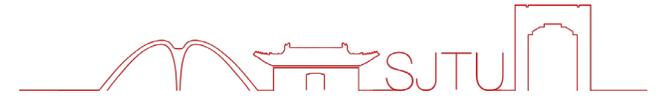




上海交通大学
SHANGHAI JIAO TONG UNIVERSITY



环境水动力学数值仿真研究

张景新

上海交通大学船舶海洋与建筑工程学院工程力学系

Tel: 13917108421

Email: zhangjingxin@sjtu.edu.cn

饮水思源 · 爱国荣校



研究背景

研究内容

研究成果



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

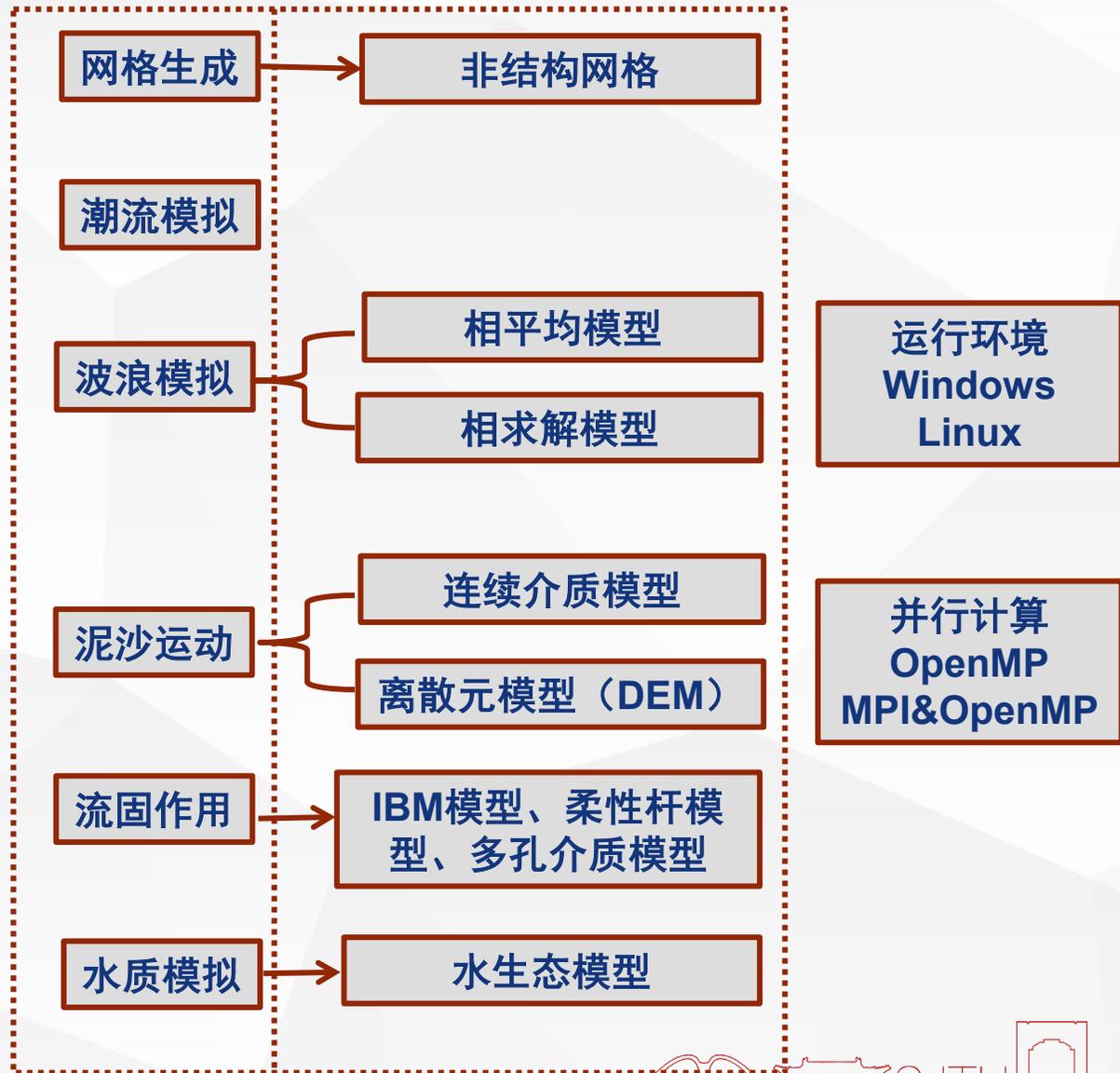
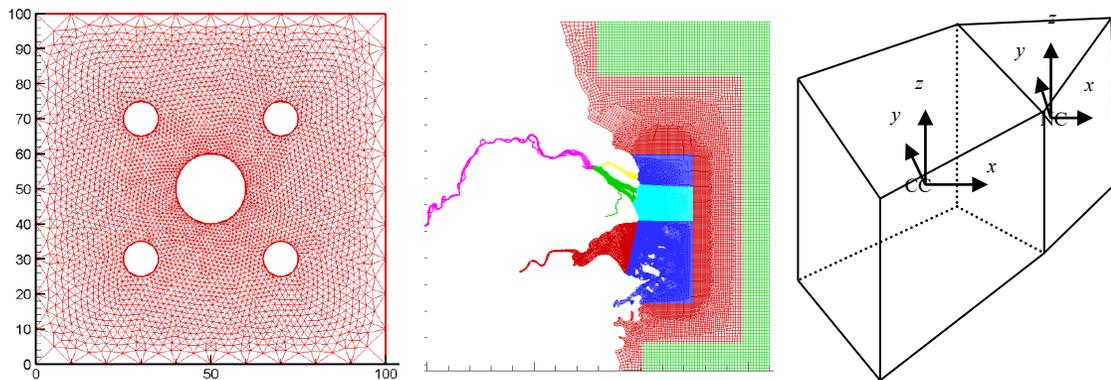
- ◆ 高精度反演相关物理过程，完成实验所不能
- ◆ 关键动力因素的提取与机理溯源分析
- ◆ 时空尺度的限制需要数值模拟兼顾精度与效率



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 (2nd TVD、5th 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





退化模型——静压模型

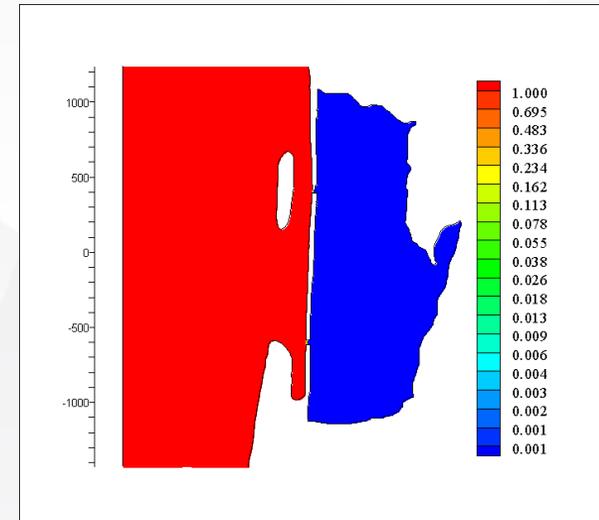
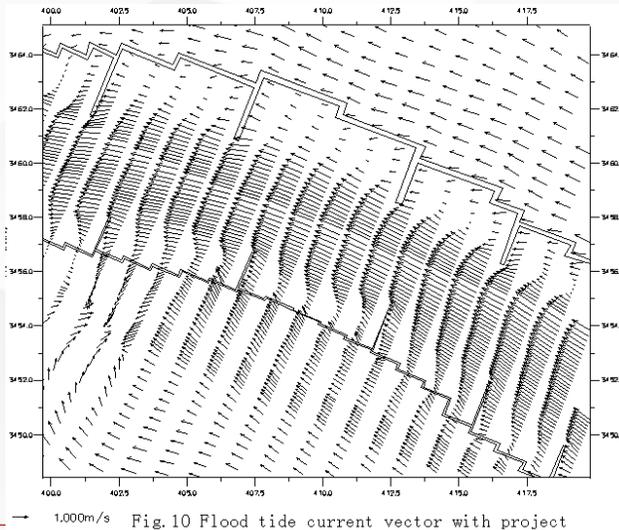
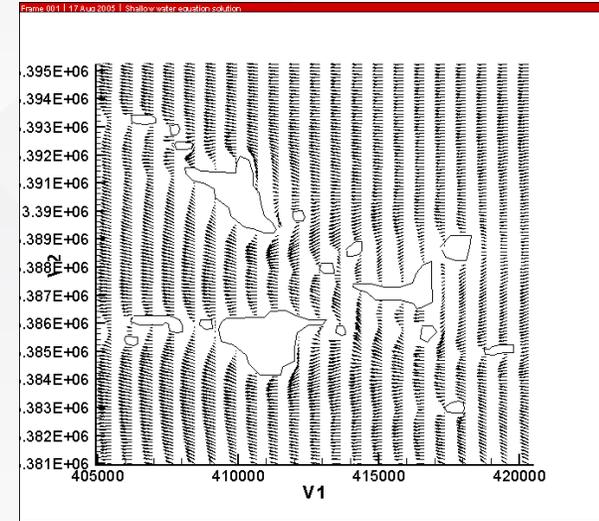
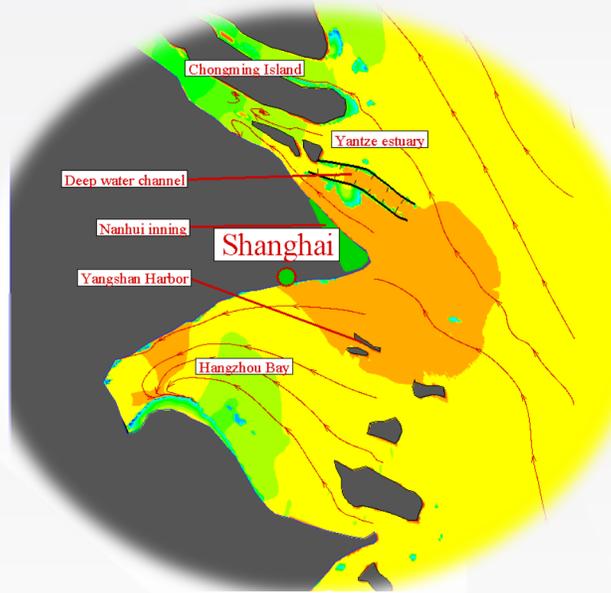
二步法——预估校正

数值求解

- 预估流场：静压模型
- 校正流场：非静压模型

适用范围

- 洋流、河流、湖泊水流
- 非色散水波

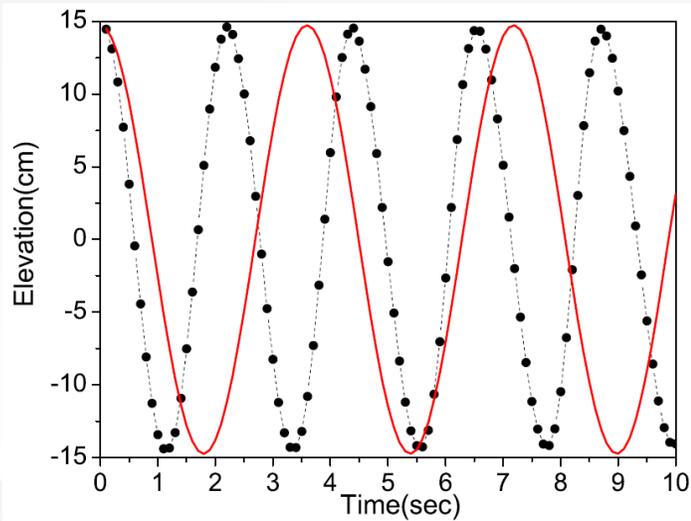




非静压模型的适用性

适用条件

- 非浅水长波
- 地形变化显著
- 结构物局部绕流



非静压与静压效应理论分析

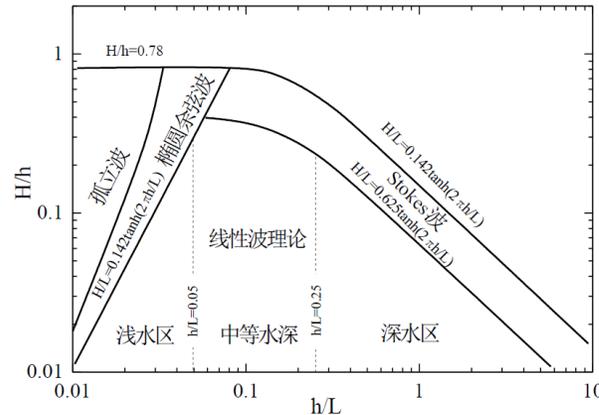


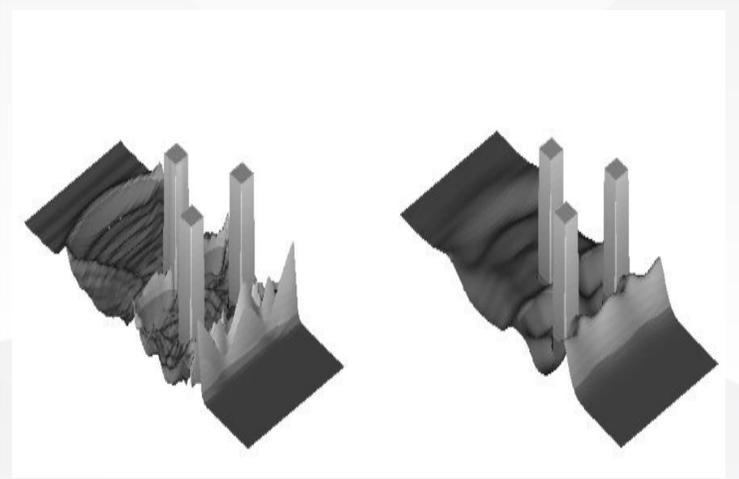
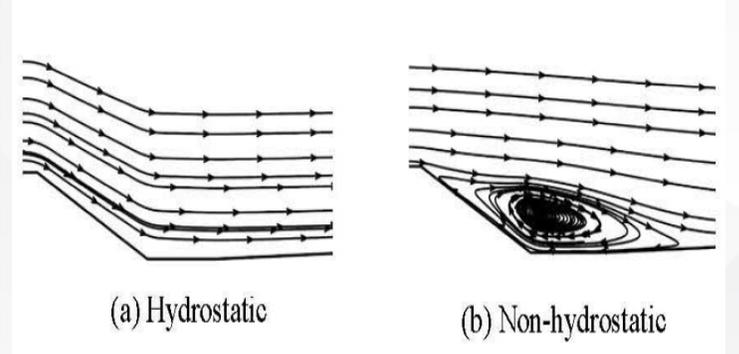
图 1-1 波浪理论适用范围 (Muir Wood, 1969)

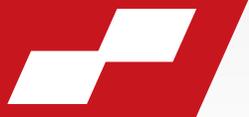
$$\frac{p_n}{\rho} = -i\omega \hat{\eta} e^{i(kx - \omega t)} \frac{1}{k} [\cosh k(\eta + h) - \cosh k(z + h)]$$

$$\frac{\partial \bar{u}}{\partial t} = -g \frac{\partial \eta}{\partial x} - \frac{\partial \bar{p}_n}{\rho \partial x}$$

