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STATE KEY LABORATORY OF COASTAL AND OFFSHORE ENGINEERING

Experimental study on dead water resistance of a barge in a two-layer fluid

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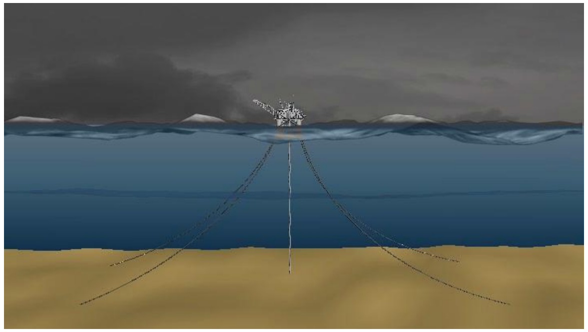
Motivation

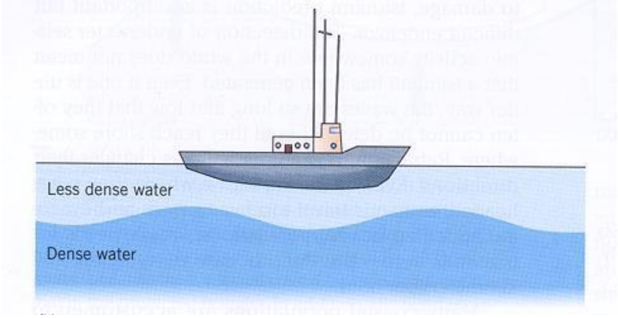
- In order to simulate drift motion of the deep sea platform, the drift damping is introduced. Drift damping can be obtained approximately by towing behavior with low speed.

$$F_d^{(2)}(\omega,U)=F_d^{(2)}(\omega,0)+U\underbrace{\frac{\partial F_d^{(2)}}{\partial U}}_{B(\omega)}+O(U^2)$$



Platform in deep water

- Density stratification is common in real ocean. '**Dead water**' is possible phenomenon when the boat sailing on the stratified ocean.



Dead water: comes from the increased resistance that boats experience in stratified fluid. (Nansen's observation, 1893)

Motivation

- Flow of ice and the towing operation of barge could be affected by the ocean stratification.

Flow of ice floe

Platform with towing operation

Outline

1. Background

- 1.1 Research progress
- 1.2 Objective of present study

2. Experimental setup

- 2.1 Experimental layout
- 2.2 Measurement method
- 2.3 Experiment parameters

3. Results and discussions

- 3.1 Drag resistance in uniform fluid
- 3.2 Drag resistance in a two-layer fluid
- 3.3 Dead water resistance coefficient in a two-layer fluid
- 3.4 Pycnocline elevation

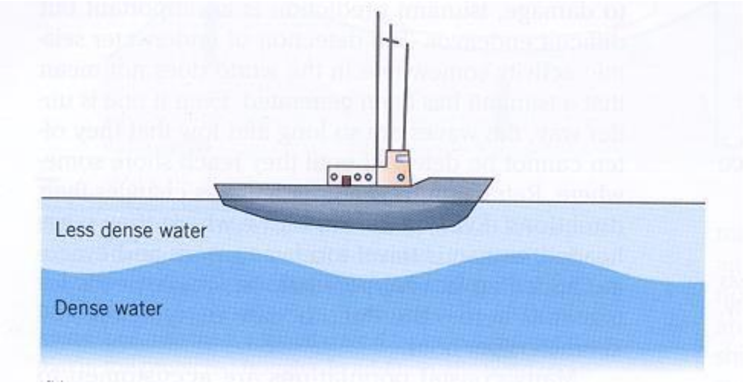
4. Conclusions

1. Background

1. Background

1.1 Research progress

■ Ekman (1904)
On dead water, Ph.D Thesis



■ Hudimac (1961)
Ship waves in a stratified ocean. *J. Fluids Mechanics*
Asymptotic expansion method. A thin ship.

■ Miloh, Tulin, Zilman. (1993)
Dead-water effects of a ship moving in stratified seas. *Journal of Offshore Mechanics and Arctic Engineering*
Boundary integral equation
Slender body: prolate spheroid

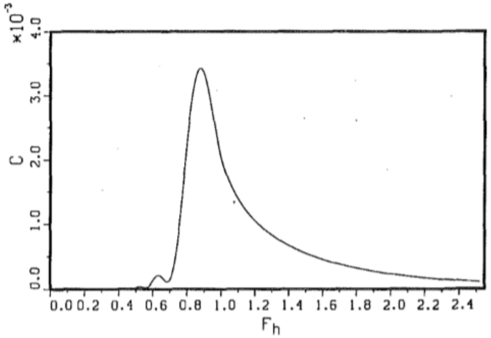
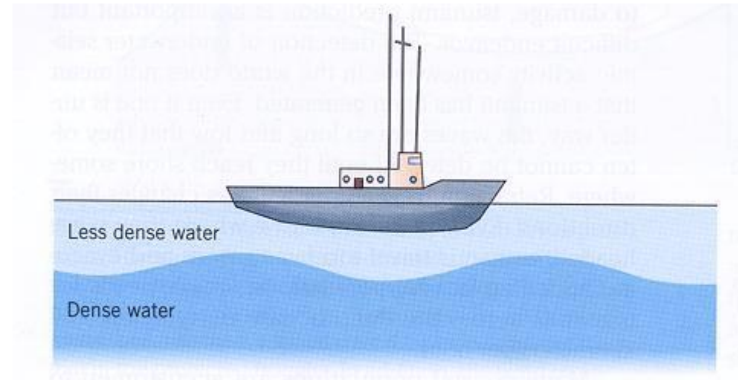


Fig. 1 Wave resistance coefficient $C = 4R_w/\rho_1 U^2 DL$ of a prolate-spheroid of length L and maximum diameter D moving on the free-surface of a two-layer fluid: $h_1 = h$, $h_2 \to \infty$, $D/h = 0.9$, $L/h = 10.0$

1. Background

1.1 Research progress



- Linton and McIver (1995)
- Cadby and Linton(2000)

Multipole expansions method

- Yeung and Nguyen(1999)

Waves generated by a moving source in a two-layer ocean of finite depth. *J. Eng. Math.*

Green Function

Scattering of floating structure

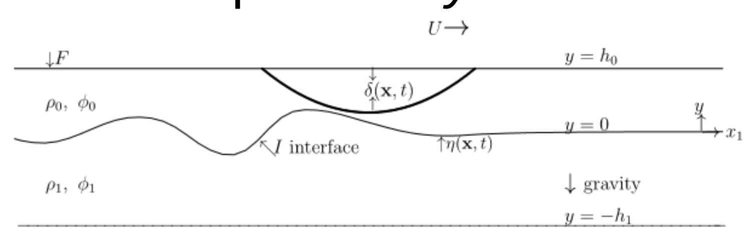
- Grue (2015).

