



7th International Conference on Ship Manoeuvring in Shallow and Confined Water
18-21 May 2025, Bruges, Belgium

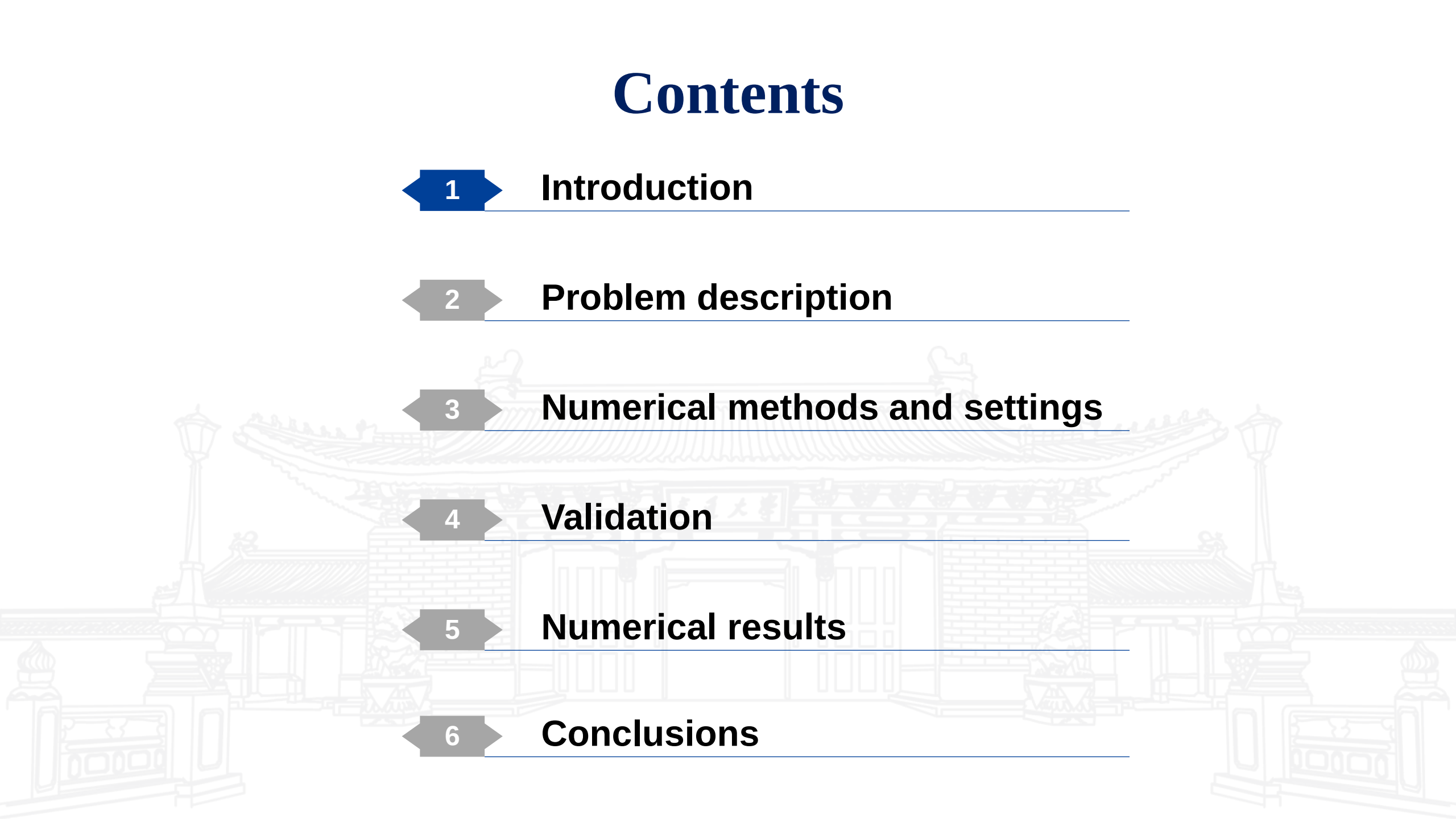
Course-keeping simulations of a ship in confined waterways based on integrated CFD method and control algorithm

Zi-Qiang Zheng, Yu He, Lu Zou, Zao-Jian Zou

School of Ocean and Civil Engineering
Shanghai Jiao Tong University, China

May 19, 2025

Contents

- 
- 1** Introduction
 - 2** Problem description
 - 3** Numerical methods and settings
 - 4** Validation
 - 5** Numerical results
 - 6** Conclusions

1. Introduction



➤ Suez canal grounding accident (2021)

- 2021, the Ever Given container ship **grounded** on the banks of the Suez Canal



Ever Given container ship grounded (from the internet)

1. **Main cause: loss of maneuverability**
(squat, bank suction, and bank cushion effects)



Bank and shallow-water effects **significantly increase** the challenge of ship control

2. **Direct cause: improper maneuvering decisions** by pilots



control strategy for safe navigation

1. Introduction



➤ Ship performance in confined waterways

- model tests, potential flow code, CFD
- topics of shallow-water and bank effects
- **captive perspective** without dynamic changes of rudder angle, heading angle, sway motions
- static, specified path, only qualitative, not intuitive for practical guidelines



Model test on bank effects (MASHCON 2009)

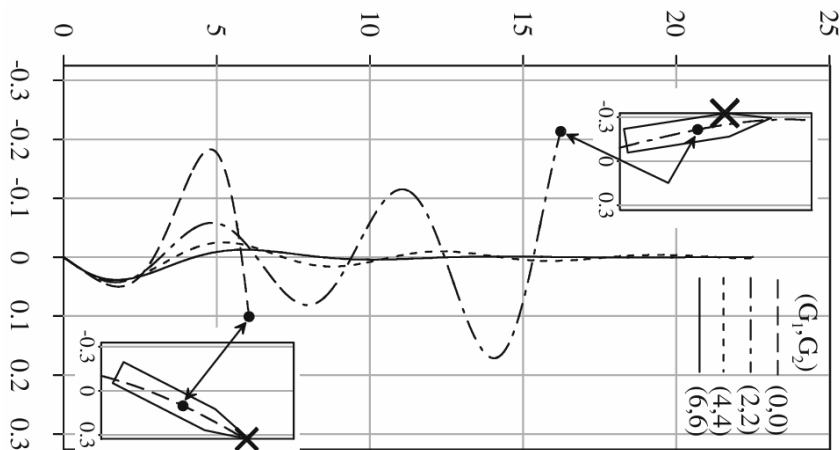
1. Introduction



➤ Ship maneuvering (with dynamic motions) in confined waterways

mathematic model (derived from model tests) + simulation

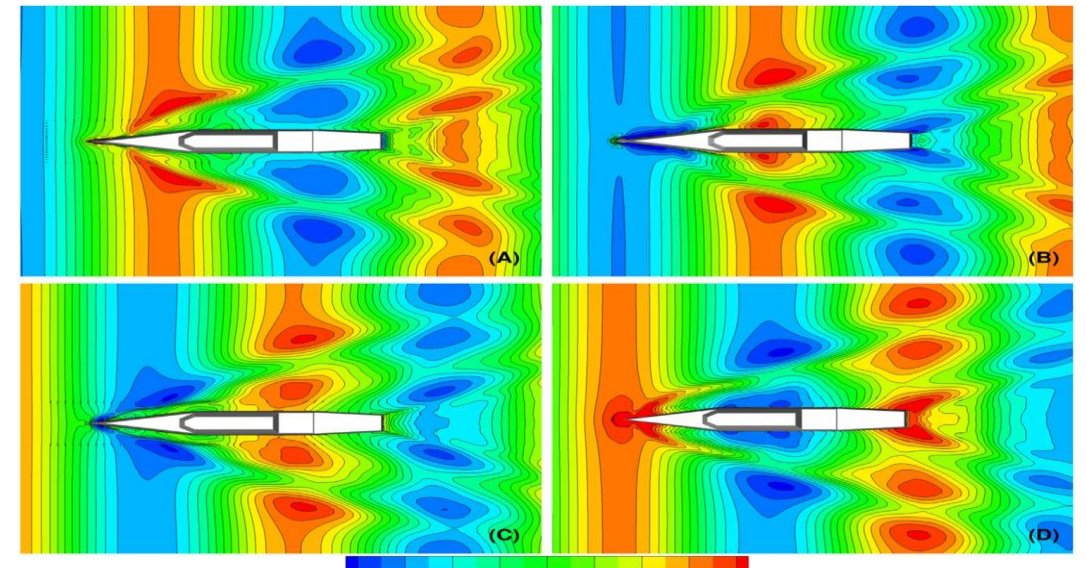
- require **specific model tests**
- **high** facility requirements and costs
- **highly** rely on the **accuracy** of the mathematic model



Simulation based on mathematic model (Sano et al., 2014)

CFD free-running simulation

- **only** require ship geometry
- **flow field** information
- successfully applied in open water



Free-running simulation in waves (Wang et al., 2017)

1. Introduction



➤ Ship maneuvering (with dynamic motions) in confined waterways

CFD free-running simulation

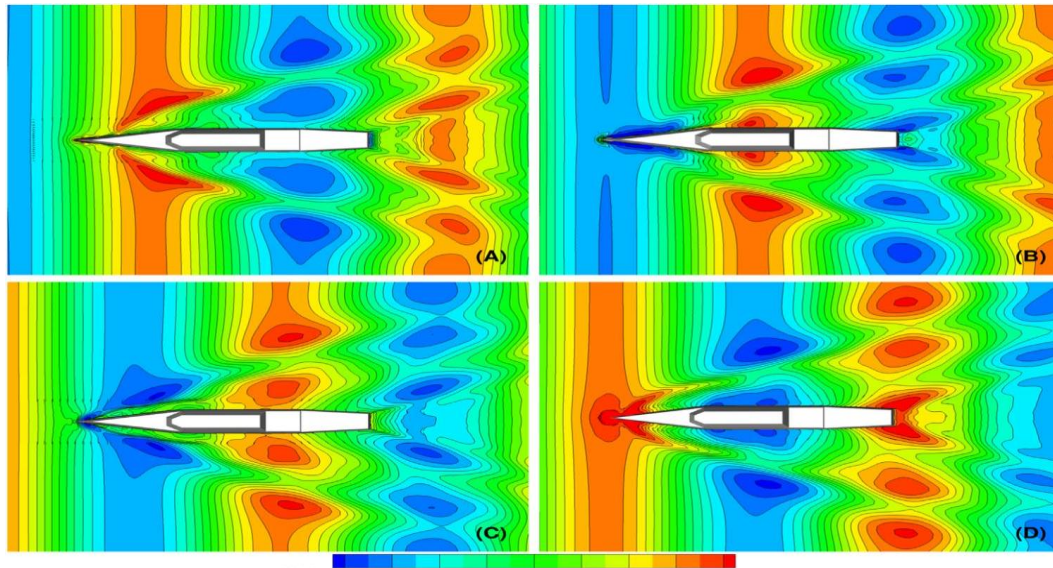


- **only** require ship geometry
- **flow field** information
- successfully applied in open water



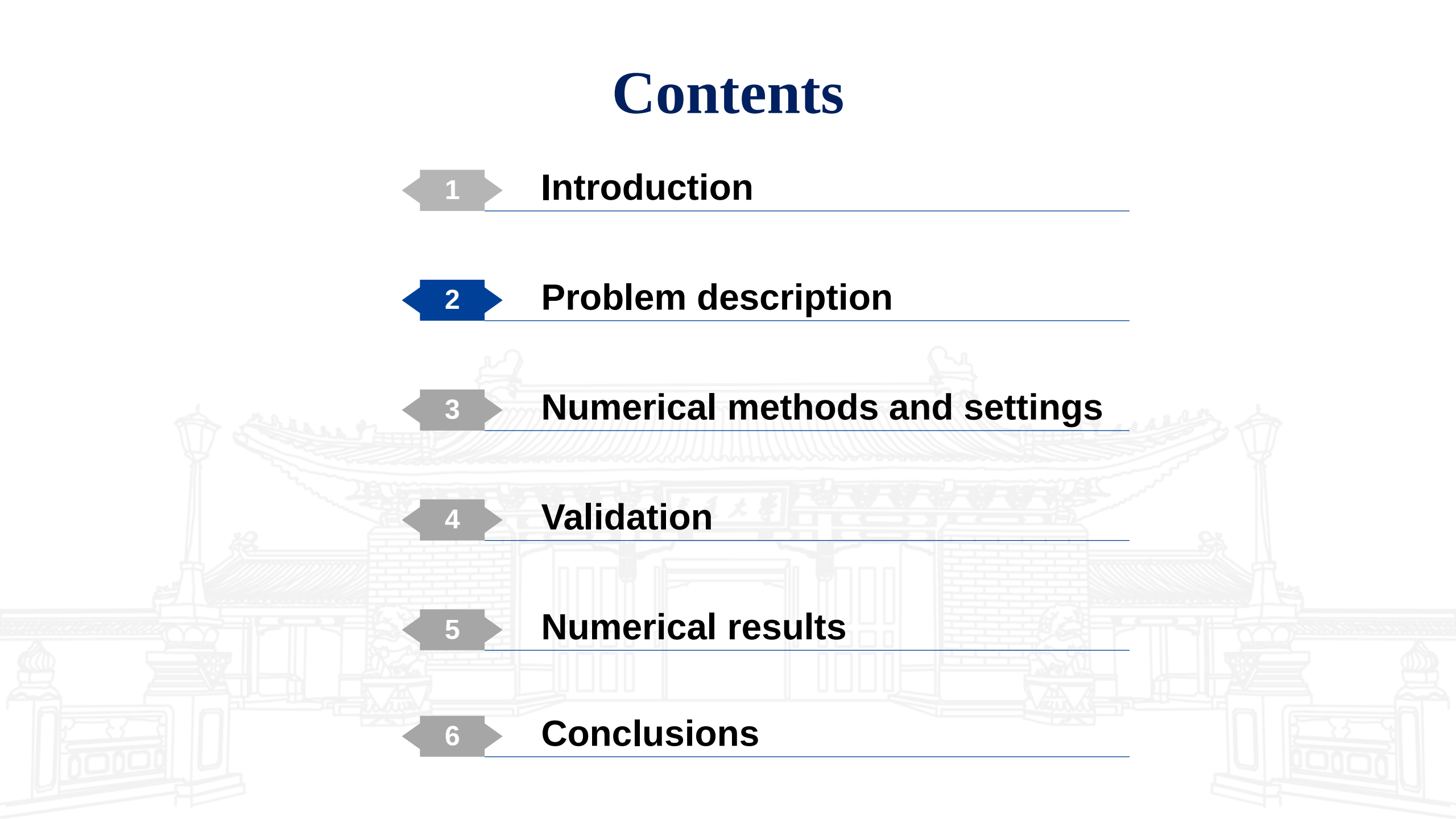
Ever Given container ship grounded (from the internet)

- directly simulate **course-keeping maneuvering in confined waterways**
- provide **in-depth analyses** of bank-effects mechanism
- offer **practical guidelines** for safe navigations in confined waterways

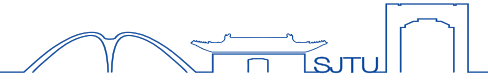


Free-running simulation in waves (Wang et al., 2017)