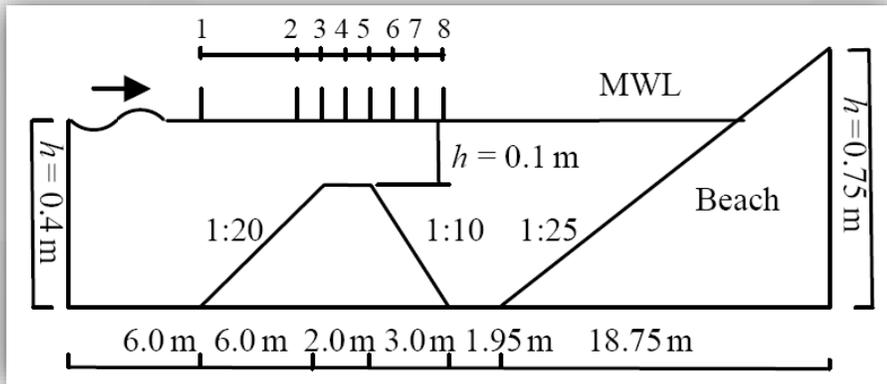
$$\omega^2 = gk \tanh kh$$

非静压适用性的数值分析



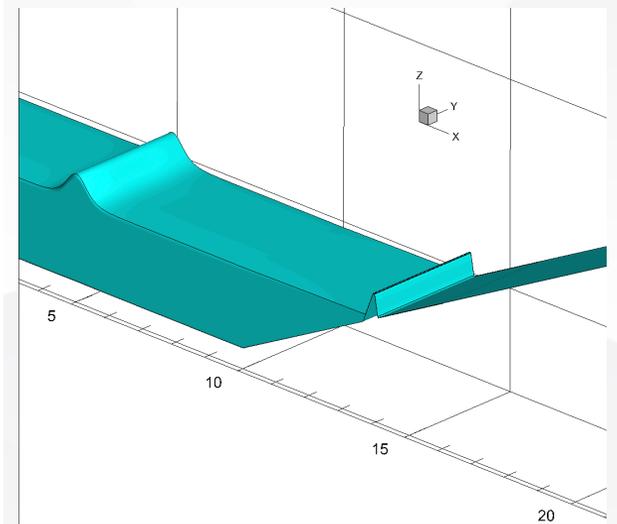
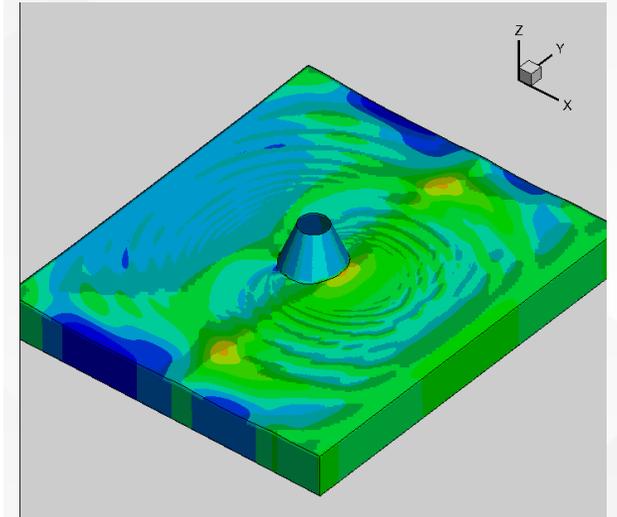
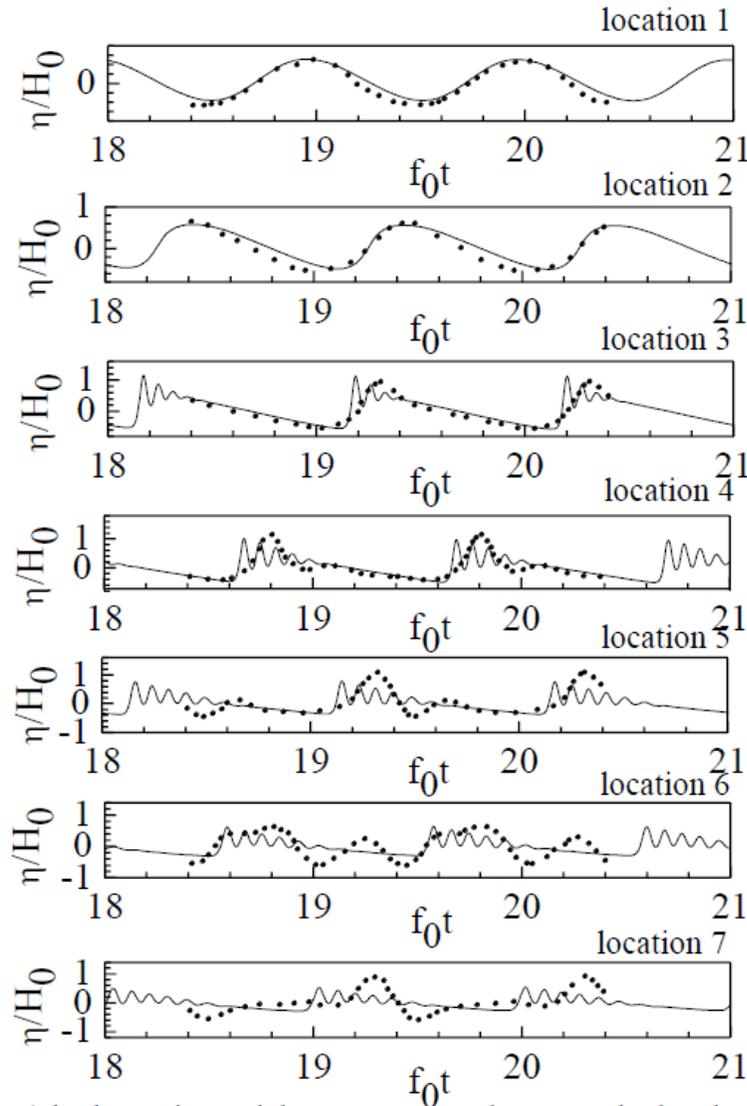
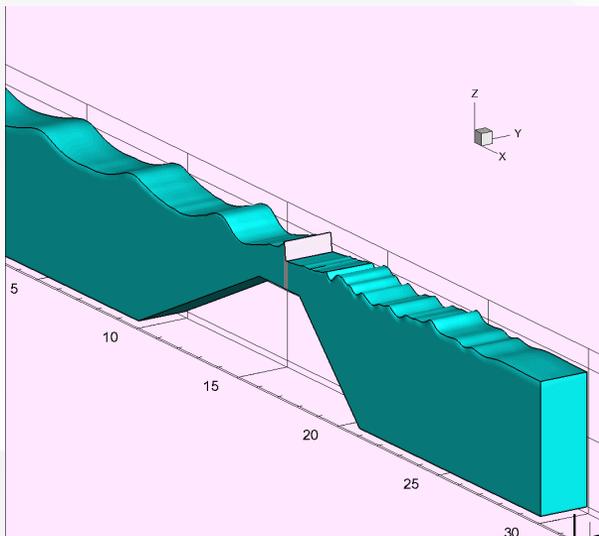