Nonlinear dead water resistance at subcritical speed. *Physics of Fluids.*

Fourier translation method

Nonlinear theory

Ship geometry



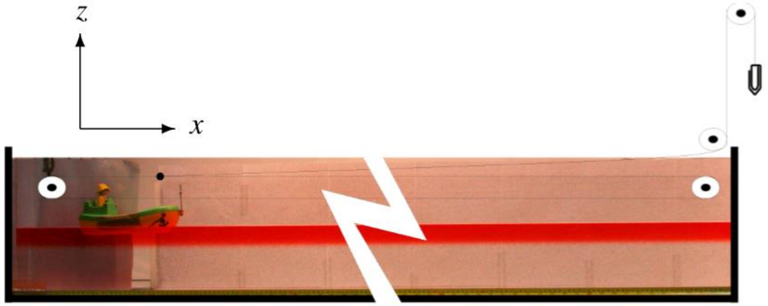
1. Background

1.1 Research progress

- Mercier, Vasseur, and Dauxois, (2011).

Resurrecting dead-water phenomenon. *Nonlinear Processes in Geophysics*

2D experiment; Steady force



Wave flume: *L*=3.0m, *W*=0.105m, *D*=0.5m

- Lacaze et al., 2013.

Wave patterns generated by an axisymmetric obstacle in a two-layer flow.

Experiments in Fluids

3D experiment; Focus on the wave wake

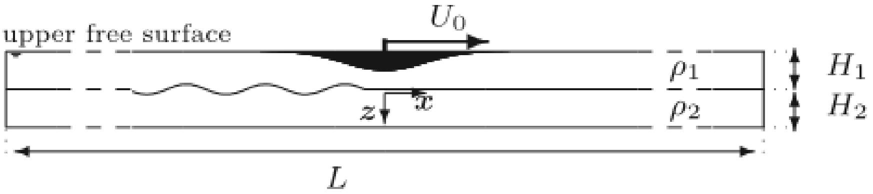
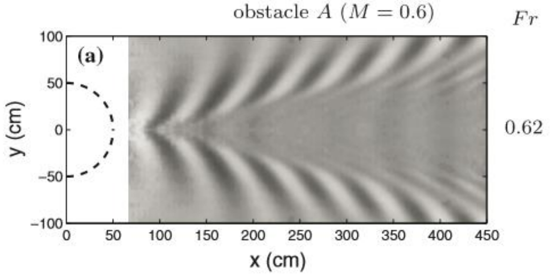


Fig. 1 Sketch of the experimental set-up ($L = 22$ m and $H_1 \approx H_2 \approx 15$ cm)



1. Background

1.1 Research progress

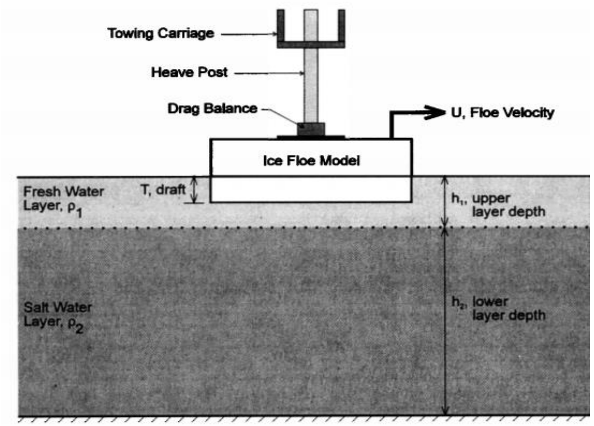
- J. K. Waters, M.S.Bruno (1995).

Internal wave generation by ice floes moving in stratified water: Results from a laboratory study.

Journal of Geophysical Research

3D experiment;

Focus on the effect of ice profile on resistance



Wave flume: *W*=3.6m
Ice flow: 0.91m×0.91m×0.3m

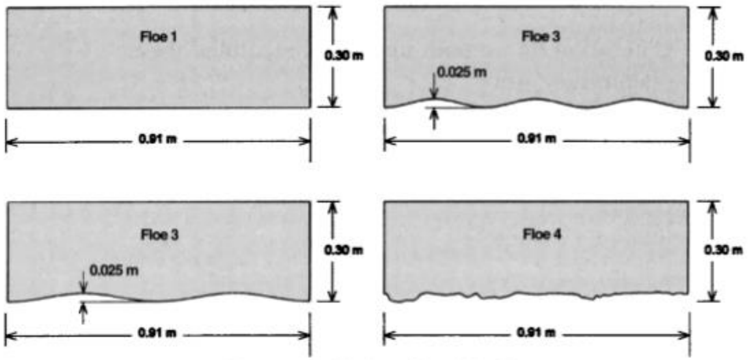


Figure 1. Profile views of model ice floes.

1. Background

1.2 Objective of present study

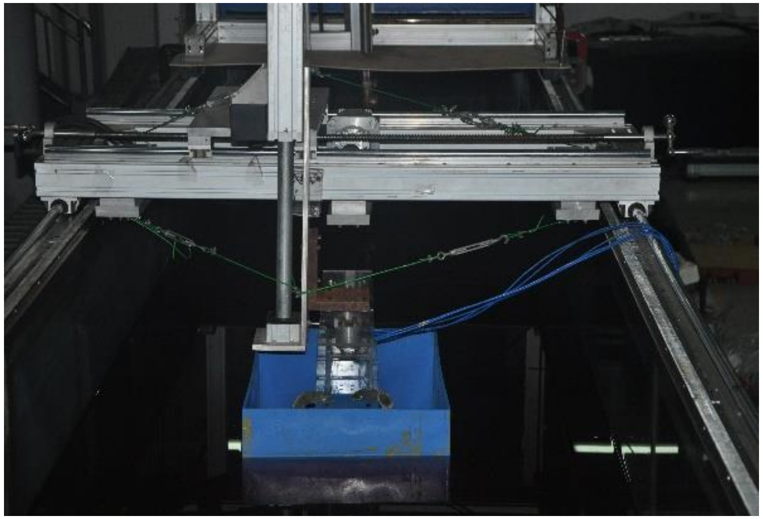
- This experiment study is to investigate the dead water resistance on box-type structure in a two-layer fluid.
- The draft and towing speed are varied to achieve the informations on the corresponding trends.

