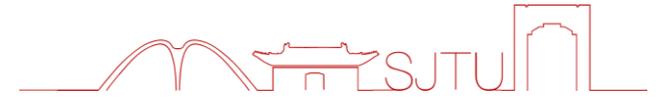




上海交通大学  
SHANGHAI JIAO TONG UNIVERSITY



# 环境水动力学数值模型研究及应用

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饮水思源 · 爱国荣校



**研究背景**

**研究内容**

**研究成果**



# ➤ 研究背景

## ➤ 三山、六水、一分田

- ◆ 地表大面积被水体覆盖，海洋
- ◆ 海岸带、河流、湖泊甚至地下水系



## ➤ 流水不腐

- ◆ 运动的水体是生态系统健康的保障
- ◆ 运动的水体是物质运输的载体



## ➤ 文明发展的摇篮

- ◆ 人类文明发源于古老的河系
- ◆ 促进现代经济社会的发展



# 研究背景



海洋工程、海岸工程、水利工程、水环境工程等的基础问题——水动力学、流固耦合动力学、多物理（化学）过程耦合：调查、反演、推理



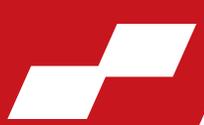


## 浅水流动特征

- ◆ 通常时空尺度较大，且水平流动尺度通常远大于垂向流动尺度
- ◆ 岸线、底床非规则几何边界
- ◆ 风、浪、流、传质、传热多尺度物理过程的耦合

## 数值模拟需求

- ◆ 高精度反演相关物理过程，完成实验所不能
- ◆ 关键动力因素的提取与机理溯源分析
- ◆ 时空尺度的限制需要数值模拟兼顾精度与效率



## 非静压模型 (Non-hydrostatic model)

理论基础：压力分解

数值方法：预估-校正数值求解方法

本质：等同于NS方程模型，但关于压力计算的分解使得求解效率提高

### 发展及应用

Jankowski (1999), Casulli (1999,2002), Kocyigit et al. (2002), Fringer et al.(2006), Zijlema&Stelling(2008), Tamazaki(2009), Zhang et al. (2006,2014,2021), 《非静压水波模型理论及应用》

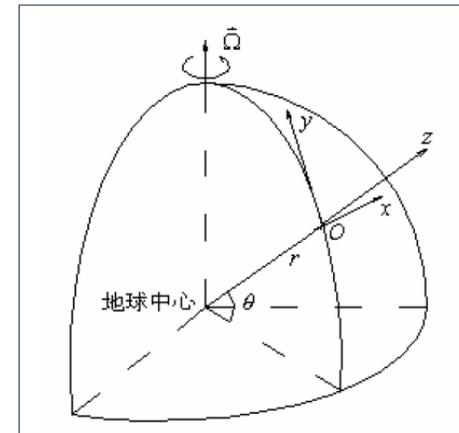
$$\frac{\partial V}{\partial t} + V \cdot \nabla V = -\frac{1}{\rho} \nabla p + g - \Omega \times V + \nu \nabla^2 V$$

压力分解

$$p = p_H + p_n$$

静压

动压

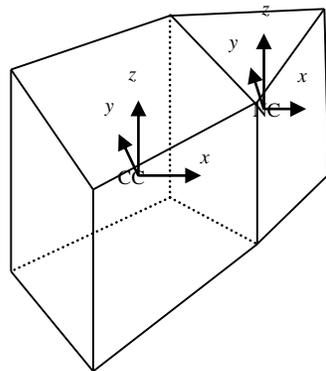
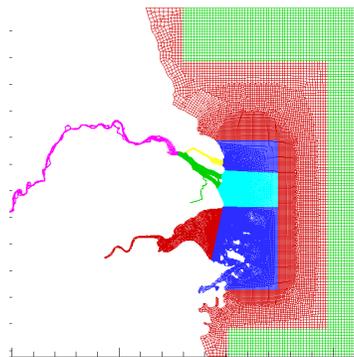
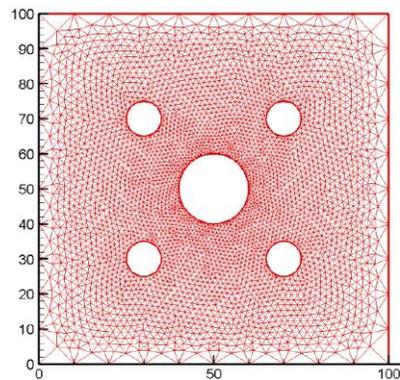




# ➤ 研究内容——仿真系统研发



- 非结构混合网格
- FVM数值方法
- 高阶离散格式 (2<sup>nd</sup> TVD、5<sup>th</sup> WENO离散格式.....)
- 湍流模式——SA、 $k-\epsilon$ 、SST  $k-\omega$ 、DES、LES
- 流固耦合模型——DEM-CFD、IBM-CFD、ETR-CFD(Elastic thin rod)、变密度流.....
- MPI/OpenMP混合并行计算