非静压模型的适用性



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





模型分析

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

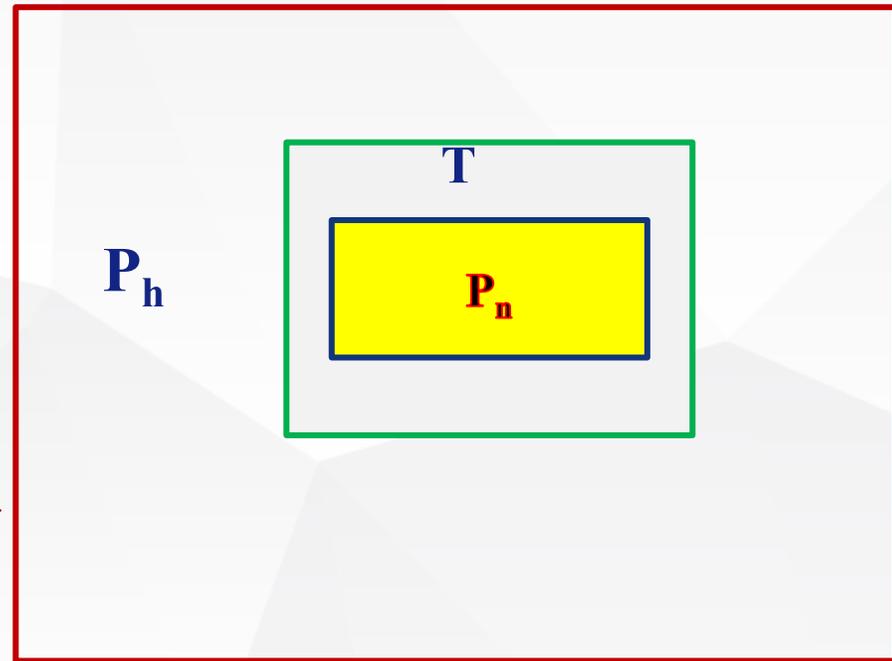
混合模型设计方法

- 1、区域划分
- 2、局部动压求解



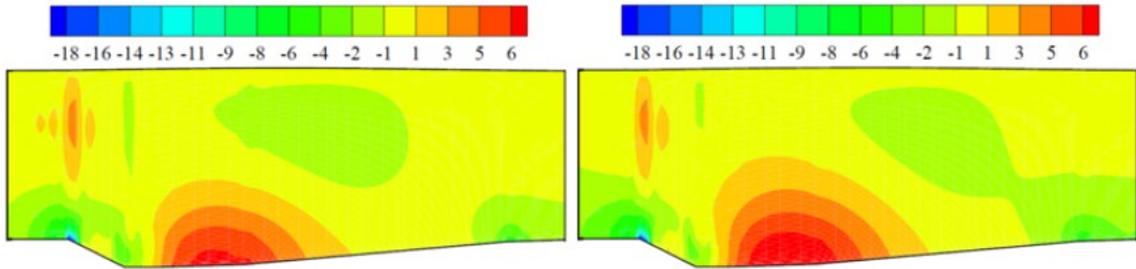
压力泊松方程（椭圆型）

$$\Delta P_n = B \quad \text{边值问题}$$



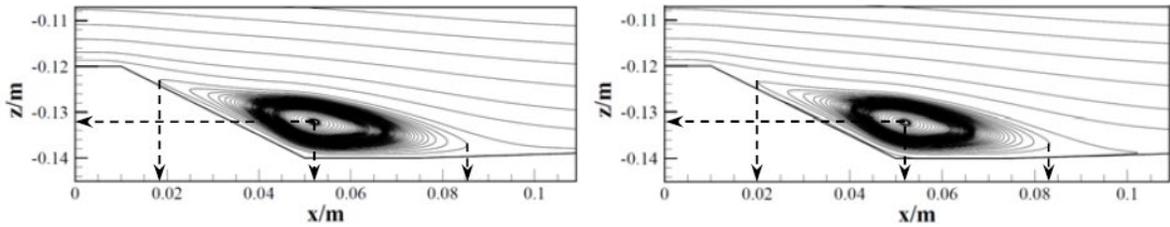


模拟效率的提升



非静压模型

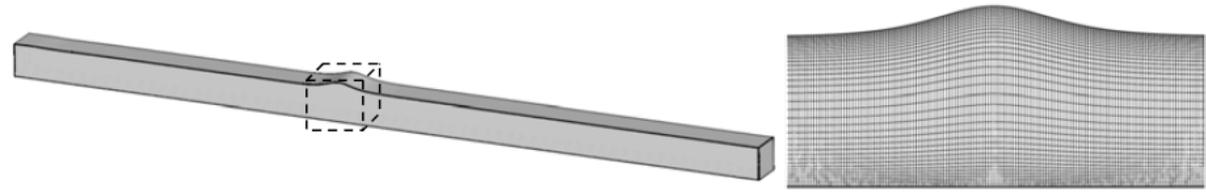
混合模型



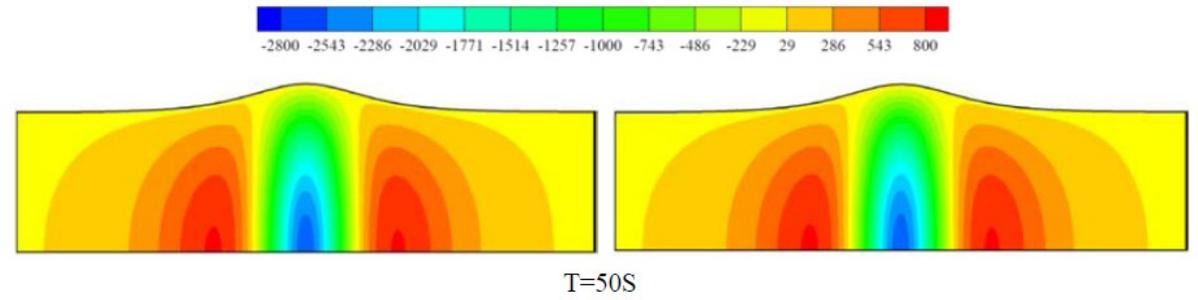
非静压模型

混合模型

	网格数	动压网格占比	CPU时间
非静压模型	141,750	100%	100%
混合模型	141,750	70%	77%



计算域及计算网格



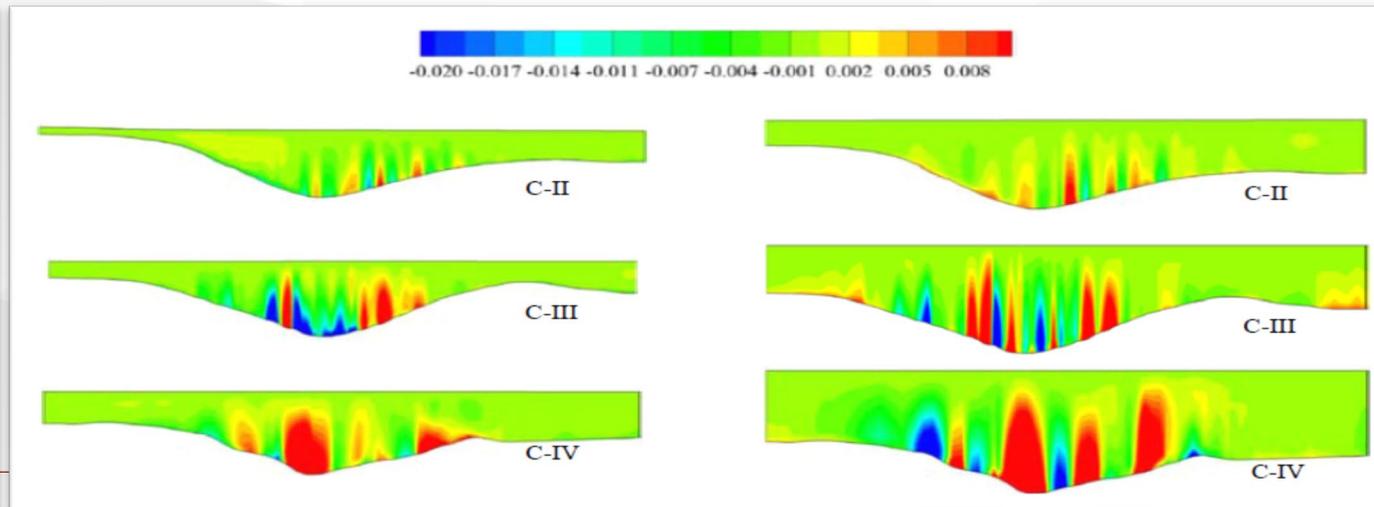
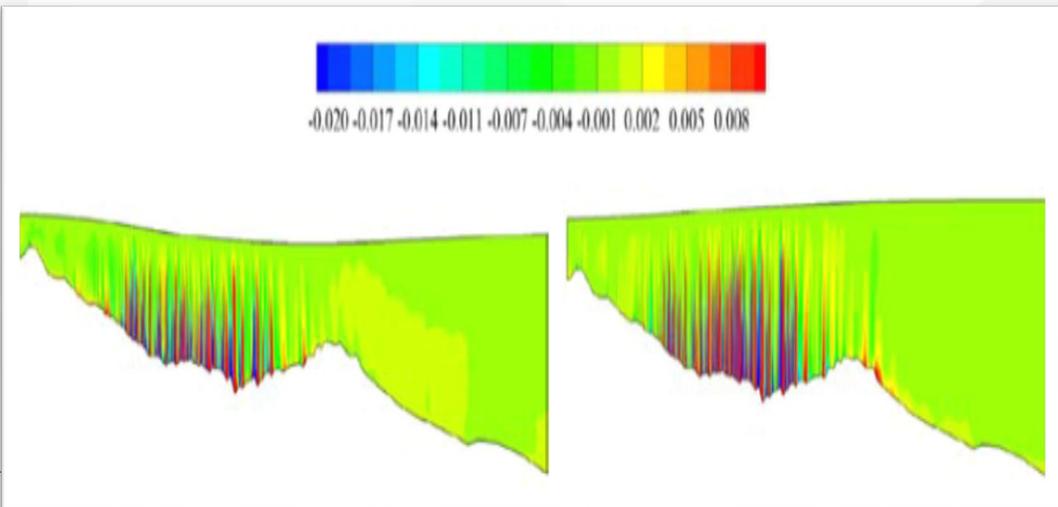
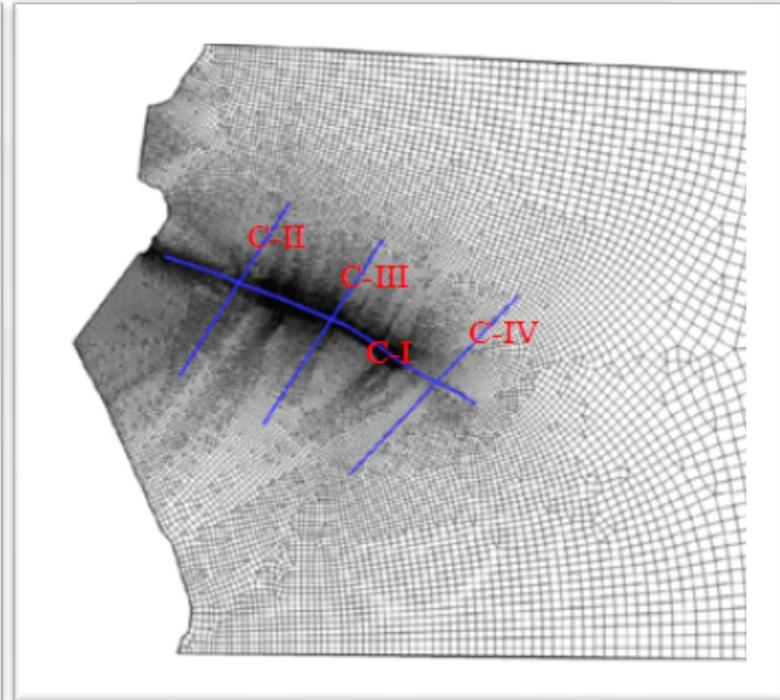
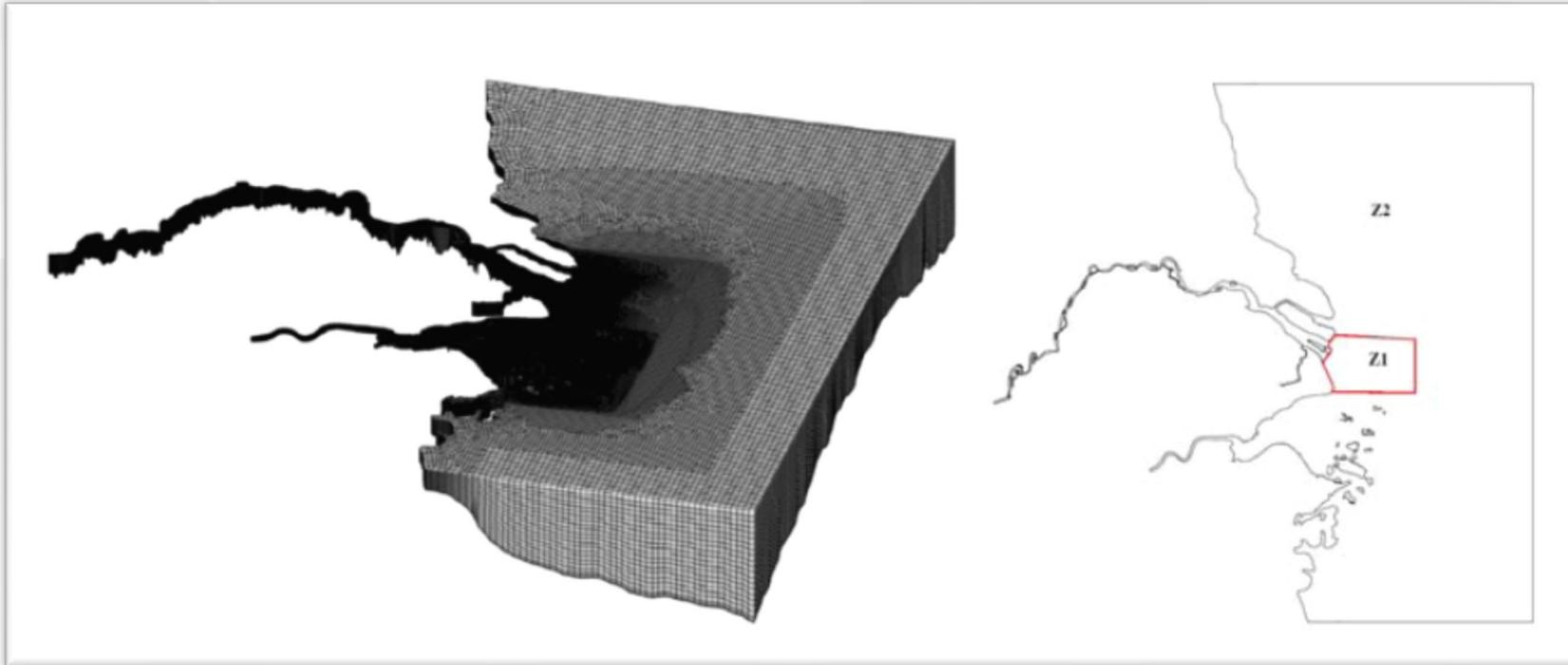
非静压模型

混合模型

	网格数	动压网格占比	CPU时间
非静压模型	234,000	100%	100%
混合模型	234,000	22%	51%

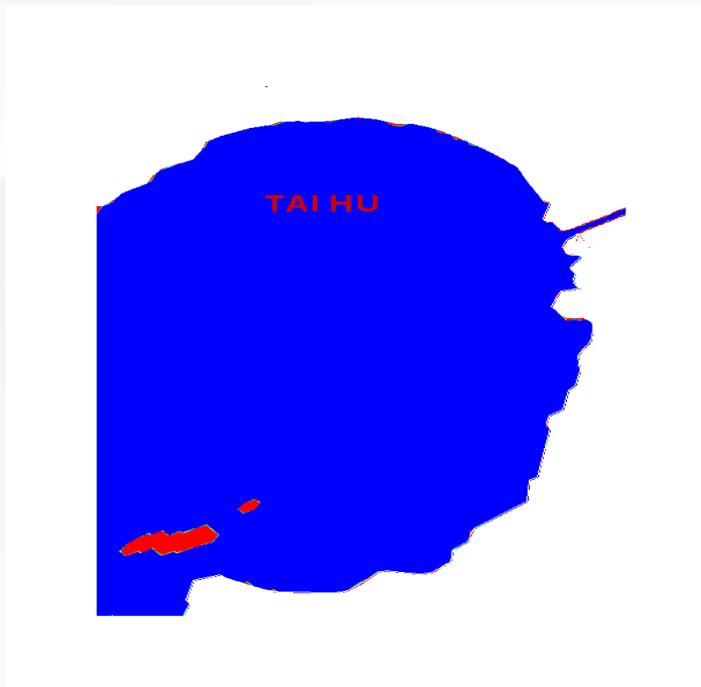


模拟效率的提升

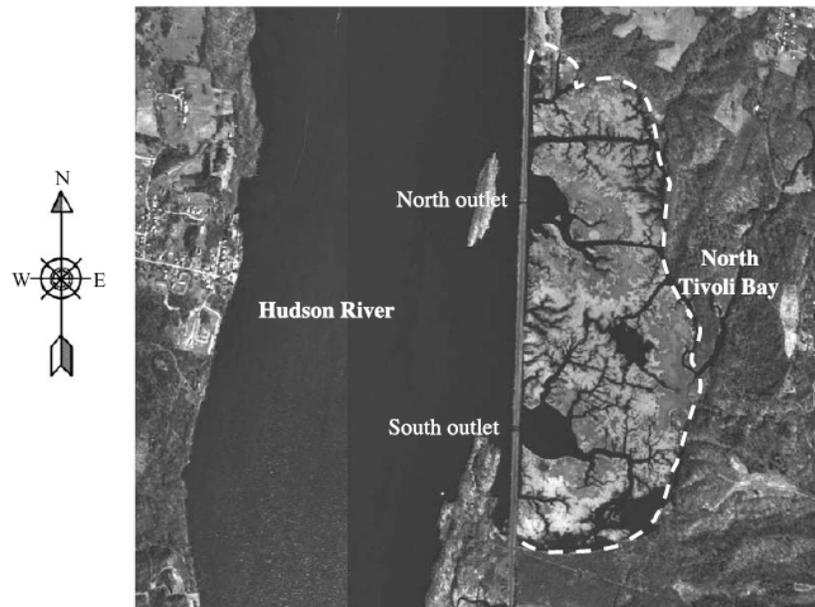




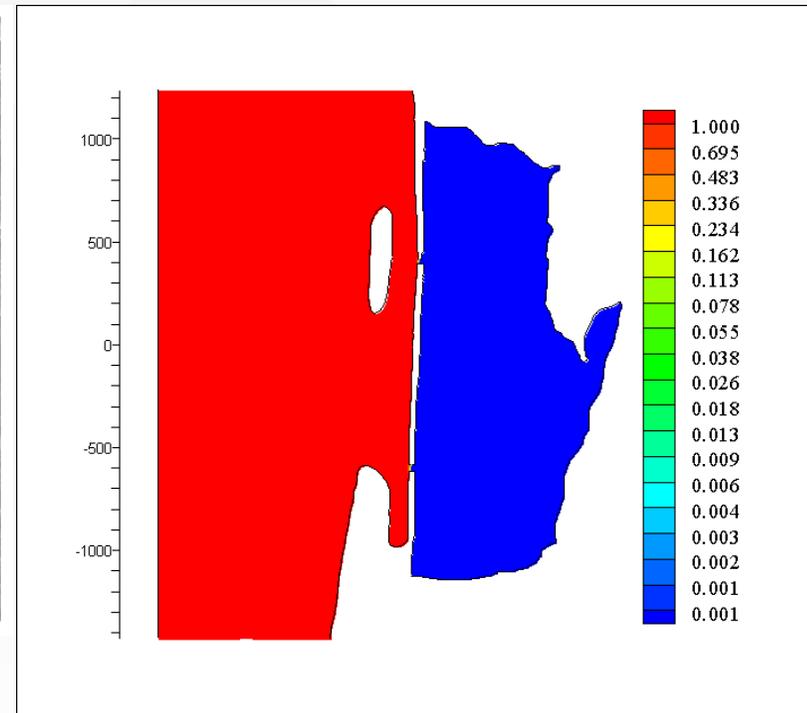
污染物迁移的数值模拟



太湖温水排放模拟

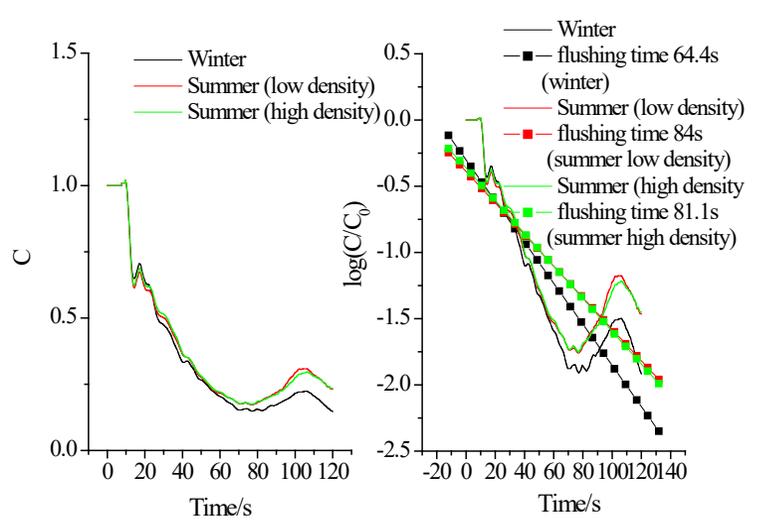
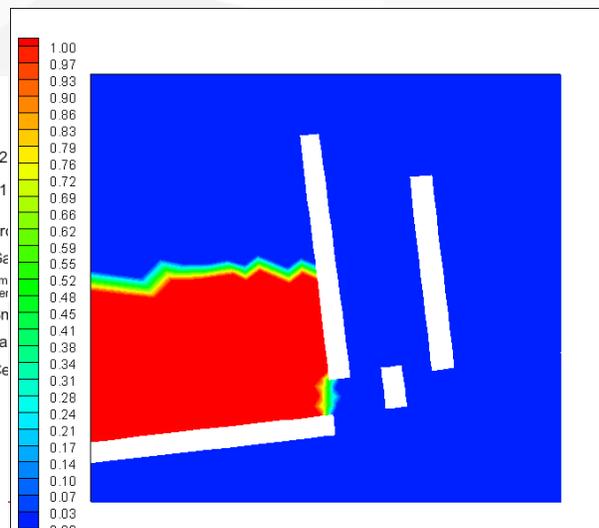
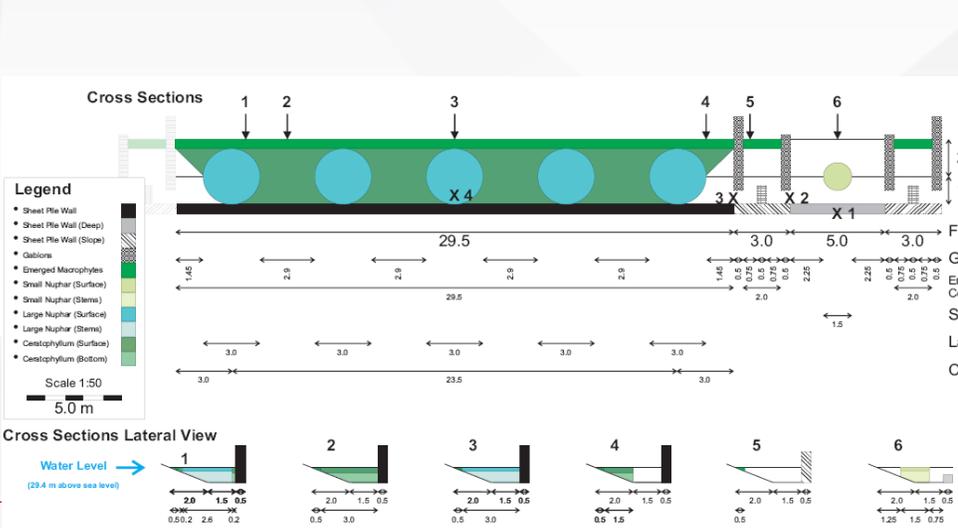
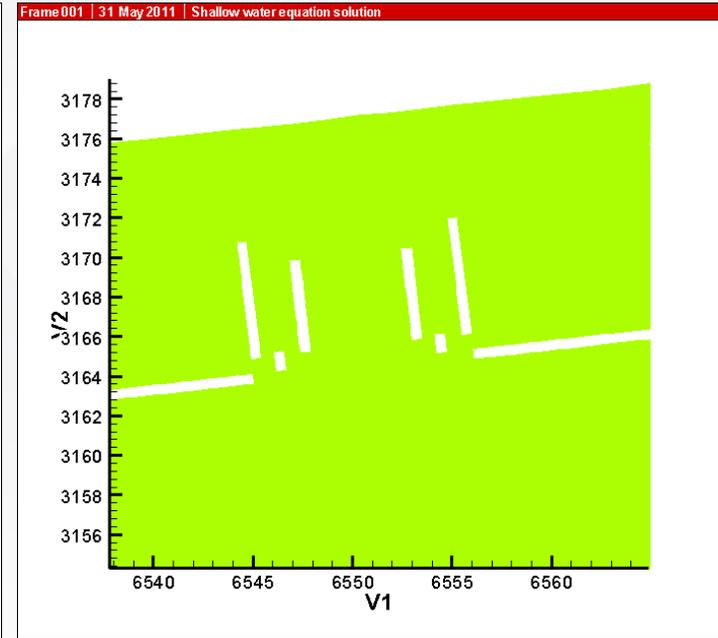
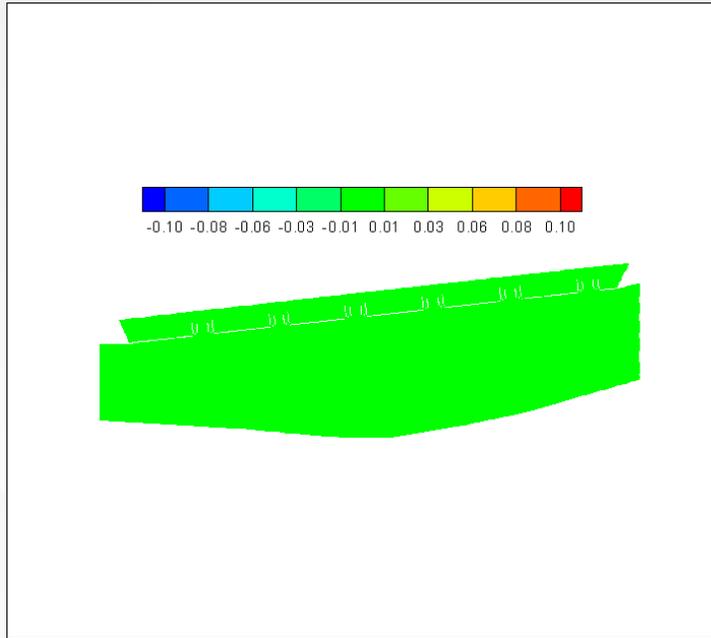