Arctic iceberg. Image: Florida State University

2. Experimental setup

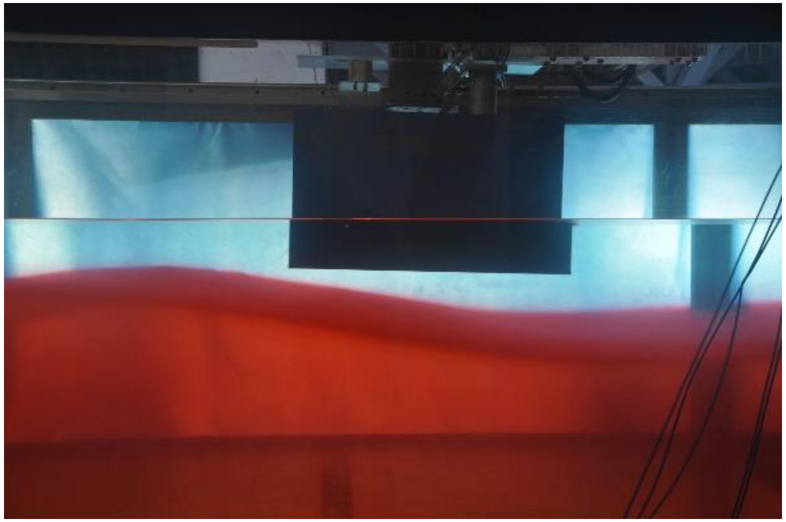
2.1 Experimental layout

- **Wave flume: *L*=12.0m, *B*=1.2m, *H*=0.6m**
- **Barge model: *l*=0.6m, *b*=0.45m**



Front end view

The flume is equipped with a low speed towing system.

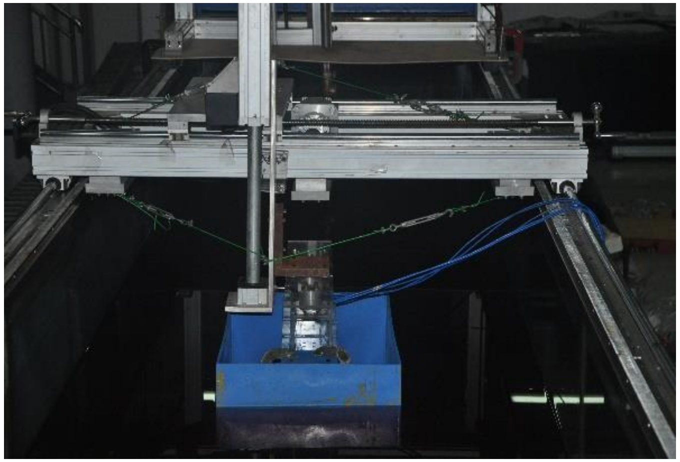


Side view

The fresh water with depth h_1 is layered above the colored saline water with depth h_2

2.2 Measurement method

- Force sensor is use to measure the drag resistance. Sample frequency is in the range of 120HZ~480HZ
- Force sensor connected the model to the towing system with an aluminum alloy column
- The resistance values were obtained by averaging the data over the steady stage with stable towing speed.

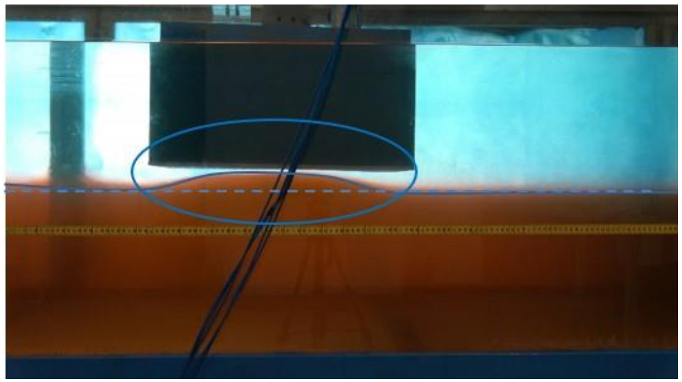


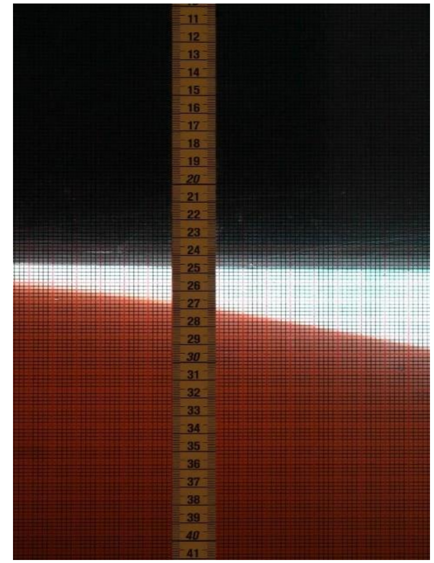
$$\overline{f} = \frac{\sum_{i=1}^{N} f_i}{N}$$

- The equation of drag resistance is:

$$F = \frac{1}{2} C S \rho V^2 \qquad C_d = C_{two-layer} - C_{uniform}$$

2.2 Measurement method





- Pycnocline elevation is measured by camera and ruler.

2.3 Experimental parameters

Test in two-layer fluid

Interfacial position	Barge draft (m)	Towing speed (m/s)
h_1=0.2m h_2=0.4m	0.10	0.06; 0.08; 0.10; 0.12; 0.14; 0.16; 0.18; 0.20; 0.24
	0.12	
	0.14	
	0.20	
h_1=0.3m h_2=0.3m	0.20	
	0.22	
	0.24	

ρ_1=0.997g/cm^3， ρ_2=1.025g/cm^3， ρ_1/ρ_2=0.973

Test in uniform fluid

Water depth	Barge draft	Towing speed (m/s)
h=0.6m	0.10, 0.12, 0.14, 0.20, 0.22, 0.24	0.06; 0.08; 0.10; 0.12; 0.14; 0.16; 0.18; 0.20; 0.24

3. Results and discussions

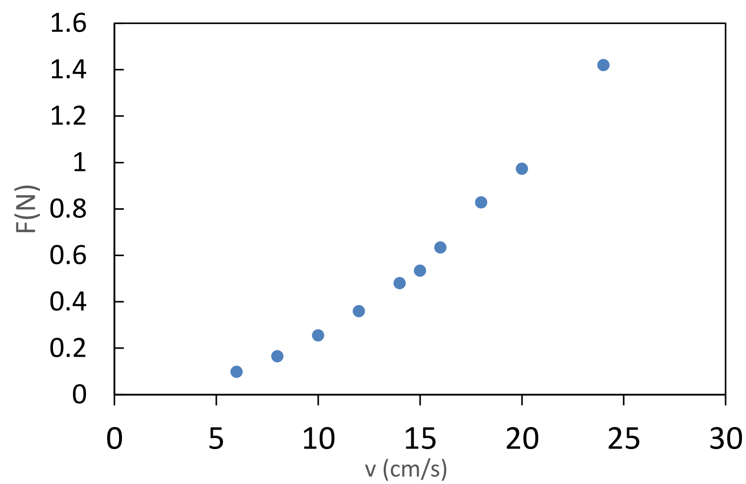
3.1 Drag force in uniform fluid

- **The resistance is directly proportional to the square of the towing velocity *V*.**
- **That means the drag resistance coefficient $C_{uniform}$ = constant with a certain draft**