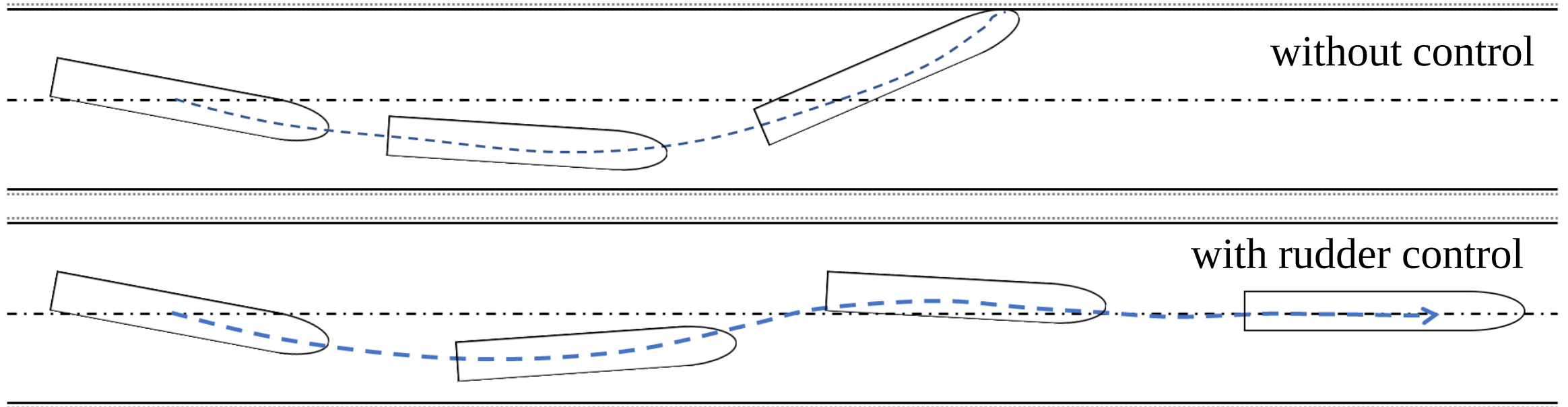
Contents

- 
- 1 Introduction
 - 2 Problem description
 - 3 Numerical methods and settings
 - 4 Validation
 - 5 Numerical results
 - 6 Conclusions

2. Problem description



➤ Course-keeping problems in confined waterways



Illustrations for course-keeping problems

- without control: **deviate** from the desired course
- aim to use rudder control to realize **course-keeping** for safe navigation

2. Problem description



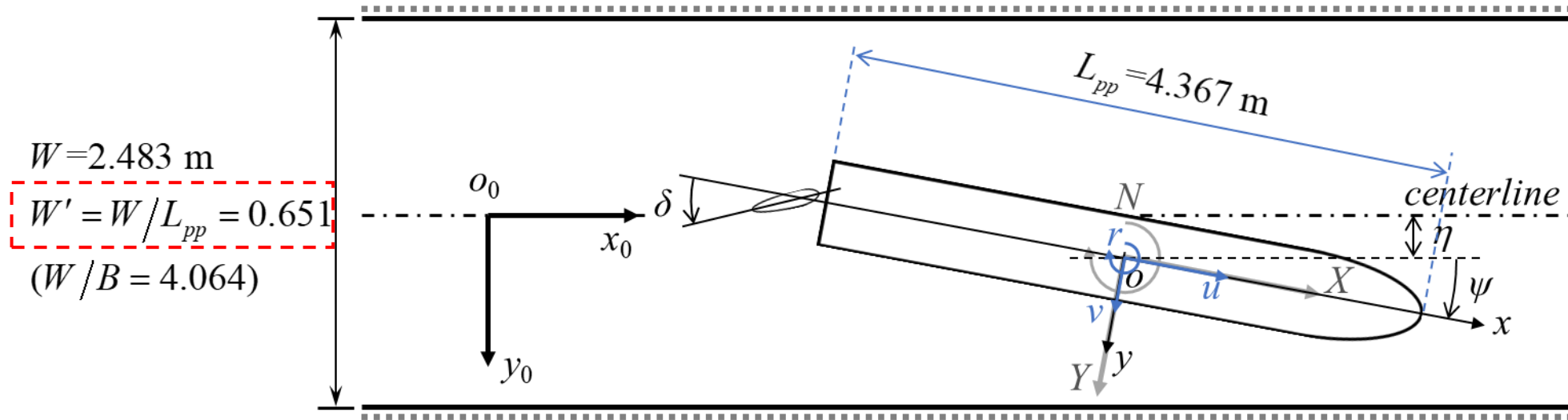
- Course-keeping problems in confined waterways
 - **hull-rudder-propeller system** is considered in numerical simulations (**free-running**)



Item	Parameter	Unit	Value
Hull	Scale ratio (λ)	-	1:52.667
	Length between Perpendiculars (L_{pp})	m	4.367
	Breadth (B)	m	0.611
	Draft (d)	m	0.205
Propeller	Diameter (D)	m	0.15
	Blade number	-	5
	Hub ratio	-	0.227
	Rotation direction	-	right
Rudder	Rudder area	m ²	0.0415
	Lateral area	m ²	0.0196

➤ Coordinate system

- two coordinate systems: earth-fixed coordinate system, ship-fixed coordinate system
- ship position: (x'_0, η') , $x'_0 = x_0 / L_{pp}$ and $\eta' = y_0 / L_{pp}$, course: ψ



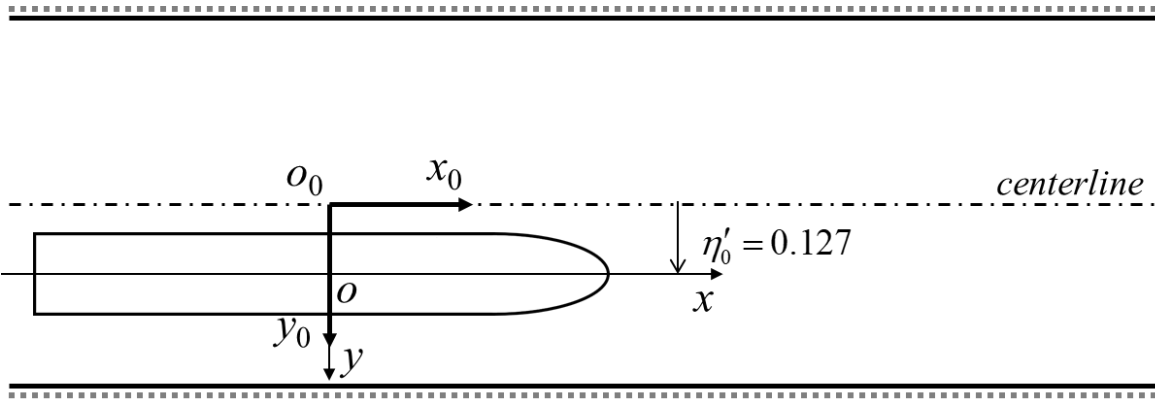
2. Problem description



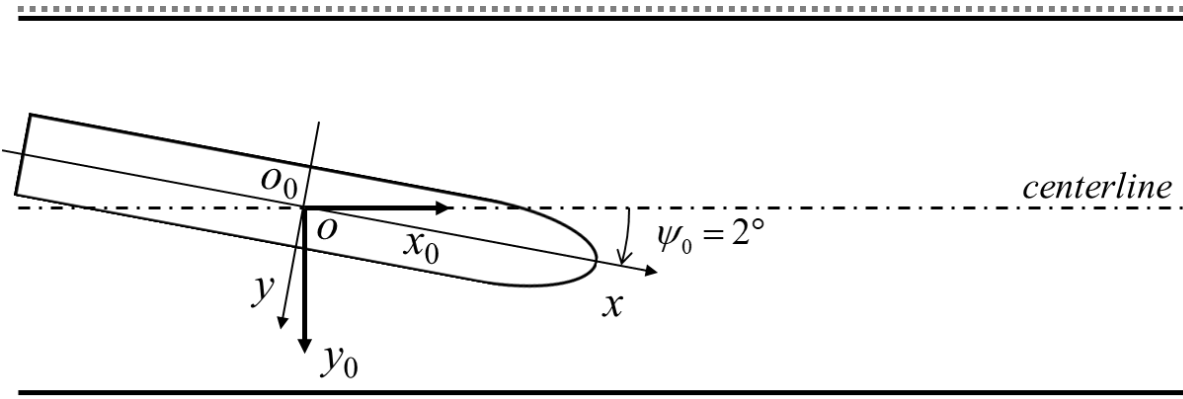
➤ Investigated cases

- Two scenarios with **initial disturbances**: initial **off-centerline deviation**, initial **heading angle**

	Case No.	η'_0	ψ_0 (°)	h/d
Initial off-centerline deviation	Case1-1	0.127	0	2.0
	Case1-2	-0.127	0	
Initial heading angle	Case2-1	0	2	
	Case2-2	0	-2	

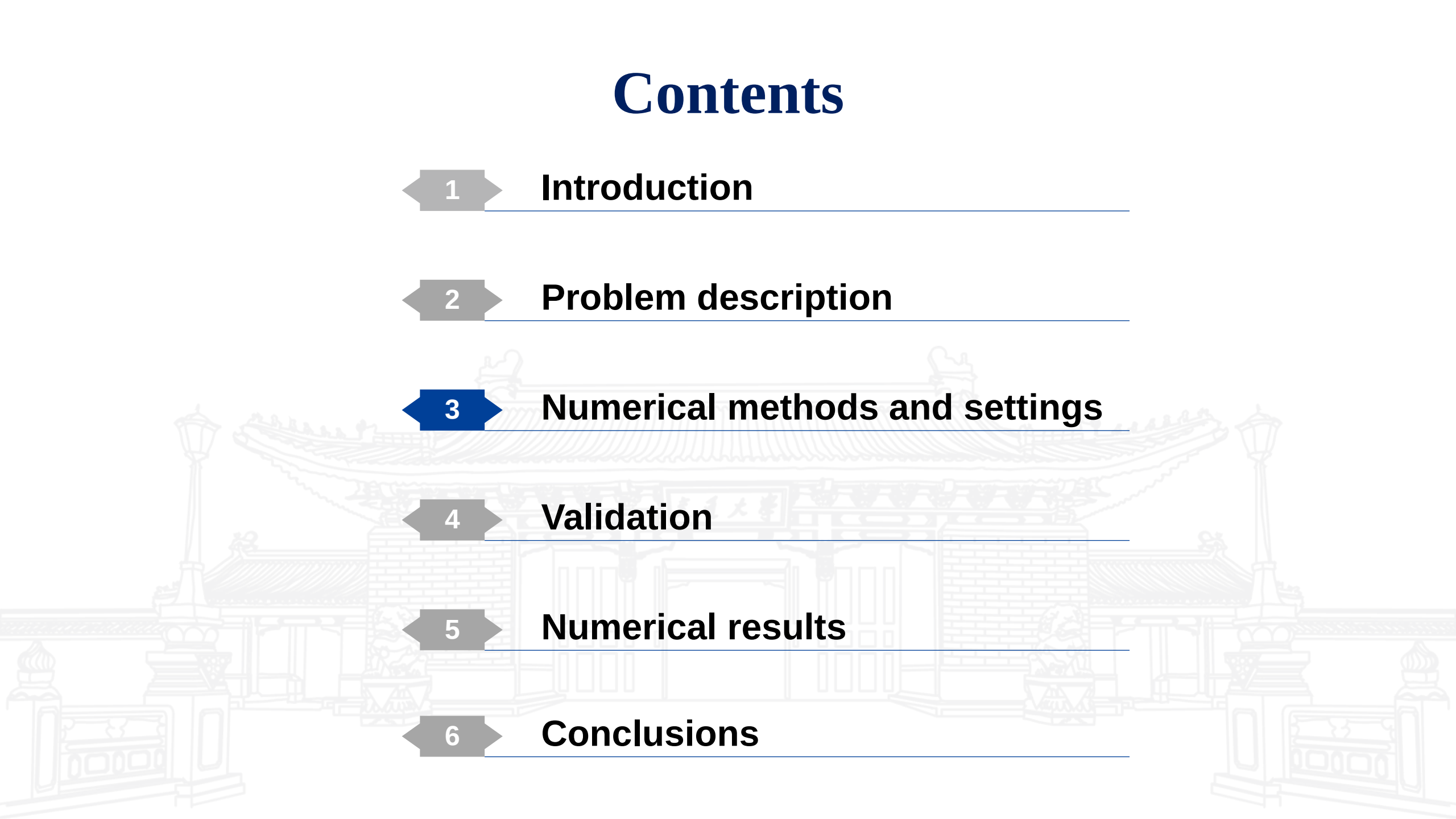


Case1-1: $\eta'_0=0.127$



Case2-1: $\psi_0=-2^\circ$

Contents

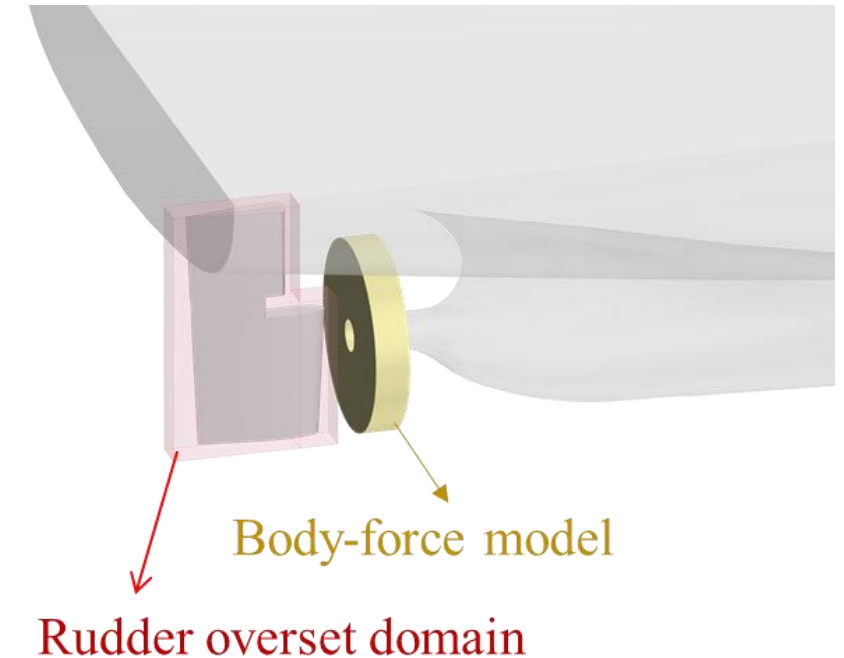
- 
- 1 Introduction
 - 2 Problem description
 - 3 Numerical methods and settings
 - 4 Validation
 - 5 Numerical results
 - 6 Conclusions

3. Numerical methods and settings



➤ Numerical settings

Models/variables	Setup
CFD solver	STAR-CCM+
Governing equations	URANS
Turbulence model	SST $k-\omega$
Free-surface simulation	VOF + HRIC
Time model	implicit unsteady
Time step	0.01s, $t < 100$ s 0.02s, $t \geq 100$ s
Maximum inner iterations	40
Propeller model	Body-force model
Rudder rotation	Overset mesh