河口湿地污染物迁移模拟





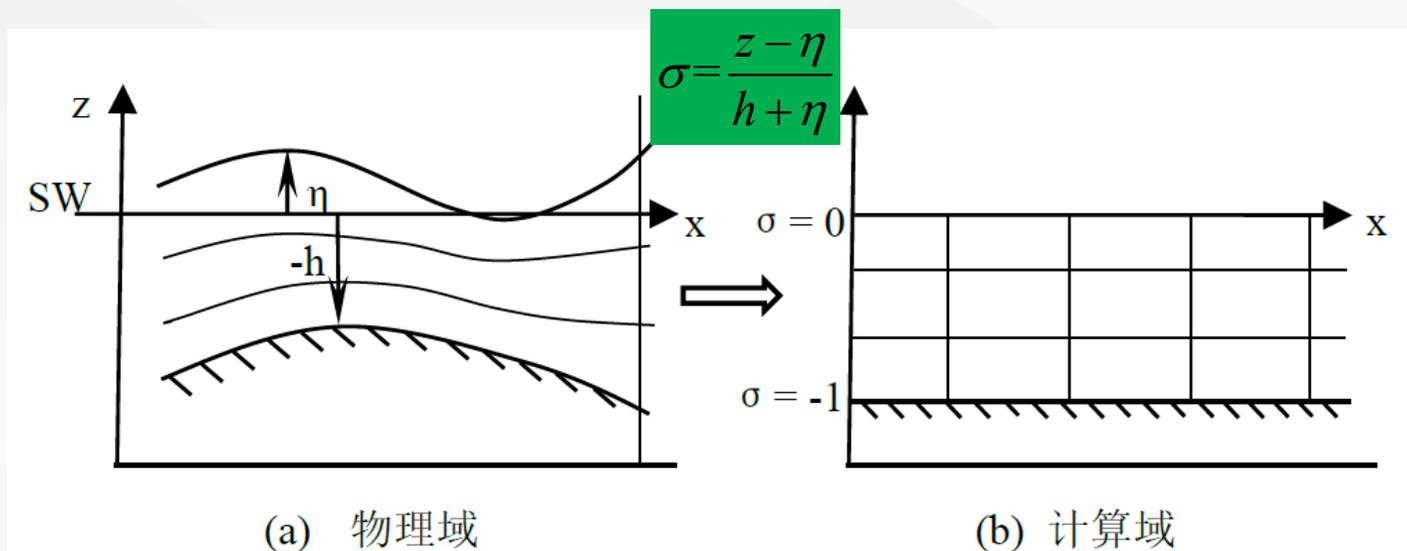
污染物迁移的数值模拟





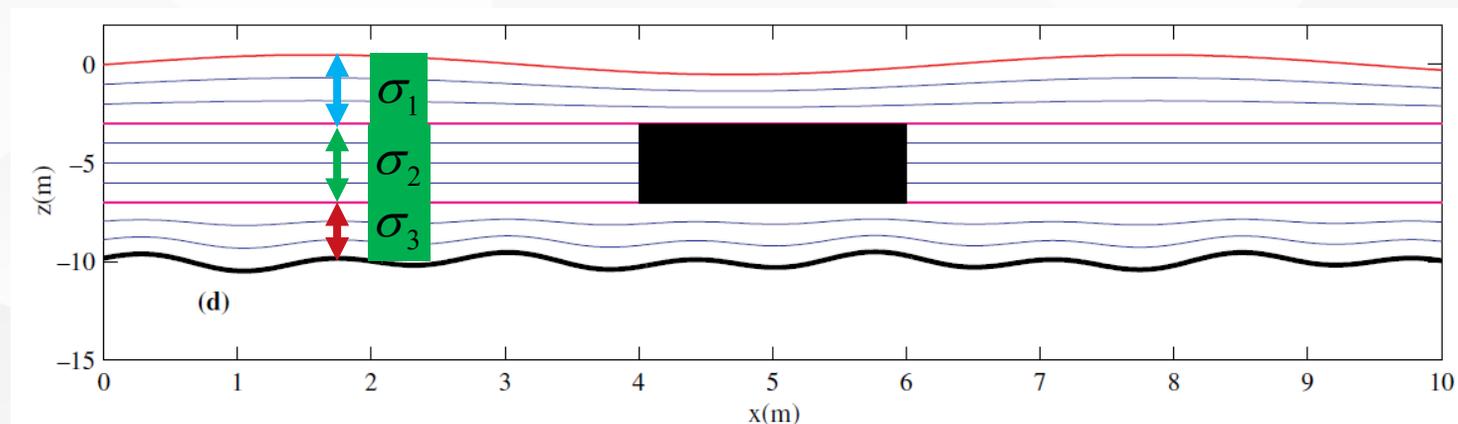
计算网格系统的优点

- 充分利用浅水方程的自由液面的计算手段——效率高
- 自动捕捉自由液面和床面



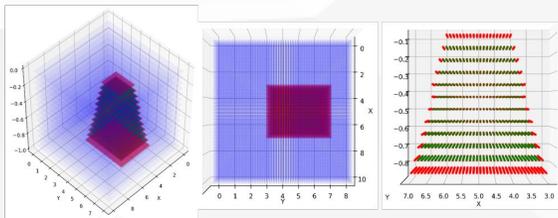
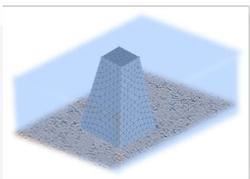
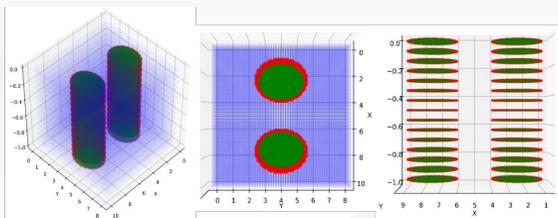
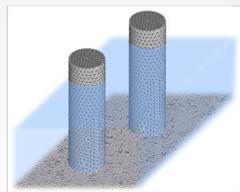
计算网格系统的不足

- 垂向流体域需连通
- 淹没固体难模拟



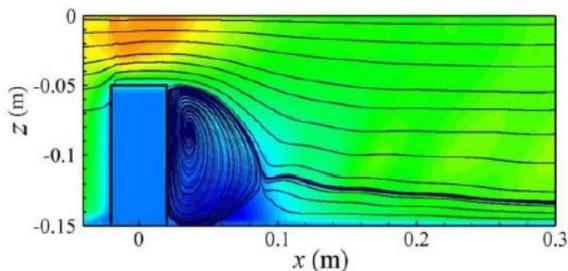
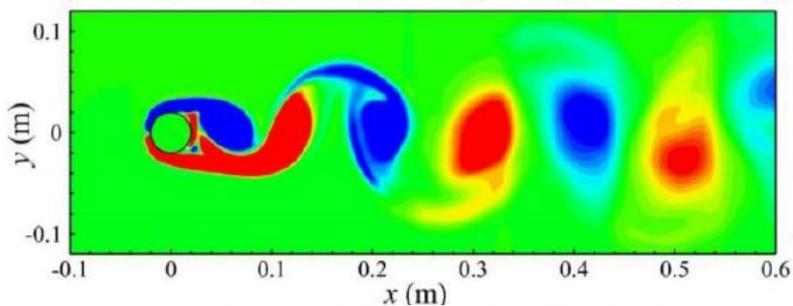


流固耦合IBM模拟——静止结构

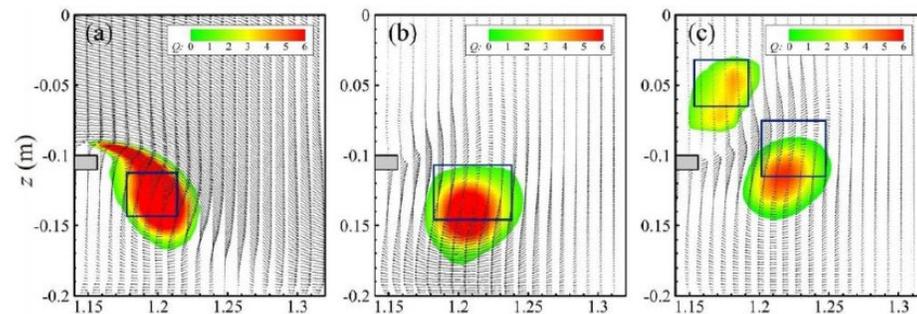
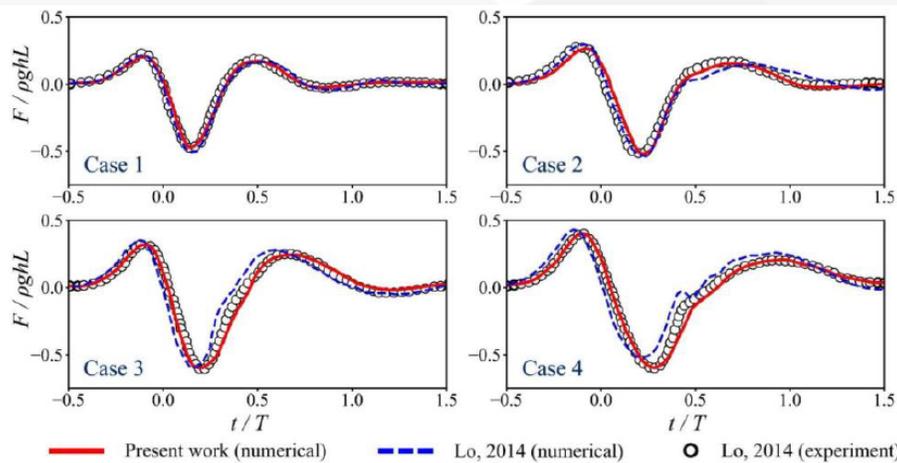
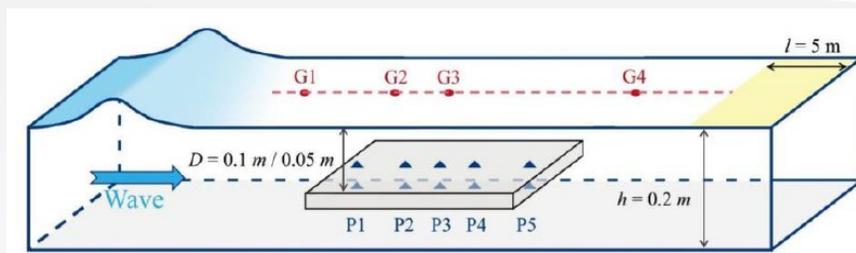


● Fluid cells ● Solid cells ★ Ghost cells

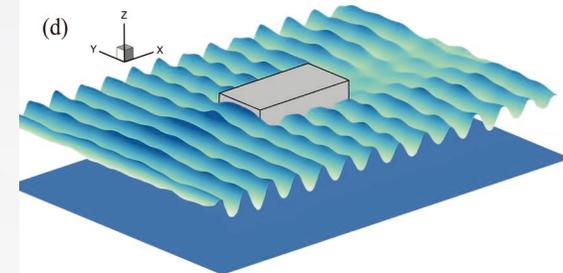
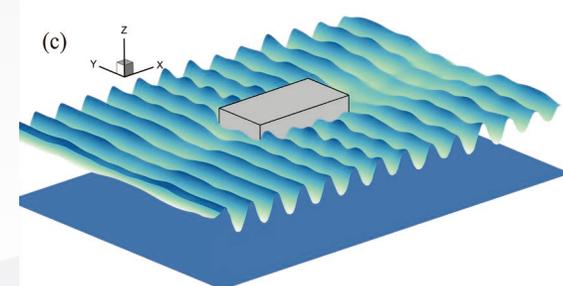
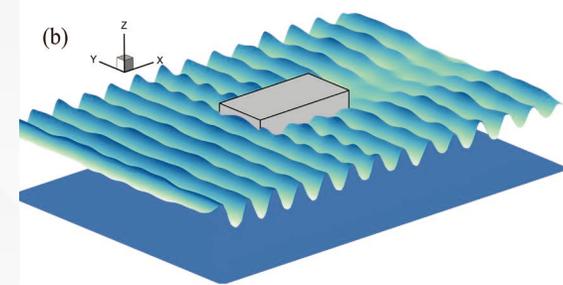
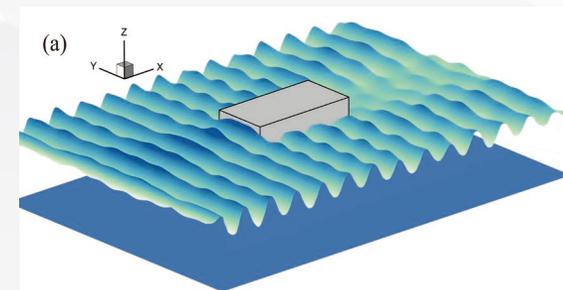
边界识别