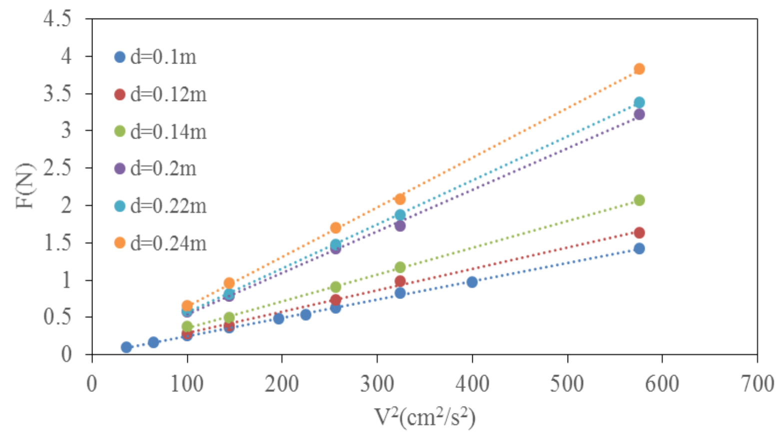
$$F = \frac{1}{2} C S \rho V^2$$

$$\boldsymbol{F} = \boldsymbol{F}_{\boldsymbol{friction}} + \underline{\boldsymbol{F}_{\boldsymbol{form\,drag}}} + \boldsymbol{F}_{\boldsymbol{wave-making}}$$

$$0.025 < Fr = \frac{V}{\sqrt{gL}} < 0.099$$



Drag force vs. *V*, *d*=0.1m

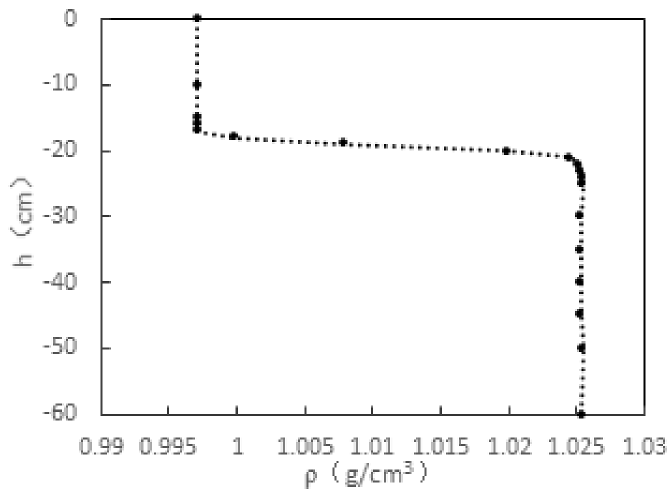


Drag force vs. V^2

3.2 Drag force in a two-layer fluid

- **Density profile before towing tests**

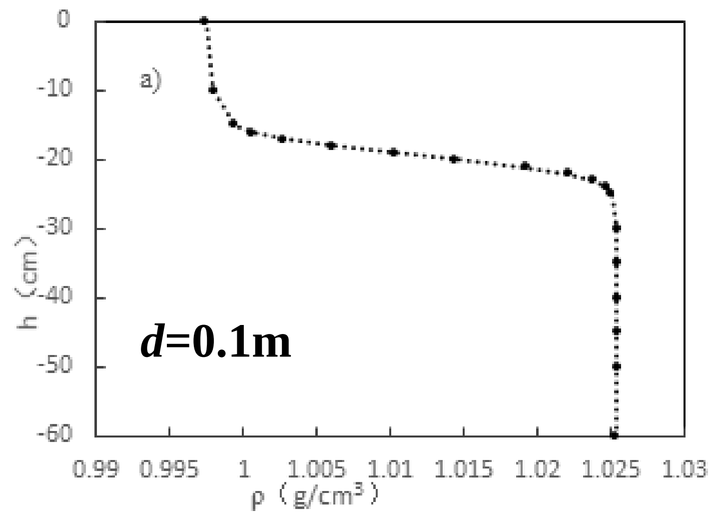
Pycnocline thickness is about 0.05m before the towing test