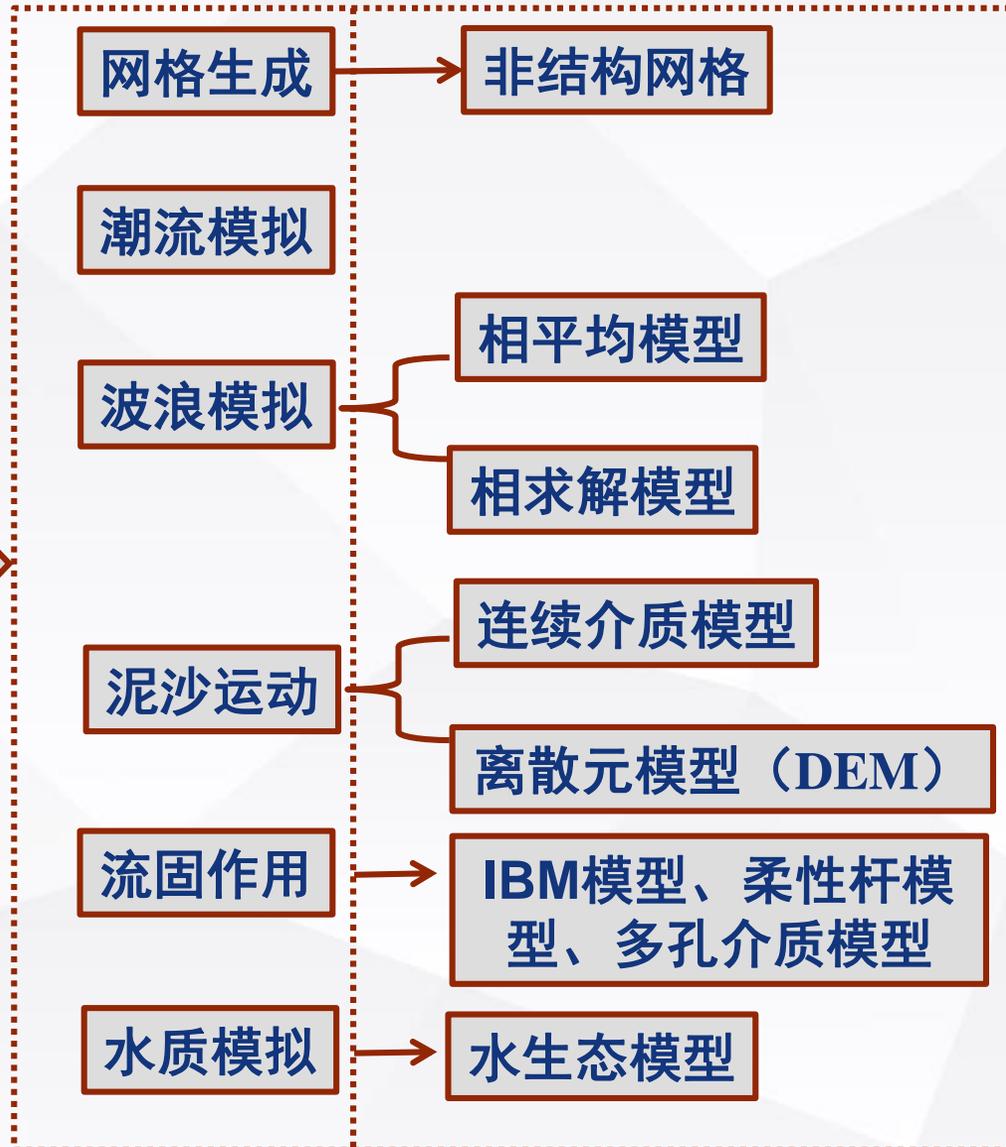




# 研究内容——仿真系统研发

## 计算软件系统

计算模块



### 运行环境

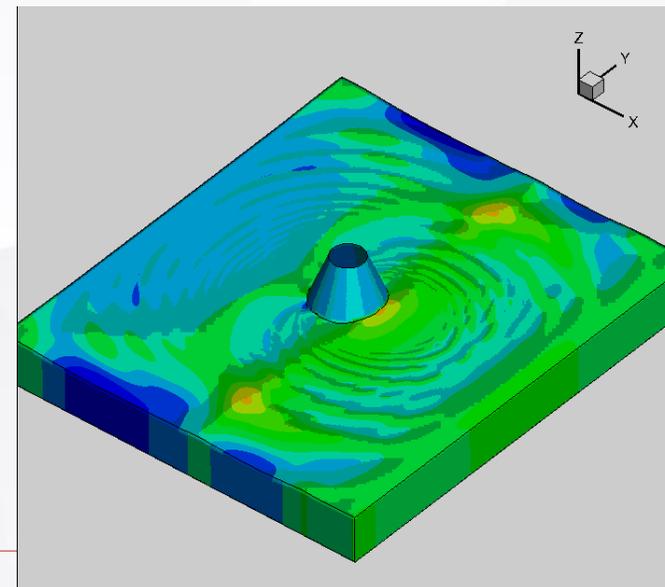
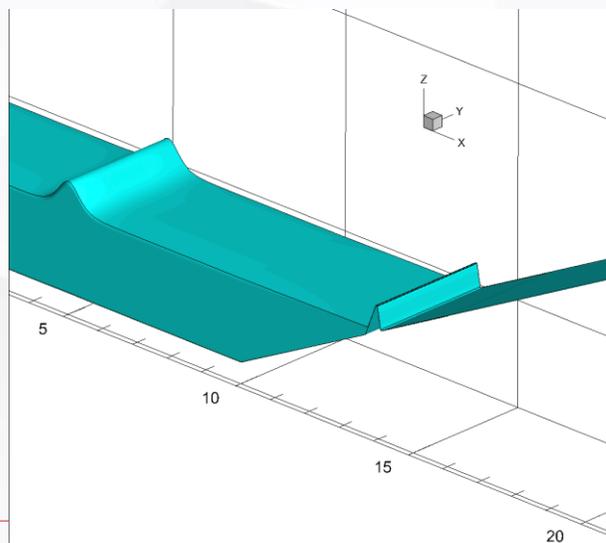
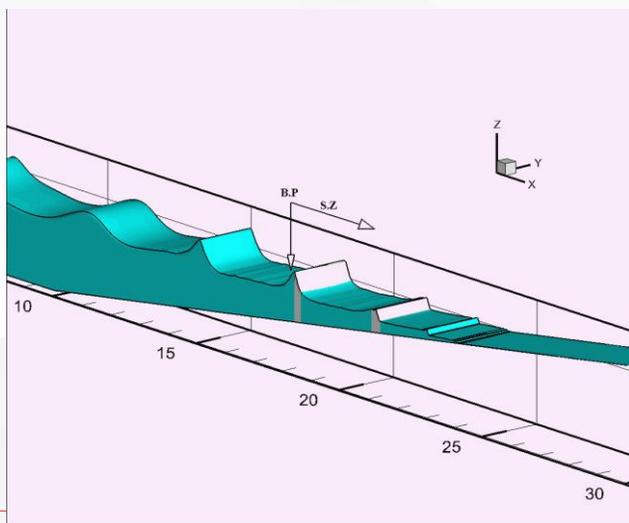
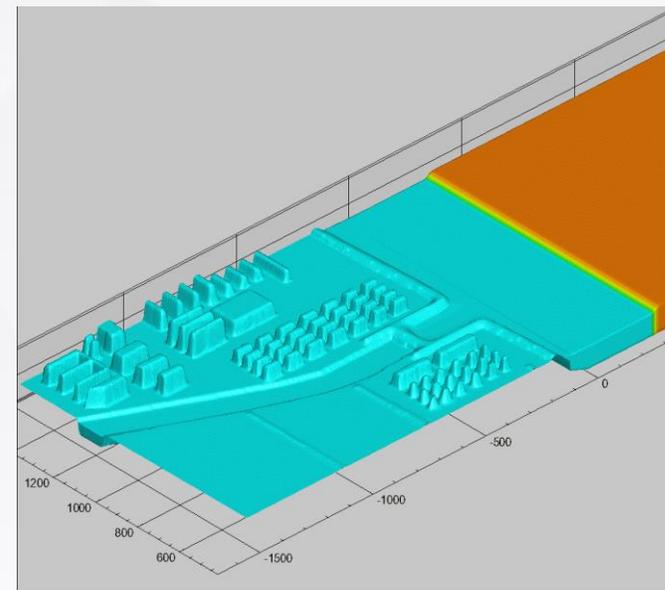
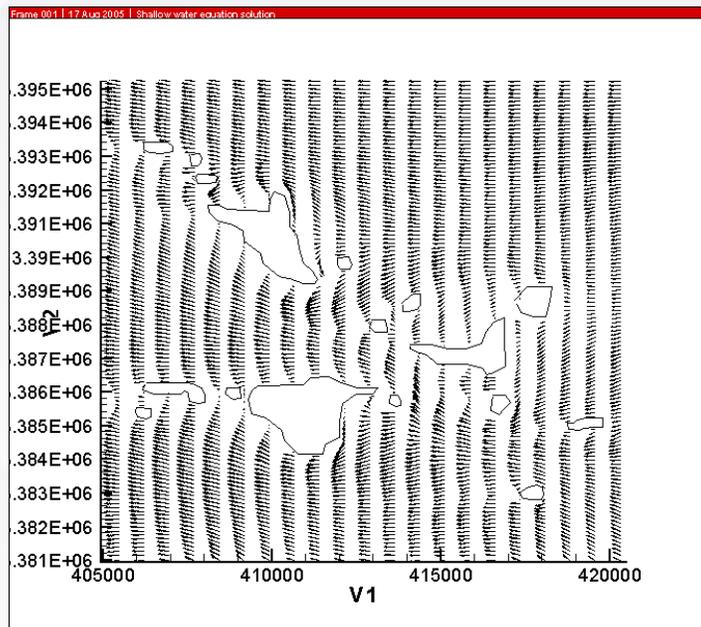
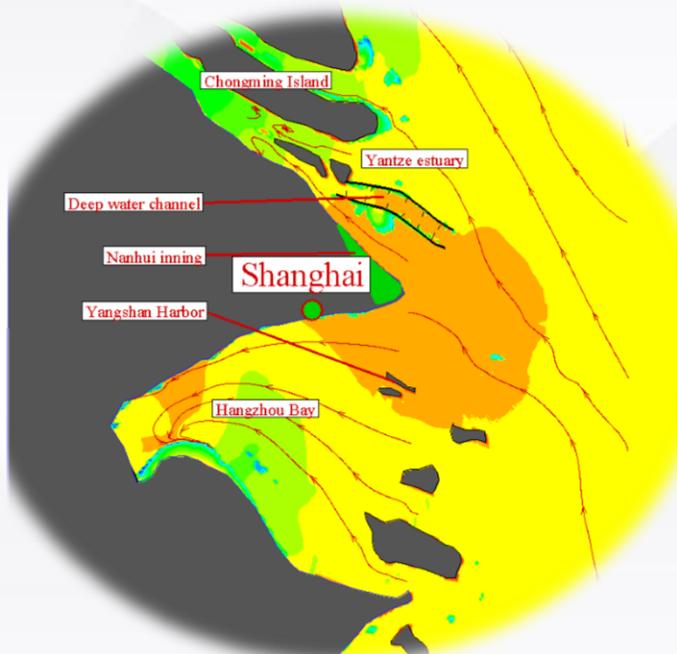
- Windows
- Linux