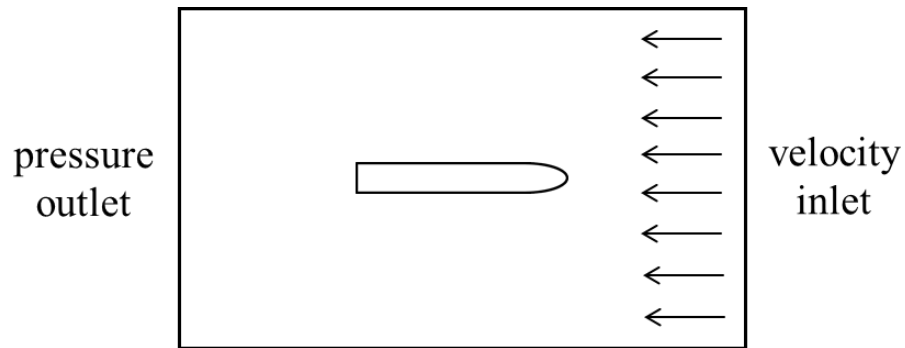


3. Numerical methods and settings

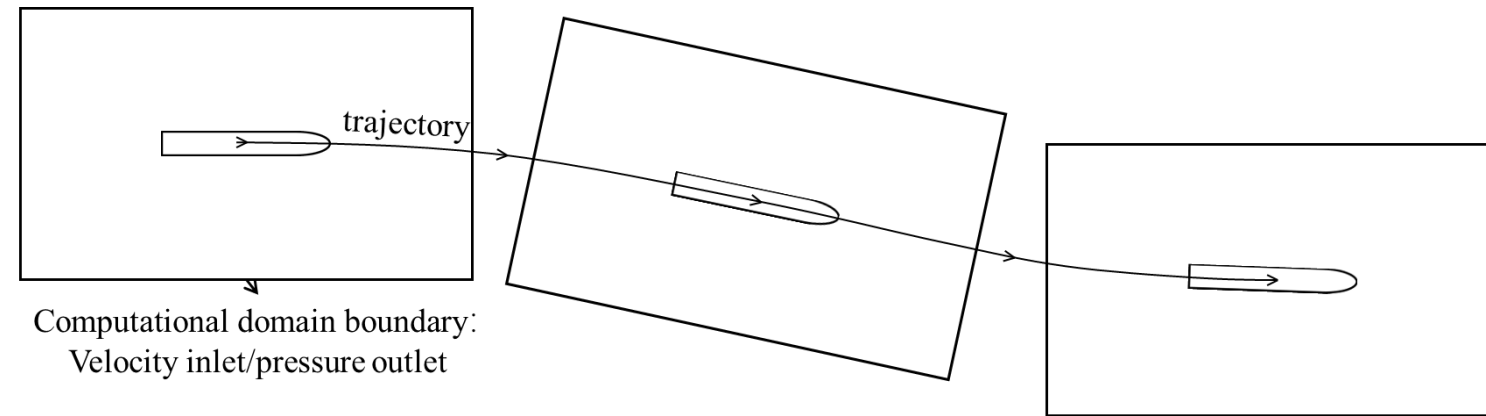


➤ Traditional simulation strategy of free-running in **open water**

- Two approaches of free-running simulations in **open water**:
 - (1) ship is fixed, and water **flows across** the stationary ship (Galilean relativity)
 - (2) the ship **moves through** water
- no relative motions** between the ship and the boundaries: **small computational domain**



(1) water flows across the stationary ship

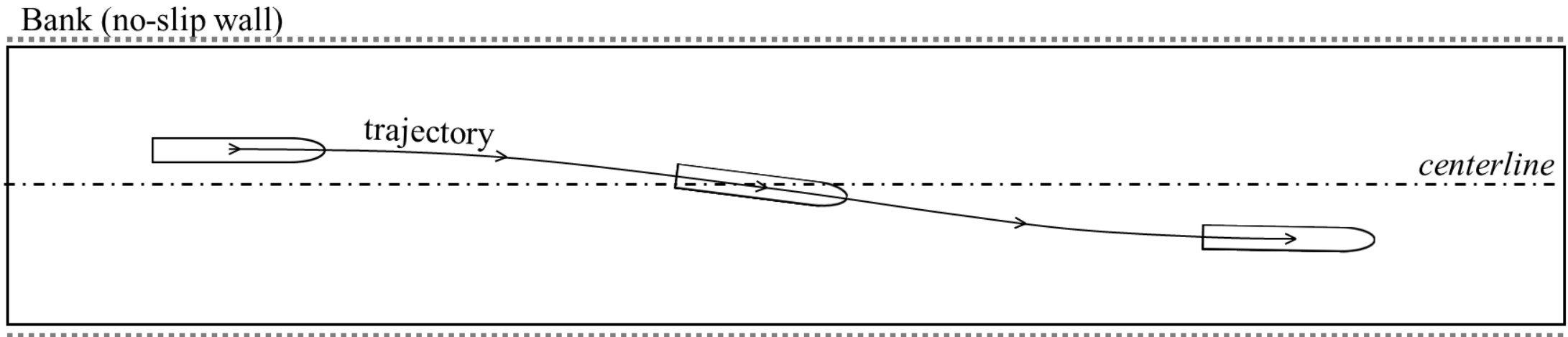


(2) the ship moves through water

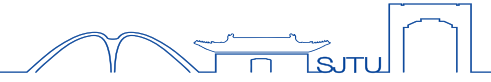
3. Numerical methods and settings



- **Traditional simulation strategy of free-running in confined waterways**
 - Normally involve with **relative motions** between the ship and banks
 - Narrow and long numerical channel needs to be modelled: **huge computational domain**
 - **Overset mesh technique** is applied to handle the relative motions: **additional simulation challenges**



3. Numerical methods and settings

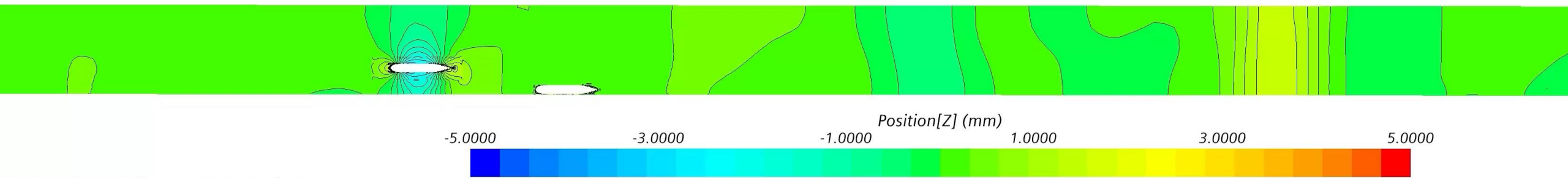


➤ Traditional simulation strategy of free-running in **confined waterways**

- Narrow and long numerical channel needs to be modelled: **huge computational cost**
- **Overset mesh technique** is applied to handle the relative motions: **additional simulation challenges**

A similar example: simulations of the MASHCON2022 benchmark case: **captive case** but still involve with **relative motions between ship and bank**

Free-running simulations in confined waterways are **more challenging**



Solution Time 59.8 (s)

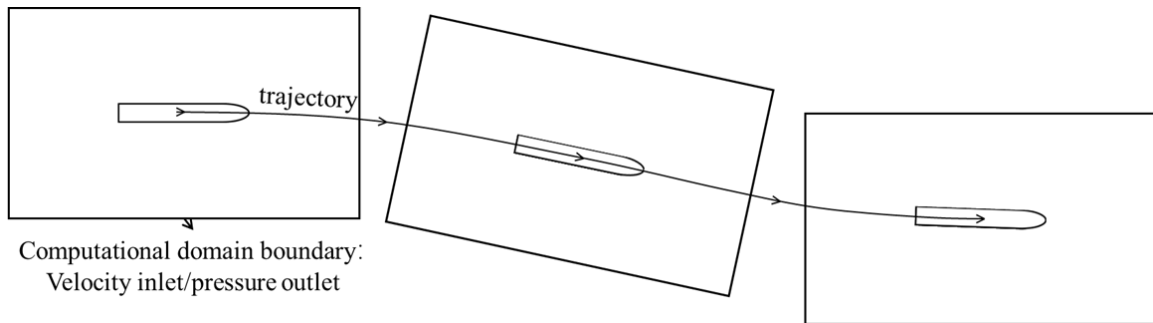
MASHCON2022 case simulation

3. Numerical methods and settings



➤ Virtual bank method

- simulation strategy of **open water** for **confined waterways' problems** (to **reduce** the **computational cost** and **numerical challenges**)
- Divide the sway force Y and yaw moment N into two parts:
 - (1) Y_{bank} and N_{bank} : the force and moment induced by the banks
 - (2) Y_{hydro} and N_{hydro} : the remainder part, likewise the hydrodynamic sway force and yaw moment when the ship moves in the **limited but open water** (with the **same depth**)

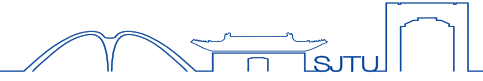


this part can be directly simulated by this method

$$\begin{cases} Y = Y_{hydro} + Y_{bank} \\ N = N_{hydro} + N_{bank} \end{cases}$$

How to consider this part?

3. Numerical methods and settings



➤ Virtual bank method

- **mathematic model** of bank effect to evaluate: Y_{bank} and N_{bank}
- this model (Sano et al., 2014) is related to: ship length L_{pp} , draft d , ship speed U_0 , η (reflect ship-bank distance), drift angle β , rudder angle δ
- above parameters are calculated in simulations to obtain Y_{bank} and N_{bank} in real time

$$\begin{cases} Y = Y_{hydro} + Y_{bank} \\ N = N_{hydro} + N_{bank} \end{cases}$$

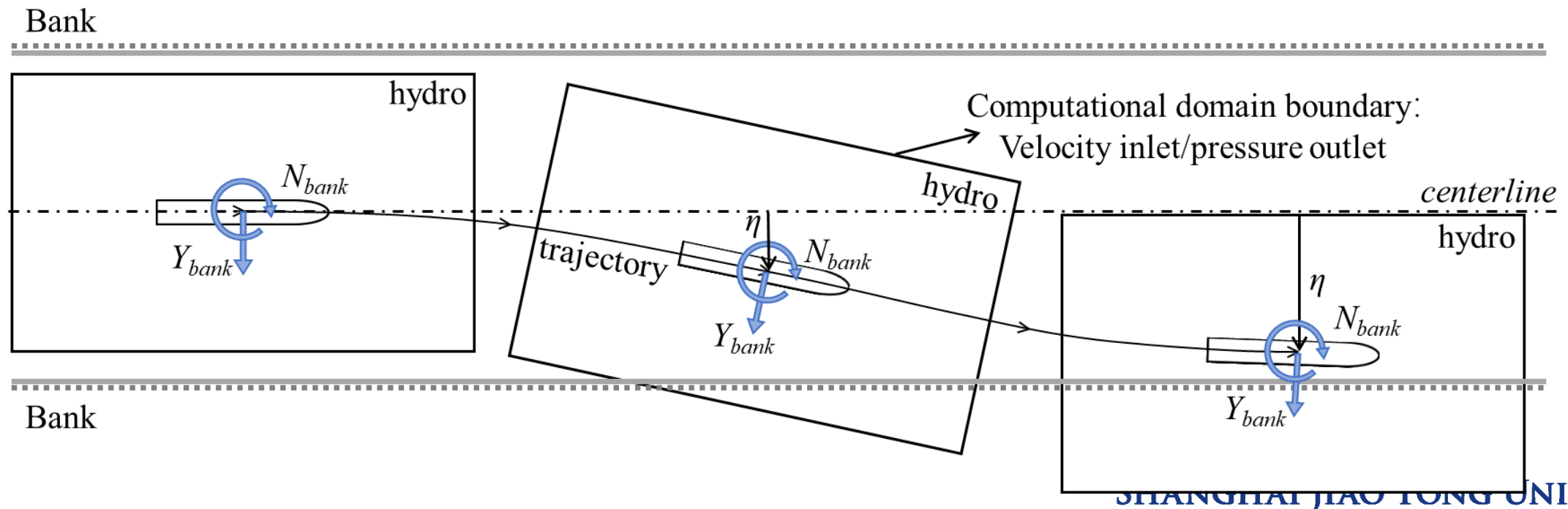
$$\begin{cases} Y_{bank} = 0.5\rho L_{pp} d U_0^2 \left(Y'_\eta \eta' + Y'_{\beta\beta\eta} \beta^2 \eta' + Y'_{\beta\eta\eta} \beta \eta'^2 + Y'_{\eta\eta\eta} \eta'^3 + Y'_{\eta\eta\delta} \eta'^2 \delta \right) \\ N_{bank} = 0.5\rho L_{pp}^2 d U_0^2 \left(N'_\eta \eta' + N'_{\beta\beta\eta} \beta^2 \eta' + N'_{\beta\eta\eta} \beta \eta'^2 + N'_{\eta\eta\eta} \eta'^3 + N'_{\eta\eta\delta} \eta'^2 \delta \right) \end{cases}$$

3. Numerical methods and settings

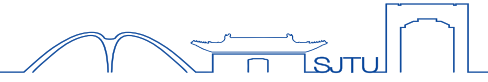


➤ Virtual bank method

- bank force and moment (Y_{bank} and N_{bank}) are **directly imposed** on the ship in the simulations
- hydrodynamic force and moment (Y_{hydro} and N_{hydro}) are **predicted by the simulated flow field** (pressure integral)
- based on the resultant force and moment ($Y=Y_{hydro}+Y_{bank}$, $N=N_{hydro}+N_{bank}$), the ship's **velocity components, attitudes** and **positions** are **calculated** and **updated in real time** in the simulations



3. Numerical methods and settings



➤ **Virtual bank method** CFD simulation + Mathematic model of bank effect

□ Rationality

- this model is **specifically** purposed for **confined waterways**: a series of parameters to reflect the bank effects, and also incorporates **cross derivative terms** to consider the **combined impacts**
- the derivatives are determined from **captive model tests** by Sano et al. (2014)

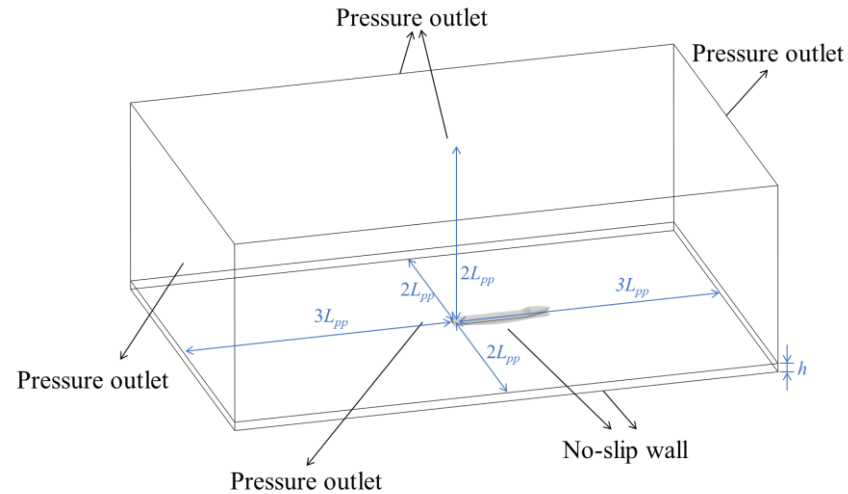
□ Advantages

- Small computational domain: low computational cost
- Not involve with multiple sets of overset domains: reduce numerical challenges
- Provide flow field results