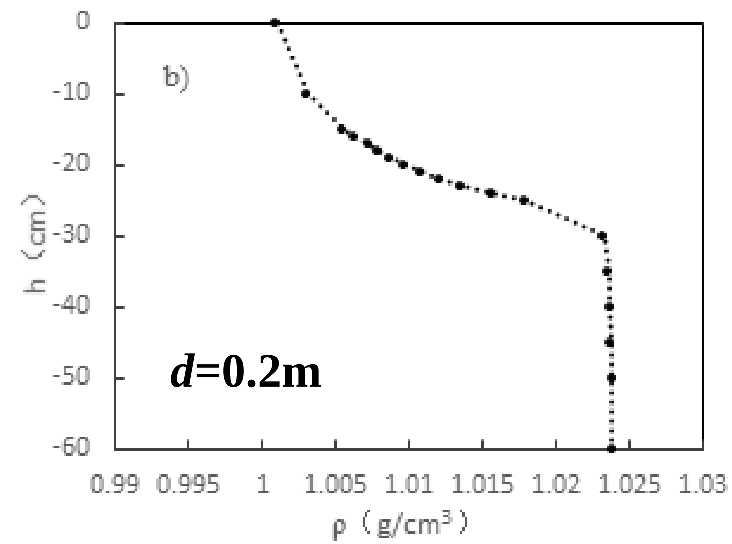


h_1=0.2m, ρ_1=0.997g/cm^3
h_2=0.4m, ρ_2=1.025g/cm^3

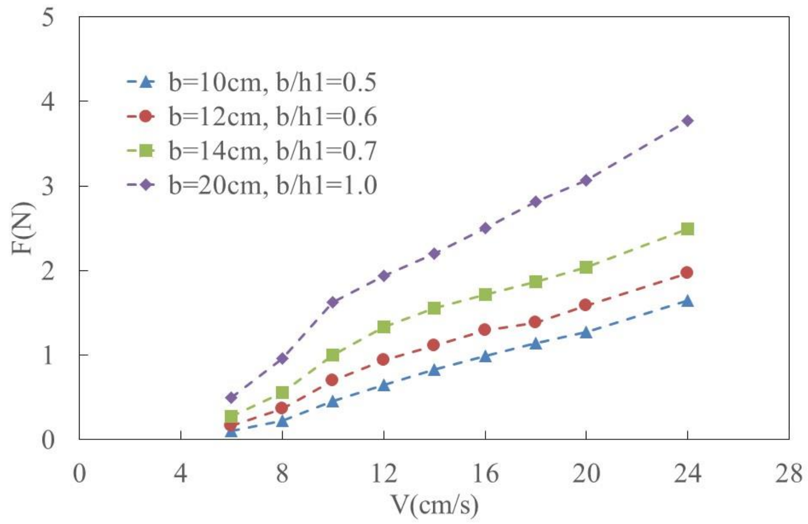
ρ_1/ρ_2=0.973

- **Density profile after towing tests**

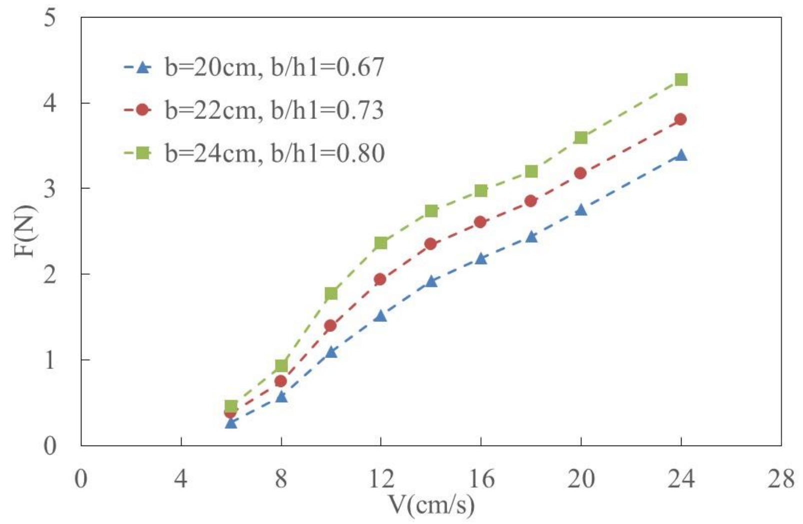




3.2 Drag force in a two-layer fluid



(a) h_1=0.2m, h_2=0.4m

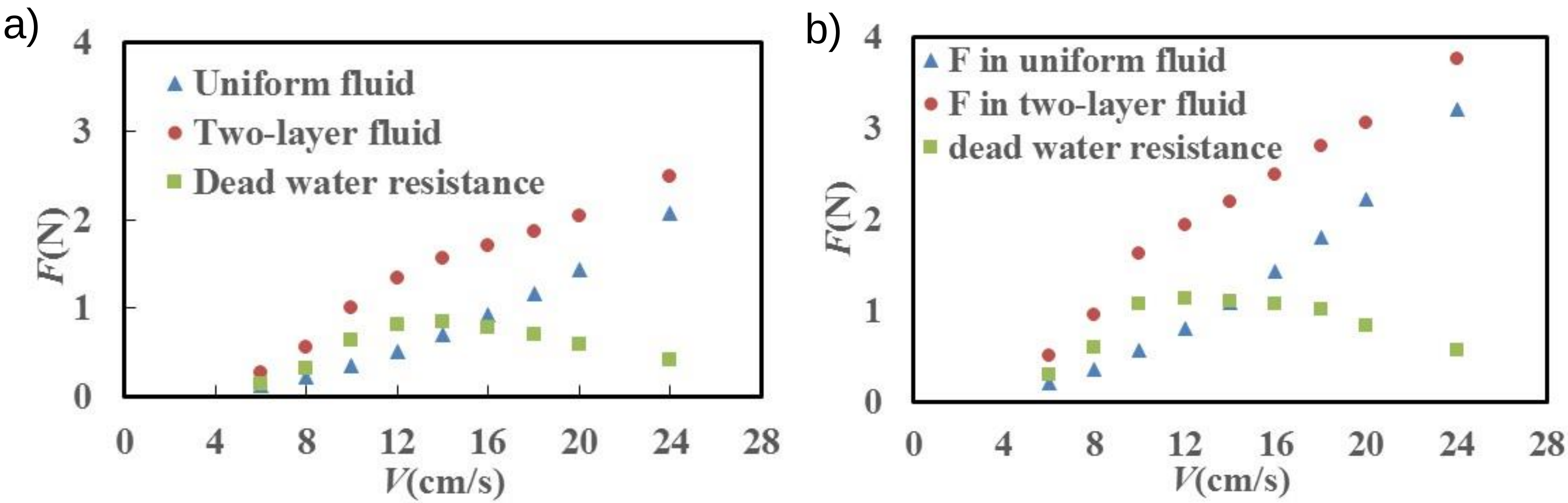


(b) h_1=0.3m, h_2=0.3m

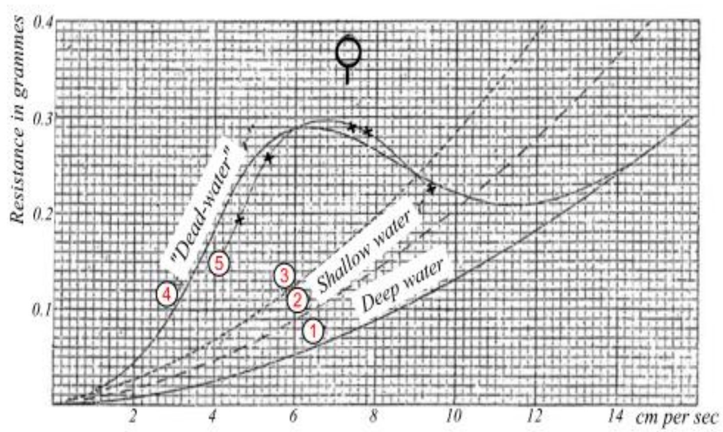
- **Shallow draft: the drag resistance increases approximate linearly with the increase of the towing speed**

- **Deep draft: there is a local maximum**

3.2 Drag force in a two-layer fluid



Drag force with draft *d*=0.14m (a) and *d*=0.2m (b) vs. towing speed.
h1=0.2m, h2=0.4m



① h=23cm
② h=5cm
③ h=2.5cm
④ h1=2cm
⑤ h1=2cm, experiment data

(Ekman, 1904)