### 并行计算

- OpenMP
- MPI&OpenMP

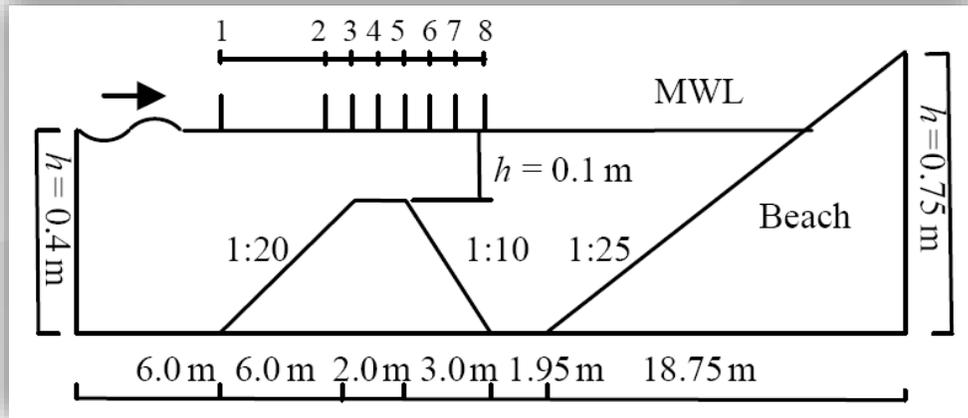


# 研究内容及应用 I：近海波浪数值模拟





# 研究内容及应用 II：水利工程



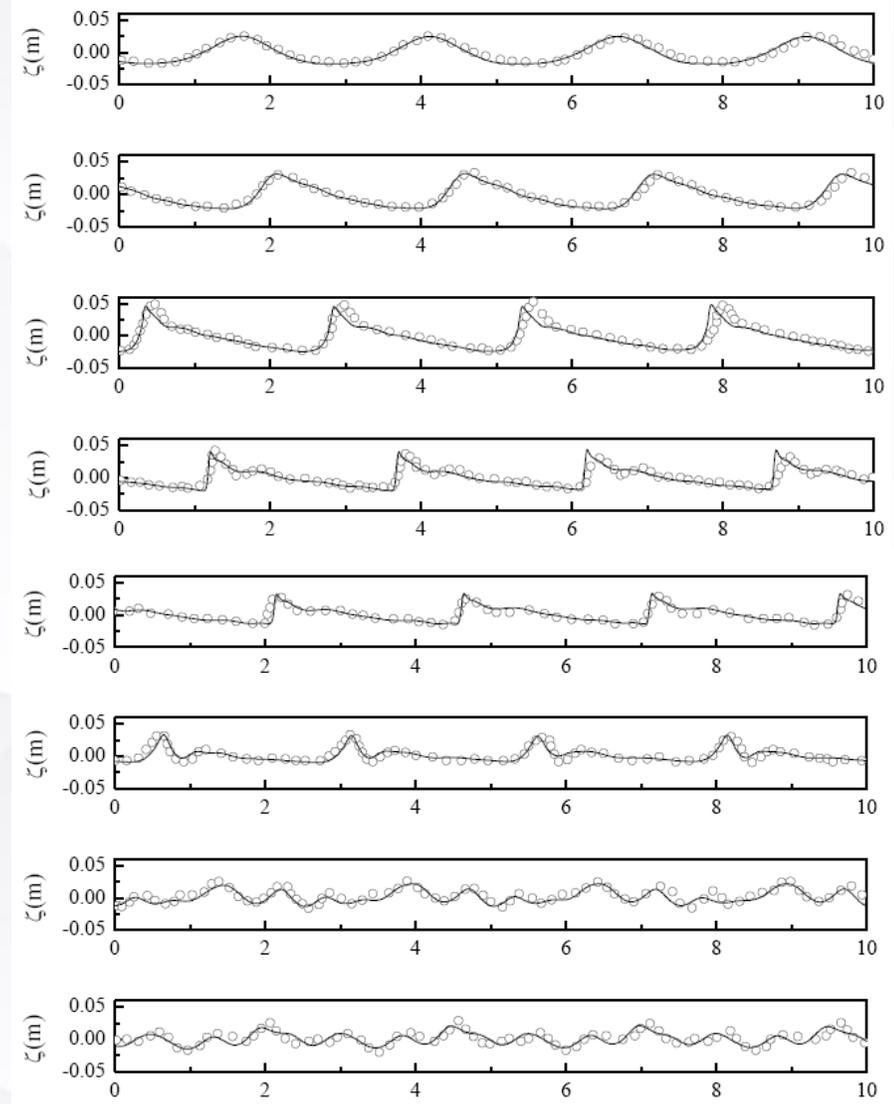
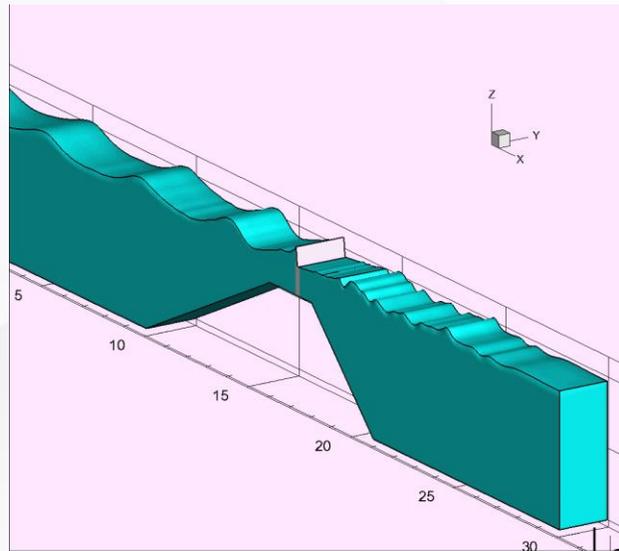
实验装置 (Beji and Battjes (1993))

入射波参数:  $H = 5.4\text{cm}$ ,  $f = 0.4\text{Hz}$

网格分辨率:  $\delta_x = \delta_y = 0.02\text{m}$

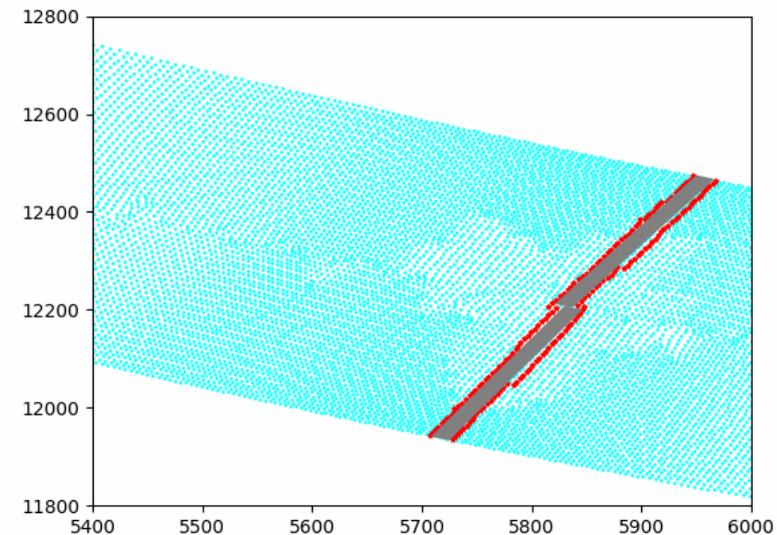
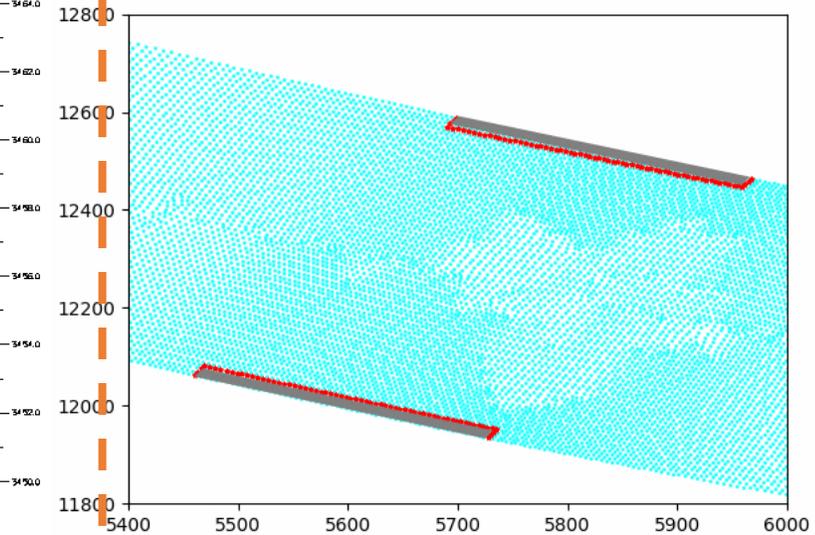
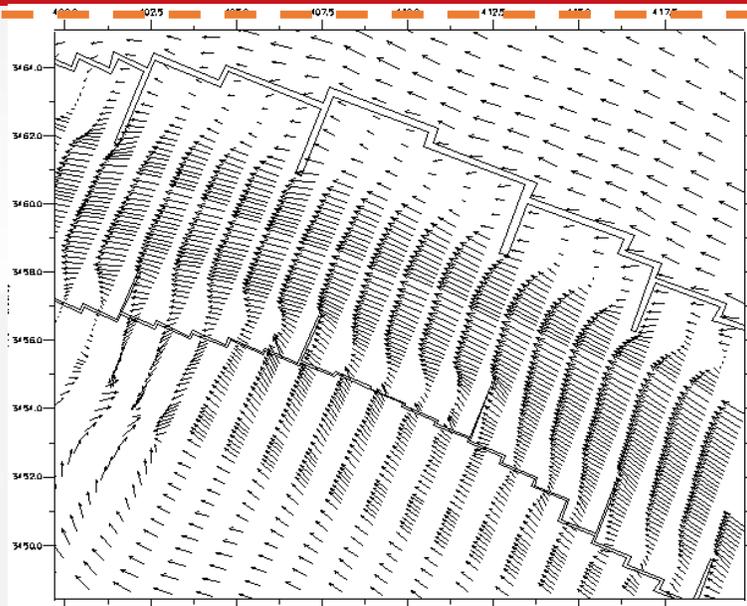
## 波浪破碎过程描述

- ◆ 入射波沿斜坡逐渐浅化, 波高逐渐增加
- ◆ 在坡顶发生破碎
- ◆ 破碎持续至后坡
- ◆ 后坡波浪演化出一列小波

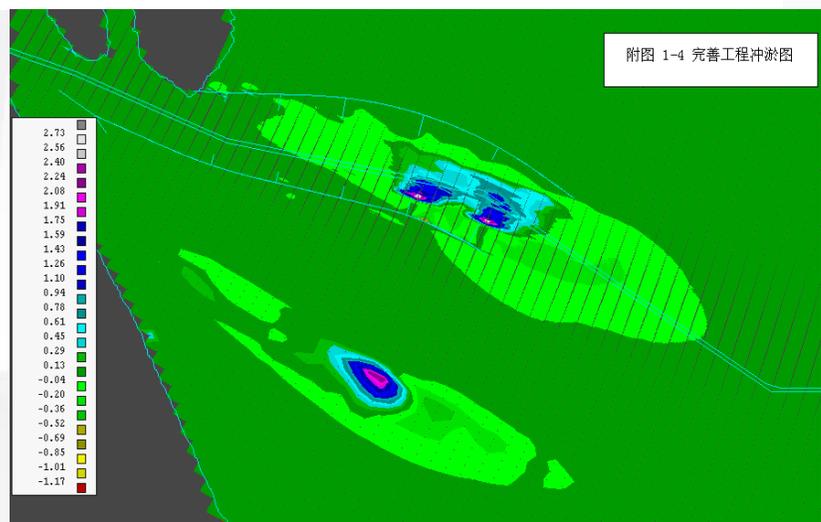




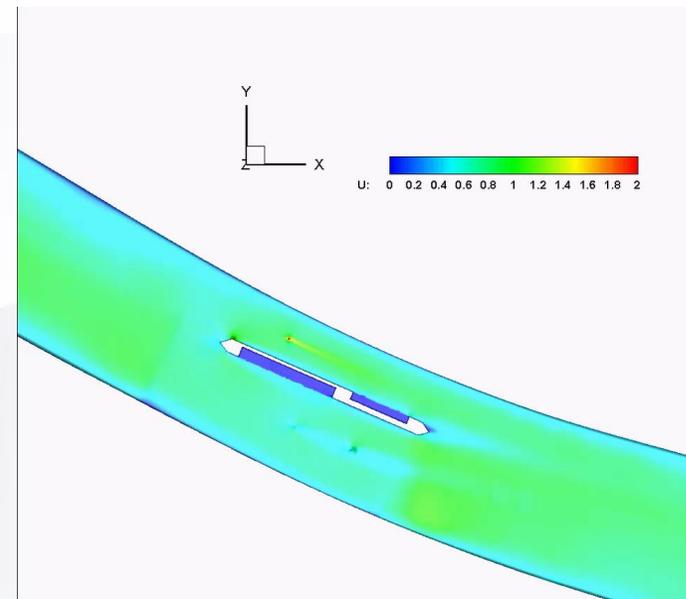
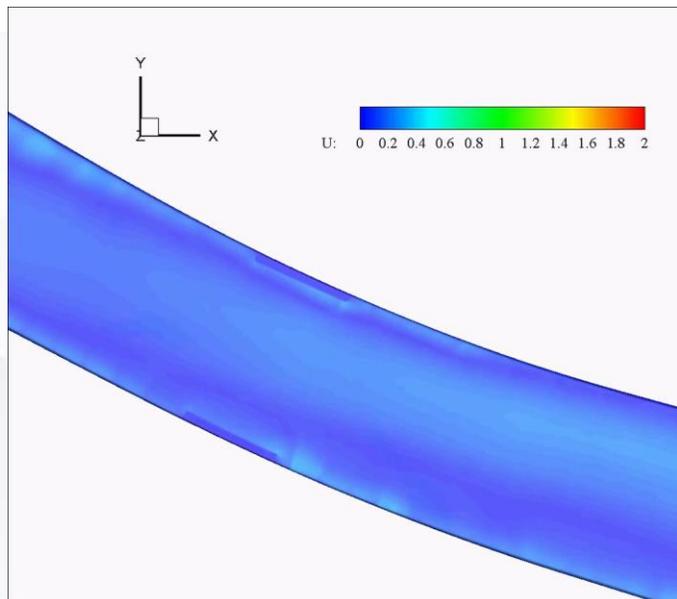
# 研究内容及应用 II：水利工程