结构物绕流

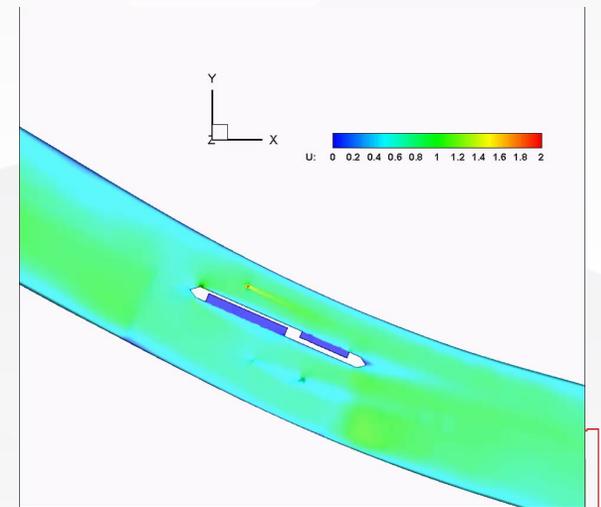
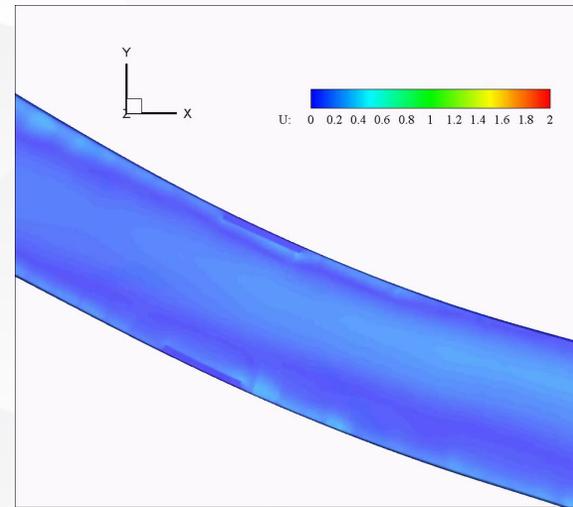
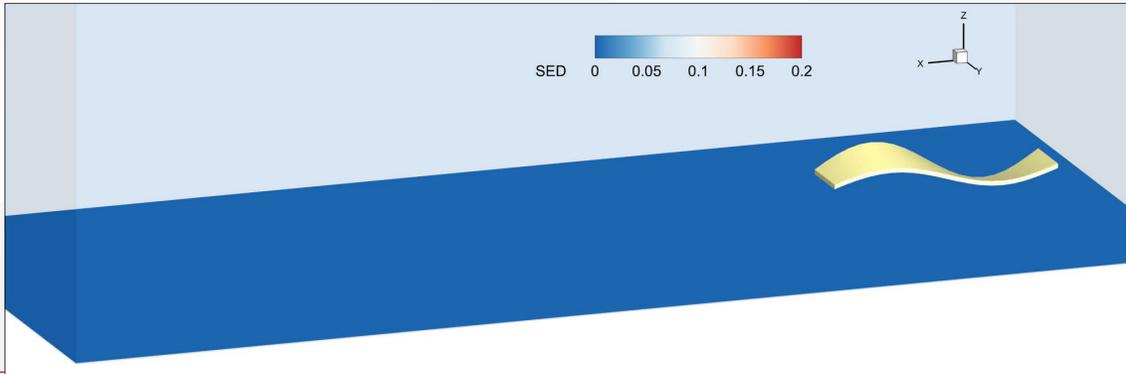
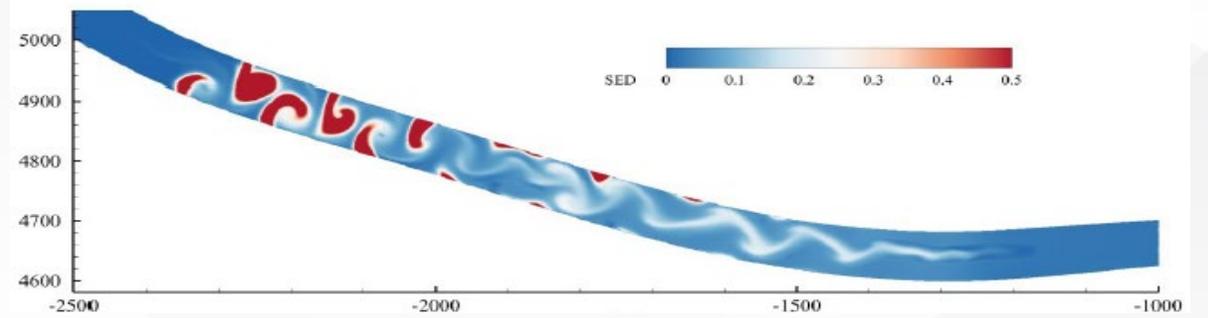
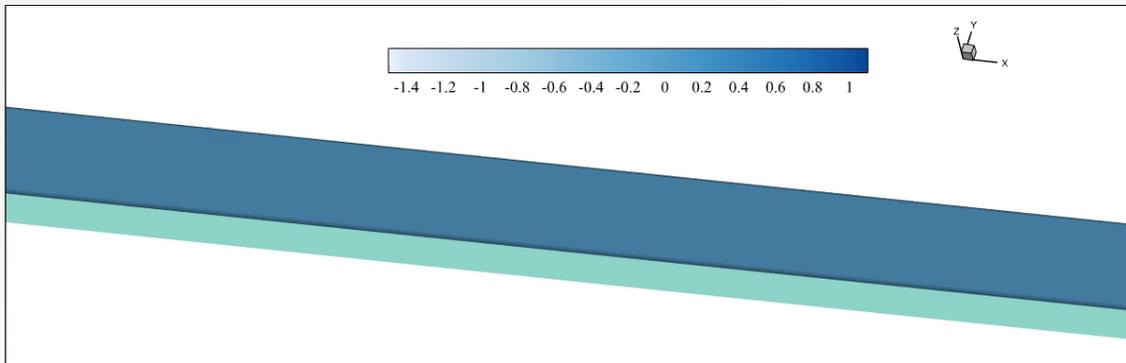
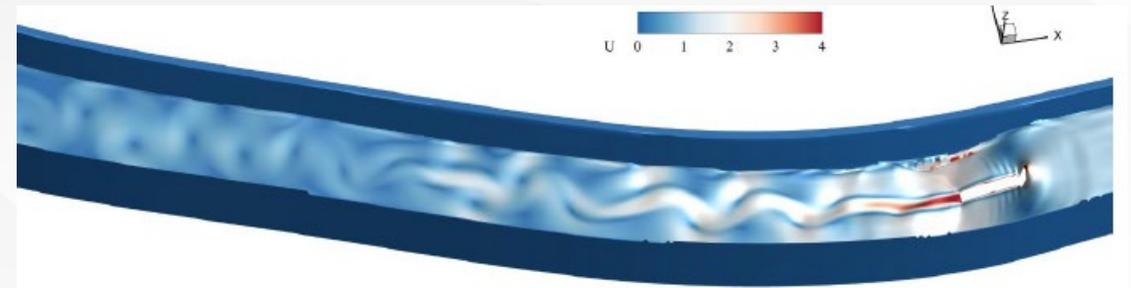
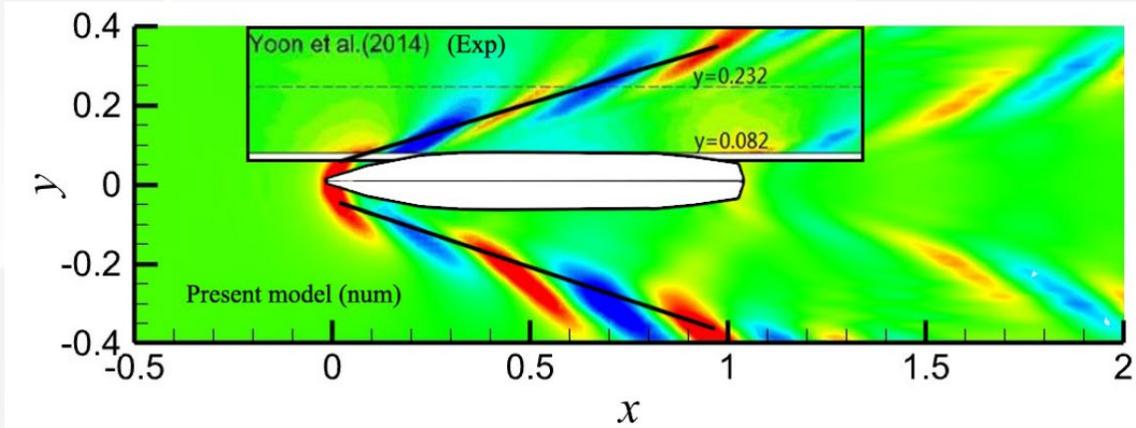


浮式结构物波浪作用





流固耦合IBM模拟——运动机构

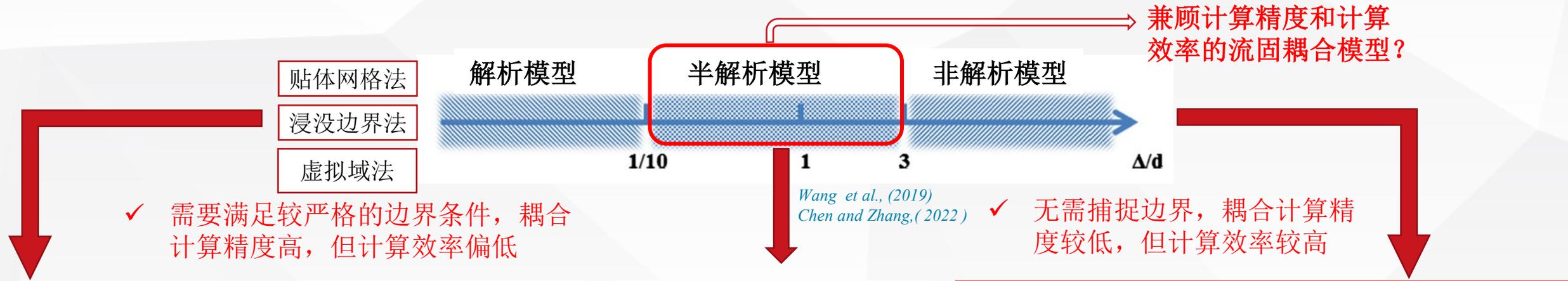




流固耦合模拟——CFD & DEM

数值模型研究现状

空间耦合：可根据是否完全求解固体周围流场，并根据流场结果计算流体作用力分为解析模型和非解析模型



- 贴体网格法
- 浸没边界法
- 虚拟域法

贴体网格法 浸没完整边界法 虚拟域法

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$r(s,t)$

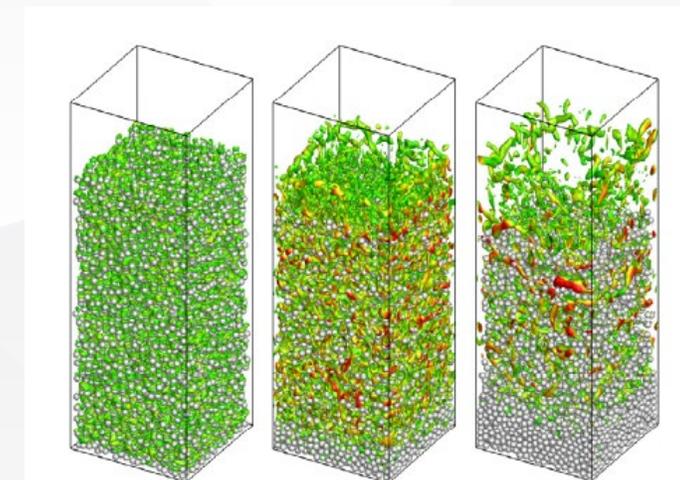
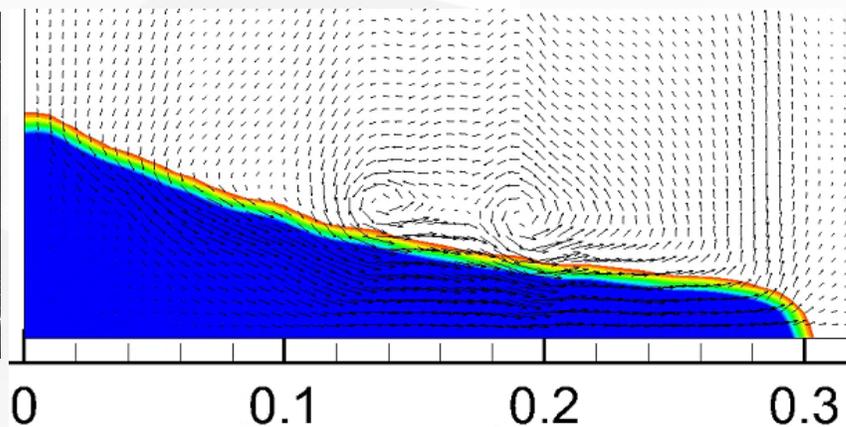
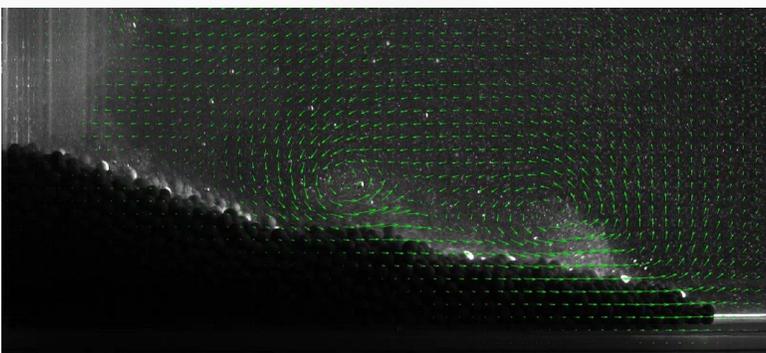
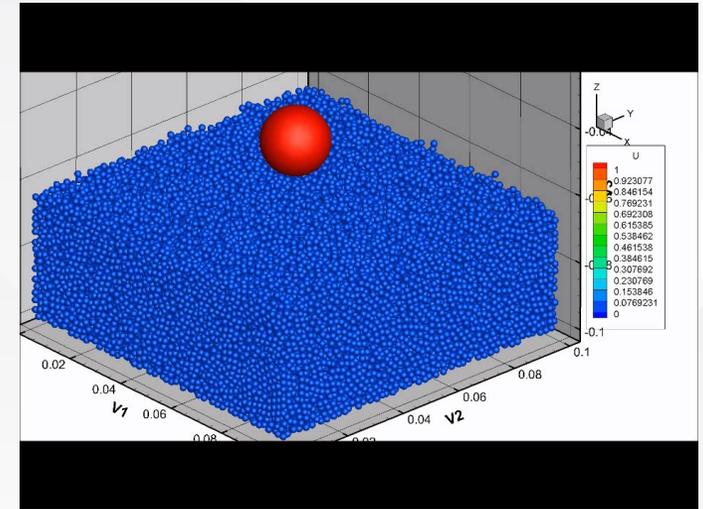
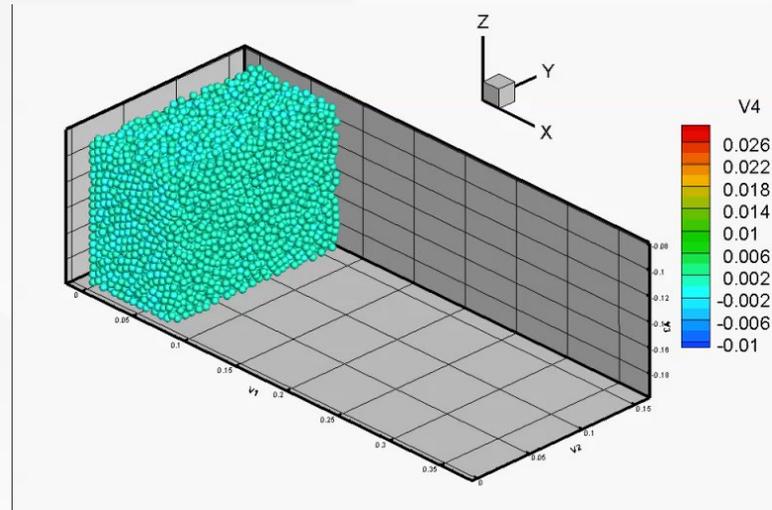
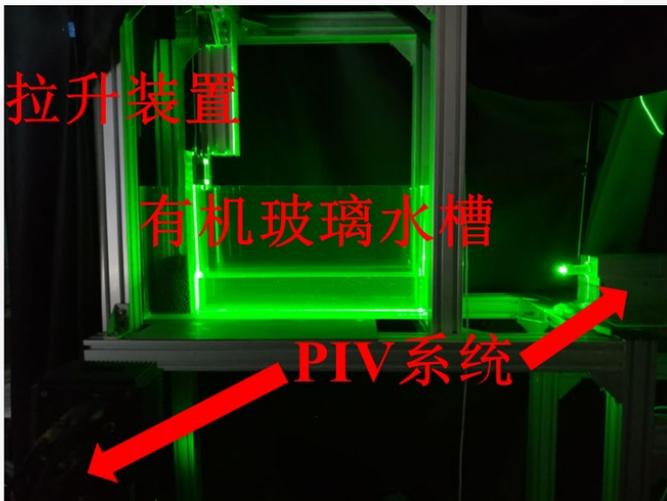
x (流场网格)