3.3 Dead water coefficient in a two-layer fluid

- **Dead water resistance coefficient**

$$F = \frac{1}{2} C \rho S V^2$$

$$C_d = C_{two\text{-}layer} - C_{uniform}$$

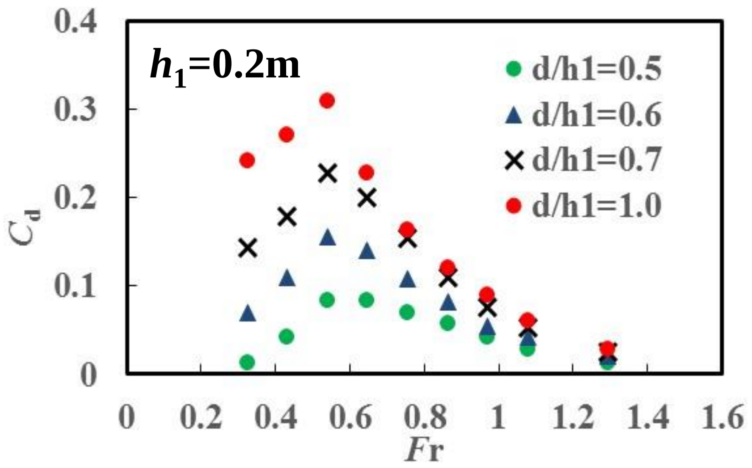
- ***Fr* in a two-layer fluid**

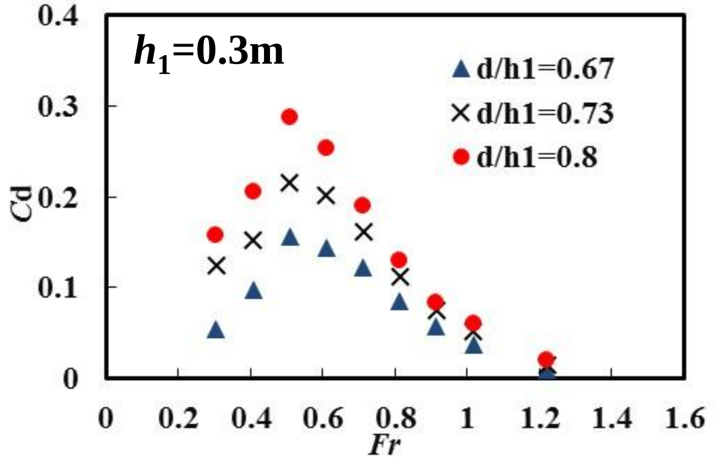
$$Fr = \frac{V}{c_0}$$

The maximum wave speed in two-layer fluid:

$$c^2 = \frac{g(\rho_2 - \rho_1)}{\rho_2} \frac{h_1 h_2}{h_1 + h_2}$$

h_1=0.2m, c_0=0.1785m/s
h_1=0.3m, c_0=0.1793m/s

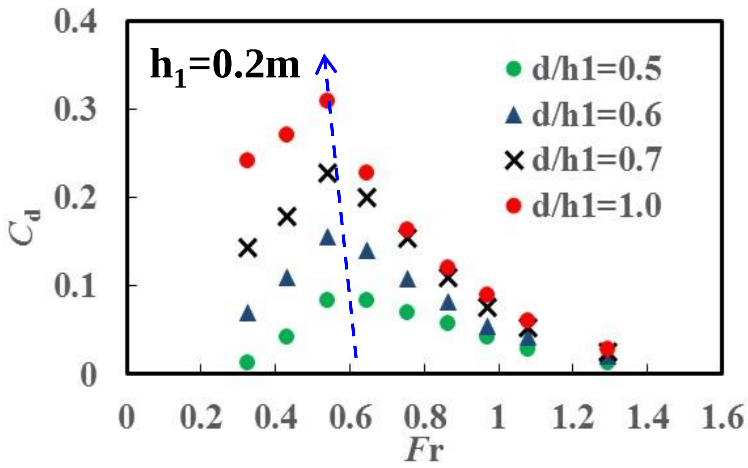




Dead water resistance coefficient C_d vs. Fr

3.3 Dead water coefficient in a two-layer fluid

- **C_d attains a maximum and the corresponding *F*r down shifts slightly with the increase of draft.**
- **When C_d gets the maximum, the *F*r is much smaller than the critical *F*r 1.0, about 0.5~0.6.**



Added resistance coefficient C_{add} vs. *F*r

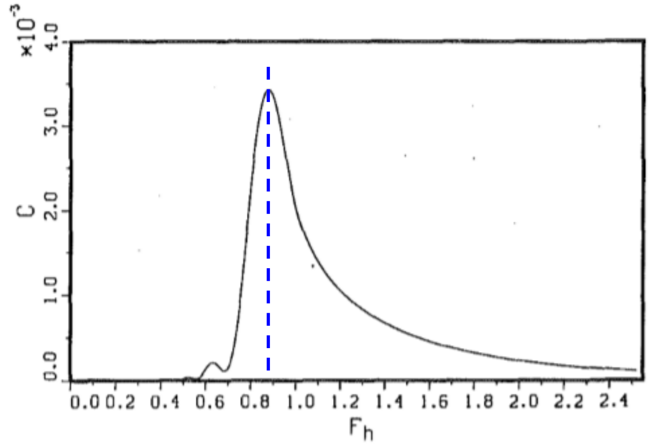


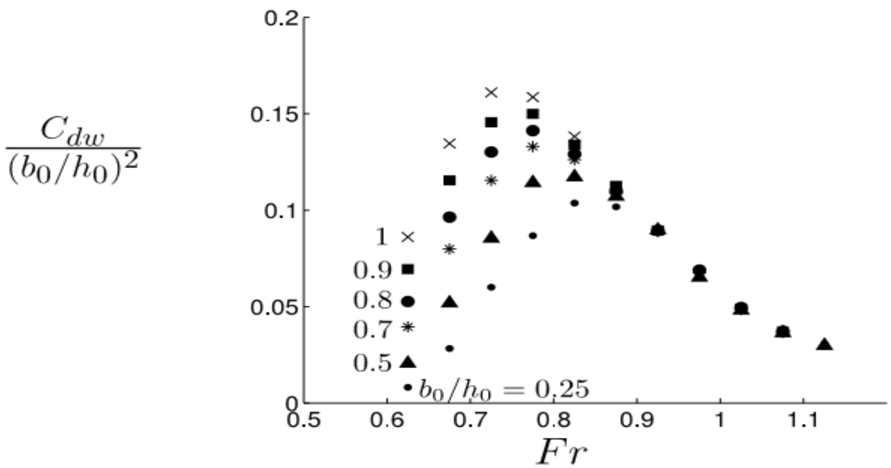
Fig. 1 Wave resistance coefficient $C = 4R_w/\rho_1 U^2 DL$ of a prolate-spheroid of length L and maximum diameter D moving on the free-surface of a two-layer fluid: $h_1 = h$, $h_2 \rightarrow \infty$, $D/h = 0.9$, $L/h = 10.0$

Miloh, Tulin, Zilman. (1993)