→ 1.000m/s Fig.10 Flood tide current vector with project



附图 1-4 完善工程冲淤图

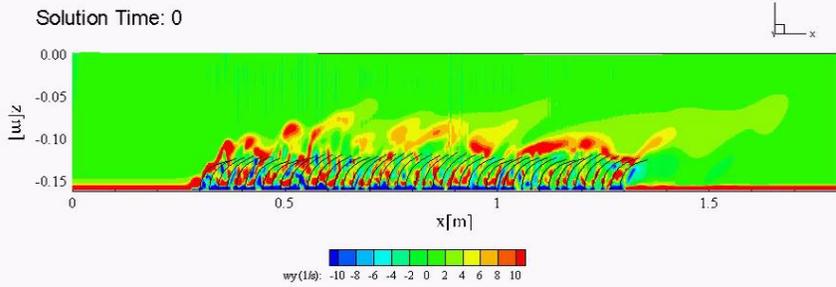
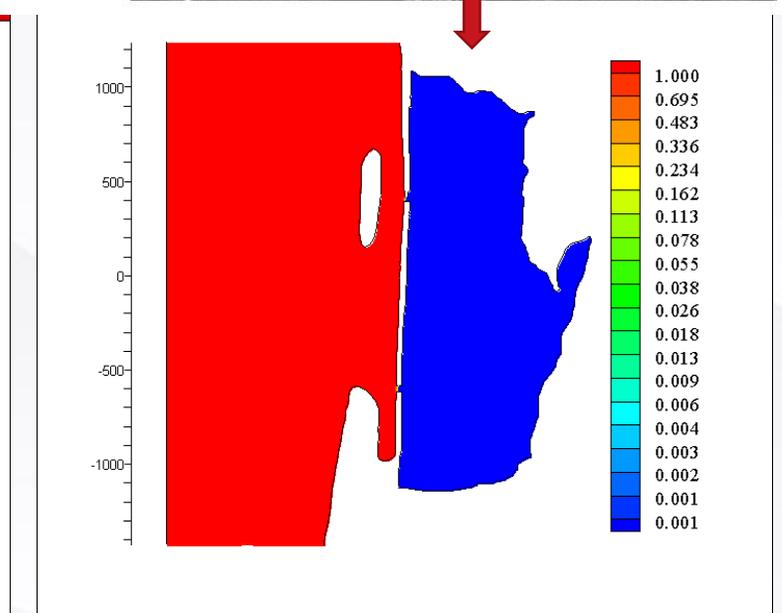
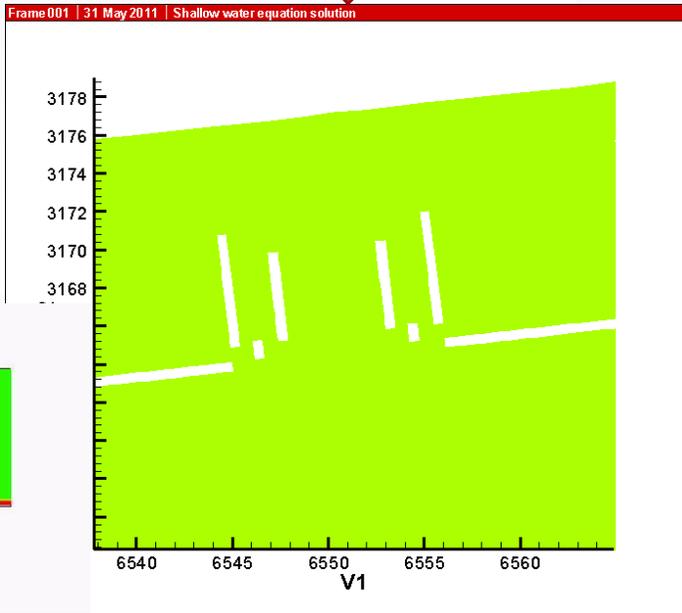
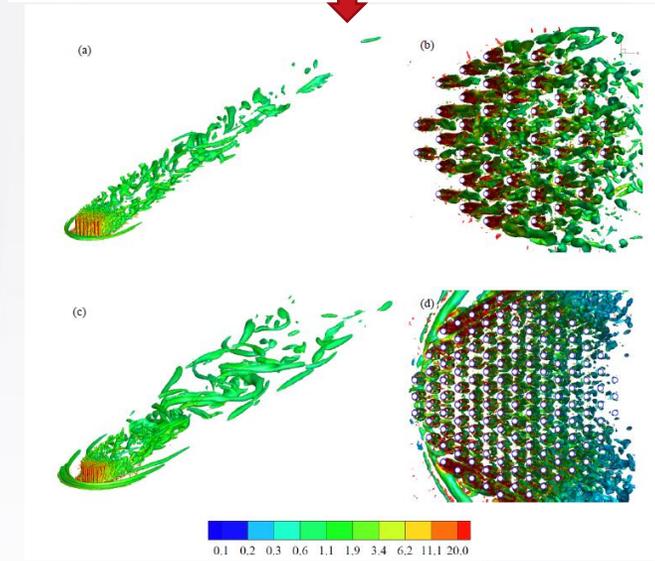
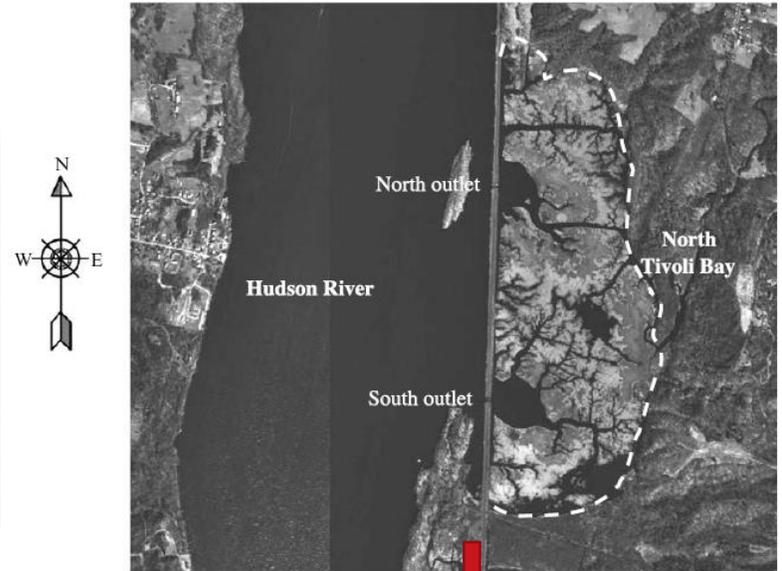
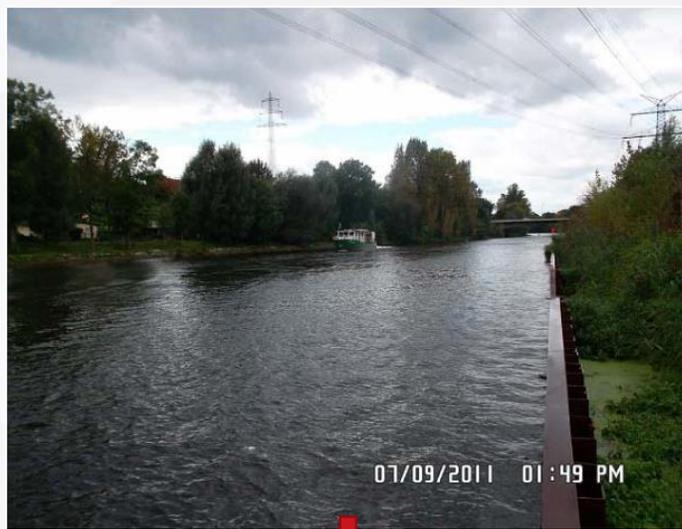
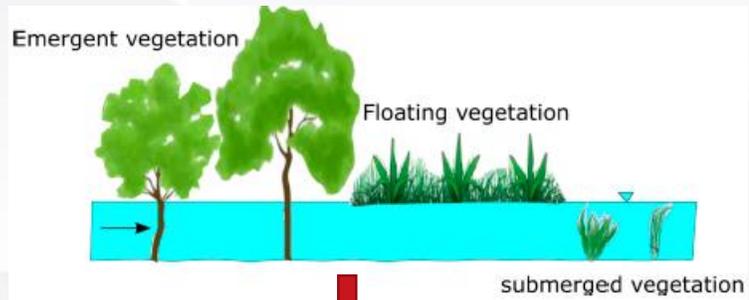