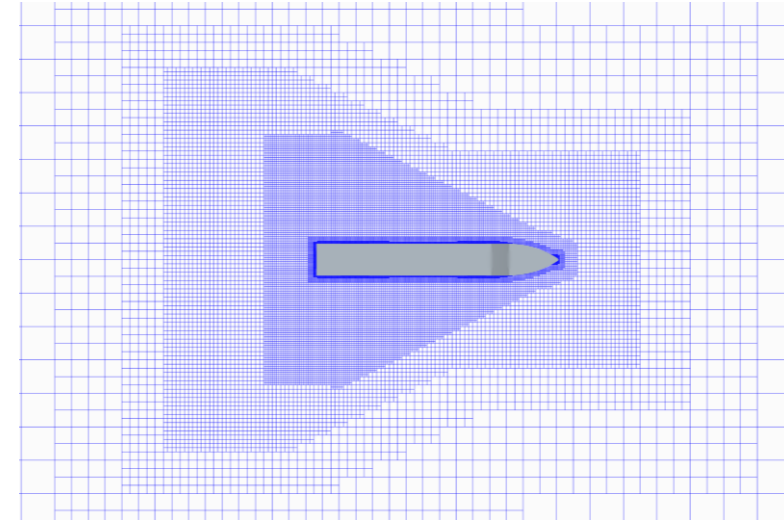
3. Numerical methods and settings



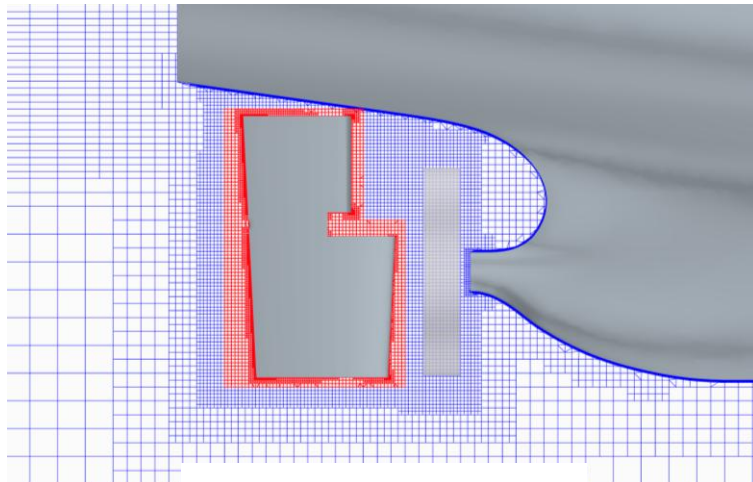
➤ Computational domain and mesh distribution



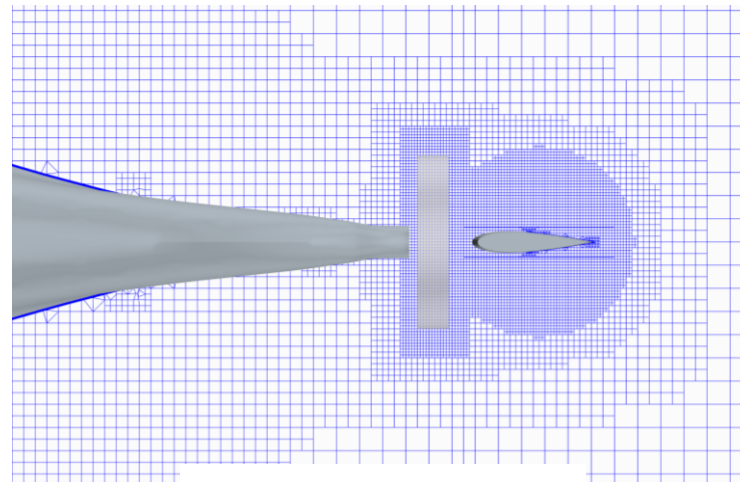
computational domain



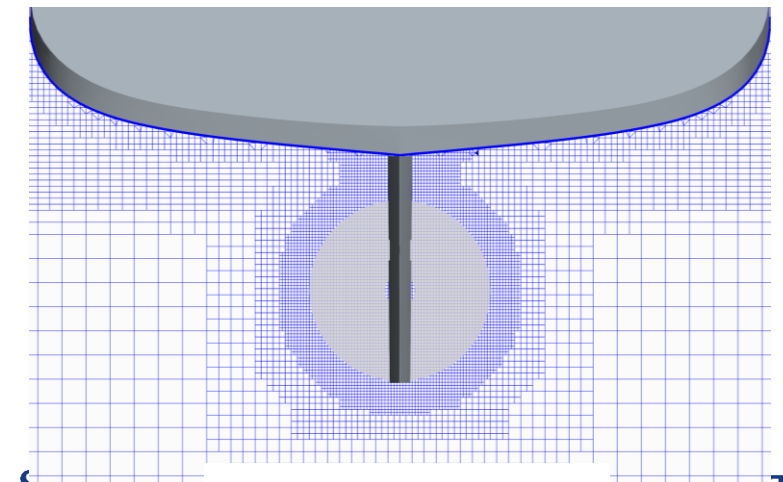
global view



local side view

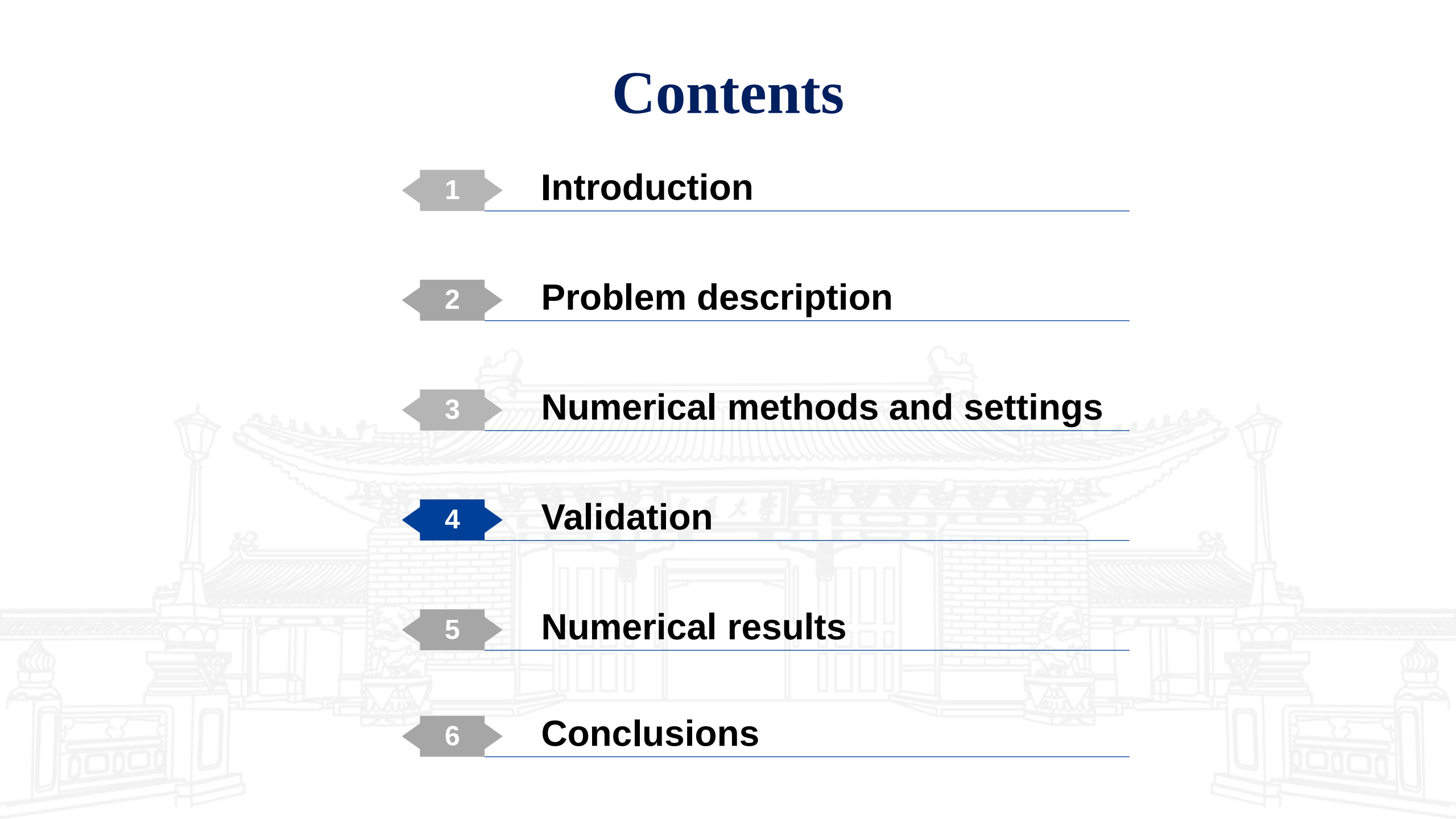


local bottom view



local stern view

Contents

- 
- 1 Introduction
 - 2 Problem description
 - 3 Numerical methods and settings
 - 4 Validation
 - 5 Numerical results
 - 6 Conclusions

4. Validation



➤ Mesh convergence study

- Select the **static rudder test** of KCS in **shallow water ($h/d = 2.0$)** by FHR
- Three sets of mesh configurations, uniform refinement ratio: $\sqrt[3]{2}$
- Number of mesh cells: 3.92 million (fine mesh), 2.49 million (medium mesh), 1.97 million (coarse mesh)
- GCI method: select **Y** and **N** at $\delta = -30^\circ$ as the numerical solutions
- The **mesh convergence** can be regarded as reasonable, the **fine mesh** is adopted in the subsequent numerical simulations

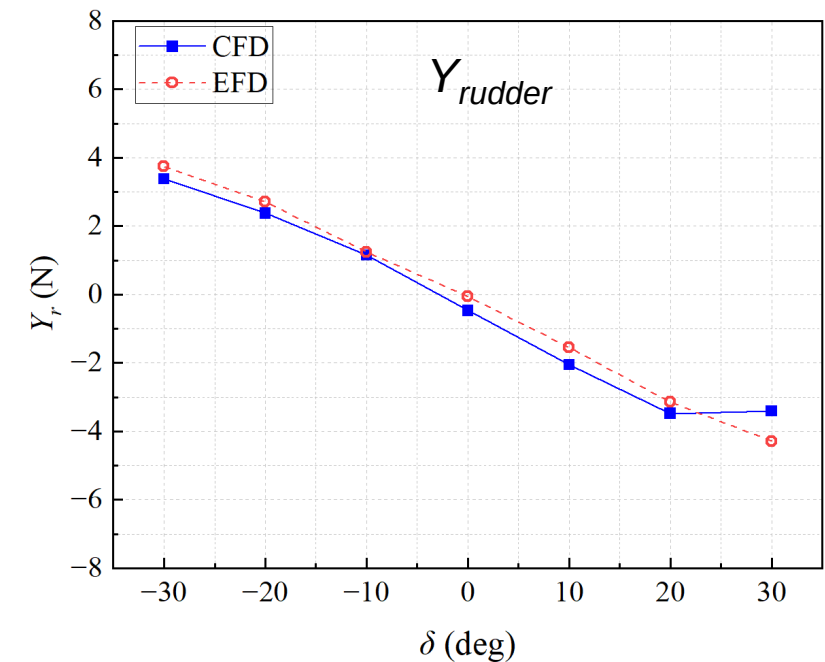
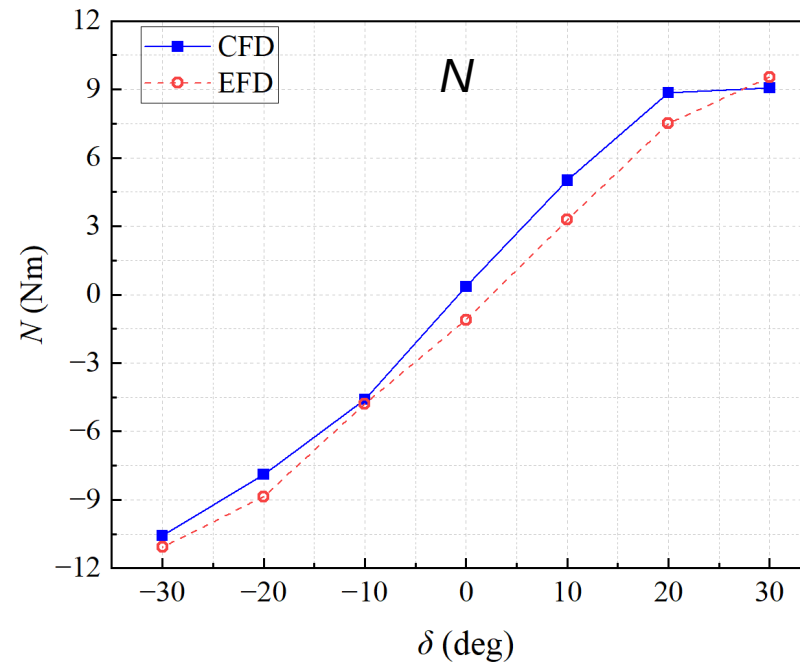
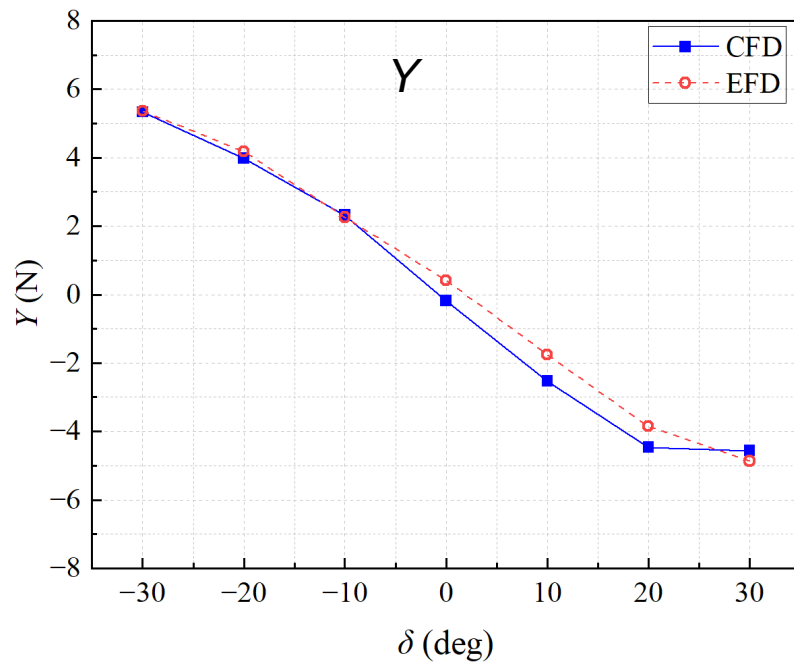
	Fine S_1	Medium S_2	Coarse S_3	Convergence ratio R	Uncertainty GCI
Y	5.33	5.39	5.46	0.86	8.16%
N	-10.56	-10.63	-10.76	0.59	1.29%