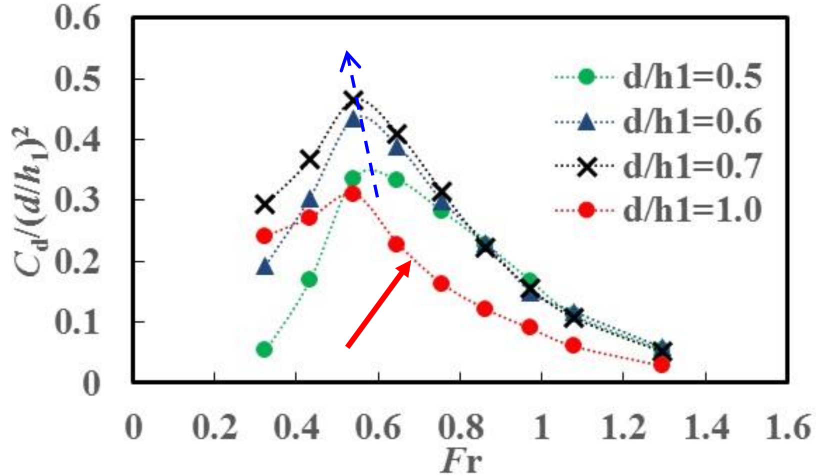
3.3 Dead water coefficient in a two-layer fluid

$C_d/(d/h_1)^2$

h_1=0.2m



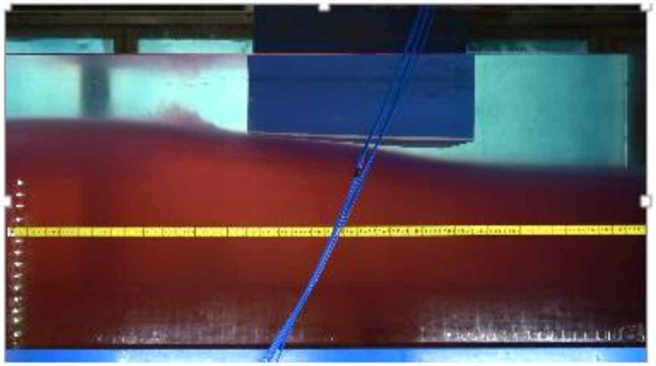
(J. Grue, 2015)



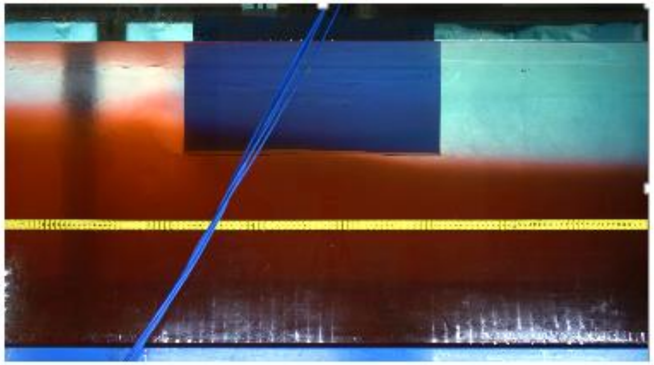
$C_d/(d/h_1)^2$ vs. *Fr*

- **d/h_1=0.5~0.7: $C_d/(d/h_1)^2$ depends on the Froude number only in the range close to critical speed (Fr>0.85 in the present), irrespective of the draft.**
- **The above conclusion is not suitable for the draft d/h_1=1.0**