长江口深水航道整治工程水沙调整

黄浦江挡潮闸的设计及优化



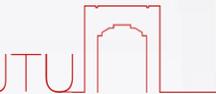
# 研究内容及应用 III：环境水动力学



植被水流

船行波对河岸的影响

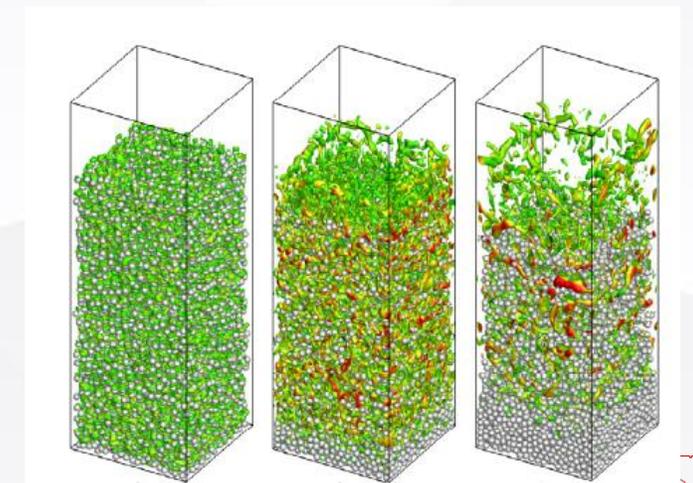
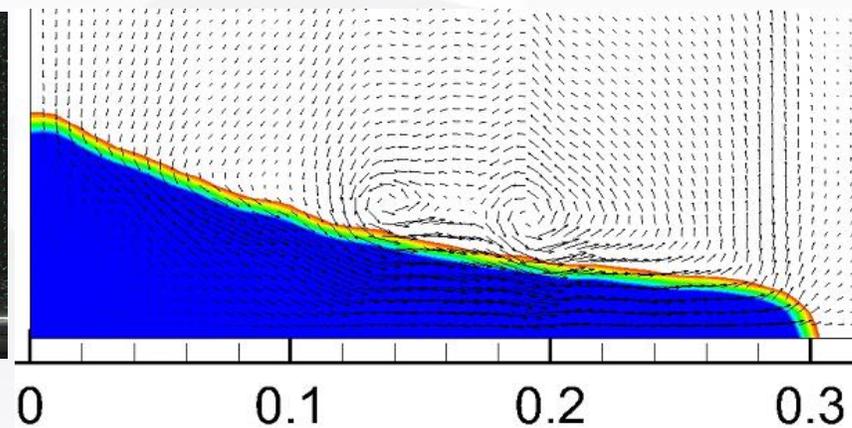
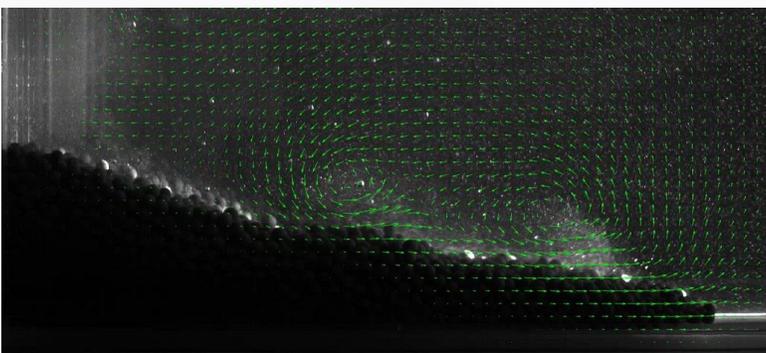
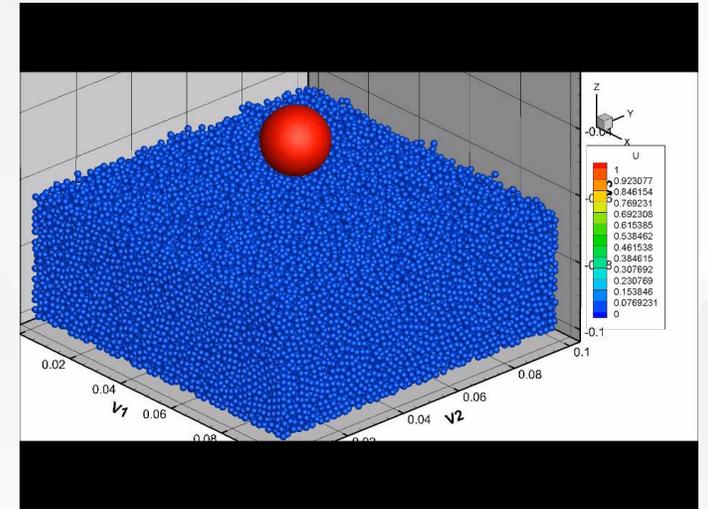
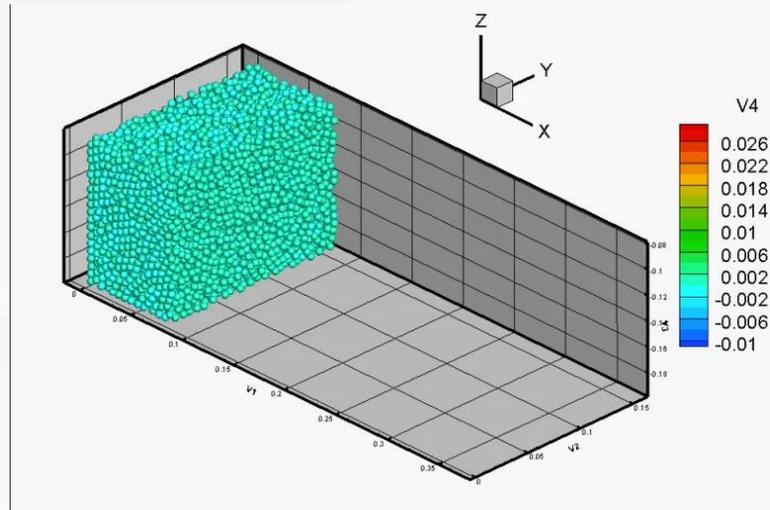
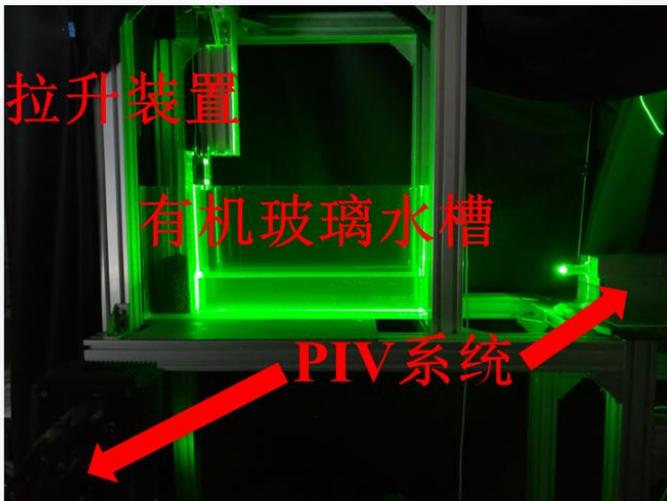
潮汐河口物质交换