4. Validation

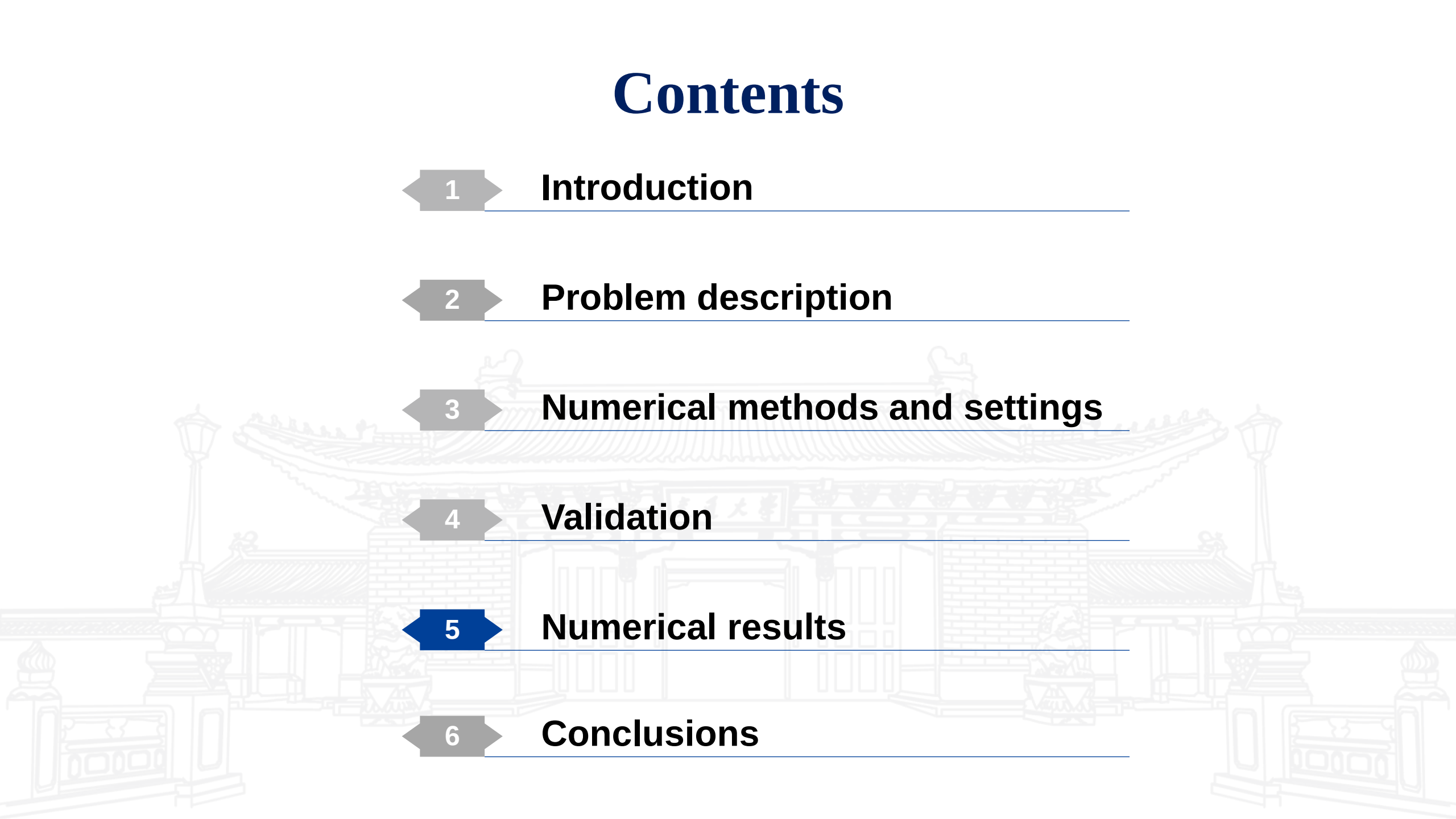


➤ Comparison with test data

- $\delta = \pm 30^\circ, \pm 20^\circ, \pm 10^\circ, 0^\circ$
- Numerical results **agree well** with the test data
- Numerical model applied in this paper is reliable



Contents

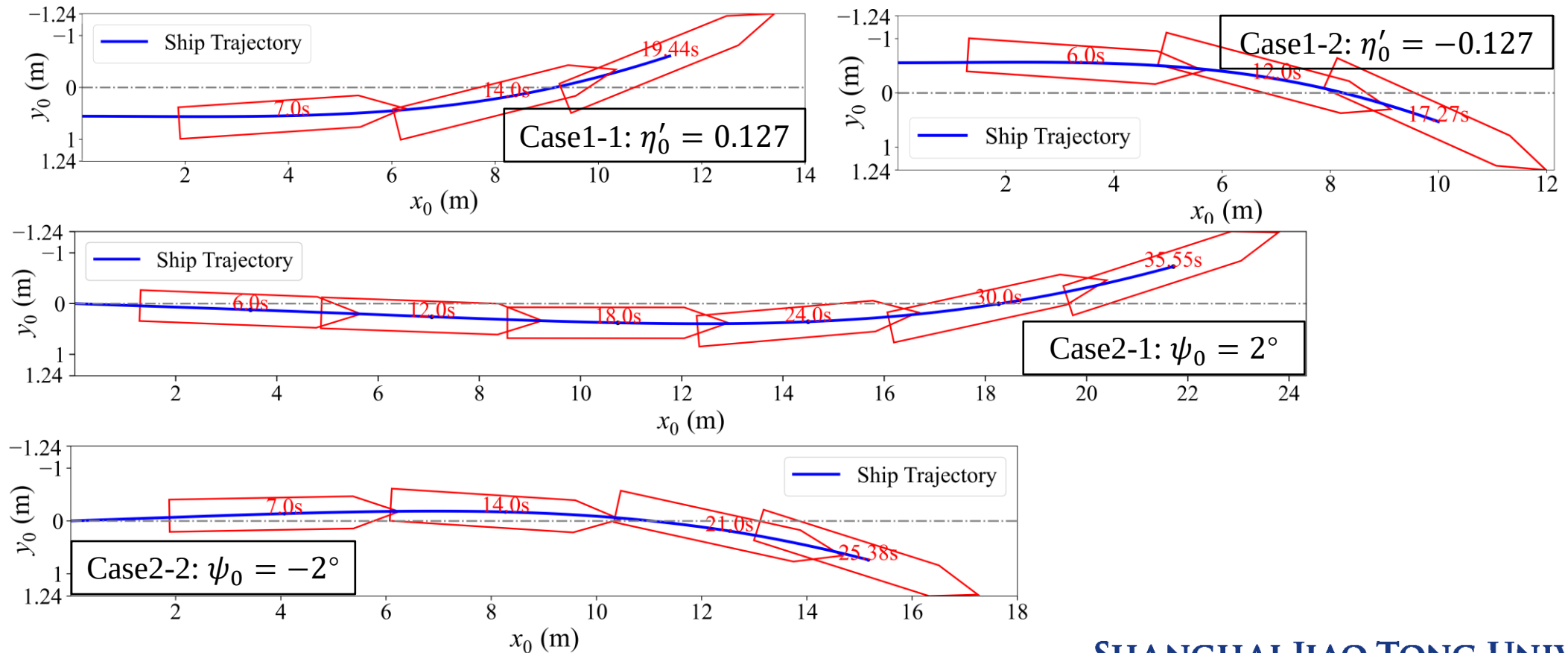
- 
- 1 Introduction
 - 2 Problem description
 - 3 Numerical methods and settings
 - 4 Validation
 - 5 Numerical results
 - 6 Conclusions

5. Numerical results



➤ Navigation in confined waterways without control

- the initial disturbances will **lead to ship collisions** with the waterway bank
- the applied virtual bank method **effectively models** the bank effects

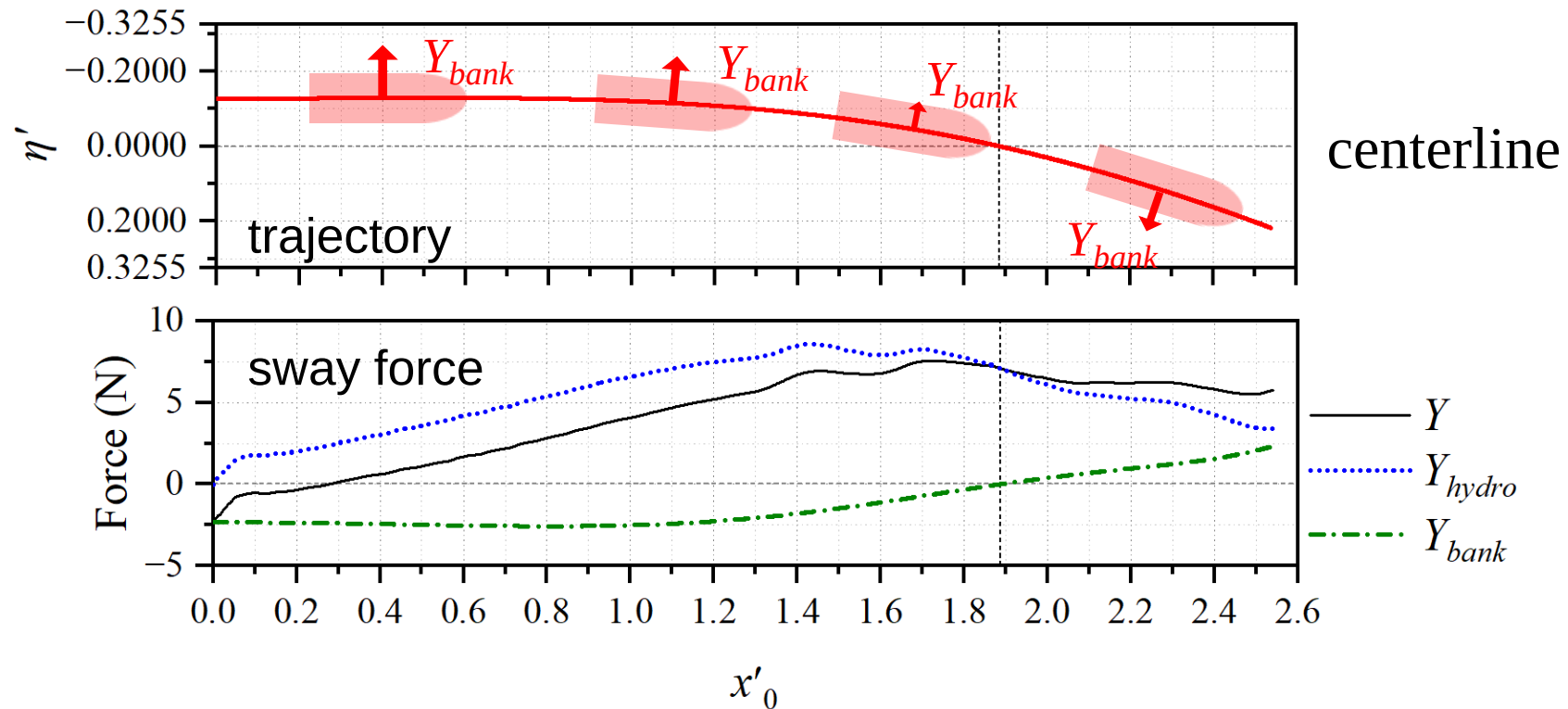


5. Numerical results



➤ Navigation in confined waterways without control

Case1-2: $\eta'_0 = -0.127$



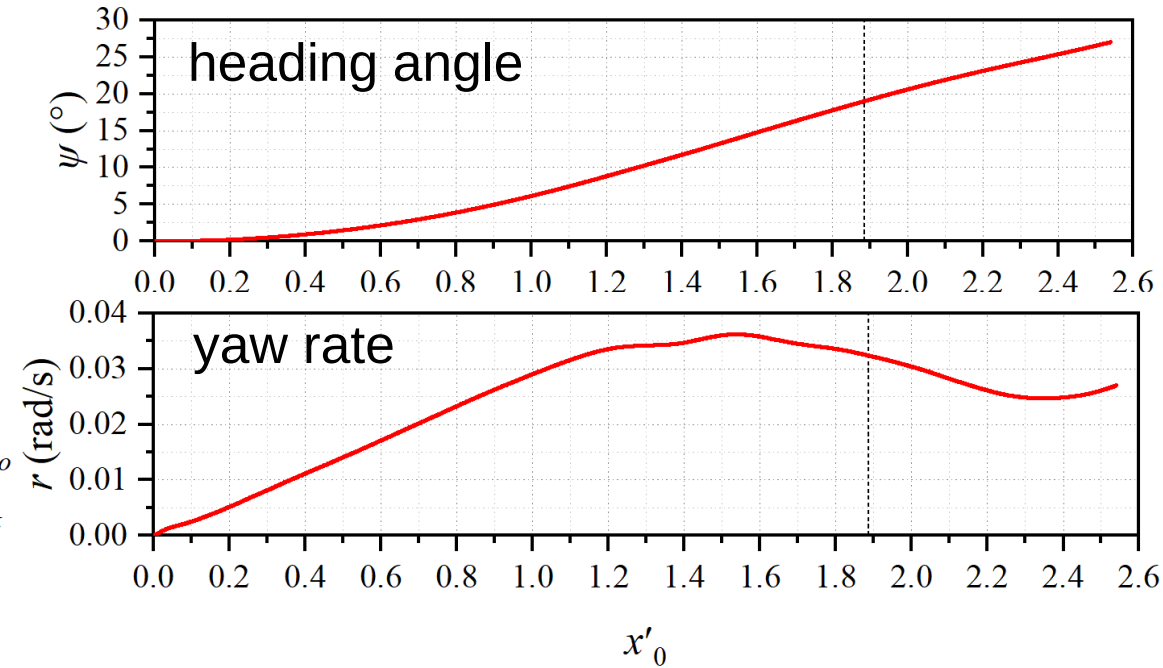
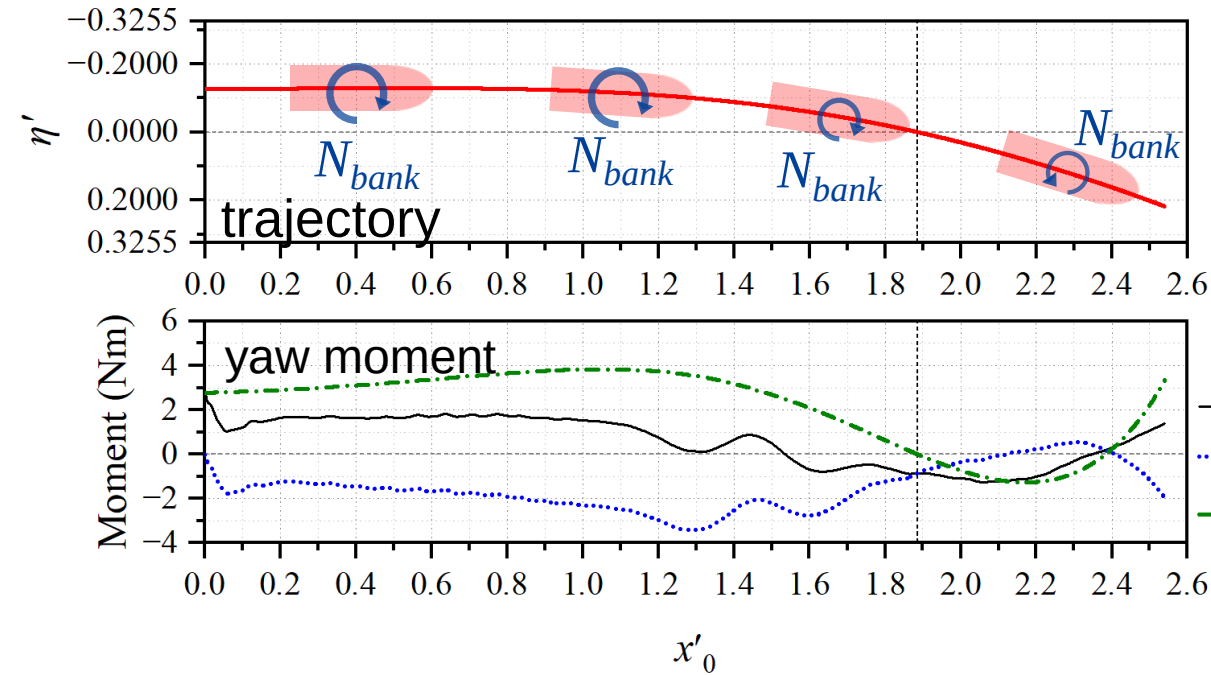
- Y_{bank} **attracts** the ship toward the closer bank wall