流固耦合模拟——CFD & DEM



◆ 基于域扩展的高精度CFD-DEM耦合模型

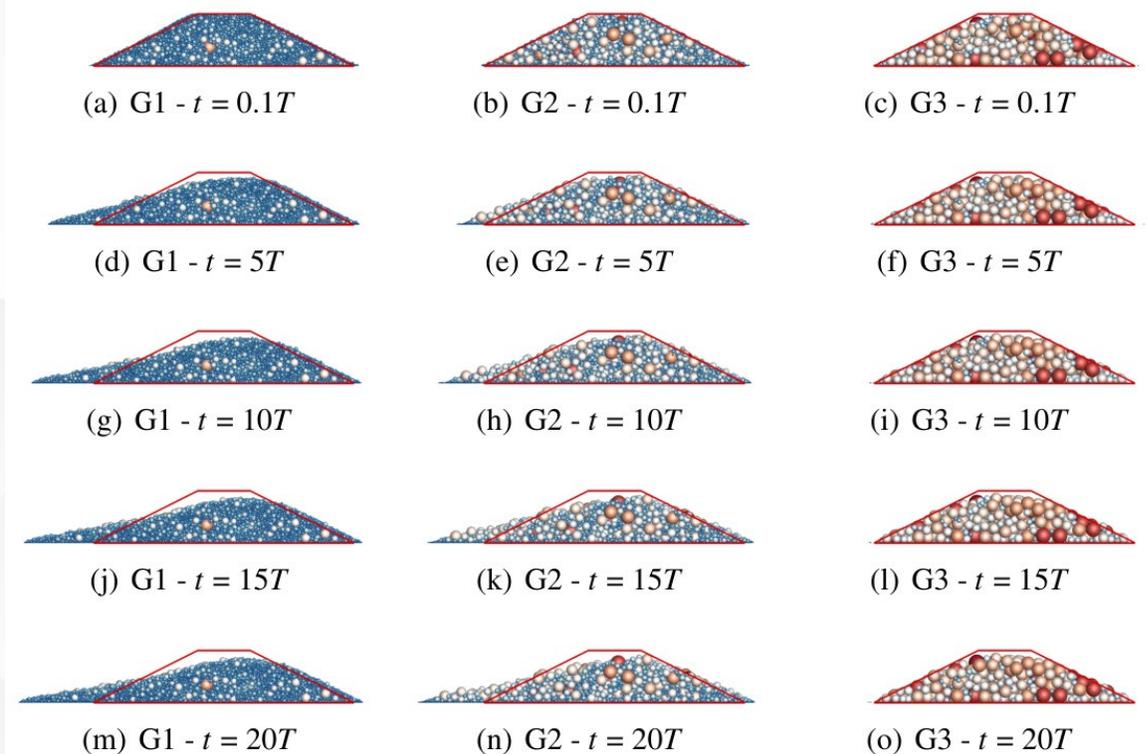
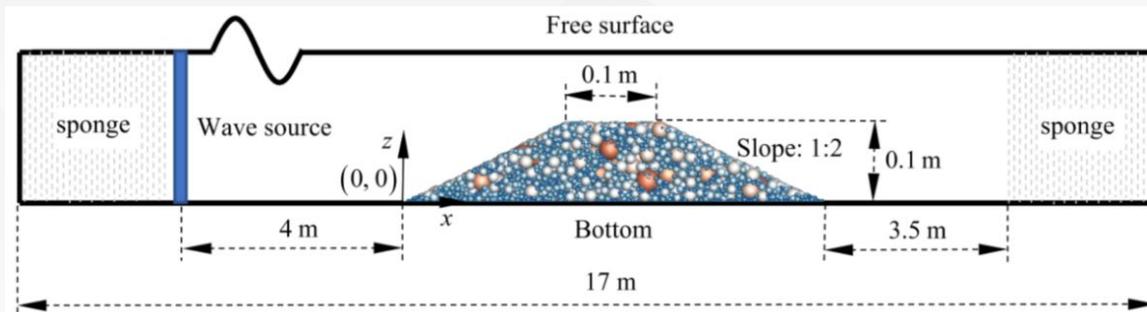
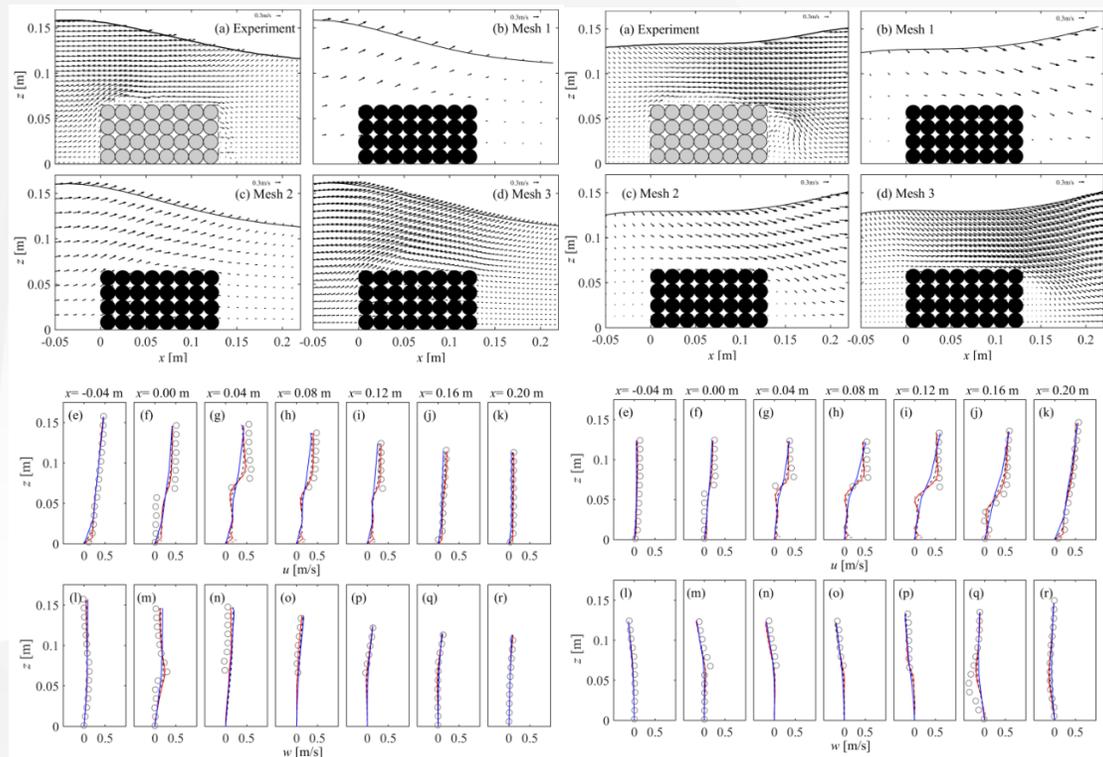
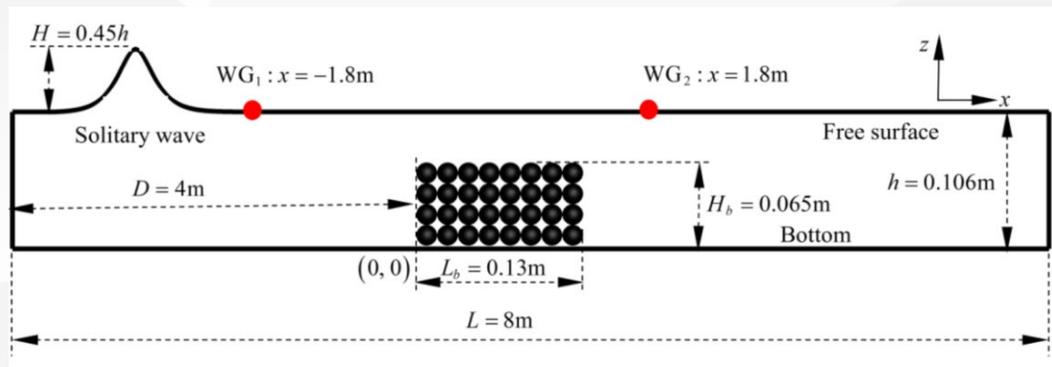


颗粒堆坍塌模拟





流固耦合模拟——CFD & DEM



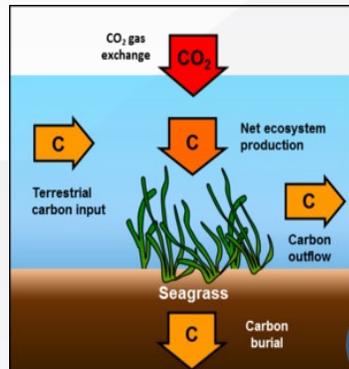
透水结构的水动力特征

碎石体的波致损毁



流固耦合—植被水流模拟

生化环境



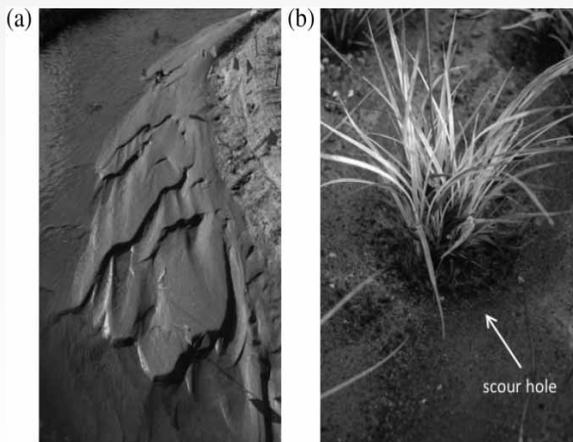
食物链



河道减阻



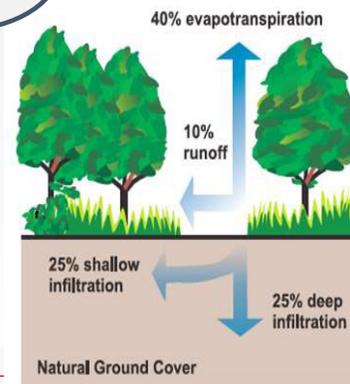
河床地貌



防洪林



降雨截留





流固耦合—植被水流模拟



弹性细杆流固耦合模拟

离散形式的运动微分方程和拉伸控制方程

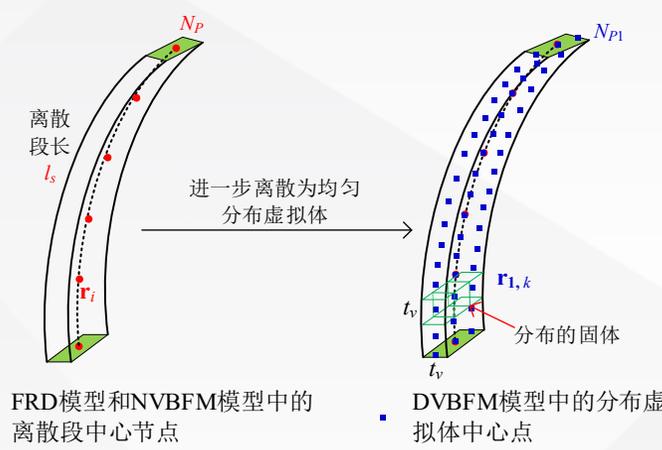
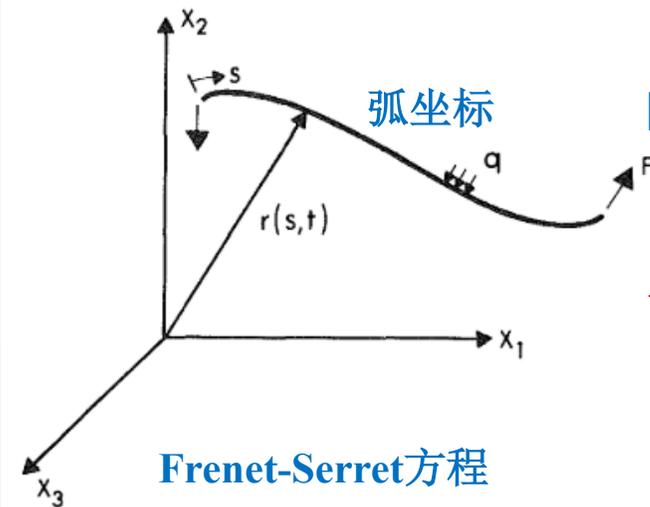
$$\begin{cases} M \ddot{\mathbf{r}} + \rho_f A_f C_m \dot{\mathbf{r}}^N + (EI r''')'' - (\bar{\lambda} \mathbf{r}')' = \bar{\mathbf{w}} + \bar{\mathbf{F}}_d \\ \mathbf{r}' \cdot \mathbf{r}' = 1 + 2 \frac{\lambda}{EA_t} \end{cases}$$

伽辽金法积分得到求解非线性方程组

$$\begin{cases} (M_{ijkl} + M_{ijkl}^a) \ddot{U}_{jk} + (K_{ijkl}^1 + \lambda_n K_{nijlk}^2) U_{jk} - F_{il} = 0 \\ A_{mlk} U_{jl} U_{jk} - B_m - C_{mn} \varepsilon_n = 0 \end{cases}$$

Taylor公式

$$\begin{bmatrix} K_{ijkl}^{t1(n)} & K_{iln}^{t2(n)} \\ D_{mjk}^{t1(n)} & D_{mn}^{t2(n)} \end{bmatrix} \begin{Bmatrix} \Delta U_{jk} \\ \Delta \lambda_n \end{Bmatrix} = \begin{Bmatrix} (\bar{\mp}) R_{il}^{(n)} \\ -G_m^{(n)} \end{Bmatrix}$$



插值算法

$$\psi_{k,j} = \begin{cases} f(\mathbf{R}_{kj}, \sigma_0) V_j / \sum_{j=1}^{NC} (f(\mathbf{R}_{kj}, \sigma_0) V_j), & \|\mathbf{R}_{kj}\| \leq 0.5 D_e \\ 0, & \|\mathbf{R}_{kj}\| > 0.5 D_e \end{cases}$$