# 研究内容及应用 IV : 流固耦合

## 基于域扩展的高精度CFD-DEM耦合模型

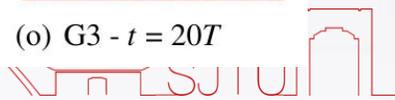
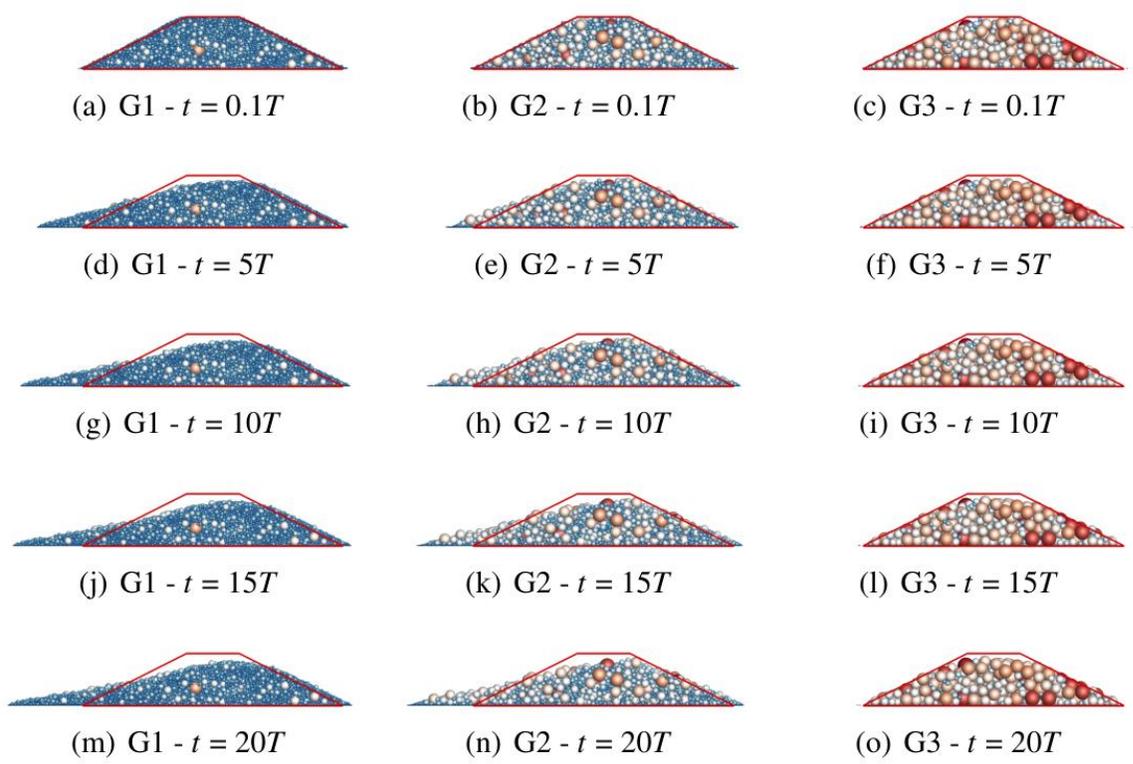
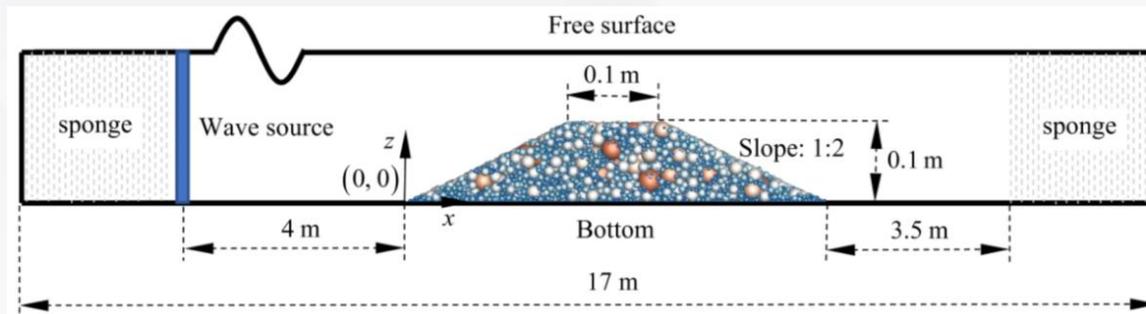
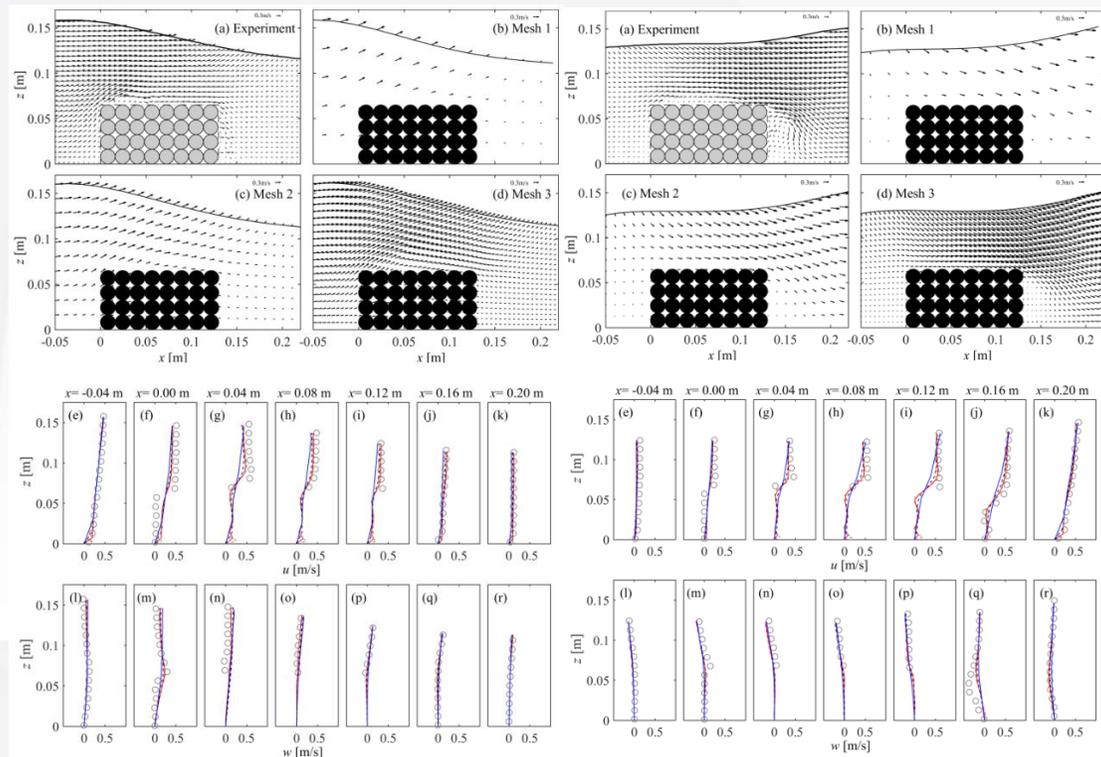
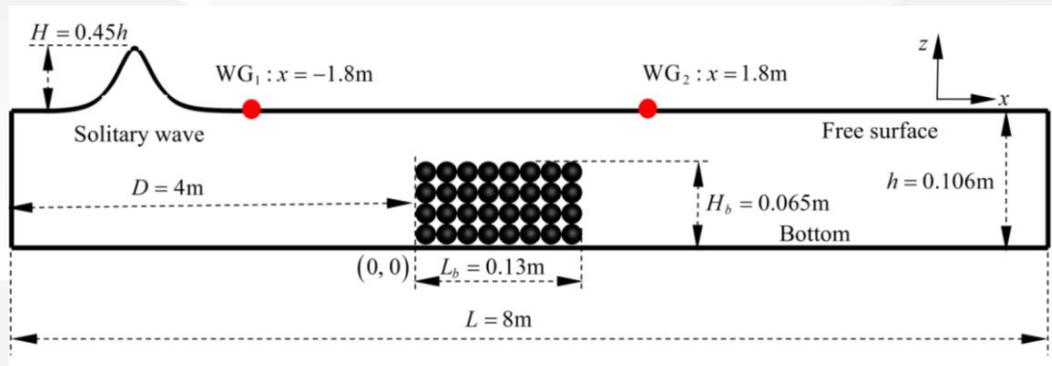


颗粒堆坍塌模拟





# 研究内容及应用 IV : 流固耦合

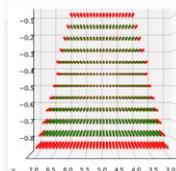
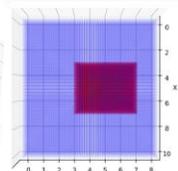
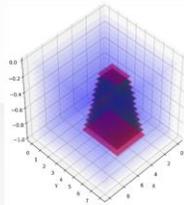
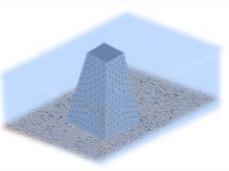
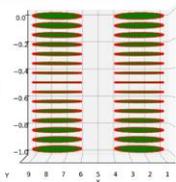
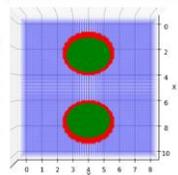
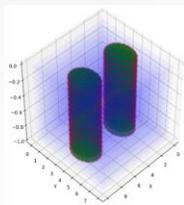
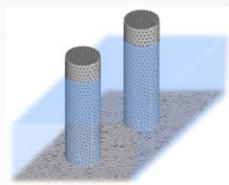
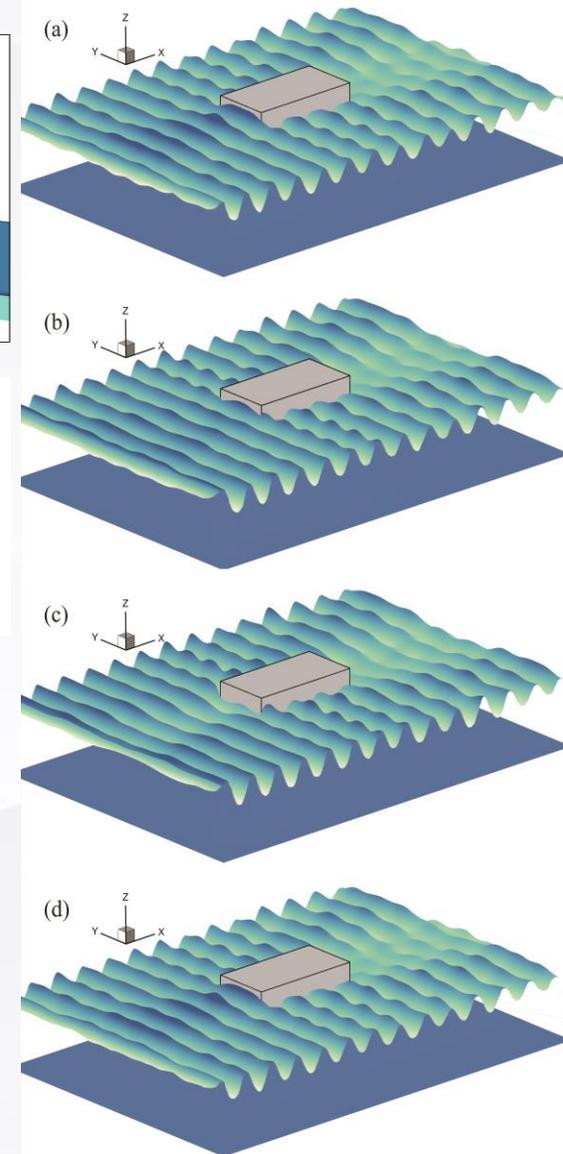
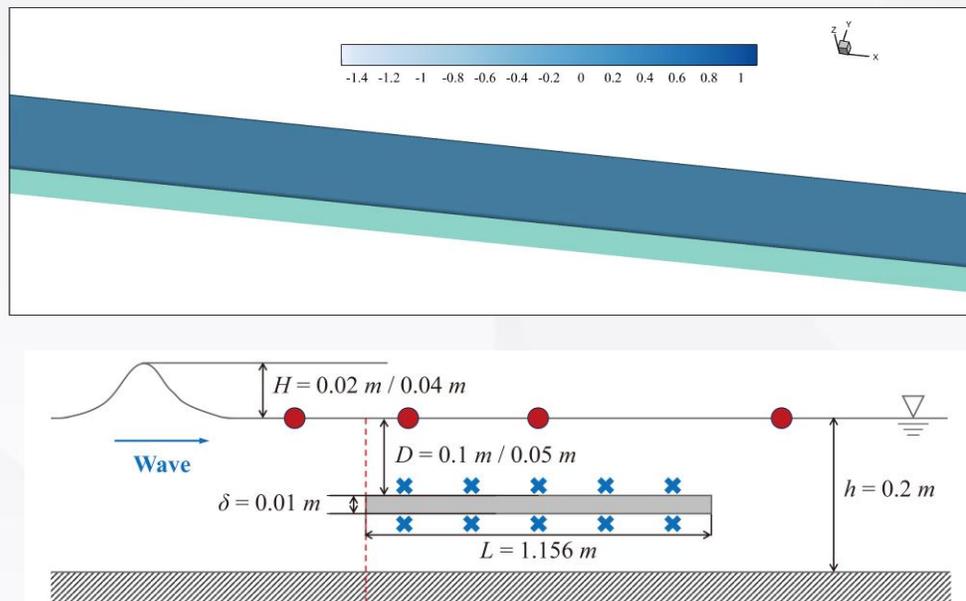
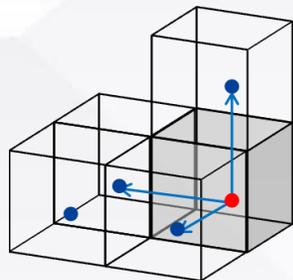
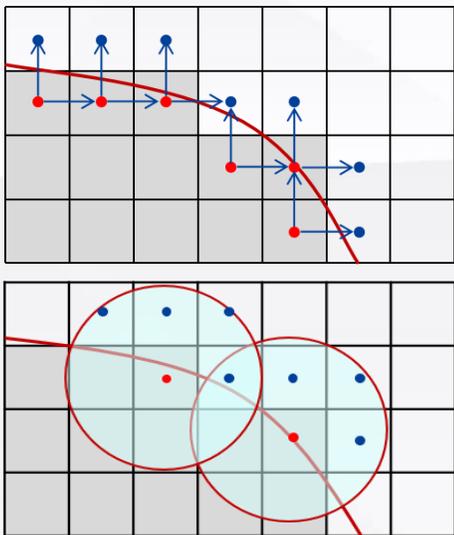