5. Numerical results



➤ Navigation in confined waterways without control

Case1-2: $\eta'_0 = -0.127$



- N_{bank} **repels** the bow far away from the closer bank wall
- N_{bank} **dominates** during the whole process, causing **consistently positive** r and **continuously increasing heading angle** ψ

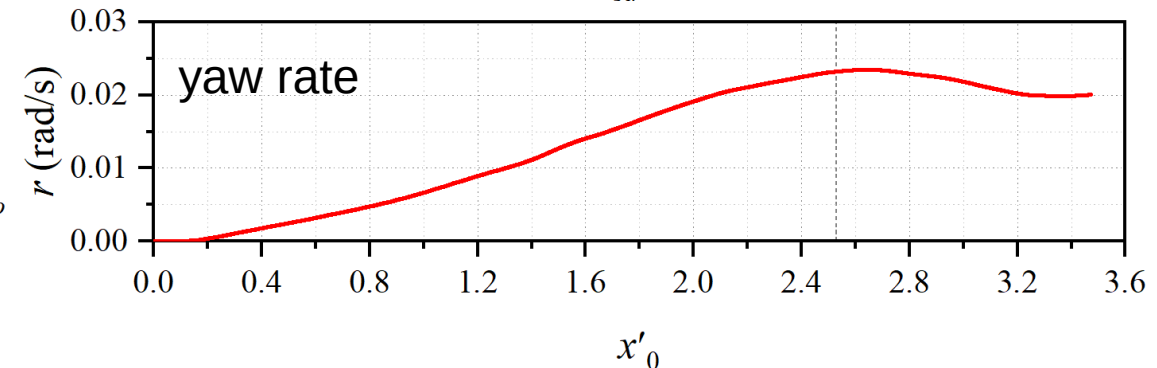
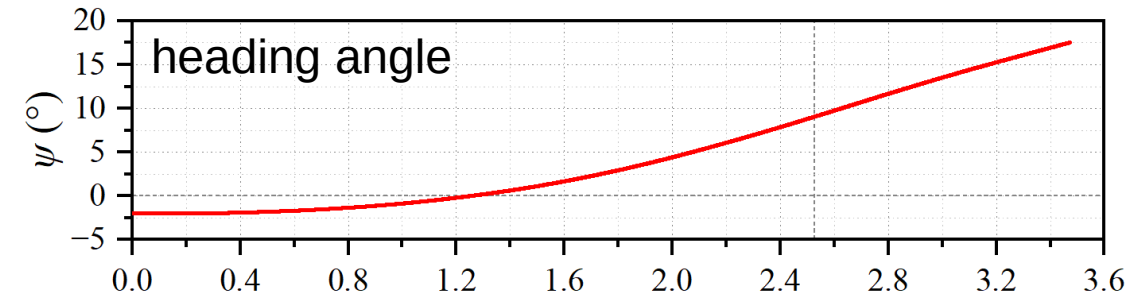
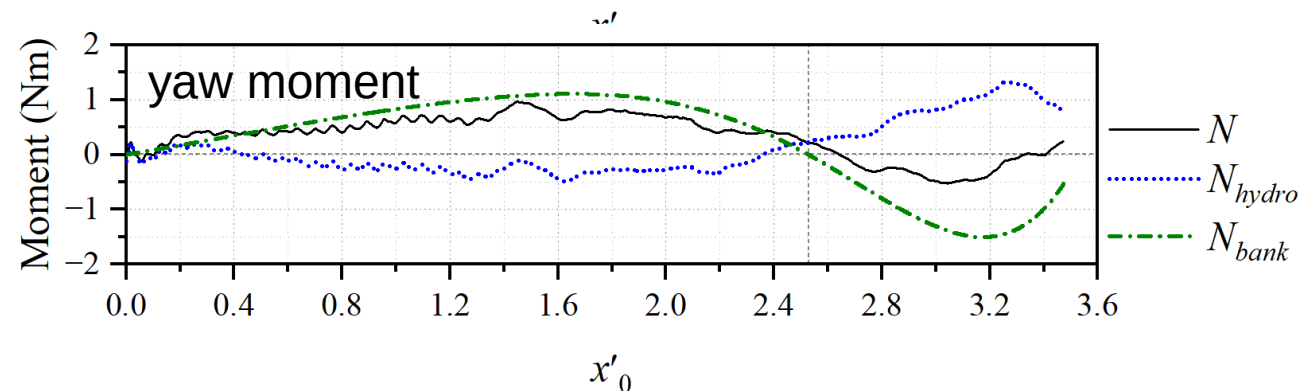
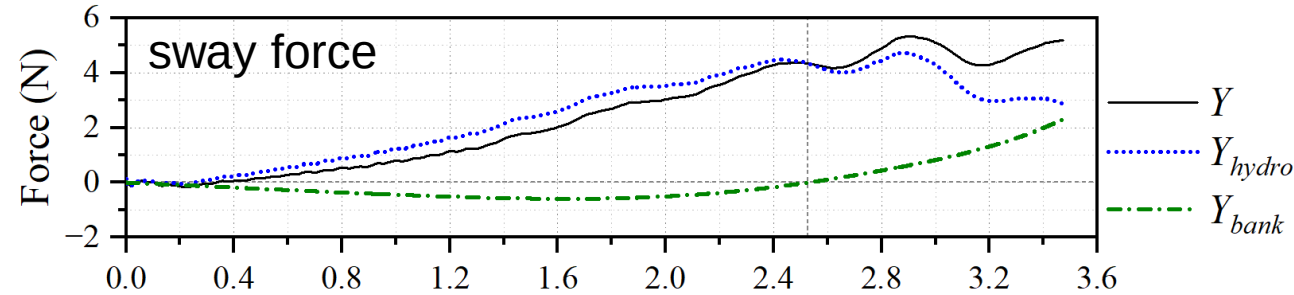
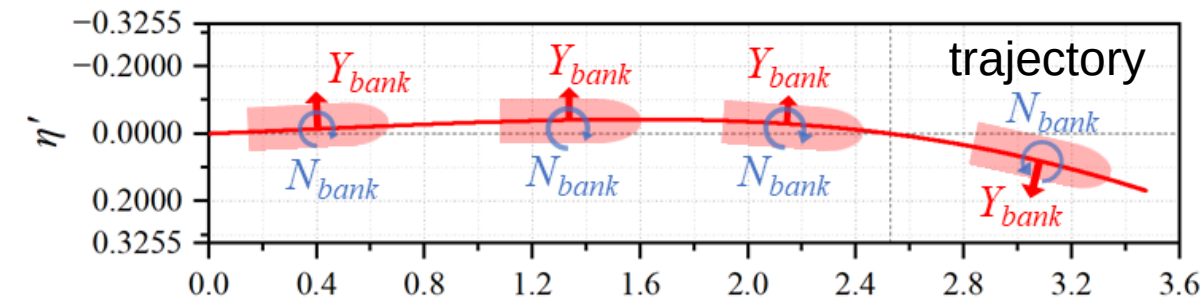
5. Numerical results



➤ Navigation in confined waterways without control

Case2-2: $\psi_0 = -2^\circ$

- N_{bank} is the **major factor** causing the ship collision with the bank wall



➤ Navigation in confined waterways with control

- Above results demonstrate that the **course-keeping** in confined waterways is significant
- Rudder angle is controlled by a Proportional-Derivative (PD) algorithm to maintain the heading angle close to 0

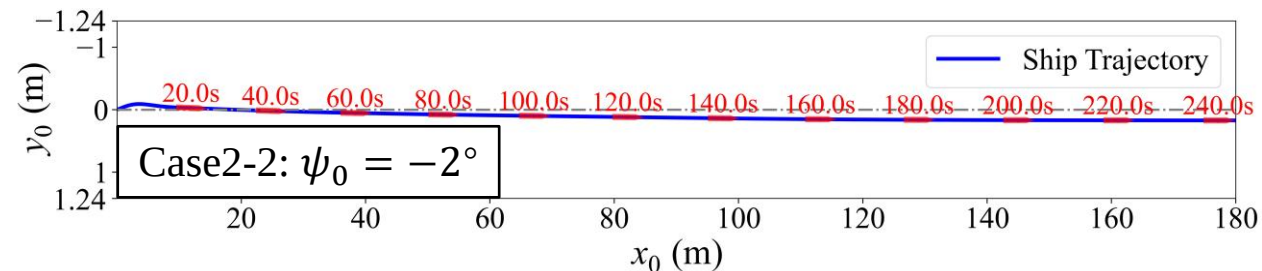
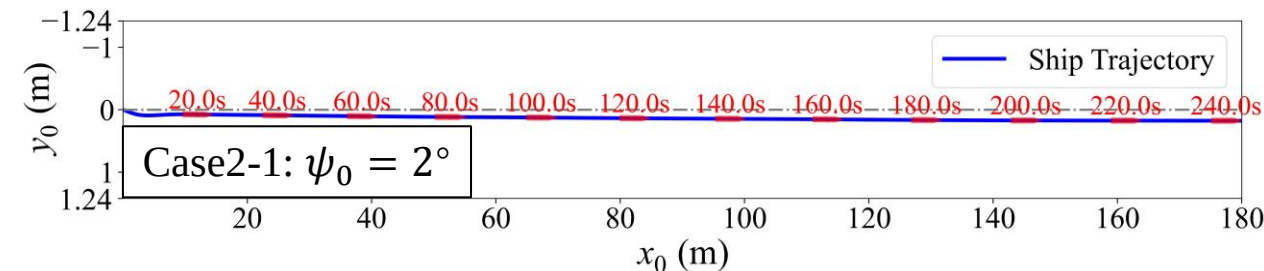
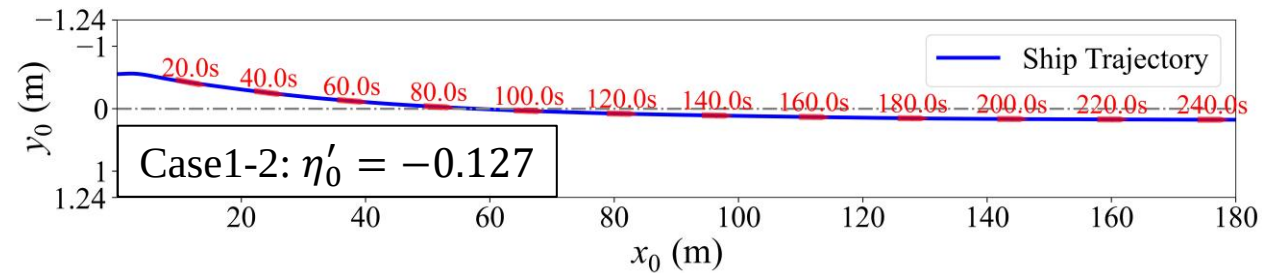
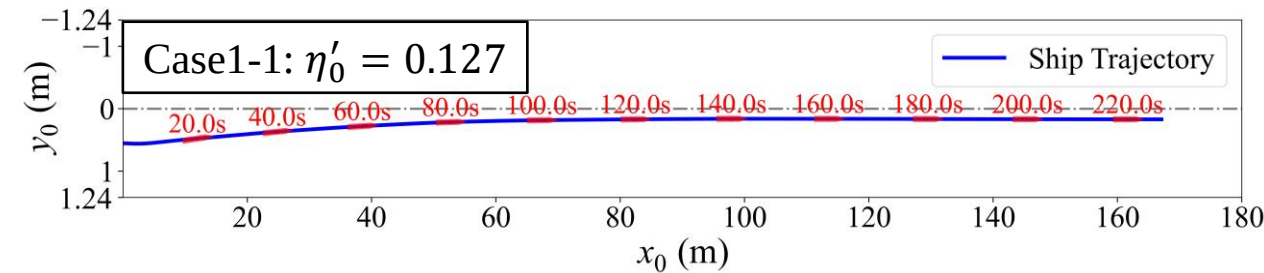
$$\delta = -K_p \psi - K_d r$$

5. Numerical results



➤ Navigation in confined waterways with control

- all cases achieve course-keeping
- after approximately 150s, the trajectories stabilize into **quasi-linear paths**
- A **constant deviation** from centerline: ship course deviates by approximately a certain distance (0.2 m) from the centerline