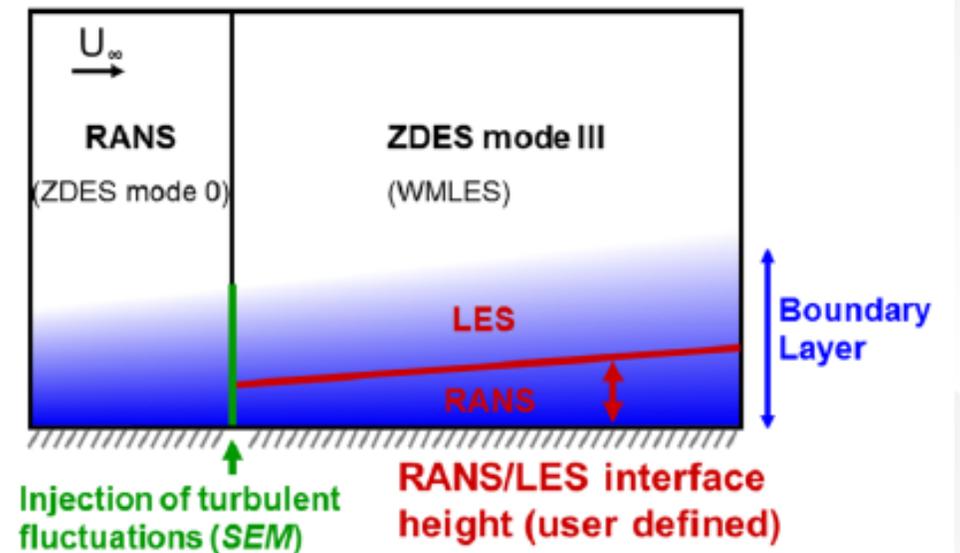
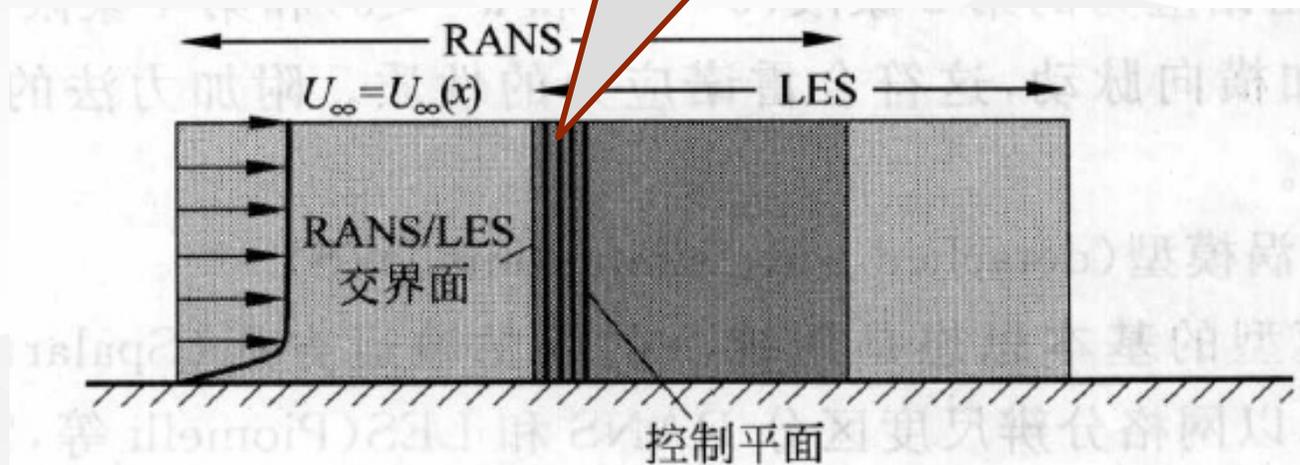
$$\begin{aligned} \varphi_k &= \sum_{j=1}^{NC} (\psi_{k,j} \varphi_j) \\ \mathbf{u}_k &= \sum_{j=1}^{NC} \psi_{k,j} \mathbf{u}_j, \quad \dot{\mathbf{u}}_k = \sum_{j=1}^{NC} \psi_{k,j} \dot{\mathbf{u}}_j \\ k_{f,k} &= \sum_{j=1}^{NC} \psi_{k,j} k_{f,j}, \quad \omega_{f,k} = \sum_{j=1}^{NC} \psi_{k,j} \omega_{f,j} \end{aligned}$$



带自由水面流动的高精度模拟

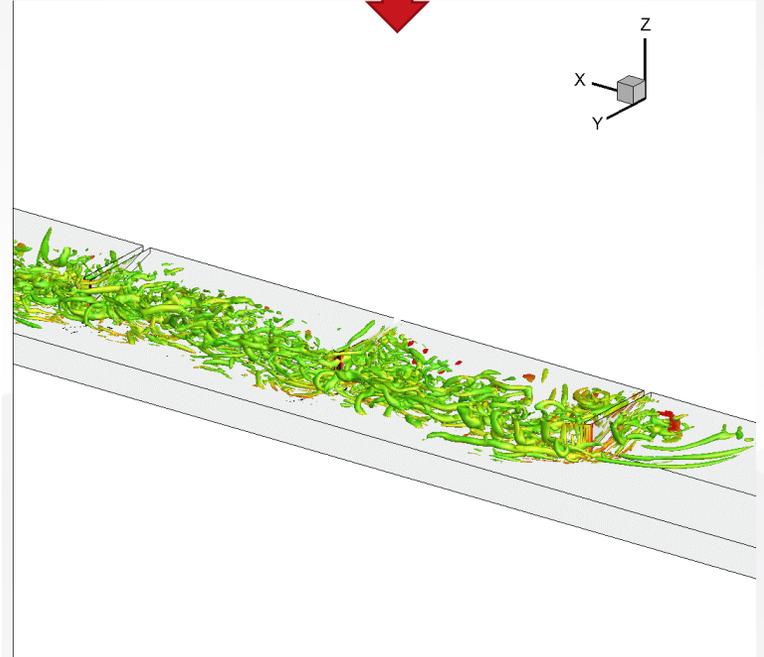
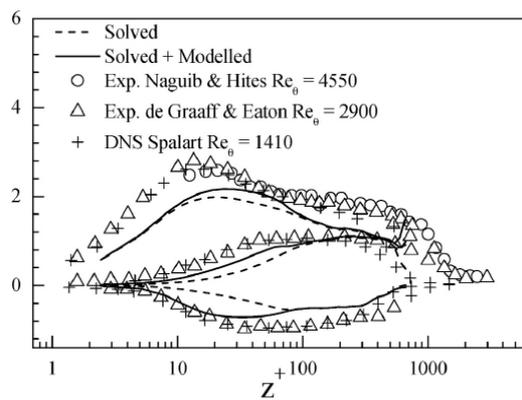
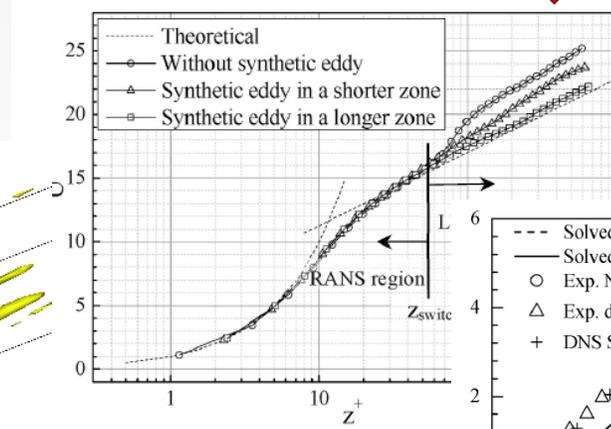
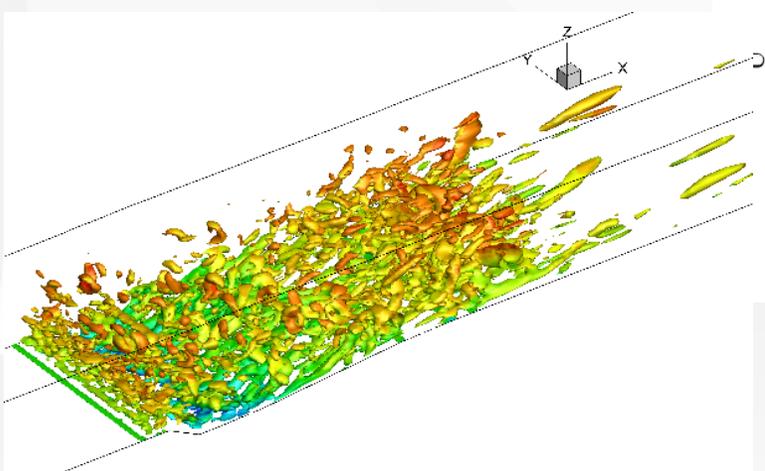
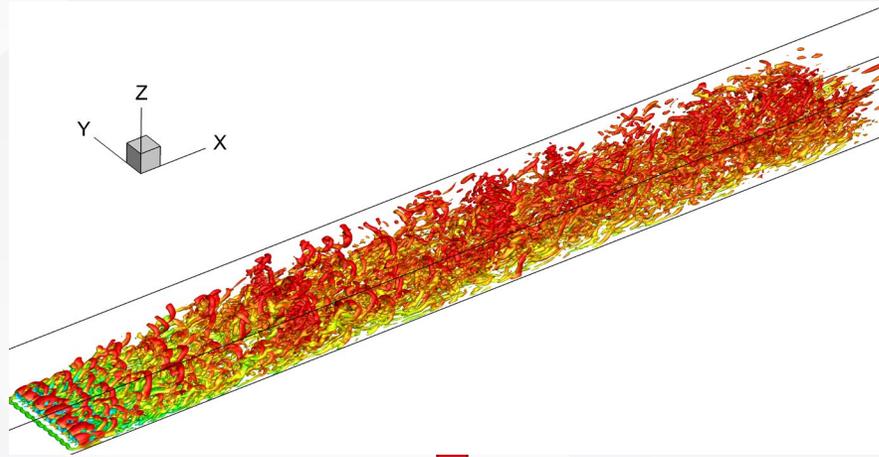
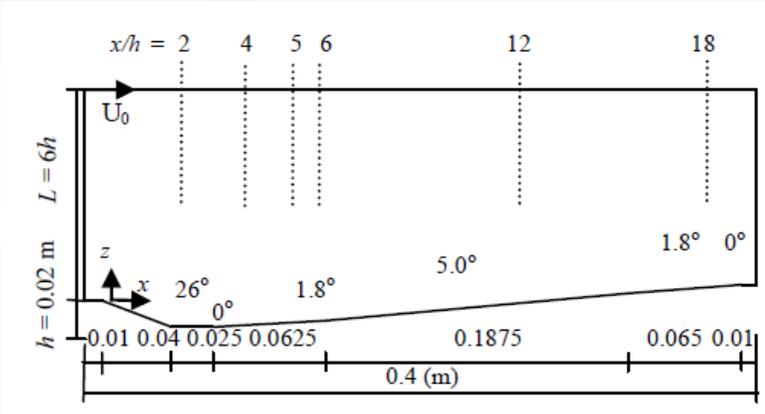
- 复杂边界下高雷诺数流动模拟 (DNS, LES) 的困难
- 混合模型的实用性
- 混合模型种类
 - 混合湍流模型 (涡尺度混合)
 - 界面分区模型

交界面数据交换





带自由水面流动的高精度模拟





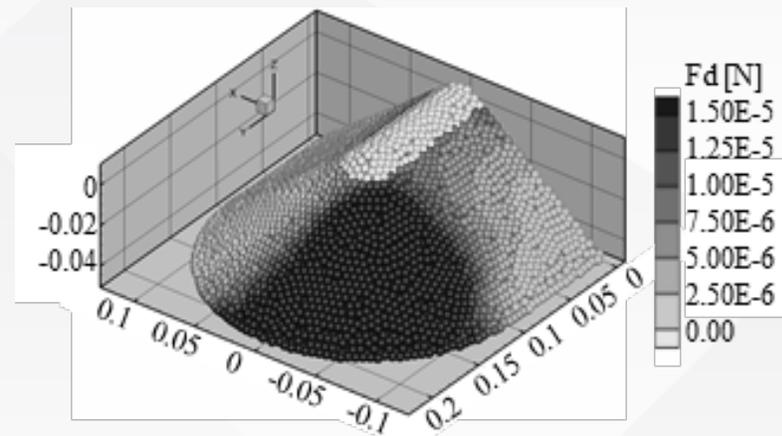
水工结构物的局部冲刷数值模拟



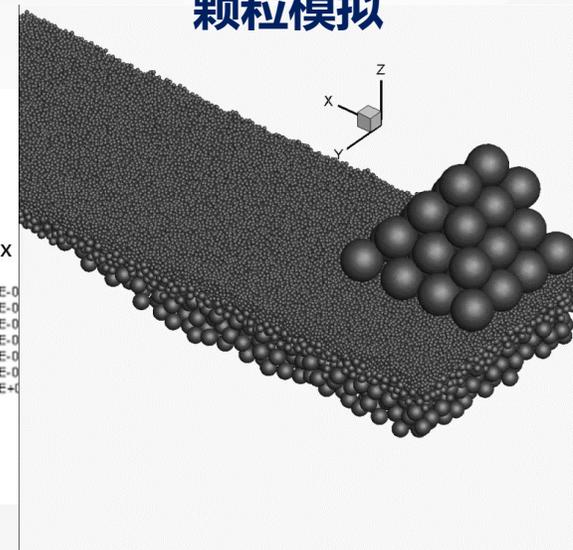
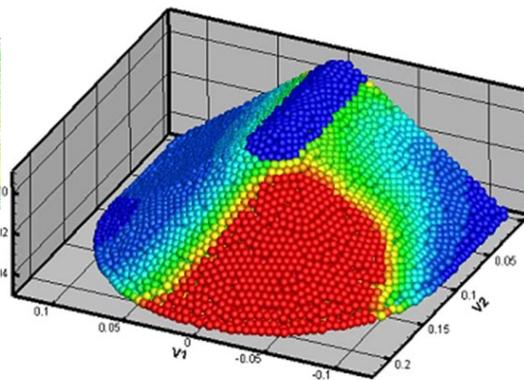
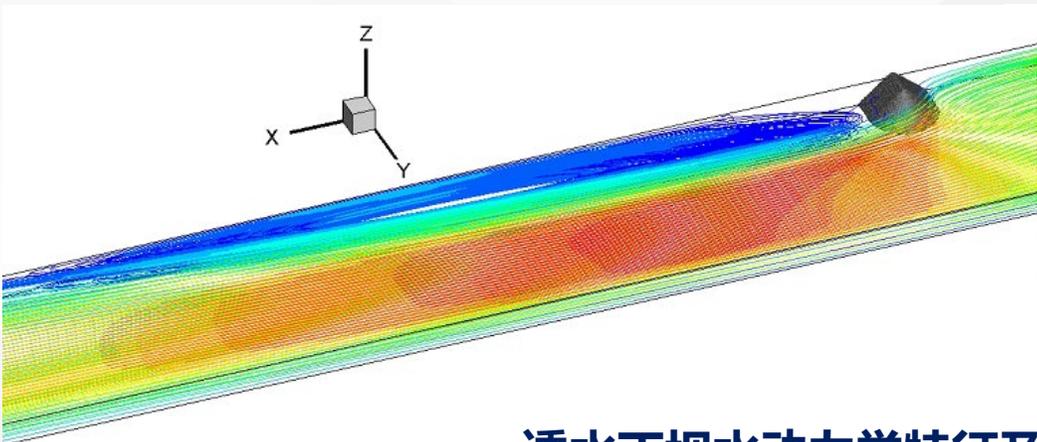
局部泥沙颗粒运动的细观行为研究