# 研究内容及应用 IV : 流固耦合



## ◆ CFD-IBM流固耦合模型



● Fluid cells ● Solid cells ★ Ghost cells

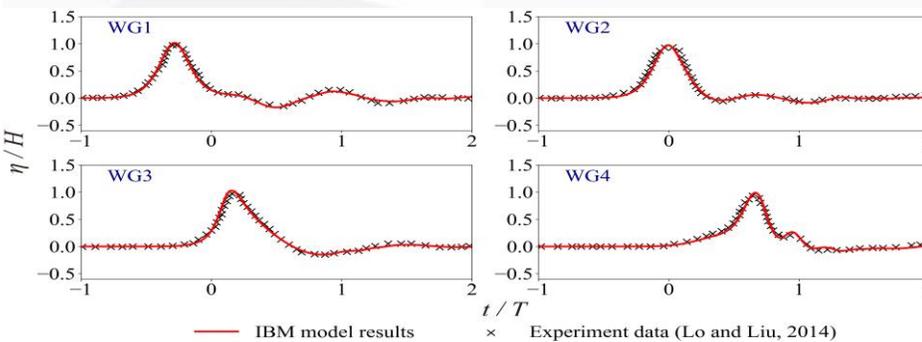
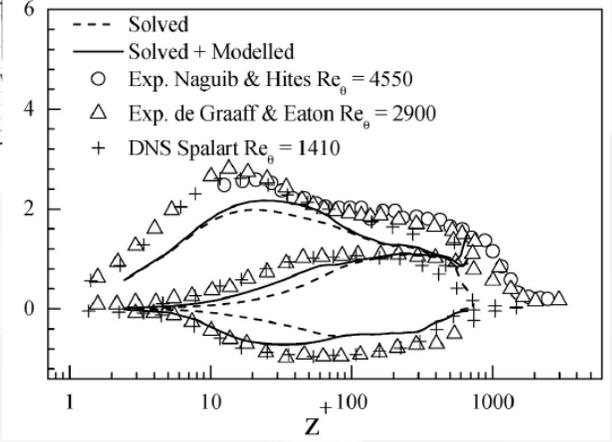
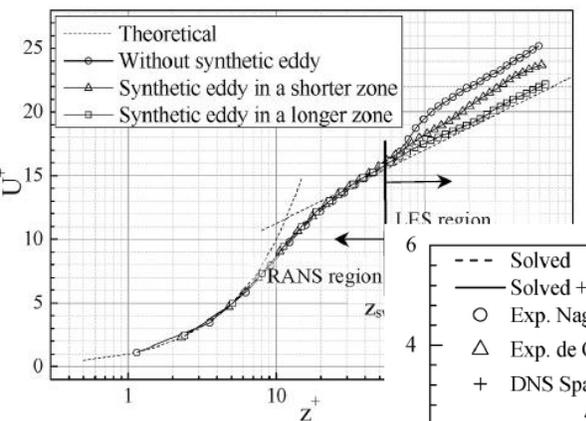
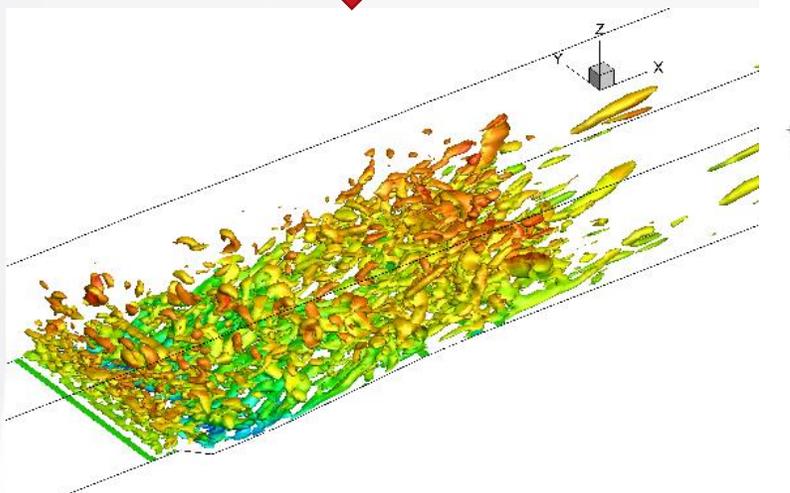
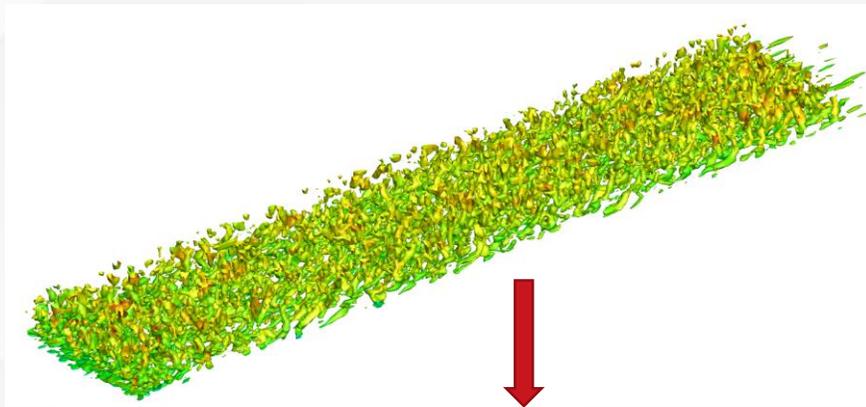
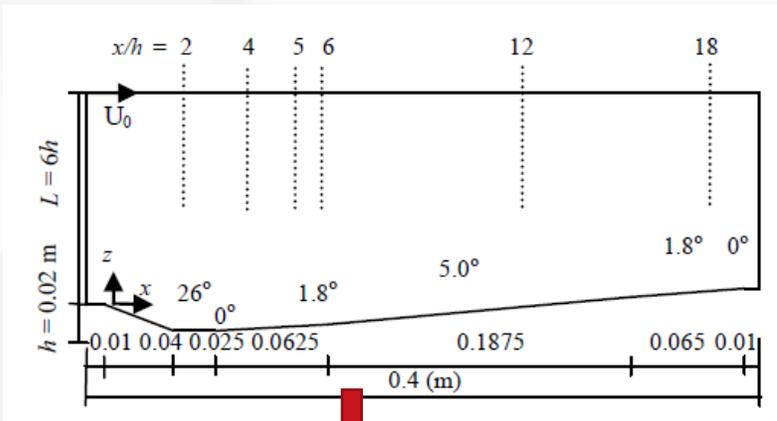


图18 浪高仪位置处水位计算结果对比  
( $H = 0.04$ ,  $D = 0.1$ )



