of gravity currents over plastic vegetation canopy. (a) $\phi = 0.006$, (b) $\phi = 0.010$, (c) $\phi = 0.024$.

DISCUSSIONS

Density Distribution:

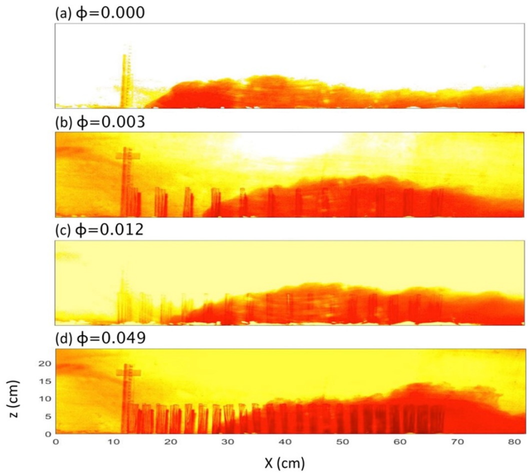


Figure 15. Same traveling time comparison between acrylic cylinder array cases.

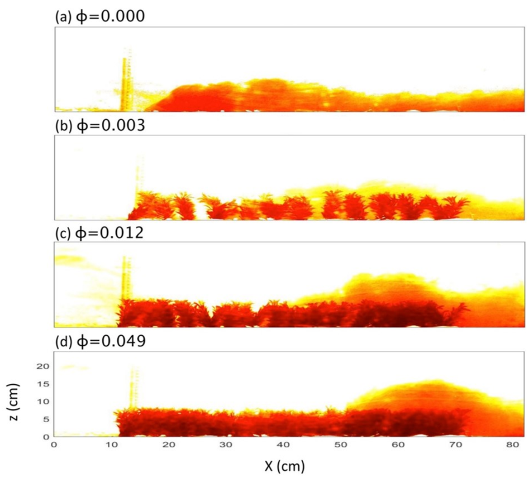


Figure 16. Same traveling time comparison between plastic vegetation canopy cases.

Head Velocity:

Buoyant velocity: $u_b = \sqrt{g'h}$

Current Froude number: $Fr = \overline{U_f}/u_b$

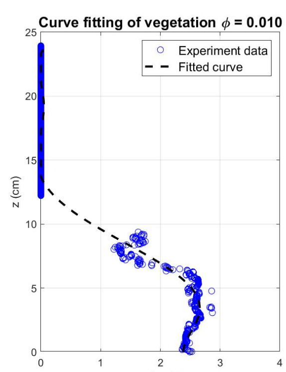


Figure 17. Curve fitting of time-averaged stream-wise velocity of ϕ=0.010 plastic vegetation canopy case.

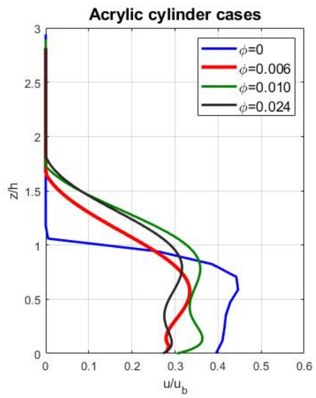


Figure 18. Time-averaged stream-wise velocity profile of acrylic cylinder array cases.

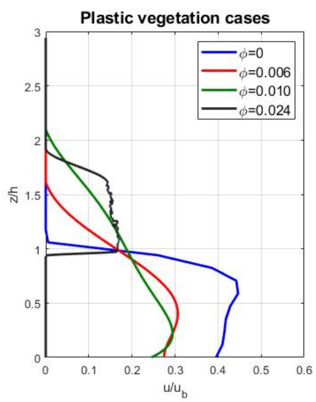


Figure 19. Time-averaged stream-wise velocity profile of plastic vegetation canopy cases.

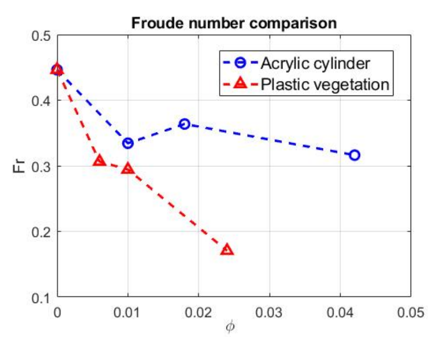


Figure 20. Comparison of Froude number between acrylic cylinder array cases and plastic vegetation canopy cases under different array density ϕ.

Effective Drag Coefficient

Momentum balance: $g'hS = C_D\overline{U_f}^2$

Estimated effective drag coefficient: $C_D = g'hS/\overline{U_f}^2$

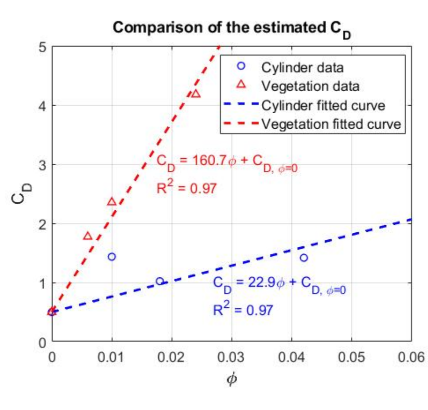


Figure 21. Comparison of estimated effective drag coefficient between acrylic cylinder array cases and plastic vegetation canopy cases under different array density ϕ.

CONCLUSIONS AND FUTURE WORK

Conclusions:

1. When the array density ϕ is higher, the canopy exerts higher drag to the gravity current, which further slows down the current.

2. When the array density ϕ is high, the current tends to flow over the top of the canopy, and only a small portion of the current can go directly through the canopy.

3. The effect of plastic vegetation is analogous to higher array density of acrylic cylinders due to the non-uniform shape with higher stem frontal area A_f.

Future Work:

By conducting Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF), we expect to further investigate:

1. Turbulence statistics

2. Quantitative mixing behavior description

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Sorry but time is up!

CV

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ABSTRACT

Gravity currents frequently occur when excess suspended sediments are flushed along a river and discharged into greater natural water environments such as lakes, reservoirs, and estuaries. Gravity and turbidity currents have been broadly investigated, but the effect of aquatic vegetation on their propagation in natural waters still presents several open questions.

We conducted a series of laboratory experiments to investigate how submerged vegetation affects the propagation and flow structure of gravity currents on a constant slope. We used both rigid acrylic cylinders and flexible synthetic plants to mimic natural submerged vegetation canopies. By varying density configurations of the vegetation array and comparing the outcomes of rigid cylinders and flexible plants, the data showed distinct patterns based on array density and plant morphology. A two-layer current was created when the array density is large enough to redirect the flow, as opposed to sparser conditions where the denser fluid passes swiftly through the array. Flexible vegetation further suppresses the propagation speed of gravity currents compared to arrays of rigid cylinder with the same density, highlighting the importance of the multi-scale processes driven by complex plant morphologies that are not represented by rigid cylinder arrays.

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SWITCH TEMPLATE