3.3 Dead water coefficient in a two-layer fluid



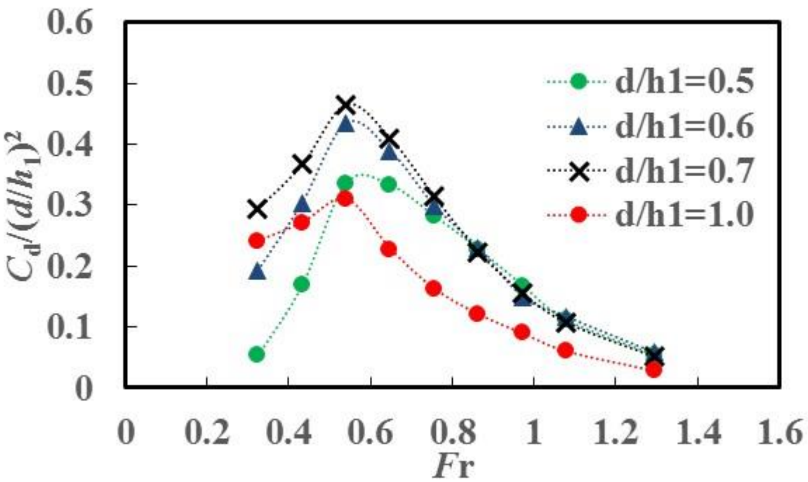
d=0.14m, d/h_1=0.7



d=0.2m, d/h_1=1.0

V=0.12m/s

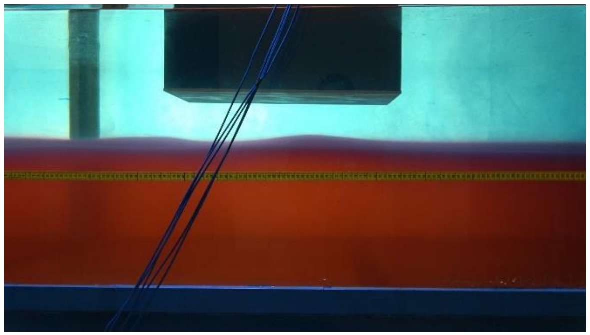
h_1=0.2m



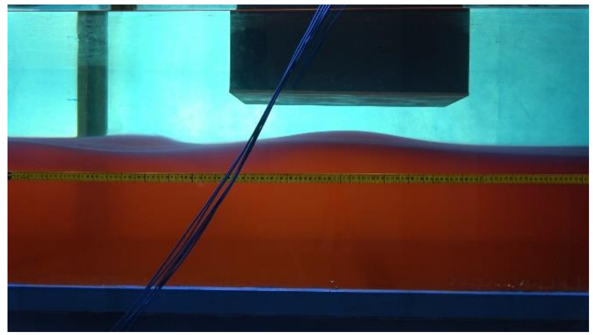
$C_d/(d/h_1)^2$ vs. Fr

- Nonlinear effect
- Turbulent effect

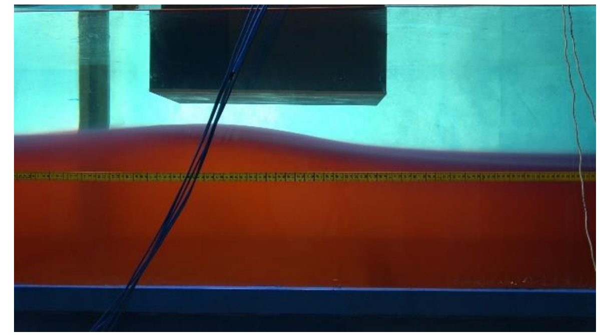
3.4 Pycnocline elevation



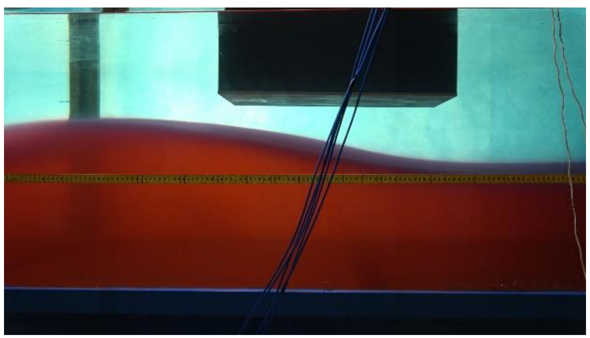
8cm/s



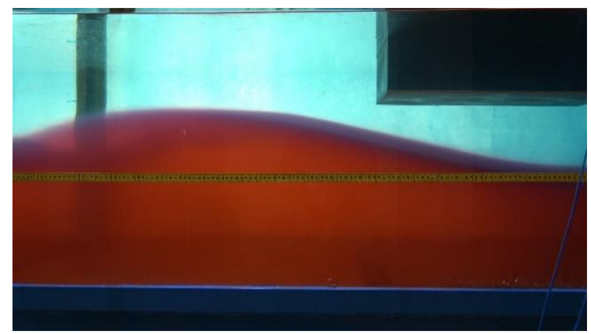
10cm/s



12cm/s



14cm/s



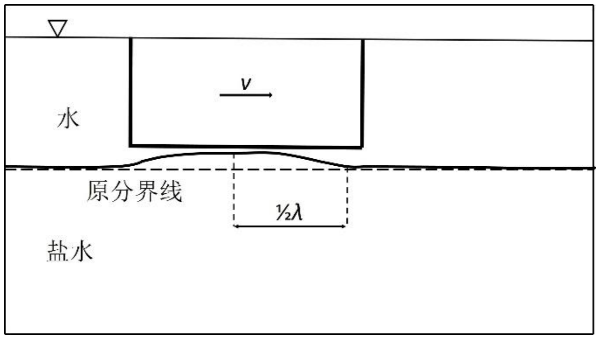
16cm/s

d=10cm, h_1=20cm, d/h_1=0.5

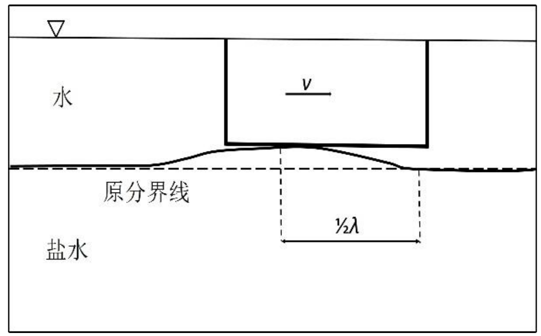
With the increase of towing velocity :

- Internal wave length becomes longer
- The position of internal wave crest is farther away from the box

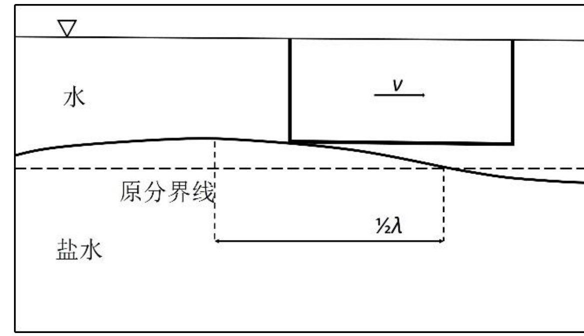
3.4 Pycnocline elevation



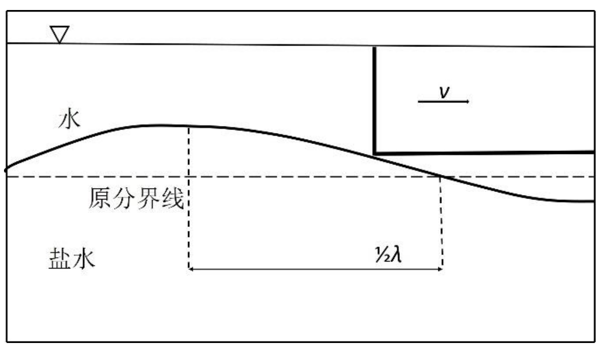
(a) *v*=8cm/s



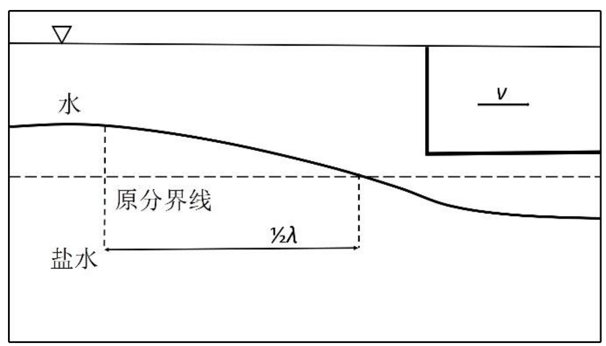
(b) *v*=10cm/s



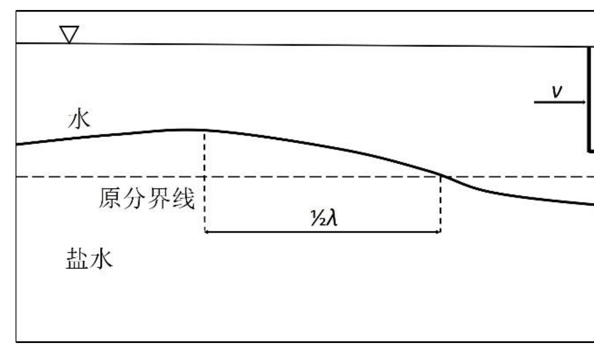
(c) *v*=12cm/s



(d) *v*=14cm/s



(e) *v*=18cm/s



(f) *v*=24cm/s

d=22cm, h_1=0.3m, d/h_1=0.73

Conclusions

Three-dimensional experiments are carried out to investigate the drag resistance on a barge model in a two-layer fluid.

- **C_d attains a maximum and the corresponding Fr down-shifts slightly to smaller Fr with the increase of draft.**
- **C_d reaches its maximum when the Fr in the range 0.5~0.6, much smaller than the critical Fr=1.0.**
- **For relative small drafts, $C_d/(d/h_1)^2$ depends on Fr only in the range close to critical speed (Fr>0.85), irrespective of the draft. But this conclusion is not suitable for the case d/h_1=1.0 because of the nonlinear and turbulence effect.**

Thank you for your attention!