透水丁坝损毁



颗粒模拟



透水丁坝水动力学特征及稳定性分析

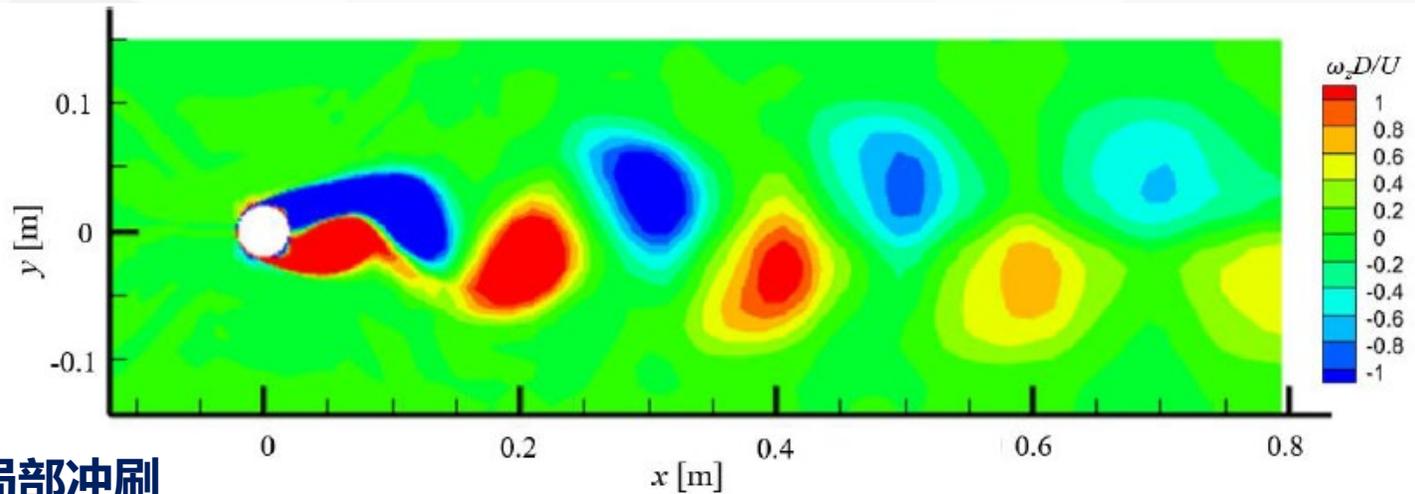
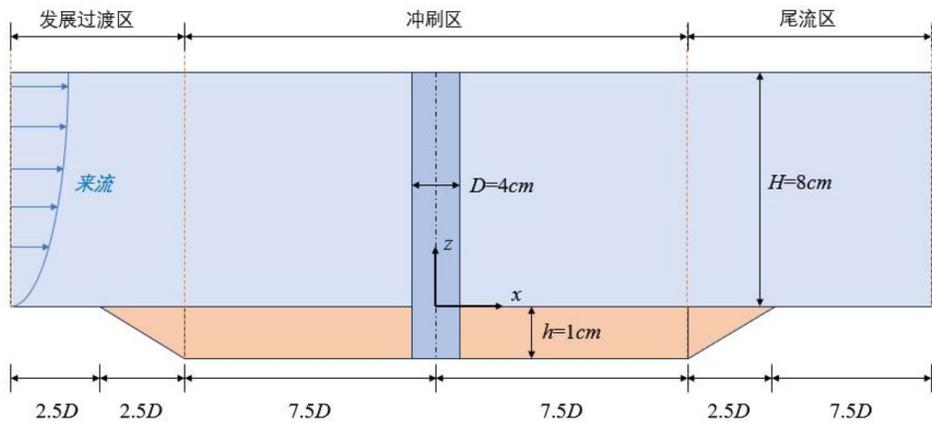
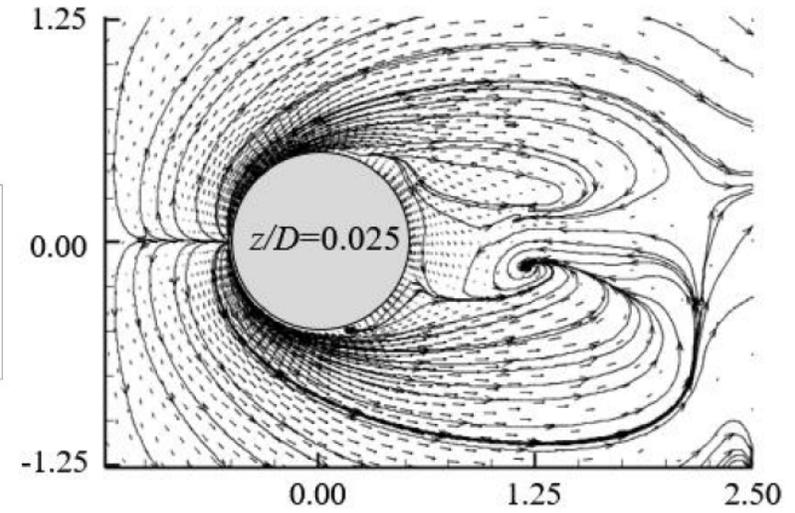
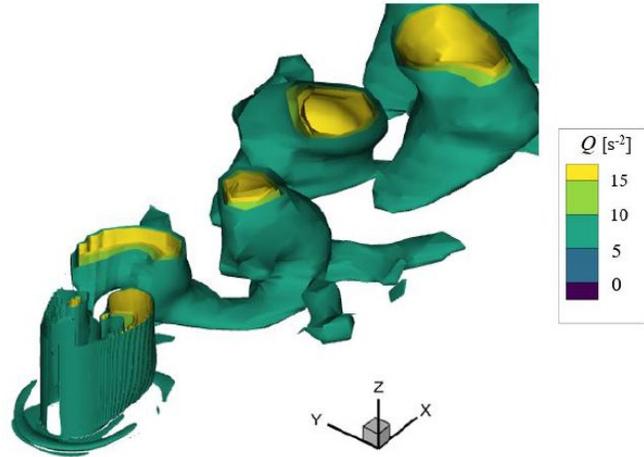
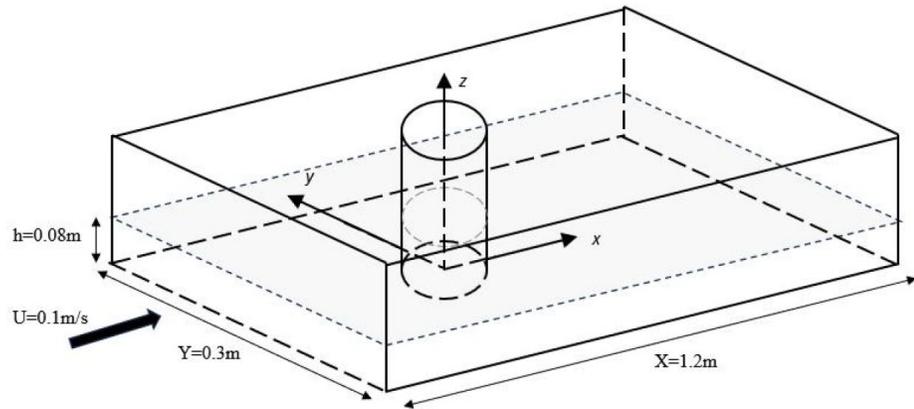




水工结构物的局部冲刷数值模拟



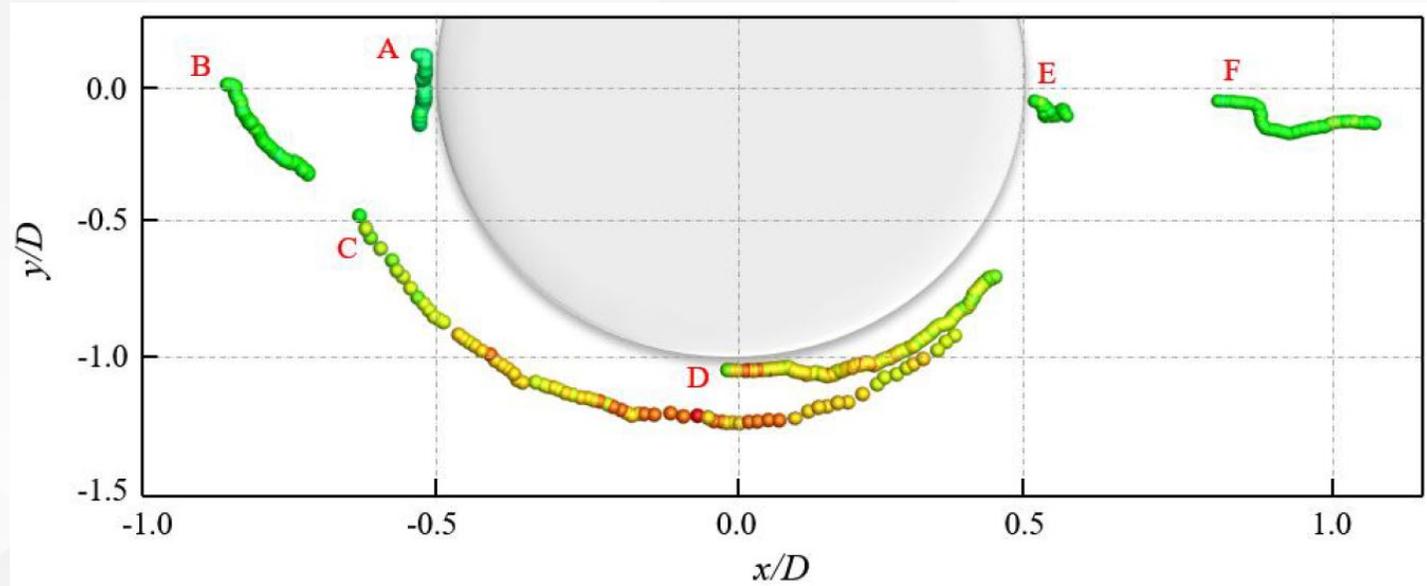
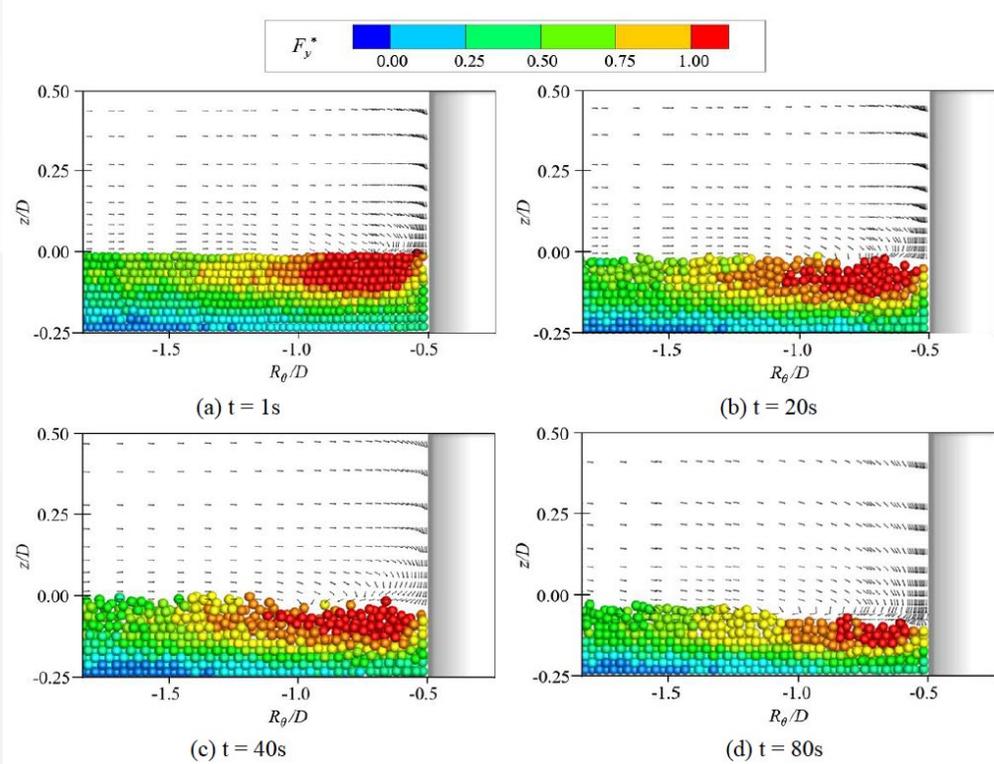
局部泥沙颗粒运动的细观行为研究



圆柱局部冲刷



水工结构物的局部冲刷数值模拟



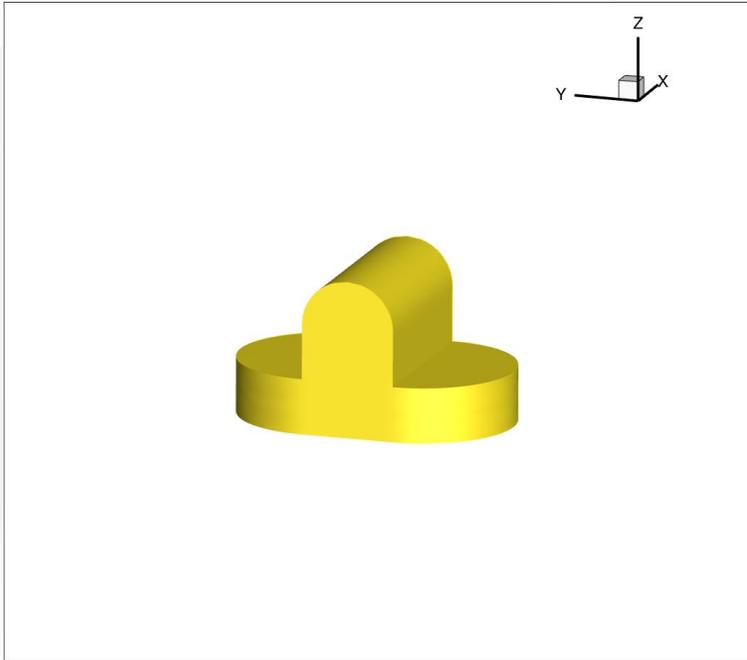
圆柱局部颗粒运动

- 精细至单颗粒流固耦合运动模拟
- 机理研究深入

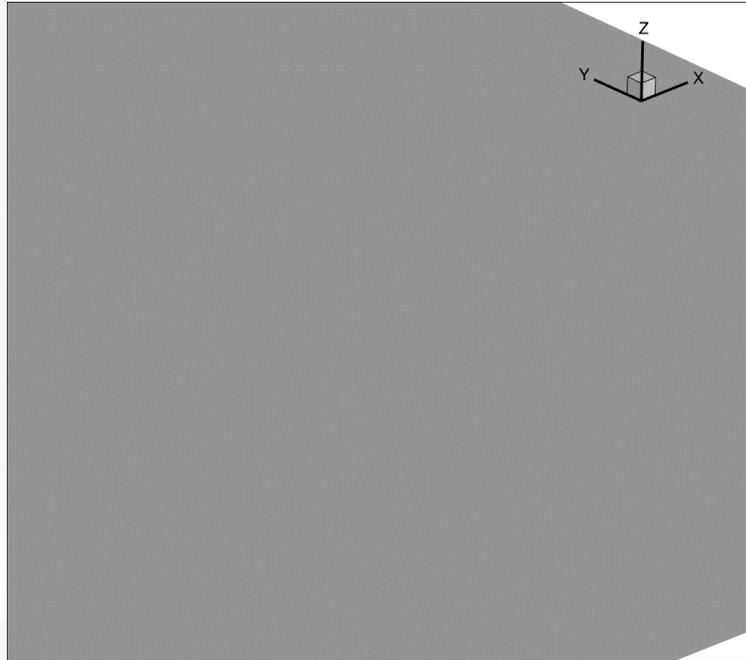
- 计算消耗大
- 难以工程应用



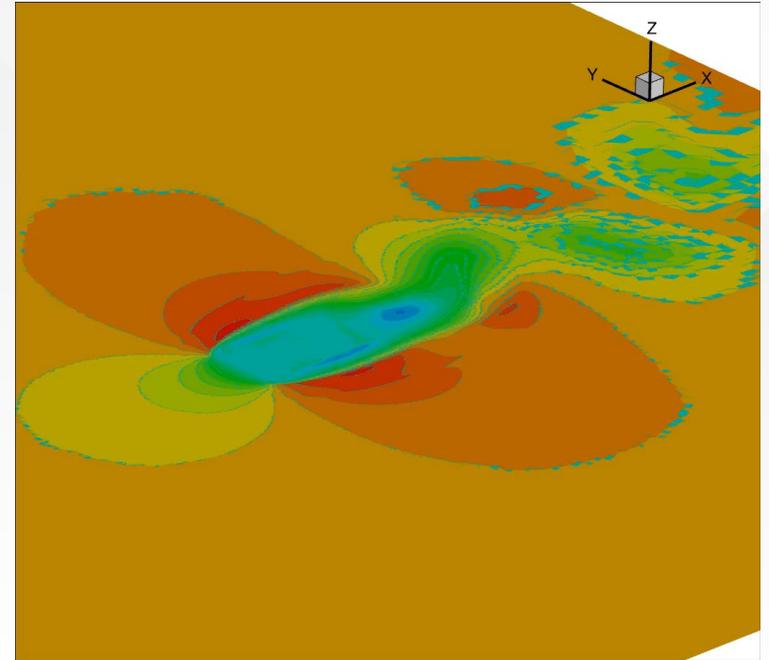
局部冲刷的连续相数值模型



复合结构



局部冲刷及悬沙输运



局部冲刷及局部流速



提高精度

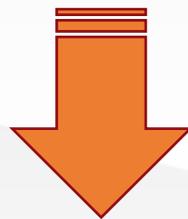
- LES/RANS
- 高阶数值格式

提升效率

- MPI/OpenMP
- 异构型平台CPU+GPU

拓宽应用

- 多场耦合
- 工程实际场景



仿真系统平台



谢谢

饮水思源 爱国荣校