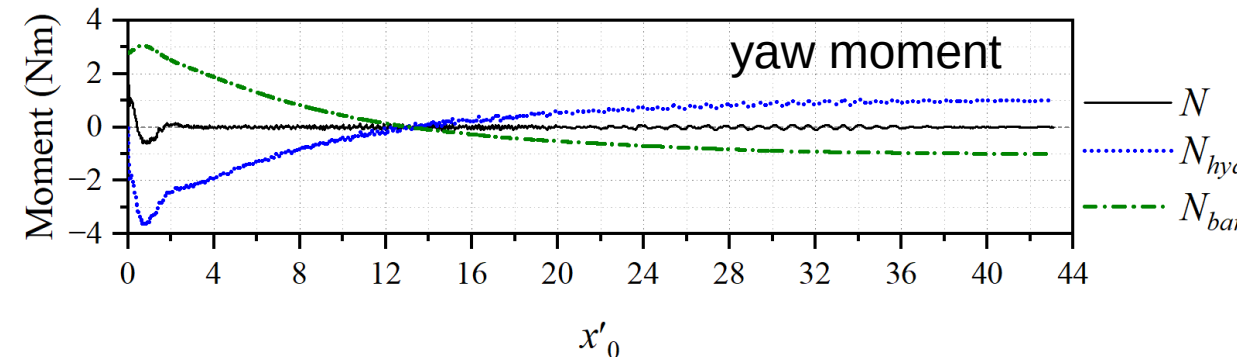
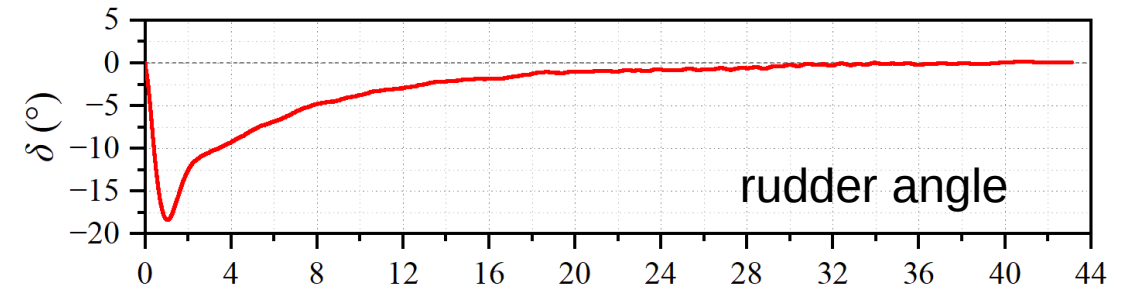
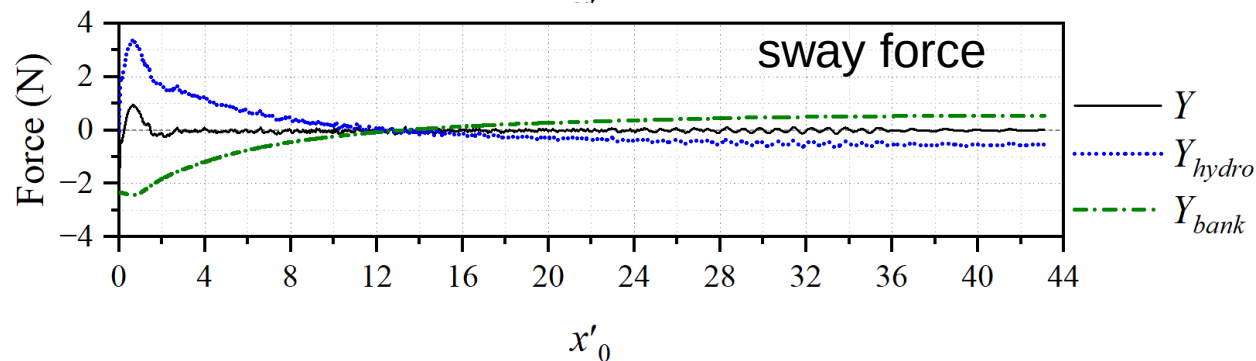
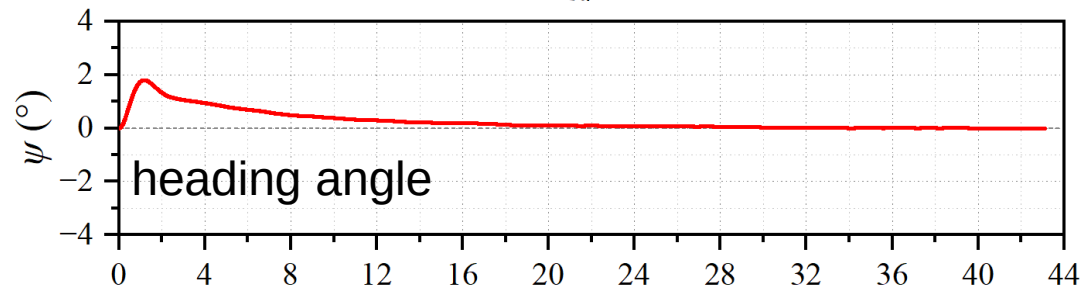
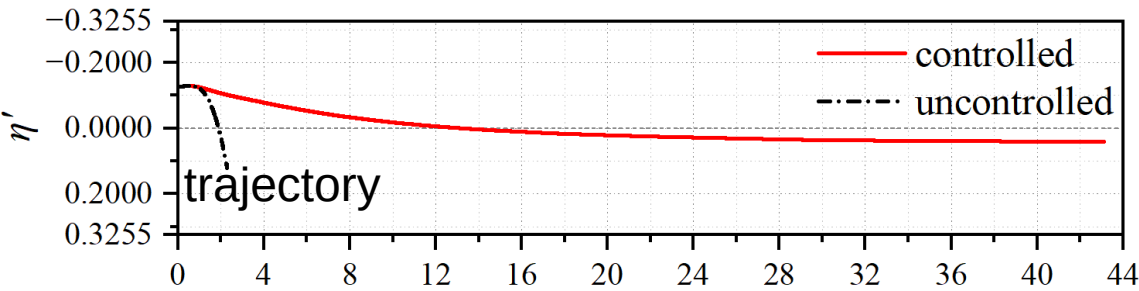
5. Numerical results



➤ Navigation in confined waterways with control

Case1-2: $\eta'_0 = -0.127$

- **significant rudder deflection** during the initial phase to control the heading angle

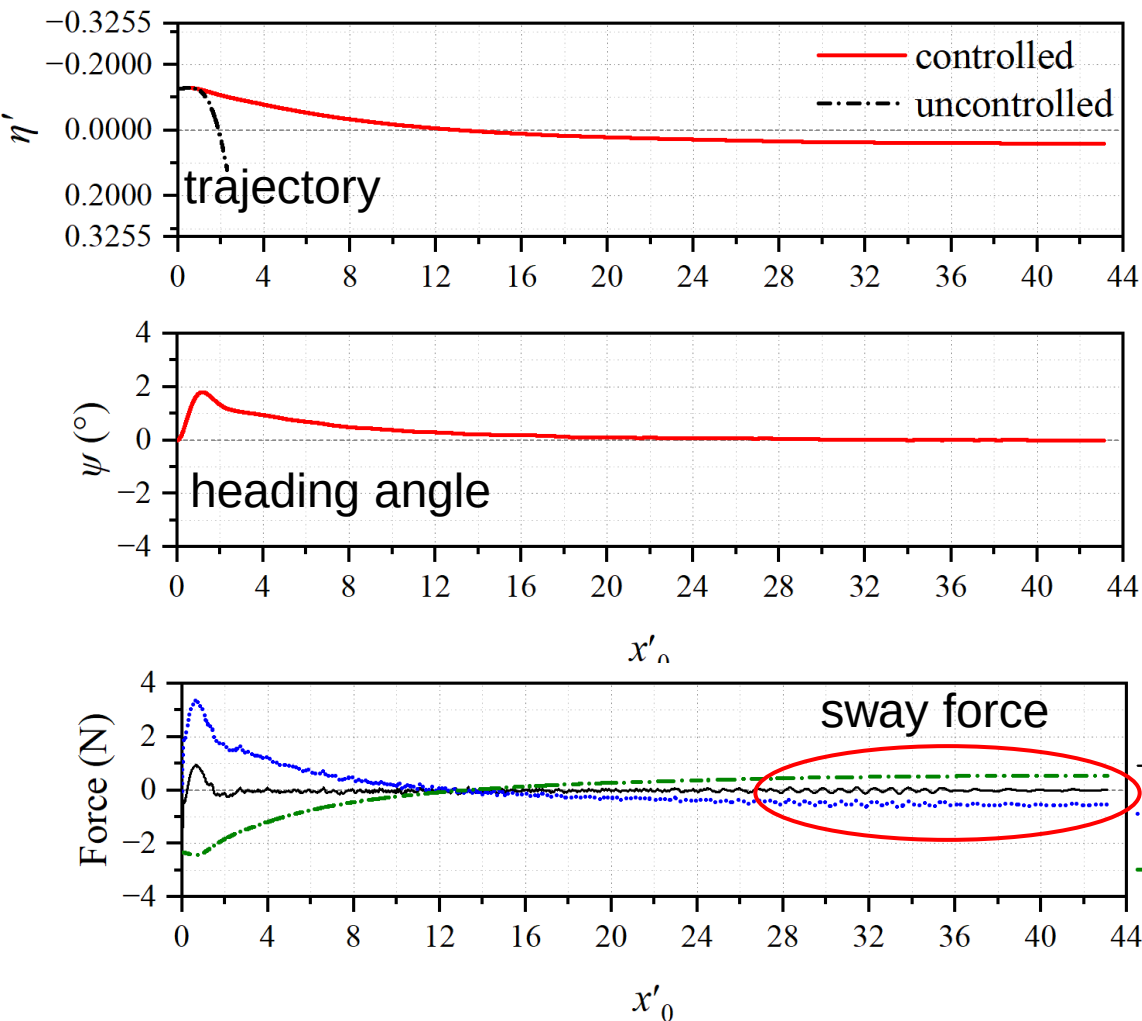


5. Numerical results

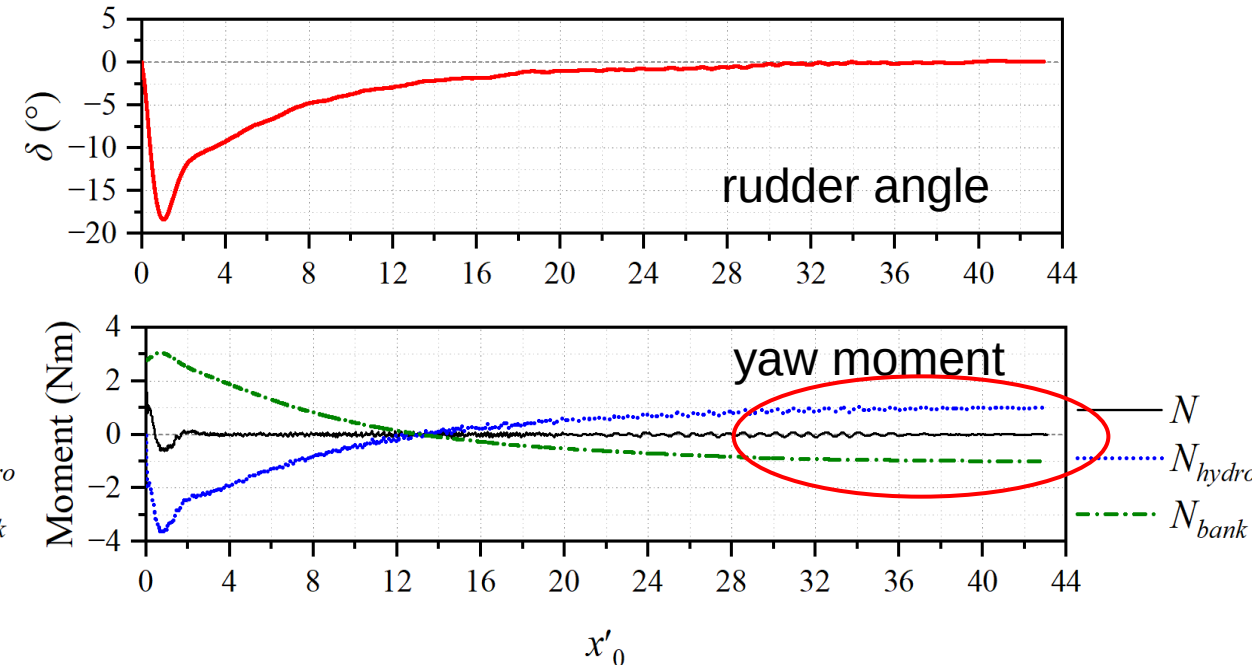


➤ Navigation in confined waterways with control

Case1-2: $\eta'_0 = -0.127$



- **two pairs of stable** sway forces (Y_{hydro} and Y_{bank}) and yaw moments (N_{hydro} and N_{bank}) have nearly **equal magnitudes but opposite directions**

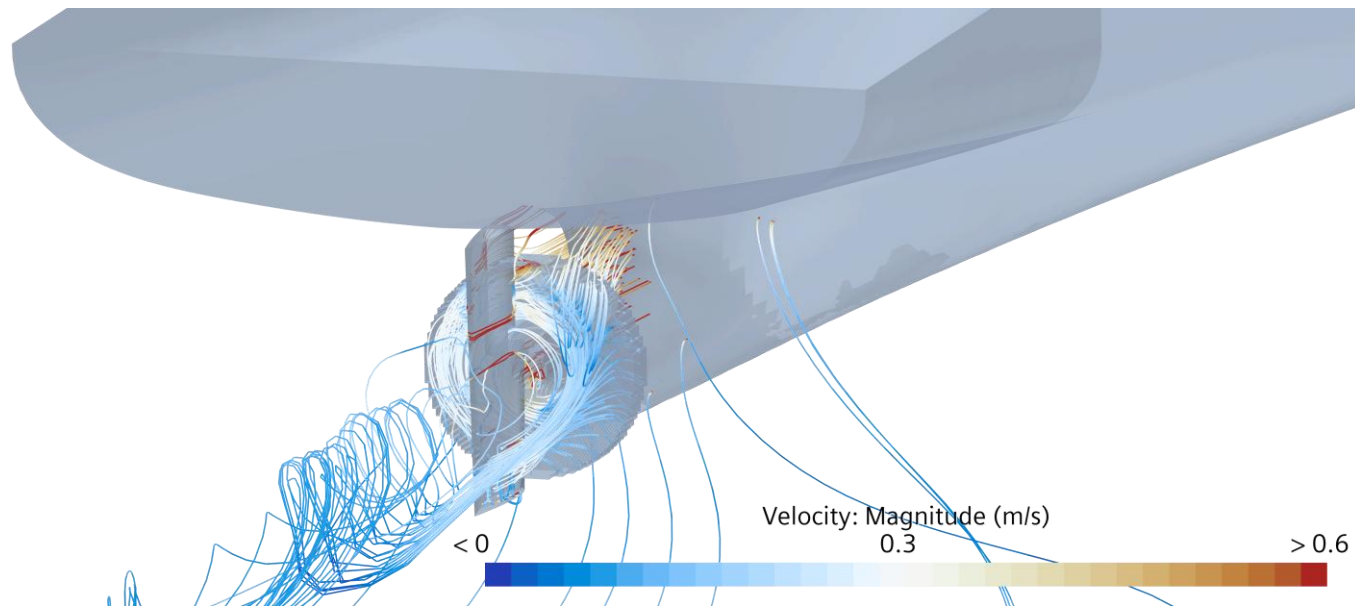


5. Numerical results

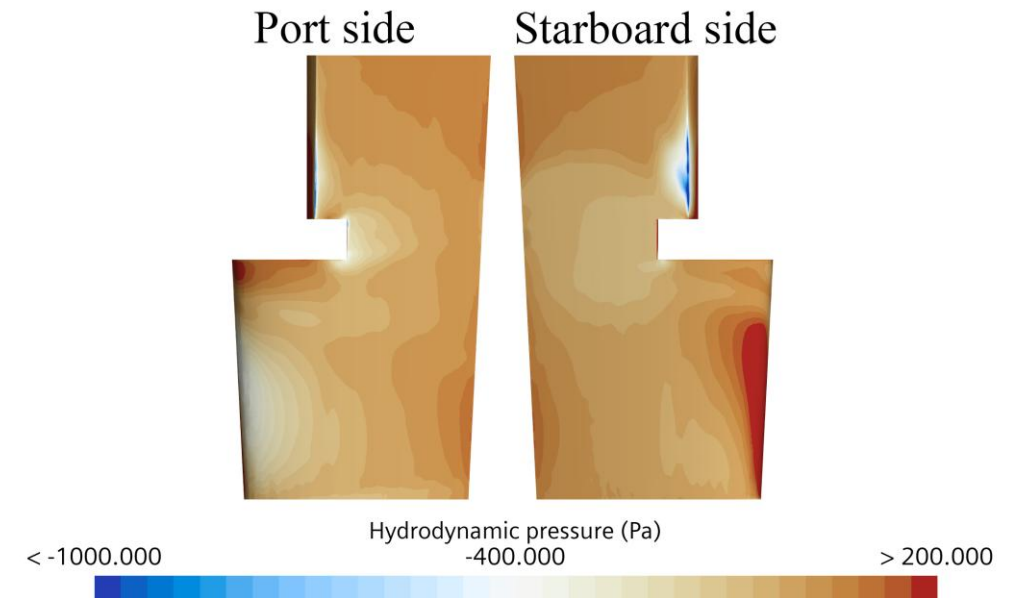


➤ Flow fields in the stabilized phase

- The rotating propeller generates a **circumferential flow downstream** passing the rudder
- The asymmetric flow leads to an **imbalance in the pressure distributions**
- The ship experiences **additional sway force Y_{hydro}** and **yaw moment N_{hydro}** in straight-ahead motions even without the rudder angle and drift angle