# 研究内容及应用 V : 高精度湍流模拟



水下沙丘地形近壁流动

平板边界层流动

丁坝群流动





# ➤ 研究内容及应用 VI : 大尺度流动的高效模拟

## ◆ 非静压模型的压力泊松方程

$$\Delta P_n = B$$

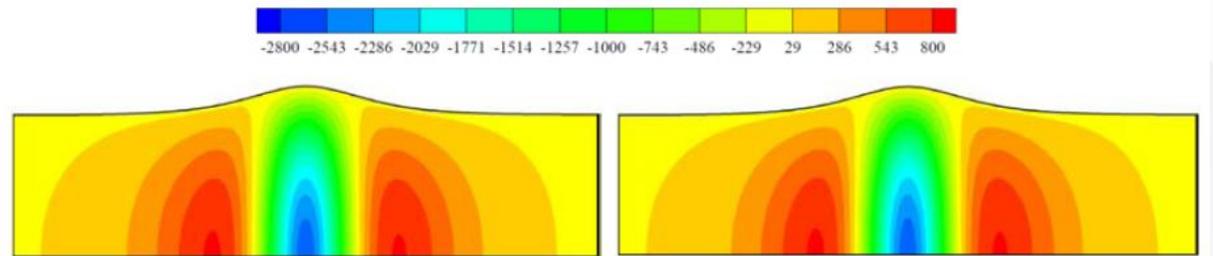
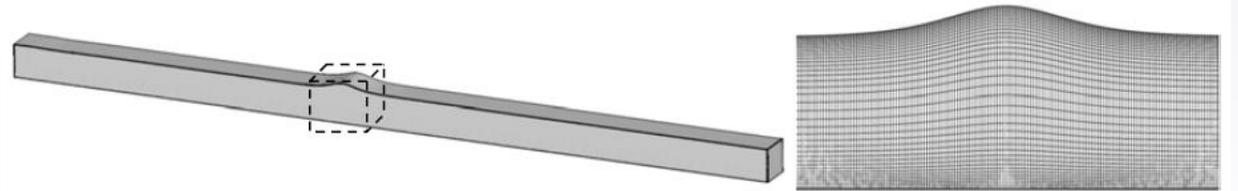
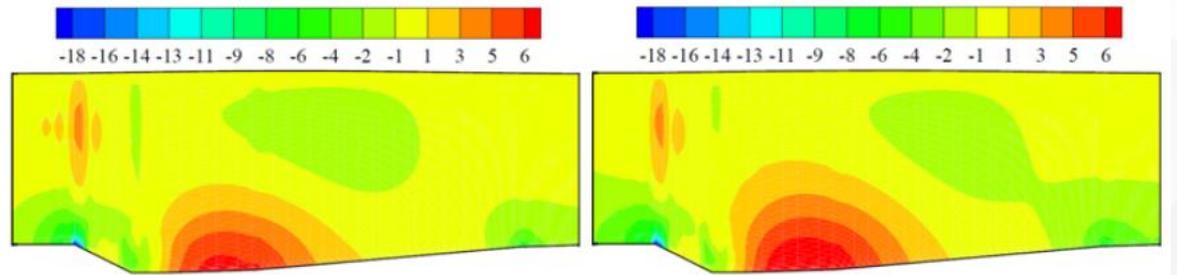
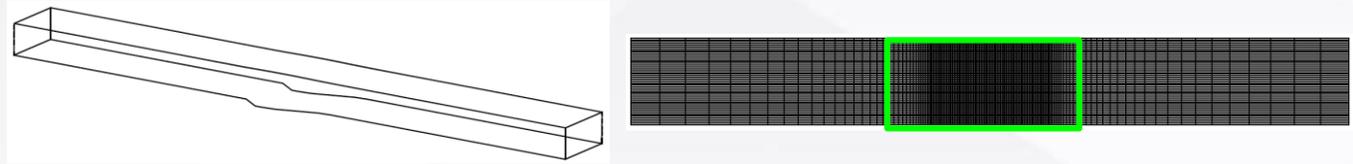
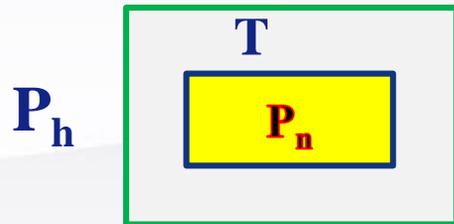
### 分析: 1、模型应用范围

- 静压模型应用范围
- 动压模型应用范围

### 2、动压泊松方程性质

### 混合模型设计方法

- 1、区域划分
- 2、局部动压求解



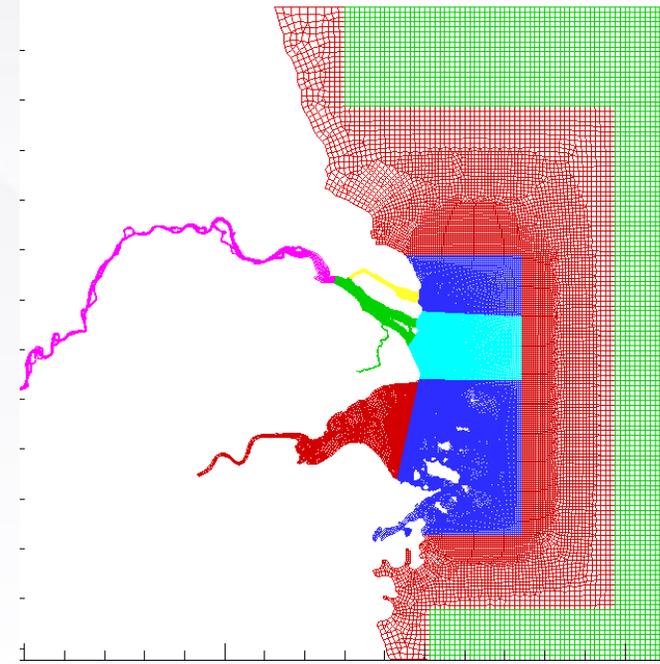
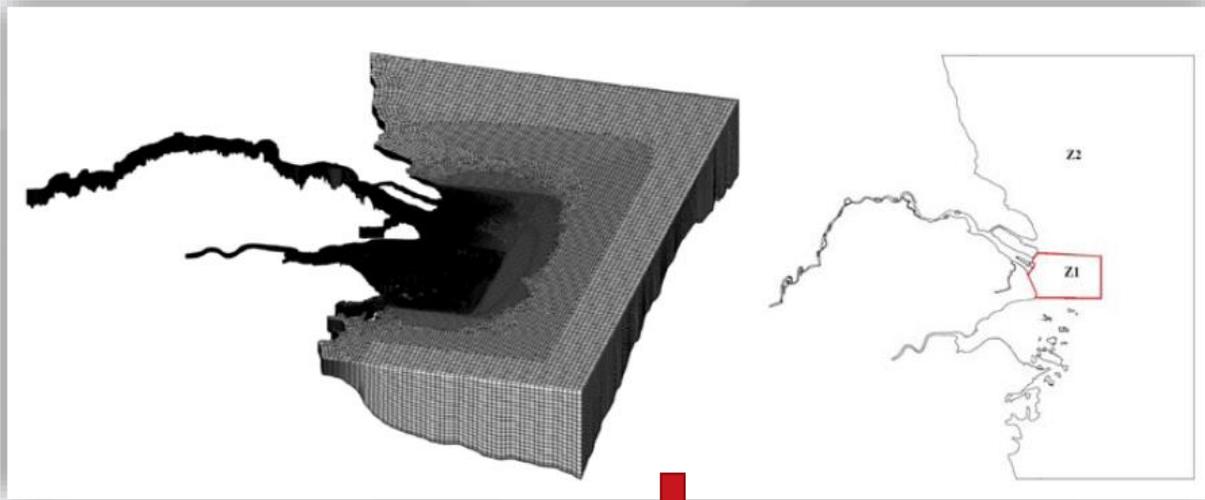
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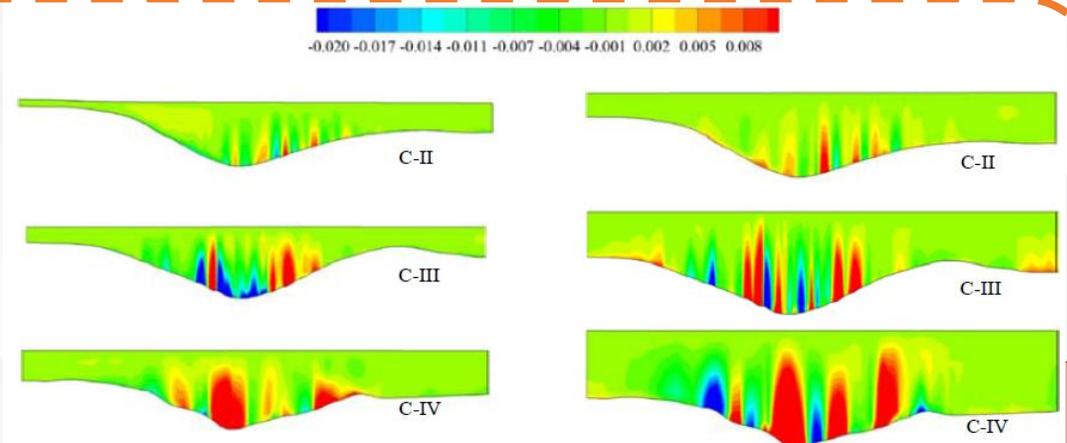
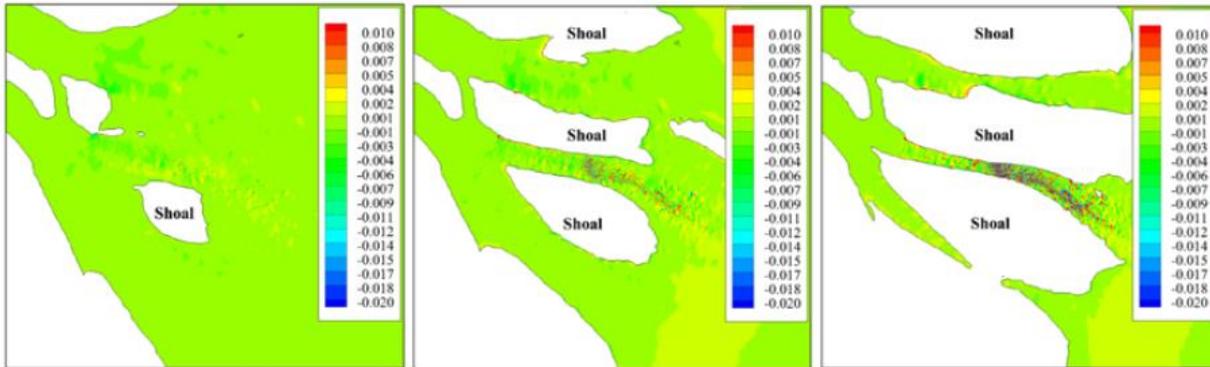
# 研究内容及应用 VI：大尺度流动的高效模拟



## 长江口潮汐流模拟



➤ 基于域划分的一/二/三维数值模型





可持续性 —— 系统的架构、通用求解器



可扩展性 —— 良好的模块接口



可实用性 —— 兼顾精度与效率的工程应用



# 谢谢

饮水思源 爱国荣校