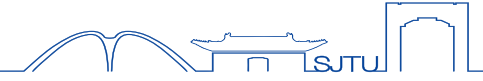


streamlines around rudder



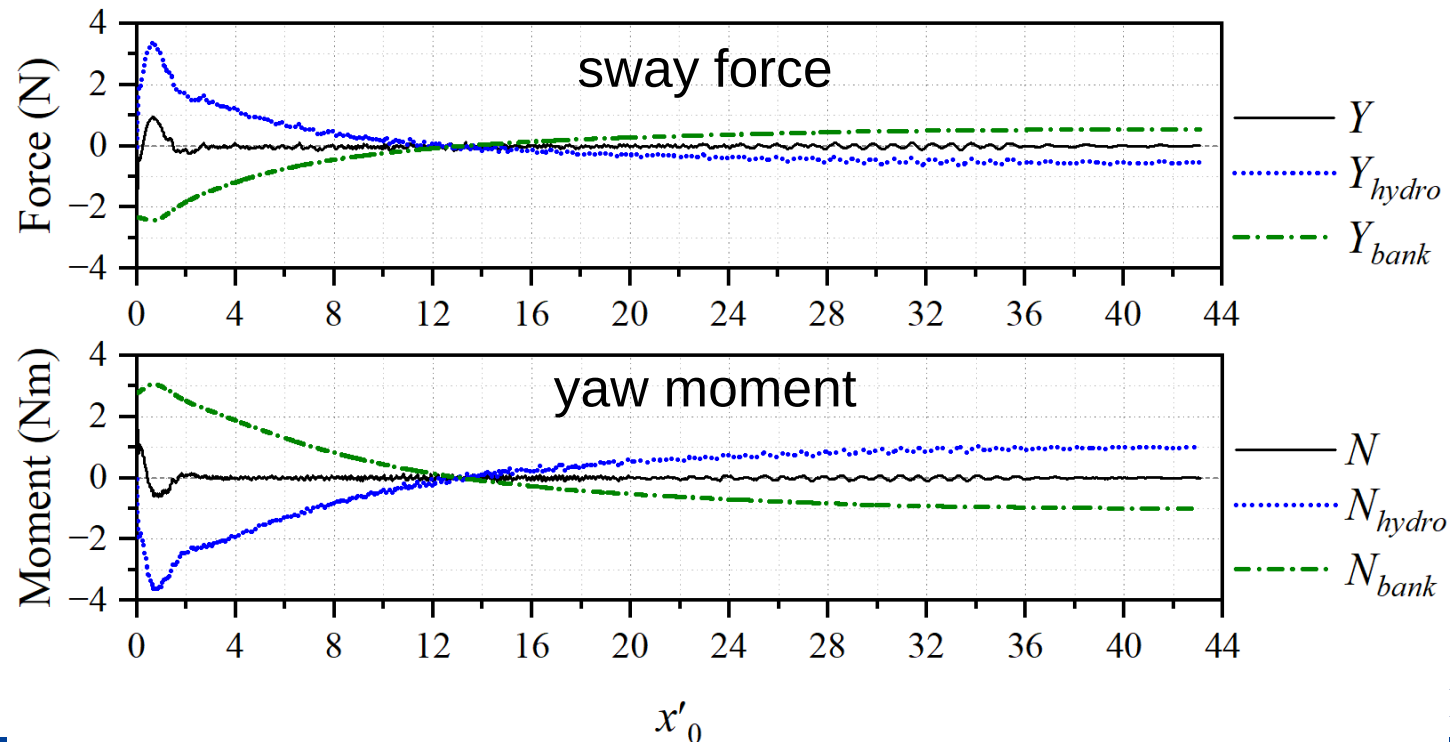
pressure distribution on rudder

5. Numerical results



➤ Navigation in confined waterways with control

- The ship experiences **additional rudder force Y_{hydro}** and **moment N_{hydro}** in straight-ahead motions (without rudder angle and drift angle for course-keeping purpose)
- The ship is forced to slightly deviate from the centerline to generate the **bank force Y_{bank}** and **moment N_{bank}** to **counterbalance rudder force and moment**, causing resultant sway force Y and yaw moment N to be 0

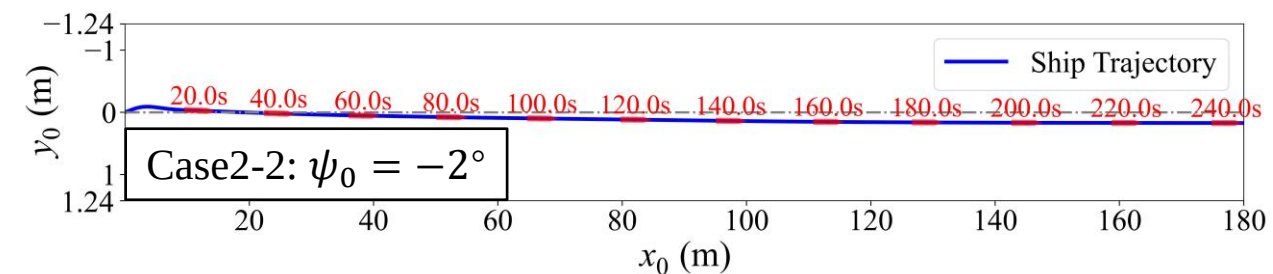
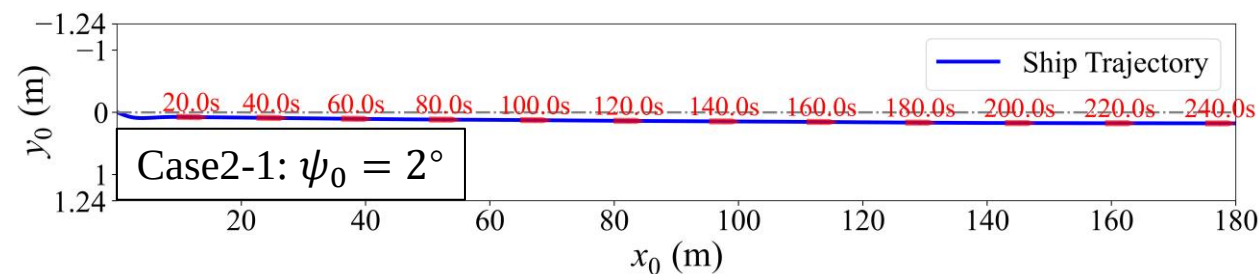
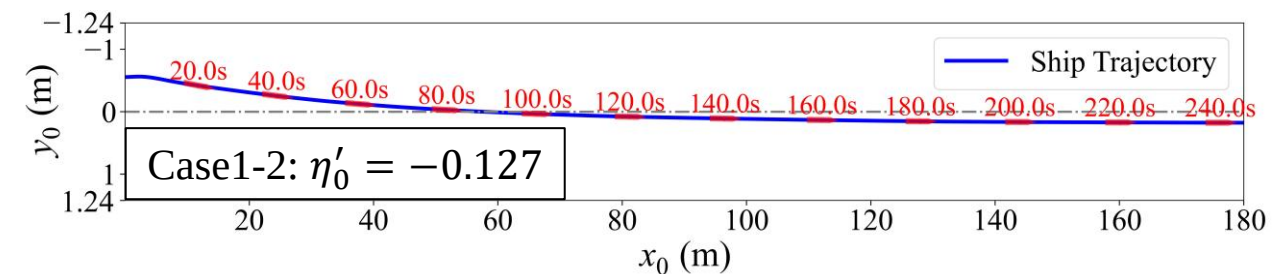
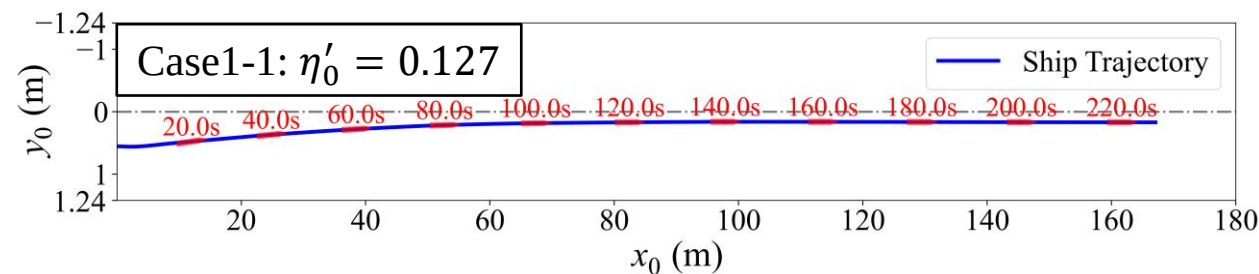


5. Numerical results

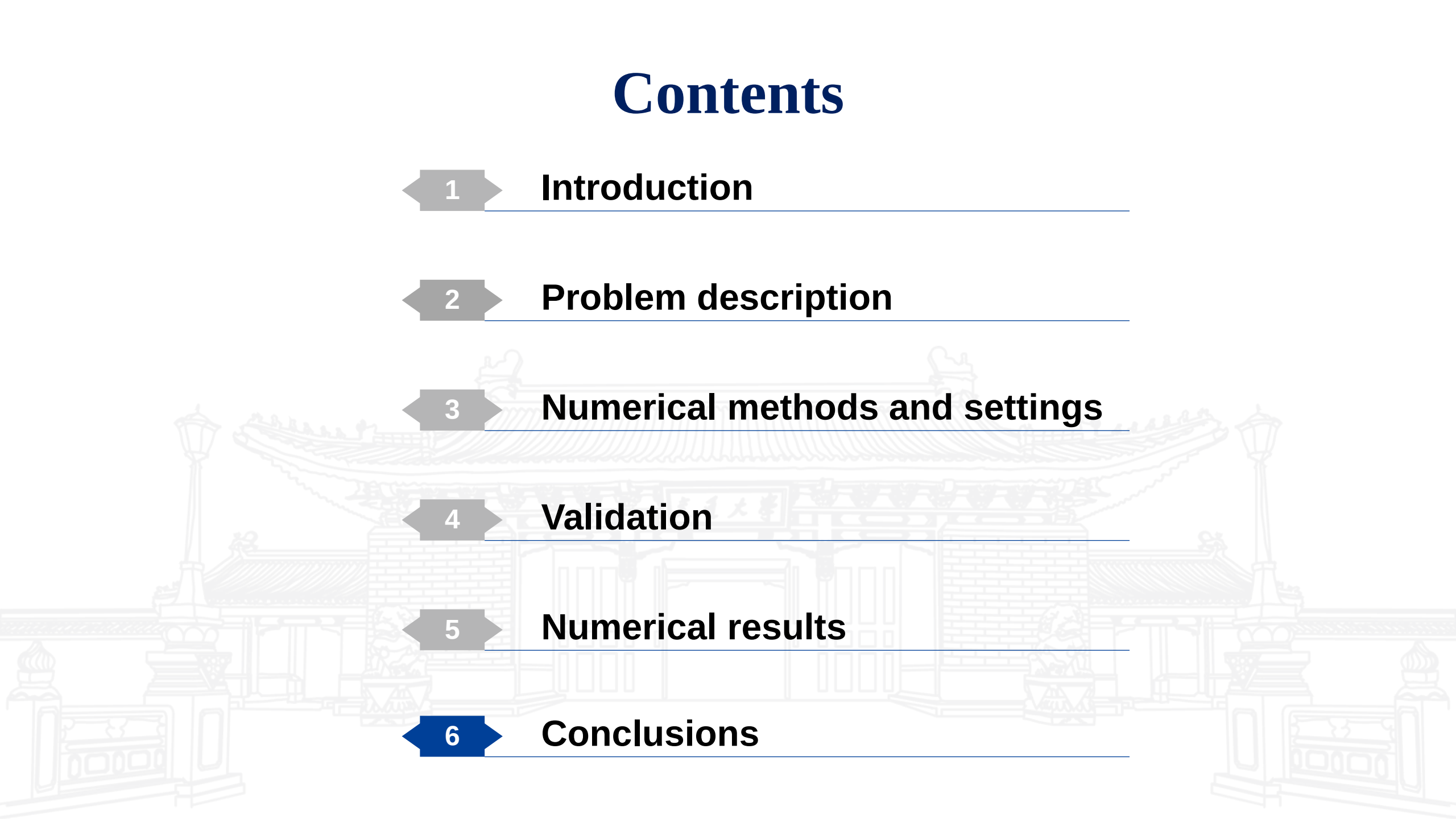


➤ Navigation in confined waterways with control

- The applied control algorithm for course-keeping only aims to **maintain the heading angle close to 0**, but the **deviation from the centerline is not considered**
- The **movement along the centerline or specified paths** in confined waterways is significant for navigation safety
- The application of the additional module: **LOS (line of sight) guidance law**



Contents

- 
- 1 Introduction
 - 2 Problem description
 - 3 Numerical methods and settings
 - 4 Validation
 - 5 Numerical results
 - 6 Conclusions

6. Conclusion



- Ship **course-keeping control** is **directly simulated** using CFD method in this paper.
- To **address the challenges** in traditional free-running simulations, this study develops a **virtual bank method** to simplify the modeling of bank wall effects
- Two types of scenarios with **initial disturbances** are investigated: one is the ship navigating with an **initial off-centerline displacement**, and the other is the ship navigating with an **initial heading angle**
- The simulation results demonstrate that, the ship without the rudder control will deviate from the desired course and ultimately collide with the waterway bank, where N_{bank} is the **major factor**.
- The navigation with the rudder control **successfully achieves course-keeping**
- The **asymmetrical flow** induces additional force and moment without rudder angle, forcing the ship to deviate from the centerline slightly. This deviation allows the bank-induced force and moment to **counterbalance** the rudder force and moment, to achieve course-keeping purpose.



SHANGHAI JIAO TONG
UNIVERSITY

Flanders
Hydraulics



Flanders
State of the Art



Thanks for your kind attention !

